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ENGINEERING

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Semester - 5 Electrical & Electronics Engineering

Power System - I

- Topic-wise coverage of entire syllabus in Question-Answer form.
- Short Questions (2 Marks)

Includes solution of following AKTU Question Papers
2015-16 • 2016-17 • 2017-18 • 2018-19 • 2019-20

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KEE–501 : POWER SYSTEM - I

UNIT 1

Power Generation

CONTENTS

PART-1

Introduction : Basic Structure of Power System, Sources of Electric Energy : Conventional and Non Conventional, Layout of Hydro Electric, Thermal and Nuclear Power Plants.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 1.1. **Draw the basic structure of power system.**

Answer

An electrical power system is a network of electrical elements that are used to transfer the power from the power stations to the end consumers. A power system has three main stages :

1. **Generation :** The place where power is generated is known as 'power plant' or 'power house'.

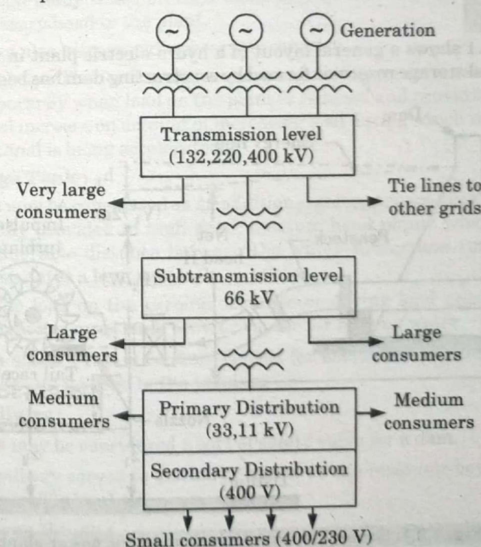

Fig. 1.1.1.

2. **Transmission :** Transmission of electrical supply is the part of a power system where the electric supply is transmitted from one station to another station.
3. **Distribution :** Distribution of power supply is the part of power system where the supply is distributed among the consumers.

Que 1.2. **Explain the conventional and non-conventional energy sources.**

Answer

A. **Conventional energy sources :** The conventional sources of energy are generally non-renewable source of energy. These are the sources of energy which are exhaustible *i.e.*, cannot be replaced if once they are used, e.g., coal, petroleum, natural gas, etc.

B. **Non-conventional energy sources :** Non-conventional source of energy are generally renewable source of energy. These are the sources of energy which are inexhaustible *i.e.*, can be used to produce energy again and again, e.g., solar, wind, etc.

Que 1.3. **Give general layout and function of essential element of hydro-electric power plant.**

Answer

1. Fig.1.3.1 shows a general layout of a hydro-electric plant in which an artificial storage reservoir formed by constructing dam has been shown.

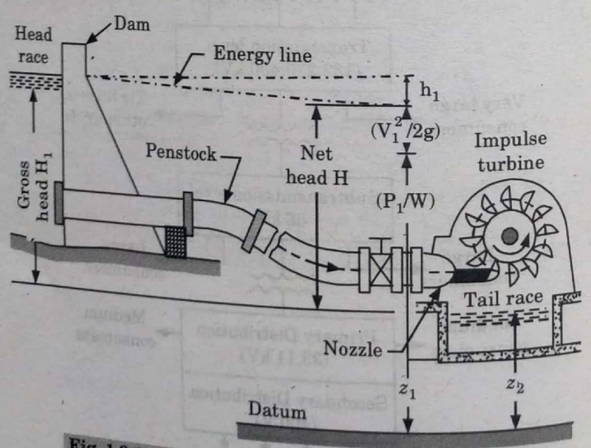

Fig. 1.3.1. General layout of a hydro-electric power plant.

2. The water surface in the storage reservoir is known as head race level or simply head race.
3. Water from the storage reservoir is carried through penstocks or canals to the power house.
4. Penstocks are pipes of large diameter usually made of steel wood or reinforced concrete which carry water under pressure from the storage reservoir to the turbine.
5. Water after passing through the turbines is discharged to the tail race.
6. The tail race is the channel which carries water (known as tail water) away from the power house after it has passed through the turbine.

Functions of different Components in storage reservoir plants

1. **Reservoir :**
   i. It is a basic requirement of a hydro-electric plant.
   ii. Its purpose is to store water which may be utilised to run the prime mover to produce electrical power.
   iii. A reservoir stores water during the rainy season and supplies the same during the dry season.
2. **Dam :**
   i. The function of dam is to provide a head of water to be utilised in the water turbine.
   ii. Though many times all high dams may be built solely to provide the necessary head to the plant.
   iii. A dam also increases the reservoir capacity.
3. **Forebay :** The forebay serves as a regulating reservoir storing water temporarily when load on the plant is reduced and providing water for initial increase on account of increasing load during which time water in the canal is being accelerated.
4. **Surge Tank :**
   i. This may be considered as an additional storage space near the turbine, usually provided in high-head, medium head plants when there is a considerable distance between the water source and turbine which necessitates a long penstock.
   ii. As the load on the turbine decrease or during load rejection by the turbine the surge tank provides space for holding water.
5. **Pen stock :** It is a conduit system for taking water from the intake works and forebay to the turbines.
6. **Spillway :**
   i. This may be considered a sort of safety valve for a dam.
   ii. A spillway serves to discharge excess in the reservoir beyond the full permissible level.
7. **Power House :**
   i. It is generally located at the foot of the dam and near the storage reservoir.

ii. If the power house is near the dam, the loss of head due to friction in the penstock would be less.

8. **Prime Mover :**

i. The purpose of prime mover is to convert kinetic energy of water into mechanical energy.

ii. Commonly used prime movers are Pelton wheel, Francis, Kaplan and propeller turbines.

Que 1.4. **Give the layout of a modern thermal power plant and explain it briefly.**

Answer

The layout of a modern thermal power plant comprises of the following four circuits :

1. **Coal and ash circuit :** Coal arrives at the storage yard and after necessary handling, passes on to the furnaces through the fuel feeding device. As resulting from combustion of coal, it collects at the back of the boiler and is removed to the ash storage yard through ash handling equipment.

2. **Air and gas circuit :** Air is taken in from atmosphere through the action of a forced or induced draught fan and passes on the furnace through the air pre-heater, where it has been heated by the heat of flue gases which passes to the chimney via the pre-heater.

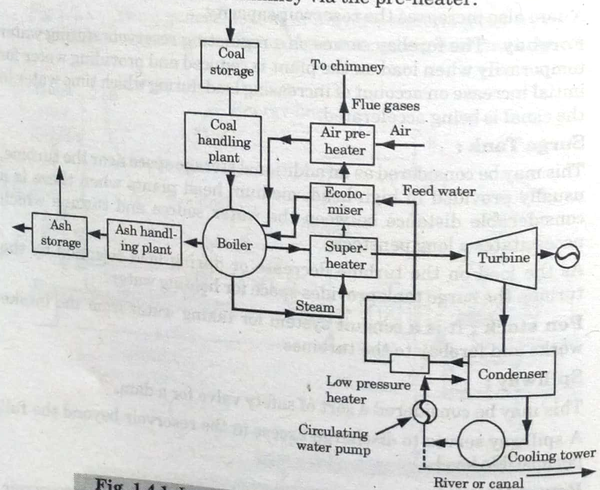

Fig. 1.4.1. Layout of a thermal power plant.

3. **Feed water and steam flow circuit :** Water and the condensed steam leaving the condenser is first heated in a closed feed water heater through extracted steam from the lowest pressure extraction point of the turbine. It then passes through the deaerator and a few more water heaters before going into the boiler through economiser.

4. **Cooling water circuit :** The cooling water supplied to the condenser helps in maintaining a low pressure in it. The water may be taken from a natural source such as river, lake or sea or the same water may be cooled and circulated over again.

Que 1.5. **Give general layout and operation of nuclear power plant.**

Answer

1. A nuclear power system consists of the following :

a. A controlled fission heat source.

b. A coolant system to remove and transfer the heat produced.

c. Equipment to convert the thermal energy contained in the hot coolant to electric power.

2. Regardless of the type of fission heat sources used, the basic mechanism is fission of nuclear fuel to produce thermal energy.

3. This thermal energy is removed from the heat source by contacting the fuel with a coolant which can be used directly as the working fluid.

4. In some cases, an intermediate heat-transfer loop is inserted between the reactor coolant and the working fluid, to increase isolation of the radioactive reactor coolant from the conventional power-producing equipment. The working fluid is then used to drive a turbo-generator set to produce electrical power.

5. Nuclear power system differ in a number of respects from fossil-fuel systems some of more important consideration that differentiate nuclear.

6. The schematic representation of nuclear power systems using the direct and indirect heat transfer approaches are as shown in Fig. 1.5.1 and Fig. 1.5.2.

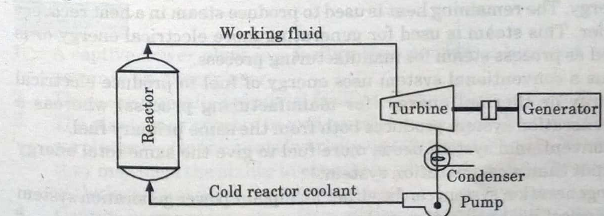

Fig. 1.5.1. Direct cycle, reactor coolant used as the working fluid.

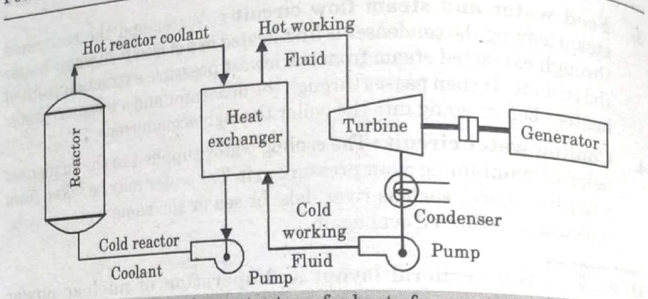

Fig. 1.5.2. Indirect cycle reactor transfer heat of separate working fluid.

PART-2

Concept of Cogeneration, Combined Heat and Power, and Captive Power Plants.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 1.6. **Explain the concept of cogeneration (combined heat and power).**

Answer

1. Cogeneration means sequential conversion of energy contained in fuel into two or more usable forms.
2. In one manifestation the energy of coal is converted into heat in the boiler to produce steam. This steam is used to generate electrical energy and in addition provides heat for manufacturing process.
3. In another manifestation gas is used in gas turbine to generate electrical energy. The remaining heat is used to produce steam in a heat recovery boiler. This steam is used for generating more electrical energy or is used as process steam for manufacturing process.
4. Thus a conventional system uses energy of fuel to produce electrical energy or thermal energy (for manufacturing process) whereas a cogeneration system produces both from the same primary fuel.
5. A conventional system needs more fuel to give the same total energy output than a cogeneration system.
6. A cogeneration system can be either an inplant power generation system or a reject heat utilisation system.
7. The inplant power generation is used in industries and is shown in Fig. 1.6.1. The industry needs both process steam and electricity.

8. In conventional method steam is produced by a boiler and electricity is either purchased from a utility or generated by a diesel generating set.
9. If cogeneration is used, the boiler is made to produce steam at a higher temperature and pressure than needed for manufacturing purposes. This steam is used in a turbine generator set to produce electricity. The exhaust steam (from turbine) is used for manufacturing purpose.

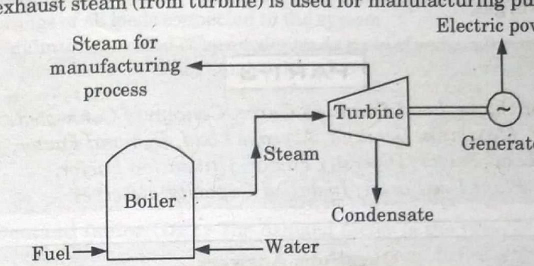

Fig. 1.6.1. Inplant power generation system (Cogeneration).

10. The reject heat utilization system is used in power plant. Some steam is extracted from the turbine (at a suitable temperature and pressure) and supplied to an adjacent industry for manufacturing purposes. This is shown in Fig. 1.6.2.

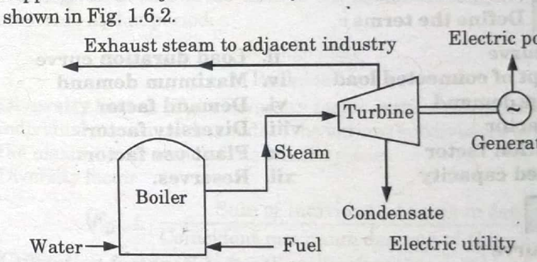

Fig. 1.6.2. Reject heat utilization system.

Que 1.7. **Discuss the captive power plants.**

Answer

1. A captive power plant is a facility that provides a localised source of power to an energy user.
2. These are typically industrial facilities, large offices or data centres.
3. The plants may operate in grid parallel mode with the ability to export surplus power to the local electricity distribution network. Alternatively they may have the ability to operate in island mode, *i.e.*, independently of the local electricity distribution system.
4. Captive power plants are a form of distributed generation, generating power close to the source of use. Distributed generation facilities the

high fuel efficiency along with minimising losses associated with the transmission of electricity from centralised power plants.

5. Gas engine can be combined with other power generation or storage technologies in microgrids.
6. Gas engines make ideal captive power plants where there is a localised supply of gas.

PART-3

Load Curve, Load Duration Curve, Concept of Connected Load, Maximum Demand, Average Load, Demand Factor, Load Factor, Diversity Factor, Utilization Factor, Plant Use Factor, Installed Capacity, Reserves.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 1.8. **Define the terms :**

i. Load curve
ii. Load duration curve
iii. Concept of connected load
iv. Maximum demand
v. Average demand
vi. Demand factor
vii. Load factor
viii. Diversity factor
ix. Utilization factor
x. Plant use factor
xi. Installed capacity
xii. Reserves.

Answer

i. **Load curve :**

1. Load curve is a graphical representation between load and time where the load in kW or (MW) and the time in hours. It shows the variation of load on the power station.

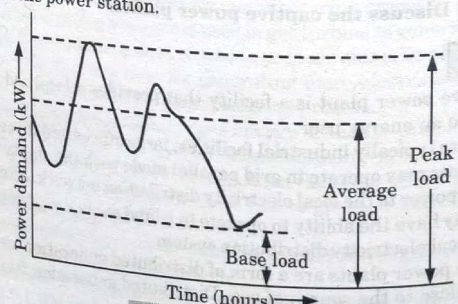

Fig. 1.8.1. Load curve.

ii. **Load duration curve :** A load duration curve represents re-arrangements of all the load elements of chronological load curve in order of descending magnitude. This curve is derived from the chronological load curve.

iii. **Concept of connected load :** Connected load is the sum of continuous ratings of all loads connected to the system.

iv. **Maximum demand :** The maximum demand of an installation or system is the greatest of all demands which have occurred during the specific period of time.

v. **Average demand :** It is the ratio of energy consumed in a given period of the time in hours.

$$\text{Average load} = \frac{\text{Energy consumed in a given period}}{\text{Hours in that time period}}$$

vi. **Demand factor (DF) :** The demand factor is the ratio of the actual maximum demand of the sytem to the total connected load of the system.

$$\text{DF} \triangleq \frac{\text{Maximum demand}}{\text{Total connected load}}$$

vii. **Load factor :** Load factor of a system is the ratio of the average load over a given period of the time to the maximum demand (peak load) occurring in that period.

$$\text{Load factor} \triangleq \frac{\text{Average load}}{\text{Peak load}}$$

viii. **Diversity factor (F_D) :** Diversity factor is the ratio of the sum of the individual maximum demands of the various subdivisions of a system to the maximum demand of the whole system.

Diversity factor

$$(F_D) \triangleq \frac{\text{Sum of individual maximum demands}}{\text{Coincident maximum demand of the whole system}}$$

ix. **Utilization factor (F_u) :** It is the ratio of maximum demand of a system to the rated capacity of the system.

$$F_u \triangleq \frac{\text{Maximum demand}}{\text{Rated system capacity}}$$

x. **Plant use factor :** Plant use factor is the ratio of kWh generated to the product of plant capacity and the number of hours for which the plant was in operation.

Plant use factor = Actual energy produced/(plant capacity * plant operation time in hours)

xi. **Installed capacity :** Installed capacity of a power system represents the maximum capacity that the system is designed to run at. It is also known as "peak installed capacity" or rated capacity.

xii. **Reserves capacity :** It is the difference between plant capacity and maximum demand.

Reserved capacity = Plant capacity – Maximum demand

Que 1.9. **The load-duration curve for a system is shown in Fig. 1.9.1. Determine the load factor.**

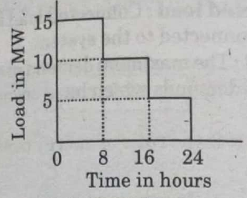

Fig. 1.9.1.

Answer

1. From the load-duration curve, the actual energy consumed $= 15 \times 8 + 10 \times 8 + 5 \times 8 = 240$ MWh
2. Average load $= \dfrac{240}{24} = 10$ MW
3. Maximum demand = 15 MW
4. Load factor $= \dfrac{\text{Average load}}{\text{Maximum demand}} = \dfrac{10}{15} = 0.666$

Que 1.10. **The yearly load duration curve of a power plant is a straight line. The maximum load is 500 MW and the minimum load is 400 MW. The capacity of the plant is 750 MW. Find (a) plant capacity factor, (b) load factor, (c) utilization factor, (d) reserve capacity.**

Answer

Given : Maximum load = 500 MW, Minimum load = 400 MW, Capacity of the plant = 750 MW

To Find : Plant capacity factor, load factor, utilization factor, reserve capacity.

1. Average annual load $= \dfrac{500 + 400}{2} = 450$ MW
2. Capacity factor $= \dfrac{\text{Average annual load}}{\text{Capacity of the plant}} = \dfrac{450}{750} = 0.6$
3. Load factor $= \dfrac{\text{Average load}}{\text{Maximum demand}} = \dfrac{450}{500} = 0.9$
4. Utilization factor $= \dfrac{\text{Maximum demand}}{\text{Capacity of the plant}} = \dfrac{500}{750} = 0.667$
5. Reserve capacity = Plant capacity – Maximum demand $= 750 - 500 = 250$ MW

PART-4

Role of Load Diversity in Power System Economy, Load Sharing Between Base Load and Peak Load.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 1.11. **What do you understand by load diversity ? Explain the role of the load diversity in power system economy.**

Answer

A. Load diversity : It is the difference between the sum of the peaks of two or more individual loads and the peak of the combined load.

$$\text{Load diversity} \triangleq \left[\sum_{i=1}^{n} D_i\right] - D_g$$

B. Role of load diversity :

1. Diversity between the loads of different consumers and different areas leads to a reduction in generation, transmission and distribution facilities.
2. The most significant time periods for considering diversity are the day and the year.
3. Daily diversity is caused by a marked and consistent difference between the daily load cycles in two or more adjoining load areas which results in peaks at different times during the day. Daily load diversity results in reduced operating expenses.
4. The benefits of daily diversity can be attained by economy energy transaction or daily diversity exchange agreements.
5. Such transactions reduce fuel expense and unit start up and shut down costs but may not have any effect on capital requirements.
6. Annual diversity usually results from a marked and consistent difference in the annual weather and customer's load requirement patterns between two or more load areas.
7. One system may have its annual peak load during winter while another may have its peak load during summer.
8. Similarly one system may have peak in the morning while another may have the evening peak.
9. Annual load diversity affords an opportunity for capital savings by reducing the installed generating capacity requirements.
10. This requires a prediction of future diversity and a commitment to a decision many years in advance of the new capacity requirements.

11. The factors which affect load diversity between systems are such that about 10 years of historical data is required before any high degree of confidence can be attributed to the future predictions.
12. These factors include temperature, weather, economic conditions, time behaviour patterns of electric users, new electric devices etc.
13. The diversity analysis is an integral part of generation capacity planning and as such should not be separated as a component since its identity does not result in fully reduced margin requirements.
14. Therefore in coordinated planning between systems, all types of diversities can be fully accounted for by combining the system loads so that adequate capacity and interconnection capability can be determined.
15. Any variation in diversity caused by statistical and historical analysis can be incorporated in the load fore-casting error.

Que 1.12. **Discuss the load sharing between base load and peak load.**

Answer

A. **Base Load :**
1. The base load is the load below which the demand never falls and is supplied 100 % of the time.
2. The base load plants are heavily loaded because continuous operation of base load plants at high load factor improves the capacity factor of these plants and this makes the operation of costly plant an economic preposition.
3. A high capital cost is permissible if low operating costs can be maintained.

B. **Peak Load :** Peak load is the maximum load supplied for a particular day. The peaking load occurs for about 15 % of the time.

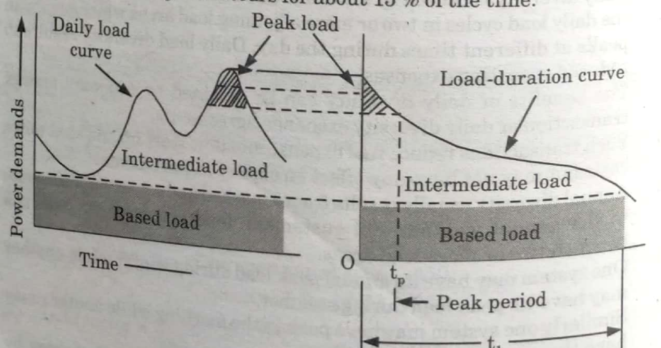

Fig. 1.12.1.

VERY IMPORTANT QUESTIONS

Following questions are very important. These questions may be asked in your SESSIONALS as well as UNIVERSITY EXAMINATION.

Q. 1. Draw the basic structure of power system.
Ans. Refer Q. 1.1, Unit-1.

Q. 2. Give general layout and function of essential element of hydro-electric power plant.
Ans. Refer Q. 1.3, Unit-5.

Q. 3. Give the layout of a modern thermal power plant and explain it briefly.
Ans. Refer Q. 1.4, Unit-1.

Q. 4. Give general layout and operation of nuclear power plant.
Ans. Refer Q. 1.5, Unit-1.

Q. 5. Explain the concept of cogeneration (combined heat and power).
Ans. Refer Q. 1.6, Unit-1.

Q. 6. Discuss the captive power plants.
Ans. Refer Q. 1.7, Unit-1.

Q. 7. Define the terms :
i. Load curve
ii. Load duration curve
iii. Concept of connected load
iv. Maximum demand
v. Average demand
vi. Demand factor
vii. Load factor
viii. Diversity factor
ix. Utilization factor
x. Plant use factor
xi. Installed capacity
xii. Reserves.
Ans. Refer Q. 1.8, Unit-1.

Q. 8. Discuss the load sharing between base load and peak load.
Ans. Refer Q. 1.12, Unit-1.

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2 UNIT

Transmission and Distribution of Electric Power-I

CONTENTS

PART-1

Single Line Diagram of Power System, Choice of Transmission Voltage, Different Kinds of Supply System and Their Comparison.

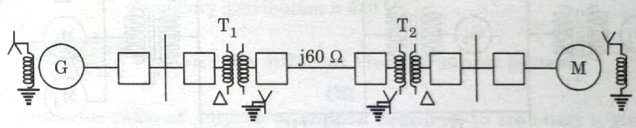
Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 2.1. **Draw and explain single line diagram of power system.**

Answer

1. The single line diagram of a power system network shows the main connections and arrangements of the system components along with their data (such as output rating, voltage, resistance and reactance etc.).



Generator	:	40 MVA, 11 kV, X″ = 20 %
Motor	:	30 MVA, 11 kV, X″ = 30 %
Transformer T_1	:	40 MVA, 11/220 kV, X″ = 15 %
Transformer T_2	:	40 MVA, 220/11 kV, X″ = 15 %

Fig. 2.1.1. Single line representation of a typical power system.

2. In a single line diagram, the system components are usually drawn in the form of their symbols.

S. No.	Components	Symbol
1.	Motor or generator	
2.	Two winding transformer	
3.	Transmission line	
4.	Liquid (oil) circuit breaker	
5.	Air circuit breaker	

6.	Delta connection	
7.	Y-connection, ungrounded	
8.	Y- connection, grounded	

Que 2.2. **Draw single line diagram of a three bus system having generator G_1 connected to bus-1 through transformer T_1, generator G_2 connected to bus-2 through transformer T_2, three synchronous motors M_1 to M_3 connected to bus-3 through transformer T_3, transmission lines TL_1, TL_2 and TL_3 connected between bus 1-2, 2-3 and 1-3 respectively.** **AKTU 2019-20, Marks 07**

Answer

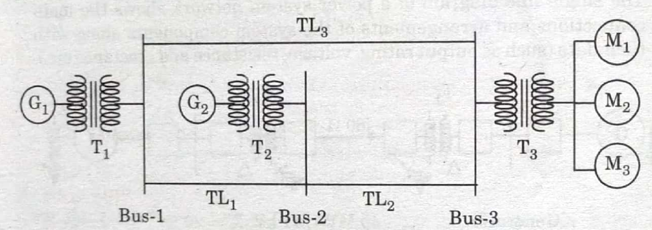


Fig. 2.2.1. Single line diagram.

Procedure :

1. Draw buses 1, 2, and 3.
2. Connect transmission lines TL_1, TL_2, TL_3.
3. Connect G_1 to bus 1 through T_1.
4. Connect G_2 to bus 2 through T_2.
5. Connect M_1, M_2, M_3, to bus 3 through T_3.

Que 2.3. **Discuss choice of transmission voltage in power system.**

Answer

While selecting an optimum transmission voltage following two factors are to be considered :

1. **Power to be transmitted :** If the power to be transmitted is large, large generating and transforming units are required which reduces the cost per kW of terminal station equipment.

2. **Distance of transmission line :** If power is transmitted over a long distance then the cost of terminal equipments is decreased which causes reduction in overall cost of transmission.
3. Above two terms can be related in an empirical formula which is as follows :

$$V = 5.5\left[\frac{L}{1.6}+\frac{P}{100}\right]^{0.5}$$

where, V = Line voltage in kV
L = Distance of line in km
P = Power to be transmitted in kW

A standard voltage nearest to this calculated value should be selected.

4. Following are voltages which are generally adopted :

Generation = 6.6 kV, 11 kV
Primary transmission = 132 kV, 220 kV, 400 kV
Secondary transmission = 11 kV, 22 kV, 33 kV
Primary distribution = 11 kV, 22 kV, 33 kV
Secondary distribution = 440 V

Que 2.4. **What are the different kinds of supply system ?**

OR

Find the ratio of volume of copper required to transmit a given power over a given distance by overhead system using (i) DC two wire system (ii) 3-phase 4-wire system. **AKTU 2017-18, Marks 10**

OR

Derive formula to calculate the ratio of copper volume used in two phase four-wire system and a two-wire dc system.

AKTU 2019-20, Marks 07

OR

Compare the relative weight of copper required for a distribution network on the DC-3 wire, and 3-phase 4-wire system. Assume in both cases the same voltage at the consumer's terminals, the same copper losses, the loads are balanced, and unity power factor in 3-phase case. Neglect the losses in neutral.

AKTU 2018-19, Marks 07

Answer

1. In overhead system, maximum voltage between each conductor and earth forms the basis of comparison.
2. Maximum voltage to earth is same.

a. **DC Systems :**

i. DC 2-Wire system with one conductor earthed :

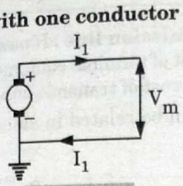


Fig. 2.4.1.

1. Maximum voltage between conductors = V_m volts
   Power to be transmitted = P watts

   Load current, $I_1 = \dfrac{P}{V_m}$

2. Line losses, $W = 2I_1^2R_1 = 2\left(\dfrac{P}{V_m}\right)^2 \rho\dfrac{l}{a_1}$ $\left[R_1 = \rho\dfrac{l}{a_1}\right]$

3. Area of cross section of conductor, $a_1 = \dfrac{2\rho P^2 l}{WV_m^2}$

4. Volume of conductor material required $= 2a_1 l = \dfrac{4\rho P^2 l^2}{WV_m^2} = K$ (say)

ii. DC two-wire system with midpoint earthed :

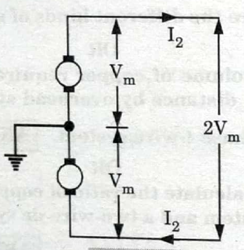


Fig. 2.4.2.

1. Load current, $I_2 = \dfrac{P}{2V_m}$

2. Line losses, $W = 2I_2^2R_2 = 2\left(\dfrac{P}{2V_m}\right)^2 \rho\dfrac{l}{a_2} = \dfrac{P^2\rho l}{2a_2V_m^2}$

3. $a_2 = \dfrac{P^2\rho l}{2WV_m^2}$

4. Volume of conductor material required $= 2a_2 l = \dfrac{P^2\rho l^2}{WV_m^2} = 0.25\,K$

5. Hence volume of conductor material required is one-fourth of that required in two-wire DC system with one conductor earthed.

iii. DC three-wire system :

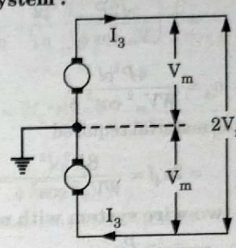


Fig. 2.4.3.

1. Load current, $I_3 = \dfrac{P/2}{V_m} = \dfrac{P}{2V_m}$

2. Line losses, $W = 2I_3^2R_3 = 2\left(\dfrac{P}{2V_m}\right)^2 \dfrac{\rho l}{a_3} = \dfrac{P^2\rho l}{2a_3V_m^2}$

   $a_3 = \dfrac{P^2\rho l}{2WV_m^2}$

3. Assuming area of cross section of neutral wire as half of that of any of the outers.

   Volume of conductor material required $= 2.5a_3 l = \dfrac{2.5P^2\rho l^2}{2WV_m^2} = 0.3125\,K$

b. Single-phase AC systems :

i. AC single-phase two-wire system with one conductor earthed :

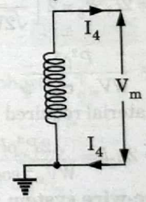


Fig. 2.4.4.

1. Peak value of voltage between conductors = V_m volts

   RMS value of voltage between conductors $= \dfrac{V_m}{\sqrt{2}}$ volts

   Load current, $I_4 = \dfrac{P}{\dfrac{V_m}{\sqrt{2}}\cos\phi} = \dfrac{\sqrt{2}P}{V_m\cos\phi}$

   where $\cos\phi$ is the power factor of the load

2. Line losses, $W = 2I_4^2R_4$

$$= 2\left(\frac{\sqrt{2}P}{V_m \cos\phi}\right)^2 \frac{\rho l}{a_4} = \frac{4P^2\rho l}{a_4 V_m^2 \cos^2\phi}$$

$$a_4 = \frac{4P^2\rho l}{WV_m^2 \cos^2\phi}$$

Volume of conductor material required

$$= 2a_4 l = \frac{8P^2\rho l^2}{WV_m^2\cos^2\phi} = \frac{2}{\cos^2\phi}K$$

ii. AC single-phase two-wire system with midpoint earthed :

1. Load current, $I_5 = \dfrac{P}{\sqrt{2}V_m \cos\phi}$

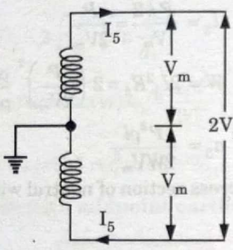


Fig. 2.4.5.

2. Line losses, $W = 2I_5^2R_5 = 2\left(\dfrac{P}{\sqrt{2}V_m\cos\phi}\right)^2 \dfrac{\rho l}{a_5} = \dfrac{P^2\rho l}{a_5 V_m^2 \cos^2\phi}$

$$a_5 = \frac{P^2\rho l}{WV_m^2\cos^2\phi}$$

3. Volume of conductor material required

$$= 2a_5 l = \frac{2P^2\rho l^2}{WV_m^2\cos^2\phi} = \frac{0.5\,K}{\cos^2\phi}$$

iii. AC single-phase three-wire system :

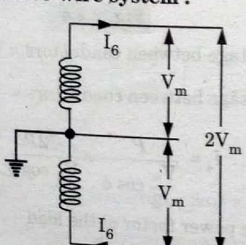


Fig. 2.4.6.

1. Load current, $I_6 = \dfrac{P/2}{\dfrac{V_m}{\sqrt{2}}\cos\phi} = \dfrac{P}{\sqrt{2}V_m\cos\phi}$

2. Line losses, $W = 2I_6^2R_6 = 2\left(\dfrac{P}{\sqrt{2}V_m\cos\phi}\right)^2\dfrac{\rho l}{a_6} = \dfrac{P^2\rho l}{V_m^2\cos^2\phi\, a_6}$

$$a_6 = \frac{P^2\rho l}{WV_m^2\cos^2\phi}$$

3. Volume of conductor material required

$$= 2.5a_6 l = \frac{2.5P^2\rho l^2}{WV_m^2\cos^2\phi} = \frac{0.625\,K}{\cos^2\phi}$$

c. Two-phase AC systems :

i. AC two-phase four-wire system :

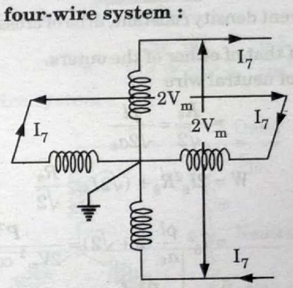


Fig. 2.4.7.

1. Load supplied by each phase $= \dfrac{P}{2}$

2. $I_7 = \dfrac{P}{2\sqrt{2}V_m\cos\phi}$

3. Line losses, $W = 4I_7^2R_7$

$$= 4\left(\frac{P}{2\sqrt{2}V_m\cos\phi}\right)^2 \rho\frac{l}{a_7} = \frac{P^2\rho l}{2V_m^2 a_7\cos^2\phi}$$

$$a_7 = \frac{P^2\rho l}{2V_m^2 W\cos^2\phi}$$

4. Volume of conductor material required

$$= 4a_7 l = \frac{2P^2\rho l^2}{V_m^2\cos^2\phi W} = \frac{0.5\,K}{\cos^2\phi}$$

ii. AC two-phase three-wire system :

1. Current in each of outer conductors, $I_8 = \dfrac{P/2}{V_m/\sqrt{2}\cos\phi} = \dfrac{P}{\sqrt{2}V_m\cos\phi}$

2. Current in neutral wire $= \sqrt{(I_8^2 + I_8^2)} = \sqrt{2}I_8$

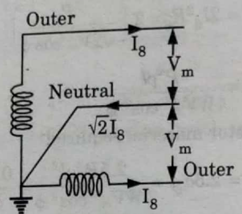


Fig. 2.4.8.

3. Assuming current density constant, area of cross section of neutral wire is $\sqrt{2}$ times of that of either of the outers.
So resistance of neutral wire

$$= \frac{R_8}{\sqrt{2}} = \frac{\rho l}{\sqrt{2}a_8}$$

4. Line losses, $W = 2I_8^2R_8 + (\sqrt{2}I_8)^2\dfrac{R_8}{\sqrt{2}}$

$$= I_8^2\frac{\rho l}{a_8}(2+\sqrt{2}) = \frac{P^2\rho l}{2V_m^2\cos^2\phi a_8}(2+\sqrt{2})$$

$$a_8 = \frac{P^2\rho l}{2V_m^2 W\cos^2\phi}(2+\sqrt{2})$$

5. Volume of conductor material required

$$= 2a_8l + \sqrt{2}a_8l = a_8l(2+\sqrt{2})$$

$$= \frac{P^2\rho l^2}{2V_m^2 W\cos^2\phi}(2+\sqrt{2})^2$$

$$= \frac{P^2\rho l^2}{2V_m^2 W\cos^2\phi}(\sqrt{2}+1)^2 = \frac{1.457}{\cos^2\phi}K$$

d. 3-phase AC systems :

i. AC 3-phase 3-wire system :

1. Load current per phase, $I_9 = \dfrac{P/3}{\dfrac{V_m}{\sqrt{2}}\cos\phi} = \dfrac{\sqrt{2}P}{3V_m\cos\phi}$

2. Line losses, $W = 3I_9^2R_9$

$$= 3\left(\frac{\sqrt{2}P}{3V_m\cos\phi}\right)^2\frac{\rho l}{a_9} = \frac{2P^2\rho l}{3V_m^2\cos^2\phi a_9}$$

$$a_9 = \frac{2P^2\rho l}{3V_m^2 W\cos^2\phi}$$

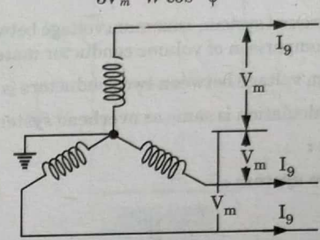


Fig. 2.4.9.

3. Volume of conductor material required

$$= 3a_9l = \frac{2P^2\rho l^2}{V_m^2 W\cos^2\phi} = \frac{0.5K}{\cos^2\phi}$$

ii. AC 3-phase 4-wire system :

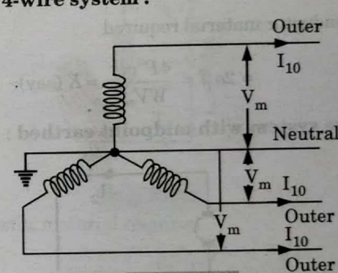


Fig. 2.4.10.

1. Assuming balanced load, there will be no current in neutral wire and copper losses will be same as in 3-phase 3-wire system

i.e.,
$$W = \frac{2P^2\rho l}{3V_m^2\cos^2\phi a_{10}}$$

$$a_{10} = \frac{2P^2\rho l}{3V_m^2\cos^2\phi W}$$

2. Taking cross section of neutral wire as half of either outer.
Volume of conductor material required

$$= 3.5a_{10}l = \frac{7\rho P^2 l^2}{3\cos^2\phi V_m^2 W} = \frac{0.583}{\cos^2\phi}K$$

Que 2.5. **Discuss comparison of cost of conductors for underground systems.**

Answer

1. In the underground system, maximum voltage between conductors forms the basis of comparison of volume conductor material required.
2. The maximum voltage between two conductors is same (say, V_m volts).
3. Remaining calculation is same as overhead system.

a. DC systems :

i. DC two-wire system :

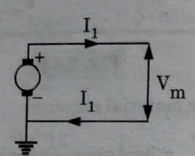


Fig. 2.5.1.

Volume of conductor material required

$$= 2a_1 l = \frac{4P^2 \rho l^2}{WV_m^2} = K \text{ (say)}$$

ii. DC two-wire system with midpoint earthed :

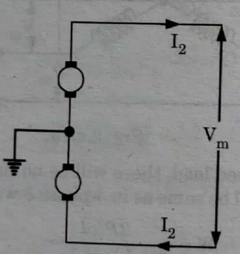


Fig. 2.5.2.

Volume conductor material required

$$= \frac{4P^2 \rho l^2}{WV_m^2} = K$$

iii. DC three-wire system :

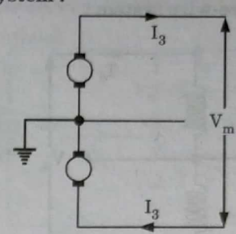


Fig. 2.5.3.

Volume of conductor material required $= 2.5 a_3 l = \dfrac{5P^2 \rho l^2}{V_m^2 W} = 1.25\, K$

b. Single-phase AC systems :

i. AC single-phase two-wire system :

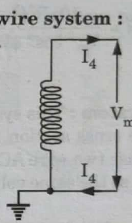


Fig. 2.5.4.

Volume of conductor material required

$$= 2a_4 l = \frac{8P^2 \rho l^2}{V_m^2 \cos^2 \phi W} = \frac{2K}{\cos^2 \phi}$$

ii. AC single-phase two-wire system with midpoint earthed :

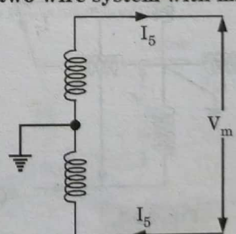


Fig. 2.5.5.

This system is the same as a 2-wire single-phase AC system.

iii. **AC single-phase three-wire system :**

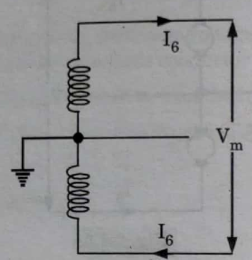


Fig. 2.5.6.

Volume of conductor material required

$$= 2.5a_4 l = \frac{10\rho P^2 l^2}{V_m^{\,2}\cos^2\phi W} = \frac{2.5}{\cos^2\phi}K$$

c. **Two-phase AC systems :**

i. **AC two-phase four-wire system :** This system is equivalent to two-wire AC system. In this case cross section area of each conductor is taken half of that of single phase two-wire AC system but four wires are required in place of two wires, so the same volume of conductor material is required *i.e.*, $\frac{2}{\cos^2\phi}$ times of that required in case of two-wire DC system.

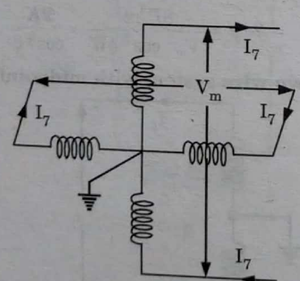


Fig. 2.5.7.

ii. **AC two-phase three-wire system :**

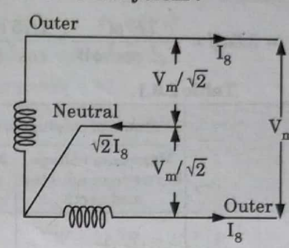


Fig. 2.5.8.

Volume of conductor material required = $\frac{2.914\,K}{\cos^2\phi}$

d. **3-phase AC systems :**

i. **AC three-phase three-wire system :**

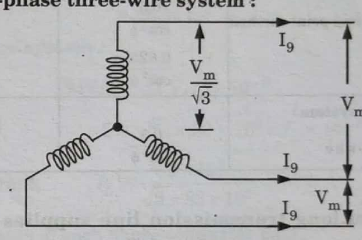


Fig. 2.5.9.

Volume of conductor material required

$$= 3a_9 l = \frac{6P^2\rho l^2}{V_m^{\,2}\cos^2\phi W} = \frac{1.5}{\cos^2\phi}K$$

ii. **AC three-phase four-wire system :**

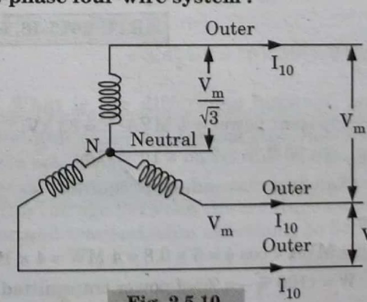


Fig. 2.5.10.

Volume of conductor material required

$$= 3.5a_g l = \frac{7P^2 \rho l^2}{V_m^2 \cos^2 \phi W} = \frac{1.75\text{ K}}{\cos^2 \phi}$$

Table 2.5.1.

S. No.	System	Volume of conductor material required	
		Maximum voltage between conductor and earth	Maximum voltage between any two conductors
1.	**DC System :**		
i.	Two-wire	1	1
ii.	Two-wire with mid point earthed	0.25	1
iii.	Three-wire	0.3125	1.25
2.	**AC single phase system :**		
i.	Two-wire	$\frac{2}{\cos^2\phi}$	$\frac{2}{\cos^2\phi}$
ii.	Two-wire with mid point earthed	$\frac{0.5}{\cos^2\phi}$	$\frac{2}{\cos^2\phi}$
iii.	Three wire	$\frac{0.625}{\cos^2\phi}$	$\frac{2.5}{\cos^2\phi}$
3.	**AC two-phase system :**		
i.	Two-phase four-wire	$\frac{0.5}{\cos^2\phi}$	$\frac{2}{\cos^2\phi}$

Que 2.6. **A 50 km long transmission line supplies a load of 5 MVA, 33 kV at 0.8 power factor lagging. The efficiency of transmission is 90 %. Calculate the volume of aluminium conductor required for the line when**
i. 1ϕ, 2-wire system is used.
ii. 3ϕ, 3-wire system is used.
Take the resistivity of aluminium as 2.85×10^{-8} Ω-m.

AKTU 2015-16, Marks 05

Answer

Given : $l = 50$ km; Apparent power = 5 MVA; $V = 33$ kV; $\cos \phi = 0.8$ (lagging), $\eta = 90$ %, $\rho = 2.85 \times 10^{-8}$ Ω-m
To Find : Volume of aluminium conductor required.

i. 1ϕ, 2-wire system :

1. Power transmitted = MVA × cos ϕ = 5 × 0.8 = 4 MW = 4×10^6 W
2. Line loss, $W = (100\,\% - \eta\,\%)$ of power transmitted.

$= 10\,\%$ of power transmitted $= (10/100) \times 4 \times 10^6$
$= 4 \times 10^5$ W

3. For single phase, 2-wire system :
Apparent power = VI_1

$$\therefore \quad I_1 = \frac{\text{Apparent power}}{V} = \frac{5 \times 10^6}{33 \times 10^3} = 151.5 \text{ A}$$

4. Suppose a_1 is the area of cross-section of aluminium conductor.

Line loss, $$W = 2I_1^2 R_1 = 2I_1^2 \left(\rho \frac{l}{a_1}\right)$$

$$\therefore \quad a_1 = \frac{2I_1^2 \rho l}{W} = \frac{2 \times (151.5)^2 \times (2.85 \times 10^{-8}) \times 50 \times 10^3}{4 \times 10^5}$$
$$= 1.635 \times 10^{-4} \text{ m}^2$$

5. Volume of conductor required $= 2a_1 l = 2 \times (1.635 \times 10^{-4}) \times 50 \times 10^3$
$= 16.35 \text{ m}^3$

ii. 3ϕ, 3-wire system :

1. $$\text{MVA} = \sqrt{3}\, V_L I_L \times 10^{-6}$$
$$5 = \sqrt{3} \times 33 \times 10^3 \times I_L \times 10^{-6}$$

Line current, $$I_L = \frac{5 \times 10^6}{\sqrt{3} \times 33 \times 10^3} = 87.5 \text{ A}$$

2. Let the area of each phase conductor be A_2.

Total line loss, $$p_L = 3I_L^2 R_2 = 3I_L^2 \rho \frac{l}{A_2}$$

$$A_2 = \frac{3I_L^2 \rho l}{p_L} = \frac{3 \times (87.5)^2 \times 2.85 \times 10^{-8} \times 50 \times 10^3}{4 \times 10^5}$$
$$= 0.818 \times 10^{-4} \text{ m}^2$$

3. Volume of aluminium required,
$= 3lA_2 = 3 \times 50 \times 10^3 \times 0.818 \times 10^{-4} = 12.27 \text{ m}^3$

Que 2.7. **What is the difference between isolator and circuit breaker ? A single phase AC system supplies load of 200 kW and if this system is converted to 3-phase, 3-wire ac system by running a third similar conductor, calculate the 3-phase load that can now be supplied if the voltage between the conductors is the same. Assume power factor and transmission efficiency to be same in both cases.**

AKTU 2016-17, Marks 10

Answer

A. Difference between isolator and circuit breaker :

S. No.	Isolator	Circuit breaker
1.	Isolator is an off-load device.	Circuit breaker is an on-load device.
2.	It is a switch, operated manually.	Circuit breaker operated automatically.

B. Numerical :

Given : Load, $P_1 = 200$ kW.
To Find : 3ϕ load can be supplied.

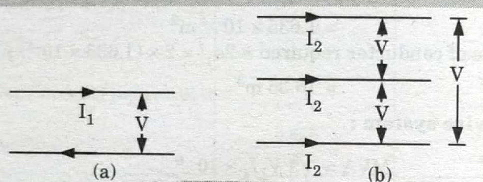


Fig. 2.7.1.

Suppose V is the voltage between conductors for the two cases. Power factor is unity. Let R be resistance per conductor in each case.

i. Single phase ac system :

1. Power supplied, $P_1 = VI_1 = 200$ kW
2. Power loss, $W_1 = 2I_1^2R$
3. Percentage of power loss

$$= \frac{2I_1^2R}{VI_1} \times 100 \qquad \text{...(2.7.1)}$$

ii. 3-phase, 3 wire AC system :

1. Power supplied, $P_2 = \sqrt{3}\, VI_2$
2. Power loss, $W_2 = 3I_2^2R$
3. Percentage power loss $= \frac{3I_2^2R}{\sqrt{3}\, VI_2} \times 100$ ...(2.7.2)
4. The transmission efficiency is same in both cases. Hence, percentage of power loss will become

$$\frac{2I_1^2R}{VI_1} \times 100 = \frac{3I_2^2R}{\sqrt{3}VI_2} \times 100$$

$$2I_1 = \sqrt{3}\, I_2$$

$$\therefore \quad I_2 = \frac{2}{\sqrt{3}} I_1$$

5. Now,

$$\frac{P_2}{P_1} = \frac{\sqrt{3}\, VI_2}{VI_1} = \frac{\sqrt{3}\, V \times \frac{2}{\sqrt{3}} I_1}{VI_1}$$

$$\frac{P_2}{P_1} = 2$$

$$\therefore \quad P_2 = 2P_1 = 2 \times 200 = 400 \text{ kW}$$

PART-2

Configurations of Transmission Lines : Types of Conductors, Resistances of line, Skin Effect, Kelvin's Law, Proximity Effect.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 2.8. **Explain different types of conductors in power system.**

Answer

Conductors which are generally used for transmission lines are :

A. Hard-Drawn Copper Conductor :

1. It is mostly used for short lines for voltages up to 33 kV. It has high electrical conductivity and long life.
2. It is most suitable for distribution work where tappings are more. Also hard drawn copper has high tensile strength.

B. Aluminium Conductor Steel Reinforced (ACSR) :

1. ACSR is used for high voltage lines having large span and heavy weight is to be supported.
2. Aluminium alone cannot be used for construction of long span transmission line due to low mechanical strength. So to make it strong we use steel wire in the core aluminium conductors.

C. Cadmium Copper Conductor :

1. By adding cadmium to copper, the strength can be increased to 50 percent but the conductivity decreases by 15 percent.

2. Due to high tensile strength the longer spans of transmission line can be erected with same sag.
3. This conductor is widely used in hilly areas.

D. Steel Cored Copper Conductor (SCC) :

1. In SCC a steel wire is surrounded by layers of copper strands. Steel core increases the tensile strength of conductor. So the overall strength of conductor increases.
2. Bituminized cotton tape is used between the steel core and copper strands to protect conductor from the galvanic action.

E. Hard-Drawn Aluminium Conductor :

1. Due to increase in the cost of copper, the aluminium is replacing copper for transmission work. For a given resistance the cross-section of aluminium is greater while weight is lesser.
2. So handling, transportation and erection of aluminium conductor lines is economical. For conductor use, aluminium is electrolytically refined and is rolled and hard drawn.
3. These conductors are used in urban areas having short transmission lines with lower voltages. Corona effect is also reduced due to higher conductor diameter.

F. Phosphor-Bronze Conductor :

1. Phosphor-Bronze Conductor is stronger than copper conductor, but has a low conductivity. Its conductivity can be improved by using cadmium copper core.
2. It is generally used as a conductor material where very long spans are required such as river crossings.

G. Galvanized Steel Conductor :

1. This conductor is used for very long spans particularly in rural areas where load is small. These conductors have high tensile strength.
2. Galvanized steel conductor is a magnetic material having large resistance, inductance and voltage drop. It has comparatively short life.

Que 2.9. **What is a bundle conductor and how does the use of bundled conductor reduce corona loss in EHV line ?**

AKTU 2015-16, Marks 05

Answer

1. A bundled conductor is a conductor made up of two or more conductors, called the sub-conductors, per phase in close proximity compared with the spacing between phases Fig. 2.9.1.

2. A bundled conductor is the sub-conductors of a bundled conductor separated from each other by a constant distance varying from 0.2 m to 0.6 m depending upon designed voltage and surrounding conditions throughout the length of the line with the help of spacers.
3. The bundled conductors have filter material or air space inside so that the overall diameter is increased.

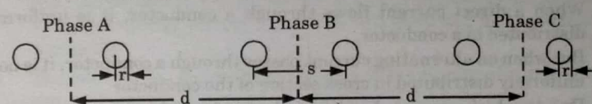


Fig. 2.9.1.

4. The use of bundled conductors per phase reduces the voltage gradient in the vicinity of the line and thus, reduces the possibilities of the corona discharge.
5. Hence the bundled conductors are used on EHV transmission lines to reduce corona loss and radio interference.

Que 2.10. **What are ACSR conductors ? Explain the advantages of ACSR conductors.**

AKTU 2015-16, Marks 05

Answer

A. Aluminium Conductor Steel Reinforced (ACSR) : Refer Q. 2.8, Page 2–18B, Unit-2.

B. Advantages :

1. High mechanical strength.
2. Low corona loss.
3. Less skin effect.
4. Less expensive than copper conductor.
5. Longer span possible.
6. Breakdown possibility is low.

Que 2.11. **Explain resistance of transmission line. Also discuss effect of skin effect on effective resistance of conductor.**

OR

What is Skin effect ?

Answer

A. Resistance of transmission line :

1. Every electric conductor offers opposition to the flow of current and this opposition is called the resistance.
2. The resistance of a solid conductor (wire) is given by

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

where, ρ = Resistivity of conductor
l = Length of conductor
a = Cross-sectional area of conductor

B. Skin effect :

1. When a direct current flows through a conductor, it is uniformly distributed in a conductor.
2. But when an alternating current passes through a conductor, it is non-uniformly distributed in cross section of the conductor.
3. Due to which current density at the surface of conductor is higher than the current density at the centre of the conductor. This effect is known as skin effect.

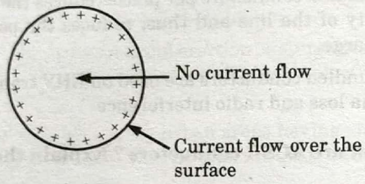


Fig. 2.11.1.

C. Skin effect on resistance of conductor :

1. Due to skin effect, the effective cross-section of conductor, through which the current flows, is reduced.
2. Since, resistance $\propto \frac{1}{\text{Area of cross-section}}$. Hence, skin effect increases effective resistance of conductor.

Que 2.12. Explain Kelvin's Economy Law and derive the condition for most economical cross-sectional area of the conductor.

OR

Explain Kelvin's law for economic size of conductor. Discuss limitations. Show how skin effect increases effective resistance of the conductor.

AKTU 2017-18, Marks 10

Answer

A. Kelvin's law : The most economical area of conductor is that for which the total cost of transmission line is minimum. This is known as Kelvin's law.

B. Derivation :

1. Total annual cost consists of two parts :

i. **The fixed standing charges :** The fixed charges consist of the interest on the capital cost of the conductor, the allowance for depreciation, and the maintenance cost.

ii. **The running charges :** The running charges consist of cost of electrical energy wasted due to losses during operation.

2. But, the capital cost (the interest and depreciation on it) and cost of electrical energy wasted in the line are governed by the size of the conductor.
3. The interest and depreciation on the initial investment will be directly proportional to the area of cross-section of the conductor.
4. The cost of energy loss will be inversely proportional to the conductor cross-section.
5. Mathematically,

i. Annual interest and depreciation cost

$$C_1 \propto a \text{ or } C_1 = K_1 a$$

and annual cost of energy dissipated in the line

$$C_2 \propto 1/a \text{ or } C_2 = \frac{K_2}{a}$$

where K_1 and K_2 are constants, and a represents the area of cross-section of conductor. The total annual cost may be given by

$$C = C_1 + C_2 = K_1 a + \frac{K_2}{a}$$

ii. For an economical design there will be one size of conductor at which the total cost is minimum.

iii. For the most economical cross-section, the total annual cost is differentiated with respect to the cross-section and the result is equated to zero.

$$\frac{dC}{da} = 0$$

$$\frac{d}{da}\left(K_1 a + \frac{K_2}{a}\right) = 0$$

$$K_1 - \frac{K_2}{a^2} = 0; K_1 a = \frac{K_2}{a}$$

$$C_1 = C_2 \text{ and } a = \sqrt{\frac{K_2}{K_1}} \quad ...(2.12.1)$$

iv. Hence the most economical cross-sectional area of the conductor is that which makes the annual cost of energy loss equal to the annual interest and depreciation on the capital cost of the conductor material. This is known as Kelvin's law.

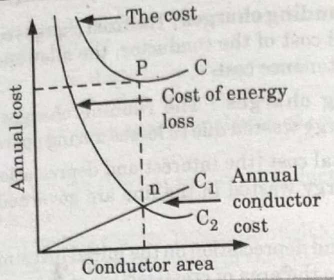


Fig. 2.12.1. Graphical representation of Kelvin's law.

C. Limitations :

i. Total amount of energy losses cannot be estimated accurately due to difference in load, load factors and future load conditions, which are difficult to predict accurately.

ii. Cost of energy loss is difficult to calculate because prices of conductor material and the rates of interest are continuously changing.

iii. Two systems having same energy demand can have different cost due to different energy costs.

iv. Voltage drop may be beyond the permissible limits in some cases if economical conductor size is selected.

v. Most economical size of conductor may not be suitable to carry the required amount of current due to its thermal rating and temperature rise limits.

vi. Economical section may not have adequate mechanical strength.

vii. Problems of corona, leakage currents, skin effect etc. oppose the use of economical section at extra high voltage.

D. Skin effect on resistance of conductor : Refer Q. 2.11, Page 2–20B, Unit-2.

Que 2.13. Briefly explain Proximity effect.

OR

Explain briefly skin effect and proximity effect in reference to overhead lines.

AKTU 2018-19, Marks 07

Answer

A. Skin effect : Refer Q. 2.11, Page 2–20B, Unit-2.

B. Proximity effect :

1. When two or more conductors are near to each other, their magnetic field interacts and it results in circulating currents inside the conductor. This effect is known as proximity effect.

2. Due to proximity effect, the current in each conductor is redistributed and it flows through that part of conductor which is farthest from the other conductors. This effect results in apparent increase in resistance of conductor.

3. Proximity effect can be influenced by following factors :

i. Size of conductor

ii. Frequency of supply

iii. Resistivity of material

iv. Distance between conductors.

Que 2.14. The daily-load cycle of a three-phase, 33 kV, 10 km transmission line is as follows : 2500 kVA for 8 hours, 2000 kVA for 9 hours and 1500 kVA for 7 hours. Determine the most economical cross section if the cost of line including erection is Rs. (7500) + 6000*a*) per km where *a* is the area of each conductor in sq. cm. The rate of interest and depreciation is 8 percent and cost of energy is 15 paise per unit. The line is in use for 250 working days a year. The resistance per km and per sq. cm. is 0.173 ohm.

AKTU 2015-16, Marks 10

Answer

Given : Cost of line = Rs. $(7500 + 6000a) \times 10$; $V_L = 33$ kV
$l = 10$ km; kVA = 2500 kVA for 8 hour, 2000 kVA for 9 hour, 1500 kVA for 7 hour ; rate of interest and depreciation = 8 %;
Cost of energy = 15 paise per unit; working days in a year = 250,
Resistance per km and per sq. cm. = 0.173 ohm
To Find : Most economical cross section.

1. Cost of line = Rs. $(7500 + 6000a) \times 10$
2. Annual interest and depreciation on capital cost
$$= \text{Rs. } (7500 + 6000a) \times 10 \times 8/100$$
$$= \text{Rs. } (6000 + 4800a)$$
3. Resistance of each conductor,
$$R = \frac{0.173 \times 10}{a} = \frac{1.73}{a}$$
$$\frac{\sqrt{3} V_L I_L}{1000} = \text{kVA}$$
4. The load current at various loads are calculated by the above formula as follows :
At 2500 kVA, load current
$$I_1 = \frac{2500 \times 1000}{\sqrt{3} \times 33 \times 1000} = 43.8 \text{ A}$$
At 2000 kVA, load current

$$I_2 = \frac{2000 \times 1000}{\sqrt{3} \times 33 \times 1000} = 35 \text{ A}$$

At 1500 kVA, load current

$$I_3 = \frac{1500 \times 1000}{\sqrt{3} \times 33 \times 1000} = 26.2 \text{ A}$$

5. Daily energy loss

$$= 3I_1^2R \times \frac{8}{1000} + 3I_2^2R \times \frac{9}{1000} + 3I_3^2R \times \frac{7}{1000}$$

$$= \frac{3R}{1000}(8I_1^2 + 9I_2^2 + 7I_3^2)$$

$$= 3 \times \frac{1.73}{a} \times 10^{-3}\,[8(43.8)^2 + 9(35)^2 + 7(26.2)^2]$$

$$= \frac{79.8}{a} + \frac{57.2}{a} + \frac{24.9}{a} = \frac{161.9}{a} \text{ kWh}$$

6. Annual energy loss = $\frac{161.9}{a} \times 250$ kWh

7. Cost of energy loss per annum

$$= \text{Rs. } \frac{161.9}{a} \times 250 \times \frac{15}{100} = \text{Rs. } \frac{6071}{a}$$

8. ∴ By Kelvin's law,

$$\frac{6071}{a} = 4800a$$

$$a = \sqrt{\frac{6071}{4800}} = 1.124$$

9. ∴ The most economical cross-section

$$= 1.124 \text{ cm}^2 = 112.4 \text{ mm}^2$$

Que 2.15. **Explain the limitations of Kelvin law. A 2-wire feeder carries a constant current of 250 A throughout the year. The portion of capital cost which is proportional to the area of cross section is Rs. 5 per kg of copper conductor. The interest and depreciation of total 10 % per annum and the cost of energy is 5 paisa per kWh. Find the most economical area of cross section of the conductor. Given that the density of copper is 8.93 gm/cm² and its specific resistance is 1.73 × 10⁻⁸ Ω-m.**

AKTU 2016-17, Marks 10

Answer

A. **Limitations of Kelvin law :** Refer Q. 2.12, Page 2–21B, Unit-2.

B. Numerical :

Given : I = 250 A; Capital cost = Rs. 5 per kg
Cost of energy = 5 paise per kWh
To Find : Most economical area of cross section.

1. Let l = Length of each conductor in m
a = Area of cross section in sq m

2. Volume of conductor = la m³

3. Mass of conductor = $la \times 8.93 \times 10$ kg

4. Capital cost of conductor
= Rs. $5 \times 8.93 \times 10 \times la$
= Rs. $446.5\,la$

5. Interest and depreciation cost

$$= \text{Rs. } 446.5 \times \frac{10}{100} la$$

= Rs. $44.65la$

6. Copper loss per conductor

$$= I^2 R \times 10^{-3} \text{ kW}$$

$$= (250)^2 \left(1.73 \times 10^{-8} \times \frac{l}{a}\right) \times 10^{-3}$$

$$= 1.08 \times 10^{-6} \frac{l}{a} \text{ kW}$$

7. Cost of energy loss per year

$$= \text{Rs. } 1.08 \times 10^{-6} \frac{l}{a} \times 365 \times 24 \times \frac{5}{100}$$

$$= \text{Rs. } 4.73 \times 10^{-6} \frac{l}{a}$$

8. According to Kelvin's law, interest and depreciation cost and cost of energy loss must be equal for most economical area of cross-section of conductor.

$$44.65la = 4.73 \times 10^{-6} \frac{l}{a}$$

$$\therefore \quad a = 0.00325 \text{ m}^2 = 3.25 \text{ cm}^2$$

Que 2.16. **Determine the best current density in amperes/mm² for a three phase overhead line. The line is in use for 3600 hours per year and if the conductor costs Rs. 3.0/kg. It has a specific resistance of 1.73 × 10⁻⁸ Ω-m and weights 6200 kg/m³ cost of energy is 12 paise/unit. Interest and depreciation is 10 % of conductor cost.**

AKTU 2017-18, Marks 10

Answer

Given : Line in use = 3600 hours per year;
Conductor costs = Rs. 3 per kg; $\rho = 1.73 \times 10^{-8}\ \Omega$-m
Weights = 6200 kg/m^3; Cost of energy = 12 paise/unit.
To Find : Current density in amperes/mm^2.

1. l = Length of each conductor
   a = Area of cross section
2. Volume of conductor = $la \times 6200$ kg
   $= 6200 \times la$ kg
3. Capital cost of the conductor
   $=$ Rs. $3 \times la \times 6200$
   $=$ Rs. $18600 \times la$
4. Interest and depreciation
   $=$ Rs. $186 \times la \times 10$
   $=$ Rs. $1860 \times la$
5. Cupper loss per conductor

$$= I^2R \times 10^{-3}\text{ kW} = I^2\left[\frac{\rho l}{a}\right] \times 10^{-3}$$

$$= I^2\left[1.73 \times 10^{-6} \times \frac{l}{a}\right] \times 10^{-3}$$

$$= I^2 \times 1.73 \times 10^{-9}\frac{l}{a}$$

$$= 1.73 \times 10^{-9} \times I^2\frac{l}{a}\text{ kW}$$

6. According to Kelvin's law, the two costs should be equal for the best current density.

$$1860\, la = 1.73 \times 10^{-9} \times I^2\frac{l}{a}$$

$$\frac{I^2}{a^2} = \frac{1860}{1.73} \times 10^9$$

$$\frac{I}{a} = 1.03 \times 10^6\text{ A/mm}^2$$

Que 2.17. **State Kelvin's law. Determine the best current density in amp/mm^2 for a three phase overhead line. The line is in use for 2600 hours per year and conductor costs Rs. 3.0 / kg. It has a specific resistance of 1.73 × 10^{-8} Ω-m and weights 6200 kg/m^3. Cost of energy is 10 paise/unit. Interest and depreciation is 12 % of conductor costs.**

AKTU 2019-20, Marks 07

Answer

i. **Kelvin's law :** Refer Q. 2.12, Page 2–21B, Unit-2.
ii. **Numerical :** The procedure is same as Q. 2.16, Page 2–26B, Unit-2.
Ans.
The best current density :

$$\frac{I}{a} = 0.705\text{ A/mm}^2$$

PART-3

Corona Effect, Factors Affecting The Corona, Corona Power Loss, Advantages and Disadvantages.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 2.18. **Discuss phenomenon of corona and how it is formed.**

Answer

A. **Corona :** The phenomenon of violet glow, hissing noise and production of ozone gas in an overhead transmission line is known as corona.

B. **Phenomenon of corona :**

1. When an alternating potential difference is applied across two conductors, whose spacing is large in comparison with their diameters, then the atmospheric air surrounding the conductors is subjected to electrostatic stresses.
2. At low voltage there is no change in the condition of atmospheric air around the conductors.
3. However, when the potential difference is gradually increased, a stage arrives when a luminous glow of violet colour appears together with a hissing noise and production of ozone gas.
4. If the potential difference is raised still further, the glow and the noise will increase until a spark-over owing to breakdown of air insulation will take place.

B. **Theory of corona formation :**

1. The air around the conductor contains a number of free electrons. When the potential is applied between the two conductors a potential gradient is established and under its influence the electrons acquire a uniformly increasing acceleration.

2. Thus, the free electrons attain speed and these free electrons collide with the other slow moving or neutral molecules and in the process dislodge electron from it.

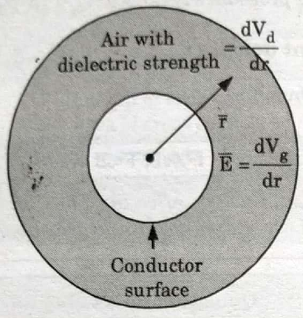


Fig. 2.18.1. Corona formation.

3. When the potential gradient reaches about 30 kV (max. value) per cm, the velocity acquired by the free electrons dislodge one or more electrons from it.
4. These dislodged electrons and the previous free electrons strike other neutral molecules producing more number of electrons. When the saturation point is reached the insulating property of air is destroyed and the air becomes conducting and corona forms.
5. Corona occurs if

$$\frac{dV_d}{dr} < \frac{dV_g}{dr}$$

where, $\frac{dV_g}{dr}$ = Electric potential at conductor surface

$\frac{dV_d}{dr}$ = Dielectric strength

where r is a radial vector, perpendicular to conductor surface. If potential gradient (dV_g/dr) exceeds the dielectric strength (dV_d/dr) the corona occurs.

Que 2.19. **Deduce expressions for critical disruptive voltage and visual critical voltage.**

Answer

1. Let us consider the two-wire line shown in Fig. 2.19.1,

r = Radius of line conductor
d = Distance between their centres
$+q$ = Charge on conductor A

$-q$ = Charge on conductor B

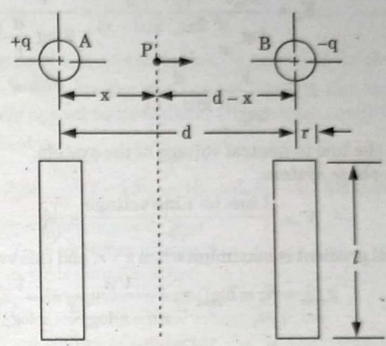


Fig. 2.19.1.

2. Consider point P at a distance of x metres from conductor A.
3. Electric field intensity at point P due to charge on conductor $A = \frac{q}{2\pi\varepsilon_0 x}$ acting towards B.
4. Electric field intensity at point P due to induced charge on conductor $B = \frac{q}{2\pi\varepsilon_0(d-x)}$ acting towards B.
5. Resultant electric field intensity at point P,

$$E_x = \frac{q}{2\pi\varepsilon_0 x} + \frac{q}{2\pi\varepsilon_0 (d-x)} = \frac{q}{2\pi\varepsilon_0}\left(\frac{1}{x} + \frac{1}{d-x}\right)$$

6. Potential difference between conductors A and B,

$$V = \int_r^{d-r} E_x\, dx = \int_r^{d-r} \frac{q}{2\pi\varepsilon_0}\left(\frac{1}{x} + \frac{1}{d-x}\right) dx$$

$$= \frac{q}{2\pi\varepsilon_0}\left[\log_e x - \log_e (d-x)\right]_r^{d-r} = \frac{q}{\pi\varepsilon_0}\log_e \frac{d-r}{r}$$

7. Now, since r is very small as compared to d, $d - r \simeq d$ and, therefore,

$$V = \frac{q}{\pi\varepsilon_0}\log_e \frac{d}{r} \quad ...(2.19.1)$$

8. Now gradient at any point x from the centre of the conductor A is given by

$$E_x = \frac{q}{2\pi\varepsilon_0}\left(\frac{1}{x} + \frac{1}{d-x}\right) = \frac{q}{2\pi\varepsilon_0}\,\frac{d}{x(d-x)} \quad ...(2.19.2)$$

9. Substituting for q from eq. (2.19.1) in eq. (2.19.2), we have

$$E_x = \frac{\pi\varepsilon_0 V}{\log_e \frac{d}{r}} \frac{1}{2\pi\varepsilon_0} \frac{d}{x(d-x)} = \frac{V}{2\log_e \frac{d}{r}} \frac{d}{x(d-x)}$$

and
$$E_x = \frac{V'}{\log_e \frac{d}{r}} \frac{d}{x(d-x)} \quad ...(2.19.3)$$

where V' is the line to neutral voltage of the system.

10. In case of 3-phase system,
$$V' = \frac{\text{Line-to-Line voltage}}{\sqrt{3}} = \frac{V_L}{\sqrt{3}}$$

11. The potential gradient is maximum when $x = r$, and this value is given by
$$g_{\max} = E_r = E_{\max} = \frac{V'd}{r(d-r)\log_e \frac{d}{r}} \simeq \frac{V'}{r\log_e \frac{d}{r}} \quad ...(2.19.4)$$
where, r = Radius

12. When the disruptive gradient of air is reached at the conductor surface
$$g_0 = \frac{V_{d_0}}{r\log_e \frac{d}{r}}$$
Critical disruptive voltage,
$$V_{d_0} = g_0\, r \log_e \frac{d}{r} \quad ...(2.19.5)$$
The complete formula becomes
$$V_{d_0} = g_0\, \delta m_0 r \log_e \frac{d}{r} \quad ...(2.19.6)$$
where δ = Air density factor
m_0 = Conductor surface condition factor.

13. The value of V_{d_0} is known as critical disruptive voltage, and is defined as the minimum phase to neutral voltage at which corona occurs.

Visual critical voltage :

1. Visual critical voltage is defined as the minimum phase to neutral voltage at which glow appears all along the line conductors.
2. Thus the visual critical voltage is
$$V_{v_0} = g_0 \delta m_v r\left(1+\frac{0.3}{\sqrt{\delta r}}\right)\log_e \frac{d}{r} \text{ kV (rms) to neutral} \quad ...(2.19.7)$$
where m_v = Roughness factor, which is unity for smooth conductors.

Que 2.20. **Explain corona loss. How is critical disruptive voltage estimated ? Give advantages and disadvantages of corona loss.**

AKTU 2016-17, Marks 10

Answer

A. Corona loss :

1. Power wasted due to corona in lines is known as corona power loss.
2. F.W. Peek's formula for the corona loss for the single phase and equilaterally spaced 3ϕ lines under fair weather conditions is given by,

Peek's formula :
$$P_c = \frac{244}{\delta}(f+25)\sqrt{\frac{r}{D}}(E_n - E_0)^2 \times 10^{-5} \text{ kW/km/phase}$$
where, P_c = Corona power loss
f = Frequency of supply
δ = Air density factor
E_n = Rms phase voltage (line to neutral)
E_0 = Disruptive critical voltage per phase
r = Radius of conductor
D = Spacing or equivalent spacing between conductors

For single phase,
$$E_n = \frac{1}{2} \times \text{line voltage}$$
For three phase,
$$E_n = \frac{1}{\sqrt{3}} \times \text{line voltage}$$

3. Peek's formula is not accurate when losses are low and E_n/E_0 is less than 1.8. In that condition, we use Peterson's formula.

Peterson's Formula :
$$P_c = 2.1 f F \frac{E_n^2}{\left(\log_{10}\frac{D}{r}\right)^2} \times 10^{-5} \text{ kW/km/conductor}$$
where, P_c = Corona power loss
f = Supply frequency in hertz
E_n = Voltage per phase (line to neutral) voltage in kV (rms)
r = Radius of conductor in metres
F = Corona loss function
$$E_0 = g_{0\max}\, m_0\, r\, \delta^{2/3} \ln\frac{D_{eq}}{r} \text{ V/phase (rms)}$$
D = Spacing

B. Estimation of critical disruptive voltage : Refer Q. 2.19, Page 2–29B, Unit-2.

C. Advantages of corona :

1. Due to corona, the air surrounding the conductor is ionised and becomes conducting. This increases the virtual diameter of the conductor.
2. Corona reduces the effect produced by the surges and conductor is saved from possibility of lighting. It acts as a safety device.

D. Disadvantages of corona :

1. It reduces the transmission efficiency.
2. The third harmonic components produced due to corona makes the current non-sinusoidal. This increases the corona loss.
3. The ozone gas formed due to corona chemically reacts with the conductor and can cause corrosion.

Que 2.21. **Explain the phenomenon of corona formation and factors affecting corona. What is visual critical voltage ?**

AKTU 2017-18, Marks 10

OR

Explain the situation under which corona phenomenon starts in high voltage power transmission lines. Identify the factors with reason that affect corona. **AKTU 2019-20, Marks 07**

Answer

A. **Phenomena of Corona :** Refer Q. 2.18, Page 2–28B, Unit-2.

B. **Factors affecting corona :**

1. **Effect of frequency :** Corona loss depends on the supply frequency. Higher the supply frequency, higher is the corona loss.
2. **Line voltage :** The line voltage directly affects the corona and the corona loss. For lower line voltage corona may be absent. But for voltages higher than disruptive voltage, corona starts. Higher the line voltage, higher is the corona loss.
3. **Atmospheric conditions :** The pressure and temperature together decide the value of δ which affects the disruptive voltage and the corona loss. Lower the value of δ, higher is the corona and vice-versa.
4. **Size of the conductor :** The corona loss is directly proportional to square root of radius of conductor. Hence, loss is more if size of conductor is more.
5. **Surface conditions :** The corona depends on the surface conditions. For rough and uneven surfaces, the value of disruptive voltage is less and corona effect is dominant. Similarly corona loss is also more for rough and dirty surfaces.
6. **Number of conductors per phase :** For higher voltages a single conductor per phase produces large corona loss. Hence bundled conductors are used due to which self GMD of the conductor δ increases, which increases the disruptive voltage, reducing corona loss.
7. **Spacing between conductors :** If the spacing is made very large, corona can be absent.
8. **Clearance from ground :** The height of the conductors from the ground also affects the corona loss. The smaller the clearance of the conductors from the ground, higher is the corona loss.

C. **Visual critical voltage :** Refer Q. 2.19, Page 2–29B, Unit-2.

Que 2.22. **What are the methods of reducing corona loss ?**

OR

Explain the phenomenon of corona. What are the various factors affecting it ? How can it be reduced ? **AKTU 2018-19, Marks 07**

Answer

A. **Phenomenon of corona :** Refer Q. 2.18, Page 2–28B, Unit-2.

B. **Factors affecting corona :** Refer Q. 2.21, Page 2–33B, Unit-2.

C. **Methods of reduced corona :**

1. **Voltage of the line :** There is negligible corona loss below disruptive critical voltage. So if voltage is below disruptive critical voltage, there is no corona loss and as the line voltage goes beyond it, corona losses become large.
2. **Spacing between conductors :** Spacing between the conductors increases disruptive critical voltage. But this method increases overall cost of line as cross arm length got increased. Also there is an increase in voltage drop due to increase in the inductive reactance.
3. **Increasing diameter of conductor :** Increasing diameter of conductor is widely used to reduce corona loss. Diameter of conductor can be increased either by using Aluminum Conductor Steel Reinforced conductor (ACSR) or by using hollow conductor.
4. **Bundled conductors :**
   i. Presently bundled conductors are used more often to reduce corona loss.
   ii. It consists of two or more parallel conductors grouped together having spaces between them. Bundle acts as conductor having diameter much larger than component conductors.
   iii. It reduces the voltage gradient thus reducing corona loss.

Que 2.23. **Determine the corona characteristics of a three phase 160 km long line having conductor diameter 1.036 cm, 2.44 m delta spacing, air temperature 26.67 degree having an appropriate barometric pressure of 73.15 cm, operating voltage 110 kV at 50 Hz. Surface irregularity factor is 0.85. Assume a value of m_v = 0.72, . Disruptive voltage dielectric strength of air = 21.1 kV/cm (rms). Disruptive voltage under foul weather = 0.8 times fair weather value.**

AKTU 2015-16, Marks 10

Answer

Given : Diameter = 1.036 cm, d = 2.44 m, t = 26.67°, m_v = 0.72, b = 73.15 cm, f = 50 Hz
To Find : Corona characteristics.

1. Radius of conductor = $\frac{1.036}{2} = 0.518\,\text{cm}$

The ratio $\frac{d}{r} = \frac{2.44}{0.518} \times 100 = 471$

$$\sqrt{\frac{r}{d}} = \sqrt{\frac{1}{471}} = 0.046075$$

2. $$\delta = \frac{3.92b}{273+t} = \frac{3.92 \times 73.15}{273+26.67} = 0.957$$

3. Assuming a surface irregularity factor 0.85, the critical disruptive voltage

$$V_d = 21.1 \times 0.85\delta r \ln \frac{d}{r}$$
$$= 21.1 \times 0.85 \times 0.957 \times 0.518 \ln 471$$
$$= 54.72 \text{ kV line to neutral}$$

4. Visual critical voltage $V_v = 21.1 m_v \delta r \left(1 + \frac{0.3}{\sqrt{r\delta}}\right) \ln \frac{d}{r}$

$$V_v = 21.1 \times 0.72 \times 0.957 \times 0.518 \left[1 + \frac{0.3}{\sqrt{0.518 \times 0.957}}\right] \ln 471 = 66 \text{ kV}$$

5. Power loss = $244 \times 10^{-5} \frac{f+25}{\delta} \sqrt{\frac{r}{d}}\,(V - V_d)^2$ kW/phase/km

$$= 244 \times 10^{-5} \times \frac{75}{0.957} \times 0.046075 (63.5 - 54.72)^2$$
$$= 0.679 \text{ kW/phase/km}$$
$$= 108.64 \text{ kW/phase} = 325.92 \text{ kW for three phase}$$

6. Corona loss under foul weather condition will be when the disruptive voltage is taken as 0.8 × fair weather value, *i.e.*,

$$V_d = 0.8 \times 54.72 = 43.77 \text{ kV}$$

7. Loss per phase/km will be

$$244 \times 10^{-5} \frac{75}{0.975} 0.046075(63.5 - 43.77)^2 = 3.3664 \text{ kW/km/phase}$$
$$= 537.6 \text{ kW/phase}$$

8. Total loss = 1612.8 kW for all the three phases.

Que 2.24. **An 110 kV, 50 Hz, 175 km long, 3-phase transmission line consists of 1.2 cm diameter stranded copper conductor spaced in 2 m delta arrangement. Assume that temperature is 25 °C and barometric pressure is 74 cm. Assume surface irregularity factor m = 0.85, m_v for local corona = 0.72 and m_v for general corona = 0.82. Find :**

i. Disruptive critical voltage.
ii. Visual corona voltage for local corona.
iii. Visual corona voltage for general corona.
iv. Power loss due to corona using peek's formula under fair weather and wet weather conditions.

AKTU 2018-19, Marks 07

Answer

The procedure is same as Q. 2.23, Page 2–34B, Unit-2.

(**Ans.** i. 61.15 kV
ii. 72.13 kV
iii. 82.14 kV
iv. 115.25 kW)

Que 2.25. **Discuss electromagnetic interference with communication lines.**

Answer

1. Electromagnetic interference (EMI) is caused when a power conductor with a strong magnetic field is placed near other conductors (communication lines). The flux lines of the strong magnetic field cut the nearby conductors (communication lines) and induce voltages on them. Presence of EMI can interfere with the communication signal.
2. Consider a three-phase overhead transmission system consisting of three conductors R, Y and B spaced at the corners of a triangle and two telephone conductors P and Q below the power line conductors running on the same supports as shown in Fig. 2.25.1.

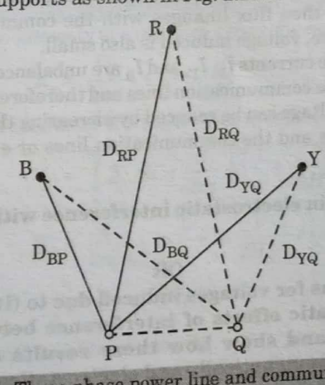


Fig. 2.25.1. Three-phase power line and communication line.

3. Let us assume that the radius of each conductor is r and consider the loop formed by the conductors R and P. Now the distances between R and P, and R and Q are D_{RP} and D_{RQ}, respectively.

4. Flux linkages of conductor P due to currents in all conductors of power line given by ;

$$\Psi_p = 2\times10^{-7}\left(I_R \ln\frac{1}{D_{RP}} + I_Y \ln\frac{1}{D_{YP}} + I_B \ln\frac{1}{D_{BP}}\right)$$

5. Flux linkages of conductor Q due to currents in all conductors of power line,

$$\Psi_Q = 2\times10^{-7}\left(I_R \ln\frac{1}{D_{RQ}} + I_Y \ln\frac{1}{D_{YQ}} + I_B \ln\frac{1}{D_{BQ}}\right)$$

6. Total flux linkages of communication lines,

$$\Psi = \Psi_P - \Psi_Q$$

$$= 2\times10^{-7}\left(I_R \ln\frac{1}{D_{RP}} + I_Y \ln\frac{1}{D_{YP}} + I_B \ln\frac{1}{D_{BP}}\right) - \left(I_R \ln\frac{1}{D_{RQ}} + I_Y \ln\frac{1}{D_{YQ}} + I_B \ln\frac{1}{D_{BQ}}\right)$$

$$= 2\times10^{-7}\left(I_R \ln\frac{D_{RQ}}{D_{RP}} + I_Y \ln\frac{D_{YQ}}{D_{YP}} + I_B \ln\frac{D_{BQ}}{D_{BP}}\right)$$

Therefore, the induced voltage in the communication line,

$$V = 2\pi f \Psi \text{ V/m}$$

7. Here, the voltage induced and flux linkages of communication line depends upon the values of I_R, I_Y, and I_B

Case-I : If the currents I_R, I_Y, and I_B are balanced and power lines are transposed, then flux linkages with the communication lines are zero. Therefore, voltage induced is also zero.

Case-II : If the currents I_R, I_Y, and I_B are balanced and power lines are untransposed, then flux linkages with the communication lines are small. Therefore, voltage induced is also small.

Case-III : If the currents I_R, I_Y, and I_B are unbalanced, then there is flux linkage with the communication lines and therefore, voltage is induced.

8. The induced voltage can be reduced by increasing the distance between the power lines and the communication lines or even by transposing them.

Que 2.26. **Explain electrostatic interference with communication lines.**

OR

Derive expressions for voltages induced due to (i) electromagnetic and (ii) electrostatic effects of interference between power and telephone lines and show how these results can be used for calculating electromagnetically and electrostatically induced emf's on telephone line when the power line is 3-phase and there are two telephone conductors.

AKTU 2019-20, Marks 07

Answer

A. Electrostatic interference :

1. In electrostatic interference the electric potential of the communication lines is raised which may be dangerous.
2. Consider a three-phase system consisting of three conductors R, Y, and B, which are placed at the corners of a triangle and two telecommunication lines P, Q connected parallel to the three-phase system as shown in Fig. 2.26.1.
3. The potential distribution between the three-phase system and plane (earth) is the same as the potential distribution between the image of the three-phase system and the plane.
4. Consider a conductor R of a three-phase system. Let H_R be the height of conductor R from the ground. q is the charge per metre length of conductor R and $-q$ is the charge on image of conductor R'.

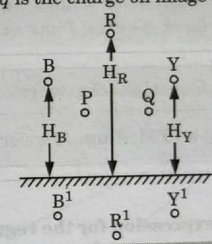


Fig. 2.26.1. Three-phase power line communication line and image of power line.

5. The electric-field intensity at a distance x from the centre of conductor R,

$$E_x = \frac{q}{2\pi\varepsilon\, x} + \frac{q}{2\pi\varepsilon\,(2H_R - x)}$$

The potential of conductor R with respect to earth,

$$V_R = \int_r^{H_R} E_x\, dx = \frac{q}{2\pi\varepsilon}\int_r^{H_R}\left(\frac{1}{x} + \frac{1}{(2H_R - x)}\right)dx$$

$$V_R = \frac{q}{2\pi\varepsilon}\left(-\ln\frac{1}{r} + \ln\frac{1}{2H_R - r}\right) = \frac{q}{2\pi\varepsilon}\ln\frac{2H_R - r}{r}$$

$$= \frac{q}{2\pi\varepsilon}\ln\frac{2H_R}{r} \qquad (\because 2H_R >> r)$$

where, r is the radius of conductor R

6. Suppose P is placed at a distance D_{PR} from the conductor R, then the potential of conductor P with respect to earth,

$$V_{PR} = \int_{D_{PR}}^{H_R} E_x\, dx = \frac{q}{2\pi\varepsilon}\int_{D_{PR}}^{H_R}\left(\frac{1}{x} + \frac{1}{(2H_R - x)}\right)dx$$

$$= \frac{q}{2\pi\varepsilon} \ln \frac{2H_R - D_{PR}}{D_{PR}} = V_R \frac{\ln\left(\frac{2H_R - D_{PR}}{D_{PR}}\right)}{\ln \frac{2H_R}{r}}$$

Similarly, the potential at P due to the charge on conductors Y and B *i.e.*, V_{PY} and V_{PB} can be calculated.

7. In addition, the resultant potential of P with respect to earth due to charge on conductors R, Y and B is $V_P = V_{PR} + V_{PY} + V_{PB}$ (vector addition).

In a similar way, the resultant potential of conductor Q with respect to the earth due to charge on conductors, R, Y, and B can be calculated.

B. Electromagnetic interference : Refer Q. 2.25, Page, 2–36B, Unit-2.

PART-4

Performance of Lines : Representation of Lines, Short Transmission Lines Medium Length Lines, Nominal T and π representations.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 2.27. **Derive the expression for the regulation and efficiency of a short transmission line. Draw the required circuit and phasor diagram.**

Answer

1. From the equivalent circuit of Fig. 2.27.1,

$$V_r = V_s - IZ \quad (\text{since } I = I_r = I_s) \quad ...(2.27.1)$$

where, IZ = Voltage drop along the line.

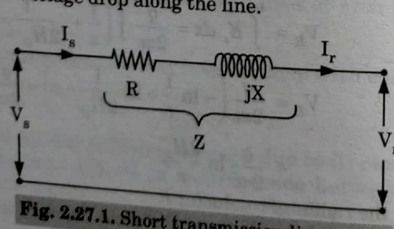


Fig. 2.27.1. Short transmission-line model.

2. From Fig. 2.27.2, we can write

$$V_s = OC = \sqrt{(OE)^2 + (EC)^2}$$

$$= \sqrt{(OD + DE)^2 + (EB + BC)^2}$$

$$= \sqrt{(V_r \cos\phi_r + IR)^2 + (V_r \sin\phi_r + IX)^2}$$

$$= \sqrt{V_r^2 + 2V_r IR\cos\phi_r + 2V_r IX\cos\phi_r + I^2(R^2 + X^2)}$$

$$= V_r\sqrt{1 + \frac{2IR}{V_r}\cos\phi_r + \frac{2IX}{V_r}\sin\phi_r + \frac{I^2}{V_r^2}(R^2 + X^2)}$$

$$\cong V_r\sqrt{1 + \frac{2(IR\cos\phi_r + IX\sin\phi_r)}{V_r}}$$

because $\frac{I^2(R^2 + X^2)}{V_r^2}$ is very small when compared with the other terms

$$\therefore \quad V_s = V_r\left(1 + 2\frac{(IR\cos\phi_r + IX\sin\phi_r + \text{Higher order terms})}{2V_r}\right) \quad ...(2.27.2)$$

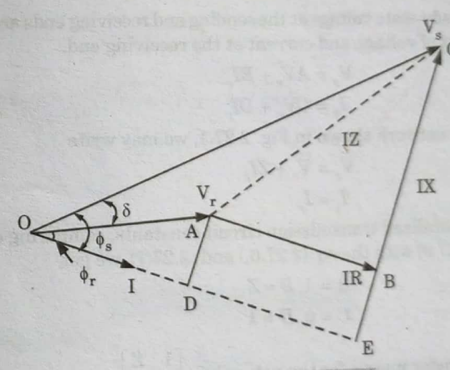


Fig. 2.27.2. Phasor diagram.

3. In practice, the value of higher order terms of eq. (2.27.2) are small and can be neglected, and therefore we get the approximate formula for V_s for

$$V_s \cong V_r + IR\cos\phi_r + IX\sin\phi_r \quad ...(2.27.3)$$

4. From Fig. (2.27.2), the power factor at sending end is given by

$$\cos\phi_s = \frac{OE}{OC} = \frac{V_r\cos\phi_r + IR}{V_s}$$

Regulation :

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

$$= \frac{V_r + IR\cos\phi_r + IX\sin\phi_r - V_r}{V_r} \times 100$$

$$= \frac{IR\cos\phi_r + IX\sin\phi_r}{V_r} \times 100 \quad ...(2.27.4)$$

Efficiency :

1. Power delivered, $P_r = V_r I \cos\phi_r$

Line losses per phase $= I^2R$

Power supplied per phase, $P_s = V_r I \cos\phi_r + I^2R$

2. The efficiency of a short transmission line,

$$\eta\,\% = \frac{\text{Power delivered}}{\text{Power supplied}} \times 100$$

$$= \frac{P_r}{P_s} \times 100 \quad ...(2.27.5)$$

A, B, C, D constants for short transmission lines :

The steady-state voltage at the sending and receiving ends are expressed in terms of voltage and current at the receiving end.

$$V_s = AV_r + BI_r \quad ...(2.27.6)$$

$$I_s = CV_r + DI_r \quad ...(2.27.7)$$

1. For the network shown in Fig. 2.27.1, we may write

$$V_s = V_r + ZI_r \quad ...(2.27.8)$$

and $$I_s = I_r \quad ...(2.27.9)$$

2. For generalized transmission circuit constants, comparing eq. (2.27.8) and (2.27.9) with the eq. (2.27.6.) and (2.27.7), we get

$$A = 1, B = Z$$

$$C = 0, D = 1$$

The transfer matrix for the network is $\begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix}$

Que 2.28. **Deduce an expression for transmission efficiency and regulation for medium transmission line using nominal π-method.**

OR

Derive A, B, C and D parameters for nominal π model of a medium transmission line and draw its phasor diagram.

AKTU 2017-18, Marks 10

OR

Derive A, B, C and D parameters for nominal π model of a medium line and draw its phasor diagram.

AKTU 2015-16, Marks 10

Answer

1. The steady-state voltage at the sending and receiving ends are expressed in terms of voltage and curren' at the receiving end.

$$V_s = AV_r + BI_r \quad ...(2.28.1)$$

$$I_s = CV_r + DI_r \quad ...(2.28.2)$$

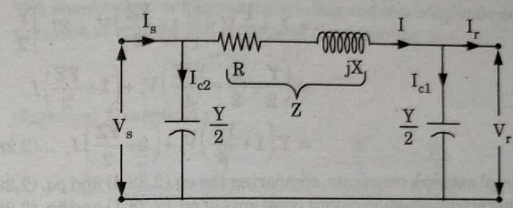


Fig. 2.28.1. π-equivalent circuit of medium transmission line.

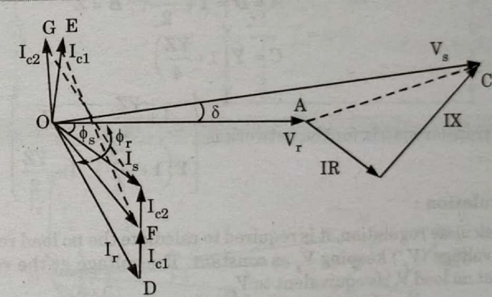


Fig. 2.28.2. Phasor diagram.

2. From Fig. 2.28.1,

$$V_{c1} = V_r$$

$$I_{c1} = V_{c1}\frac{Y}{2} = \frac{Y}{2}V_r$$

$$I = I_r + I_{c1}$$

$$= I_r + \frac{Y}{2}V_r \quad ...(2.28.3)$$

$$V_{c2} = V_{c1} + IZ$$

$$= V_r + \left(I_r + \frac{Y}{2}V_r\right)Z$$

$$V_{c2} = \left(1 + \frac{YZ}{2}\right)V_r + ZI_r$$

V_{c2} is also equal to V_s

$\therefore \quad V_s = \left(1+\frac{YZ}{2}\right)V_r + ZI_r$ ...(2.28.4)

3. The charging current, $I_{c2} = V_s \frac{Y}{2}$

The sending-end current, $I_s = I + I_{c2}$

$$= I_r + \frac{Y}{2}V_r + \left[\left(1+\frac{YZ}{2}\right)V_r + ZI_r\right]\frac{Y}{2}$$

$$= \left(\frac{Y}{2}+\frac{Y}{2}+\frac{Y^2Z}{4}\right)V_r + \left(1+\frac{YZ}{2}\right)I_r$$

$$= Y\left(1+\frac{YZ}{4}\right)V_r + \left(1+\frac{YZ}{2}\right)I_r \quad ...(2.28.5)$$

4. For general network constants, comparing the eq.(2.28.4) and eq. (2.28.5) with general transmission circuit constants of eq. (2.28.1) and eq. (2.28.2)

$$A = D = 1+\frac{YZ}{2}; \quad B = Z$$

$$C = Y\left(1+\frac{YZ}{4}\right)$$

5. The transfer matrix for the network is $\begin{bmatrix} 1+\frac{YZ}{2} & Z \\ Y\left(1+\frac{YZ}{4}\right) & 1+\frac{YZ}{2} \end{bmatrix}$

Regulation :

1. To calculate regulation, it is required to calculate the no load receiving-end voltage (V_r') keeping V_s as constant. The voltage at the receiving end at no load V_r' is equivalent to V_{c1}.
2. From Fig. 2.28.1, the voltage at the receiving end under no load is

$$V_r' = \frac{V_s\left(-\frac{j2}{\omega C}\right)}{R + jX - \frac{j2}{\omega C}}$$

$$\% \text{ Regulation} = \frac{V_r' - V_r}{V_r} \times 100$$

Efficiency :

$$\eta = \frac{\text{Power delivered at the receiving end } (P_r)}{\text{Power delivered at the receiving end } (P_r) + 3I^2R}$$

Que 2.29. **Deduce an expression for transmission efficiency and regulation for medium transmission line using (i) Nominal *T*-method (ii) Nominal π-method. Also calculate *A*, *B*, *C* and *D* parameter.**

OR

Draw a phasor diagram of a nominal-T transmission line and find its A, B, C, D constants. **AKTU 2019-20, Marks 07**

Answer

The steady-state voltage at the sending and receiving ends are expressed in terms of voltage and current at the receiving end

$$V_s = AV_r + BI_r \quad ...(2.29.1)$$

$$I_s = CV_r + DI_r \quad ...(2.29.2)$$

i. **Nominal *T* method :**

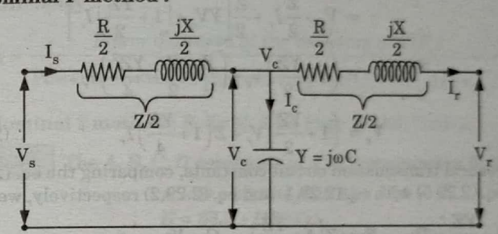


Fig. 2.29.1. T-equivalent circuit of medium transmission line.

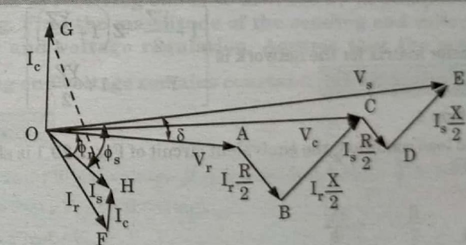


Fig. 2.29.2. Phasor diagram.

1. From Fig. 2.29.1,

$$V_c = V_r + \frac{Z}{2}I_r \quad ...(2.29.3)$$

2. The current through the shunt admittance is

$$I_c = V_cY$$

$$= \left(V_r + \frac{Z}{2}I_r\right)Y$$

$$I_c = YV_r + \frac{YZ}{2}I_r$$

3. Now the sending-end current is

$$I_s = I_r + I_c$$

$$= I_r + YV_r + \frac{YZ}{2} I_r$$

$$I_s = YV_r + \left(1 + \frac{YZ}{2}\right) I_r \quad \text{...(2.29.4)}$$

and the sending-end voltage is

$$V_s = V_s + \frac{Z}{2} I_s$$

$$= V_r + \frac{Z}{2} I_r + \frac{Z}{2}\left[YV_r + \left(1 + \frac{YZ}{2}\right) I_r\right]$$

$$= \left(1 + \frac{YZ}{2}\right) V_r + \left(\frac{Z}{2} + \frac{Z}{2} + \frac{YZ^2}{4}\right) I_r$$

$$\therefore \quad V_s = \left(1 + \frac{YZ}{2}\right) V_r + Z\left(1 + \frac{YZ}{4}\right) I_r \quad \text{...(2.29.5)}$$

4. For general transmission circuit constants, comparing the eq. (2.29.4) and eq. (2.29.5) with eq. (2.29.1) and eq. (2.29.2) respectively, we get

$$A = 1 + \frac{YZ}{2} = D; \quad B = Z\left(1 + \frac{YZ}{4}\right), \quad C = Y$$

5. The transfer matrix for the network is $\begin{bmatrix} 1 + \frac{YZ}{2} & Z\left(1 + \frac{YZ}{4}\right) \\ Y & 1 + \frac{YZ}{2} \end{bmatrix}$ ...(2.29.6)

Regulation :

1. Under no load condition, the equivalent circuit of Fig. 2.29.1 is shown in Fig. 2.29.3.

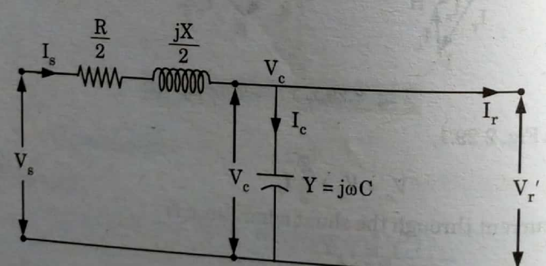


Fig. 2.29.3.

2. At no load, the voltage at the receiving end (V_r') of the transmission line is same as the voltage (V_c) across the admittance, which is located at midpoint of the transmission line.

3. From Fig. 2.29.3, the voltage across the capacitor by using voltage divider rule is

$$V_c = \frac{V_s\left(\frac{-j}{\omega C}\right)}{\frac{R}{2} + j\frac{X}{2} - \frac{j}{\omega C}}$$

When the receiving end is on no load, the no-load voltage, $V_r' = V_c$

$$\% \text{ Regulation} = \frac{V_r' - V_r}{V_r} \times 100$$

Efficiency :

$$\eta = \frac{\text{Power delivered at the receiving end } (P_r)}{\text{Power delivered at the receiving end } (P_r) + 3\frac{R}{2}(I_r^2 + I_s^2)}$$

ii. **Nominal π method :** Refer Q. 2.28, Page 2–41B, Unit-2.

Que 2.30. **The *A, B, C, D* constants of a 3ϕ transmission line are**

$$A = D = 0.936 + j0.016,$$
$$B = 33.5 + j138\ \Omega$$

and $C = (-0.9280 + j901.223) \times 10^{-6}$ **mho**

The load at receiving end is 40 MW, 200 kV at power factor of 0.86 lagging. Find the magnitude of the sending end voltage, current, power and voltage regulation. Assume that the magnitude of sending end voltage remains constant. **AKTU 2015-16, Marks 7.5**

Answer

Given : Phase voltage at receiving end, Load = 40 MW, V = 200 kV, pf = 0.86 (lag).
To Find : V_s, I_s, P_s, V_r.

1. Receiving end voltage to neutral,

$$V_r = \frac{200 \times 10^3}{\sqrt{3}} = 115.47 \text{ kV}$$

2. Receiving end current,

$$I_r = \frac{40000 \times 10^3}{\sqrt{3} \times 200 \times 10^3}$$

$$= 115.47 \angle -\cos^{-1} 0.86 \text{ A}$$

$$= 115.47 \angle -30.68 \text{ A}$$

$$= (99.3 - j58.9) \text{ A}$$

3. Sending end voltage to neutral :

$$V_s = AV_r + BI_r$$
$$= (0.936 + j0.016) \times 115.47 \times 10^3 + (33.5 + j138) \times 115.47 \angle -30.68$$
$$= 120306.07 \angle 6.480° \text{ V}$$
$$= 120.30607 \angle 6.480° \text{ kV}$$

4. Line voltage at sending end

$$|V_{sl}| = \sqrt{3}\,|V_s| = \sqrt{3} \times 120.306 = 208.376 \text{ kV}$$

5. Sending end current

$$I_s = CV_r + DI_r$$
$$= (-0.9280 + j901.223) \times 10^{-6} \times 115.47 \angle 0.\ 10^3 + (0.936 + j0.016) \times 115.47 \angle -30.68$$
$$= 106.52 \angle 28.30 \text{A}$$

6. Power factor at sending end = $\cos \phi_s = \cos (6.48° - 28.30°)$

$$= 0.92$$

7. ∴ Power at sending end = $D_s = 3\, V_{sl} I_s \cos \phi_s$

$$= 3 \times 120306.07 \times 106.52 \times 0.92$$
$$= 35369407.11 \text{ W} = 35.36 \text{ MW}.$$

8. **Voltage regulation :**

$$V_s = A\, V_{nl},$$

So,
$$V_{nl} = \frac{V_s}{A} = \frac{120306.07}{0.936} = 128532.12 \text{ V}$$

$$VR = \frac{|V_{nl}| - |V_{fl}|}{|V_{fl}|} \times 100$$

$$VR = \frac{128532.12 - 115.47 \times 10^3}{115.47 \times 10^3} \times 100$$
$$= 11.31\ \%.$$

Que 2.31. **In a 3-phase line with 132 kV at the receiving end the following are the transmission constants :**

$A = D = 0.98 \angle 30°$, $B = 110 \angle 750°\ \Omega$,
$C = 0.0005 \angle 880°$ S

If load at the receiving end is 50 MVA at 0.8 pf lagging, determine the value of the sending end voltage.

AKTU 2018-19, Marks 07

Answer

The procedure is same as Q. 2.30, Page 2–46B, Unit-2.
(Ans. $V_s = 95.03 \angle 38.73°$ kV)

Que 2.32. **A 50 Hz, three-phase transmission line has total series impedance per phase of (40 + *j*125) ohms and shunt admittance of 10^{-3} mho. The load is 50 MW at 220 kV, 0.8 pf lagging. Using nominal π method, calculate the sending end voltage current and power factor.**

AKTU 2018-19, Marks 07

Answer

Given : $Z = 40 + j125 = 131.24 \angle 72.20\ \Omega$, $Y = 10^{-3}$ mho, $V_r = 220$ kV, $\cos \phi_r = 0.8$ lag.
To Find : V_s, I_s and $\cos \phi_s$.

1. $V_r = \dfrac{220}{\sqrt{3}} \times 10^3 = 127.01$ kV/ph

2. $I_r = \dfrac{P}{\sqrt{3}\ V \cos \phi} = \dfrac{50 \times 10^6}{\sqrt{3} \times 220 \times 10^3 \times 0.8} = 164.02$ A (lagging)

3. $I_{c1} = \dfrac{V_r Y}{2} = \dfrac{(127.01 \times 10^3 \angle 0°) \times (10^{-3} \angle 90°)}{2}$ $(\because V_{c1} = V_r)$

$$= 63.5 \angle 90° \text{ A}$$

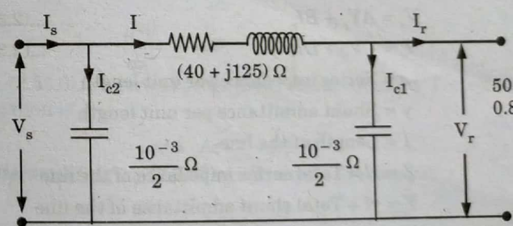


Fig. 2.32.1.

4. $I = I_r + I_{c1} = 164.02 \angle -\cos^{-1} 0.8 + 63.5 \angle 90°$

$$= 164.02 \angle -36.86 + 63.5 \angle 90°$$
$$= 135.79 \angle -14.8\ °\text{A}$$

5. $V_s = V_{c2} = V_{c1} + IZ = V_r + IZ$

$$= 127.01 \times 10^3 \angle 0° + (135.79 \angle -14.8) \times (131.24 \angle 72.2°)$$
$$= 137.45 \angle 6.26° \text{ kV/ph}$$

6. $I_{c2} = \frac{V_s Y}{2} = \frac{(137.45 \times 10^3 \angle 6.26°) \times (10^{-3} \angle 90°)}{2} = 137.45 \angle 96.26°$ A

7. $I_s = I + I_{c2} = 135.79 \angle -14.8° + 137.45 \angle 96.26° = 154.65 \angle 41.23°$ A

8. $\cos \phi_s = \cos (96.26° - 41.23°) = 0.57$

PART-5

Long Transmission Lines, The Equivalent Circuit Representation at Long Line A, B, C, D Constants Ferranti Effect.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 2.33. **Deduce the expression for sending end voltage and current in terms of receiving end voltage and current for long transmission lines.**

Answer

1. The steady-state voltage at the sending and receiving ends are expressed in terms of voltage and current at the receiving end

$$V_s = AV_r + BI_r \quad ...(2.33.1)$$

$$I_s = CV_r + DI_r \quad ...(2.33.2)$$

2. Let
   z = Series impedance per unit length
   y = Shunt admittance per unit length
   l = Length of the line
   Then,
   $Z = zl$ = Total series impedance of the line
   $Y = yl$ = Total shunt admittance of the line
3. Consider a very small element of length Δx at a distance of x from the receiving-end of the line.
4. The voltage and current at distance x from the receiving-end are V, I and at distance $x + \Delta x$ are $V + \Delta V$ and $I + \Delta I$, respectively.
   So, the change of voltage, $\Delta V = Iz\Delta x$
   where, $z\Delta x$ is the impedance of the element considered.

$$\frac{\Delta V}{\Delta x} = Iz$$

$$\underset{\Delta x \to 0}{\text{Lt}} \frac{\Delta V}{\Delta x} = \frac{dV}{dx} = Iz \quad ...(2.33.3)$$

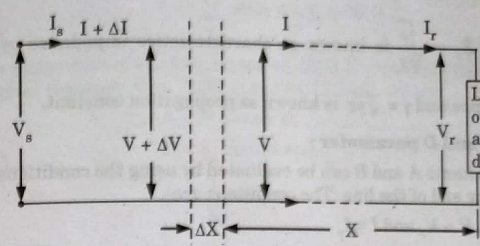


Fig. 2.33.1. Equivalent single-phase representation of a long transmission line.

5. Similarly, the change of current, $\Delta I = Vy\Delta x$
   where, $y\ \Delta x$ is the admittance of element considered

$$\frac{\Delta I}{\Delta x} = Vy$$

$$\underset{\Delta x \to 0}{\text{Lt}} \frac{\Delta I}{\Delta x} = \frac{dI}{dx} = Vy \quad ...(2.33.4)$$

6. Differentiating the eq. (2.33.3) with respect to x, we get

$$\frac{d^2V}{dx^2} = z\frac{dI}{dx} \quad ...(2.33.5)$$

7. Substituting the value of $\frac{dI}{dx}$ from eq. (2.33.4) in eq. (2.33.5), we get

$$\frac{d^2V}{dx^2} = zyV \quad ...(2.33.6)$$

8. Eq. (2.33.6) is a second order differential equation. The solution of this equation is

$$V = Ae^{\sqrt{yz}x} + Be^{-\sqrt{yz}x} \quad ...(2.33.7)$$

9. Differentiating eq. (2.33.7) with respect to x, we get

$$\frac{dV}{dx} = A\sqrt{yz}\, e^{\sqrt{yz}x} - B\sqrt{yz}\, e^{-\sqrt{yz}x} \quad ...(2.33.8)$$

10. From eq. (2.33.3) and eq. (2.33.8)

$$Iz = A\sqrt{yz}\, e^{\sqrt{yz}x} - B\sqrt{yz}\, e^{-\sqrt{yz}x}$$

$$I = A\sqrt{\frac{y}{z}}\, e^{\sqrt{yz}x} - B\sqrt{\frac{y}{z}}\, e^{-\sqrt{yz}x} \quad ...(2.33.9)$$

11. From eq. (2.33.7),

$$V = Ae^{\gamma x} + Be^{-\gamma x} \quad ...(2.33.10)$$

12. From eq. (2.33.9),

$$I = \frac{A}{Z_c}e^{\gamma x} + \frac{B}{Z_c}e^{-\gamma x} \quad ...(2.33.11)$$

where, $Z_c = \sqrt{\dfrac{z}{y}}$ is known as characteristics impedance or surge impedance and $\gamma = \sqrt{yz}$ is known as propagation constant.

***A, B, C* and *D* parameter :**

1. The constants *A* and *B* can be evaluated by using the conditions at the receiving end of the line. The conditions are

at $x = 0$, $V = V_r$ and $I = I_r$

Substitute the above conditions in eq. (2.33.10) and eq. (2.33.11), we get

$$\therefore \quad V_r = A + B \quad \text{...(2.33.12)}$$

$$\text{and} \quad I_r = \frac{1}{Z_c}(A - B) \quad \text{...(2.33.13)}$$

2. Solving eq. (2.33.12) and eq. (2.33.13), we get

$$A = \frac{V_r + I_r Z_c}{2} \text{ and } B = \frac{V_r - I_r Z_c}{2}$$

3. Now substituting the values of *A* and *B* in eq. (2.33.10) and (2.33.11), *V* can be expressed as :

$$V = \frac{V_r + I_r Z_c}{2} e^{\gamma x} + \frac{V_r - I_r Z_c}{2} e^{-\gamma x}$$

$$= V_r\left[\frac{e^{\gamma x} + e^{-\gamma x}}{2}\right] + I_r Z_c\left[\frac{e^{\gamma x} - e^{-\gamma x}}{2}\right]$$

$$\therefore \quad V = V_r \cosh \gamma x + I_r Z_c \sinh \gamma x \quad \text{...(2.33.14)}$$

$$I = \frac{1}{Z_c}\left[\frac{V_r + I_r Z_c}{2} e^{\gamma x} - \frac{V_r - I_r Z_c}{2} e^{-\gamma x}\right]$$

$$= \frac{1}{Z_c} V_r\left(\frac{e^{\gamma x} - e^{-\gamma x}}{2}\right) + I_r\left(\frac{e^{\gamma x} + e^{-\gamma x}}{2}\right)$$

$$= \frac{V_r}{Z_c} \cosh \gamma x + I_r \sinh \gamma x \quad \text{...(2.33.15)}$$

where, *V* and *I* are the voltages and currents at any distance *x* from the receiving end.

4. At $x = l$, $V = V_s$ and $I = I_s$

Putting these values in eq. (2.33.14) and eq. (2.33.15), V_s and I_s is expressed as

$$V_s = V_r \cosh \gamma l + I_r Z_c \sinh \gamma l \quad \text{...(2.33.16)}$$

$$I_s = \frac{V_r}{Z_c} \sinh \gamma l + I_r \cosh \gamma l \quad \text{...(2.33.17)}$$

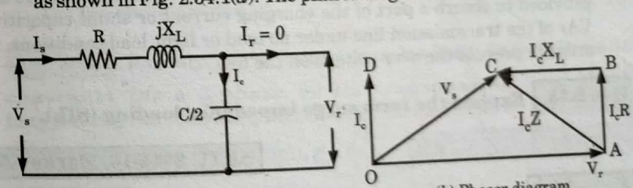
5. By comparison of eq. (2.33.16) and eq. (2.33.17) with general transmission circuit constant of eq. (2.33.1) and eq. (2.33.2), we get

$$A = D = \cosh \gamma l,$$
$$B = Z_c \sinh \gamma l \text{ and}$$
$$C = \frac{1}{Z_c} \sinh \gamma l.$$

Que 2.34. **Explain Ferranti effect.**

Answer

1. When medium or long transmission lines are operated at no-load or light-load, the receiving-end voltage becomes more than the sending-end voltage. The phenomenon of rise in voltage at the receiving-end of a transmission line during no load or light load condition is called the Ferranti effect.
2. The charging current produces a voltage drop in the series reactance of the line. This voltage drop is in phase opposition to the receiving-end voltage, and hence the sending-end voltage becomes smaller than the receiving-end voltage.
3. In order to determine the magnitude of voltage rise, one-half of the total line capacitance will be assumed to be concentrated at the receiving-end as shown in Fig. 2.34.1(*a*). The phasor diagram is shown in Fig. 2.34.1(*b*).



(*a*) Circuit diagram. (*b*) Phasor diagram

Fig. 2.34.1.

4. Taking receiving-end voltage as reference phasor, we have

$$V_r = V_r \angle 0°$$

and is represented by phasor *OA*.

5. Charging current

$$I_c = YV_r$$

This is represented by phasor *OD*.

6. The sending-end voltage

$$V_s = V_r + I_c(R + jX_L)$$
$$= V_r + jYV_r(R + jX_L)$$
$$= V_r - YX_LV_r + jYRV_r$$

7. The vector OC represents the sending-end voltage under no-load condition and is less than the receiving-end voltage. The line resistance is usually small as compared to the line inductive reactance. Hence, the resistance is neglected.
8. Neglecting resistive drop of the line, I_cR, we get

Rise in voltage, $V' = OC - OA$
$$= V_s - V_r$$
$$= -YX_LV_r \quad ...(2.34.1)$$

The negative sign in eq. (2.34.1) indicates that V_r is more than V_s.

9. If C_0 and L_0 are the capacitance and inductance of the transmission line per meter length, respectively and l is the length of the line in meters, then eq. (2.34.1) becomes,

$$V' = -\frac{\omega C_0 l}{2} \times \omega L_0 l \times V_r$$

$$V' = -\frac{\omega^2 C_0 L_0 l^2 V_r}{2}$$

10. In case of short lines, the effect is negligible, but it increases rapidly with the increase in length of the line. Therefore, this phenomenon is observable only in medium and long lines.
11. For long high voltage and EHV transmission lines, shunt reactors are provided to absorb a part of the charging current or shunt capacitive VAr of the transmission line under no load or light load conditions, in order to prevent the over voltage on the line.

Que 2.35. **Explain the term surge impedance loading (SIL).**

AKTU 2015-16, Marks 7,5

Answer

1. The surge impedance loading (SIL) of a transmission line is the power (MW) loading of a transmission line when the line is lossless.
2. A transmission line produces reactive power (MVAr) due to their capacitance. The amount of MVAr produced is dependent on the transmission line capacitive reactance (X_c) and the voltage (kV) at which the line is energized.
3. Now the MVAr produced is,

$$\text{MVAr} = \frac{(kV)^2}{X_c}$$

4. MVAr used by transmission line = I^2X_L where, I is in kA.
5. Transmission line SIL is the MW loading (at a unity power factor) at which the line MVAr usage is equal to the line MVAr production. Hence, SIL occurs when :

$$I^2X_L = \frac{(kV)^2}{X_c}$$

$$X_LX_c = \frac{(kV)^2}{I^2} \quad ...(2.35.1)$$

And the eq. (2.35.1), can be rewritten as

$$\sqrt{\frac{V^2}{I^2}} = \frac{2\pi fL}{2\pi fC} \quad \text{(Since for lossless line, } R \approx 0\text{)}$$

$$\frac{V}{I} = \sqrt{\frac{L}{C}} = \text{Surge impedance}$$

6. The surge impedance loading SIL is equal to the ratio of voltage squared (in kV) to surge impedance (in ohms).

$$\therefore \quad \text{SIL (MW)} = \frac{V_{L-L}^2}{\text{Surge impedance}}$$

7. For loading much higher than SIL, shunt capacitor may be needed for improving the voltage profile along life and for light load conditions, *i.e.*, load much less than the SIL, shunt inductors may be needed to reduce the line charging current.

Que 2.36. **Explain surge impedance loading. Determine *ABCD* constants for a 3-phase 50 Hz transmission line 200 km long having the following distributed parameters $l = 1.3 \times 10^{-3}$ H/km, $c = 9\times 10^{-9}$ F/km, $r = 0.20\ \Omega$/km, $g = 0$.**

AKTU 2016-17, Marks 15

Answer

A. Surge impedance loading : Refer Q. 2.35, Page 2–53B, Unit-2.

B. Numerical :

Given : $f = 50$ Hz, $l = 1.3 \times 10^{-3}$ H/km, $c = 9 \times 10^{-9}$ F/km
$r = 0.20\ \Omega$/km, $g = 0$
To Find : A, B, C and D constants.

1. $$z = r + j\omega l$$
$$= 0.2 + j \times 2\pi \times 50 \times 1.3 \times 10^{-3}$$
$$= 0.2 + j0.408407$$

$= 0.454748 \angle 63.9°$ ohm/km.

2. $y = j\omega c$

$= j \times 2\pi \times 50 \times 9 \times 10^{-9}$

$= 2827.4334 \times 10^{-9} \angle 90°$ S/km

3. $$Z_c = \sqrt{\frac{z}{y}} = \sqrt{\frac{0.454748\angle 63.9°}{2827.4334 \times 10^{-9} \angle 90°}}$$

$= 401.04 \angle -13.04567°$ ohm

4. $\gamma = \sqrt{zy}$

$= 1.1339 \times 10^{-3} \angle 76.95°$

5. $\gamma l = 0.22678 \angle 76.95°$

$= 0.051189 + j0.2208$

6. $\cosh \gamma l = \cosh (0.051189 + j0.2208)$

$= \cosh 0.051189. \cos 0.2208$

$+j \sinh 0.51189 \sin 0.2208$

$= 1.001310 \times 0.9757 + j0.0512113 \times 0.2190$

$= 0.97698 + j0.0112158$

$= 0.97704 \angle 0.65770°$

7. $\sinh \gamma l = \sinh (0.97698 + j0.00112158)$

$= \sin h\, 0.97698 \cos 0.0112158$

$+ j \cosh 0.97698 \sin 0.112158$

$= 0.05112113 \times 09757 + j1.001310 \times 0.219$

$= 0.04995 + j\, 0.21928 = 0.22489 \angle 77.167°$

8. $A = D = \cosh \gamma l$

$= 0.97704 \angle 0.65770°$

9. $B = Z_c \sinh \gamma l$

$= 401.04 \angle -13.04657° \times 0.22489 \angle 77.167°$

$= 90.18989 \angle 64.12133°$

10. $$C = \frac{1}{Z_c} \sinh \gamma l = \frac{0.22489\angle 77.167°}{401.04\angle -13.04567}$$

$= 0.000561 \angle 90.21267°$

VERY IMPORTANT QUESTIONS

Following questions are very important. These questions may be asked in your SESSIONALS as well as UNIVERSITY EXAMINATION.

Q. 1. Find the ratio of volume of copper required to transmit a given power over a given distance by overhead system using (i) DC two wire system (ii) 3-phase 4-wire system.

Ans. Refer Q. 2.4, Unit-2.

Q. 2. Explain different types of conductors in power system.

Ans. Refer Q. 2.8, Unit-2.

Q. 3. Explain resistance of transmission line. Also discuss effect of skin effect on effective resistance of conductor.

Ans. Refer Q. 2.11, Unit-2.

Q. 4. Explain Kelvin's Economy Law and derive the condition for most economical cross-sectional area of the conductor.

Ans. Refer Q. 2.12, Unit-2.

Q. 5. Briefly explain Proximity effect.

Ans. Refer Q. 2.13, Unit-2.

Q. 6. Explain corona loss. How is critical disruptive voltage estimated ? Give advantages and disadvantages of corona loss.

Ans. Refer Q. 2.20, Unit-2.

Q. 7. Explain the phenomenon of corona formation and factors affecting corona. What is visual critical voltage ?

Ans. Refer Q. 2.21, Unit-2.

Q. 8. Derive the expression for the regulation and efficiency of a short transmission line. Draw the required circuit and phasor diagram.

Ans. Refer Q. 2.27, Unit-2.

Q. 9. Deduce an expression for transmission efficiency and regulation for medium transmission line using (i) Nominal *T*-method (ii) Nominal π-method. Also calculate *A*, *B*, *C* and *D* parameter.

Ans. Refer Q. 2.29, Unit-2.

Q. 10. Explain Ferranti effect.

Ans. Refer Q. 2.34, Unit-2.

☺☺☺

3

UNIT

Transmission and Distribution of Electric Power-II

CONTENTS

PART-1

Mechanical Design of Over Headlines : Catenary Curve, Calculation of Sag and Tension.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 3.1. **Explain sag. Also derive expression for sag of a conductor in overhead transmission line when supported at equal levels and at two different levels.**

OR

Deduce an expression for sag in overhead transmission lines when
i. Supports are at equal levels
ii. Supports are at unequal levels. AKTU 2018-19, Marks 07

Answer

A. Sag : The difference in levels between point of support and the lowest point on the conductor is called sag.
The sag is denoted by S as shown in Fig. 3.1.1.

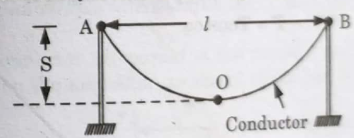


Fig. 3.1.1.

B. Supports at equal levels :

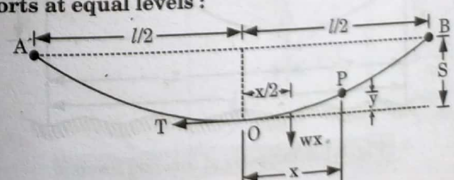


Fig. 3.1.2. Supports at equal level.

1. Let
l = Span length
w = Weight per unit length of conductor
T = Tension in the conductor
S = Sag

2. Consider a point P on the conductor. Its coordinates are x and y, taking O as the origin.
3. If the curvature is considered so small that curved length is equal to its horizontal projection, *i.e.*, $OP = x$, then the forces acting on the portion OP are :
   i. The weight wx of the conductor acting at a distance $x/2$ from O.
   ii. The tension T acting at O.
4. Taking moments of these forces about point P, we get

$$T \times y = wx \times x / 2$$

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

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

5. At support A (or B),

$$x = l/2 \text{ and } y = S$$

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

C. Supports at unequal level :

1. Let
   l = Span length
   h = Difference in levels between two supports
   x_1 = Distance of support A from O
   x_2 = Distance of support B from O
   w = Weight per unit length of conductor
   T = Tension

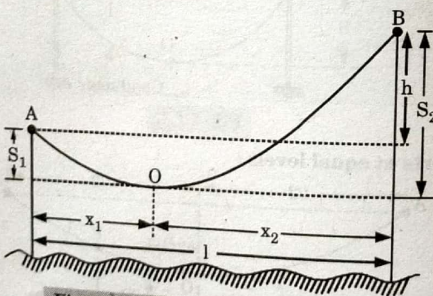


Fig. 3.1.3. Supports at unequal levels.

2. Now,

$$S_1 = \frac{wx_1^2}{2T}, \text{ and } S_2 = \frac{wx_2^2}{2T}$$

Also,

$$x_1 + x_2 = l$$

3. $\therefore$

$$S_2 - S_1 = \frac{wx_2^2}{2T} - \frac{wx_1^2}{2T} = \frac{w}{2T}(x_2^2 - x_1^2) \quad ...(3.1.1)$$

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

$$S_2 - S_1 = \frac{wl}{2T}(x_2 - x_1)$$

4. But,

$$S_2 - S_1 = h$$

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

$$(x_2 - x_1) = \frac{2Th}{wl} \quad ...(3.1.2)$$

5. Adding eq. (3.1.1) and (3.1.2), we get

$$2x_2 = l + \frac{2Th}{wl}$$

$$x_2 = \frac{l}{2} + \frac{Th}{wl}$$

6. And,

$$x_1 = l - \left[\frac{l}{2} + \frac{Th}{wl}\right] = \frac{l}{2} - \frac{Th}{wl}$$

After finding x_1 and x_2, the values of S_1 and S_2 can be calculated.

Que 3.2. **Explain catenary method for the calculation of sag and tension in transmission line.**

Answer

1. When sag is comparable with the span then conductor takes the form of catenary.
2. Consider a conductor, supported at the points A and B with O as the lowest point on the conductor, as shown in the Fig. 3.2.1.

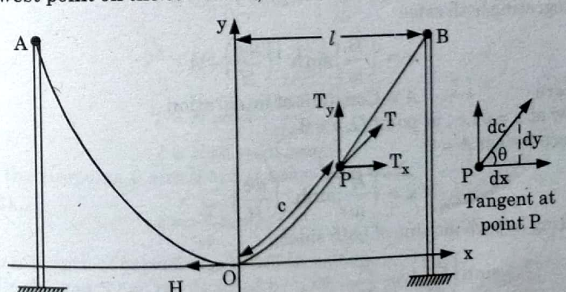


Fig. 3.2.1.

3. Let
   w = Weight per unit length
   T = Tension at point P.
4. Let P be the point on the conductor such that $OP = c$. The point O is origin and the co-ordinates of point P are (x, y). The tension T is acting tangentially at point P.

5. The various forces acting on the curve portion OP of the wire are
i. Horizontal tension, H acting at O.
ii. Weight of the portion OP which is wc acting vertically downward through centre of gravity.
iii. Horizontal and vertical components of tension T in the conductor *i.e.*, T_x and T_y acting at P.
6. In the equilibrium condition, horizontal and vertical components will balance each other.

$$\therefore \quad T_x = H$$

and $$T_y = wc$$

Now $$\tan\theta = \frac{T_y}{T_x} = \frac{wc}{H}$$

7. $\tan\theta$ can also be written as,

$$\tan\theta = \frac{dy}{dx} = \frac{wc}{H} \quad \text{...(3.2.1)}$$

8. Now $$(dc)^2 = (dx)^2 + (dy)^2$$

$$\therefore \quad \left(\frac{dc}{dx}\right)^2 = 1 + \left(\frac{dy}{dx}\right)^2$$

9. Substituting from equation (3.2.1) we get,

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

$$\therefore \quad dx = \frac{dc}{\sqrt{1+\frac{w^2c^2}{H^2}}}$$

10. Integrating both sides

$$x = \left(\frac{H}{w}\right)\sinh^{-1}\left(\frac{wc}{H}\right) + A$$

where A = Constant of integration

11. Now at $x = 0$ *i.e.*, at point O, $c = 0$
hence we get $A = 0$

$$x = \left(\frac{H}{w}\right)\sinh^{-1}\left(\frac{wc}{H}\right) \quad \text{...(3.2.2)}$$

12. Taking hyperbolic sine of both sides,

$$\sinh\left(\frac{wx}{H}\right) = \frac{wc}{H}$$

$$\therefore \quad c = \frac{H}{w}\sinh\left(\frac{wx}{H}\right) \quad \text{...(3.2.3)}$$

13. From eq. (3.2.1),

$$\frac{dy}{dx} = \frac{wc}{H}$$

$$\therefore \quad \frac{dy}{dx} = \frac{w}{H}\left[\frac{H}{w}\sinh\left(\frac{wx}{H}\right)\right]$$

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

14. Integrating both sides,

$$y = \frac{H}{w}\cosh\left(\frac{wx}{H}\right) + B \quad \text{...(3.2.4)}$$

where B = Constant of integration

15. when $y = 0, x = 0$ at point O

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

$$\therefore \quad B = -\frac{H}{w}$$

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

$$\therefore \quad y = \frac{H}{w}\left[\cosh\left(\frac{wx}{H}\right) - 1\right] \quad \text{...(3.2.5)}$$

This is the required equation of the catenary form of conductor.

Calculation of tension T and conductor half span length :

1. The tension T at any point P is,

$$T^2 = T_x^2 + T_y^2 = H^2 + w^2c^2$$

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

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

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

$$\therefore \quad T = H\cosh\left(\frac{wx}{H}\right)$$

2. l = Half span length
and the supports A and B are at same level then,

$$c = \frac{H}{w}\sinh\left(\frac{wl}{H}\right)$$

This is length of curved conductor in half span.

3. While the sag S can be obtained by putting $y = S$ in eq. (3.2.5).

$$\therefore \quad S = \frac{H}{w}\left[\cosh\left(\frac{wl}{H}\right) - 1\right]$$

$$= \frac{H}{w}\left[\cosh\left(\frac{wL}{2H}\right) - 1\right]$$

4. The eq. (3.2.3) giving the arc length c can be expanded as,

$$c = \frac{H}{w}\sinh\left(\frac{wx}{H}\right)$$

$$= \frac{H}{w}\left[\frac{wx}{H} + \frac{w^3x^3}{3!H^3} + \ldots\ldots\right] \cong x + \frac{w^2x^3}{6H^2}$$

5. In such approximation we can assume $H = T$.

$$\therefore \quad c \approx x + \frac{w^2x^3}{6T^2}$$

6. So half span length can be obtained by substituting $x = l$,

$$\therefore \quad c = l + \frac{w^2l^3}{6T^2} = l\left[1 + \frac{w^2l^2}{6T^2}\right]$$

Que 3.3. **Explain catenary method for the calculation of sag and tension in transmission line.**

An overhead line has a span of 200 metres, the line conductor weights 0.7 kg per meter. Calculate the maximum sag if allowable tension in the line is 1,400 kg. Prove formula used. **AKTU 2017-18, Marks 10**

Answer

A. **Catenary method for calculation of sag and tension :** Refer Q. 3.2, Page 3–4B, Unit-3.

B. **Numerical :**

Given : l = 200 m, w = 0.7 kg per meter, T = 1400 kg
To Find : Maximum sag, S.

Maximum sag,
$$S = \frac{wl^2}{8T} = \frac{0.7 \times 200 \times 200}{8 \times 1400}$$
$$= 2.5 \text{ m}$$

Proof of $S = \frac{wl^2}{8T}$: Refer Q. 3.1, Page 3–2B, Unit-3.

PART-2

Effects of Wind and Ice Loading, Sag Template, Vibration Dampers.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 3.4. **Discuss the effect of atmospheric condition on transmission line.**

OR

Derive expression for sag and tension in power conductor string between two supports at equal heights taking into account wind and ice loading. **AKTU 2015-16, Marks 10**

AKTU 2019-20, Marks 07

Answer

A. **Expression for sag and tension for supports at equal heights :** Refer Q. 3.1, Page 3–2B, Unit-3.

B. **Effect of atmospheric condition on transmission line :**

a. **Effect of Ice coating :**

1. When the transmission line is coated with ice, the thickness and size of the conductor increases. This thickness depends on the weather conditions.
2. This causes increase in weight of the conductor; increase in weight increases the vertical sag.
3. The weight of ice acts vertically downwards, in the same direction as that of the conductor.
4. Consider a conductor with diameter d. It is coated with ice thickness t as shown in Fig. 3.4.1. Hence the overall diameter of the coated conductor is D.

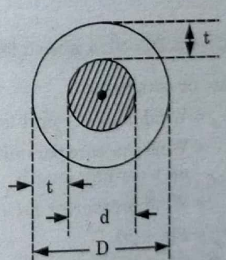


Fig. 3.4.1. Ice coated conductor.

$$D = d + 2t$$

and the area of the coated conductor is

$$= \frac{\pi}{4}D^2$$

5. Area of the ice covering,

$$A_i = \frac{\pi}{4}[D^2 - d^2]$$

6. The density of ice is 915 kg/m^3. Hence the total weight of ice can be obtained as,

$$w_i = 915 \times \frac{\pi}{4}[D^2 - d^2] \text{ kg/m}$$

= Weight of ice per unit length

$$= 915 \times \frac{\pi}{4}[(d+2t)^2 - d^2]$$

$$= 915 \times \frac{\pi}{4}[d^2 + 4dt + 4t^2 - d^2]$$

$$= 915 \times \pi\,[dt + t^2]$$

$$w_i = 915\pi t\,(d + t) \text{ kg/m}$$

B. Effect of wind pressure :

1. The wind flows horizontally and hence the wind pressure on the conductor is considered to be acting perpendicular to the conductor.
2. Thus force due to wind act at right angles to the projected surface of the conductor as shown in Fig. 3.4.2.

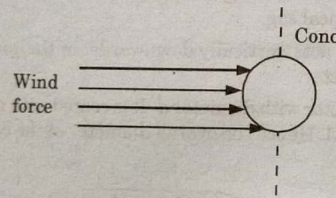


Fig. 3.4.2. Direction of wind force.

3. The wind force w_w can be obtained as,

w_w = Wind force per unit length in kg/m

= Wind pressure per unit area × Projected surface area per unit length

= Wind pressure × $[(d + 2t) \times 1]$

$$w_w = P[d + 2t]$$

where, P = Wind pressure in kg/m^2

d = Diameter of conductor

t = Thickness of ice coating if exists

C. Effect of ice and wind :

1. Let w = Weight of conductor itself acting vertically downward

w_i = Weight of ice acting vertically downward

w_w = Wind force acting horizontally

2. Hence the total force acting on the conductor is vector sum of the horizontal and vertical forces as shown in Fig. 3.4.3.

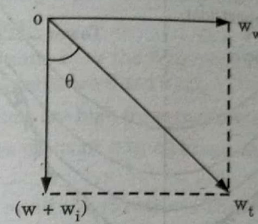


Fig. 3.4.3.

w_t = Total weight acting on conductor

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

3. The sag direction is at an angle θ measured with respect to vertical. Hence the sag is called slant sag. This is calculated by the expression considering the total weight w_t.

$$\text{Slant sag, } S = \frac{w_t l^2}{8T}$$

4. The conductor adjusts itself in a plane which is at an angle θ with respect to vertical; the angle is given by,

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

5. As slant sag S is the direction of an angle θ with respect to vertical, the vertical sag is cosine component of slant sag S,

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

Que 3.5. Explain sag template and its use.

Answer

1. Sag template is a convenient device used in the design of a transmission line to determine the location and height of tower.
2. For locating the tower positions, for normal spans and for standard towers, the sag and the nature of conductor curve are calculated under expected load condition and plotted on a thin stiff plastic sheet such a graph is called sag template.

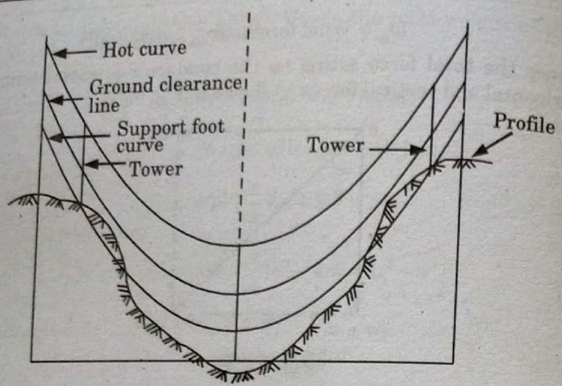


Fig. 3.5.1. Sag template.

3. The curves which are marked on it are :

i. **Location of support (tower) or Hot curve :** These curves are obtained by plotting sags at maximum temperature against span lengths. It gives us the location of supports to maintain proper ground clearance.

ii. **Ground clearance curve :** This curve is below hot curve. It is drawn parallel to the hot curve and at a vertical distance equal to ground clearance as prescribed by the regulations for the given line.

iii. **Support foot curve or tower curve :** It is drawn to locate the position of support for tower lines. It shows height from the base of standard support to the point of attachment of the lowest conductor.

iv. **Uplift curve or cold curve :** These are obtained by plotting the sags at minimum temperature without ice or wind loading against span length. These are drawn to check whether uplift of conductors occurs at any support.

4. **Use of sag template :**

i. For correct design and economy.

ii. It is used to allocate the position and height of the support correctly on the profile.

Que 3.6. **Why do the vibrations get generated in conductors ? How are they damped ? Explain effect of wind and ice loading on the mechanical design of a line.**

AKTU 2017-18, Marks 10

Answer

A. Vibrations :

1. The conductors are supported on the string insulators at each tower.

2. Under widely varying atmospheric conditions like strong wind velocities, the conductor can start vibrating mechanically in the vertical plane. Such vibrations can have different frequencies amplitudes & modes.

Types of vibrations in the vertical plane :

a. **Aeoline vibrations :**

1. The Aeoline vibrations have the frequency range of 5 to 50 Hz with amplitudes varying between 2 and 5 cm.

2. Thus these vibrations are high frequency low amplitude vibrations.

3. The wind velocities of about 2 to 40 kmph can generate such type of vibrations.

Minimization of aeoline vibration : The effect of aeoline vibration can be minimized by,

1. Use of bundle conductor
2. Proper design and location of spacers
3. Use of damper
4. Use of clamps.

b. **Galloping of conductor/dancing of conductor :**

1. The galloping means dancing of conductors at the low frequency and high amplitude.

2. These are the oscillations of complete span of conductors.

3. The frequencies of galloping are about 0.5 to 2 Hz with the amplitude of about 6 m.

Minimization of galloping of conductor :

There are no method by which galloping can be restricted but in icing conditions height of the conductors can be designed properly considering the amplitude of possible of possible galloping.

B. **Vibration dampers :** Vibration damper are the devices used to minimize the vibrations in the conductors. The following two devices are used to prevent vibration in conductors :

a. **Armour rods :**

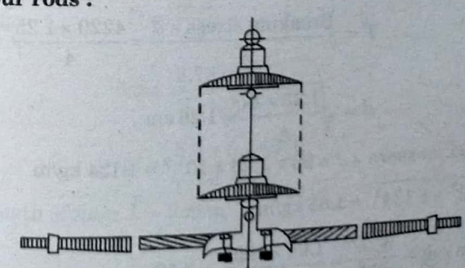


Fig. 3.6.1. Armour rod.

1. Armour rods are spiral layers of small round rods and are tapered at each end.
2. They are much larger in diameter than the actual conductor, so they provide resistance to bending at suspension point thus reducing amplitude of vibration by distributing stresses at support point.
3. They also provide excellent protection against flashover.

b. Stockbridge damper :

1. It is a device which absorbs vibrational energy. It consists of two hollow weights joined by a flexible steel wire and a clamp in the middle point to attach it to conductors.
2. Two dampers are required at each point of suspension of conductors, one on either side. Each span of conductor contains two dampers but for longer span the number of dampers may increase.

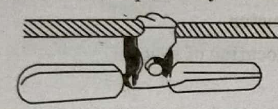


Fig. 3.6.2. Stockbridge damper.

C. Effect of wind and ice loading : Refer Q. 3.4, Page 3–8B, Unit-3.

Que 3.7. A transmission line has a span of 150 m between level supports. The line conductor has a cross sectional area of 1.25 cm^2 and it weights 120 kg per 100 m. If the breaking stress of the copper conductor is 4220 kg/cm^2, calculate the maximum sag for a safety factor of 4. Assume maximum wind pressure of 90 kg/m^2 of projected surface.

AKTU 2018-19, Marks 07

Answer

Given : L = 150 m, a = 1.25 cm^2, k = 4, Weight = 120 kg/100 m = 1.2 kg/m, Breaking stress = 4220 kg/cm^2
To Find : Maximum sag.

1. Tension, $T = \dfrac{\text{Breaking stress} \times a}{k} = \dfrac{4220 \times 1.25}{4} = 1319 \text{ kg}$
2. Diameter, $d = \sqrt{\dfrac{1.25 \times 4}{\pi}} = 1.26 \text{ cm}$
3. W_W = Wind pressure $\times d = 90 \times 1.26 \times 10^{-2} = 1.134$ kg/m
4. $W_r = \sqrt{1.2^2 + 1.134^2} = 1.65$ kg/m
5. Maximum sag $= \dfrac{W_r L^2}{8T} = \dfrac{1.65 \times 150^2}{8 \times 1319} = 3.52$ m

Que 3.8. A transmission line conductor has an effective diameter of 19.5 mm and weights 1.0 kg/m. If the maximum permissible sag with a horizontal wind pressure of 39 kg/m^2 of projected area and 12.7 mm radial ice coating is 6.3 m. Calculate the permissible span between two supports at the same level allowing a safety factor of 2. Ultimate strength of the conductor is 8,000 kg and weight of ice is 910 kg/m^3.

Answer

Given : Diameter of the conductor is, d = 19.5 cm, Weight of conductor, w_c = 1.0 kg/m, Wind pressure, P = 39 kg/m^2, Radial ice coating, t = 12.7 mm, Maximum permissible sag, D = 6.3 m, Safety factor = 2, Ultimate strength = 8000 kg, Weight of ice, w_i = 910 kg/m^3
To Find : Permissible span between two supports at the same level (L)

1. Maximum allowable tension, $T = \dfrac{\text{Ultimate strength}}{\text{Safety factor}} = \dfrac{8000}{2} = 4000$ kg
2. Are of ice-section $= \pi t(d + t)$
$$= \pi \times 12.7(19.5 + 12.7)$$
$$= 1284.723 \text{ mm}^2$$
$$= 1284 \times 10^{-6} \text{ m}^2$$
3. Weight of ice, $w_i = 910 \times 1284 \times 10^{-6}$
$$= 1.1691 \text{ kg/m}$$
4. Wind pressure, $w_w = 39(d + 2t)$
$$= 39(19.5 + 2 \times 12.7) \times 10^{-3}$$
$$= 1.751 \text{ kg/m}$$
5. Resultant weight, $w_r = \sqrt{w_w^2 + (w_c + w_i)^2} = \sqrt{1.751^2 + (1.0 + 1.1691)^2}$
$$= 2.7876 \text{ kg/m}$$
6. $\therefore$ Sag, $D = \dfrac{w_r L^2}{8T}$
$$6.3 = \frac{2.7876 L^2}{8 \times 4000}$$
$$L^2 = \frac{6.3 \times 8 \times 4000}{2.7876}$$
7. $\therefore$ Length of span, L = 269 m

Que 3.9. **Why do the vibrations get generated in conductors ? How are they damped ?**
A 132 kV transmission line has the following data :
Weight of conductor = 680 kg/km; Length of span = 260 m
Ultimate strength = 3100 kg; Safety factor = 2
Calculate the height above ground at which the conductor should be supported. Ground clearance required is 10 m.

AKTU 2016-17, Marks 10

Answer

A. **Generation of vibration :** Refer Q. 3.6, Page 3–11B, Unit-3.

B. **Numerical :**

Given : l = 260 m, w = 680 kg/km, Ultimate strength = 3100 kg, S_F = 2, Ground clearance = 10 m

To Find : Height of conductor above ground.

1. Maximum working tension,

$$H = \frac{\text{Ultimate tensile strength}}{\text{Safety factor}} = \frac{3100}{2} = 1550 \text{ kg}$$

2. Sag,

$$S = \frac{wl^2}{8H} = \frac{680 \times (260)^2}{8 \times 1550} = 3.70 \text{ m}$$

3. Height above ground = S + Ground clearance = 3.70 + 10 = 13.70 m

PART-3

Overhead Line Insulators : Types of Insulators and their Applications.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 3.10. **Discuss the different types of Insulator.**

OR

Describe pin type, suspension type and strain type insulators with net sketch.

AKTU 2017-18, Marks 10

Answer

A. **Pin type insulator :**

1. Pin type insulators are used for transmission and distribution of electric power at voltage upto 33 kV.

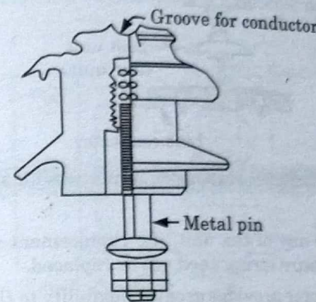


Fig. 3.10.1. Pin type insulators.

2. Beyond operating voltage of 33 kV the pin type insulator become bulky and hence uneconomical.
3. On the upper end, there is a groove for housing the conductor. The pin insulators are very firmly secured to the cross arm on the transmission pole with the help of steel bolts.
4. The conductor passes through the groove on the upper end and is bound by the binding wire of soft copper or soft aluminum *i.e.*, of the same material as that of conductor.

Advantage : It is cheaper for upto operating voltage of 33 kV.

Disadvantage : This type of insulator becomes very bulky and cost also increase rapidly for higher operating voltage.

B. **Suspension insulator :**

1. These insulator used for high transmission lines. These insulators have number of porcelain disc units. These units are connected to one another in series with the help of metal links.
2. This forms a string of porcelain discs. The topmost insulators unit is connected to the cross arm of the tower while the lowest insulator is made to hold the conductor along the conductor shoe.
3. Each unit is designed for the low voltage for say 11 kV but a string of such units give us the proper insulation against high level voltage.
4. The overall string of suspension type insulator is shown in the Fig. 3.10.2.

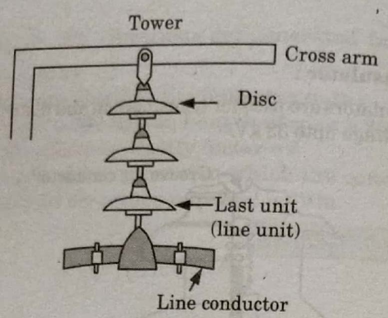


Fig. 3.10.2. String suspension insulator with 3 units.

Advantages :

1. In case of failure any of the unit, the replacement work can be done very easily and entire string need not be replaced.
2. This type of insulator provides greater flexibility to the line.

Disadvantage : Suspension type insulators require large spacing between the conductors of string.

C. Strain insulators :

1. These insulators are used when there is dead end of the line is at a sharp curve or the line is crossing the river etc.
2. These insulators reduce the excessive tension on the line under such abnormal condition. For high voltage strain insulators are used.
3. The discs of the strain insulators are in a vertical plane.
4. In case of condition like crossing of river, there is excessive tension on the line. In such a case two or more strings of the insulators are used in parallel.

Advantage : It is economical for high operating voltage.

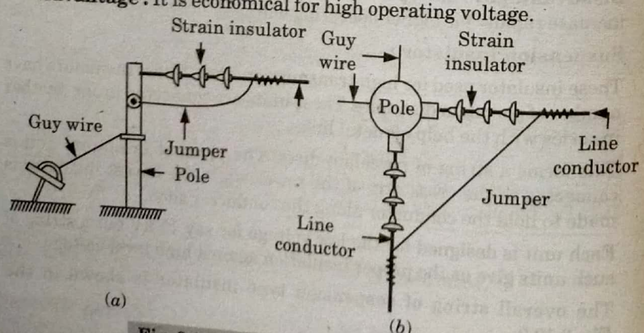


Fig. 3.10.3. Use of strain insulator.

D. Shackle insulator :

1. This is also called spool insulators. These are primarily used for low voltage distribution lines.
2. These insulators can be used in horizontal position or in vertical position. These are used at the dead end of the aerial wire of service connection to a house or a factory where there is excessive mechanical stress on the line.

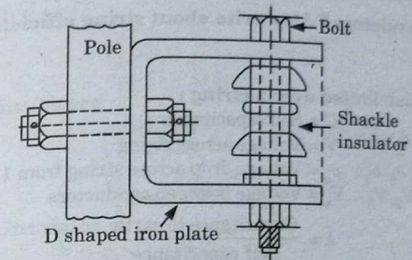


Fig. 3.10.4. Shackle insulator.

E. Stay insulators :

1. The stay insulators are also called egg insulators. In case of low voltage lines, it is necessary that the stays are to be insulated at a height of not less than 3 meters from ground.
2. The stay insulators are used on stay wire to create insulation between pole and stay clamp.
3. It is usually made of porcelain. It has two holes for the stay wires and the design is such that in case the insulator breaks then the stay wires will not fall on the ground.

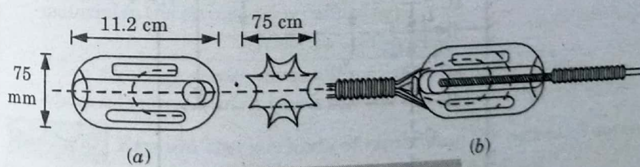


Fig. 3.10.5. Stay insulator.

PART-4

Potential Distribution Over a String of Insulators, Methods of Equalizing the Potential, String Efficiency.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 3.11. **Explain how the potential is distributed over a string of suspension insulators ? Also write about string efficiency.**

Answer

A. Voltage distributed over a string :

1. Let
C = Self capacitance
V = Voltage across string
$v_1, v_2, v_3 \dots v_n$ = Voltage drop across string from 1, 2, ... n
$V_1, V_2, V_3 \dots V_n$ = Voltage between conductors

$$k = \frac{\text{Capacitance to earth}}{\text{Self capacitance}}$$

Capacitance to earth = k × self capacitance = kC

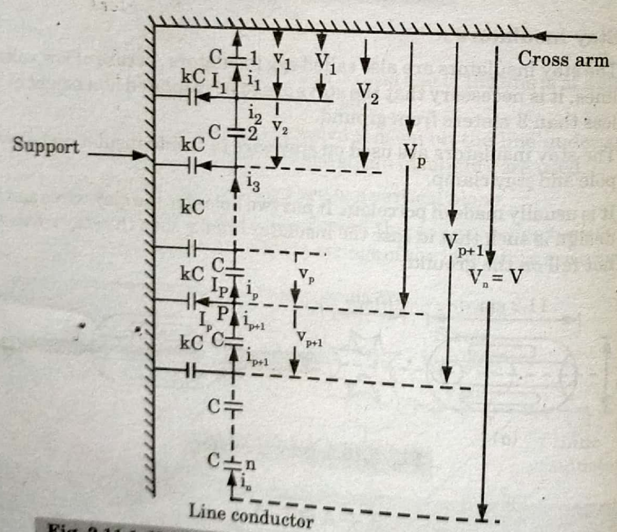


Fig. 3.11.1. Voltage distribution across the units of a string.

2. Applying KCL at node P,

$$i_{p+1} = i_p + I_p$$
$$v_{p+1}(j\omega C) = v_p(j\omega C) + V_p(j\omega kC)$$
$$v_{p+1} = v_p + kV_p \quad \text{...(3.11.1)}$$

$$v_1 + v_2 + v_3 \dots\dots v_n = V \quad \text{...(3.11.2)}$$

We can find voltage across any string using eq. (3.11.1) and (3.11.2).

3. Let us find voltage across each insulator of each string *i.e.*, to calculate $v_2, v_3, v_4, \dots\dots v_n$ in terms of v_1.
4. **Top most insulator or first insulator :**
Voltage across insulator = v_1
5. **Second insulator :**
Using eq. (3.11.1),
$$v_2 = v_1 + kV_1$$
But $V_1 = v_1$
$$v_2 = (1 + k)\, v_1 \quad \text{...(3.11.3)}$$
6. **Third insulator :**
$$v_3 = v_2 + kV_2$$
But $V_2 = v_1 + v_2$
$$v_3 = v_2 + k(v_1 + v_2)$$
$$v_3 = kv_1 + (1 + k)\, v_2 \quad \text{...(3.11.4)}$$
7. **Fourth insulator :**
$$v_4 = v_3 + kV_3$$
But $V_3 = v_1 + v_2 + v_3$
$$v_4 = v_3 + k(v_1 + v_2 + v_3)$$
$$v_4 = k(v_1 + v_2) + (1 + k)v_3 \quad \text{...(3.11.5)}$$
Similarly, we can calculate for all insulators.
8. It is clear that
$$v_1 < v_2 < v_3 < v_4 \dots\dots\dots\dots < v_n$$
Since mutual capacity of each disc is same and the current through the top most unit is minimum, the voltage drop across that unit will be minimum. Going towards power conductor the current goes on increasing, and will be maximum in the lowest unit. So the voltage drop is maximum there.

B. String Efficiency : String efficiency is measure of the utilization of material in the string and is defined as :

$$\eta = \frac{\text{Voltage across the string}}{n \times \text{Voltage across the insulator nearest to line conductor}}$$

where n is number of disc or insulator.

Que 3.12. **Explain the methods of equalizing the potential across the string insulator. And define string efficiency.**

AKTU 2017-18, Marks 10

Answer

A. Methods of equalizing potential :

a. **By using longer cross-arms :**

1. The value of string efficiency depends upon the value of K is ratio of shunt capacitance to mutual capacitance.

2. 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.
3. In order to reduce shunt capacitance, the distance of conductor from tower must be increased *i.e.*, longer cross-arms should be used.
4. However, limitations of cost and strength of tower do not allow the use of very long cross-arm.

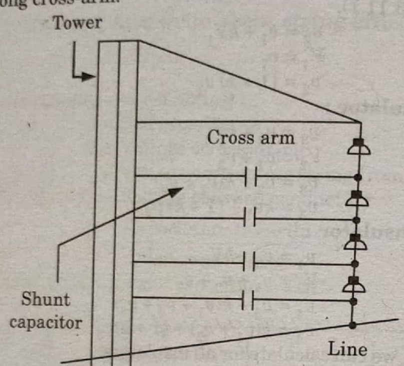


Fig. 3.12.1.

b. By using a guard ring :

1. A guard ring is simply a metal ring which is electrically connected to the conductor and surrounding the bottom insulator.
2. The potential across unit in a string can be equalized by using a guard ring which is metal ring electrically connected to the conductor and surrounding the bottom insulator as shown in the Fig. 3.13.2.

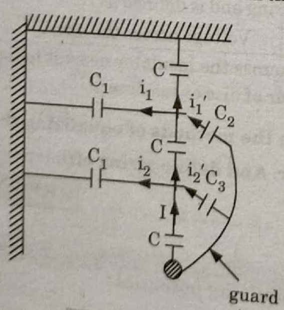


Fig. 3.12.2.

3. 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 i_1, i_2 etc., are equal to metal fittings line capacitance currents i'_1, i'_2 etc.

4. The result is that same charging current I flows through each unit of string. Consequently, there will be uniform potential distribution across the unit.

c. By grading the insulators :

1. In this method, insulators of different dimensions are so chosen that each has a different capacitance.
2. 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 is reached.
3. Since voltage is inversely proportional to capacitance. This method tends to equalise the potential distribution across the units in the string.

B. String efficiency : Refer Q. 3.11, Page 3–19B, Unit-3.

Que 3.13. Explain why the voltage does not divide equally across the units of a string insulator.
Find the voltage distribution and string efficiency of a three unit suspension insulator string if the capacitance of the link pins to earth and to the line are respectively 20 % and 10 % of the self capacitance of each unit. If a guard ring increases the capacitance to the line of lower link pin to 35 % of the self capacitance of each unit, find the redistribution of voltage and string efficiency.

AKTU 2018-19, Marks 07

Answer

A. Reason : The voltage does not divide equally across the various units of a string insulator. The capacitance between the metal parts of the insulators and the tower structure is the main reason for this.

B. Numerical :

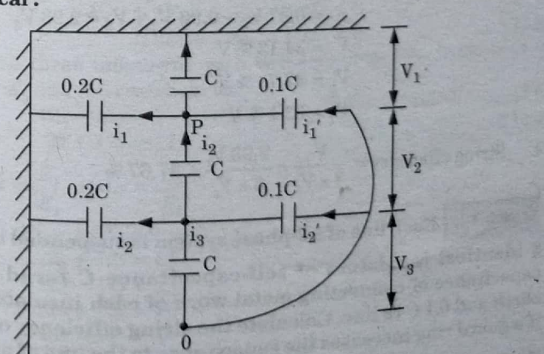


Fig. 3.13.1.

1. Applying KCL at node P,

$$I_2 + i_1' = I_1 + i_1$$

$$V_2\omega C + (V_2 + V_3)\,0.1\,\omega C = V_1\,\omega C + 0.2\,V_1\,\omega C$$

$$1.2\,V_1 - 1.1\,V_2 - 0.1\,V_3 = 0 \quad ...(3.13.1)$$

2. Similarly at Q,

$$I_3 + i_2' = I_2 + i_2$$

$$V_3\omega C + 0.1\,V_3\omega C = V_2\,\omega C + 0.2\,(V_1 + V_2)\,\omega C$$

$$0.2\,V_1 - 1.2\,V_2 - 1.1\,V_3 = 0 \quad ...(3.13.2)$$

3. From eq. (3.13.1) and (3.13.2), we get

$$V_2 = 0.78\,V_3 \text{ and } V_1 = 0.80\,V_3$$

4.
$$V = V_1 + V_2 + V_3$$
$$= 0.80\,V_3 + 0.78\,V_3 + V_3 = 2.58\,V_3$$
$$V_3 = 38.76\,\%\,V$$
$$V_2 = 30.23\,\%\,V$$
$$V_1 = 31\,\%\,V$$

5. String efficiency $= \dfrac{V}{3V_3} \times 100 = \dfrac{2.58\,V_3}{3\,V_3} \times 100 = 86\,\%$

With guard ring : Pin to line capacitance is increased from 0.1C to 0.35C.

1. $1.2\,V_1 - 1.1\,V_2 - 0.1\,V_3 = 0$ ...(3.13.3)

   $0.2\,V_1 + 1.2\,V_2 - 1.35\,V_3 = 0$ ...(3.13.4)

2. From eq. (3.13.3) and (3.13.4),

$$V_2 = 0.96\,V_3 \text{ and } V_1 = 0.97\,V_3$$

3.
$$V = V_1 + V_2 + V_3$$
$$= 0.97\,V_3 + 0.96\,V_3 + V_3 = 2.93\,V_3$$
$$V_3 = 34.13\,\%\,V$$
$$V_2 = 32.76\,\%\,V$$
$$V_1 = 33.1\,\%\,V$$

4. String efficiency $= \dfrac{V}{3 \times V_3} = \dfrac{2.93\,V_3}{3 \times V_3} = 97.67\,\%$

Que 3.14. **Each line of a 3-phase system is suspended by a string of 3 identical 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.**

AKTU 2015-16, Marks 7.5

Answer

Given : Conductor to earth capacitance = 0.2C
Conductor to line capacitance = 0.01C
To Find : String efficiency if the guard ring increases the capacitance to the line of metal work of the lowest insulator to 0.3C

1. Let E_1, E_2 and E_3 be the voltage drops across the discs as shown in Fig. 3.14.1. Applying Kirchhoff's current law at node A, we have

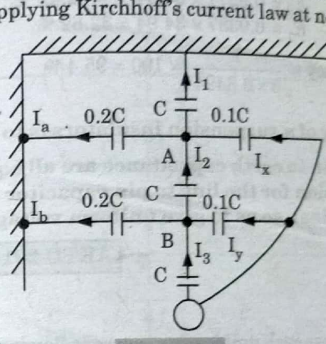


Fig. 3.14.1.

$$I_2 + I_x = I_1 + I_a$$
$$E_2\omega C + (E_2 + E_3)\omega 0.1C - E_1\omega C - 0.2E_1\omega C = 0$$
$$E_2 + (E_2 + E_3)\,0.1 - E_1 - 0.2E_1 = 0$$
$$1.1E_2 + 0.1E_3 - 1.2E_1 = 0$$
$$1.2E_1 - 1.1E_2 - 0.1E_3 = 0 \quad ...(3.14.1)$$

2. Again writing equation at node B

$$I_3 + I_y - I_2 - I_b = 0$$
$$E_3C\omega + E_3 0.1\omega C - E_2\omega C - (E_1 + E_2)\,0.2C = 0$$
$$E_3 + 0.1E_3 - 1.2E_2 - 0.2E_1 = 0$$
$$0.2E_1 + 1.2E_2 - 1.1E_3 = 0 \quad ...(3.14.2)$$

3. There are three unknowns with two equations. We divide both of them by E_3 and rewrite them as

$$12x - 11y = 1 \quad ...(3.14.3)$$
$$2x + 12y = 11 \quad ...(3.14.4)$$

where, $x = \dfrac{E_1}{E_3}$ and $y = \dfrac{E_2}{E_3}$

$$0.2E_1 + 1.2E_2 - 1.3E_3 = 0$$
$$2x + 12y = 13$$
$$12x - 11y = 1$$
$$12x + 72y = 78$$
$$12x - 11y = 1$$
$$83y = 77$$

Now, $y = 0.9277$

$$2x = 13 - 12 \times 0.9277$$
$$x = 0.9337$$

4. $\therefore$ $\dfrac{E_1}{E_3} = 0.9337$ and $\dfrac{E_2}{E_3} = 0.9277$

$$E_1 = 0.9337E_3 \text{ and } E_2 = 0.9277E_3$$
$$E = E_1 + E_2 + E_3 = 0.9337E_3 + 0.9277E_3 + E_3$$
$$E_3 = 0.3494E \text{ or } 34.94\ \%$$
$$E_2 = 0.9277 \times 34.94\ \% = 32.42\ \%$$
$$E_1 = 0.9337 \times 34.94 = 32.62\ \%$$

5. $\%$ String efficiency $= \dfrac{1}{3 \times 0.3494} \times 100 = 95.4\ \%$

Que 3.15. **A string of n suspension insulators is to be fitted with a guard ring. If the pin to earth capacitance are all equal to C, derive the general expression for the line to pin capacitor in terms of n, C and p (number of pins), so as to give uniform voltage distributions over the string.**

AKTU 2016-17, Marks 10

Answer

1. Since voltage across each unit is same, current flowing in each unit, *i.e.*, $I_1, I_2.....I_6, I_7$ etc., will be equal.
2. Applying KCL at junction P,

$$I_1 + I_a = I_A + I_2$$

But $\quad I_1 = I_2$

$\therefore \quad I_a = I_A$

i.e., $\quad EC = (n-1)EA$

$$A = \frac{C}{n-1}$$

3. Similarly, by applying KCL at Q,

$$I_2 + I_b = I_B + I_3$$

But $\quad I_2 = I_3$

$\therefore \quad I_b = I_B$

$$2EC = (n-2)\,EB$$

$$B = \frac{2C}{n-4}$$

4. Similarly, $\quad C = \dfrac{3C}{n-3}, D = \dfrac{4C}{n-4}, E = \dfrac{5C}{n-5}$

$$F = \frac{6C}{n-6} \text{ and } G = \frac{7C}{n-7}$$

5. In general the capacitance from the shield to the p^{th} link from the top is given by $C_p = \dfrac{pC}{n-p}$

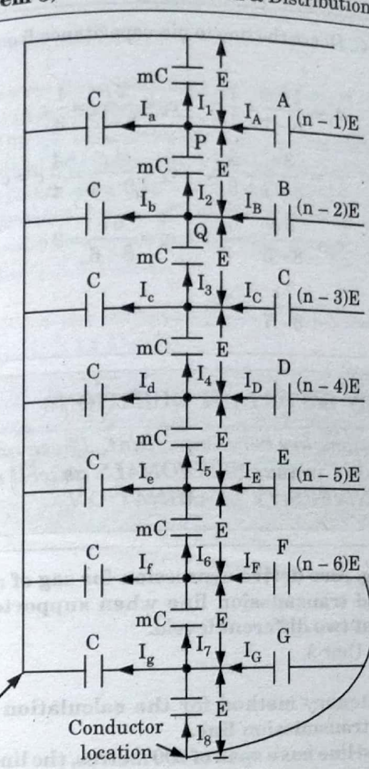


Fig. 3.15.1.

Que 3.16. **Explain the methods of equalizing the potential across the string insulator. A string of 8 suspension insulators is to be fitted with a grading ring. If the pin to earth capacitance is equal to C, find the values of line of pin capacitances that would give a uniform voltage distribution over the string.**

AKTU 2019-20, Marks 07

Answer

i. **Methods of equalizing the potential :** Refer Q. 3.12, Page 3–20B, Unit-3.

ii. **Numerical :**

1. The capacitance of the p^{th} link from the top is given by,

$$C_p = \frac{pC_g}{n-p}$$

2. Here $n = 8$, $C_g = C$. Hence the line to pin capacitance from the top are given by,

$$c_1 = \frac{1 \times c}{8-1} = \frac{1}{7}c, \quad c_2 = \frac{2c}{8-2} = \frac{1}{3}c$$

$$c_3 = \frac{3c}{8-3} = \frac{3}{5}c, \quad c_4 = \frac{4c}{8-4} = \frac{4}{4}c = c$$

$$c_5 = \frac{5c}{8-5} = \frac{5c}{3}, \quad c_6 = \frac{6c}{8-6} = 3c$$

$$c_7 = \frac{7c}{8-7} = 7c$$

VERY IMPORTANT QUESTIONS

Following questions are very important. These questions may be asked in your SESSIONALS as well as UNIVERSITY EXAMINATION.

Q. 1. Explain sag. Also derive expression for sag of a conductor in overhead transmission line when supported at equal levels and at two different levels.

Ans. Refer Q. 3.1, Unit-3.

Q. 2. Explain catenary method for the calculation of sag and tension in transmission line.
An overhead line has a span of 200 metres, the line conductor weights 0.7 kg per meter. Calculate the maximum sag if allowable tension in the line is 1,400 kg. Prove formula used.

Ans. Refer Q. 3.3, Unit-3.

Q. 3. Discuss the effect of atmospheric condition on transmission line.

Ans. Refer Q. 3.4, Unit-3.

Q. 4. Explain sag template and its use.

Ans. Refer Q. 3.5, Unit-3.

Q. 5. A transmission line has a span of 150 m between level supports. The line conductor has a cross sectional area of 1.25 cm² and it weights 120 kg per 100 m. If the breaking stress of the copper conductor is 4220 kg/cm², calculate the maximum sag for a safety factor of 4. Assume maximum wind pressure of 90 kg/m² of projected surface.

Ans. Refer Q. 3.7, Unit-3.

Q. 6. Why do the vibrations get generated in conductors ? How are they damped ?
A 132 kV transmission line has the following data :
Weight of conductor = 680 kg/km; Length of span = 260 m
Ultimate strength = 3100 kg; Safety factor = 2
Calculate the height above ground at which the conductor should be supported. Ground clearance required is 10 m.

Ans. Refer Q. 3.9, Unit-3.

Q. 7. Discuss the different types of Insulator.

Ans. Refer Q. 3.10, Unit-3.

Q. 8. Explain the methods of equalizing the potential across the string insulator. And define string efficiency.

Ans. Refer Q. 3.12, Unit-3.

☺☺☺

4 UNIT

Transmission Line Parameters

CONTENTS

PART-1

Inductance and Capacitance Calculations of Transmission Lines : Line Conductors, Inductance and Capacitance of Single Phase and three Phase Lines with Symmetrical and Unsymmetrical Spacing.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 4.1. **What do you understand by line conductor ? Also explain the different types of line conductors in power system.**

Answer

A. **Line conductors :** It is a material or element which allows free movement of electrons and therefore allows easy flow of electricity.

B. **Types :** Refer Q. 2.8, Page 2–18B, Unit-2.

Que 4.2. **Explain the factors, which are considered during designing a transmission line. Also explain how ground wire selection is done ?**

AKTU 2016-17, Marks 10

Answer

1. **Choice for transmission voltage :** The line voltage affects the performance of line and its cost. For getting the optimum operation transmission voltage, we may use following empirical formula

$$V = 5.5\left(\frac{D}{1.6}+\frac{P}{100}\right)^{0.5}$$

Here V = Operating line voltage in kV

D = Distance of transmission in km

P = Power handled in kW

A standard voltage nearer to that obtained with above formula is selected for the given line. The formula gives the basic estimate. By considering various technical and economic aspects, it is possible to obtain the most economical voltage.

2. **Conductor size selection :** The size of conductors should be properly selected during the design as about 30 to 45 % of total cost of line is involved in cost of conductor. The size of conductor decides cost of towers

and foundations. The losses in line are also dependent on size of conductor selected. Normally ACSR conductors are used which are available in variety of sizes.

3. **Choice of span and conductor configuration :** If line span is long then less number of towers will be required but the towers will be taller and expensive. The longer line span is used for higher operating voltage so that high cost of insulators is reduced.
4. **Number of circuits :** A transmission line may consist of single circuit or double circuit. With double circuit line high power can be transferred and reliability is more than that of single circuit line.
5. **Ground wire selection :** The phase conductors are protected from lightning strokes using ground wire. The ground wire is placed above the phase conductors. It is grounded at every or alternate tower due to which lightning current are diverted to ground.

   The ground wire should be designed to carry the maximum expected lightning current without heating. It must have enough mechanical strength so as to avoid excessive heating of ground wire due to maximum lightning current. The size of ground wire is based on the mechanical strength and normally material used for ground wire is galvanized steel.
6. **Insulation design :** The performance of line is greatly affected by insulation design. It should take care of switching temporary and atmospheric overvoltage.

Que 4.3. **Describe the various conductor configurations and choice of number of circuits for EHV transmission lines.**

AKTU 2016-17, Marks 15

OR

Describe the various conductor configurations and choice of voltage, number of circuits for EHV transmission lines. Make economic comparison of EHV-AC & HVDC system.

AKTU 2017-18, Marks 10

Answer

A. **Conductor configuration for EHV transmission line :** For high voltagelines above 400 kV, bundled conductors are used.

Bundled conductor : Refer Q. 2.9, Page 2–19B, Unit-2.

B. **Number of circuit of lines :**

1. **Single circuit :** In this configuration three conductors run parallel to each other carrying three phase of current.

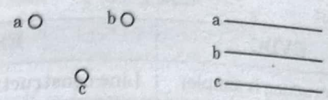


Fig. 4.3.1. Single circuit.

2. **Single circuit transposed line :** In this configuration 3 parallel conductors are so placed that after particular span each conductor takes the position of other conductor.

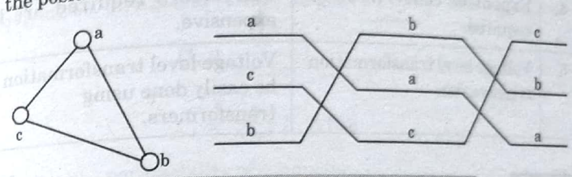


Fig. 4.3.2. Transposition of conductors.

3. **Double circuit :** In this configuration two sets of three conductors run parallel to each other.

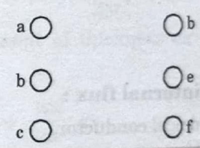


Fig. 4.3.3. Double circuit.

4. **Double circuit transposed :** In this configuration two set of three parallel conductors are so placed such that each conductor takes the position of other conductor after a fixed span of length.

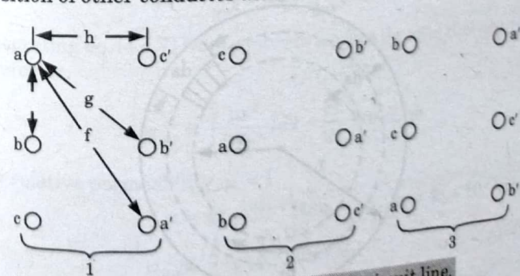


Fig. 4.3.4. Transposed double circuit line.

C. **Choice of Voltage :** Refer Q. 4.2, Page 4–2B, Unit-4.

D. Comparison :

S. No.	HVDC	EHV-AC
1.	Line construction is simpler.	Line construction is complex.
2.	No skin effect.	Skin effect is prominent.
3.	Less corona and radio interference.	More corona and radio interference.
4.	Expensive converters are required.	Converters required are less expensive.
5.	Voltage level transformation is not easier.	Voltage level transformation can be easily done using transformers.

Que 4.4. **Derive the expression for inductance of a conductor due to :**

i. Internal flux.
ii. External flux.

Answer

i. Inductance due to internal flux :

1. Consider a long, cylindrical conductor.
2. Let us assume that I is the current flowing through it and conductor through which current is returning is so far away that magnetic field due to returning conductor is not affecting the flux lines due to conductor under consideration. Lines of flux are concentric with conductor.

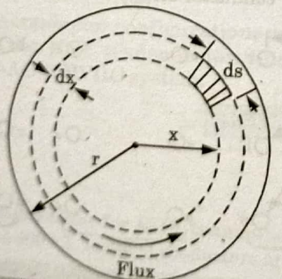


Fig. 4.4.1. Cross-section of a cylindrical conductor.

3. By Ampere's Law, $\oint H_x ds = I_x$ ...(4.4.1)

where, H_x = Magnetic field intensity at distance x from centre

s = Distance along path

I_x = Current enclosed

4. Integration of ds along closed circular path = $2\pi x$, eq. (4.4.1) becomes
$$2\pi x H_x = I_x \quad ...(4.4.2)$$
5. Assuming uniform current density inside conductor.
$$I_x = \frac{\pi x^2}{\pi r^2} I \quad ...(4.4.3)$$
6. Solving eq. (4.4.2) and (4.4.3), we get
$$H_x = \frac{\pi x^2}{\pi r^2 2\pi x} I$$
$$= \frac{x}{2\pi r^2} I \text{ AT/m} \quad ...(4.4.4)$$
7. If $\mu = \mu_o \mu_r$, permeability of conductor
Flux density at distance x from centre of conductor,
$$B_x = \mu H_x = \frac{\mu x I}{2\pi r^2} \text{ Wb/m}^2 \quad ...(4.4.5)$$
8. Flux enclosed in element of thickness dx per metre axial length of conductor,
$$d\phi = \frac{\mu x I}{2\pi r^2} dx \quad ...(4.4.6)$$
This flux links with current I_x.
9. Flux linkage per metre length of conductor is given by,
$$d\psi = \frac{\pi x^2}{\pi r^2} \times d\phi = \frac{\mu x^3}{2\pi r^4} I \, dx \text{ Wb-T} \quad ...(4.4.7)$$
10. Integrating eq. (4.4.7) from centre to surface for total flux linkage inside conductor.
$$\psi_{\text{int}} = \int_0^r \frac{\mu x^3}{2\pi r^4} I dx = \frac{\mu I}{8\pi} \text{ Wb-T/m} \quad ...(4.4.8)$$
11. For relative permeability, $\mu_r = 1$
$$\mu = 4\pi \times 10^{-7} \text{ H/m} \quad (\because \mu_o = 4\pi \times 10^{-7} \text{ H/m})$$
$$\psi_{\text{int}} = \frac{I}{2} \times 10^{-7} \text{ Wb-T/m} \quad ...(4.4.9)$$
Inductance per unit length
$$L_{\text{int}} = \frac{\psi_{\text{int}}}{I} = \frac{1}{2} \times 10^{-7} \text{ H/m} \quad ...(4.4.10)$$

ii. Inductance due to external flux :

1. Flux linkage of an isolated conductor due to only that portion of the external flux lies between two points P_1 and P_2 at distance D_1 and D_2 respectively from the centre of conductor.
2. Conductor carries I ampere current. Flux lines are concentric circles.

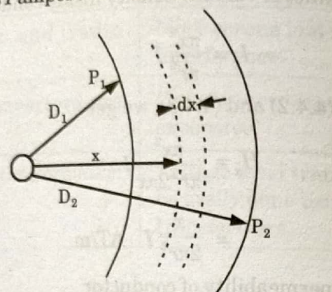


Fig. 4.4.2. A conductor at external points P_1 and P_2.

3. Taking element dx at distance x from centre of conductor, field intensity is H_x.

mmf around element

$$\oint H_x dx = I_x = I$$

$$H_x 2\pi x = I$$

$$H_x = \frac{I}{2\pi x} \text{ AT/m} \quad \text{...(4.4.11)}$$

4. Flux density in element, $B_x = \mu H_x = \dfrac{\mu I}{2\pi x}$ Wb/m^2 ...(4.4.12)

5. Flux in the element dx, $d\phi = \dfrac{\mu I}{2\pi x} dx$ Wb/m ...(4.4.13)

6. Flux linkages $d\psi$ per meter are equal to the flux $d\phi$ since external flux links all the current in the conductor.

$$d\psi = \frac{\mu I}{2\pi x} dx \text{ Wb–T/m} \quad \text{...(4.4.14)}$$

7. Total flux linkages between point P_1 and P_2 are obtained by integrating $d\psi$ from $x = D_1$ to $x = D_2$

$$\psi_{12} = \int_{D_1}^{D_2} \frac{\mu I}{2\pi x} dx = \frac{\mu I}{2\pi} \ln \frac{D_2}{D_1}$$

8. For relative permeability $\mu_r = 1$, and $\mu = \mu_0 \mu_r$

$$\psi_{12} = 2 \times 10^{-7} I \ln \frac{D_2}{D_1} \text{ Wb-T/m}$$

Inductance due to flux between P_1 and P_2

$$L_{12} = \frac{\psi_{12}}{I} = 2 \times 10^{-7} \ln\left(\frac{D_2}{D_1}\right)$$

Que 4.5. **Deduce an expression for the total inductance of a single phase line.**

Answer

1. First conductor carries current. Second conductor is return circuit of other. Both conductors are solid round conductor having radii r_1 and r_2.

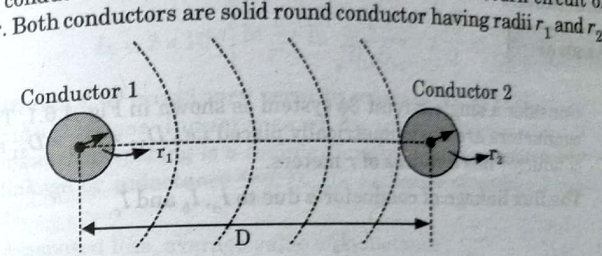


Fig. 4.5.1. Single phase two wire line.

2. For internal flux : $L_{1(\text{int})} = \dfrac{1}{2} \times 10^{-7}$

For external flux : $L_{1(\text{ext})} = 2 \times 10^{-7} \ln \dfrac{D}{r_1}$

3. Total Inductance,

$$L_1 = 2 \times 10^{-7} \left[\frac{1}{4} + \ln \frac{D}{r_1}\right]$$

$$= 2 \times 10^{-7} \left[\ln e^{1/4} + \ln \frac{D}{r_1}\right]$$

$$= 2 \times 10^{-7} \ln \frac{D}{e^{-1/4} r_1}$$

$$= 2 \times 10^{-7} \ln \frac{D}{0.7788 r_1} \quad [e^{-1/4} = 0.778]$$

$$= 2 \times 10^{-7} \ln \frac{D}{r_1'} \text{ H/m}$$

where, r_1' = Geometric mean radius (GMR) of conductor.

4. Similarly, inductance due to current in second conductor

$$L_2 = 2 \times 10^{-7} \ln \frac{D}{r_2'} \text{ H/m}$$

$r_1' = r_2' = r'$

5. If
Total inductance of single-phase circuit is given by

$$L = 4 \times 10^{-7} \ln \frac{D}{r'} \text{ H/m}$$

Que 4.6. **Derive the expression for the inductance of three phase line with conductors untransposed (unsymmetrical spacing). What is the significance of imaginary term in the expression for inductance ?**

Answer

1. Consider a single circuit 3ϕ system as shown in Fig. 4.6.1. The three conductors are unsymmetrically placed *i.e.*, $D_{12} \neq D_{23} \neq D_{31}$ and each conductor has a radius of r meters.
2. The flux linkage of conductor a due to I_a, I_b and I_c

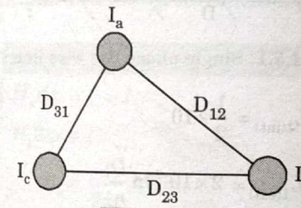


Fig. 4.6.1.

$$\psi_a = 2 \times 10^{-7}\left[I_a \ln\frac{1}{r'} + I_b \ln\frac{1}{D_{12}} + I_c \ln\frac{1}{D_{31}}\right] \quad ...(4.6.1)$$

3. Similarly,

$$\psi_b = 2 \times 10^{-7}\left[I_a \ln\frac{1}{D_{12}} + I_b \ln\frac{1}{r'} + I_c \ln\frac{1}{D_{23}}\right] \quad ...(4.6.2)$$

$$\psi_c = 2 \times 10^{-7}\left[I_a \ln\frac{1}{D_{31}} + I_b \ln\frac{1}{D_{23}} + I_c \ln\frac{1}{r'}\right] \quad ...(4.6.3)$$

4. Now taking I_a as a reference phasor of unbalanced three phase system

$$I_b = k^2 I_a \text{ and } I_c = kI_a$$

where,

$$k = -0.5 + j0.866$$
$$k^2 = -0.5 - j0.866$$

5. Substituting the values of I_b and I_c in the eq. (4.6.1), we get

$$\psi_a = 2 \times 10^{-7}\left[I_a \ln\frac{1}{r'} + I_a(-0.5 - j0.866)\right.$$

$$\left.\ln\frac{1}{D_{12}} + I_a(-0.5 + j0.866)\ln\frac{1}{D_{31}}\right]$$

$$\therefore \quad L_a = \frac{\psi_a}{I_a} = 2 \times 10^{-7}\left[\ln\frac{1}{r'} - \ln\frac{1}{\sqrt{D_{31}D_{12}}} - j\frac{\sqrt{3}}{2}\ln\frac{D_{31}}{D_{12}}\right]$$

6. Similarly

$$L_b = 2 \times 10^{-7}\left[\ln\frac{1}{r'} - \ln\frac{1}{\sqrt{D_{23}D_{12}}} - j\frac{\sqrt{3}}{2}\ln\frac{D_{12}}{D_{23}}\right]$$

$$L_c = 2 \times 10^{-7}\left[\ln\frac{1}{r'} - \ln\frac{1}{\sqrt{D_{23}D_{31}}} - j\frac{\sqrt{3}}{2}\ln\frac{D_{23}}{D_{31}}\right]$$

7. **Significance of imaginary term in expression of inductance :** Individual phase inductance of an untransposed line with unsymmetrical spacing is a complex number. The imaginary part of flux-linkage or inductance represents exchange of energy between phases.
8. For transposed line, average value of inductance

$$L = \frac{L_a + L_b + L_c}{3}$$

$$= \frac{1}{3}\left[2 \times 10^{-7}\left(3\ln\frac{1}{r'} - \ln\frac{1}{D_{23}D_{31}D_{12}} - j\frac{\sqrt{3}}{2}\ln 1\right)\right]$$

$$= 2 \times 10^{-7} \ln\frac{\sqrt[3]{D_{23}D_{31}D_{12}}}{r'}$$

$$= 2 \times 10^{-7} \ln\frac{D_{eq}}{r'} \text{ H/m}$$

Que 4.7. **Deduce en expression for inductance of a three phase transmission line.**

OR

Derive the inductance per phase for a three phase transposed transmission line. Also calculate the inductance for horizontal and equilateral triangular configuration. **AKTU 2015-16, Marks 10**

Answer

i. **Three phase line :** Three phase line can be of two types :
Inductance of a three phase transmission with unsymmetrical spacing : Refer Q. 4.6, Page 4–9B, Unit-4.
ii. **Symmetrical three phase line :**
1. As shown in Fig. 4.7.1, in such arrangement conductors are situated at the corners of an equilateral triangle.

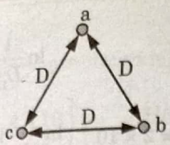


Fig. 4.7.1. Symmetrical 3ϕ line.

D = Spacing between conductors.

r = Radius of each conductor.

2. Flux linkage of conductor a

$$\psi_a = 2\times10^{-7}\left[I_a \ln\frac{1}{D_{aa}} + I_b \ln\frac{1}{D_{ab}} + I_c \ln\frac{1}{D_{ac}}\right]$$

$$D_{ab} = D_{ac} = D$$
$$D_{aa} = r' = re^{-1/4}$$

$$\psi_a = 2\times10^{-7}\left[I_a \ln\frac{1}{r'} + I_b \ln\frac{1}{D} + I_c \ln\frac{1}{D}\right]$$

$$= 2\times10^{-7}\left[I_a \ln\frac{1}{r'} + (I_b + I_c)\ln\frac{1}{D}\right]$$

3. For three wire system algebraic sum of current in conductor is zero

$$I_a + I_b + I_c = 0$$
$$I_b + I_c = -I_a$$

$$\psi_a = 2\times10^{-7}\left[I_a \ln\frac{1}{r'} - I_a \ln\frac{1}{D}\right] = 2\times10^{-7}\times I_a\left[\ln\frac{1}{r'} - \ln\frac{1}{D}\right]$$

$$= 2\times10^{-7}\times I_a \ln\frac{D}{r'} \text{ Wb-T/m}$$

4. Inductance of conductors a is

$$L_a = \frac{\psi_a}{I_a} = 2\times10^{-7}\ln\frac{D}{r'} \text{ H/m}$$

5. The inductance of conductors b and c will also be the same as that of a, because of symmetry

$$L_b = L_c = 2\times10^{-7}\ln\frac{D}{r'} \text{ H/m}$$

iii. Unsymmetrical spacing but transposed :

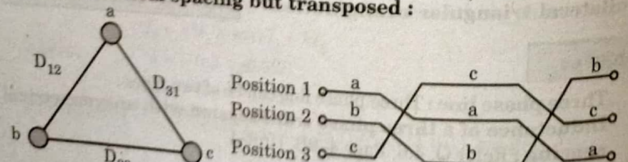


Fig. 4.7.2. Transposition cycle of unequally spaced three phase line conductors.

1. Flux linkage of conductor a; when a is in the position 1, b in position 2 and c in position 3

$$\psi_{a1} = 2\times10^{-7}\left[I_a \ln\frac{1}{r'} + I_b \ln\frac{1}{D_{12}} + I_c \ln\frac{1}{D_{31}}\right]$$

2. When conductor a is in position 2, b in position 3 and c in position 1

$$\psi_{a2} = 2\times10^{-7}\left[I_a \ln\frac{1}{r'} + I_b \ln\frac{1}{D_{23}} + I_c \ln\frac{1}{D_{12}}\right]$$

3. When conductor a is in position 3, b in position 1 and c in position 2

$$\psi_{a3} = 2\times10^{-7}\left[I_a \ln\frac{1}{r'} + I_b \ln\frac{1}{D_{31}} + I_c \ln\frac{1}{D_{23}}\right]$$

4. Average value of flux linkages of a is

$$\psi_a = \frac{1}{3}\times[\psi_{a1} + \psi_{a2} + \psi_{a3}]$$

$$= \frac{1}{3}\times2\times10^{-7}\left[\left(I_a \ln\frac{1}{r'} + I_b \ln\frac{1}{D_{12}} + I_c \ln\frac{1}{D_{31}}\right)\right.$$

$$\left. + \left(I_a \ln\frac{1}{r'} + I_b \ln\frac{1}{D_{23}} + I_c \ln\frac{1}{D_{12}}\right) + \left(I_a \ln\frac{1}{r'} + I_b \ln\frac{1}{D_{31}} + I_c \ln\frac{1}{D_{23}}\right)\right]$$

$$= \frac{2}{3}\times10^{-7}\left[\left(3I_a \ln\frac{1}{r'} + I_b \ln\frac{1}{D_{12}D_{23}D_{31}} + I_c \ln\frac{1}{D_{12}D_{23}D_{31}}\right)\right.$$

$$= \frac{2}{3}\times10^{-7}\left[\left(3I_a \ln\frac{1}{r'} + (I_b + I_c)\ln\frac{1}{D_{12}D_{23}D_{31}}\right)\right.$$

5. For balanced condition $I_a + I_b + I_c = 0$

$$I_b + I_c = -I_a$$

$$\psi_a = 2\times10^{-7}\left[I_a \ln\frac{1}{r'} - \frac{1}{3}I_a \ln\frac{1}{D_{12}D_{23}D_{31}}\right]$$

$$= 2\times10^{-7}\times I_a \ln\frac{(D_{12}D_{23}D_{31})^{1/3}}{r'}$$

6. Average inductance of phase a

$$L_a = \frac{\psi_a}{I_a} = 2\times10^{-7}\ln\frac{(D_{12}D_{23}D_{31})^{1/3}}{r'} \text{ H/m}$$

7. Similarly,

$$L_b = L_c = 2\times10^{-7}\ln\frac{(D_{12}D_{23}D_{31})^{1/3}}{r'} \text{ H/m}$$

Que 4.8. **Discuss the concept of self GMD and mutual GMD with the help of suitable example.**

Answer

A. Self-GMD (D_s) :

1. It is also called geometrical mean radius (GMR).
2. Inductance per conductor per meter length is given by,

$$L = 2 \times 10^{-7}\left(\frac{1}{4} + \ln\frac{D}{r}\right)$$

$$L = \left(2 \times 10^{-7} \times \frac{1}{4}\right) + \left(2 \times 10^{-7}\ \ln\frac{D}{r}\right)$$

$$L = 2 \times 10^{-7} \ln\frac{D}{D_s}$$

where, D_s = Self-GMD or GMR = $0.7788r$

Sometimes GMR is denoted by r'.

3. Self-GMD of a conductor depends upon the size and shape of the conductor and is independent of the spacing between the conductors.

B. Mutual-GMD (D_m) :

1. The mutual-GMD is the geometrical mean of the distance from one conductor to the other. It simply represents the equivalent geometrical spacing.

Example :

1. The conductor arrangement of the double circuit is shown in Fig. 4.8.1. Let the radius of each conductor be r.

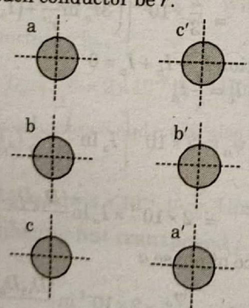


Fig. 4.8.1.

2. Self-GMD of conductor = $0.7788r$
3. Self-GMD of combination aa',

$$D_{s1} = (D_{aa} \times D_{aa'} \times D_{a'a'} \times D_{a'a})^{1/4}$$

4. Self-GMD of combination bb',

$$D_{s2} = (D_{bb}\, D_{bb'}\, D_{b'b'}\, D_{c'c})^{1/4}$$

5. Self-GMD of combination cc',

$$D_{s3} = (D_{cc}\, D_{cc'}\, D_{c'c'}\, D_{c'c})^{1/4}$$

6. Equivalent self-GMD of one phase,

$$D_s = (D_{s1} \times D_{s2} \times D_{s3})^{1/3}$$

7. Since each conductor has the same radius, therefore the value of D_s is same for the all phases.
8. Mutual-GMD between phases A and B,

$$D_{AB} = (D_{ab} \times D_{ab'} \times D_{a'b} \times D_{a'b'})^{1/4}$$

Mutual-GMD Between phases B and C,

$$D_{BC} = (D_{bc} \times D_{bc'} \times D_{b'c} \times D_{b'c'})^{1/4}$$

$$D_{CA} = (D_{ca} \times D_{ca'} \times D_{c'a} \times D_{c'a'})^{1/4}$$

9. Equivalent mutual-GMD, $D_m = (D_{AB} \times D_{BC} \times D_{CA})^{1/3}$
10. Mutual-GMD is independent of exact size, shape and orientation of the conductor and depends only upon the spacing.

Que 4.9. **Find the inductance per phase of symmetrically spaced double circuit 3-phase line.**

AKTU 2019-20, Marks 07

Answer

Double circuit three phase lines with transposition :

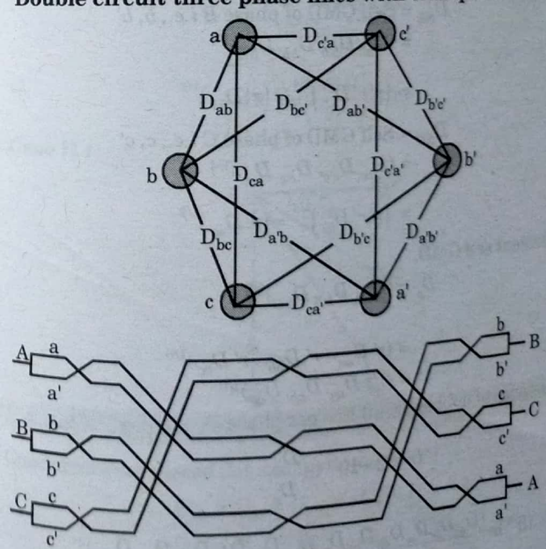


Fig. 4.9.1.

1. Formula for inductance of a 3ϕ unsymmetrical line

$$L = 2\times10^{-7}\ln\left(\frac{\text{Mutual GMD}}{\text{Self GMD}}\right) \quad ...(4.9.1)$$

2. For double circuit line

D_{AB} = Mutual GMD between phase A & B *i.e.*, between a, a' and b, b'

$$= (D_{ab}\, D_{ab'}\, D_{a'b}\, D_{a'b'})^{1/4}$$

D_{BC} = Mutual GMD between phases B and C *i.e.*, between b, b' and c, c'

$$= (D_{bc}\, D_{bc'}\, D_{b'c}\, D_{b'c'})^{1/4}$$

D_{CA} = Mutual GMD between phases C and A *i.e.*, between c, c' and a, a'

$$= (D_{ca}\, D_{ca'}\, D_{c'a}\, D_{c'a'})^{1/4}$$

3. Mutual GMD of line

$$D_m = (D_{AB}\, D_{BC}\, D_{CA})^{1/3}$$

$$= (D_{ab}\, D_{bc}\, D_{ca}\, D_{ab'}\, D_{bc'}\, D_{ca'}\, D_{a'b}\, D_{b'c}\, D_{c'a}\, D_{a'b'}\, D_{b'c'}\, D_{c'a'})^{1/12}$$

D_{SA} = Self GMD of phase A *i.e.*, a, a'

$$= (D_{aa}\, D_{a'a'}\, D_{a'a}\, D_{aa'})^{1/4}$$

$$= \left(r'r'D_{aa'}^2\right)^{1/4} = \left(r'D_{aa'}\right)^{1/2}$$

D_{SB} = Self GMD of phase B *i.e.*, b, b'

$$= (D_{bb}\, D_{b'b'}\, D_{bb'}\, D_{b'b})^{1/4}$$

$$= \left(r'r'D_{bb'}^2\right)^{1/4} = \left(r'D_{aa'}\right)^{1/2}$$

D_{SC} = Self GMD of phase C *i.e.*, c, c'

$$= (D_{cc}\, D_{c'c'}\, D_{c'c}\, D_{cc'})^{1/4}$$

$$= \left(r'r'D_{bb'}^2\right)^{1/4} = \left(r'D_{aa'}\right)^{1/2}$$

4. Equivalent self GMD,

$$D_s = (D_{SA}\, D_{SB}\, D_{SC})^{1/3}$$

$$= (r'\, D_{aa'} \cdot r'\, D_{bb'} \cdot r'\, D_{cc'})^{1/6}$$

$$= (r'^3\, D_{aa'}\, D_{bb'}\, D_{cc'})^{1/6}$$

5. Inductance of double circuit line per phase

$$L = 2\times10^{-7}\ln\frac{D_m}{D_s}$$

$$= 2\times10^{-7}\ln\frac{(D_{ab}D_{bc}D_{ca}D_{ab'}D_{bc'}D_{ca'}D_{a'b}D_{b'c}D_{c'a}D_{a'b'}D_{b'c'}D_{c'a'})^{\frac{1}{2}}}{(r'^3\, D_{aa'}D_{bb'}D_{cc'})^{1/6}}$$

Case I :

Inductance of 3ϕ double circuit line with hexagonal spacing as shown in Fig. 4.9.2.

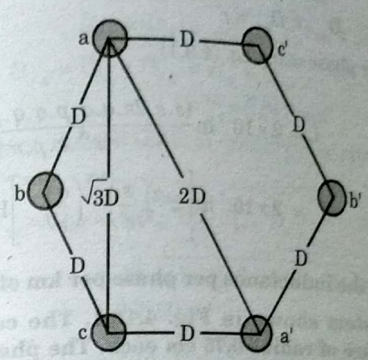


Fig. 4.9.2. Double circuit three phase line with hexagonal spacing.

1.
$$D_{ab} = D_{bc} = D_{ca'} = D_{c'a} = D_{a'b'} = D_{b'c'} = D$$
$$D_{ca} = D_{ab'} = D_{bc'} = D_{a'b} = D_{b'c} = D_{c'a'} = \sqrt{3}D$$
$$D_{aa'} = D_{bb'} = D_{cc'} = 2D$$

2. Inductance per phase

$$L = 2\times10^{-7}\ln\frac{[D^6(\sqrt{3}D)^6]^{1/12}}{[2r'(2D)^3]^{1/6}}$$

$$= 2\times10^{-7}\ln\frac{(\sqrt{3}D^2)^{1/2}}{[r'2D]^{1/2}}$$

$$= 10^{-7}\ln\left(\frac{\sqrt{3}D}{2r'}\right)\text{H/m}$$

Case II :

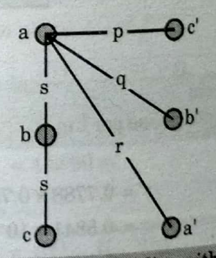


Fig. 4.9.3. Double circuit three phase line with flat vertical spacing.

1. Conductors are placed flat and vertically spaced.

$$D_{ab} = D_{bc} = D_{a'b'} = D_{b'c'} = D_{c'a'} = s$$
$$D_{ac} = D_{a'c'} = 2s$$

$$D_{ac'} = D_{bb'} = D_{ca'} = p$$
$$D_{ab'} = D_{ba'} = D_{bc'} = D_{cb'} = q$$
$$D_{aa'} = D_{cc'} = r$$

2. Inductance per phase using eq. (4.9.1)

$$L = 2\times10^{-7}\ln\frac{(s.s.2s.q.q.p.q.q.p.s.s.2s)^{\frac{1}{12}}}{(r'^3.r.p.r.)^{1/6}}$$

$$= 2\times10^{-7}\ln\left[2^{1/6}\left(\frac{s}{r'}\right)^{1/2}\left(\frac{q}{r}\right)^{1/3}\right]\text{H/ m}$$

Que 4.10. **Find the inductance per phase per km of double circuit 3-phase line system shown in Fig. 4.10.1. The conductors are transposed and are of radius 0.75 cm each. The phase sequence is *abc*.**

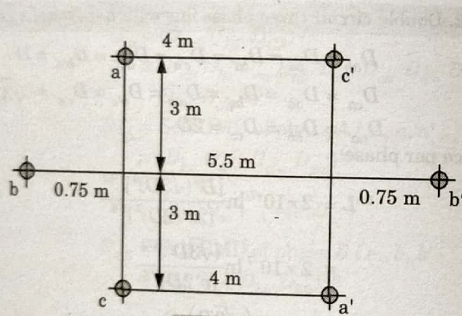


Fig. 4.10.1.

AKTU 2016-17, Marks 10

Answer

Given : Radius = 0.75 cm
To Find : Inductance per phase per km.

1. GMR of conductor

$$r' = 0.7788 \times 0.75 \times 10^{-2}$$
$$= 0.5841 \times 10^{-2}\text{ m}$$
$$= 5.841\text{ mm}$$

2. $$D_{ab} = D_{b'c'} = D_{bc} = D_{a'b'} = \sqrt{3^2 + 0.75^2} = 3.09\text{ m}$$

3. $$D_{ab'} = D_{bc'} = D_{b'c} = D_{a'b} = \sqrt{(5.5+0.75)^2 + 3^2}$$

$$= 6.93\text{ m}$$
$$D_{ca} = D_{a'c'} = 3 + 3 = 6\text{ m}$$
$$D_{aa'} = D_{cc'} = \sqrt{(5.5)^2 + 6^2} = 8.14\text{ m}$$

4. $$D_{aa} = D_{a'a'} = D_{bb} = D_{b'b'} = D_{cc} = D_{c'c'}$$
$$= r' = 5.841\text{ mm}$$

5. From symmetry, the self GMD of conductors of phase *A* and phase *C* must be equal.

$$\therefore \quad D_{SA} = D_{SC} = \sqrt[4]{D_{aa}\,D_{aa'}\,D_{a'a'}\,D_{a'a}}$$
$$= \sqrt[4]{5.841\times10^{-3}\times8.14\times5.841\times10^{-3}\times8.14}$$
$$= 0.2180\text{ m}$$

$$D_{SC} = \sqrt[4]{D_{bb}\,D_{bb'}\,D_{b'b'}\,D_{b'b}}$$
$$= \sqrt[4]{r'\times7\times r'\times7} = \sqrt{r'\times7} = 0.2022\text{ m}$$

6. Now, net self GMD of the circuit

$$D_S = \sqrt[3]{D_{SA}\,D_{SB}\,D_{SC}}$$
$$= \sqrt[3]{0.2180\times0.2020\times0.2180}$$
$$= 0.2126\text{ m}$$

7. Again from symmetry, the mutual GMD between phase *A* and *B* must be equal to the GMD between *B* and *C*.

$$\therefore \quad D_{AB} = D_{BC} = \sqrt[4]{D_{ab}\,D_{ab'}\,D_{a'b}\,D_{a'b'}}$$
$$= \sqrt[4]{3.09\times6.93\times6.93\times3.09}$$
$$= 4.6274\text{ m}$$

Mutual GMD between phase *A* and *C*

$$D_{CA} = \sqrt[4]{D_{ca}\,D_{ca'}\,D_{c'a}\,D_{c'a'}}$$
$$= \sqrt[4]{6\times4\times4\times6}$$
$$= 4.8990\text{ m}$$

8. Net mutual GMD, D_m

$$= \sqrt[3]{D_{AB}\,D_{BC}\,D_{CA}}$$
$$= \sqrt[3]{4.6274\times4.8990\times4.6274}$$
$$= 4.7162\text{ m}$$

9. Inductance per phase per km

$$= 2\times 10^{-4}\ln\frac{D_m}{D_S}\ \text{H/km/phase}$$

$$= 2\times 10^{-4}\ln\frac{4.7162}{0.2126}$$

$$= 0.6199\ \text{mH/km/phase}$$

Que 4.11. **A three phase 50 Hz transmission line consists of three equal conductors of radii π, placed in a horizontal plane, with a spacing of 6 m between the middle and each outer conductor. Determine the inductive reactance per phase per km of the transposed line if the radius of each conductor is 12.5 mm.**

Answer

Given : f = 50 Hz, r = 12.5 mm
To Find : Inductive reactance per phase per km.

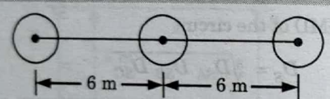


Fig. 4.11.1.

1. $D_{eq} = (D.D.2D)^{1/3}$
$= (6 \times 6 \times 12)^{1/3} = 7.558$

2. Inductance/phase/m

$$L = \left(0.5 + 2\ln\frac{D_{eq}}{r}\right)\times 10^{-7}$$

$$= \left(0.5 + 2\ln\left(\frac{7.558\times 10^3}{12.5}\right)\right)\times 10^{-7}$$

$= 13.31 \times 10^{-7}$ H/m
$= 13.31 \times 10^{-7} \times 1000$ H/km
$= 13.31 \times 10^{-4}$ H/km

Que 4.12. **A single circuit 3-phase line operated at 50 Hz is arranged as follows. The conductor diameter is 0.6 cm. Determine the inductance per km.**

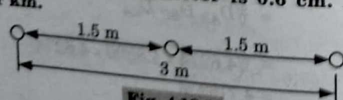


Fig. 4.12.1.

AKTU 2018-19, Marks 07

Answer

The procedure is same as Q. 4.11, Page 4–19B, Unit-4.
(**Ans.** $L = 13.39 \times 10^{-4}$ H/km)

Que 4.13. **Derive an expression for the capacitance of a single phase overhead transmission line. What do you mean by self G.M.D. and mutual G.M.D.**

AKTU 2017-18, Marks 10

Answer

A. **Expression for potential difference :**

1. From Gauss's law, electric field density (D) at a point distance x metres from a conductor having charge q is,

$$D = \frac{q}{2\pi xl}\ \text{C/m}^2 \quad ...(4.13.1)$$

(Taking length of conductor = 1 m)

2. Electric field intensity at distance x,

$$E = \frac{D}{\varepsilon} = \frac{q}{2\pi\varepsilon x}\ \text{V/m}$$

3. Voltage between P_1 and P_2,

$$V_{12} = \int_{D_1}^{D_2} E\,dx = \int_{D_1}^{D_2}\frac{q}{2\pi\varepsilon x}\,dx$$

$$= \frac{q}{2\pi\varepsilon}\ln\frac{D_2}{D_1}\ \text{V} \quad ...(4.13.2)$$

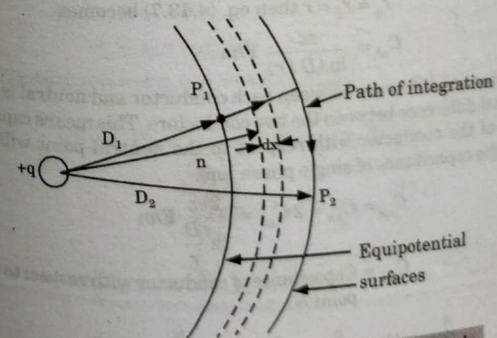


Fig. 4.13.1. Cylindrical conductor having uniformly distributed positive charge.

B. **Capacitance of single phase line :**

1. Potential due to q_a using eq. (4.13.2)

$$V_{ab}' = \frac{q_a}{2\pi\varepsilon}\ln\frac{D}{r_a} \qquad \text{...(4.13.3)}$$

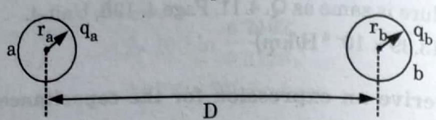


Fig. 4.13.2. Single phase line.

2. Potential due to q_b using eq. (4.13.2)

$$V_{ab}'' = \frac{q_b}{2\pi\varepsilon}\ln\frac{r_b}{D} \qquad \text{...(4.13.4)}$$

3. Net potential from a to b,

$$V_{ab} = V_{ab}' + V_{ab}'' = \frac{1}{2\pi\varepsilon}\left\{q_a \ln\frac{D}{r_a} + q_b \ln\frac{r_b}{D}\right\} \qquad \text{...(4.13.5)}$$

4. Since b is return conductor,

$$q_a = -q_b$$

5. On putting $q_a = -q_b$, eq. (4.13.5) becomes

$$V_{ab} = \frac{1}{2\pi\varepsilon} q_a \ln\left(\frac{D^2}{r_a r_b}\right)$$

$$= \frac{1}{\pi\varepsilon} q_a \ln\frac{D}{\sqrt{r_a r_b}} \qquad \text{...(4.13.6)}$$

6. Now capacitance of line,

$$C_{ab} = \frac{q_a}{V_{ab}} = \frac{\pi\varepsilon}{\ln(D/\sqrt{r_a r_b})} \text{ F/m} \qquad \text{...(4.13.7)}$$

7. If $r_a = r_b = r$ then eq. (4.13.7) becomes

$$C_{ab} = \frac{\pi\varepsilon}{\ln(D/r)} \text{ F/m} \qquad \text{...(4.13.8)}$$

8. The potential difference between each conductor and neutral is half the potential difference between the two conductors. This means capacitance of one of the conductor with respect to the neutral point will be two times the capacitance of single phase line.

$$C_{an} = C_{bn} = 2\,C_{ab} = \frac{2\pi\varepsilon}{\ln\frac{D}{r}} \text{ F/m}$$

C_{an} = Capacitance of conductor with respect to neutral point N.

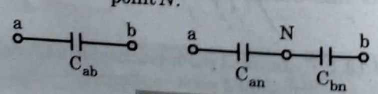


Fig. 4.13.3.

C. **Self GMD and mutual GMD :** Refer Q. 4.8, Page 4–12B, Unit-4.

Que 4.14. **Derive expression for capacitance of three phase line.**

OR

Derive the expression for capacitance of unsymmetrically and symmetrically spaced three phase lines. Compare the results.

OR

Give the concept of self GMD. Starting from first principles, derive the expression for capacitance of a 3-phase symmetrical spaced transmission line.

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Answer

A. **3 φ line symmetrically spaced or equilateral spacing :**

1. Taking conductor a

Voltage between conductor a and b

$$V_{ab} = \frac{1}{2\pi\varepsilon}\left\{q_a \ln\frac{D}{r} + q_b \ln\frac{r}{D}\right\} \qquad \text{...(4.14.1)}$$

2. Voltage between conductor a and c

$$V_{ac} = \frac{1}{2\pi\varepsilon}\left\{q_a \ln\frac{D}{r} + q_c \ln\frac{r}{D}\right\} \qquad \text{...(4.14.2)}$$

3. Adding eq. (4.14.1) and (4.14.2)

$$V_{ab} + V_{ac} = \frac{1}{2\pi\varepsilon}\left\{2q_a \ln\frac{D}{r} + (q_b + q_c)\ln\frac{r}{D}\right\} \qquad \text{...(4.14.3)}$$

4. Also, $\quad q_a + q_b + q_c = 0$

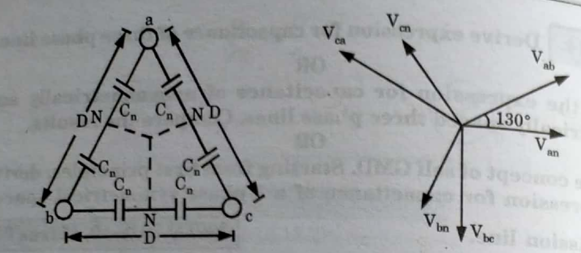
$$q_b + q_c = -q_a$$

5. Substituting value of $q_b + q_c$ in eq. (4.14.3)

$$V_{ab} + V_{ac} = \frac{1}{2\pi\varepsilon}\left\{2q_a \ln\frac{D}{r} - q_a \ln\frac{r}{D}\right\}$$

$$= \frac{1}{2\pi\varepsilon}\left\{2q_a \ln\frac{D}{r} + q_a \ln\frac{D}{r}\right\}$$

$$V_{ab} + V_{ac} = \frac{3q_a}{2\pi\varepsilon}\ln\frac{D}{r} \qquad \text{...(4.14.4)}$$



(*a*) Three phase line with equilateral spacing. (*b*) Phasor diagram of voltages.

Fig. 4.14.1.

6.
$$V_{ab} = \sqrt{3}\, V_{an} \angle 30^\circ$$
$$V_{ac} = -V_{ca}$$
$$= \sqrt{3}\, V_{an} \angle -30^\circ$$
$$V_{ab} + V_{ac} = 3V_{an} \quad \text{...(4.14.5)}$$

7. From eq. (4.14.4) and (4.14.5)
$$3V_{an} = \frac{3q_a}{2\pi\varepsilon} \ln \frac{D}{r}$$
$$V_{an} = \frac{q_a}{2\pi\varepsilon} \ln \frac{D}{r} \quad \text{...(4.14.6)}$$

8. Line to neutral capacitance,
$$C_n = \frac{q_a}{V_{an}} = \frac{2\pi\varepsilon}{\ln D/r} \text{ F/m} \quad \text{...(4.14.7)}$$

For air, $\varepsilon_r = 1$
Since $\varepsilon = \varepsilon_o \varepsilon_r$
$$C_n = \frac{2\pi\varepsilon_0}{\ln D/r} \text{ F/ m} \quad \text{...(4.14.8)}$$

B. 3ϕ line unsymmetrically spaced but transposed :

1. When phase *a* is in position 1, *b* in position 2 and *c* in position 3.
$$V_{ab} = \frac{1}{2\pi\varepsilon}\left\{ q_a \ln \frac{D_{12}}{r} + q_b \ln \frac{r}{D_{12}} \right\} \quad \text{...(4.14.9)}$$

2. When *a* in position 2, *b* in position 3 and *c* in position 1
$$V_{ab} = \frac{1}{2\pi\varepsilon}\left\{ q_a \ln \frac{D_{23}}{r} + q_b \ln \frac{r}{D_{23}} \right\} \quad \text{...(4.14.10)}$$

3. When *a* in position 3, *b* in position 1 and *c* in position 2
$$V_{ab} = \frac{1}{2\pi\varepsilon}\left\{ q_a \ln \frac{D_{31}}{r} + q_b \ln \frac{r}{D_{31}} \right\} \quad \text{...(4.14.11)}$$

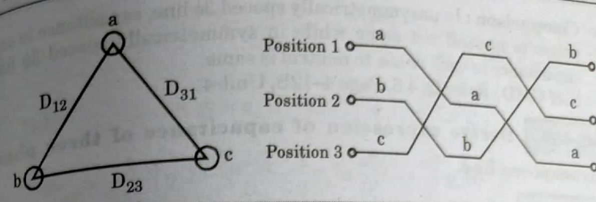


Fig. 4.14.2. Transposition cycle of unequally spaced three phase line conductors.

4. Average voltage between conductor *a* and *b* :
$$V_{ab} = \frac{1}{3} \times \frac{1}{2\pi\varepsilon}\left\{ q_a \ln \frac{D_{12}D_{23}D_{31}}{r^3} + q_b \ln \frac{r^3}{D_{12}D_{23}D_{31}} \right\} \quad \text{...(4.14.12)}$$
$$V_{ab} = \frac{1}{6\pi\varepsilon} \times \left\{ q_a \ln \left(\frac{D_m}{r}\right)^3 + q_b \ln \left(\frac{r}{D_m}\right)^3 \right\}$$
$$V_{ab} = \frac{1}{2\pi\varepsilon} \times \left\{ q_a \ln \frac{D_m}{r} + q_b \ln \frac{r}{D_m} \right\} \quad \text{...(4.14.13)}$$

where $D_m = (D_{12}D_{23}D_{31})^{1/3}$
is mutual geometric mean distance between phase

5. Similarly, average voltage between conductor *a* and *c*
$$V_{ac} = \frac{1}{2\pi\varepsilon}\left\{ q_a \ln \frac{D_m}{r} + q_c \ln \frac{r}{D_m} \right\} \quad \text{...(4.14.14)}$$

6. Similarly, average voltage between conductor *b* and *c*
$$V_{bc} = \frac{1}{2\pi\varepsilon}\left\{ q_b \ln \frac{D_m}{r} + q_c \ln \frac{r}{D_m} \right\} \quad \text{...(4.14.15)}$$

7. Let line to neutral voltage of conductor *a* is V_{an}
$$3V_{an} = V_{ab} + V_{ac}$$
$$= \frac{1}{2\pi\varepsilon}\left\{ 2q_a \ln \frac{D_m}{r} + q_b \ln \frac{r}{D_m} + q_c \ln \frac{r}{D_m} \right\} \quad \text{...(4.14.16)}$$

8. Here, $q_a + q_b + q_c = 0$
$$q_b + q_c = -q_a$$
Eq. (4.14.16) becomes
$$3V_{an} = \frac{3}{2\pi\varepsilon} q_a \ln\left(\frac{D_m}{r}\right) \quad \text{...(4.14.17)}$$

9. Capacitance of line *a* to neutral
$$C_{an} = \frac{q_a}{V_{an}} = \frac{2\pi\varepsilon}{\ln (D_m / r)} \text{ F/m} \quad \text{...(4.14.18)}$$

Comparison : In unsymmetrically spaced 3ϕ line, capacitance to each phase to neutral not same while in symmetrically spaced 3ϕ line, capacitance to each phase to neutral is same.

C. Self GMD : Refer Q. 4.8, Page 4–12B, Unit-4.

Que 4.15. **Derive expression of capacitance of three phase untransposed line.**

Answer

1. A three-phase single circuit untransposed line is shown in Fig. 4.15.1.

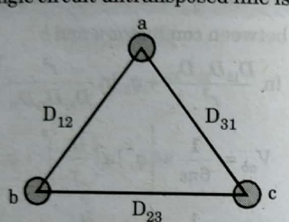


Fig. 4.15.1. Three-phase single-circuit untransposed line.

2. The potential difference between a and b is given by

$$V_{ab} = \frac{1}{2\pi\varepsilon_0}\left(q_a \ln\frac{D_{12}}{r} + q_b \ln\frac{r}{D_{12}} + q_c \ln\frac{D_{23}}{D_{31}}\right)$$

3. The potential difference between a and c is given by

$$V_{ac} = \frac{1}{2\pi\varepsilon_0}\left(q_a \ln\frac{D_{31}}{r} + q_b \ln\frac{D_{23}}{D_{12}} + q_c \ln\frac{r}{D_{31}}\right)$$

4. But $\quad V_{ab} + V_{ac} = 3\, V_{an}$

Therefore,

$$3V_{an} = \frac{1}{2\pi\varepsilon_0}\left[q_a\left(\ln\frac{D_{12}}{r} + \ln\frac{D_{31}}{r}\right) + q_b\left(\ln\frac{r}{D_{12}} + \ln\frac{D_{23}}{D_{31}}\right) + q_c\left(\ln\frac{D_{23}}{D_{31}} + \ln\frac{r}{D_{31}}\right)\right]$$

5. Since for a three-phase three-wire circuit

$$q_a + q_b + q_c = 0$$

$$q_c = -q_a - q_b$$

$$\therefore \quad 3V_{an} = \frac{1}{2\pi\varepsilon_0}\left[q_a\left(\ln\frac{D_{12}}{r} + \ln\frac{D_{31}}{r}\right) + q_b\left(\ln\frac{r}{D_{12}} + \ln\frac{D_{23}}{D_{31}}\right) - q_a \ln\frac{D_{23}\, r}{D_{31}^2} - \ln\frac{rD_{23}}{D_{31}^2}\right]$$

$$= \frac{1}{2\pi\varepsilon_0}\left(q_a \ln\frac{D_{12}D_{31}D_{31}^2}{r^2\, r\, D_{23}} + q_b \ln\frac{rD_{23}D_{31}^2}{D_{12}^2\, r\, D_{23}}\right)$$

6. But

$$q_b = q_a \angle -120° = q_a\left(-\frac{1}{2} - j\frac{\sqrt{3}}{2}\right).$$

$$\therefore\ 3V_{an} = \frac{1}{2\pi\varepsilon_0}\left(q_a \ln\frac{D_{12}D_{31}^3}{r^3\, D_{23}} - \frac{1}{2}q_a \ln\frac{D_{31}^2}{D_{12}^2} - j\frac{\sqrt{3}}{2}q_a \ln\frac{D_{31}^2}{D_{12}^2}\right)$$

$$= \frac{1}{2\pi\varepsilon_0}q_a\left(\ln\frac{D_{12}D_{31}^3D_{12}}{r^3\, D_{23}D_{31}} + j\sqrt{3}\ln\frac{D_{12}}{D_{31}}\right)$$

$$= \frac{1}{2\pi\varepsilon_0}q_a\left[\ln\left(\frac{D_{31}}{r}\right)^3 \frac{D_{12}^2}{D_{23}D_{31}} + j\sqrt{3}\ln\frac{D_{12}}{D_{31}}\right]$$

$$C_{an} = \frac{q_a}{V_{an}} = \frac{2\pi\varepsilon_0}{\frac{1}{3}\left[\ln\left(\frac{D_{31}}{r}\right)^3\left(\frac{D_{12}^2}{D_{23}\, D_{31}}\right) + j\sqrt{3}\ln\frac{D_{12}}{D_{31}}\right]}$$

$$= \frac{2\pi\varepsilon_0}{\frac{1}{3}\left[\ln\left(\frac{D_{31}}{r}\right)^3\left(\frac{D_{12}^2\, D_{12}}{D_{12}\, D_{23}\, D_{31}}\right) + j\sqrt{3}\ln\frac{D_{12}}{D_{31}}\right]}$$

$$= \frac{2\pi\varepsilon_0}{\frac{1}{3}\left[\ln\left(\frac{D_{31}}{r}\right)^3 \frac{D_{12}^3}{D_m^3} + j\sqrt{3}\ln\frac{D_{12}}{D_{31}}\right]}$$

$$\therefore \quad C_{an} = \frac{2\pi\varepsilon_0}{\left(\ln\frac{D_{31}D_{12}}{r\, D_m} + j\frac{1}{\sqrt{3}}\ln\frac{D_{12}}{D_{31}}\right)} \text{ F/m}$$

7. Similarly,

$$C_{ab} = \frac{2\pi\varepsilon_0}{\left(\ln\frac{D_{12}D_{23}}{r\, D_m} + j\frac{1}{\sqrt{3}}\ln\frac{D_{23}}{D_{12}}\right)}$$

$$C_{cn} = \frac{2\pi\varepsilon_0}{\left(\ln\frac{D_{31}D_{23}}{r\, D_m} + j\frac{1}{\sqrt{3}}\ln\frac{D_{31}}{D_{23}}\right)} \text{ F/m}$$

It is found that the phase capacitances are complex numbers.

Que 4.16. **A two conductor, single phase line operates at 60 Hz. The diameter of each conductor is 5 cm and is spaced 3 m apart : calculate (i) the capacitance of each conductor to neutral per km (ii) line to line capacitance (iii) capacitive susceptance to neutral per km.**

AKTU 2017-18, Marks 10

Answer

Given : $D = 3$ m, $r = 0.025$, $f = 60$ Hz
To Find : C_n, C_l, and b_c.

1. The capacitance of each conductor to neutral

$$C_n = \frac{2\pi\varepsilon_0}{\ln\frac{D}{r}} = \frac{1}{18 \times 10^9 \ln\frac{3}{0.025}} = 1.16 \times 10^{-11} \text{ F/m}$$
$$= 1.16 \times 10^{-8} \text{ F/km.}$$

2. Line to line capacitance

$$C_l = \frac{1}{2} C_n = 0.58 \times 10^{-8} \text{ F/km}$$

3. Capacitive susceptance to neutral

$$b_c = \frac{1}{X_c} = 2\pi f C_n = 2\pi \times 60 \times 1.16 \times 10^{-8}$$
$$= 4.37 \times 10^{-6} \text{ S/km.}$$

Que 4.17. **A 3-phase, 50 Hz transmission line has flat horizontal configuration with 3.5 m between adjacent conductors. The conductors are hard drawn 7 strand copper wire (outside conductor diameter = 1.05 cm). The voltage of the line is 110 kV. Find the capacitance to neutral and charging current per km.**

AKTU 2019-20, Marks 07

Answer

1. $$D_{eq} = (3.5 \times 3.5 \times 7)^{1/3}$$
$$= 4.4 \text{ m}$$

2. $$C_n = \frac{0.0242}{\log(D_{eq}/r)} = \frac{0.0242}{\log(440/0.525)}$$
$$= 0.00826 \ \mu\text{F/km}$$

3. $$X_n = \frac{1}{\omega C_n} = \frac{10^6}{314 \times 0.00826}$$
$$= 0.384 \times 10^6 \ \Omega\text{/km to neutral}$$

4. Charging current

$$= \frac{V_n}{X_n} = \frac{(110/\sqrt{3}) \times 1000}{0.384 \times 10^6}$$
$$= 0.17 \text{ A/km}$$

PART-2

Composite Conductors-Transposition, Bundled Conductors, and Effort of Earth on Capacitance.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 4.18. **Calculate inductance of a single-phase system (with composite conductors).**

Answer

1. Consider a single-phase system consisting of two composite conductors A and B, each having m and n number of strands, respectively as shown in Fig. 4.18.1.

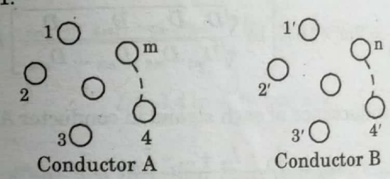


Fig. 4.18.1.

2. The current is assumed to be equally divided amongst all the strands of 'A' conductor and is equal to $\frac{I}{m}$ (acts as "go" conductor for the single-phase line) and current in all the strands of 'B' conductor is $\frac{-I}{n}$ (acts as "return" conductor for the single-phase line).

3. Using eq. $\psi_1 = 2 \times 10^{-7}\left(I_1 \ln\frac{1}{D_{11}} + I_2 \ln\frac{1}{D_{12}} + ... + I_n \ln\frac{1}{D_{1n}}\right)$ Wb-T/m the flux linkages of strand 1 due to currents in all conductors is given by,

$$\psi_1 = 2 \times 10^{-7} \frac{I}{m}\left(\ln\frac{1}{D_{11}} + \ln\frac{1}{D_{12}} + ... + \ln\frac{1}{D_{1m}}\right)$$
$$- 2 \times 10^{-7} \frac{I}{n}\left(\ln\frac{1}{D_{11'}} + \ln\frac{1}{D_{12'}} + ... + \ln\frac{1}{D_{1n}}\right) \quad ...(4.18.1)$$

$$\psi_1 = 2 \times 10^{-7} \frac{I}{m}\left(\ln \frac{1}{D_{11}D_{12} \ldots D_{1m}}\right) - 2 \times 10^{-7} \frac{I}{n}\left(\ln \frac{1}{D_{11'}D_{12'} \ldots D_{1n}}\right)$$

$$\psi_1 = 2 \times 10^{-7} I\left(\ln \frac{1}{\sqrt[m]{D_{11}D_{12} \ldots D_{1m}}} - \ln \frac{1}{\sqrt[n]{D_{11'}D_{12'} \ldots D_{1n}}}\right)$$

$$= 2 \times 10^{-7} I\left(\ln \frac{\sqrt[n]{D_{11'}D_{12'} \ldots D_{1n}}}{\sqrt[m]{D_{11}D_{12} \ldots D_{1m}}}\right) \quad \ldots(4.18.2)$$

4. Inductance of strand 1 of conductor A is

$$L_1 = \frac{\psi_1}{I/m} = 2m \times 10^{-7} \ln \frac{\sqrt[n]{D_{11'}D_{12'} \cdot D_{13'} \ldots D_{1n}}}{\sqrt[m]{D_{11}D_{12} \cdot D_{13} \ldots D_{1m}}} \, H/m \quad \ldots(4.18.3)$$

5. Inductance of strand 2 of conductor A is

$$L_2 = \frac{\psi_2}{I/m} = 2m \times 10^{-7}\left[\ln \frac{\sqrt[n]{D_{21'}D_{22'} \cdot D_{23'} \ldots D_{2n}}}{\sqrt[m]{D_{21}D_{22} \cdot D_{23} \ldots D_{2m}}}\right] H/m \quad \ldots(4.18.4)$$

6. Similarly, the inductance of strand m of conductor A is

$$\therefore L_m = \frac{\psi_m}{I/m} = 2m \times 10^{-7}\left[\ln \frac{\sqrt[n]{D_{m1'}D_{m2'} \cdot D_{m3'} \ldots D_{mn}}}{\sqrt[m]{D_{m1} \cdot D_{m2} \cdot D_{m3} \ldots D_{mm}}}\right] H/m \quad \ldots(4.18.5)$$

7. The average inductance of each strand in conductor A is

$$L_{av} = \frac{L_1 + L_2 + \ldots + L_m}{m} \quad \ldots(4.18.6)$$

8. Since conductor A is composed of m subconductors electrically in parallel. Thus the inductance of conductor A is

$$L_A = \frac{L_{avg}}{m} = \frac{L_1 + L_2 + \ldots + L_n}{m^2} \quad \ldots(4.18.7)$$

9. Substituting the logarithmic expression for inductance of each strand in eq. (4.18.7) and combining terms, we get

$$L_A = 2 \times 10^{-7} \ln\left(\frac{\sqrt[mn]{(D_{11'}D_{12'} \ldots D_{1n})(D_{21'}D_{22'} \ldots D_{2n}) \ldots (D_{n1'}D_{n2'} \ldots D_{nn})}}{\sqrt[m^2]{(D_{11}D_{12} \ldots D_{1m})(D_{21}D_{22} \ldots D_{2m}) \ldots (D_{m1}D_{m2} \ldots D_{mn})}}\right) \quad \ldots(4.18.8)$$

10. In eq. (4.18.8), the numerator is known as Geometric Mean Distance (GMD or mutual GMD) and is denoted as D_m and is equal to

$$D_m = \sqrt[mn]{(D_{11'}D_{12'} \ldots D_{1n})(D_{21'}D_{22'} \ldots D_{2n}) \ldots (D_{n1'}D_{n2'} \ldots D_{nn})} \quad \ldots(4.18.9)$$

11. It is the mn^{th} root of the product of the mn distances between m strands of conductor A and n strands of conductor B.

12. The denominator is known as GMR or self GMD, denoted as D_s and is equal to

$$D_s = \sqrt[m^2]{(D_{11}D_{12} \ldots D_{1m})(D_{21}D_{22} \ldots D_{2m}) \ldots (D_{m1}D_{m2} \ldots D_{mn})}$$

13. It is the m^2 root of the product of m^2 distances within the conductor A.

13. Now eq. (4.18.8) can be written as,

$$L_A = 2 \times 10^{-7} \ln \frac{D_m}{D_{sA}} \text{ H/m} \quad \ldots(4.18.10)$$

14. Similarly, the inductance of composite conductor B is

$$L_B = 2 \times 10^{-7} \ln \frac{D_m}{D_{sB}} \quad \ldots(4.18.11)$$

15. Therefore, the total inductance of a single-phase system of composite conductor is

$$L = L_A + L_B \quad \ldots(4.18.12)$$

16. If conductors A and B are identical *i.e.*, $D_{sA} = D_{sB} = D_s$, then the inductance is

$$\therefore \quad L = 4 \times 10^{-7} \ln \frac{D_m}{D_s} \text{ H/m}$$

or

$$L = 0.4 \ln \frac{D_m}{D_s} \text{ mH/km} \quad \ldots(4.18.13)$$

Que 4.19. **What are bundled conductors ? How to calculate self GMR of bundled conductor ?**

Answer

A. **Bundle Conductors :** Refer Q. 2.9, Page 2–19B, Unit-2.

B. **Calculation of GMR :**

1. Let r be the radius of each subconductor in a bundle and r' is GMR, of any one of the subconductor.

$$r' = 0.7788\, r$$

2. Consider the bundle of two subconductors.

Fig. 4.19.1.

3. Let D be the spacing between two conductors in a bundle.

D_S = Self GMR of bundled conductor

$$D_S = \sqrt[x^2]{(D_{aa}\, D_{ab} \ldots D_{ax})(D_{ba}\, D_{bb} \ldots D_{bx}) \ldots (D_{xa}\, D_{xb} \ldots D_{xx})}$$

Here x is number of subconductors in each bundle.

4. In case of two conductor bundle $x = 2$

$$\therefore D_S = \sqrt[2^2]{D_{aa}D_{ab}D_{bb}D_{ba}} = \sqrt[4]{D_{11}D_{12}D_{22}D_{21}}$$

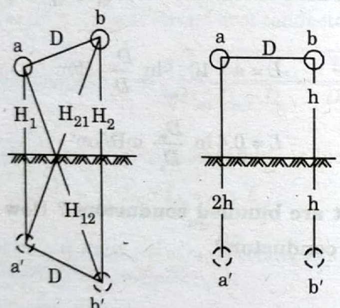
$$= \sqrt{r'dr'.D} = \sqrt[4]{r'^2 D^2} = \left[(r' D)^2\right]^{1/2}$$

$$\therefore D_S = \sqrt{r'D} = \sqrt{0.7788r.d.}$$

Que 4.20. **What is the effect of earth on line capacitance ? Explain the method of images to calculate the capacitance of two wire single phase line.**

Answer

1. Fig. 4.20.1(a) shows a two-wire single-phase line having conductors a and b. The spacing between the conductors is D. a' and b' are images of a and b respectively. The charges on a and b are $+q$ and $-q$ respectively.



(a) (b)

Fig. 4.20.1. Single-phase single-circuit line.

2. The potential difference between a and b can be written as

$$V_{ab} = \frac{1}{2\pi\varepsilon_0}\left[q_a \ln\frac{D_{ab}}{D_{aa}} + q_b \ln\frac{D_{bb}}{D_{ba}} + q_{a'} \ln\frac{D_{a'b}}{D_{a'a}} + q_{b'} \ln\frac{D_{b'b}}{D_{b'a}}\right] \quad ...(4.20.1)$$

3. But

$$q_a = q,\ q_b = -q_a = -q$$

$$q_{a'} = -q,\ q_{b'} = q$$

$$D_{aa} = D_{bb} = r$$

$$D_{ab} = D_{a'b'} = D,\ D_{aa'} = H_1,\ D_{bb'} = H_2$$

$$D_{ab'} = H_{12},\ D_{ba'} = H_{21}$$

4. Substituting these values in eq. (4.20.1), we get

$$V_{ab} = \frac{1}{2\pi\varepsilon_0}\left(q\ln\frac{D}{r} - q\ln\frac{r}{D} - q\ln\frac{H_{21}}{H_1} + q\ln\frac{H_2}{H_{12}}\right)$$

$$= \frac{1}{2\pi\varepsilon_0}\left(q\ln\frac{D}{r} - q\ln\frac{H_{12}H_{21}}{H_1H_2}\right)$$

$$= \frac{2q}{2\pi\varepsilon_0}\left(\ln\frac{D}{r} - \frac{1}{2}\ln\frac{H_{12}H_{21}}{H_1H_2}\right)$$

$$= \frac{q}{\pi\varepsilon_0}\left(\ln\frac{D}{r} - \ln\frac{(H_{12}H_{21})^{1/2}}{(H_1H_2)^{1/2}}\right)$$

5. Mean distances

$$H_s = (H_1 H_2)^{1/2},\quad H_m = (H_{12}H_{21})^{1/2}$$

Then the expression for V_{ab} can be written as

$$V_{ab} = \frac{q}{\pi\varepsilon_0}\left(\ln\frac{D}{r} - \ln\frac{H_m}{H_s}\right)$$

6. The line-to-line capacitance

$$C_{ab} = \frac{q}{V_{ab}} = \frac{\pi\varepsilon_0}{\ln\frac{D}{r} - \ln\frac{H_m}{H_s}} \text{ F/m} \quad ...(4.20.2)$$

7. Line-to-neutral capacitance

$$C_n = \frac{q}{V_{an}} = \frac{q}{\frac{1}{2}V_{ab}} = \frac{2\pi\varepsilon_0}{\ln\frac{D}{r} - \ln\frac{H_m}{H_s}}$$

$$= \frac{1}{18\times10^9\left(\ln\frac{D}{r} - \ln\frac{H_m}{H_s}\right)} \text{ F/m} \quad ...(4.20.3)$$

Special Case :

i. When the conductors a and b are at the same height h from the ground as shown in Fig. 4.20.1(b).

$H_1 = H_2 = 2h$, $\quad H_{12} = H_{21} = (D^2 + 4h^2)^{1/2}$

$H_s = (H_1 H_2)^{1/2} = 2h$, $\quad H_m = (H_{12} H_{21})^{1/2} = (D_2 + 4h^2)^{1/2}$

Eq. (4.20.3) shows that there is a slight increase in capacitance of the line due to presence of earth.

ii. The effect diminishes as the height of the conductor above the earth is increased. It is not possible to calculate the capacitance accurately.

VERY IMPORTANT QUESTIONS

Following questions are very important. These questions may be asked in your SESSIONALS as well as UNIVERSITY EXAMINATION.

Q. 1. Explain the factors, which are considered during designing a transmission line. Also explain how ground wire selection is done ?

Ans. Refer Q. 4.2, Unit-4.

Q. 2. Describe the various conductor configurations and choice of voltage, number of circuits for EHV transmission lines. Make economic comparison of EHV-AC & HVDC system.

Ans. Refer Q. 4.3, Unit-4.

Q. 3. Derive the expression for inductance of a conductor due to :

i. Internal flux.

ii. External flux.

Ans. Refer Q. 4.4, Unit-4.

Q. 4. Deduce an expression for the total inductance of a single phase line.

Ans. Refer Q. 4.5, Unit-4.

Q. 5. Derive the expression for the inductance of three phase line with conductors untransposed (unsymmetrical spacing). What is the significance of imaginary term in the expression for inductance ?

Ans. Refer Q. 4.6, Unit-4.

Q. 6. Derive the inductance per phase for a three phase transposed transmission line. Also calculate the inductance for horizontal and equilateral triangular configuration.

Ans. Refer Q. 4.7, Unit-4.

Q. 7. Find the inductance per phase of symmetrically spaced double circuit 3-phase line.

Ans. Refer Q. 4.9, Unit-4.

Q. 8. Derive an expression for the capacitance of a single phase overhead transmission line. What do you mean by self G.M.D. and mutual G.M.D.

Ans. Refer Q. 4.13, Unit-4.

Q. 9. Derive expression for capacitance of three phase line.

Ans. Refer Q. 4.14, Unit-4.

☺☺☺

5 UNIT Insulated Cables

CONTENTS

PART-1

Insulated Cables : Introduction, Insulation, Insulating Materials, Extra High Voltage Cables, Grading of Cables.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 5.1. Explain the basic introduction of insulated cable.

Answer

1. The transmission and distribution of an electrical power can be done with the help of overhead transmission lines or by underground cables (insulated cables).
2. It is well known fact that in thickly populated area like town and cities, the use of overhead lines is not practicable.
3. In such cases electrical energy is transmitted and distributed with the help of underground cables.
4. In its basic form, an underground cable is a conductor provide with proper insulation. As the voltage level increases, the cost of insulation increases rapidly and thus the used of underground cables is restricted to low and medium voltage distribution.

Que 5.2. What should be the desirable characteristics of insulating materials used in cables ? Also discuss general construction of cable.

Answer

A. Characteristics of insulating materials :

1. To prevent leakage current, its insulation resistance must be very high.
2. To avoid electrical breakdown, its dielectric strength must be very high.
3. It should be flexible.
4. To withstand the mechanical injuries, it must be mechanically very strong.
5. It should be non-inflammable.
6. It should be non-hygroscopic so that it will not absorb the moisture from the surrounding.
7. It should be unaffected by acid and alkalis.
8. It should be capable of withstanding high breakdown voltage.
9. It should have high temperature withstanding capability.

B. The main insulating materials which are in use are :

1. Polyvinyl chloride (PVC)
2. Paper
3. Cross linked polythene
4. Vulcanised India Rubber (VIR)

C. General construction of cable :

The Fig. 5.2.1 shows the general construction of a cable. Its various parts are :

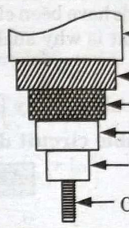


Fig. 5.2.1. General construction of a cable.

1. **Conductor or core :**
   i. This section consists of single conductor or more than one conductor. The conductors are also called cores.
   ii. The conductors used are aluminium or annealed copper. The conductors are stranded in order to provide flexibility to the cable.
2. **Insulation :** Each conductor or core is covered by insulation of proper thickness. The commonly used insulating materials are varnished cambric, vulcanized bitumen and impregnated paper.
3. **Metallic sheath :** The insulated conductors are covered by lead sheath or aluminium sheath. This provides the mechanical protection but mainly restricts moisture and other gases to reach to the insulation.
4. **Bedding :**
   i. The metallic sheath is covered by another layer called bedding. The bedding consists of paper tape compounded with a fibrous material like jute strands or hessian tape.
   ii. The purpose of bedding is to protect the metallic sheath from corrosion and from mechanical injury resulting due to armouring.
5. **Armouring :** This layer consists of the layers of galvanized steel which provide protection to the cable from the mechanical injury.
6. **Serving :** The last layer above the armouring is serving. It is a layer of fibrous material like jute cloth which protects the armouring from the atmospheric conductions.

Que 5.3. Discuss extra high voltage cables.

Answer

1. The operating voltage of extra high voltage cables are 66 kV.

2. These cables are also known as solid cable and there is no extra facility used to increase the dielectric strength and to avoid the possibility of formation of voids.
3. Thus the solid cables above 66 kV are unsound and owing to development of modern technique it would be impossible to avoid the formation of voids.
4. When these voids are subjected to electrostatic stresses, ionisation takes place and sometimes acts as a primary cause of breakdown of cables.
5. In above mentioned cables voids have been eliminated by increasing the pressure of compound and that is why such cables are also called as pressure cables.

Que 5.4. **What is grading of cable ? Why is it necessary ? Explain capacitance grading with suitable circuit diagram.**

AKTU 2017-18, Marks 10

Answer

A. **Grading of cables :** The process of obtaining uniform distribution of stress in insulation of cables is called grading of cables.

B. **Necessity :** Grading of cables is done because the unequal distribution has following two unwanted effects :

i. Greater insulation thickness is required, which increases the cost and size.

ii. It may lead to the breakdown of insulation.

C. **Capacitance grading or dielectric grading :**

1. The grading done by using the layers of dielectric having different permittivities between core and sheath is called capacitive grading.
2. Let r = Radius of conductor
   r_1, r_2, R = Radius of dielectrics
   $\varepsilon_1, \varepsilon_2, \varepsilon_3$ = Permittivity of dielectrics
   $\varepsilon_1 > \varepsilon_2 > \varepsilon_3$

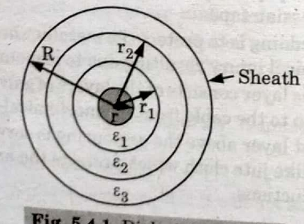


Fig. 5.4.1. Dielectric grading.

3. Dielectric stress is given by,

$$g_x = \frac{q}{2\pi\,\varepsilon_0\,\varepsilon_1 x}$$

4. Potential difference across inner layer,

$$V_1 = \int_r^{r_1} g_x\,dx = \int_r^{r_1} \frac{q}{2\pi\,\varepsilon_0\,\varepsilon_1 x}\,dx = \frac{q}{2\pi\,\varepsilon_0\,\varepsilon_1}\ln\frac{r_1}{r}$$

$$= \frac{q}{2\pi\,\varepsilon_0\,\varepsilon_1 r} \times r\ln\frac{r_1}{r} = g_{max1}\, r\ln\frac{r_1}{r}$$

5. Similarly, the potential difference between r_1 and r_2, $V_2 = g_{max2}\, r_1 \ln\frac{r_2}{r_1}$

6. Potential difference between r_2 and R, $V_3 = g_{max3}\, r_2 \ln\frac{R}{r_2}$

7. Total potential difference between core and earthed sheath

$$V = V_1 + V_2 + V_3$$

$$= g_{max1}\, r\ln\frac{r_1}{r} + g_{max2}\, r_2\ln\frac{r_2}{r_1} + g_{max3}\, r_2\ln\frac{R}{r_2}$$

8. Capacitance of cable, $C = \dfrac{q}{V}$

$$= \frac{q}{\left[\dfrac{q}{2\pi\,\varepsilon_0}\left(\dfrac{1}{\varepsilon_1}\ln\dfrac{r_1}{r} + \dfrac{1}{\varepsilon_2}\ln\dfrac{r_2}{r_1} + \dfrac{1}{\varepsilon_3}\ln\dfrac{R}{r_2}\right)\right]}$$

$$= \frac{2\pi\,\varepsilon_0}{\dfrac{1}{\varepsilon_1}\ln\dfrac{r_1}{r} + \dfrac{1}{\varepsilon_2}\ln\dfrac{r_2}{r_1} + \dfrac{1}{\varepsilon_3}\ln\dfrac{R}{r_2}}$$

9. Maximum stresses,

$$g_{max1} = \frac{q}{2\pi\,\varepsilon_0\,\varepsilon_1 r}$$

$$g_{max2} = \frac{q}{2\pi\,\varepsilon_0\,\varepsilon_2 r_1}$$

$$g_{max3} = \frac{q}{2\pi\,\varepsilon_0\,\varepsilon_3 R}$$

10. If maximum stress is same in each layer,

$$g_{max1} = g_{max2} = g_{max3} = g_{max} \text{ (say)}$$

$$\therefore \quad \varepsilon_1 r = \varepsilon_2 r_1 = \varepsilon_3 R$$

11. Total voltage applied across the cable,

$$V = g_{max}\left(r\ln\frac{r_1}{r} + r_1\ln\frac{r_2}{r_1} + r_2\ln\frac{R}{r_2}\right)$$

Que 5.5. **Explain Intersheath grading.**

OR

Discuss different methods of grading.

Answer

Methods of grading :

A. Capacitive grading : Refer Q. 5.4, Page 5–4B, Unit-5.

B. Intersheath grading :

1. In intersheath grading, a homogeneous dielectric is used, but it is divided into various layers by placing metallic intersheaths between the core and lead sheath. The intersheaths are held at suitable potentials, which are in between the core potential and earth potential.
2. Consider a cable of core radius r and outer lead sheath of radius R. Suppose that two intersheaths of radius r_1 and r_2 are inserted into the homogeneous dielectric and maintained at some fixed potentials. V_1, V_2 and V_3 respectively be the voltage between core and intersheath 1, between intersheath 1 and 2 and between intersheath 2 and outer sheath.
3. Since there is a definite potential difference between the inner and outer layers of each intersheath, therefore, each sheath can be treated as a homogeneous single core cable.
4. Maximum stress between core and the intersheath 1 is,

$$g_{1\max} = \frac{V_1}{r\log_e \frac{r_1}{r}}$$

5. Similarly,

$$g_{2\max} = \frac{V_2}{r_2 \log_e \frac{r_2}{r}}$$

$$g_{3\max} = \frac{V_3}{R\log_e \frac{R}{r}}$$

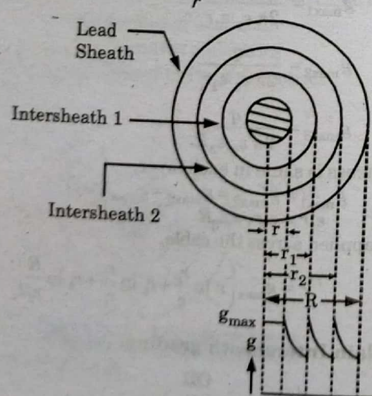


Fig. 5.5.1.

6. The dielectric is homogeneous, the maximum stress in each layer is the same *i.e.*, $g_{1\max} = g_{2\max} = g_{3\max}$

$$\frac{V_1}{r\log_e \frac{r_1}{r}} = \frac{V_2}{r_2\log_e \frac{r_2}{r}} = \frac{V_3}{R\log_e \frac{R}{r}}$$

7. As the cable behaves like three capacitors in series, therefore, all the potentials are in phase *i.e.*, voltage between conductor and earthed lead sheath is

$$V = V_1 + V_2 + V_3$$

PART-2

Insulation Resistance of a Cable, Capacitance of a Single Core and Three Core Cables.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 5.6. **Derive expression for dielectric stress in a single core cable.**

Answer

1. Let
   r = Radius of conductor or inner radius of insulation.
   R = Internal radius of sheath or outer radius of insulation.
   ε_o = Permittivity of free space.
   ε_r = Relative permittivity of the dielectric.
   q = Charge on the conductor per unit length
   V = Operating phase-to-neutral voltage
2. The electric flux density at a distance x from the center is, $D_x = \frac{q}{2\pi x}$

   and the electric stress is given by,

$$g_x = \frac{D_x}{\varepsilon_o \varepsilon_r} = \frac{q}{(2\pi\varepsilon_o\varepsilon_r)x} \quad ...(5.6.1)$$

3. The potential difference between the conductor and the sheath is equal to the work done to move a unit charge from the conductor to sheath.

   Thus,

$$V = \int_r^R g_x dx = \int_r^R \frac{q}{(2\pi\,\varepsilon_o\varepsilon_r)x}\,dx \quad ...(5.6.2)$$

$$= \frac{q}{2\pi\,\varepsilon_o\varepsilon_r}\ln\frac{R}{r}$$

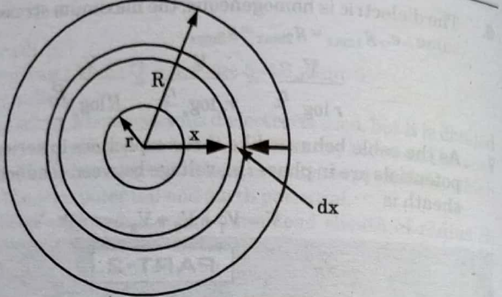


Fig. 5.6.1. Single-core cable.

4. Combining eq. (5.6.1) and (5.6.2), we get

$$g_x = \frac{V}{x \ln\left(\frac{R}{r}\right)}$$

5. The maximum stress will occur at $x = r$, $g_{max} = \dfrac{V}{r \ln\left(\frac{R}{r}\right)}$ ...(5.6.3)

6. The minimum stress occurs at $x = R$, $g_{min} = \dfrac{V}{R \ln\left(\frac{R}{r}\right)}$

7. Ratio of maximum and minimum stress is,

$$\frac{g_{max}}{g_{min}} = \frac{V / r \ln (R/r)}{V / R \ln (R/r)} = \frac{R}{r} = \frac{D}{d} = \frac{\text{Outer diameter}}{\text{Inner diameter}}$$

Economical core diameter :

1. The value of g_{max} will be minimum when $\dfrac{\partial g_{max}}{\partial d} = 0$

2. Putting $r = \dfrac{d}{2}$ and $R = \dfrac{D}{2}$ in eq. (5.6.3), we get

$$g_{max} = \frac{2V}{d \ln\left[\frac{D}{d}\right]}$$

$$\frac{\partial g_{max}}{\partial d} = \frac{d \ln\left[\frac{D}{d}\right]\frac{\partial}{\partial d}(2V) - 2V\frac{\partial}{\partial d}\left[d \ln\left(\frac{D}{d}\right)\right]}{\left[d \ln\left(\frac{D}{d}\right)\right]^2}$$

$$= \frac{0 - 2V\frac{\partial}{\partial d}\left[d \ln\left(\frac{D}{d}\right)\right]}{\left[d \ln\left(\frac{D}{d}\right)\right]^2}$$

$$= \frac{-2V}{\left[d \ln\left(\frac{D}{d}\right)\right]^2}\left\{\ln\left(\frac{D}{d}\right) + d\,\frac{1}{\left(\frac{D}{d}\right)}\left(\frac{-D}{d^2}\right)\right\}$$

$$\therefore \quad \frac{\partial g_{max}}{\partial d} = \frac{-2V}{\left[d \ln\left(\frac{D}{d}\right)\right]^2}\left\{\ln\left(\frac{D}{d}\right) - 1\right\} \quad ...(5.6.4)$$

3. Now the value of $\dfrac{\partial g_{max}}{\partial d}$ must be zero to get minimum g_{max}.

$$\ln\left(\frac{D}{d}\right) - 1 = 0$$

$$\ln\left(\frac{D}{d}\right) = 1$$

$$\frac{D}{d} = e_1 = 2.718$$

$$\therefore \quad d = \frac{D}{2.718}$$

4. Hence, the core diameter must be $1/2.718$ times the sheath diameter D so as to give the minimum value of g_{max}.

5. The value of minimum g_{max} is,

$$\text{Minimum } g_{max} = \frac{2V}{d}$$

$$\therefore \quad \text{Minimum } g_{max} = \frac{V}{r}$$

Que 5.7. **Derive the expression for insulation resistance and capacitance of a single core cable.**

OR

What are the main requirements of the insulating materials used for cables ? Derive an expression for the insulation resistance of a single core metal sheathed cable.

AKTU 2015-16, Marks 7.5

OR

Derive the expression for insulation resistance of single core cable.

AKTU 2018-19, Marks 07

Answer

A. **Requirements of insulating materials :** Refer Q. 5.2, Page 5–2B, Unit-5.

B. **Insulation resistance of single core cable :**

1. The resistance offered by cable to path of the leakage current is called an insulation resistance.

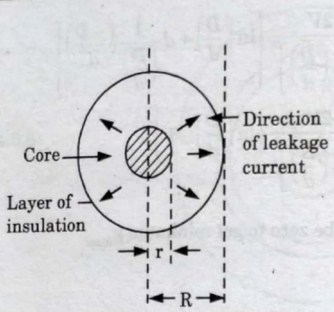


Fig. 5.7.1. Single cable.

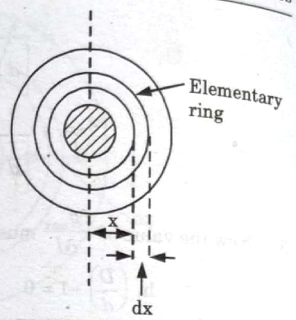


Fig. 5.7.2. Elementary Ring.

2. Load current flows through the core of cable while some leakage current flows radially from the conductor to the sheath through the dielectric material.
3. Resistance of any material is given by,

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

where, ρ = Specific resistance of material.
l = Length of material.
A = Area of cross-section of material.

4. Resistance of elemental circular ring at distance x,

$$dR = \rho \frac{dx}{2\pi x} \text{ (unit length of cable)}$$

dR = Differential leakage resistance,

$$R = \frac{\rho}{2\pi} \int_r^R \frac{dx}{x}$$

$$= \frac{\rho}{2\pi} \ln \frac{R}{r} \text{ ohms/metre}$$

5. If length of cable is l units.

Leakage resistance, $R = \dfrac{\rho}{2\pi l} \ln \dfrac{R}{r}$ ohms

C. Insulation capacitance :

1. Let,
d = Conductor diameter
D = Total diameter with sheath
Q = Charger per meter length of conductor in coulombs
ε = Permittivity of a material between core and sheath
ε_0 = Permittivity of free space = 8.854×10^{-12} F/m
ε_r = Relative permittivity of the medium
2. Consider an elementary cylinder with radius x and axial length of 1m. The thickness of the cylinder is dx.

3. Flux density $D_x = \dfrac{Q}{\text{Surface area}} = \dfrac{Q}{2\pi x}$

The electric field intensity at any point P on the elementary cylinder is

$$g_x = \frac{D_x}{\varepsilon} = \frac{Q}{2\pi x \varepsilon} = \frac{Q}{2\pi x \varepsilon_0 \varepsilon_r} \text{ V/m}$$

4. Hence the work done is moving a unit charge a distance dx in the direction of an electric field is $g_x dx$.

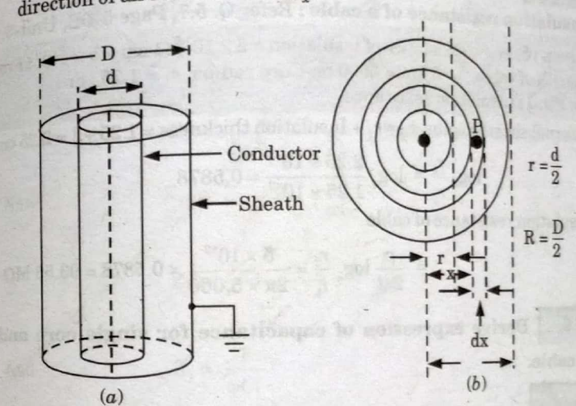


Fig. 5.7.3. Capacitance of a single-core-cable.

5. The work done in moving a unit charge from the conductor to sheath is the potential difference between the conductor and the sheath given by,

$$V = \int_{d/2}^{D/2} g_x dx = \int_{d/2}^{D/2} \frac{Q}{2\pi x \varepsilon_0 \varepsilon_r} dx$$

$$= \frac{Q}{2\pi \varepsilon_0 \varepsilon_r} \int_{d/2}^{D/2} \frac{dx}{x} = \frac{Q}{2\pi x \varepsilon_0 \varepsilon_r} [\log x]_{d/2}^{D/2}$$

$$= \frac{Q}{2\pi \varepsilon_0 \varepsilon_r} \left[\log \frac{D}{2} - \log \frac{d}{2}\right]$$

$$\therefore \quad V = \frac{Q}{2\pi \varepsilon_0 \varepsilon_r} \log \left[\frac{D}{d}\right] = \frac{Q}{2\pi \varepsilon_0 \varepsilon_r} \log \left[\frac{R}{r}\right]$$

6. The capacitance of a cable is given by,

$$C = \frac{Q}{V} = \frac{Q}{\left[\dfrac{Q}{2\pi \varepsilon_0 \varepsilon_r} \log \left(\dfrac{R}{r}\right)\right]}$$

$$C = \frac{2\pi \varepsilon_0 \varepsilon_r}{\log_e \left[\dfrac{R}{r}\right]} = \frac{2\pi \varepsilon_0 \varepsilon_r}{\log_e \left[\dfrac{D}{d}\right]} \text{ F/m}$$

Que 5.8. **Derive the formula for insulation resistance of a cable. Calculate insulation resistance for 5 km length of single core cable whose insulation resistance is 5×10^{14} Ω-cm, insulation thickness is 1cm and radius of conductor is 1.25 cm.** **AKTU 2019-20, Marks 07**

Answer

Insulation resistance of a cable : Refer Q. 5.7, Page 5–9B, Unit-5.

Given : Specific resistance of insulation = 5×10^{14} Ω-cm = 5×10^{12} Ω-m, Length of cable, l = 5 km = 5000 m, Core radius, r_1 = 1.25 cm
To Find : Insulation resistance.

1. Internal sheath radius, $r_2 = r_1$ + Insulation thickness = 1.25 + 1 = 2.25 cm

$$\log_e \frac{r_2}{r_1} = \log_e \frac{2.25 \times 10^{-2}}{1.25 \times 10^{-2}} = 0.5878$$

2. Insulation resistance of cable

$$= \frac{\rho}{2\pi l} \log_e \frac{r_2}{r_1} = \frac{5 \times 10^{12}}{2\pi \times 5{,}000} \times 0.5878 = 93.55 \text{ M}\Omega$$

Que 5.9. **Derive expression of capacitance for single core and 3-core cable.**

Answer

A. **Capacitance of single core cable :** Refer Q. 5.7, Page 5–9B, Unit-5.
B. **Capacitance of three core cable :**
1. In a 3-core cable, sheath is at earth potential and 3 conductors at supply potentials.
2. There are six capacitance formed, three capacitance between sheathed conductors and other three capacitance between conductors.
3. The capacitances are shown in the Fig. 5.9.1. The core to core capacitances are denoted as C_c while core to sheath capacitances are denoted as C_s.

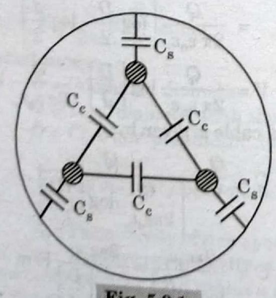


Fig. 5.9.1.

4. The core to core capacitances C_c are in delta and can be presented in the equivalent star as shown in the Fig. 5.9.2.

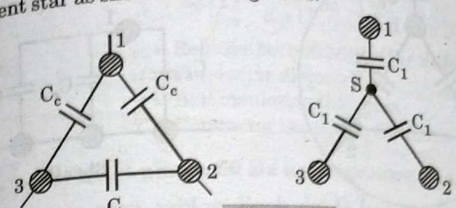


Fig. 5.9.2.

5. The impedance between core 1 and the star point Z_1 can be obtained as,

$$Z_1 = \frac{Z_{12} Z_{13}}{Z_{12} + Z_{13} + Z_{23}} \quad \text{[from delta-star conversion]}$$

Now $$Z_{12} = Z_{13} = Z_{23} = \frac{1}{\omega C_c}$$

$\therefore$ $$Z_1 = \frac{\frac{1}{\omega C_c} \times \frac{1}{\omega C_c}}{\frac{3}{\omega C_c}} = \frac{1}{3}\frac{1}{\omega C_c}$$

And $$Z_1 = \frac{1}{\omega C_1}$$

$$\frac{1}{\omega C_1} = \frac{1}{3} \cdot \frac{1}{\omega C_c}$$

$\therefore$ $$C_1 = 3C_c$$

6. If star point is assumed to be at earth potential and if sheath is also earthed then the capacitance of each conductor to neutral is,

$$C_N = C_s + C_1 = C_s + 3C_c$$

7. If V_{ph} is phase voltage then charging current per phase is,

$$I = \frac{V_{ph}}{\text{Capacitance reactance/phase}} = \frac{V_{ph}}{X_{CN}} = \frac{V_{ph}}{\frac{1}{\omega C_N}}$$

$$I = \omega C_N V_{ph} \text{ A}$$

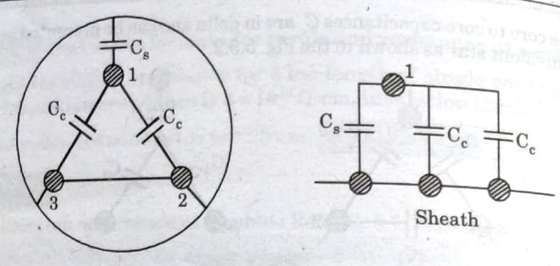
Measurement of C_s and C_c :

1. Measurement involves two cases.

Case I :

i. The core 2 and core 3 connected to sheath. Thus the C_c between cores 2 and 3 and C_s between cores 2, 3 and sheath get eliminated as shown in the Fig. 5.9.3.
ii. All the three capacitances are now in parallel across core 1 and the sheath.
iii. The capacitance of core1 with sheath is measured practically and denoted by C_a.

$$C_a = C_s + 2C_c \quad \text{...(5.9.1)}$$



(a) (b)

Fig. 5.9.3.

Case II :

i. All the three cores are bundled together. This eliminates all the core-core capacitances. This is shown in the Fig. 5.9.4.

ii. The capacitances C_s are in parallel between the common core and sheath. This capacitance is practically measured and denoted by C_b.

$\therefore \quad C_b = 3C_s$ ...(5.9.2)

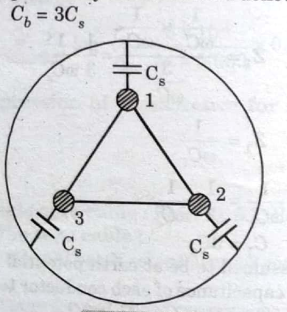


Fig. 5.9.4.

2. Solving eq. (5.9.1) and (5.9.2),

$$C_a = \frac{C_b}{3} + 2C_c$$

$$C_c = \frac{C_a}{2} - \frac{C_b}{6} \text{ and } C_s = \frac{C_b}{3}$$

3. Thus both the capacitances can be determined

$$\therefore \quad C_N = C_s + 3C_c$$

$$= \frac{C_b}{3} + 3\left[\frac{C_a}{2} - \frac{C_b}{6}\right]$$

$$C_N = \frac{3C_a}{2} - \frac{C_b}{6} \quad ...(5.9.3)$$

4. Capacitance can also be calculated by empirical formula given by Simon. The formula is given as

$$C_N = \frac{0.0299\,\varepsilon_r}{\log\left[1 + \frac{T+t}{d}\left\{3.84 - 1.7\frac{t}{T} + 0.52\frac{t^2}{T^2}\right\}\right]} \mu\text{F/km}$$

where, ε_r = Relative permittivity of the dielectric
d = Conductor diameter
t = Belt insulation thickness
T = Conductor insulation thickness.

Que 5.10. **A 33 kV, 3-phase, 50 Hz underground line, 3.4 km long, uses three single core cables. Each cable has a core diameter of 2.5 cm and the radial thickness of insulation is 0.6 cm. The relative permittivity of the dielectric is 3.1. Find (i) maximum stress and (ii) total charging kVAr.**

Answer

Given : d = 2.5 cm, thickness = 0.6 cm, ε_r = 3.1
To Find : Maximum stress and total kVAr.

1. Internal diameter of sheath, $D = 2.5 + 2 \times 0.6 = 3.7$ cm

2. Capacitance of cable, $C = \dfrac{0.024\varepsilon_r}{\log_{10}\dfrac{D}{d}} \times$ length of cable μF

$$= \frac{0.024 \times 3.1}{\log_{10}\frac{3.7}{2.5}} \times 3.4 \times 1{,}000$$

$$= 1486 \times 10^{-6} \text{ F/phase}$$

3. Charging current, $I_C = 2\pi f C V$

$$= 2\pi \times 50 \times 1486 \times 10^{-6} \times \frac{33 \times 10^3}{\sqrt{3}} \text{ A/phase}$$

$$I_C = 8.895 \text{ A/Phase}$$

4. Total charging in $kVAr = 3 \times V_P \times I_C \times 10^{-3}$

$$= 3 \times \frac{33{,}000}{\sqrt{3}} \times 8.895 \times 10^{-3}$$

$$= 508.4 \text{ kVAr}$$

5. Maximum stress in the cable

$$E_{max} = \frac{V}{\frac{d}{2}\log_e\frac{D}{d}} = \frac{33{,}000/\sqrt{3}}{\frac{2.5}{2}\log_e\frac{3.7}{2.5}}$$

$$E_{max} = 38.88 \text{ kV/cm}$$

Que 5.11. **Explain the phenomena of heating and different losses in cables.**

OR

Show that the most economical size of conductor in a single core cable is obtained when radius of cable sheath (*R*) equals *e.r.* where e is the base of radius of conductor. Explain dielectric loss and heating of a cable.

AKTU 2019-20, Marks 07

Answer

1. The temperature rise of the body depends upon the rate of generation and dissipation of heat by the body. The temperature goes on rising until the rate of heat generation becomes equal to that of heat dissipation.
2. The heat is produced within the underground cables due to following losses :

A. Copper loss in Cables :

1. The copper loss is determined by the expression I^2R. The resistance of the conductor changes at the temperature changes. The resistance increases as the temperature increases.
2. To find copper value of resistance is necessary. The resistance at any temperature t_2 is given by

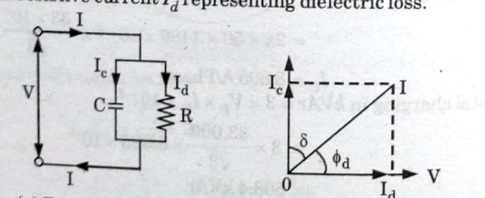
$$R = R_1 (1 + \alpha_1 \Delta t)$$

where, R_1 = Resistance at t_1

α_1 = Resistance temperature coefficient of material at t_1

B. Dielectric loss :

1. There exists a capacitance between a conductor and sheath, with a dielectric medium in between the two. This is represented as *C*. The leakage resistance is denoted as *R*.
2. The equivalent circuit of the cable is a parallel combination of *R* and *C*. So there are two currents one perpendicular to voltage *V* which is leading capacitive current I_c while other is in phase with voltage *V* which is resistive current I_d representing dielectric loss.



(*a*) Equivalent circuit (*b*) Phasor diagram

Fig. 5.11.1.

3. The dielectric loss is loss due to leakage resistance given by

$$W = \frac{V^2}{R}$$

4. Now,

$$\tan \delta = \frac{I_d}{I_c} = \frac{V/R}{V/X_C}$$

$$\frac{V}{R} = \frac{V}{X_C} \tan \delta = V\omega C \tan \delta$$

$$W = V^2 \omega C \tan \delta$$

where δ = Dielectric loss angle in radians

5. Generally δ is very small and hence $\tan \delta \approx \delta$ for low voltage cables dielectric loss can be neglected as it is small but for high voltage cables it must be considered.

C. Sheath loss :

1. In AC transmission, alternating currents flowing through the cable produce pulsating magnetic field. This electromagnetic pulsating field links with the lead sheath and induces current in it.
2. The value of this current depends on the frequency of pulsating field, sheath resistance arrangement of cables and sheath conditions whether it is bounded or unbounded.
3. The approximate formula to calculate sheath losses due to sheath eddy currents is given as,

$$\text{Sheath loss} = I^2 \left\{\frac{3\omega^2}{R_s}\left(\frac{r_m}{d}\right)^2 \times 10^{-18}\right\} \text{W/ cm/phase}$$

where, I = Current per conductor

r_m = Mean radius of sheath

R_s = Sheath resistance

d = Spacing between conductor

These losses are practically very small and hence generally neglected.

D. Most economical size of conductor : Refer Q. 5.6, Page 5–7B, Unit-5.

Que 5.12. Derive the condition for most economical size of cable using voltage gradient method. The test results for 1 km of a three-phase metal sheathed belted cable gave a measured capacitance of 0.7 µF between one conductor and the other two conductors bunched together with the earth sheath and 1.2 µF measured between the three bunched conductors and the sheath. Find :

i. the capacitance between any pair of conductors, the sheath being isolated and

ii. the charging current when the cable is connected to 11 kV, 50 Hz supply.

Answer

A. Most economical size of conductor : Refer Q. 5.6, Page 5–7B, Unit-5.

B. Numerical :

Given : $C_x = 1.2\ \mu F$, $C_y = 0.7\ \mu F$, $V = 11$ kV, $f = 50$ Hz

To Find : C, I_C.

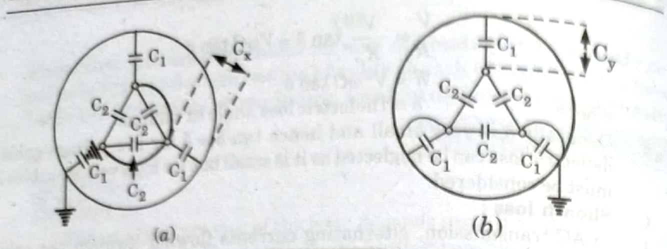


Fig. 5.12.1.

1. From Fig. 5.12.1(*a*) and (*b*)

$$C_x = 3C_1 = 1.2 \quad ...(5.12.1)$$
$$C_y = C_1 + 2C_2 = 0.7 \quad ...(5.12.2)$$

From eq. (5.12.1) and (5.12.2)

$$C_1 = 0.4 \ \mu F$$
$$C_2 = 0.15 \ \mu F$$

2. Since capacitance per phase

$$C_0 = C_1 + 3C_2$$

and $C_0 = 0.85 \ \mu F$

3. The equivalent circuit for measuring capacitance between two bunched conductors and third conductor will be as in Fig. 5.12.2.
4. The equivalent capacitance C will be

$$C = 2C_2 + \frac{2}{3}C_1$$

Substituting the values for C_1 and C_2

$$C = 0.56 \ \mu F$$

5. The charging current per phase, I_C

$$= \frac{V}{\sqrt{3}} \omega C_0 \times 10^3 \text{ amps} = \frac{10}{\sqrt{3}} \times 314 \times 0.85 \times 10^{-6} \times 10^3$$
$$= 1.54 \text{ A}$$

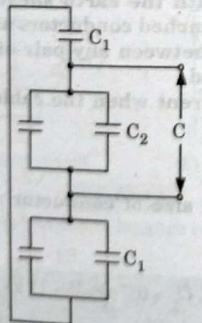


Fig. 5.12.2.

PART-3

Overhead Lines Versus Underground Cables, Types of Cables.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 5.13. **Give a comparison of an overhead line with underground cable as a medium of power transmission.**

AKTU 2015-16, Marks 05

Answer

1. **Public safety :** The underground system is safer than overhead system due to the wiring placed underground and therefore little chances of any hazard.
2. **Initial cost :** The initial cost of an underground system may be five to ten times than that of overhead system due to high cost of trenching, conduits, cables, manholes and other special equipments.
3. **Flexibility :** The overhead system is much more flexible than the underground system because in an overhead system poles, wires, transformers etc. can be easily shifted to meet the change in the load conditions.
4. **Faults :** The chances of faults in the underground system are very rare as the cables are laid underground.
5. **Fault location and repairs :** Basically, there are little chances of faults in an underground system. However, if a fault occurs, it is difficult to locate and repair an underground system.
6. **Current carrying capacity and voltage drop :** An overhead system has considerably higher current carrying capacity than an underground cable conductor of the same material and cross-section. Also there is low voltage drop in overhead system.
7. **Useful life :** The useful life of an underground system is much longer than that of an overhead system.
8. **Maintenance cost :** The maintenance cost of underground system is very low as compared to the overhead system due to less chance of faults and service interruptions from wind, ice, lighting etc.

Que 5.14. **Discuss in brief about the different types of cables.**

Answer

The type of a cable basically decided based on the voltage level for which it is manufactured and the material used for the insulation such as paper cotton, rubber etc.

Types of cable :

A. **Low tension cable (L. T. cable) :**
1. These are used for the voltage levels upto 6.6 kV.
2. The paper is used as insulation in these cables. Some time resin is also used which increases the viscosity and helps to prevent drainage.
3. The Fig. 5.14.1 shows the cross-section of a single core L.T. cable. It consists of a circular core of stranded copper or aluminium.

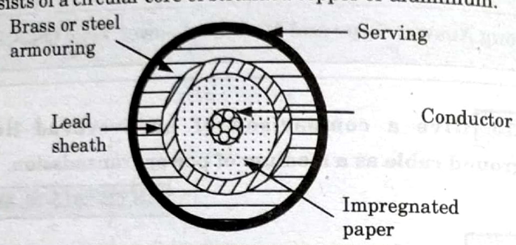


Fig. 5.14.1. Single core L.T. cable.

4. The conductor is insulated by impregnated paper over the paper insulation, the lead sheath is provided then a layer of compounded fibrous material is provided. Then armouring is provided and finally covered again with a layer of fibrous compounded material.

B. **Medium and high tension cables :**
1. The three phase medium and H.T. cables are three core cable. For voltage upto 66 kV the three core cable *i.e.*, multicore cable are used.
2. These cables are classified as :

a. **Belted cables :**
1. These are used for the voltage level upto 11 kV. The construction of belted cable is shown in Fig. 5.14.2.

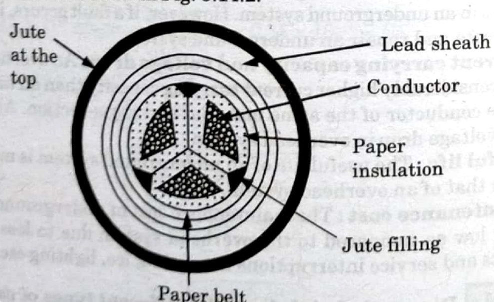


Fig. 5.14.2. Belted 3-core cable.

2. The cores are not circular in shape. The cores are insulated from each other by use of impregnated paper.
3. The three cores are grouped together and belted with the help of a paper belt.

4. The gaps are filled with fibrous material like jute. This gives circular cross-sectional shape to the cable.
5. The belt is covered with lead sheath which protects cable from moisture and also gives mechanical strength.
6. The lead sheath is finally covered by jute like fibrous compounded material.

b. **Screened type cables :** These cables are used for the voltage levels of 22 kV and 33 kV. The two types of screened cables are :

i. **H-type cable :**
1. There is no paper belt is this type of cable. Each conductor in this cable is insulated with a paper, covered with a metallic screen which is generally an aluminium foil. The construction is shown in Fig. 5.14.3.

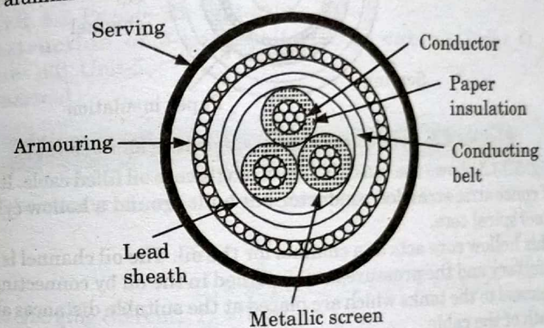


Fig. 5.14.3. H-type cable.

ii. **S.L type cable (Separate lead screened cable) :**
1. In this cable each core is insulated with an impregnated paper and each one is then covered by separate lead sheath.
2. Then there is a cotton tape covering the three cores together using a proper filter material.

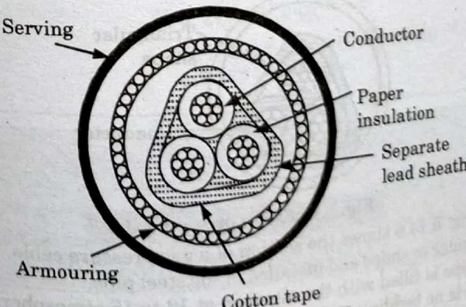


Fig. 5.14.4. S.L. type cable.

C. Super tension (S.T.) cables :

1. The S.T. cables are used for 132 kV to 275 kV voltage level.
2. Such cables using oil or gas under pressure are called pressure cables and are of two types :

a. Oil filled cables :

1. In case of oil filled cables, the channels or ducts are provided within or adjacent to the cores, through which oil under pressure is circulated.

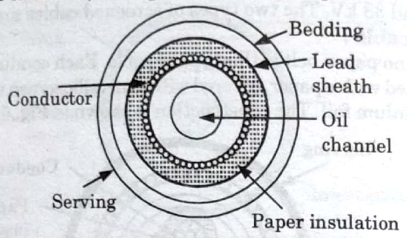


Fig. 5.14.5. Conductor channel single core oil filled cable.

2. Fig. 5.14.5 shows the construction of single core oil filled cable. It consists of concentric stranded conductor but built around a hollow cylindrical steel spiral core.
3. This hollow core acts as a channel for the oil. The oil channel is filled in a factory and the pressure is maintained in the oil by connecting the oil channel to the tanks which are placed at the suitable distances along the path of the cable.

b. Gas pressure cables :

1. In case of gas pressure cables an inert gas like nitrogen at high pressure is introduced. The pressure is about 12 to 15 atmospheres.
2. Due to such a high pressure there is a radial compression due to which the ionization is totally eliminated. The working power factor of such cables is also high.

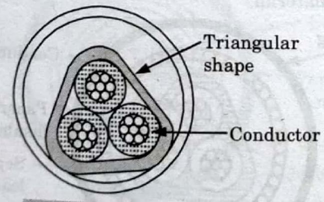


Fig. 5.14.6. Gas pressure cable.

3. The Fig. 5.14.6 shows the section of a gas pressure cable. The cable is triangular in shape and installed in the steel pipe.
4. The pipe is filled with the nitrogen at 12 to 15 atmospheric pressure. There is no bedding and serving.

Que 5.15. **What are the commonly used insulating materials for underground cables ? Describe with a neat sketch, the construction of a 3-core belted-type cable.**
Calculate the kVA taken by a 10 km long, 3-phase 3-core cable, if the capacitance measured between any two cores is 0.3 μF/km when it is connected to 10 kV, 50 Hz busbar.

AKTU 2016-17, Marks 15

Answer

A. Commonly used insulating material for underground cable : Refer Q. 5.2, Page 5–2B, Unit-5.

B. Construction of 3-core belted-type cable : Refer Q. 5.14, Page 5–19B, Unit-5.

C. Numerical :

Given : $C_L = 0.3 \times 10^{-6}$ F, $V_L = 10$ kV, $C_L = 0.3$ μF/km, $f = 50$
To Find : Total charging in kVA

1. If C_L be measured capacitance between any two core,

$$C_L = \frac{C_0}{2}$$

$$C_0 = 2C_L = 2 \times 0.3 \times 10^{-6} = 0.6\ \mu\text{F}$$

2. Line charging current, $I_C = V_p \omega C_0$

$$= \frac{V_L}{\sqrt{3}} \omega \times 2C_L$$

3. Total charging in $kVA = \sqrt{3} V_L I_C \times 10^{-3}$

$$= \sqrt{3} \times V_L \times \frac{V_L}{\sqrt{3}} \times 2\omega C_L \times 10^{-3}$$

$$= 2V_L^2 \omega C_L \times 10^{-3}$$

$$= (10000)^2 \times 2\pi \times 50 \times 0.6 \times 10^{-6} \times 10^{-3}$$

$$= 0.188\ \text{kVA}$$

VERY IMPORTANT QUESTIONS

Following questions are very important. These questions may be asked in your SESSIONALS as well as UNIVERSITY EXAMINATION.

Q. 1. What should be the desirable characteristics of insulating materials used in cables ? Also discuss general construction of cable.