DEMOCRATIC REPUBLIC OF TIMOR-LESTE

ADN

EXPERT FOR STRENGTHENING INSTITUTIONAL CAPACITY OF NATIONAL DEVELOPMENT AGENCY

FINAL REPORT (2/2)

OCTOBER 2013

JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)

DAINICHI CONSULTANT INC.
TOKYO WATERWORKS INTERNATIONAL CO.,LTD.
GEOPLAN CO.,LTD
NEWJEC INC.

ANNEX-8

CLASSROOM LESSON ON POWER

Japanese Technical Assistance
on Strengthening Institutional Capacity
of National Development Agency (ADN)
in Democratic of Timor-Leste

-- POWER --

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Introduction

- Purpose
  - To acquire fundamental knowledge on evaluation and inspection of projects
    - To understand what kind of thing the item described to BoQ is
    - To understand which equipment is what and what kind of function it has at the time of site inspections
    - To have a certain level of knowledge about the technical terms which will be used by the staff of EDTL or the contractors

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Syllabus

No.	Contents
1	Introduction
2	Power Station (Diesel)
3	Substation
4	Transmission Line (Transmission System)
5	Distribution Line (Distribution System)
6	Renewable Energy (Photovoltaic Power)
7	Protecting System
8	Power System Operation and Control
9	Others

The contents may be changed depending on conditions.
I would like to discuss about the contents with Mr. Miguel and YOU.

CONTENTS

I. INTRODUCTION

II. QUICK REVIEW OF BASIC POWER ENGINEERING

III. INTRODUCTION TO ELECTRIC POWER TRANSMISSION & DISTRIBUTION

I. INTRODUCTION

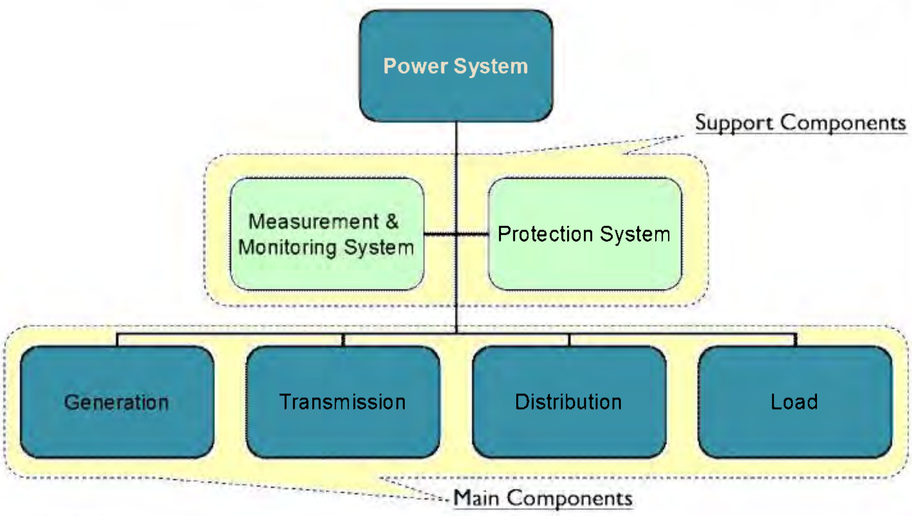
1. Introduction

- Power System provides vital service to the society.
- Electrical power is somewhat like air we breathe: We think of it only when it is missing.
- Modern society cannot exists without electricity.
- Therefore, it should be operated with the goal of achieving
  - Highest reliability standards
  - Lowest operational cost
  - Minimum environmental impact

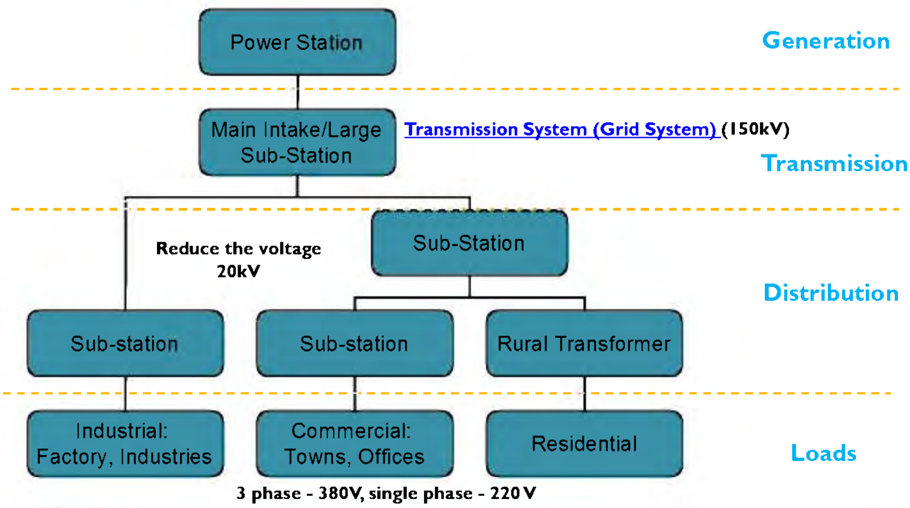
2. Historical Background

- 1882: Power station at Pearl Station New York by Edison supplying power to 59 consumers.
- 1889: AC transmission line 4kV, single phase, in north America between Willamette falls to Portland by Westinghouse.
- 1893: First three phase line in Southern California.
- 1954: HVDC transmission system by Swedish Power Board.

3. Power System Components (1)



3. Power System Components (3)



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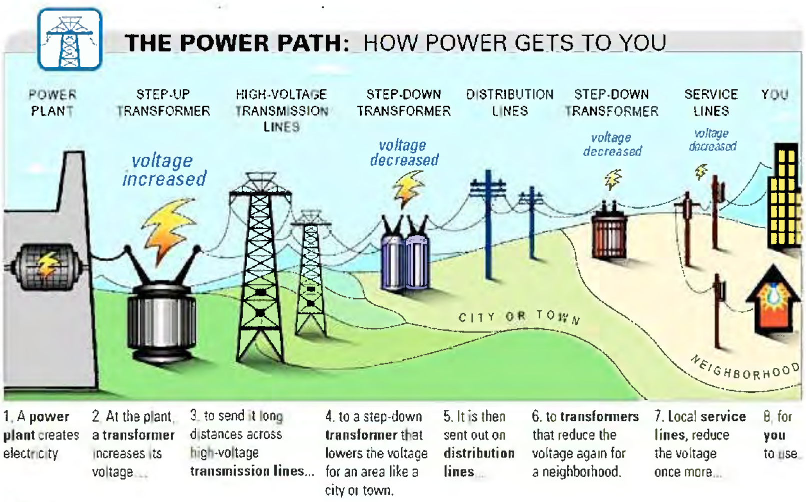
3. Power System Components (4)

- How power gets to you?



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3. Power System Components (5)

- At power generating station (generating voltage) → 11 – 20kV and frequency of 50 Hz
- Transform to higher voltage (transmission voltage) → 150kV
- Transform to lower voltage (distribution voltage; middle voltage) → 20kV
- Transform to lower voltage (distribution voltage; low voltage) → 380V

4. Power Generation (1)

- Power generation takes place in power plants which may be geographically dispersed.
- Power plant may house more than one generating unit.
- Sources of Energy:
  - Hydrocarbons (Oil, coal, natural gas, etc.)
  - Water
  - Nuclear
  - Chemical
  - Solar
  - Wind
  - Tidal

4. Power Generation (2-1)

➢ POWER PROFILE(1) : WHAT ARE THE ADVANTAGES AND DISADVANTAGES OF EACH POWER SOURCE?

Energy	Availability	Cost To Produce Electricity	By Products
COAL	Plentiful now, but nonrenewable. It is estimated that we have several hundred more years worth of coal supply.	Low at existing plants, but new plants are difficult to build. Fuel costs are low.	Air emissions such as sulfur dioxide, nitrogen oxide, carbon dioxide and particulate, or ash.
OIL	Plentiful now, but nonrenewable. Experts disagree on how long our supply will last.	Expensive and difficult to get out of the ground or buy from other countries.	Air emissions such as sulfur dioxide, nitrogen dioxide, carbon dioxide, carbon monoxide and particulate, or ash.
NATURAL GAS	Plentiful now, and we may discover more, but it is nonrenewable.	New plants are moderately expensive to build, but fuel costs can be high. Fuel prices vary, but have consistently gone up.	Cleaner than other fossil fuels, but still produces air emissions, such as nitrogen oxide, carbon monoxide and carbon dioxide.
NUCLEAR FISSION	The uranium used as fuel is plentiful and significantly cheaper than coal, but nonrenewable.	Very low at existing plants, but new plants are expensive and complex to build.	No air emissions, but spent fuel rods must be stored carefully for many years, because their radiation can be dangerous.

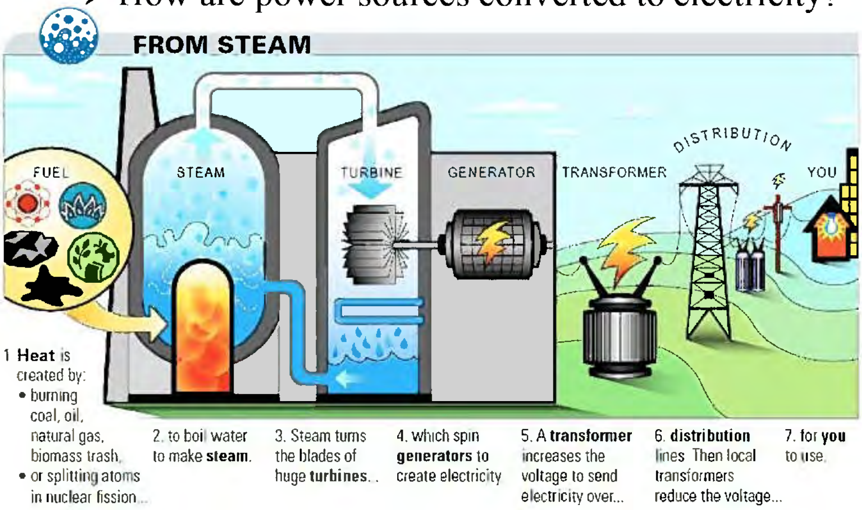
4. Power Generation (2-2)

➢ POWER PROFILE(2)

Energy	Availability	Cost To Produce Electricity	By Products
HYDRO POWER	Renewable, but limited by the number of suitable river locations, and the water flow at those locations.	Very low at existing plants, but new plants are moderately expensive to build.	No air emissions, but a dam changes the river environment for fish and other animals, and changes the natural look and flow of rivers.
WIND POWER	Renewable, but only works when the wind blows. Wind farms must be built in windy locations.	Wind is free. Wind turbines are moderately expensive to build and maintain, and new transmission lines may need to be built.	No air emissions, but wind turbines make noise and some people don't like how they look. They also may injure birds, but can designed to minimize this.
SOLAR ENERGY	Renewable, but only works when the sun is shining, and is also affected by the brightness of the sunlight.	Sunlight is free, but solar cells are expensive, and produce only small amounts of electricity.	No air emissions, but many solar cells in an array may require large areas of space.
BIOMASS	Plentiful and renewable, but requires lots of trash for fuel.	Trash is expensive to transport and sort, and new plants are expensive to build.	Small amount of air emissions, which vary by different biomass fuel sources.

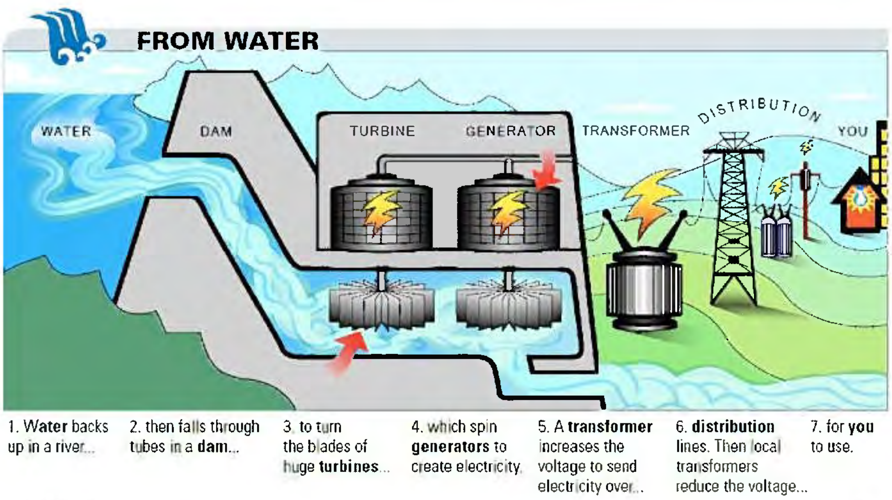
4. Power Generation (3-1)

➢ How are power sources converted to electricity?



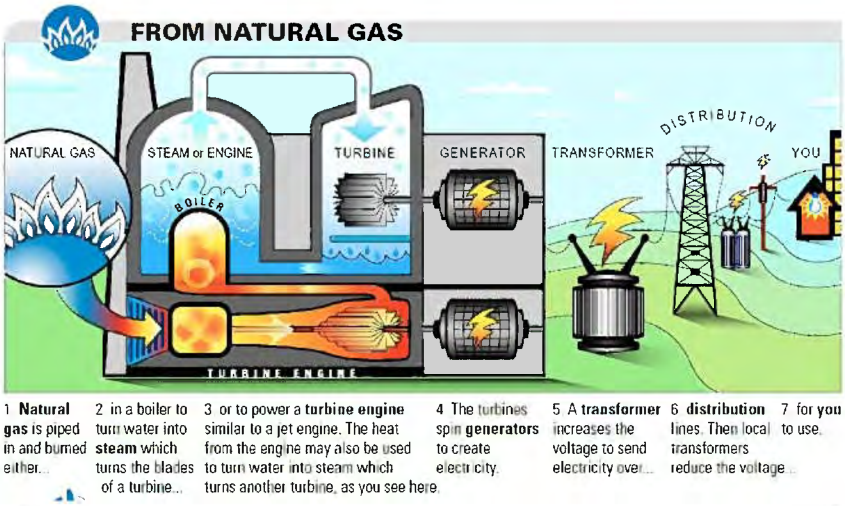
4. Power Generation (3-2)

➢ How are power sources converted to electricity?



4. Power Generation (3-3)

➢ How are power sources converted to electricity?



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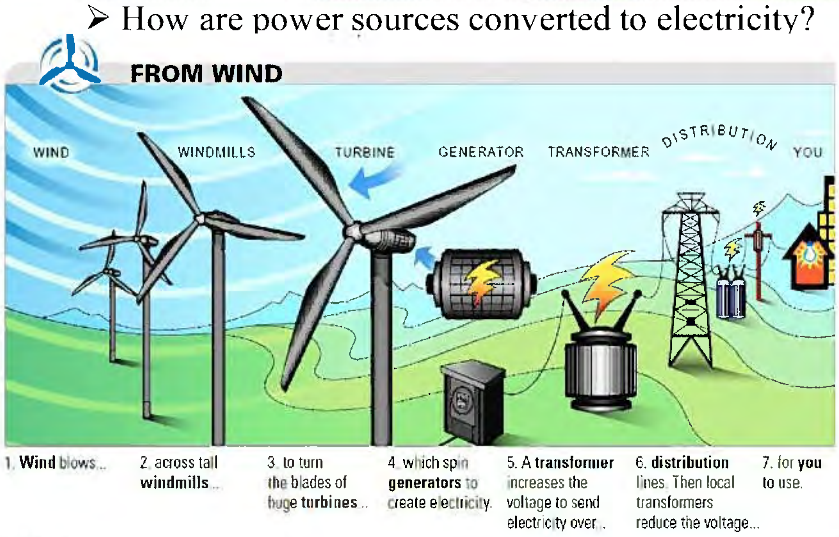
4. Power Generation (3-4)

➢ How are power sources converted to electricity?



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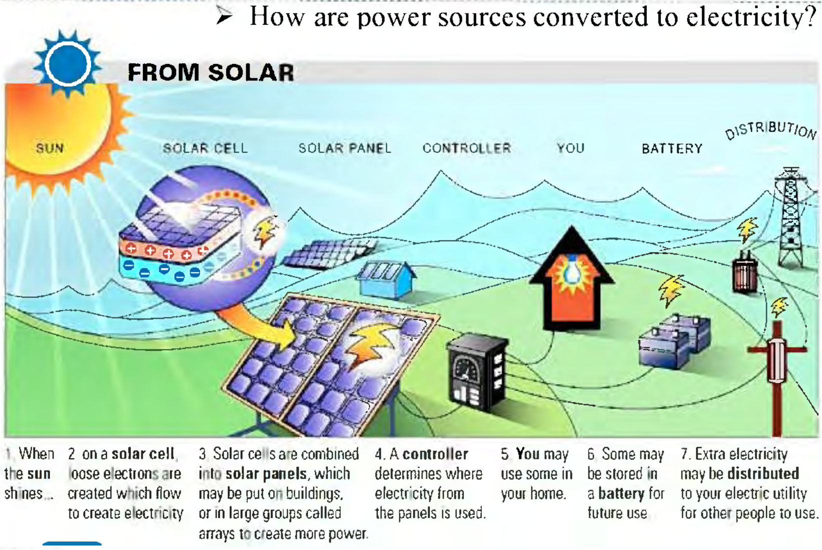
4. Power Generation (3-5)

➢ How are power sources converted to electricity?



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5. Transmission System(1)

- Lines/transformers operating at voltages above 100 kV are usually called the transmission system.
- Consists of Transmission Line and Sub-stations

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5. Transmission System(2)

- Power Transmission Equipment
  - Step-up and Step-down Power Transformers.
  - Voltage regulator
  - Phase shifter
  - Transmission lines and cables
  - Circuit breakers and isolators
  - Shunt and series reactors and capacitors
  - Lightning arresters
  - Protective relays
  - Fact devices (SVC, Statcom, TCSC, etc.)
  - Converter and Inverter

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6. Distribution System(1)

- Lines/transformers operating at voltages below 100 kV are usually called the distribution system.
- Part of the electric utility system between the bulk power source and the customer service entrances (loads).
- Receives electrical energy from HV/MV levels
- Supplies energy to the consumers At MV/LV levels and Single phase or three phase
- 20kV, 380V and 220V

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6. Distribution System(2)

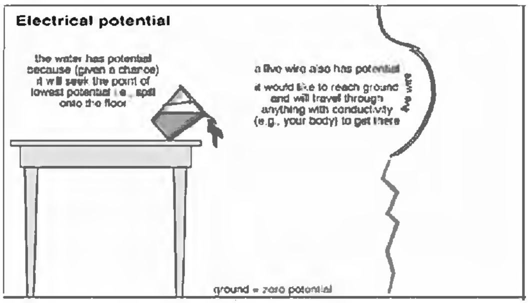
- Distribution System Equipment
  - Distribution transformers
  - Feeders (overhead or underground cables)
  - Switches, fuses, etc.
  - Protective relays
  - Lightning arrestors
  - CT/PT

Supplies to rural communities are reduced from 20kV to domestic voltages (380/220V) by pole mounted transformers.

II. QUICK REVIEW OF BASIC POWER ENGINEERING

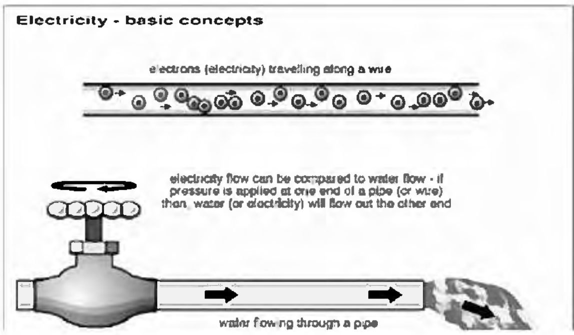
1. Voltage

- Measured in Volts (V)
- Electromotive force or potential between two points
- Reference = ground (0 Volts)
- Common analogy
  - Voltage is comparable to water pressure in a pipe. The pressure is available to cause the water to flow if a valve is opened.



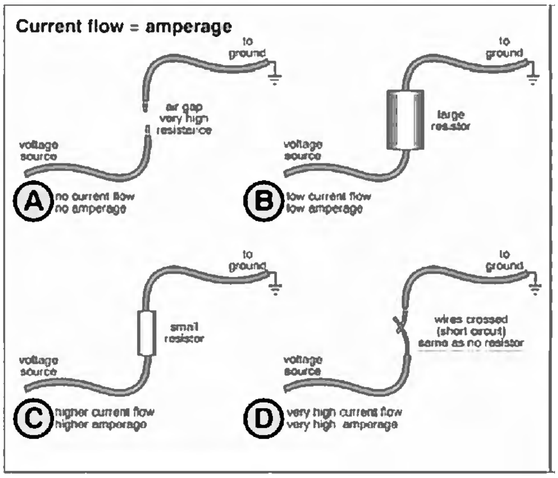
2. Current

- Measured in Amps (A)
- Referred to as "I" electrical equations
- Flow of electrons through a circuit
- Water Analogy
  - Amount of water flowing through a pipe comparable to current flowing in an electrical circuit



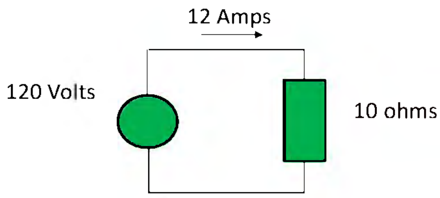
3. Resistance

- Measured in ohms (Ω)
- Referred to as "R" in electrical equations
- How easily electricity can flow through a circuit
- Dependent on physical properties of the circuit (i.e. size of wire)
- Water analogy
  - Smaller diameter pipes allow less water to flow than larger diameter pipes



4. Ohm's Law

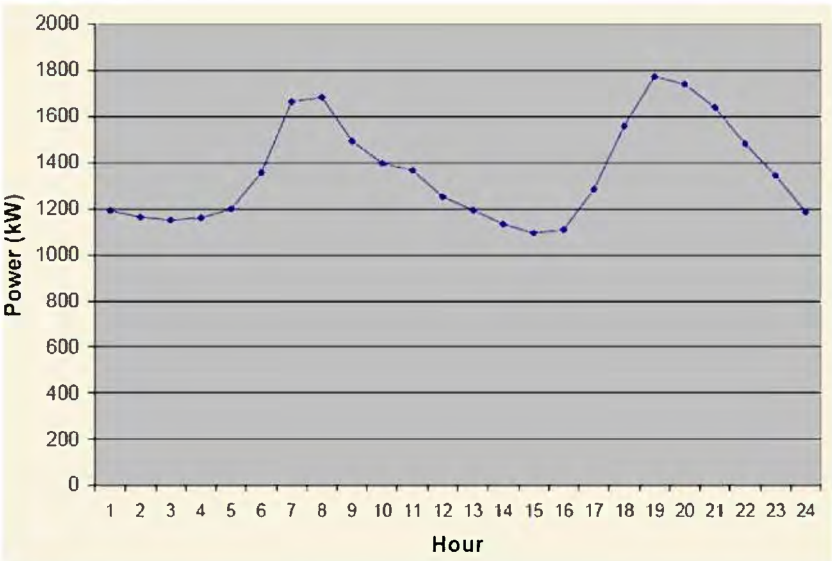
- Voltage = Current x Resistance (V = I x R)
- Current = Voltage / Resistance (I = V / R)
- Example:
  - Voltage = 120 V
  - Resistance = 10 ohms
  - Current flowing through the circuit = 120 / 10 = 12 Amps



5. Power

- Measured in Watts (W)
- 1,000 W = 1 kilowatt (kW)
- 1,000,000 W = 1 Megawatt (MW)
- Power = Volts x Amps = V x I
- Amount of electricity being consumed at some moment in time
- Commonly referred to as "demand"
- Commonly "integrated" or "averaged" over some time period – 15 minutes, 30 minutes, 60 minutes

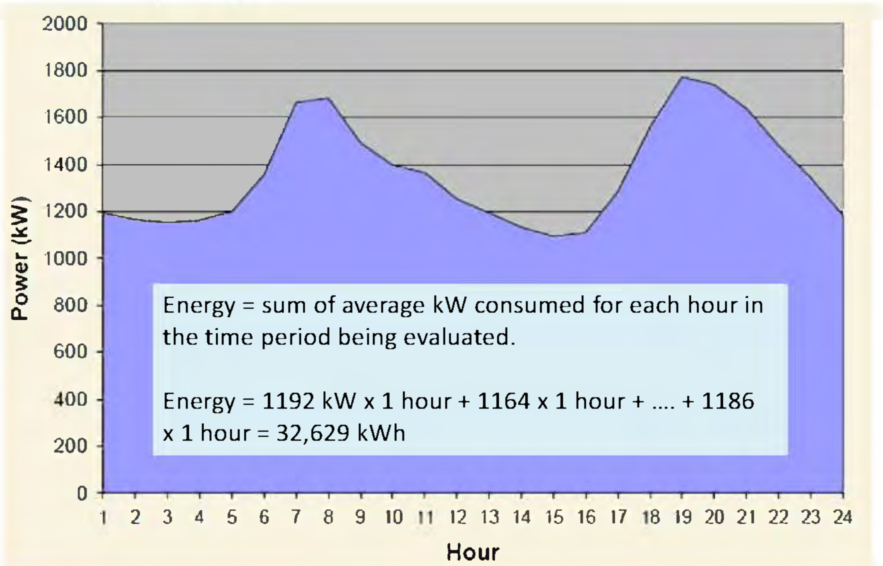
An example of Daily Power Curve



6. Energy

- Measured in Watt-hours (Wh)
- 1,000 Wh = 1 kilowatt-hour (1 kWh)
- 1,000,000 Wh = 1 Megawatt-hour (1 MWh)
- 1,000,000,000 Wh = 1 Gigawatt-hour (1 GWh)
- Power consumed over time
- Example: A 100 Watt bulb left on for 10 hours = 100W x 10h = 1,000 Wh = 1 kWh consumed
- Area under the power curve

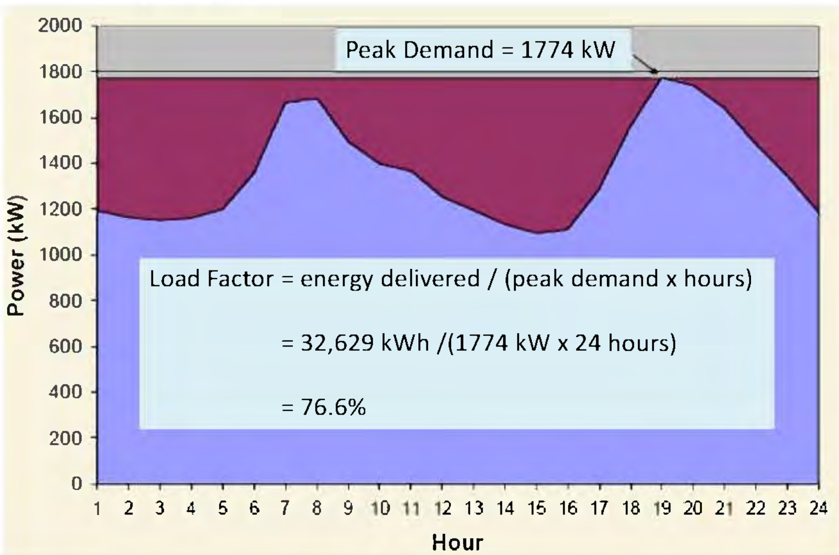
An example of Daily Power Curve



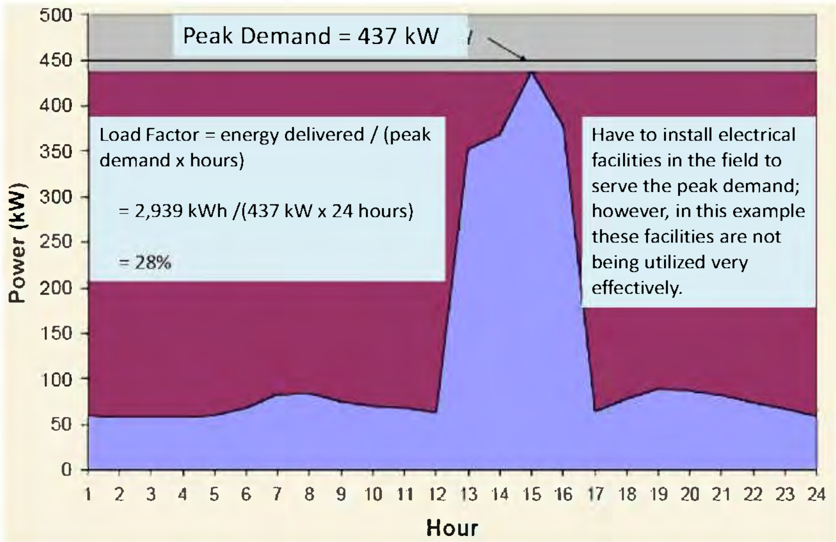
7. Load Factor(1)

- Measure of energy utilization (use of resources)
- Ratio of average demand to peak demand
  - LF = average demand / peak demand
- Also expressed as the ratio of energy delivered over a given time period to the amount of energy that could be delivered
  - LF = energy delivered / (peak demand x hours)

An example of Daily Power Curve



Poor Load Factor Example



7. Load Factor(2)

- Typical Load Factors
  - System = 50% - 70%
  - Residential = 50% - 70%
  - Small Commercial = 30% - 40%
  - Large Commercial = dependent on type of operations
  - For consumers with low load factors a retail rate factors, with a demand charge may be justified.
    - Demand charge recovers the cost of the facilities installed in the field to meet the peak demand

8. Impedance

- For Alternating Current (AC) systems, the resistance (R) is actually comprised of a resistive component and a reactive component and referred to as the impedance (Z)
- $Z = R + jX$
  - R = resistive component
  - X = reactive component
- Reactive component can be an inductance or a capacitance

9. Reactance

- Typical loads served include resistive and inductive loads
  - Incandescent light = resistive load
  - Electric resistance heat = resistive load
  - Motors = inductive load
  - Compact Florescent Lights = partially an inductive load
- The reactive component of an impedance is undesirable because it causes current to flow through the system that does not do any useful work.
  - Non-useful work measured in VARs
  - 1,000 VARs = 1 kVAR

10. Power Factor

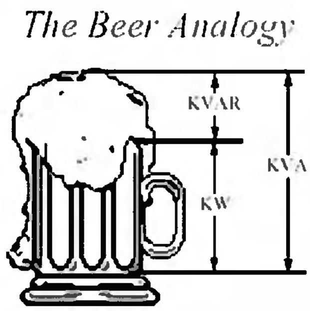
- Power factor helps to describe how much of the current flowing through a circuit is performing useful work.
- A power factor of 1.0 means that no current is flowing to serve reactive loads – amount of current required is minimized and the efficiency of the system is maximized
- A power factor < 1.0 means that there is some amount of undesirable reactive current flowing

11. Apparent Power and True Power(1)

- Recall that Power = Volts x Amps
  - This formula actually calculates the "apparent power" in AC systems
  - Gives results in Volt-Amps (VA)
  - 1,000 VA = 1 kVA
- True Power = Volts x Amps x Power Factor
  - Gives results in Watts (W)
  - 1,000 W = 1 kW
  - For a power factor of 1.0, true power = apparent power
- kW = kVA x pf ; kVA = kW /pf

11. Apparent Power and True Power(2)

- Beer Analogy



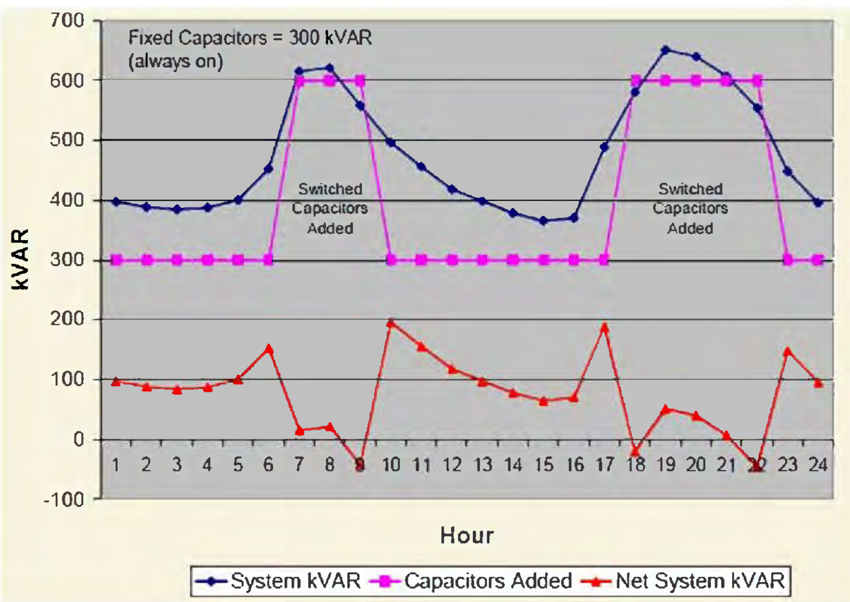
- True power (kW) that does useful work can be compared to the beer in the mug
- The non-useful power (kVAR) can be compared to the foam
- The apparent power (kVA) can be compared to the capacity of the beer mug which is required to hold both the beer and the foam

11. Apparent Power and True Power(3)

- Example:
  - A 10 kW load with a power factor of 1.0 = 10 kVA (kVA = kW / pf = 10 / 1.0 = 10 kVA)
  - For a power factor of 0.8, the apparent power = 12.5 kVA (10 / 0.8)
  - A 10 kVA transformer serving this load would be 100% loaded at a power factor of 1 0 and 125% loaded at a power factor of 0.8
  - Therefore, investment in additional system capacity is required to serve loads with power factors < 1.0

12. Correcting Power Factor

- Inductive kVARs can be cancelled by adding an equal amount of capacitive kVARs.
  - This is why capacitors are added to power systems
  - Because inductive loads on the system vary over time, some portion of the capacitors added to the system may be required to be switched in and out as the inductive load increases and decreases.
- Too many capacitors on the system are just as bad as not enough capacitors



13. System Losses(1)

System Losses = Energy purchased – Energy sold

As % of Energy purchased:

$$\frac{\textit{System losses}}{\textit{Energy purchased}}$$

CAUTION!!!

Difference in time and load when consumer meters are read compared to when substation meters are read can lead to errors in loss calculations.

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13. System Losses(2)

- Total losses from generation to member consumer can be 10% to 20% (distribution system losses are typically 5% to 10%)
- Two types of losses
  - Load losses – change with load
  - No-load losses – constant regardless of load

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13. System Losses(3)

➢Load Losses

- Current flowing through a resistance yields losses in the form of heat
- Losses (power) = V x I
- Recall from Ohm's law that V = I x R
- Therefore Losses = (I x R) x I = I^2 x R
- From this formula we can see that losses increase exponentially with current. Anything we can do to lower current will have a dramatic effect on lowering losses.
  - Reducing current by ½ will reduce losses to ¼

13. System Losses(4)

➢No-Load Losses

- Core losses of transformers
- Come from magnetizing transformer cores
- Essentially constant; however, core losses do vary with the voltage applied to the transformer

13. System Losses(5)

➢ System Losses: Contributors

- Substation Transformers
- Line Voltage Regulators
- Pri. & Sec. Conductor
- Capacitors
- Distribution Transformers

Which is the biggest contributor?

Area of System	Losses as a % of Total System Energy Requirements
Substation Transformers and Regulators	1.0
Distribution Lines and Regulators	3.5
Distribution Transformers	2.5
Secondary and Services	1.5
Metering Equipment	0.5
Total System	9.0

III. INTRODUCTION TO ELECTRIC POWER TRANSMISSION & DISTRIBUTION

1. Introductory Question

- Electric power reaches our city via high voltage transmission lines. What fraction of the electric charges traveling on those transmission lines pass through this room?

A. About 1%
B. About 0.01%
C. Exactly 0%

2. Observations

- Household electricity is alternating current (AC)
- Household voltages are typically 120V or 240V (Here, 220V)
- Power is distributed at much higher voltages
- Power transformers are common around us
- Power substations are there, but harder to find

3. 4 Questions

- Why isn't power transmitted at low voltages?
- Why isn't power delivered at high voltages?
- What is "alternating current" and why use it?
- How does a transformer transfer power?

4. Question 1

- Why isn't power transmitted at low voltages?

5. Electric Power and a Wire

- An electric current passing through a wire converts electrical power in thermal power

  power wasted = current · voltage drop in wire.
- Since the wire obeys Ohms law,

  voltage drop in wire = resistance · current,
- the power that wire wastes is

  power wasted = resistance · current^2.
- Doubling current quadruples wasted power!

6. Clicker Question

- Two long wires will carry electrical power most efficiently from a generator to a community if the voltage difference between the wires is

A. large and the current they carry is large.
B. large and the current they carry is small.
C. small and the current they carry is large.
D. small and the current they carry is small.

7. Large Currents are Wasteful

- The goal of a power distribution system is to transmit lots of electric power to a city,

  power transmitted = current · voltage drop at city,

- while wasting little electric power in the wires,

  power wasted = resistance · current^2.

- That energy efficiency can be achieved by using
  - a small current,
  - a huge voltage drop,
  - and low-resistance wires.

8. Question 2

- Why isn't power delivered at high voltages?

9. High Voltages are Dangerous

- When large voltage drops are available,
  - strong electric fields are present,
  - charges experience enormous forces,
  - and currents tend to flow through unexpected paths.
- High-voltage electrical power in a home is
  - a spark hazard,
  - a fire hazard,
  - and a shock hazard.

10. The Voltage Hierarchy

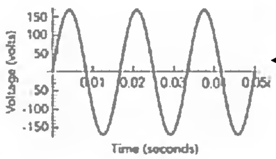
- Large currents are too wasteful for transmission
- High voltages are too dangerous for delivery
- So electric power distribution uses a hierarchy:
  - high-voltage circuits in the countryside
  - medium-voltage circuits in cities
  - low-voltage circuits in neighborhoods and homes
- Transformers transfer power between circuits!

11. Question 3

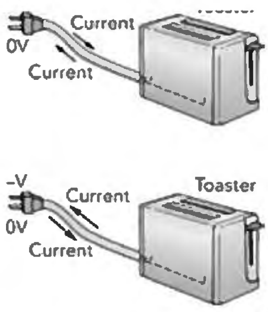
- What is "alternating current" and why use it?

12. Alternating Current (AC)

- In alternating current,
  - the voltages of the power delivery wires alternate
  - and the resulting currents normally alternate, too.
- Alternating voltage here
  - completes 50 cycles per second,
  - reversing every 1/100 second.



← This figure shows 60 cycles per second



13. AC and Transformers

- AC has little effect on simple electric devices (e.g., lightbulbs, space heaters, toasters)
- AC is a nuisance for electronic devices (e.g., computers, televisions, sound systems)
- AC permits the easy use of transformers,
  - which can move power between circuits:
  - from a low-voltage circuit to a high-voltage circuit
  - from a high-voltage circuit to a low-voltage circuit

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14. Question 4

- How does a transformer transfer power?

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15. Electromagnetism

- Magnetic fields are produced by
  - magnetic poles (but free poles don't seem to exist),
  - moving electric charges,
  - and changing electric fields [more later…].
- Electric fields are produced by
  - electric charges,
  - moving magnetic poles,
  - and changing magnetic fields.

16. Electromagnetic Induction

- Moving poles or changing magnetic fields
  - produce electric fields,
  - which propel currents through conductors,
  - which produce magnetic fields.
- Changing magnetic effects induce currents
- Induced currents produce magnetic fields

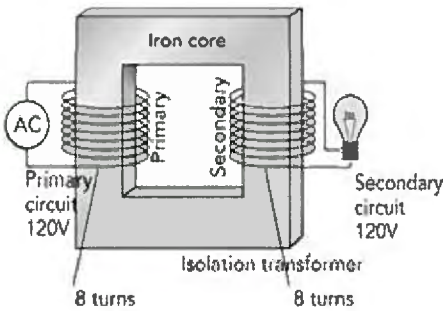
17. Lenz's Law

- Lenz's law predicts the nature of the induced magnetic fields:

"When a changing magnetic field induces a current in a conductor, the magnetic field from that current opposes the change that induced it."

18. Transformer

- Alternating current in one circuit can induce an alternating current in a second circuit
- A transformer
  - uses induction
  - to transfer power between its circuits
- but doesn't transfer any charges between its circuits



19. Current and Voltage

- A transformer must obey energy conservation
- Power arriving in its primary circuit must equal power leaving in its secondary circuit
- Since power is the product of voltage · current,
  - a transformer can exchanging voltage for current
  - or current for voltage!

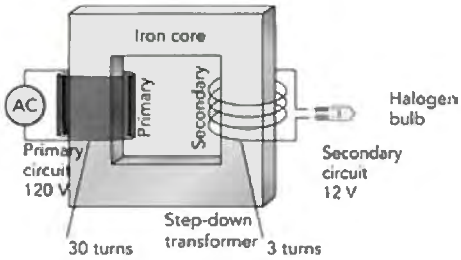
20. Clicker Question

- If you increase the number of turns of wire in the secondary coil of a transformer, each charge traveling through that wire will experience

A. the same forward force for a longer distance.
B. a larger forward force for a longer distance.
C. a larger forward force for the same distance.
D. the same forward force for the same distance.

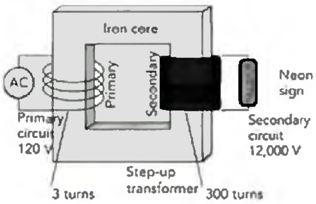
21. Step-Down Transformer

- A step-down transformer
  - has relatively few turns in its secondary coil
  - so charge is pushed a shorter distance
  - and experiences a smaller voltage rise
- A larger current at smaller voltage flows in the secondary circuit



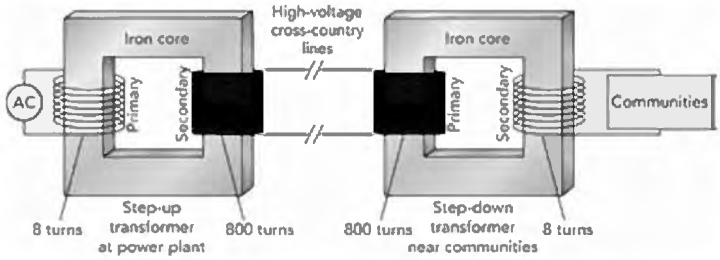
22. Step-Up Transformer

- A step-up transformer
  - has relatively many turns in its secondary coil
  - so charge is pushed a longer distance
  - and experiences a larger voltage rise
- A smaller current
  - at larger voltage
  - flows in the
  - secondary circuit



23. Transmission & Distribution

- A step-up transformer increases the voltage for efficient long-distance transmission
- A step-down transformer decreases the voltage for safe delivery to communities and homes



24. Introductory Question (revisited)

- Electric power reaches our city via high voltage transmission lines. What fraction of the electric charges traveling on those transmission lines pass through this room?

A. About 1%
B. About 0.01%
C. Exactly 0%

25. Summary

- Electric power is transmitted at high voltages
- Electric power is delivered at low voltages
- Transformers transfer power between circuits
- Transformers require AC power to operate
- The power distribution system is AC

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Thank You very much!

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Japanese Technical Assistance
on Strengthening Institutional Capacity
of National Development Agency (ADN)
in Democratic of Timor-Leste

-- POWER --

Syllabus

No.	Contents
1	Introduction
2	Power Station (Diesel)
3	Substation
4	Transmission Line (Transmission System)
5	Distribution Line (Distribution System)
6	Renewable Energy (Photovoltaic Power)
7	Protecting System
8	Power System Operation and Control
9	Others

The contents may be changed depending on conditions.
I would like to discuss about the contents with Mr. Miguel and YOU.

IV. POWER STATION

1. Introduction

- Electricity generation is the process of generating electricity from other forms of energy.
- This is achieved with the help of suitable power producing units, known as Electric Power Generating Stations, Power Stations or Power Plants.

2. Electrical energy generation arrangement

For electrical energy to be generated we need an efficient arrangement of the following parts:

- Prime mover:
  - The part of the electrical generating system responsible in converting other forms of energy into rotating mechanical one.

    Example: Steam turbine converts heat energy into mechanical energy.
- Alternator:
  - The part of the electrical generating system responsible for converting mechanical energy into electrical energy.

These working together in a closed system are called:

Prime Mover - Alternator Combination

3. Power Generation Fundamental Problem

- Electrical energy is the most used form of energy everywhere.
- Electrical energy is a result of conversion from other forms of energy that are abundant in nature.
- Unfortunately, bulk storage of electrical energy for a long duration is not possible yet.
- This is the fundamental problem in electrical energy generation.
- **Electrical energy must be generated and transmitted to the point of consumption at the instant of demand.**
- This instant is usually less than a second.

4. Sources of energy

- The three most prominent sources of energy are:
  - Fuel power (Fossil fuel power)
  - Hydro power
  - Nuclear power

Particulars	Fuel power	Hydro power	Nuclear power
Initial cost	Lowest	High	Highest
Running cost	Highest	Low	Least
Reserves	limited	permanent	Abundant
Cleanliness	Lowest	Highest	Low
Simplicity	complex	simplest	Most complex
Reliability	Low	Highest	High

5. Hydroelectric Power Station

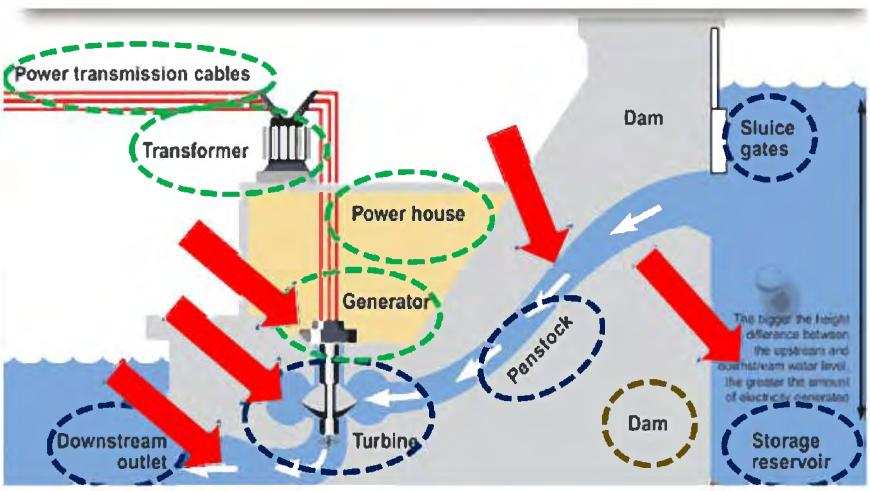
- A hydroelectric power station uses potential energy of water at high level for generating electrical energy.
- It is generally located in hilly areas where dams can be built and large water reservoirs can be obtained.
- This power station can be started and stopped easily and fast to produce large amounts of electrical energy.

6. Hydro Power Station Arrangement

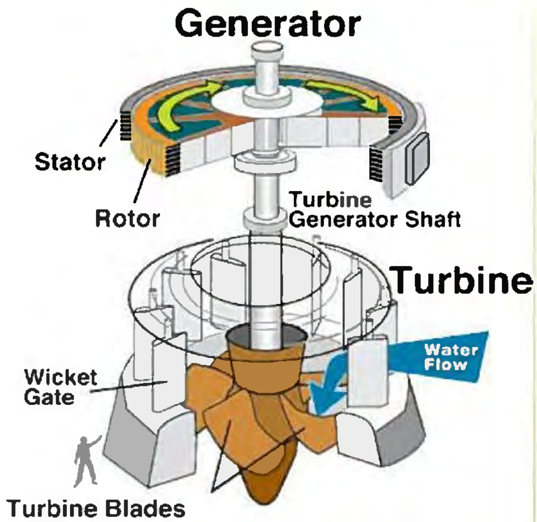
The most important constituents of this power station are:

- Reservoir: It is where water is stored for use as and when needed.
- Penstock: This is a conduit that carry water to the turbines. They are made of reinforced concrete or steel.
- Water turbine: It is used to convert hydraulic energy into mechanical one. Pelton, Francis and Kaplan turbines are the most used types.
- Generator: It is used to convert rotational mechanical energy from the turbine through the shaft, into electrical energy.
- Draft Tube: It is the outlet of water to downstream.

7. Schematic arrangement of a Hydro Power Station



8. A Typical Turbine And Generator



9. Advantages of Hydro Power Station

- It requires no fuel as water is used for the generation of electrical energy.
- It is quite neat and clean as no smoke or ash is produced.
- It requires very small running charges because water is the source of energy which is available free of cost.
- It is comparatively simple in construction and requires less maintenance.
- It does not require a long starting time like a steam power station. In fact, such plants can be put into service instantly.
- It is robust and has a longer life.
- Such plants serve many purposes. In addition to the generation of electrical energy, they also help in irrigation and controlling floods.
- Although such plants require the attention of highly skilled persons at the time of construction, yet for operation, a few experienced persons may do the job well.

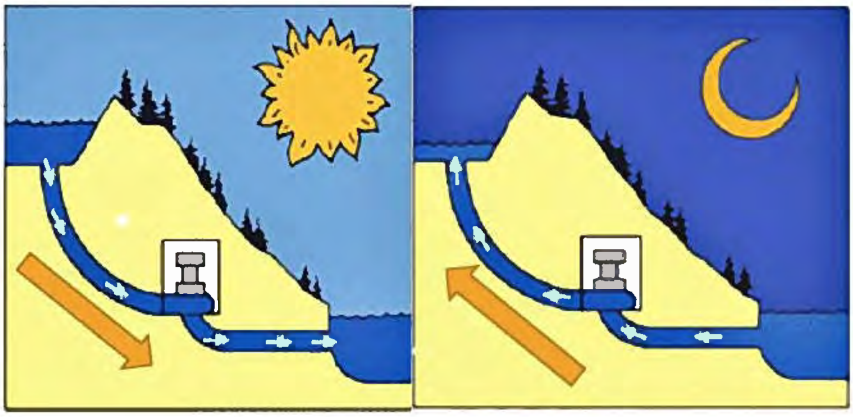
10. Disadvantages of Hydro Power Station

- It involves high capital cost due to construction of dam.
- There is uncertainty about the availability of huge amount of water due to dependence on weather conditions.
- Skilled and experienced hands are required to build the plant.
- It requires high cost of transmission lines as the plant is located in hilly areas which are quite away from the consumers.

11. Pumped Storage Scheme

- Pumped storage schemes are a convenient way of storing large quantities of energy which can be used during emergency or peaking times.
- Operation:
  - During off-Peak hours, the plant draws electric energy from the electrical grid & uses that to pump water to the upper reservoir.
  - When Peak time comes, the water from the upper reservoir is released & electric energy is generated in the lower reservoir. This cycle is repeated daily.
  - By their nature, pumped storage schemes cannot be used as base load power stations.
  - These are strictly used for peak time supply as they can be brought on-line quickly.

12. Pumped Storage Principle Diagram



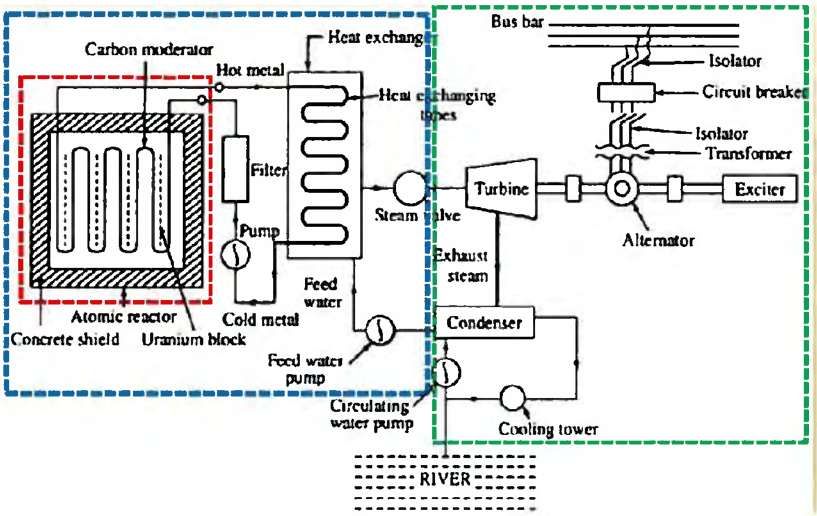
Peak Time: Water flows downhill through turbines, producing electricity

Off-Peak Time: Water pumped uphill to reservoir for tomorrow's use

13. Nuclear Power Station

- A Nuclear power station uses nuclear energy for generating electrical energy.
- It can be used to produce large amounts of electrical energy.
- It is generally located far from populated areas.
- It can be used as base load power stations.
- This is because it can take several days to be warmed up and brought on-line.

14. Schematic Diagram for Nuclear Power Plant



15. Advantages of Nuclear Power Station

- The amount of fuel required is quite small. Therefore, there is a considerable saving in the cost of fuel transportation.
- A nuclear power plant requires less space as compared to any other type of the same size.
- It has low running charges as a small amount of fuel is used for producing bulk electrical energy.
- This type of plant is very economical for producing bulk electric power.
- It can be located near the load centres because it does not require large quantities of water and need not be near coal mines. Therefore, the cost of primary distribution is reduced.
- There are large deposits of nuclear fuels available all over the world. Therefore, such plants can ensure continued supply of electrical energy for thousands of years.
- It ensures reliability of operation

16. Disadvantages of Nuclear Power Station

- The fuel used is expensive and is difficult to recover.
- The capital cost on a nuclear plant is very high as compared to other types of plants.
- The erection and commissioning of the plant requires greater technical know-how.
- The fission by-products are generally radioactive and may cause a dangerous amount of radioactive pollution.
- Maintenance charges are high due to lack of standardisation. Moreover, high salaries of specially trained personnel employed to handle the plant further raise the cost.
- Nuclear power plants are not well suited for varying loads as the reactor does not respond to the load fluctuations efficiently.
- The disposal of the by-products, which are radioactive, is a big problem. They have either to be disposed off in a deep trench or in a sea away from sea-shore.

17. Fossil Fuel Energy Power Stations

- Those power stations which convert chemical energy of fossil fuel (coal, oil etc.) into electrical energy are called thermal power stations.
- According to the prime-mover employed for driving the alternate, thermal power stations may be broadly divided into the following three important types :
  - Steam Power Stations
  - Gas Turbine Power Stations
  - Diesel Power Stations

18. Steam Power Station(1)

- A steam/thermal power station uses heat energy generated from burning Fossil Fuel (coal, oil…) to produce electrical energy.
- This type is widely used around the world.
- This is the cycle of the steam produced in the boiler, then taken to the Steam Turbine (prime mover).
- From the turbine the steam is cooled back to water in the condenser, the resulting water is fed back into the boiler to repeat the cycle.
- Because of the abundance of fuel (coal), this kind of power station can be used to produce large amounts of electrical energy.

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18. Steam Power Station(2)

- The steam power stations are slow to start and can not be used to cater for peak loads that generally occur for a short duration.
- These power stations are kept running very close to full efficiency for 24 hours a day.
- In most countries these power stations are used as base load power stations.
- They have typical life of 30 to 40 years.
- The efficiency can reach about 29% for steam power stations.

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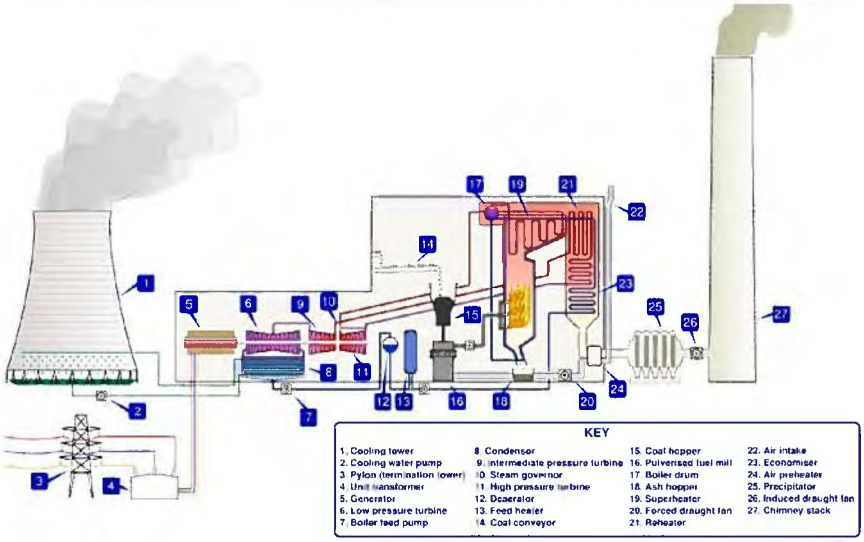
19. Steam Power Station Schematic Diagram



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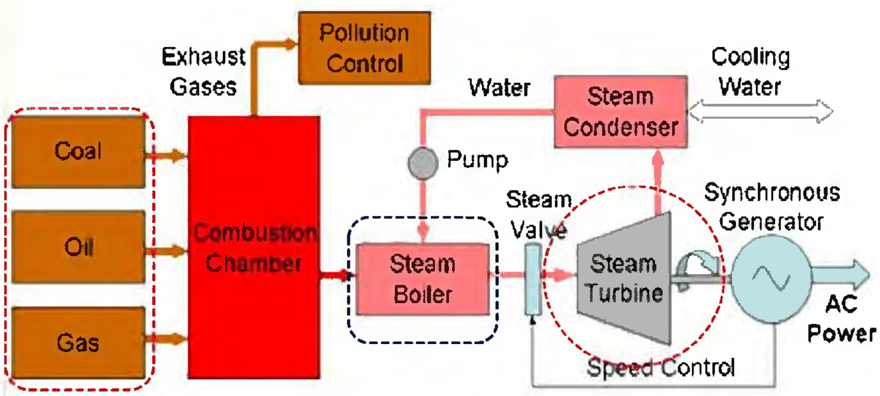
20. Steam Power Station Simplified Schematic Diagram



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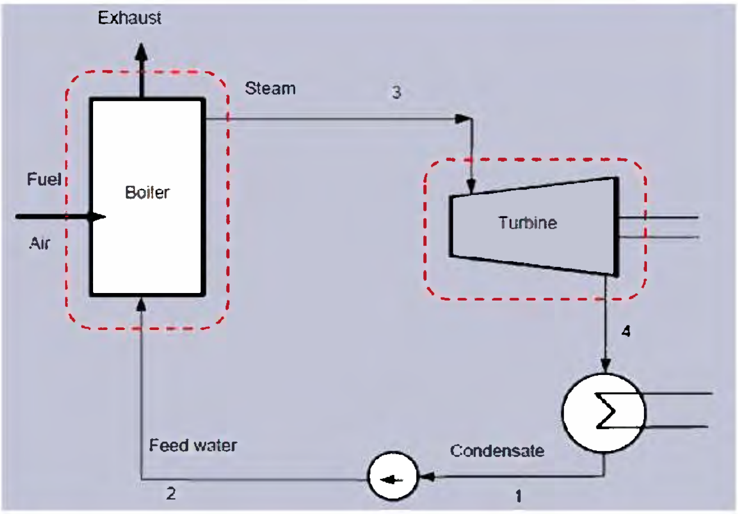
21. A Simpler Model of Steam Power Station



22. Advantages of Steam Power Station

- The fuel (i.e., coal in most cases) used is quite cheap.
- Less initial cost as compared to other generating stations.
- It can be installed at any place irrespective of the existence of coal. The coal can be transported to the site of the plant by rail or road.
- It requires less space as compared to the hydroelectric power station.
- The cost of generation is lesser than that of the diesel power station.

23. Disadvantages of Steam Power Station

- It pollutes the atmosphere due to the production of large amount of smoke and fumes.
- It is costlier in running cost as compared to hydroelectric plant.

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24. Gas Turbine Power Station

- A Gas-turbine power station uses gas turbines as prime mover for generating electrical energy.
- Gas turbines use the hot gas produced by burning a fuel to drive a turbine. They are also called combustion turbines or combustion gas turbines.
- It has the ability to be turned on and off within minutes, supplying power during peak demand.
- A large single cycle gas turbine typically produces up to 300 Mega Watts of power and have 35–40% thermal efficiency.

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25. Principle Of Operation

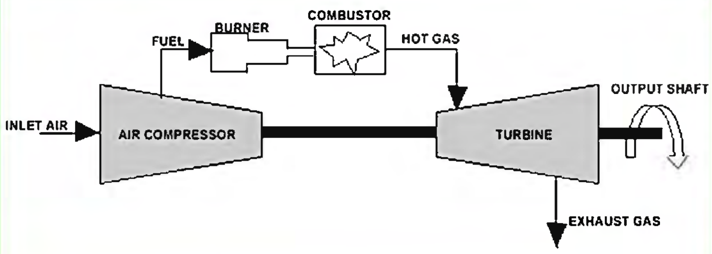

DIAGRAM OF TYPICAL LARGE GAS TURBINE

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26. Advantages of Gas Turbine Power Station

- It is simple in design as compared to steam power station since no boilers and their auxiliaries are required.
- It is much smaller in size as compared to steam power station of the same capacity. This is expected since gas turbine power plant does not require boiler, feed water arrangement etc.
- The initial and operating costs are much lower than that of equivalent steam power station.
- It requires comparatively less water as no condenser is used.
- The maintenance charges are quite small.
- Gas turbines are much simpler in construction and operation than steam turbines.
- It can be started quickly form cold conditions.
- There are no standby losses.

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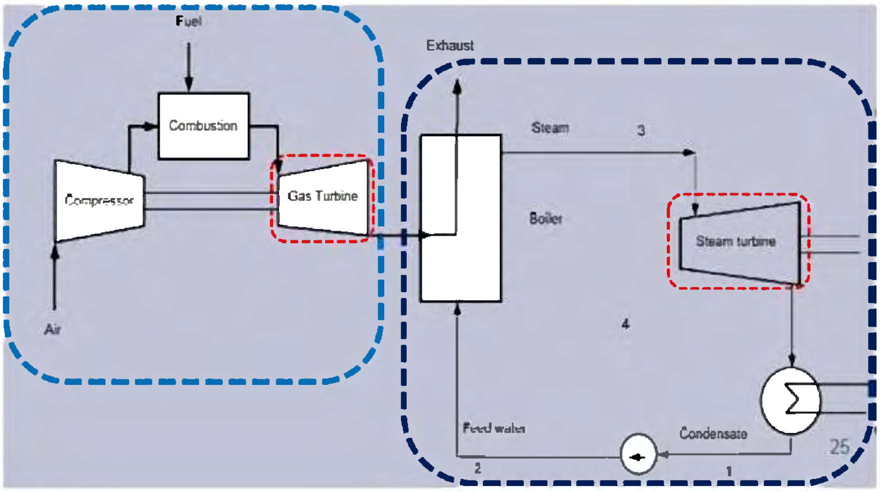
27. Disadvantages of Gas Turbine Power Station

- There is a problem for starting the unit. It is because before starting the turbine, the compressor has to be operated for which power is required from some external source. However, once the unit starts, the external power is not needed as the turbine itself supplies the necessary power to the compressor.
- Since a greater part of power developed by the turbine is used in driving the compressor, the net output is low.
- The overall efficiency of such plants is low (about 20%) because the exhaust gases from the turbine contain sufficient heat.
- The temperature of combustion chamber is quite high (3000°F) so that its life is comparatively reduced.

28. Combined Cycle Gas Turbine Plants

- Gas turbine power station is generally used in conjunction with Steam Power Station.
- The hot exit gas from the turbine still has significant amounts of energy (the gas exits at nearly atmospheric pressure but a temperature of up to 500-640°C) which is used to raise steam to drive a steam-turbine and another generator.
- This combination of gas and steam cycle gives rise to the term "Combined Cycle Gas Turbine" (CCGT) plant.
- Combined cycle gas turbine plants are driven by both steam and natural gas. They generate power by burning natural gas in a gas turbine and use residual heat to generate additional electricity from steam.
- These plants offer efficiencies of up to 60%.
- About 66 % of power is generated in gas turbine and 34 % in steam turbine.
- Efficiency of CCGT plant is typically 1.5 times the efficiency of the single cycle gas turbine plant.

29. Gas Turbine Combined Cycle



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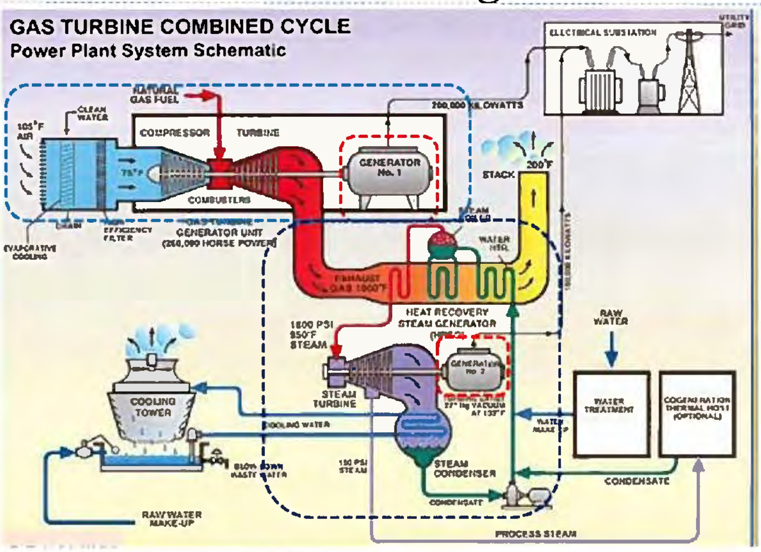
30. Combined Cycle Gas Turbine Plant Schematic Diagram



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31. Diesel Power Station

- A diesel power station uses a diesel engine as prime mover for the generation of electrical energy.
- This power station is generally compact and thus can be located where it is actually required.
- This kind of power station can be used to produce limited amounts of electrical energy.
- In most countries these power stations are used as Emergency Supply Stations.

32. Advantages of Diesel Power Station

- The design and layout of the plant are quite simple.
- It occupies less space as the number and size of the auxiliaries is small.
- It can be located at any place.
- It can be started quickly and can pick up load in a short time.
- There are no standby losses.
- It requires less quantity of water for cooling.
- The overall cost is much less than that of steam power station of the same capacity.
- The thermal efficiency of the plant is higher than that of a steam power station.
- It requires less operating staff.

33. Disadvantages of Diesel Power Station

- The plant has high running charges as the fuel (i.e., diesel) used is costly.
- The plant does not work satisfactorily under overload conditions for a longer period.
- The plant can only generate small power.
- The cost of lubrication is generally high.
- The maintenance charges are generally high.

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34. Working Principle of Diesel Power Stations & General Description

- An internal combustion engine in which the fuel is ignited by injected it into air that has been heated into a high temperature by rapid compression; hence, diesel engines are also called compression-ignition engines.

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35. What is a Compression-Ignition Engines?

- A compression-ignition engine (also known as a Diesel engine) is an internal combustion engine that uses the heat of compression to initiate ignition to burn the fuel, which is injected into the combustion chamber during the final stage of compression. This is in contrast to spark-ignition engines such as a petrol engine (gasoline engine) or gas engine (using a gaseous fuel as opposed to gasoline), which uses a spark plug to ignite an air-fuel mixture. The diesel engine is modeled on the Diesel cycle. The engine and thermodynamic cycle were both developed by Rudolph Diesel in 1897.

36. Dr. Rudolf Diesel

Generator output: 50,000 kW

37. Classification of IC Engines(1)

Internal Combustion (IC) engines are classified in different ways:

- According to cycle of operation
  - Two stroke cycle engines
  - Four stroke cycle engines
- According to cycle of combustion
  - Otto cycle (constant volume combustion)
  - Diesel cycle (constant pressure combustion)
  - Semi-Diesel cycle (Combustion partly constant volume and partly constant pressure)

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37. Classification of IC Engines(2)

- According to cylinder arrangement
  - Horizontal engine
  - Vertical engine
  - 'V' type engine
  - Radial engine
- According to the use
  - Stationary engine
  - Portable engine
  - Marine engine
  - Automobile engine
  - Aero engine

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37. Classification of IC Engines(3)

- According to the fuel used and the method of fuel supply to engine cylinder
  - Oil engine
  - Petrol engine
  - Gas engine
  - Kerosene engine
  - Carburettor, hot bulb, fuel injection, air injection etc.
- According to the speed of the engine
  - Low speed engine
  - Medium speed engine
  - High speed engine

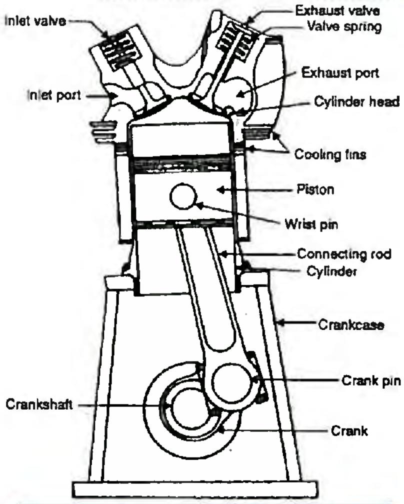
37. Classification of IC Engines(4)

- According to the method of ignition
  - Spark ignition engine
  - Compression ignition engine
- According to the method of cooling the engine
  - Air cooled engine
  - Water cooled engine
- According to the method of governing
  - Hit-and-miss governed engine
  - Quality governed engine
  - Quantity governed engine

37. Classification of IC Engines(5)

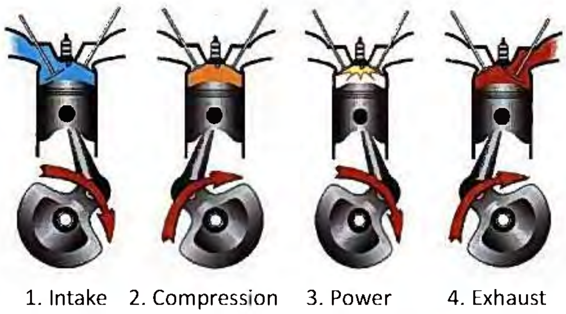
- According to valve arrangement
  - Overhead valve engine
  - L-head type engine
  - T-head type engine
  - F-head type engine
- According to number of cylinders
  - Single cylinder engine
  - Multi-cylinder engine

38. Parts of a typical IC Engine

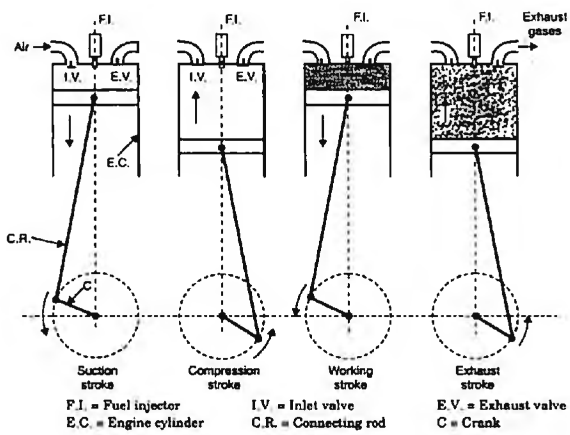


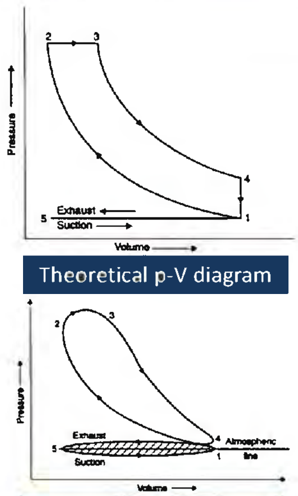
Air cooled single cylinder engine

39. Working of 4-stroke IC Engines



40. 4-stroke cycle Diesel Engines

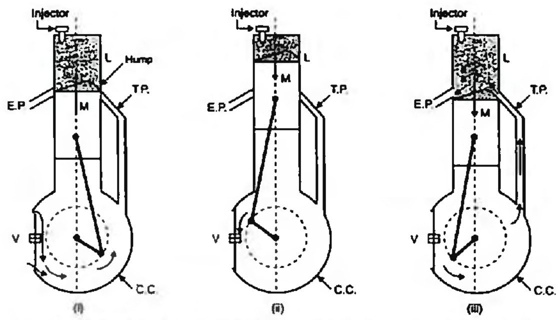




Theoretical p-V diagram

Actual p-V diagram

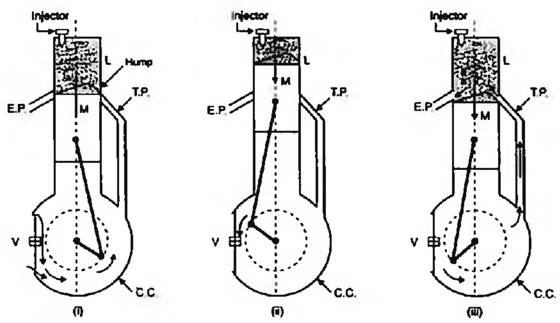
41. 2-stroke cycle Diesel Engines(1)



L = Cylinder ; M = Piston ; E.P. = Exhaust port ; T.P. = Transfer port ; C.C = Crank chamber ; V = Valve

- During upward movement of piston, air is compressed in the cylinder (L). At the same time, fresh air enters the crank chamber through valve (V).
- At the end of the stroke, fuel is injected into compressed air and combustion takes place starting the power stroke.

41. 2-stroke cycle Diesel Engines(2)



L = Cylinder ; M = Piston ; E.P. = Exhaust port ; T.P. = Transfer port ; C.C = Crank chamber ; V = Valve

- During the power stroke, valve (V) is closed and air in crank chamber is compressed and transferred to cylinder via transfer port (TP)
- At the same time, exhaust port (EP) opens to drive away burnt gases

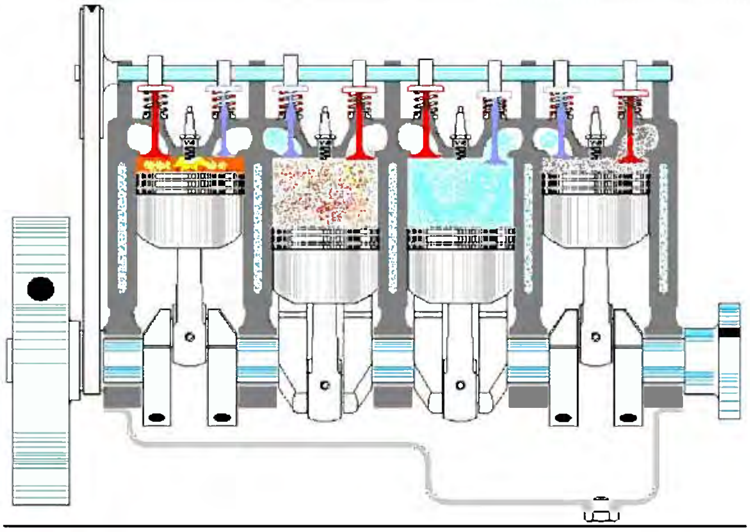
42. Characteristics of 4-stroke Diesel Engines

- Cycle is completed in 4 strokes of piston, or one power stroke in two revolutions of crankshaft.
- Turning movement is not uniform and hence requires heavy flywheel.
- Because of one power stroke in two revolutions, engine is heavy for a given power.
- Less wear and tear and hence lesser cooling and lubrication needs.
- Contains valve and valve drive mechanism.
- Higher volumetric efficiency due to higher air induction time.
- Better thermal and part load efficiency compared to two stroke engines.
- Used in applications where efficiency is important, e.g., cars, buses, trucks, tractors, airplanes, power generators etc.
- Higher initial cost.

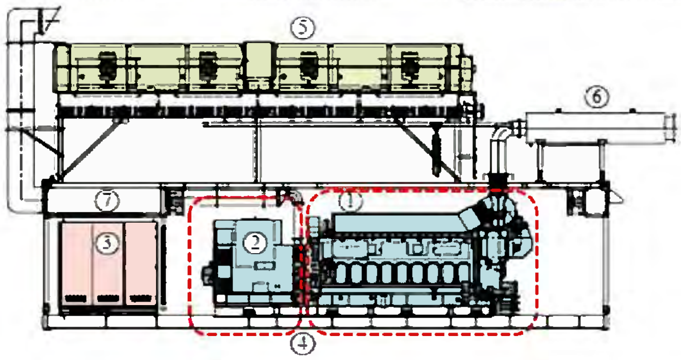
43. Characteristics of 2-stroke Diesel Engines

- Cycle is completed in two strokes of piston, or one power stroke for every rotation of crankshaft.
- More uniform turning movement and hence requires smaller flywheel.
- Theoretically the power developed is 2 times (~ 1.8 in practice) that of a 4-stroke engine. Hence lighter in weight for a given power level.
- Higher wear and tear and hence higher cooling and lubrication needs.
- Absence of valves and valve drive mechanism makes the engine simple and less expensive.
- Volumetric efficiency less due to lesser time available for air induction.
- Lower thermal and part load efficiency compared to 4-stroke engines.
- Used where low cost, low weight and compactness are desired.
- 2-stroke engines are used in very large sizes (~600 mm bore) for ship propulsion because of low weight and compactness.

44. Working of multi-cylinder 4-stroke IC Engines

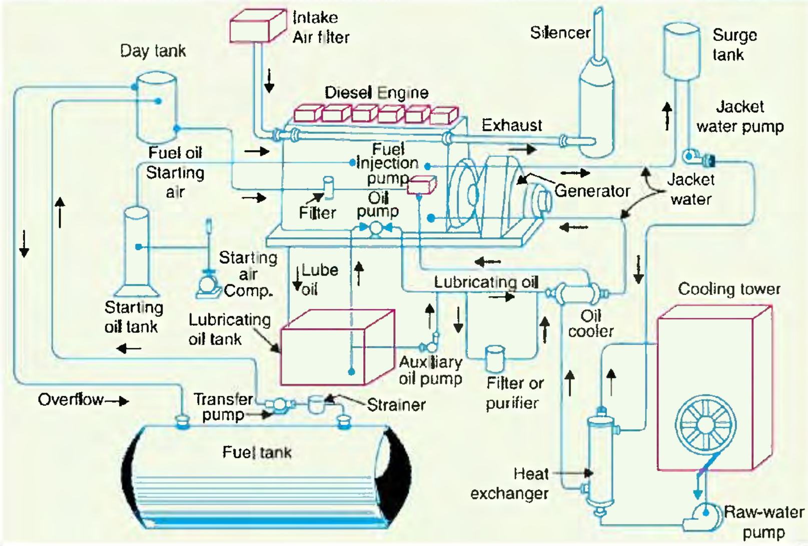


45. Schematic Arrangement for a Diesel Engine Power Station



(1) Engine (2) Generator
(3) Control panel (4) Enclosure
(5) Radiator (6) Exhaust gas silencer
(7) Ventilation air exhaust fan

46. Schematic Arrangement for a Diesel Engine Power Station



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47. Diesel Power Station Main Components

The essential components of a Diesel Power Station are:

- Engine
- Air intake system
- Exhaust system
- Fuel system
- Cooling system
- Lubrication system
- Engine starting system
- Governing system

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48. Engine

- **Engine** is the main component of the plant which develops the required power. The electrical generator is usually direct coupled to the engine.

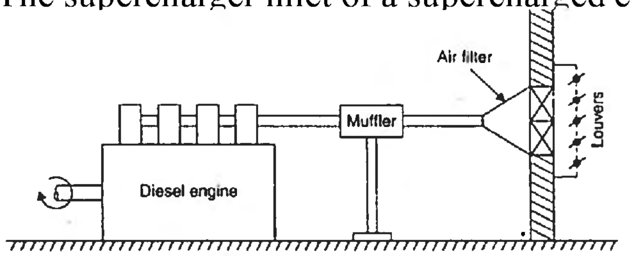
49. Air Intake System(1)

- The **air intake system** conveys fresh air through pipes or ducts to

  (i) air intake manifold of 4 stroke engine

  (ii) The scavenging pump inlet of a two stroke engine

  (iii) The supercharger inlet of a supercharged engine.



49. Air Intake System(2)

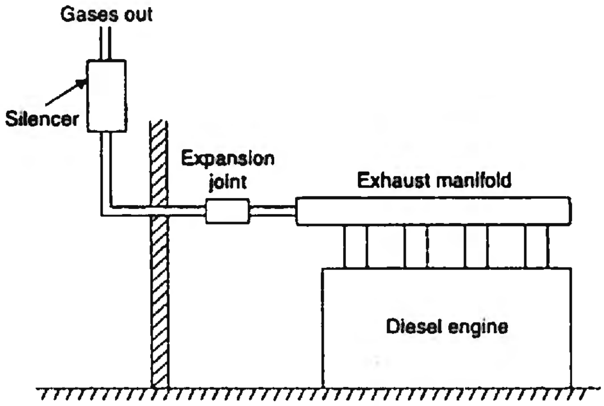
- Air is first drawn through a filter to catch dirt or particles that may cause excessive wear in cylinders. Filters may be of following types:
  - Dry type (paper, cloth, felt, glass wool etc.)
  - Wet type (oil impingement type, oil bath type where oil helps to catch particles)

49. Air Intake System(3)

- Following precautions should be taken while designing air intake systems
  - Air intake should be located outside the engine room.
  - Air intake should not be located in confined places to avoid undesirable acoustic vibrations.
  - Pressure drop in the air intake line should be minimum to avoid engine starvation.
  - Air filters should be accessible for periodic cleaning.
  - In some cases a muffler may be introduced to prevent engine noise from reaching outside air.

50. Exhaust System(1)

- The **exhaust system** discharges the engine exhaust to the atmosphere outside the building.

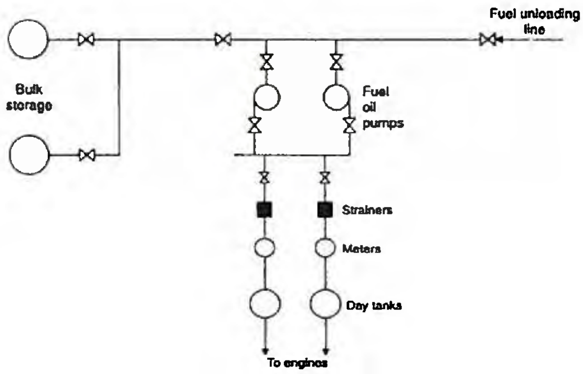


50. Exhaust System(2)

- The exhaust manifold connects the engine cylinder exhausts to the exhaust pipe.
- A muffler in the exhaust pipe reduces the pressure in the line and eliminates most of the noise that may result if exhaust gases are directly discharged to atmosphere.
- Exhaust pipe leading out of the building should be short in length with minimum number of bends to provide as low a pressure loss as possible.
- Flexible tubings may be added in exhaust pipe to take care of misalignments and expansion/contraction and also to isolate the system from engine vibrations.
- Each engine should have its independent exhaust system.
- Where possible, exhaust heat recovery should be made to improve plant thermal efficiency. E.g., air heating, low pressure steam generation in diesel-steam power plant etc.

51. Fuel System(1)

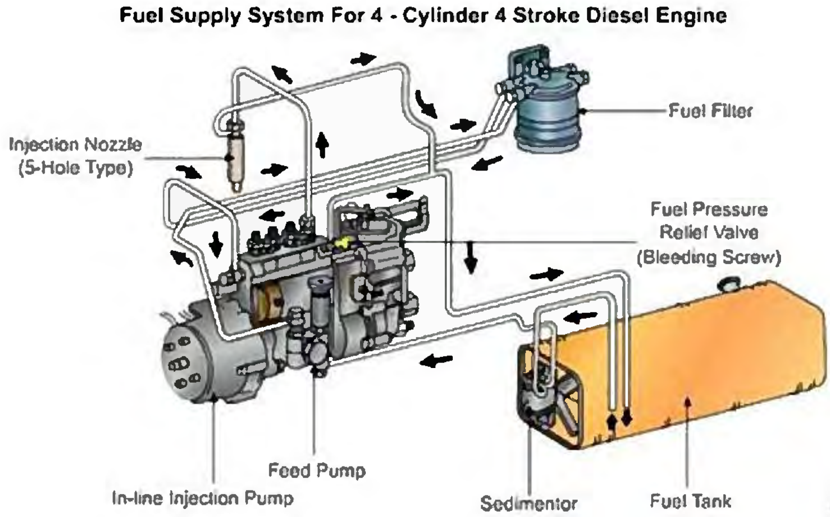
- The **fuel system** stores and distributes fuel to engines on demand. A generic schematic of fuel system is shown below



51. Fuel System(2)

- For satisfactory operation of a fuel supply system, following points must be considered:
  - System should be capable of supplying clean and measurable quantity of fuel to engines.
  - All pipe joints should be pressure tested and leak tight.
  - Filters should be easily accessible for periodic cleaning.
  - Safety interlocks should be available to take care of fuel leaks, overpressure and low fuel situations.
  - Adequate back up components should be available to take care of system failure modes.

51. Fuel System(3)



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52. Fuel injection systems(1)

- **Fuel injection system** is the heart of the Diesel engine and the performance of the engine is controlled by the efficiency of fuel injection into the cylinder.
- The problem of metering, injecting, atomizing and mixing with air for combustion becomes acute with high speed engines. However, engines driving electrical generators are low speed engines and they have simple combustion chambers.

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52. Fuel injection systems(2)

Functions of a fuel injection system

- Filter the fuel
- Meter or measure the correct quantity of fuel to be injected
- Time the fuel injection to cylinder
- Control the rate of fuel injection
- Atomise or break up the fuel to fine particles
- Properly distribute fuel in the combustion chamber

52. Fuel injection systems(3)

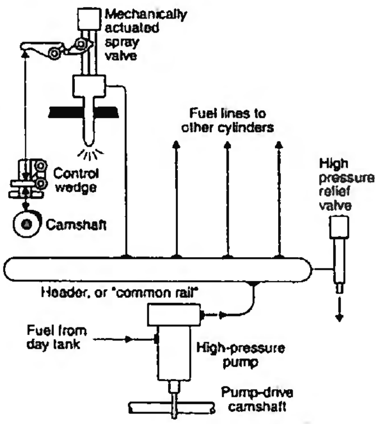
Types of fuel injection systems

- Following fuel injection systems are commonly used in Diesel power stations.
  - Common-rail injection system
  - Individual pump injection system
  - Distributor injection system
- Atomisation of fuel can be accomplished in two ways:
  - Air blast
  - Pressure spray
- Early diesel engines used air-fuel injection at about 70 bar pressure. But it called for a separate compressor for air supply. Present day practice is to use a fuel pressure between 100 and 200 bar to atomise the fuel as it flows through the spray nozzles.

52. Fuel injection systems(4)

Common Rail Injection System(Type-1)

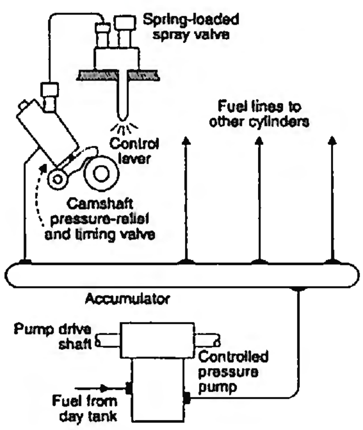
- One type of common rail fuel injection system is shown here.
  - A single pump supplies high pressure (100 – 200 bar) fuel to a header
  - A relief valve on header maintains constant pressure
  - Quantity of fuel injected and time of injection are dictated by a control wedge that adjusts the lift of a mechanically operated valve.



52. Fuel injection systems(5)

Common Rail Injection System (Type-2)

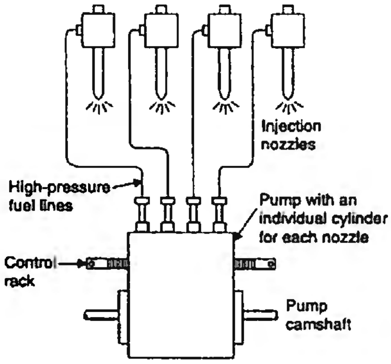
- A second type of common rail fuel injection system is shown here.
  - A single pump supplies high pressure (100 – 200 bar) fuel to an accumulator
  - Pressure relief and timing valves regulate injection time and amount
  - Spring loaded spray valves merely act as check valves



52. Fuel injection systems(6)

Individual pump Injection System

- The schematic is shown here.
  - An individual pump or pump cylinder connects directly to each fuel nozzle.
  - Metering and injection timing controlled by individual pumps
  - Nozzle contains a delivery valve actuated by the fuel pressure



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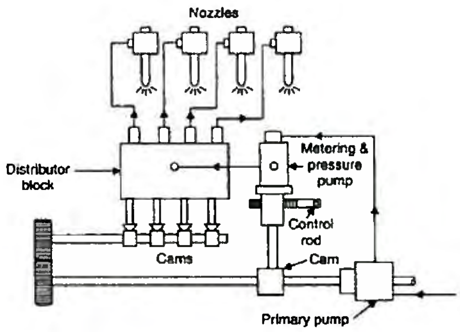
52. Fuel injection systems(7)

Distributor System

- The schematic is shown here.
  - The fuel is metered at a central point
  - A pump meters, pressurises and times the fuel injection
  - Fuel is distributed to cylinders in correct firing order by cam operated poppet valves which admit fuel to nozzles



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53. Cooling System(1)

Engine cooling is necessary for the following reasons:

- The temperature of combustion gases inside the cylinder can reach 2750° C. If there is no external cooling, average temperature of cylinder and piston can be as high as 1000° to 1500° C which may melt them.
- Lubricating oils have an operating temperature range of 160° to 200° C. Above these temperatures, oil will burn and carbon deposition will occur. In other words, lubrication will no longer be effective.

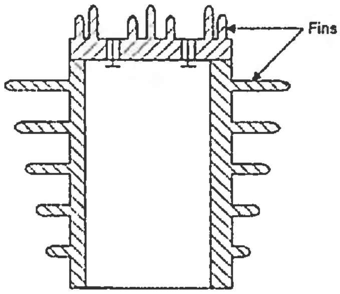
53. Cooling System(2)

- Strength of materials of construction decreases with increase in temperature and there is a limiting temperature for every material beyond which the material becomes too weak for the intended application.
- Hot exhaust valves can result in pre-ignition and detonation or knocking.
- High cylinder head temperature can reduce volumetric efficiency and hence the power output.

53. Cooling System(3)

- Almost 25% to 35% of total heat supplied in the engine is removed by the cooling medium. An additional 3% to 5% heat loss occurs through lubricating oil and radiation.
- There are two methods of cooling I.C. engines:

1. Air cooling
2. Liquid cooling



Air cooling : In this method, heat is carried away by the air flowing over and around the cylinder. Fins are added on the cylinder which provide additional ***mass of material for conduction*** as well as additional area for convection and radiative modes of heat transfer.

53. Cooling System(4)
Advantages of air cooling

- Simpler engine design as no liquid coolant jackets are needed.
- Absence of cooling pipes and radiator makes cooling system simpler.
- No danger of coolant leakage etc.
- Engine is not subjected to problems associated with frozen coolant during winter as is the case with water cooled engines.
- For a given power, the weight of an air cooled engine is less than that of a liquid cooled engine.
- Engine is self contained and easier to install.

53. Cooling System(5)
Disadvantages of air cooling

- Noisy movement
- Non uniform cooling
- Output of an air cooled engine is less than that of a liquid cooled engine.
- Smaller useful compression ratio
- Maintenance is not easy
- Not practical for diesel engines

53. Cooling System(6)

Liquid cooling : In this method, the cylinder walls and head are provided with jackets through which the cooling liquid can circulate.

- The heat is transferred from the cylinder walls to the liquid by convection and conduction.
- The liquid gets heated during its passage through the cooling jackets and is itself cooled by means of an air cooled radiator system. The heat from liquid in turn is transferred to air.

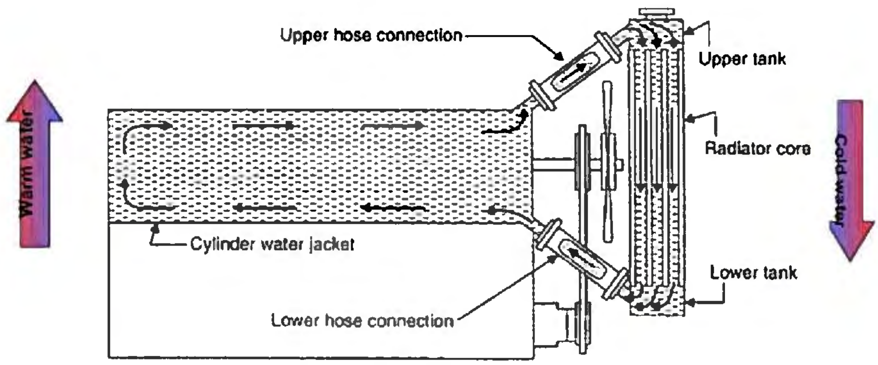
53. Cooling System(7)

There are several methods of circulating coolant liquid around the cylinder walls and head:

- Thermo-syphon cooling
- Forced or pump cooling
- Cooling with thermostatic regulator
- Pressurised cooling
- Evaporative cooling

53. Cooling System(8)

Thermo-syphon cooling : In this method works on the fact that water becomes lighter with increase in temperature.



53. Cooling System(9)

Thermo-syphon cooling : Schematic of a thermo-syphon cooling system is shown in the previous slide.

- Top and bottom ends of radiator are connected to the top and bottom water jackets of the engine.
- Water travels down the radiator across which air is passed to cool it.
- Air flow across the radiator can be due to the motion of the vehicle or by a fan.
- The system is simple and works on the basis of convective currents of water – hot water raises within the engine water jacket due to reduction of density and cold water drops down in the radiator due to increase in density.
- Disadvantage is that the cooling depends only on temperature differences and not on engine speed.
- Circulation of water starts only after the engine begins to work

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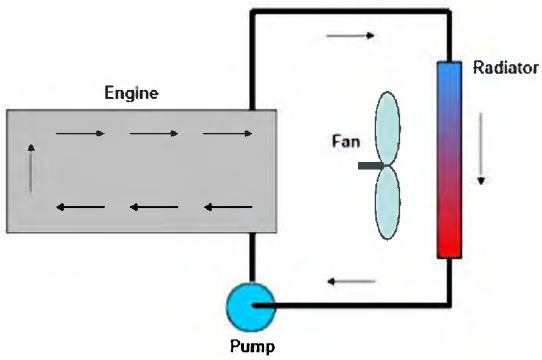
53. Cooling System(10)

Forced or Pump cooling : In this method, a pump is used to cause circulation of coolant in the water jacket of the engine. The pump is usually belt driven from the engine.



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53. Cooling System(11)

Forced or Pump cooling : Schematic of a forced pump cooling system is shown in the previous slide.

- Advantage of this system is that cooling is ensured under all conditions of operation.
- The system has following disadvantages:
  - Cooling is independent of temperature. This may result overcooling the engine.
  - While moving uphill, cooling requirement is more but the coolant circulation may reduce because of reduced engine speed. This may result in overheating of engine.
  - Cooling stops as soon as engine stops. Residual heat in engine can cause overheating. This is undesirable as cooling should continue until engine reaches normal temperature.

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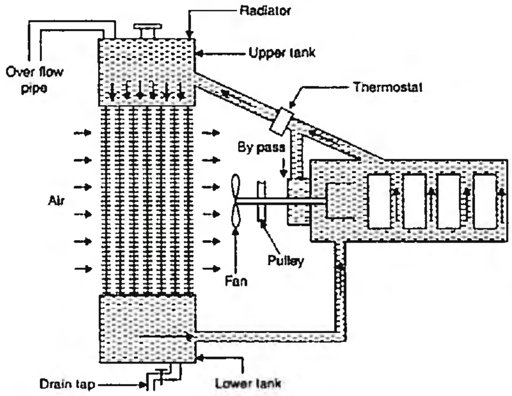
53. Cooling System(12)

Cooling with thermostatic regulator : A thermostat is a temperature controlling device used to stop flow of coolant below a preset cylinder barrel temperature.



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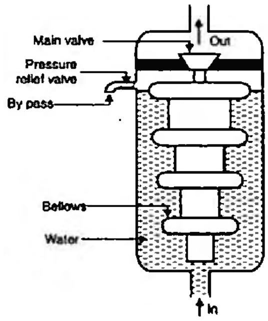
53. Cooling System(13)

Cooling with thermostatic regulator :

- Modern cooling systems employ thermostatic valves to prevent coolant in the engine jacket from circulating through radiator for cooling until its temperature has reached a value suitable for efficient engine operation.
- A thermostat consists of thin copper bellows filled with volatile liquid like ether or ethyl alcohol.
- The volatile liquid changes to vapour at the correct working temperature, thus creating enough pressure to expand the bellows.
- The movement of the bellows opens the main valve in proportion to the temperature, thus increasing or decreasing the flow of coolant from engine to radiator
- When the thermostat valve is not open, engine operation raises the coolant pressure. This opens the bypass pressure relief valve to maintain coolant circulation within the engine block.



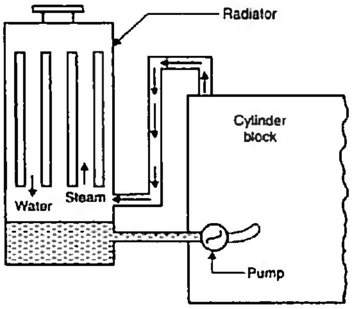
53. Cooling System(14)

Pressurized cooling : This system employs high pressure coolant to increase its boiling point and thereby increased heat transfer.

- The boiling point of the coolant can be increased by increasing its pressure. This allows a greater heat transfer to occur in the radiator due to larger temperature differential between radiator and ambient.
- Usually the coolant pressure is maintained between 1.5 and 2 bar.
- Pressurized cooling system requires an additional valve called "vacuum valve" to avoid formation of vacuum when the coolant temperature drops on shutting down the engine.
- A safety valve in the form of pressure relief valve is provided on the radiator top tank so that whenever the radiator cap is opened, the pressure is immediately relieved.

53. Cooling System(16)

Evaporative cooling : In this system, also called steam or vapour cooling, the temperature of cooling water is allowed to reach 100° C. This type of cooling utilizes ***the high latent heat of vaporization*** of water to obtain cooling with minimum water. In this system, the coolant is always liquid but the steam formed is flashed off in a separate vessel to condense.



53. Cooling System(17)
Advantages of liquid cooling

- Compact design of engine with minimal frontal area.
- Fuel consumption of a high compression liquid cooled engine is lower than that for an air cooled engine.
- Uniform cooling of cylinder barrels and heads due to jacketing. Easier to reduce temperatures of cylinder head and valve seating.
- Cooling system can be conveniently located anywhere, while for air cooled engines, installation is necessarily at the front end of mobile vehicles.
- Very effective for high horse power engines compared to air cooled systems which need large quantity of air for cooling.

53. Cooling System(17) Disadvantages of liquid cooling

- A dependent system which requires water / coolant for circulation in the jacket.
- Power absorbed by coolant pumps is considerably higher than that for cooling fans.
- In the event of failure of cooling system, serious damage may be caused to the engine.
- System is complex due to coolant jackets, pump, pipes, radiator etc.
- Cost of the system is considerably high compared to air cooled systems.
- Requires periodic maintenance.

54. Lubrication System(1)

Lubrication is the admittance of oil or grease between two surfaces having relative motion to reduce friction. The purpose of lubrication may be one or more of the following:

- To reduce friction and wear between parts having relative motion.
- To cool the surfaces by carrying away heat generated due to friction.
- To seal a space against leakage, such as space between piston rings and cylinder liner.
- To clean the surfaces by carrying away carbon and metal particles caused by wear.
- To absorb shock between bearings and other parts, consequently reduce noise.

54. Lubrication System(2)

Main parts of an engine requiring lubrication are:

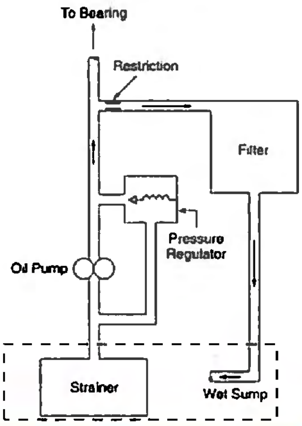
1. Main crankshaft bearings
2. Connecting rod big end bearing
3. Connecting rod small end or gudgeon pin bearing
4. Piston rings and cylinder walls
5. Timing gears
6. Valve mechanism
7. Valve guides, valve tappets and rocker arms

54. Lubrication System(3) Classification of lubrication systems

Lubrication systems used for I.C. engines may be classified as follows:

1. Wet sump lubrication system
2. Dry sump lubrication system
3. Mist lubrication system

Wet sump lubrication system:
This system uses a large capacity oil sump at the base of crank chamber, from which the oil is drawn by a low pressure oil pump and delivered to various parts. Oil then returns back to the sump after serving the purpose.

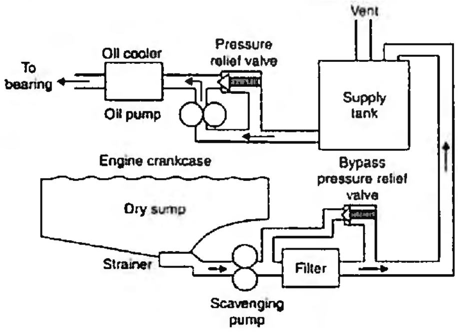


Wet sump lubrication system

54. Lubrication System(4) Classification of lubrication systems

Dry pump lubrication system:

Oil from the sump is carried to a separate storage tank outside the cylinder block. Oil from the sump is pumped to storage tank by a scavenging pump. Oil from the storage tank is pumped to the engine cylinder through another pump and oil cooler. Oil pressure varies from 3 to 8 bar. This type of lubrication is generally adopted ***for high capacity engines***.



54. Lubrication System(5) Classification of lubrication systems

Mist lubrication system:

- This system is used for 2-stroke engines.
- Most of these engines are crank charged i.e., they employ crank case compression and therefore, are not suitable for crank case lubrication.
- These engines are lubricated by adding 2 to 3% lubricating oil in the fuel tank.
- The oil and fuel mixture is induced through the carburetor.
- The gasoline is vaporized and the oil in the form of mist, goes via crank case into the cylinder.
- The oil, which impinges on the crank case walls, lubricates the main and connecting rod bearings, and the rest of the oil which passes in to the cylinder during charging and scavenging periods, lubricates the piston, piston rings and the cylinder.

54. Lubrication System(6) Mist Lubrication systems

Advantages:

- System is simple
- Low cost because of absence of pumps, filters etc.

Disadvantages:

- A portion of the lubricating oil invariably burns in the combustion chamber. This results in smoky exhaust, carbon deposits on piston crown, ring grooves and exhaust port, reducing engine efficiency.
- Since the oil comes in contact with acidic vapors produced during combustion, it loses its anti corrosion property and can lead to corrosion of bearings.
- For effective lubrication, oil and fuel must be thoroughly mixed. This requires separate mixing prior to use or special additives to give good mixing characteristics.
- Unless there is a good control on the lubricating oil, 2-stroke engines may run "over oiled".

55. Engine Starting System(1)

- Diesel engine used in diesel power stations is not self starting. The Diesel engine is started by one of the following methods,
  - There are three common methods of starting I.C. engines:

1. Starting by an auxiliary engine
2. Use of electric motors or self starters
3. Compressed air system

55. Engine Starting System(2)

Starting by an auxiliary engine (normally petrol driven):

- An auxiliary engine is closely mounted to the main engine and connected through clutch and gears.
- At first, the clutch is disengaged and the auxiliary engine is started (by hand or via self starter).
- After auxiliary engine warms up, the drive gear is engaged through the clutch and the main engine is cranked for starting.
- An overrunning clutch is used to avoid damage to auxiliary engine after the main engine starts.

55. Engine Starting System(3)

Use of electric motors or self starters:

- Used for small Diesel or Petrol engines
- A storage battery of 12V to 36V is used to drive an electric motor.
- The electric motor is geared to the flywheel with a provision for automatic disengagement after the engine has started.
- The motor draws heavy current and is designed to work continuously for a short period of time (typically 30 seconds).
- When the engine is running normally, a small d.c. generator on the engine serves to charge the battery.

55. Engine Starting System(4)

Use of compressed air system:

- Compressed air system is commonly used for starting large diesel engines employed for stationary power plants.
- Compressed air is stored at about 17 bar pressure in separate air tanks.
- This compressed air is initially supplied to a few of the engine cylinders, making them work like reciprocating air motors to run the engine shaft.
- Fuel is admitted to the remaining cylinders and ignition takes place in the normal way causing the engine to start.
- The air tank is charged by a separate or engine driven compressor.
- The system includes air storage tank, safety valves and interconnecting pipes.

55. Engine Starting System(5) Method of starting and stopping engines

Starting of engines:

- In case of an electric motor starting, check the condition of battery. If compressed air is used, check the air system for any possible leaks.
- Check the engine fuel system, lubrication system and cooling system for their proper functions.
- Crank the engine after ensuring that all load is pit off and the decompression (if available) device is engaged.
- Once the engine starts, run the engine at low speed for a few minutes and observe the working of fuel, lubrication and cooling systems.
- Increase the speed gradually till it synchronizes with the station bus bar.
- Connect the generator to the bus bar when it is in synchronization and increase the engine speed till it begins to share the desired load.

55. Engine Starting System(6)
Method of starting and stopping engines

Stopping of engines:

- Reduce the speed of the engine gradually until practically no power is delivered by the generator.
- Disconnect the unit from the bus and allow the engine to idle for a few minutes and stop it in conformity with manufacturer's instructions.

Governing system:

- The function of the governing system is to maintain the speed of the engine constant irrespective of the load on the plant.
  This is generally done by gradually decreasing the fuel supply to the engine.

Terima kasih.

Power Station

- Introduction
- Hydro Power Station
  - Pumped Storage Power Station
- Nuclear Power Station
- Fossil Fuel Energy Power Station
  - Steam
  - Gus Turbine
  - **Diesel**

HYDRO POWER STATION

NUCLEAR POWER STATION

FOSSIL FUEL ENERGY POWER STATION

DIESEL POWER STATION

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Power Plant in Timor-Leste

- Hera Power Plant
- Betano Power Plant (Construction)
  - Both are Diesel Power Plants.
  - Using Heavy Oil (In case of Hera, heavy oil is carried by ship to the harbor of Dili, is once saved near the harbor (Tibar fuel unloading facilities) and is carried from there to plant by trucks. Correct?
  - Unbelievable!!!
    - High cost
    - Risky
  - How about Betano?
  - Comoro Power Plant???????

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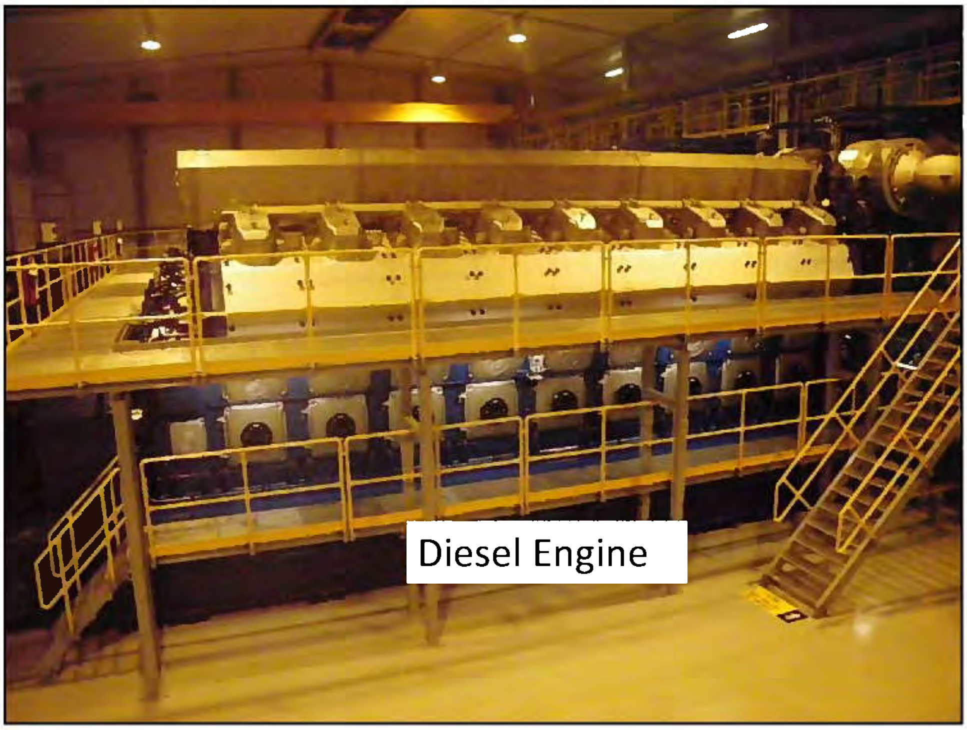
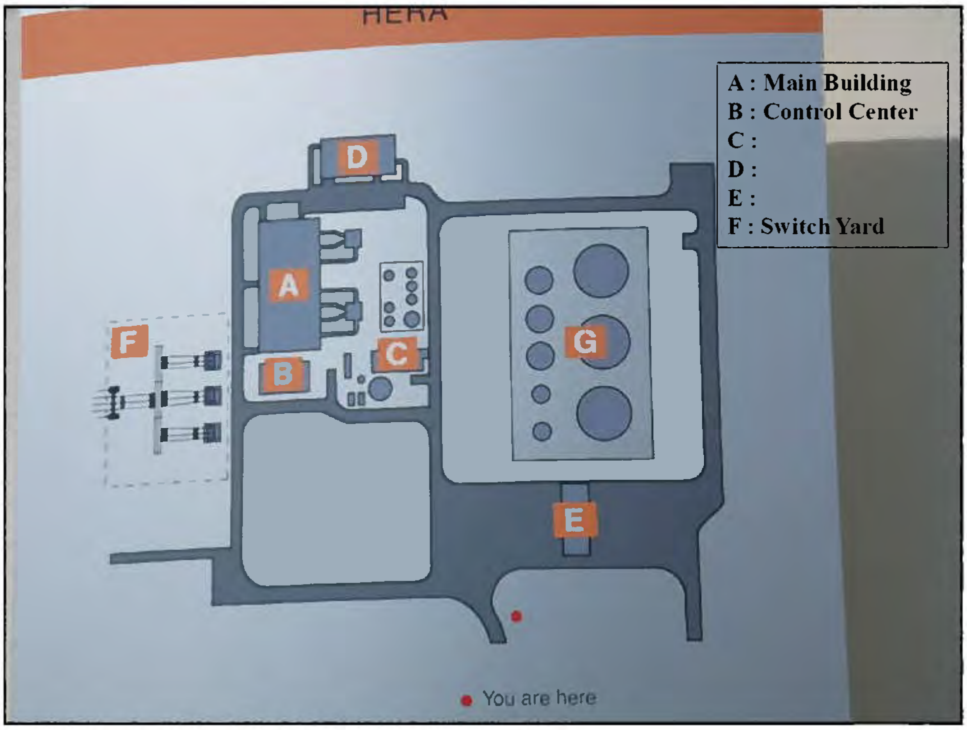
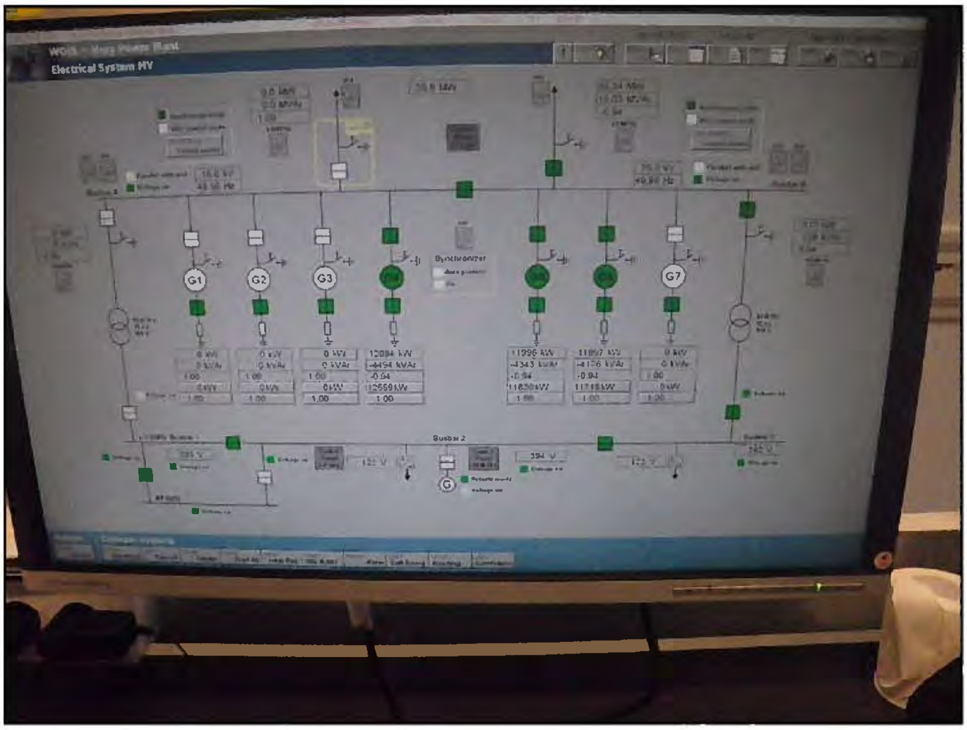

Diesel Engine


A : Main Building
B : Control Center
C :
D :
E :
F : Switch Yard
A
B
C
D
E
F
G
You are here

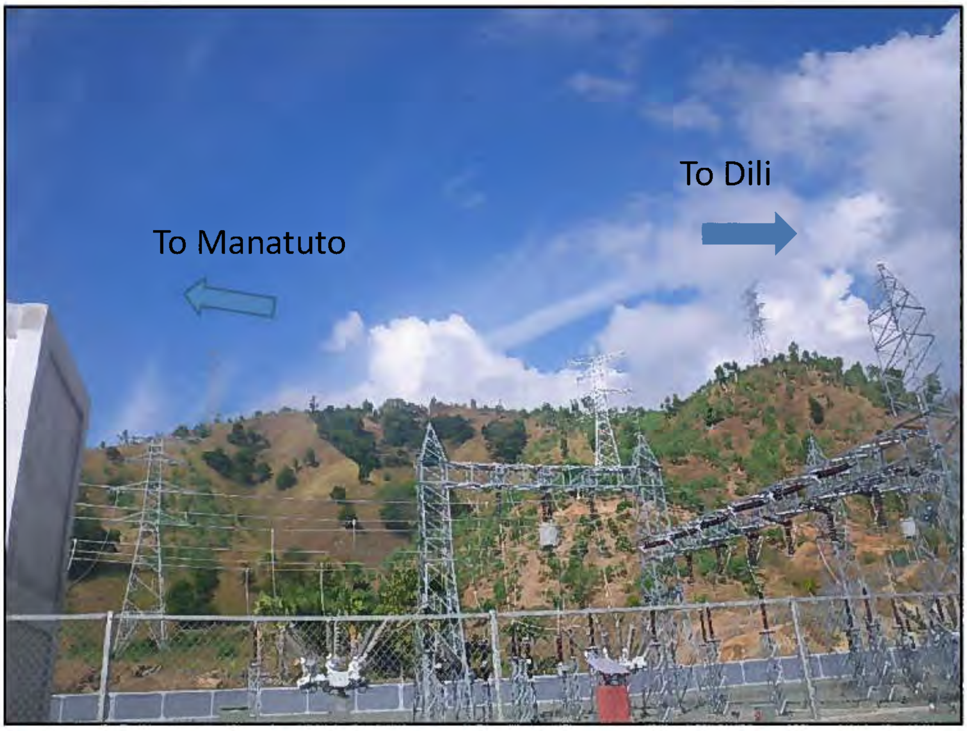

Control Room


STANDBY


Electrical System MV
G1
G2
G3
G7
Synchronizer


Switch Yard


Transformer
WÄRTSILÄ


To Dili
To Manatuto

Engine TCG 2032 V12 und V16 – Sensor arrangement (1)

1 Coolant temperature sensor
(high-temperature circuit inlet)
2 Proximity switch gas-air mixer
One switch for each gas-air mixer
3 Coolant temperature sensor
(high-temperature circuit outlet)
4 Mixture temperature sensor
One sensor for each gas-air mixer
5 Stepping motor gas-air mixer
One stepping motor for each gas-air mixer

6 Depending on version – Base bearing temperature sensor
7 Multifunction rail cylinder row A
8 Camshaft sensor
9 Crankcase pressure sensor
10 Electric pump for preheating unit (coolant)
11 Electrical preheater
for coolant and lubricating oil
12 Electric pump for preheating unit
(lubricating oil)

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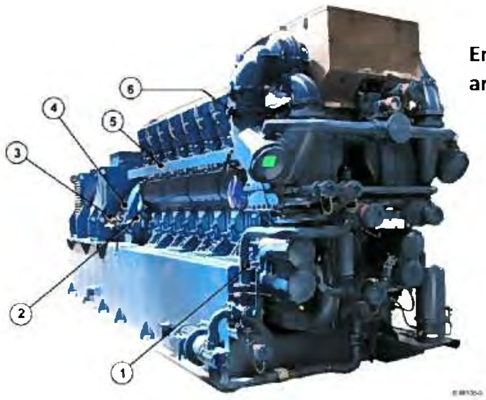

Engine TCG 2032 V12 and V16 – Sensor arrangement (2)

1 Lube oil temperature sensor
2 Start backup for engine turning device
3 Solenoid valve for air starter
4 Flywheel sensor – installation location depending on version
5 Multifunction rail cylinder row B

6 Charging mixture temperature sensor
One sensor each for A and B side
V12 engine: Between cylinder A4 and A5 as well as before B6
V16 engine: Between cylinder A6 and A7 as well as before B8

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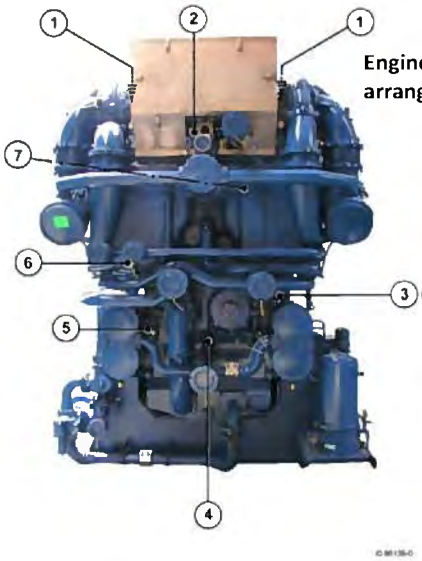
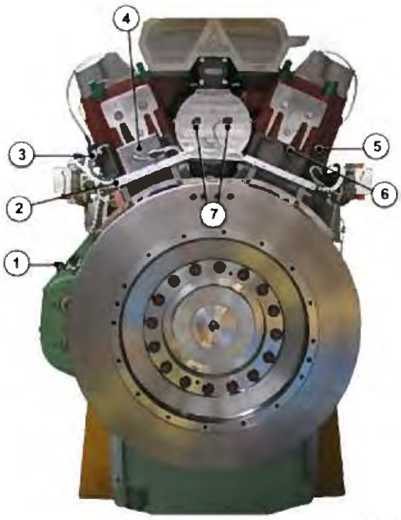


Engine TCG 2032 V12 and V16 – Sensor arrangement (3)

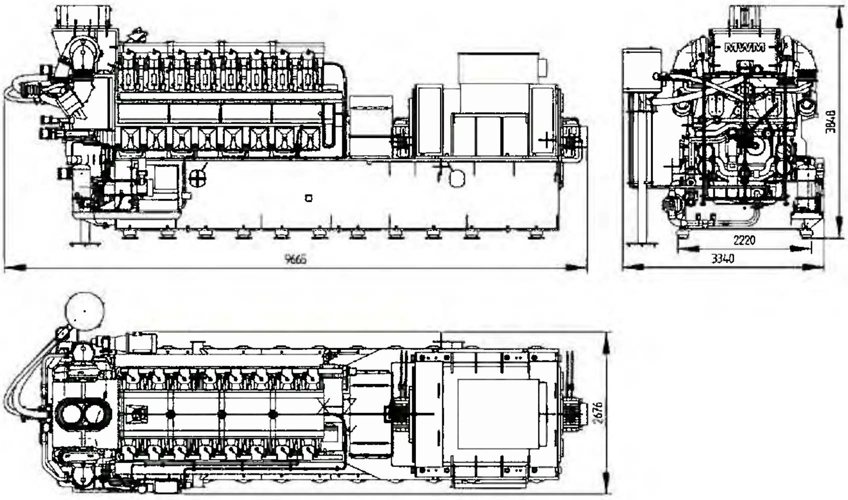
1 Exhaust turbocharger speed sensor
One sensor for every exhaust turbocharger
2 Actuator
3 Coolant temperature sensor
(high-temperature circuit inlet)
4 Lubricating oil level sensor
5 Lube oil pressure sensor
(Lube oil pressure before lubricating oil filter)
6 Coolant temperature sensor
(low-temperature circuit, inlet)
7 Charging mixture pressure sensor A side, mixture cooler – Depending on version



Engine TCG 2032 V12 and V16 – Sensor arrangement (4)

1 Flywheel sensor – installation location depending on version
2 Lube oil pressure sensor
(Lube oil pressure after filter)
3 Ignition coil
One ignition coil for every cylinder
4 Ignition control unit
5 Combustion chamber temperature sensor
One sensor for every cylinder
6 Knock sensor
One sensor for every cylinder
7 Charging mixture pressure sensor
One sensor each for A and B side

Engine TCG 20232 V16 with Marelli generator MJH 800 MC6 weight approx. 53700 kg



Generator

The types used as standard are brushless synchronous generators, which, depending on the application, may be suitable for mains-parallel and/or islands power supply operation. Depending on output and the available mains supply, these may be 400 V to 690 V three-phase generators or medium-voltage generators in the range from 3 kV to 15 kV.
The efficiency of the generators dependent upon size and power factor value (cos phi) is between 95.0 % and 97.8 %.
Thus, for example, a 494 kVA generator with a power factor of 0.8 has an efficiency level of 95.5 % and a 5336 kVA medium-voltage generator with a power factor of 0.8 is 97.2 % efficient. If the generator is operated at a power factor of 1, efficiency is increased by approx 1-1.5 %.
As per DIN VDE 0530 / DIN EN 60034 the generators are designed for an ambient temperature of 40° C and a site altitude of 1000 m. At higher ambient temperatures or higher altitude, the output must be reduced in accordance with the manufacturer's specifications.
These generators can operate as standard in a power factor range of 0.8 - 1 inductive (lagging). Thus in the case of mains-parallel operation, it is possible to improve the mains handover power factor in the event that the generators are to be used as "phase shifters".
Generators must be specially designed for use in the capacitive range! There are different country-specific regulations for static and dynamic mains support, which have to be considered when designing the gas engine gensets.
In island operation mode, the max. permissible unbalanced load for the generator must be taken into account. (Dependent upon generator output and manufacturer, 30 % between maximum and minimum phase current)


Exhaust ?????

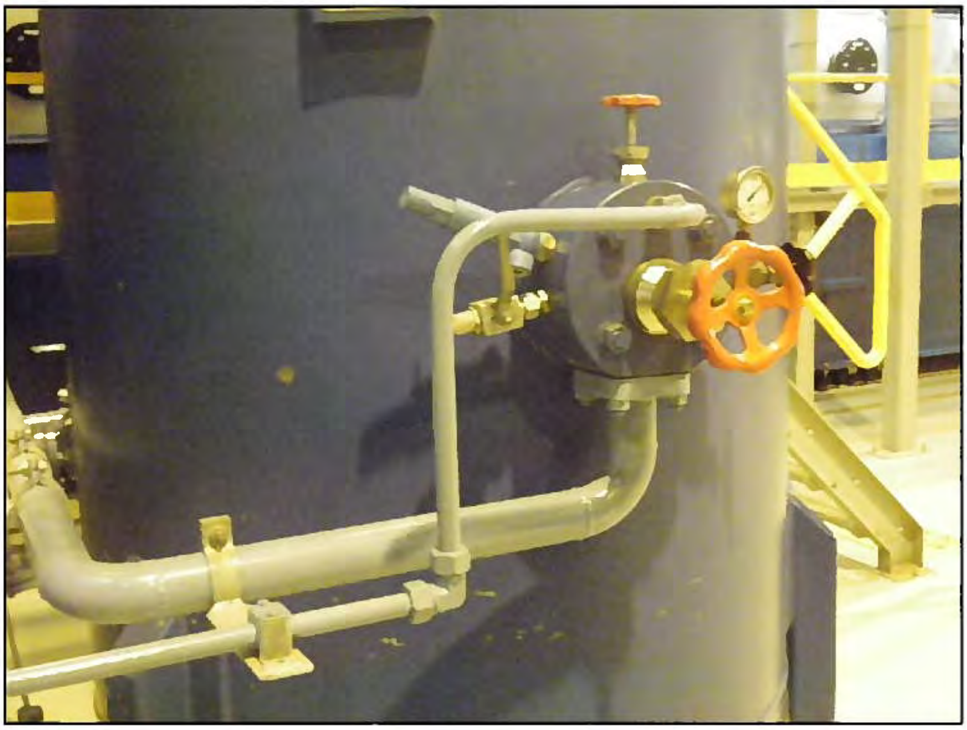

AALBORG
INDUSTRIES
EXHAUST GAS HEAT RECOVERY
CONTAINER

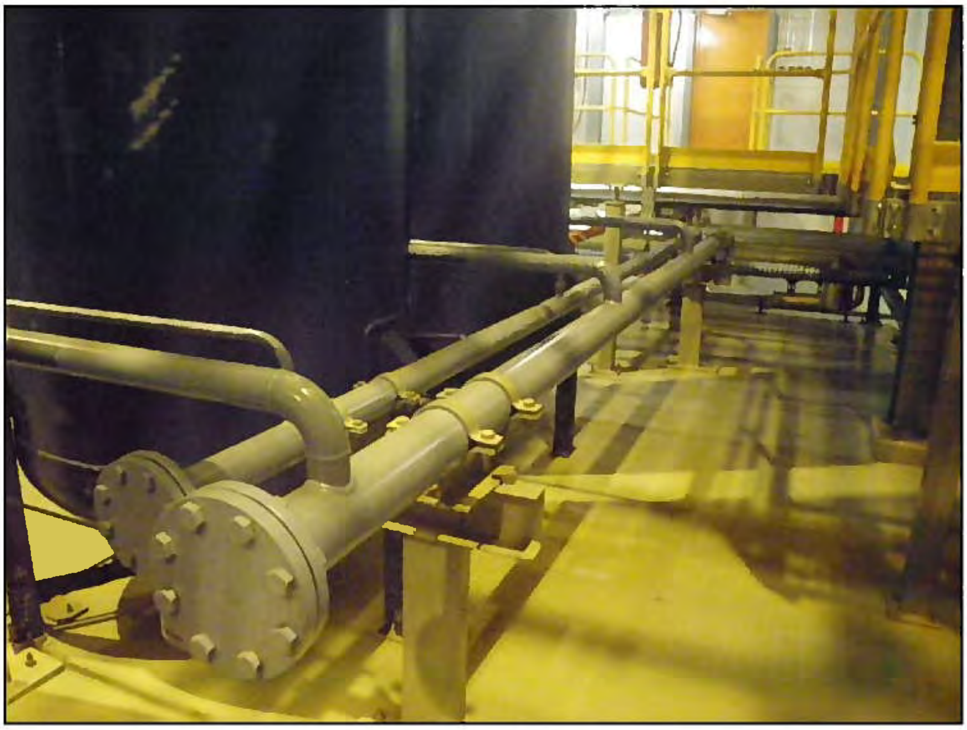

Fuel System??????


PBF 901
Fuel Tank


WÄRTSILÄ
AURA MARINE
HFO TRANSFER UNIT
PAC 901
WCO
SST

Starting Compressed Air





Japanese Technical Assistance
on Strengthening Institutional Capacity
of National Development Agency (ADN)
in Democratic of Timor-Leste

-- POWER --

Syllabus

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The contents may be changed depending on conditions.
I would like to discuss about the contents with Mr. Miguel and YOU.

V. SUBSTATION

1. Introduction(1)

- A Substation receives electric power from power station via transmission lines and delivers power via the outgoing transmission lines.
- Substations are integral parts of a power system and form important links between the power stations, transmission systems, distribution systems and the load points.
- Various substations located in power stations, transmission and distribution systems have similar layout and similar electrical components.

1. Introduction(2)

- Substation basically consists of number of incoming circuit connections and number of outgoing circuit connections connected to the busbars.
- Busbars are conducting bars to which number of circuit connections is connected.
- Each circuit has certain number of electrical components such as circuit breakers, Isolators, earth switches, current transformers, voltage transformers, etc.

2. Functions of Substations

Functions of Electrical Power Substations are:

- Supply electric power to the consumers continuously
- Supply of electric power within specified voltage limits and frequency limits
- Shortest possible fault duration.
- Optimum efficiency of plants and the network
- Supply of electrical energy to the consumers at lowest cost

3. Types Of Substations
- Based ON Nature Of Duties -

- Step up or primary substation:
  - Primary substations are associated with the power plants where the voltage is stepped up from low voltage (15kV) to 150kV for transmitting the power so that huge amount of power can be transmitted over a large distance to load centers.
- Primary Grid Substation:
  - Such substations are located at suitable load centers along with the primary transmission lines. At primary Grid Power Substations the primary transmission voltage (150kV) is stepped down (to secondary transmission voltages. This Secondary transmission lines are carried over to Secondary Power Substations situated at the load centers where the voltage is further stepped down) to Sub transmission Voltage or Primary Distribution Voltages (20kV).
- Step Down or Distribution Substations:
  - Such Substations are located at the load centers. Here the Sub transmission Voltages of Distribution Voltages (20kV) are stepped down to Secondary Distribution Voltages (380V or 220V). From these Substations power will be fed to the consumers to their terminals.

4. Types Of Substations
- Basis Of Service Rendered -

- Transformer Substation:
  - Transformers are installed on such Substations to transform the power from one voltage level to other voltage level.
- Switching Substation:
  - Switching substations are meant for switching operation of power lines without transforming the voltages. At these Substations different connections are made between various transmission lines. Different Switching Schemes are employed depends on the application to transmit the power in more reliable manner in a network.
- Converting Substation:
  - Such Substations are located where AC to DC conversion is required. In HVDC transmission Converting Substations are employed on both sides of HVDC link for converting AC to DC and again converting back from DC to AC. Converting Power Substations are also employed where frequency is to be converted from higher to lower and lower to higher. This type of frequency conversion is required in connecting to Grid Systems.

5. Types Of Substations
- Based on Operation Voltage -

- High Voltage Substation:
  - This type of Substation associated with operating voltages between 11kV and 66kV.
- Extra High Voltage Substation:
  - This type of Substation is associated where the operating voltage is between 132kV and 400kV.
- Ultra High Voltage Substation:
  - Substations where Operating Voltages are above 400kV is called Ultra High Voltage Substation

6. Types Of Substations
- Based On Substation Design -

- Outdoor Substations:
  - In Outdoor Substations, the various electrical equipment is installed in the switchyard below the sky. Electrical equipment is mounted on support structures to obtain sufficient ground clearance.
- Indoor Substations:
  - In Indoor Substations, the apparatus is installed within the substation building. Such substations are usually for the rating of 66kV. Indoor Substations are preferred in heavily polluted areas and Substations situated near the seas (saline atmosphere causes Insulator Failures results in Flashovers).

7. Types Of Substations - Based on Design Configuration(1) -

- Air Insulated Substation:
  - In Air Insulated Substations, busbars and connectors are visible. In this kind of Substations, Circuit Breakers and Isolators, Transformers, Current Transformers, Potential Transformers etc. are installed in the outdoor. Busbars are supported on the post Insulators or Strain Insulators. Substations have galvanized Steel Structures for Supporting the equipment, insulators and incoming and outgoing lines. Clearances are the primary criteria for these substations and occupy a large area for installation.

7. Types Of Substations - Based on Design Configuration(2) -

- Gas Insulated Substation:
  - In Gas Insulated Substation, Various Substation equipment like Circuit Breakers, Current Transformers, Voltage Transformers, Busbars, Earth Switches, Surge Arresters, Isolators etc. are in the form of metal enclosed SF6 gas modules. The modules are assembled in accordance with the required Configuration. The various Live parts are enclosed in the metal enclosures (modules) containing SF6 gas at high pressure. Thus the size of Substation reduces to 8% to 10% of the Air Insulated Substation.

7. Types Of Substations
- Based on Design Configuration(3) -

- Hybrid Substation:
  - Hybrid Substations are the combination of both Conventional Substation and Gas Insulated Substation. Some bays in a Substation are Gas Insulated Type and some are Air Insulated Type. The design is based on convenience, Local Conditions available, area available and Cost.

MAJOR EQUIPMENT

8. Busbars

Various incoming and outgoing circuits are connected to busbars. Busbars receive power from incoming circuits and deliver power to outgoing circuits.

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9. Power Transformers

Power Transformers are used to step up or step – down a.c. voltages and to transfer electrical power from one voltage level to another. Tap changers are used for voltage control.

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10. Circuit Breaker(1)

Circuit Breaker is used for Switching during normal and abnormal operating conditions. It is used to interrupt the short circuit currents. It is used to interrupt short circuit currents. Circuit Breaker operations include.

1. Closing
2. Opening
3. Auto – reclosing

Circuit Breaker is located near every switching point and also located at the both ends of every protection zone.

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10. Circuit Breaker(2)

Breakers are usually classified as "dead tank" or "live tank" construction.

"Dead tank" means that the circuit breaker tank and all accessories are maintained at ground potential, and the external source and load connections are made through conventional bushings.

"Dead Tank" Breaker

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10. Circuit Breaker(3)

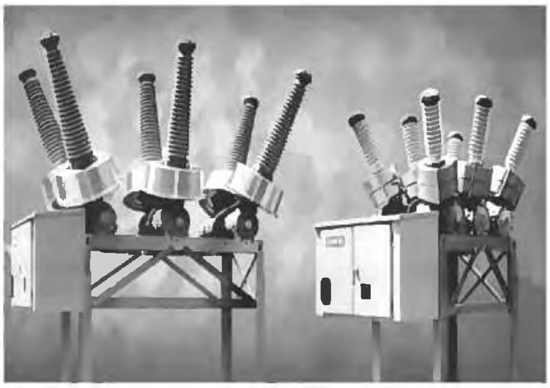
"Live tank" means that the metal and porcelain housing containing the interrupting mechanism is mounted on an insulating porcelain column and is therefore at line potential.

"Live Tank" Breaker

10. Circuit Breaker(4)

In addition to classification as "live tank" or "dead tank" construction, circuit breakers are also classified in terms of interrupting media. Breakers are also classified as three-pole, single-throw, and independent pole operation.

Three-pole single-throw breakers utilize one mechanical device to trip all three poles with a linkage to gang the operation together.



Three-Pole Single-Throw Breakers

10. Circuit Breaker(5)

With independent-pole operation, each pole is equipped with the mechanical means to trip its individual pole.


SF6 Gas Circuit Breakers

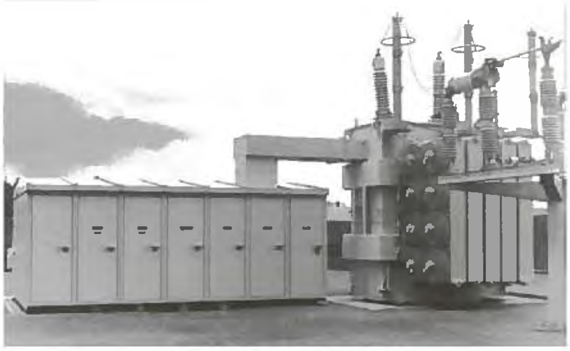
10. Circuit Breaker(6)

No general guidelines can be drawn for the application of these various types of circuit breakers. Each user has to determine the ratings of circuit breakers required and then select a type of circuit breaker acceptable with regard to rating, performance expectations, compatibility with planned or existing substation configuration, and the ability to install, operate, and maintain the circuit breaker. Cost may also be an important consideration in the final selection.
Most, but not all, domestic circuit breakers in outdoor substations of 2.4 kV through 24.9 kV utilize a vacuum technology as the insulating dielectric to interrupt load and fault currents. Although outdoor vacuum breakers can be supplied for voltages up to 38 kV, SF6 is more commonly used for voltages from 34.5 kV to 765 kV.


Type SDV Vacuum Circuit Breaker

11. Metal-clad switchgear

Metal-clad switchgear serves the same system function as comparable elements in a conventional open bus-type substation. These elements may include main power switching or interrupting devices, disconnecting switches, buses, instrument and control power transformers, and control and auxiliary devices, as well as other devices.



Typical Single-Aisle Switchgear Installation

12. voltage regulators(1)

Both three-phase and single-phase voltage regulators are used in distribution substations to regulate the loadside voltage. Substation regulators are one of the primary means, along with load-tap-changing power Transformers, shunt capacitors, and distribution line regulators, for maintaining a proper level of voltage at a customer's service entrance.

There are two general types of voltage regulators, the induction regulator and the step-type regulator. Both types are available in single- or three-phase designs. The step-type regulator has by far the wider application in the electric distribution system. The step-voltage regulator has virtually replaced the induction-voltage regulator because it is lower in cost and equally reliable.

12. voltage regulators(2)

For substation sizes used most frequently by rural electric systems, single-phase regulators are usually less expensive. They also do a better job of maintaining balanced phase voltages under conditions of unbalanced loading. Single-phase regulators are also more adaptable to line use because of the relative Bulletin ease of pole mounting. Regulation by single-phase regulators also gives maximum reliability for the system because a regulator can be removed for maintenance or repair without the need to de-energize transformers or other regulators. Special switches are available to permit removing a regulator from service without interrupting the circuit.

Single-Phase Voltage Regulator

12. voltage regulators(2)

In large distribution substations, the choice of three-phase regulators may be based on costs or on the availability of single-phase regulators of the required size. Three-phase regulators require somewhat less space than three single-phase regulators.

Three-Phase Voltage Regulator

13. Shunt Reactors

Shunt Reactors are used for long EHV transmission lines to control voltage during low load period. Shunt reactors is also used to compensate shunt capacitance of transmission line during low load periods. Usually Shunt reactors are unswitched.

14. Shunt Capacitance

Shunt capacitors are used for compensating reactive power of lagging power factor. Shunt Capacitors are used for improving the power factor. It is also used for voltage control during heavy lagging power factor loads. Shunt Capacitors are located at the receiving stations and distribution substations. Shunt Capacitors are switched in during heavy loads and switched off during low loads.

15. Series Capacitor

Series Capacitors are used for some long EHV a.c lines to improve power transferability. Capacitors are located at the sending end / receiving end of the lines. Series Capacitors are provided with bypass circuit breaker and protective spark – gaps.

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16. Series Reactors

Series reactors are used to limit short – circuit current and to limit current surges associated with fluctuating loads. Series reactors are located at the strategic locations such that the fault levels are reduced.

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17. AIR SWITCHES

The general function of an air switch is as stated in ANSI/IEEE Std. C37.100: "A switching device designed to close and open one or more electrical circuits by means of guided separable contacts that separate in air." Air, at atmospheric pressure, is also the insulating medium between contacts in the open position.

19. Isolators or Disconnecting Switches

Isolators are provided for isolation from live parts for the purpose of maintenance. Isolators are located at either side of the circuit breaker. Isolators are operated under no load. Isolator does not have any rating for current breaking or current making. Isolators are interlocked with circuit breakers.

Types of Isolators are

1.Central rotating, horizontal swing
2.Centre-Break
3.Vertical swing
4.Pantograph type

20. Earth Switch

Earth Switch is used to discharge the voltage on the circuit to the earth for safety. Earth switch is mounted on the frame of the isolators. Earth Switch is located for each incomer transmission line and each side of the busbar section.

21. Grounding Switch

"A mechanical switching device by means of which a circuit or piece of apparatus may be electrically connected to ground." Grounding switches are often mounted on the jaw or hinge end of disconnecting or horn-gap switches.

Typical Applications :

a. To ground buses or circuits (for safe maintenance) after they are first isolated

b. To intentionally ground a circuit (using an automatic high-speed device) in order to activate a remote protective relaying scheme

Horizontally Mounted Double Break Switch with Grounding Switch

22. Horn-Gap Switch

A switch provided with arcing horns.

Typical Applications :

To de-energize or energize a circuit that possesses some limited amount of magnetic or capacitive energy, such as transformer exciting current or line charging current. The arcing horns protect the main contacts during opening or closing and enhance the ability of the switch to perform its task.

Horizontally Mounted Double-Break Switch.
Note arcing horns and corona shields at blade contact points

23. Interrupter Switch

"An air switch, equipped with an interrupter, for making or breaking specified currents, or both." "The nature of the current made or broken, or both, may be indicated by suitable prefix, that is, load interrupter switch, fault interrupter switch, capacitor current interrupter switch, etc."

Typical applications are indicated by the above-named prefixes.

Horizontally Mounted Vertical-Break Interrupter

24. Various Constructions of Outdoor Air Switches(1)

Outdoor air switches are constructed in many different styles or construction.

Vertical Break Switch

"One in which the travel of the blade is in a plane perpendicular to the plane of the mounting base. The blade in the closed position is parallel to the mounting base." The hinge end includes two insulators, one of which is caused to rotate by the operating mechanism and thereby open and close the blade.

Vertically Mounted Vertical-Break Switch

24. Various Constructions of Outdoor Air Switches(2)

Double Break Switch

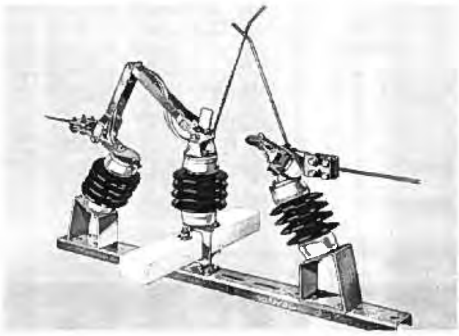
"One that opens a conductor of a circuit at two points." The center insulator stack rotates to accomplish the opening and closing operation.

Horizontally Mounted Double-Break Switch

24. Various Constructions of Outdoor Air Switches(3)

Tilting-Insulator Switch

"One in which the opening and closing travel of the blade is accomplished by a tilting movement of one or more of the insulators supporting the conducting parts of the switch." This type of switch is seldom used today. However, this switch is still in service on many existing installations. It is included here since it will be necessary to modify or replace such switches on occasion.

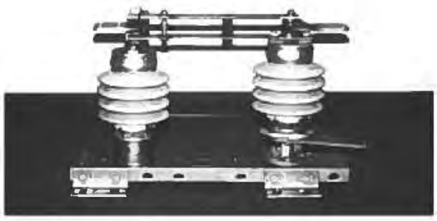


Tilting Insulator Switch

24. Various Constructions of Outdoor Air Switches(4)

Side-Break Switch

"One in which the travel of the blade is in a plane parallel to the base of the switch." The hinge-end insulator rotates to accomplish the opening and closing operation.

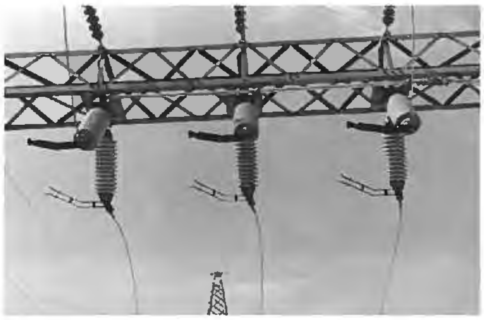


Single Side-Break Switch

24. Various Constructions of Outdoor Air Switches(5)

Center-Break Switch

One in which travel of the blade is in a plane parallel to the base of the switch and that opens in the center at only one point. Both insulators rotate to accomplish the opening and closing operation.



Underhung Center-Break V-Switch

24. Various Constructions of Outdoor Air Switches(6)

Grounding Switch

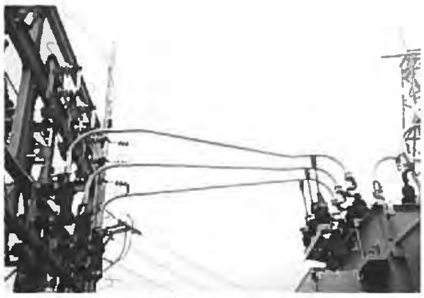
"a mechanical switching device by means of which a circuit or piece of apparatus may be electrically connected to ground. Some types use a normally grounded blade, which is made to contact the bus or equipment to be grounded.

Horizontally Mounted Double Break Switch with Grounding Switch

24. Various Constructions of Outdoor Air Switches(7)

Hook Stick Switch

One that is opened manually by means of a switch stick. Both insulators remain stationary when the blade, hinged at one end, is unlatched and opened or closed by the switch stick. These are single-pole (single-phase) switches..



Hook Stick Switches on Structure at Termination of Bus from Transformer

24. Various Constructions of Outdoor Air Switches(8)

Vertical Reach Switch

"One in which the stationary contact is supported by a structure separate from the hinge mounting base. The blade in the closed position is perpendicular to the hinge mounting base."

Vertical Reach Switch

29. Surge arrestors or Lightning arrester

Surge Arresters or Lightning Arresters discharge the over voltage surges to earth and protect the equipment insulation from switching surges and lightning surges. Surge arresters are generally connected between phase conductor and ground. In a Substation surge arrester is located at the starting of the substation as seen from incoming transmission lines and is the first equipment of the substation. Surge arresters are also provided near the transformer terminals phase to ground. Two type of surge arresters are available 1) Gapped Arresters 2) Gapless Zinc – Oxide arresters.

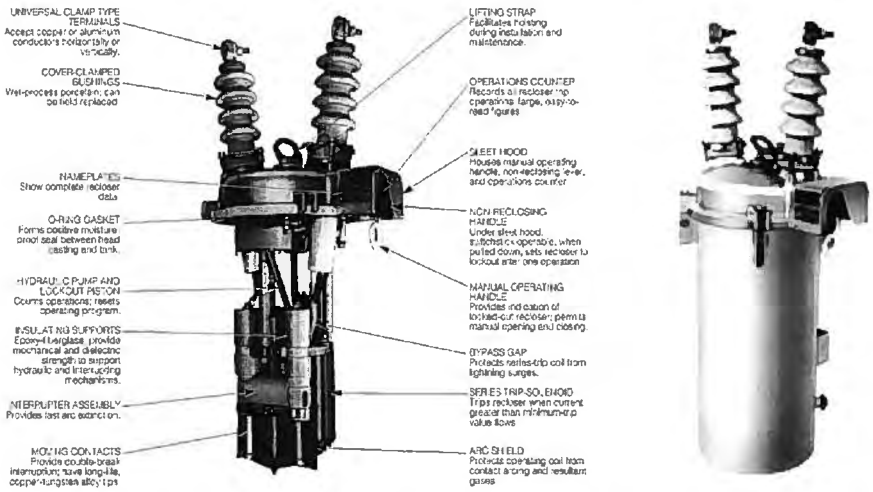
30. AUTOMATIC CIRCUIT RECLOSERS(1)

- An automatic circuit recloser is a self-controlled protective device used to interrupt and reclose automatically an alternating-current circuit through a predetermined sequence of opening and reclosing followed by resetting, lockout, or hold closed.

30. AUTOMATIC CIRCUIT RECLOSERS(2)

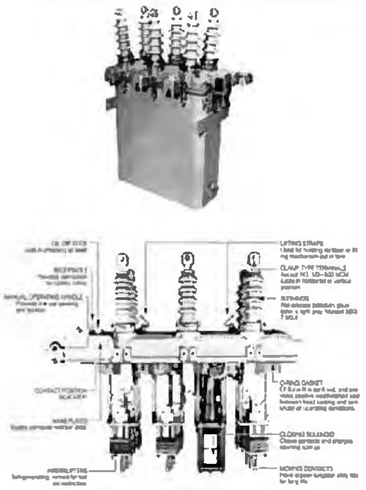
Purpose: Reclosers are installed to provide maximum continuity of service to distribution loads, simply and economically, by removing a permanently faulted circuit from the system or by instant clearing and reclosing on a circuit subjected to a temporary fault caused by lightning, trees, wildlife, or similar causes. Unlike fuse links, which interrupt either temporary or permanent faults indiscriminately, reclosers are able to distinguish between the two types of faults, permanent and temporary. They give temporary faults repeated chances to clear or to be cleared by a subordinate protective device. If the fault is not cleared, the recloser recognizes the fault as permanent and operates to lock out or, in some applications, hold closed.

30. AUTOMATIC CIRCUIT RECLOSERS(3)



Typical Single-Phase Hydraulically Controlled Oil Circuit Breaker

30. AUTOMATIC CIRCUIT RECLOSERS(4)

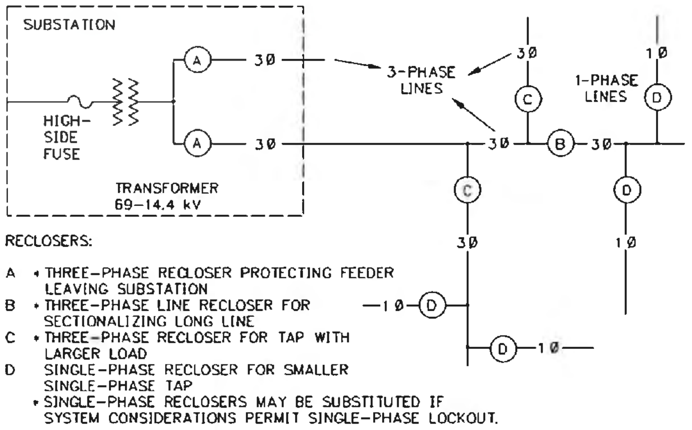


Recloser with Single-Phase Tripping and Three-Phase Lockout

30. AUTOMATIC CIRCUIT RECLOSERS(5)

Application: Automatic circuit reclosers are used in distribution substations and on branch feeders to protect distribution circuits and to switch them. (see next page). Their proper application requires a study of the load and short-circuit characteristics of both the protecting and the protected equipment. This includes high-voltage fuses or other protection in the supply to a substation transformer bank, a circuit breaker or reclosers at the distribution voltage supplying the feeder at the substation, various line reclosers, sectionalizers, line fuses, the wire arc burn-down characteristic at the fault location, ground resistance, etc.

30. AUTOMATIC CIRCUIT RECLOSERS(6)



Typical Line Diagram of Distribution Circuit Showing Application of Reclosers

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11. AUTOMATIC CIRCUIT RECLOSERS(7)

Single-Phase or Three-Phase: Both single- and three-phase reclosers are available to satisfy application requirements.

Single-Phase Reclosers: Single-phase reclosers are used to protect single-phase lines, such as branches or taps of a three-phase feeder. They can also be used on three-phase circuits where the load is predominantly single phase. Thus, when a permanent phase-to-ground fault occurs, one phase can be locked out while service is maintained to the remaining two-thirds of the system.

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30. AUTOMATIC CIRCUIT RECLOSERS(8)

Three-Phase Reclosers: Three-phase reclosers are used where lockout of all three phases is required for any permanent fault. They are also used to prevent single phasing of three-phase loads, such as large three-phase motors. Three-phase reclosers have two modes of operation.

- The first, single-phase trip and three-phase lockout, consists of three single-phase reclosers mounted in a single tank, with mechanical interconnection for lockout only. Each phase operates independently for overcurrent tripping and reclosing. If any phase operates to lockout condition due to a permanent fault, the mechanical linkage trips open the other two phases and locks them open. Thus, extended single-phase energization of three-phase loads is prevented. This type of operation is provided for smaller recloser types.
- Larger reclosers make use of the second mode of operation: three-phase trip with threephase lockout. For any fault—single-phase-to-ground, phase-to-phase, or three-phase—all contacts operate simultaneously for each trip operation. The three phases, mechanically linked together for tripping and reclosing, are operated by a common mechanism.

30. AUTOMATIC CIRCUIT RECLOSERS(9)

Construction

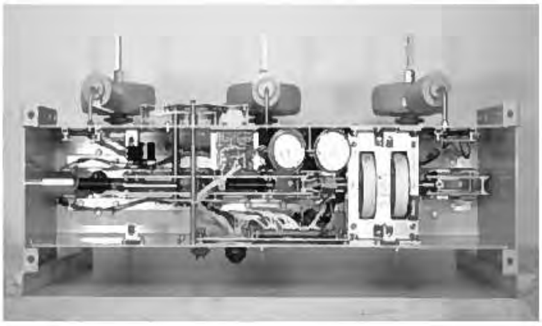
Most automatic circuit reclosers consist of five major components: tank, bushings, mechanism, interrupter, and controls. Although Figures shown refer to oil circuit reclosers, many reclosers consist of the same basic components.

Tank: The tank is that part of the recloser that houses the interrupter and tripping and closing mechanisms. The tank is usually made of steel and is rectangular for a three-phase recloser and cylindrical for a single-phase recloser. The top is usually an aluminum casting that supports the various components. Some new technologies do not utilize tanks. The interrupter may be enclosed in an epoxy bushing while the operating mechanism is enclosed in a steel housing.

Bushings: The bushings are the insulating structures including through-conductors with provision for mounting on the top of the recloser.

30. AUTOMATIC CIRCUIT RECLOSERS(10)

Operating Mechanism: The operating mechanism of an automatic circuit recloser provides the power to open, close, reclose, lock out, or hold closed the main contacts. The tripping mechanism is the device that releases the holding means and opens the main contacts. In most cases, the opening force is furnished by springs that are charged by the closing mechanism. An operating mechanism is shown in Figure.



Operating Mechanism with Housing Cover Removed

30. AUTOMATIC CIRCUIT RECLOSERS(11)

The closing mechanism is a solenoid coil, springs, or a motor and gear arrangement. The closing force serves to close the main contacts and at the same time charges the opening springs. The lockout mechanism is the device that locks the main contacts in the open position following the completion of the sequence of operation. The hold-closed mechanism is the device that holds the main contacts in the closed position following the completion of a predetermined sequence of operation. It holds the main contacts closed as long as current flows in excess of a predetermined value. When the current is reduced below this value, the hold-closed mechanism resets to its initial position.

Interrupter: The interrupter is that part of the recloser that contains separable contacts that operate within an interrupting unit. The physical configuration and method of interruption vary with manufacturer and recloser classification.

30. AUTOMATIC CIRCUIT RECLOSERS(12)

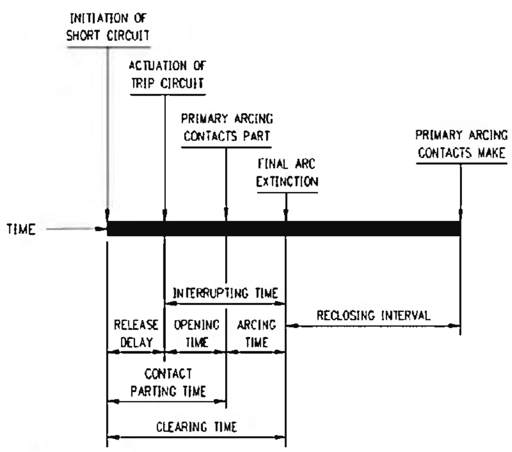
Control: Reclosers are provided with sequence control devices and operation integrator to change the recloser from instantaneous operations to time-delay operations and to lock out the recloser after a prescribed number of operations. Individual tripping operations of a recloser can be made to follow instantaneous or time-delay, time–current characteristics. Reclosers are normally set for one of the following sequences of operations:

a. Four time-delay operations
b. One instantaneous operation followed by three time-delay operations
c. Two instantaneous operations followed by two time-delay operations

30. AUTOMATIC CIRCUIT RECLOSERS(13)

Recloser Operation

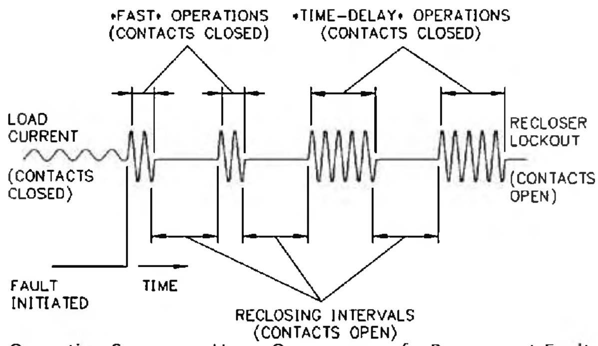
When an overcurrent of sufficient magnitude flows through the trip coil or sensing current transformers, the tripping action is initiated and the contacts are opened. The recloser contacts then reclose following a predetermined length of time (see Figure – ANSI/IEEE Std. C37.60-1981).



Unit Operation. Ref. ANSI/ IEEE Std. C37.60-1981

30. AUTOMATIC CIRCUIT RECLOSERS(14)

By the time the recloser has reassessed the circuit, the sequence control device has moved to count the trip operation. If the fault still persists on the circuit when the recloser closes, the tripping and reclosing sequence is repeated a predetermined number of times, as established by the sequence control device, until the recloser goes to either the lockout or the hold-closed position. If the fault has cleared from the circuit during any open-circuit period, however, the recloser closes and remains closed, and the sequence control device resets so that it is in position for the next sequence of operations (see Figure).



Recloser Operating Sequence Upon Occurrence of a Permanent Fault

30. AUTOMATIC CIRCUIT RECLOSERS(15)

Maintenance and Inspection

Installation: Before installing a recloser, check for external mechanical damage, oil level (oilfilled reclosers), operating sequence as specified, and the record reading on the operation counter. Periodic inspection and maintenance are essential to ensure efficient, trouble-free service of an automatic circuit recloser. Once an automatic circuit recloser is installed, it should be placed on a periodic schedule of test and inspection. Frequency of maintenance should be based on the manufacturer's recommendations, elapsed time in service, and number of operations. Many of the new vacuum technologies do not require the frequency of scheduled maintenance that traditional oil circuit reclosers do. Such test and inspection should cover timing tests and checking of bushings for cracks and of the tank for oil leakage, as well as recording the counter reading. Internal inspection should include contact maintenance or replacement; a check of all gears, linkages, timing devices; test of the oil, etc.

30. AUTOMATIC CIRCUIT RECLOSERS(16)

Mounting

Most reclosers, both single- and three-phase, are suitable for mounting on poles (see Figure) and substation structures. Single-phase reclosers can be mounted singularly or in clusters. Three-phase reclosers have mounting frames that are suitable for base mounting, pad-mount enclosure installation, or modification for pole or substation structure mounting.

Mounted Recloser

31. Current Transformer(1)

Current transformers are used for Stepping down current for measurement, protection and control. Current transformers are of two types

1. Protective CT
2. Measuring CT

31. Current Transformer(2)

Bar: A bar-type current transformer is one that has a fixed, insulated straight conductor in the form of a bar, rod, or tube that is a single primary turn passing through the magnetic circuit and that is assembled to the secondary, core, and winding.

Bushing: A bushing-type current transformer is one that has a round core and a secondary winding insulated from and permanently assembled on the core but has no primary winding or insulation for a primary winding. This type of current transformer is for use with a fully insulated conductor as the primary winding.

Wound: A wound-type current transformer is one that has a fixed primary winding mechanically encircling the core; it may have one or more primary turns. The primary and secondary windings are completely insulated and permanently assembled on the core as an integral structure.

31. Current Transformer(3)

Double-Secondary: A double-secondary current transformer is one that has secondary coils each on a separate magnetic circuit with both magnetic circuits excited by the same primary winding. Multiple-secondary (three or more) current transformers are also manufactured. Window/Donut: A window- or donut-type current transformer is one that has a secondary winding insulated from and permanently assembled on the core, but has no primary winding as an integral part of the structure. Complete or partial insulation is provided for a primary winding in the window through which one or more turns of the line conductor can be threaded to provide the primary winding.

Bushing, Window, and Wound-Type Current Transformers

31. Current Transformer(4)



High-Voltage Current Transformers

32. Voltage Transformer(1)

Voltage transformers are used to step down the voltage for measurement, protection and control. Voltage transformers are of two types.

1. Electro magnetic type
2. Capacitive VT located on the feeder side of the Circuit Breaker.

32. Voltage Transformer(2)

Voltage Transformers

33. COUPLING CAPACITORS AND COUPLING CAPACITOR VOLTAGE TRANSFORMERS(1)

Both coupling capacitors and coupling capacitor voltage transformers are single-phase devices that utilize one or more capacitor units, usually mounted on a base, to couple a communication signal to a highvoltage power line.

Coupling capacitors (CCs) are used in conjunction with line traps and line tuners for power line carrier (PLC) communication over high-voltage power lines. A CC with an electromagnetic unit is called a Coupling Capacitor Voltage Transformer (CCVT). CCVTs can be used to supply voltage for metering and protection applications similar to a voltage transformer.

The ANSI Standard applicable to the power line coupling capacitors is ANSI Std. C93.1, "Power Line Coupling Capacitors and Coupling Capacitor Voltage Transformers (CCVT) Requirements." This standard covers such items as definitions, service conditions, ratings, testing, and manufacturing requirements.

33. COUPLING CAPACITORS AND COUPLING CAPACITOR VOLTAGE TRANSFORMERS(2)

Coupling Capacitor Voltage Transformers

Coupling capacitor voltage transformers, commonly termed capacitor voltage transformers (CVTs), are devices used for coupling to a power line to provide low voltage(s) for the operation of relays and metering instruments. Power line carrier accessories or provisions for future installation of carrier accessories may be included in the base.

Coupling Capacitor Voltage Transformers With and Without Wave Trap

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34. Lightning Protection

Lightning protection is used to protect substation equipment from direct lightning strokes. Lightning Masts are located at the outdoor yard. Overhead Shielding wires are used to cover entire outdoor yard.

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35. Isolated Phase Bus System

Isolated Phase Bus System provides connection between Generator and the main Transformer. It carries very high currents.

36. Neutral Grounding Equipment

Neutral Grounding Equipment are Resistors and reactors. They are used to limit the short circuit current during ground fault. They are connected between neutral point and ground..

37. Line Trap -

Line Trap consists of Inductive coil usually connected in the outdoor yard incoming line. Line traps are usually mounted above Capacitor Voltage Transformer (CVT) or on separate structure.

38. Insulators(1)

Used for Insulation purpose. Different types of insulators are porcelain, Glass, Epoxy.

38. Insulators(2)

Post-type apparatus insulators are the type most often used today for new substation construction. The uniform profile and smaller diameter enhance insulator appearance. Post insulator types in general use are made of porcelain and polymer.

Station Post Insulator

38. Insulators(2)

Suspension insulators are used as insulation and support for strain buses in substations. Suspension insulators are available in several forms to suit individual equirements.

Suspension Insulator

39. Power Cables

Power Cables are used to carry the power. They are single core and three core. Types of power cables are PVC insulated, XLPE insulated.

40. Control Cables

Control Cables are for protection, control and measurement etc.. They are of low voltage and PVC insulated. Control Cables are Multi core and Shielded.

41. Station Earthing System(1)

Station Earthing System includes Earth Mat and Earth electrodes placed below ground level. These Earth Mat and Earth electrode is connected to the equipment structures, neutral points for the purpose of Equipment earthing and neutral point earthing.

Function earthing system is to provide low resistance earthing for

1. Discharging currents from the surge arresters, overhead shielding, earthing switches
2. For equipment body earthing
3. For safe touch potential and step potential in substation.

41. Station Earthing System(2)

42. Metering, Control and Relay panels

To house various measuring Instruments, control Instruments, Protective relays. They are located in air-conditioned building. Control Cables are laid between Switchyard equipment and these panels.

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43. Switching Schemes or Busbar Arrangements in Substation

Burbars are the important elements in the substation. Bus bars acts as nodal point in the substation which connects different incoming and outgoing circuits.

Substations present in the power system performs various operations depends on the application such as stepping up the voltage, stepping down the voltage, high voltage transmission and switching stations to route the power to desired load center..

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44. Busbars in Substation

Busbars used in the substations are generally rectangular or circular cross section bars. These busbars can be either solid or hollow structures. Hollow circular cross section busbars are employs in EHV substations to reduce the corona effect.

45. Switching Schemes

Switching schemes implies different methods employed to connect electrical circuits in the power system to transfer the electrical power in reliable manner. Switching schemes helps in deliver the electrical power to power system if any part of the system is faulty or under maintenance.

Substations use different types of busbar arrangements or switching schemes depends upon the application, reliability of the supply and cost of installation. In every substations busbars plays a common role to connect different circuits. However switching is possible in the power system with the help of circuit breakers and isolators.

46. Different busbar arrangements

Some of the switching schemes are busbar arrangements employed in the substations are listed below:

A) Single Bus-bar arrangement

B) Double Main Bus-bar scheme

C) Main and Transfer bus-bar scheme

D) One and half breaker scheme

E) Ring Main arrangement scheme.

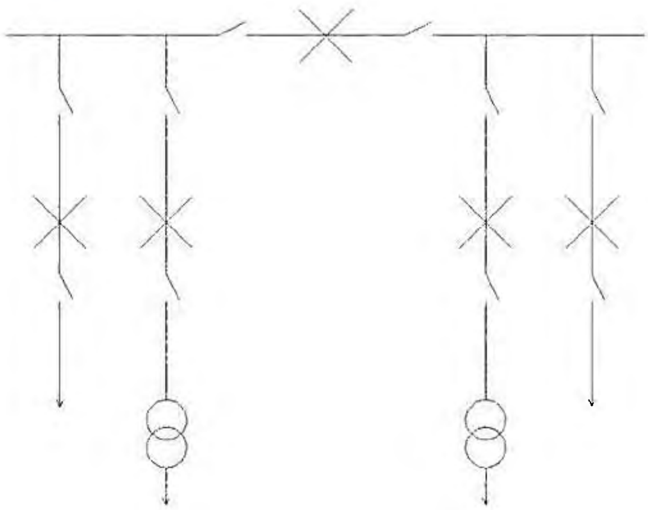
47. Single Bus-bar scheme(1)

This is the simplest busbar scheme available which consists of single set of busbars connected to the generators, transformers and load feeders. All the feeders are connected by circuit breaker and set of isolators. This arrangement helps to remove the connecting elements (Generators, transformers, etc.) for maintenance by opening the circuit breaker contacts and further opening the isolators.

Advantages:
- This busbar arrangement enjoys less cost of installation
- Less maintenance
- simple operation

Disadvantages:
- Fault on the busbar all the feeders connected to the busbars should be disconnected
- when Busbar is under maintenance total supply and all feeders should be disconnected
- Least flexibility and reliability

48. Single Bus-bar scheme(2)



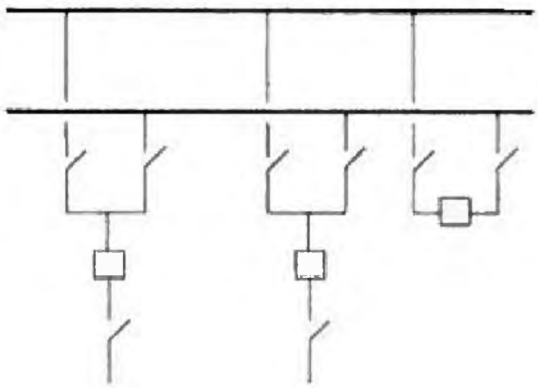
49. Double Main Busbar Scheme(1)

Normally in double main busbar scheme each circuit is connected to both the buses. In some cases half of the circuits can be connected and operated on each bus, in these cases bus or circuit breaker failure would cause loss to half of the circuits. In double main busbar arrangement one or two breakers can be provided for each circuit. Double main busbar and double breaker scheme provides high reliability in the case of fault or outage of one of the breaker.

Advantages:
- Any circuit can be taken out of circuit for maintenance
- Flexibility in connecting the feeder circuit to either of the busbars

Disadvantages:
- Most expensive
- Loose circuits connected to busbar when fault occurs on the busbar

50. Double Main Busbar Scheme(2)



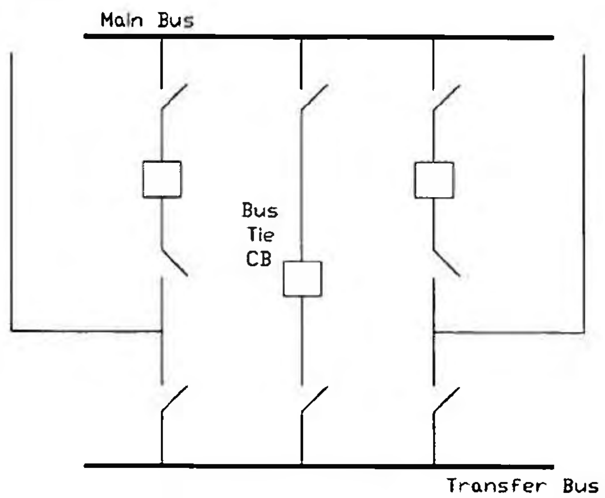
51. Main and Transfer Busbar Scheme(1)

Main and Transfer busbar scheme is similar to single busbar arrangement with additional transfer bus connected. Tie circuit breaker is provided to tie both the main and transfer bus. During normal operation all the circuits are connected to the main bus. When circuit breaker connected to the circuit (transmission line) is required to trip for maintenance, tie circuit breaker connecting the main and transfer bus is closed. The relay protection for the circuits connected to the transfer bus is taken care by the tie circuit breaker.

Advantages:
- Low initial cost
- Any breaker can be taken of circuit for maintenance

Disadvantages:
- Requires one extra breaker for bus tie
- Switching is somewhat complicated when breaker is under maintenance

52. Main and Transfer Busbar Scheme(2)



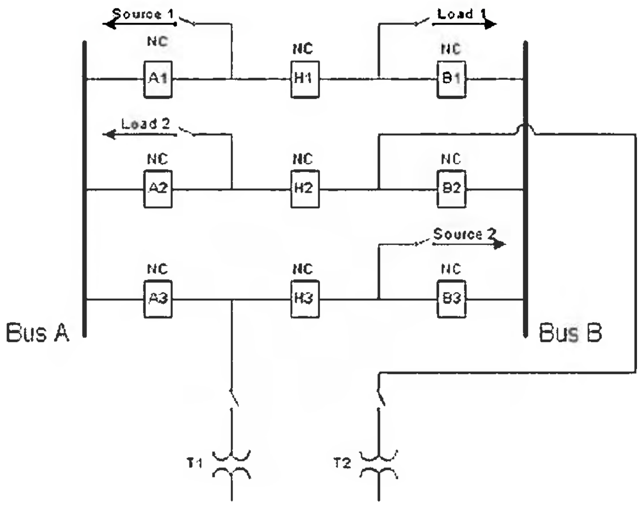
53. One and Half breaker Busbar scheme(1)

In One and half breaker scheme, two circuits are connected between the three circuit breakers. Hence One and Half breaker name was coined for this type of arrangement. Under normal operating conditions all the breakers are closed and both the busbars are energized. Any Circuit fault will trip two circuit breakers and no other circuit will be affected in this arrangement. When a busbar fault occur only breakers adjacent to busbars trips and no circuit will loose power. Two busbars can also be taken out of service with out affecting the power flow if the power source circuit (alternator circuit) and receiving circuit (transmission line) available in the same bay.

Advantages:
- Most flexible operation possible
- High reliability
- Bus failure will not remove any circuit from service

Disadvantages:
- High cost
- Relaying is somewhat complicated since the middle breaker must responsible for both the circuits on either direction and should operate

54. One and Half breaker Busbar scheme(2)



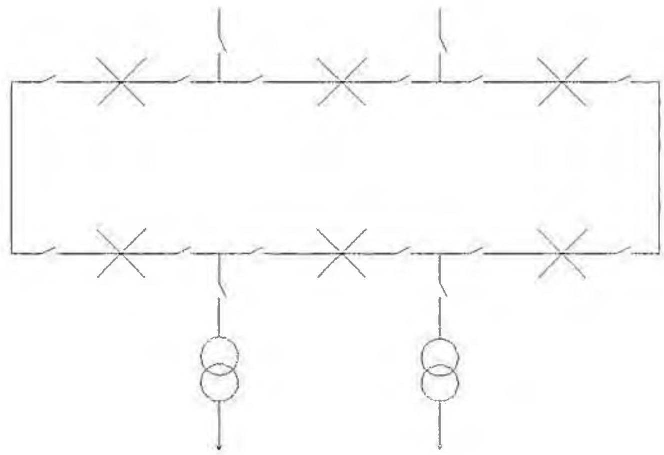
55. Ring busbar scheme(1)

In this ring main busbar scheme arrangement, breakers are connected in ring and circuits are connected between the breakers. There will be same number of circuits as the number of breakers in the arrangement. During normal operation all the breakers are closed. During circuit fault two breakers connecting the circuit trips. During breaker maintenance the ring is broken but all the lines remain in service.

Advantages:
- Low cost
- Flexible operation for breaker maintenance
- Any breaker can be taken out of service without interrupting load
- Power can be fed from both the direction

Disadvantages:
- Fault occur during maintenance will break the ring
- Relaying is complex
- Breaker failure during fault will trip one additional circuit

56. Ring busbar scheme(2)



Japanese Technical Assistance
on Strengthening Institutional Capacity
of National Development Agency (ADN)
in Democratic of Timor-Leste

-- POWER --

Syllabus

No.	Contents
1	Introduction
2	Power Station (Diesel)
3	Substation
4	Transmission and Distribution System
5	Power System Study
6	Power Flow Analysis
7	Renewable Energy (Photovoltaic Power)
8	Protecting System
9	Power System Operation and Control
10	Others

The contents may be changed depending on conditions.
I would like to discuss about the contents with Mr. Miguel and YOU.

VI. TRANSMISSION AND DISTRIBUTION SYSTEM

VI. TRANSMISSION AND DISTRIBUTION SYSTEM

INTRODUCTION

Power Transmission Equipment

- Step-up and Step-down Power Transformers.
- Voltage regulator
- Phase shifter
- Transmission lines and cables
- Circuit breakers and isolators
- Shunt and series reactors and capacitors
- Lightning arresters
- Protective relays
- Fact devices (SVC, Statcom, TCSC, etc.)
- Converter and Inverter

Distribution System Equipment

- Distribution transformers
- Feeders (overhead or underground cables)
- Switches, fuses, etc.
- Protective relays
- Lightning arrestors
- CT/PT

Overhead vs. Underground Systems

- Underground cables are technically advantages than the overhead lines
  - Not exposed to environmental conditions
  - Inductance is lower in cable so voltage drop is less
- But cables are much more costlier than overhead lines for same dispatch capability and voltage
  - Cost of conductor is high
  - Cost of insulation is high
- Erection cost is lower for cables but high maintenance cost.

Overhead vs. Underground Systems

- Capacitance is predominant in the cables.
- This gives large charging current which limits the length of the cables.
- Therefore long distance transmission overhead lines are preferred. Cables are mainly used at distribution levels.
- Cables are preferred in following conditions:
  - Public safety involved and low interference is required
  - Large populated cities
  - Scenic beauty of city is important
  - Submarine crossing, and substation and transformer connections

Choice of Working Voltage

- The cost of conductor is expensive item in overhead transmission and this is greatly affected by the choice of the voltage level.

V_1	V_2	$= mV_1$
I_1	I_2	$= I_1 / m$
R_1	R_2	$= m^2 R_1$
a_1	a_2	$= a_1 / m^2$

- There will be a saving in cost of conductor material if the power is delivered at higher voltages.

Choice of Working Voltage

- But higher system voltages will entail more cost of insulation in equipment like transformers, circuit-breakers, and switches.
- Cost of insulation increases rapidly with increasing voltages.
- Therefore for certain length of transmission line, the voltage level beyond which it becomes uneconomical.
- Therefore, the question is how to select the transmission and distribution voltages?

Choice of Working Voltage

- If C is total annual cost as function of conductor cross section A and working voltage V

$$C = f(A, V)$$

- For minimum cost

$$\delta f / \delta A = 0$$

$$\delta f / \delta V = 0$$

- This will result in most economical conductor cross section and system voltage, if the function f can be defined accurately.

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Choice of Working Voltage

- C = annual interest and depreciation on capital cost (fixed cost) + annual cost of energy losses (operational cost).
- Operational cost depends on conductor cross section, voltage, power factor, change in load time to time, harmonics, etc.
- Thus, function f depends on many factors and complicated enough to describe it mathematically.
- Hence determination based on economic basis is unsatisfactory.

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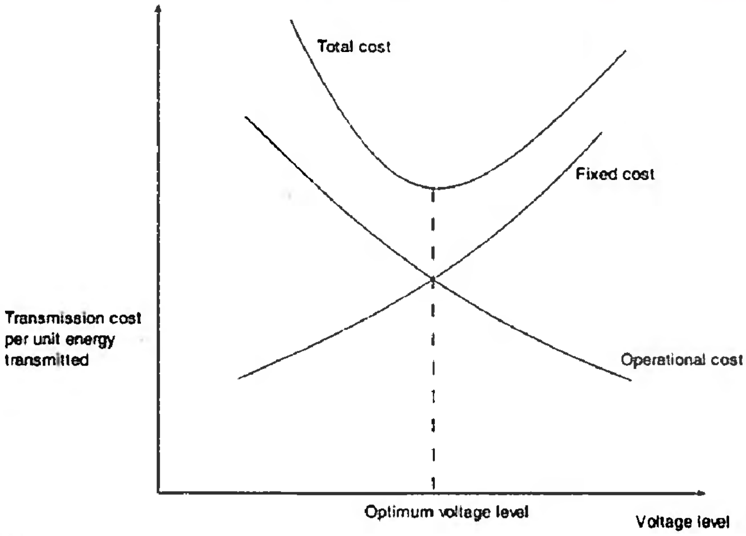
Transmission Cost as Function of Voltage Level.



Choice of Working Voltage

$$V = 5.5\sqrt{\frac{L}{1.6} + \frac{kVA}{150}}$$

$$V = 5.5\sqrt{\frac{L}{1.6} + \frac{3P}{100}}$$

- V is the line voltage in kV
- L is the line distance in km
- P is the estimated maximum power in kW per phase

- Using these empirical relations preliminary estimate is made.
- Then voltage level is chosen by doing complete economic study of existing interconnected system.

VI. TRANSMISSION AND DISTRIBUTION SYSTEM

LINE PARAMETERS

Electrical Parameters

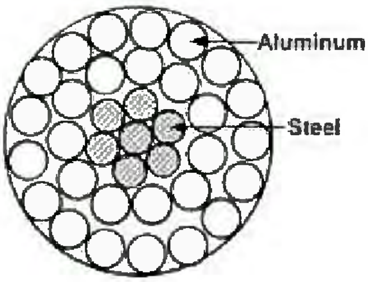
- Resistance
- Inductance
- Capacitance
- Conductance

- Conductance is due to leakage over line insulators. It is very small and can be always neglected.

Types of Conductor

- Copper
- Aluminum: Cheaper, lighter, but less conductive and less tensile strength than copper
  - ACSR (Aluminum Conductor Steel Reinforced)
  - AAC (All Aluminum Conductor)
  - AAAC (All Aluminum Alloy Conductor)
  - ACAR (Aluminum Conductor Alloy Reinforced)
  - Expanded ACSR

ACSR Conductor



- Internal steel strands increase the tensile strength
- Outer aluminum strands carry the current
- Stranded conductor with twisted wires for strength and flexibility of mechanical handling.

Resistance

- The DC resistance of conductor at specified temperature is:

$$R = \frac{\rho_T \, l}{A} \ \Omega$$

  - ρ_T is the resistivity of the conductor at temperature T
  - l is the length of the conductor in m
  - A is the cross-sectional area of conductor in m^2

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Resistance

- Temperature dependence of resistance:

$$R_t = R_0(1 + \alpha_0 T)$$

  - R_0 is the resistance at 0^0C
  - α_0 is the temperature coefficient of the resistance of conductor at 0^0C
- Thus, if the resistance at temperature T_1 is known, the resistance at any other temperature T_2 can be computed using:

$$\frac{R_{t2}}{R_{t1}} = \frac{(1/\alpha_0 + T_2)}{(1/\alpha_0 + T_1)}$$

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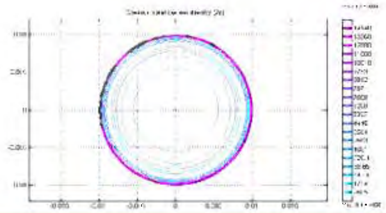
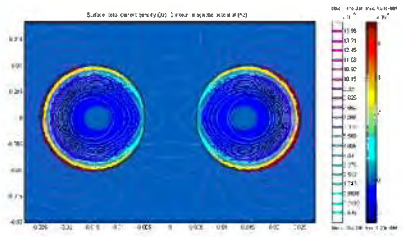
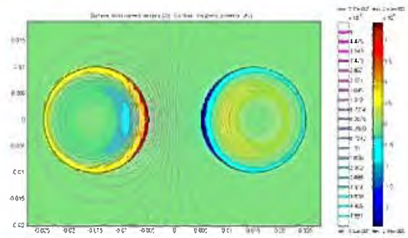
AC Resistance: Skin and Proximity Effect

Skin Effect



Proximity Effect





Resistance

Material	% Conductivity	Resistivity (20^{0}C) Ωm
Copper	100%	1.72
Aluminum	61%	2.83
Iron	17.2%	10
Silver	108%	1.59

- Resistance depends on:
  - Temperature
  - Dimensions
  - Frequency

Inductance

- Most dominant line parameter

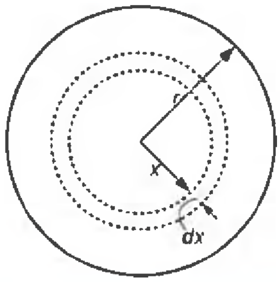
$$e = \frac{d\lambda}{dt} = \frac{d\lambda}{di} \cdot \frac{di}{dt} = L\frac{di}{dt}$$

- Therefore $L = \frac{d\lambda}{di}$
- In linear magnetic systems $L = \frac{\lambda}{i}$
- Mutual inductance is: $M_{12} = \frac{\lambda_{12}}{I_2}$

Steps in Calculating Inductance

- Magnetic field intensity (***H***) using Ampere's law
- Magnetic flux density ***B*** (=μ***H***)
- Flux linkages (λ)
- Inductance from flux linkage per ampere ($L=\lambda/I$)

Internal Inductance



$$mmf = \oint H \cdot ds = I$$

$$\oint H_x \cdot dx = I_x \Rightarrow H_x = \frac{I_x}{2\pi x}$$

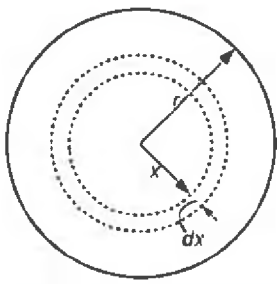
$$\frac{I}{\pi r^2} = \frac{I_x}{\pi x^2} \Rightarrow I_x = \frac{\pi x^2}{\pi r^2} I$$

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

$$B_x = \mu_0 H_x = \frac{\mu_0 I}{2\pi r^2} x$$

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

Internal Inductance



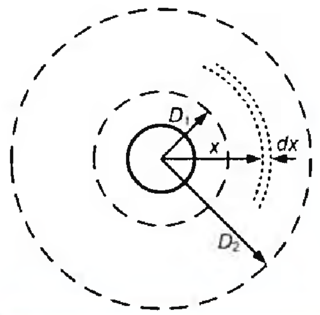
$$d\phi_x = B_x dx \times 1 = \frac{\mu_0 I}{2\pi r^2} x dx$$

$$d\lambda_x = \frac{\pi x^2}{\pi r^2} d\phi_x = \frac{\mu_0 I}{2\pi r^4} x^3 dx$$

$$\lambda_{int} = \int_0^r \frac{\mu_0 I}{2\pi r^4} x^3 dx = \frac{\mu_0 I}{8\pi} = \frac{I}{2} \times 10^{-7}$$

$$L_{int} = \frac{1}{2} \times 10^{-7}$$

External Inductance



$$2\pi x H_x = I$$

$$B_x = \frac{\mu_0 I}{2\pi x}$$

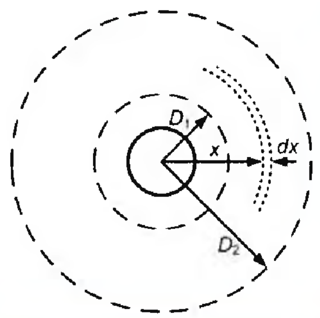
$$d\lambda_x = d\phi_x = B_x dx \cdot 1 = \frac{\mu_0 I}{2\pi x} dx$$

$$\lambda_{ext} = \frac{\mu_0 I}{2\pi} \int_{D_1}^{D_2} \frac{1}{x} dx = 2\times10^{-7} I \ln \frac{D_2}{D_1}$$

$$mmf = \oint H \cdot ds = I$$

$$L_{ext} = 2\times10^{-7} \ln \frac{D_2}{D_1}$$

External Inductance



$$2\pi x H_x = I$$

$$B_x = \frac{\mu_0 I}{2\pi x}$$

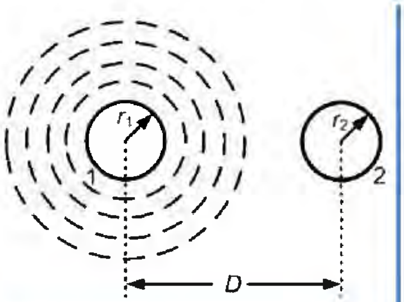
$$d\lambda_x = d\phi_x = B_x dx \cdot 1 = \frac{\mu_0 I}{2\pi x} dx$$

$$\lambda_{ext} = \frac{\mu_0 I}{2\pi} \int_{D_1}^{D_2} \frac{1}{x} dx = 2\times10^{-7} I \ln \frac{D_2}{D_1}$$

$$mmf = \oint H \cdot ds = I$$

$$L_{ext} = 2\times10^{-7} \ln \frac{D_2}{D_1}$$

Inductance of Single-Phase Line



$$L_{int} = \frac{1}{2} \times 10^{-7}$$

$$L_{ext} = 2 \times 10^{-7} \ln \frac{D_2}{D_1}$$

$$L_1 = \left(\frac{1}{2} + 2\ln\frac{D}{r_1}\right) \times 10^{-7}$$

$$L_1 = 2 \times 10^{-7}\left(\frac{1}{4} + \ln\frac{D}{r_1}\right)$$

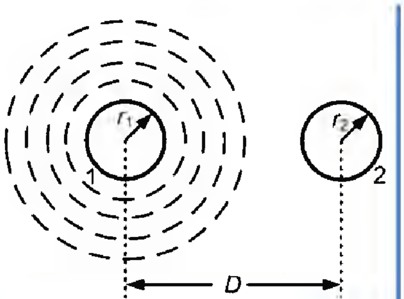
$$= 2 \times 10^{-7}\left(\ln e^{1/4} + \ln\frac{D}{r_1}\right)$$

$$= 2 \times 10^{-7}\left(\ln\frac{D}{r_1 e^{-1/4}}\right)$$

$$L_1 = 2 \times 10^{-7}\left(\ln\frac{D}{r_1'}\right)$$

$$L_2 = 2 \times 10^{-7}\left(\ln\frac{D}{r_2'}\right)$$

Inductance of Single-Phase Line



$$L_1 = 2 \times 10^{-7}\left(\ln\frac{D}{r_1'}\right)$$

$$L_2 = 2 \times 10^{-7}\left(\ln\frac{D}{r_2'}\right)$$

$$L = L_1 + L_2$$

$$= 2 \times 10^{-7}\left(\ln\frac{D}{r_1'}\right) + 2 \times 10^{-7}\left(\ln\frac{D}{r_2'}\right)$$

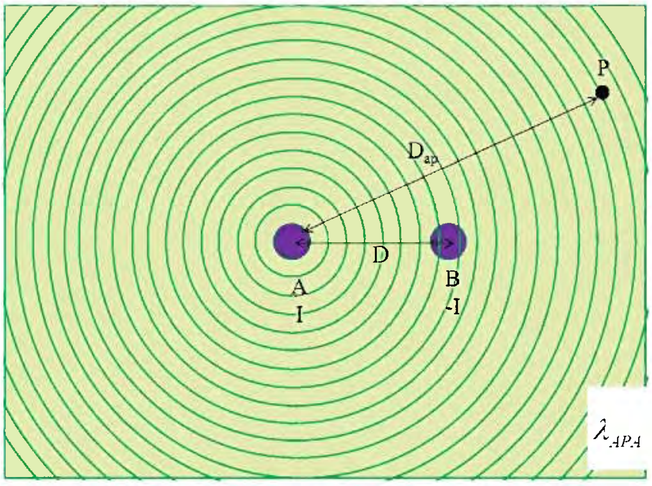
$$= 2 \times 10^{-7}\left(\ln\frac{D^2}{r_1' r_2'}\right)$$

$$= 4 \times 10^{-7}\left(\ln\frac{D}{\sqrt{r_1' r_2'}}\right) \text{ H/m}$$

If $r_1' = r_2' = r'$, then

$$L = 4 \times 10^{-7}\left(\ln\frac{D}{r'}\right)$$

Flux Linkage of Conductor A due to Current in Conductor A



$$\lambda_{APA} = 2\times10^{-7}\, I \ln\frac{D_{ap}}{r'}$$

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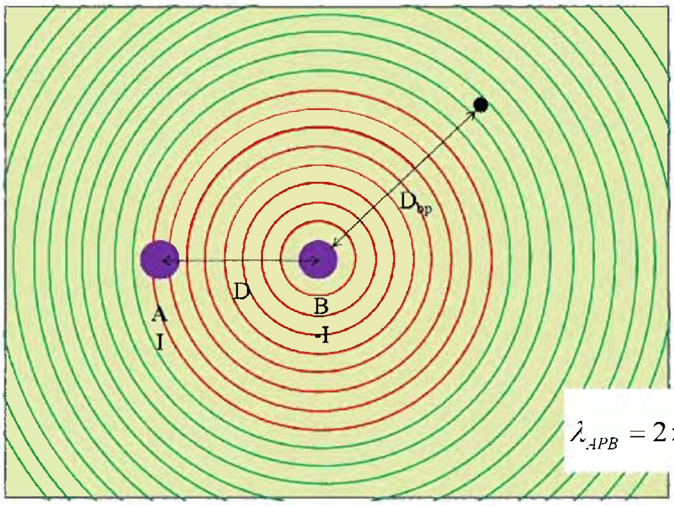
Flux Linkage of Conductor A due to Current in Conductor B



$$\lambda_{APB} = 2\times10^{-7}(-I)\ln\frac{D_{bp}}{D}$$

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Total Inductance

$$\lambda_A = \lambda_{APA} + \lambda_{APB}$$

$$= 2\times10^{-7}\, I\, \ln\frac{D_{ap}}{r'} - 2\times10^{-7}\, I\, \ln\frac{D_{bp}}{D}$$

$$= 2\times10^{-7}\, I \left(\ln\left(\frac{1}{r'}\right) + \ln D_{ap} - \ln\left(\frac{1}{D}\right) - \ln D_{bp} \right)$$

$$= 2\times10^{-7}\, I \left(\ln\left(\frac{D}{r'}\right) + \ln\left(\frac{D_{ap}}{D_{bp}}\right) \right)$$

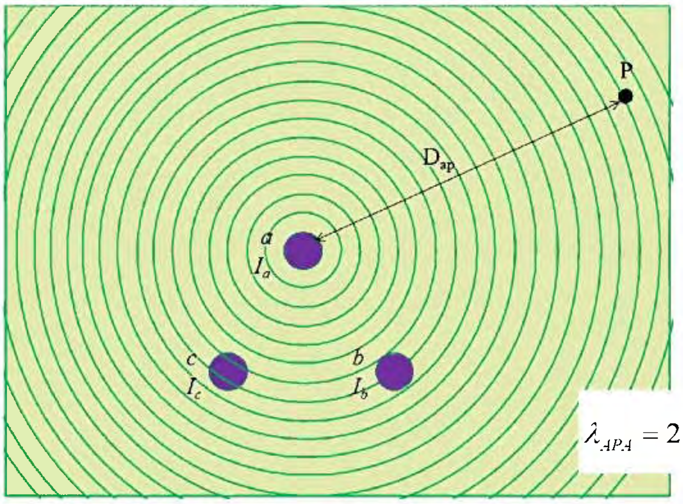
If P is at very long distance from conductor $D_{ap} \approx D_{bp}$

$$\lambda_A = 2\times10^{-7}\, I \left(\ln\left(\frac{D}{r'}\right) \right)$$

$$L_A = 2\times10^{-7} \left(\ln\left(\frac{D}{r'}\right) \right)$$

Inductance of Three-Phase Line (Symmetrical Spacing)

Flux Linkage of Conductor A due to Current in Conductor A



$$\lambda_{APA} = 2\times10^{-7}\, I_a \ln\frac{D_{ap}}{r'}$$

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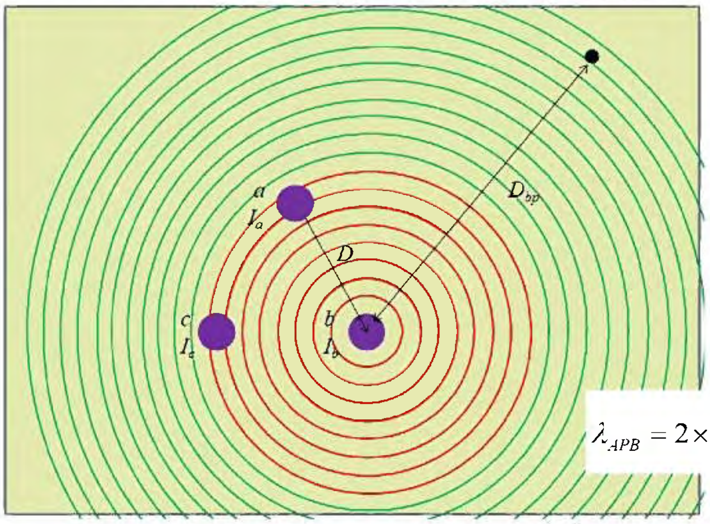
Flux Linkage of Conductor A due to Current in Conductor B



$$\lambda_{APB} = 2\times10^{-7}\, I_b \ln\frac{D_{bp}}{D}$$

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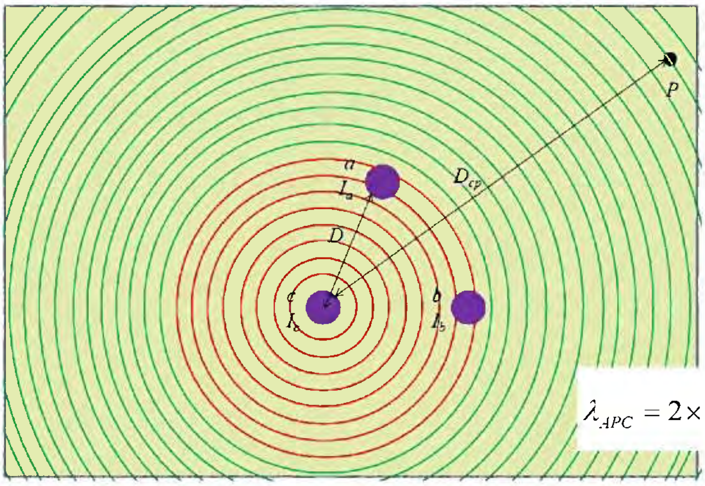
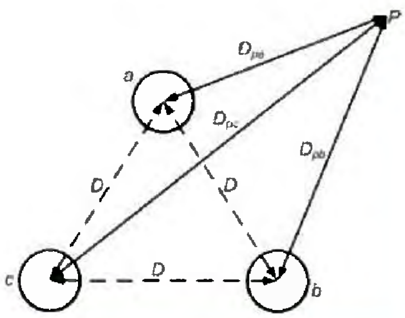
Flux Linkage of Conductor A due to Current in Conductor C



$$\lambda_{APC} = 2\times10^{-7}\, I_c \ln\frac{D_{cp}}{D}$$

Inductance of Three-Phase Line (Symmetrical Spacing)



$$L_1 = \left(\frac{1}{2} + 2\ln\frac{D}{r_1}\right)\times10^{-7}$$

$$I_a + I_b + I_c = 0$$

$$\lambda_{apa} = \left(\frac{1}{2} + 2\ln\frac{D_{pa}}{r}\right) I_a \times10^{-7}$$

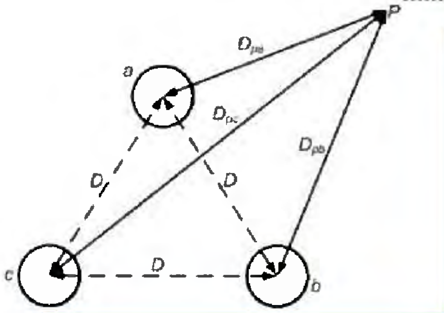
$$= 2\times10^{-7}\, I_a \ln\frac{D_{pa}}{r'}$$

Similarly,

$$\lambda_{apb} = 2\times10^{-7}\, I_b \ln\frac{D_{pb}}{D}$$

$$\lambda_{apc} = 2\times10^{-7}\, I_c \ln\frac{D_{pc}}{D}$$

Inductance of Three-Phase Line (Symmetrical Spacing)



$$\lambda_{apa} = 2\times10^{-7} I_a \ln \frac{D_{pa}}{r'}$$

$$\lambda_{apb} = 2\times10^{-7} I_b \ln \frac{D_{pb}}{D}$$

$$\lambda_{apc} = 2\times10^{-7} I_c \ln \frac{D_{pc}}{D}$$

$$\lambda_a = \lambda_{apa} + \lambda_{apb} + \lambda_{apc}$$

$$= 2\times10^{-7}\left(I_a \ln \frac{D_{pa}}{r'} + I_b \ln \frac{D_{pb}}{D} + I_c \ln \frac{D_{pc}}{D} \right)$$

Expanding,

$$\lambda_a = 2\times10^{-7}\left(I_a \ln \frac{1}{r'} + I_b \ln \frac{1}{D} + I_c \ln \frac{1}{D} + I_a \ln D_{pa} + I_b \ln D_{pb} + I_c \ln D_{pc} \right)$$

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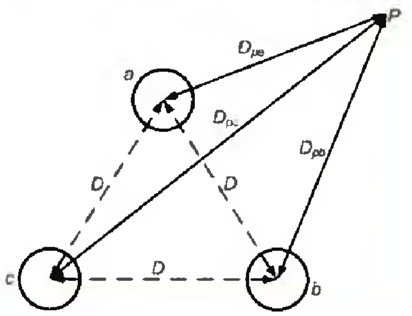
Inductance of Three-Phase Line (Symmetrical Spacing)



$$\lambda_a = 2\times10^{-7}\left(I_a \ln \frac{1}{r'} + I_b \ln \frac{1}{D} + I_c \ln \frac{1}{D} + I_a \ln D_{pa} + I_b \ln D_{pb} + I_c \ln D_{pc} \right)$$

$$I_a + I_b + I_c = 0 \Rightarrow I_a = -I_b - I_c$$

$$\lambda_a = 2\times10^{-7}\left(I_a \ln \frac{1}{r'} - I_a \ln \frac{1}{D} + I_b \ln \frac{D_{pb}}{D_{pa}} + I_c \ln \frac{D_{pc}}{D_{pa}} \right)$$

If point P far away, then we can approximate $D_{pa} \approx D_{pb} \approx D_{pc}$

$$\lambda_a = 2\times10^{-7}\left(I_a \ln \frac{1}{r'} - I_a \ln \frac{1}{D} \right)$$

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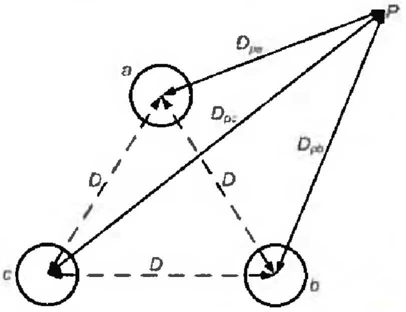
Inductance of Three-Phase Line (Symmetrical Spacing)



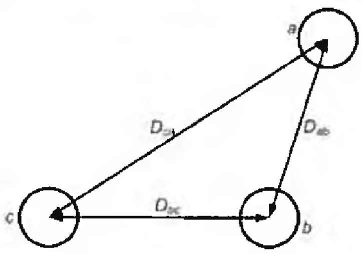
$$\lambda_a = 2\times10^{-7} I_a \ln \frac{D}{r'}$$

Inductance of phase-a

$$L_a = 2\times10^{-7} \ln \frac{D}{r'}$$

$$\lambda_a = 2\times10^{-7}\left(I_a \ln \frac{1}{r'} - I_a \ln \frac{1}{D}\right)$$

Inductance of Three-Phase Line (Asymmetrical Spacing)



$$I_a + I_b + I_c = 0 \Rightarrow I_a = -I_b - I_c$$

$$\lambda_a = 2\times10^{-7}\left(I_a \ln \frac{1}{r'} + I_b \ln \frac{1}{D_{ab}} + I_c \ln \frac{1}{D_{ca}}\right)$$

$$\lambda_b = 2\times10^{-7}\left(I_b \ln \frac{1}{r'} + I_a \ln \frac{1}{D_{ab}} + I_c \ln \frac{1}{D_{bc}}\right)$$

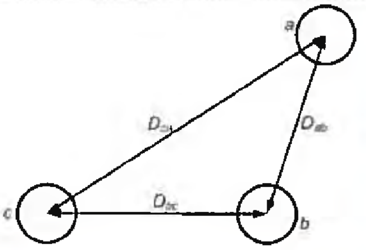
$$\lambda_c = 2\times10^{-7}\left(I_c \ln \frac{1}{r'} + I_a \ln \frac{1}{D_{ca}} + I_b \ln \frac{1}{D_{bc}}\right)$$

$$\lambda_a = 2\times10^{-7}\left(I_a \ln \frac{1}{r'} + I_b \ln \frac{1}{D} + I_c \ln \frac{1}{D} + I_a \ln D_{pa} + I_b \ln D_{pb} + I_c \ln D_{pc}\right)$$

$$a = e^{j120^0} = -\frac{1}{2} + j\frac{\sqrt{3}}{2}$$

$$a^2 = e^{j240^0} = -\frac{1}{2} + j\frac{\sqrt{3}}{2}$$

Inductance of Three-Phase Line (Asymmetrical Spacing)



$$I_b = a^2 I_a \text{ and } I_c = aI_a$$

$$\lambda_a = 2\times10^{-7}\left(I_a \ln\frac{1}{r'} + I_b \ln\frac{1}{D_{ab}} + I_c \ln\frac{1}{D_{ca}}\right)$$

$$\lambda_b = 2\times10^{-7}\left(I_b \ln\frac{1}{r'} + I_a \ln\frac{1}{D_{ab}} + I_c \ln\frac{1}{D_{bc}}\right)$$

$$\lambda_c = 2\times10^{-7}\left(I_c \ln\frac{1}{r'} + I_a \ln\frac{1}{D_{ca}} + I_b \ln\frac{1}{D_{bc}}\right)$$

$$L_a = 2\times10^{-7}\left(\ln\frac{1}{r'} + a^2 \ln\frac{1}{D_{ab}} + a\ln\frac{1}{D_{ca}}\right)$$

$$L_b = 2\times10^{-7}\left(\ln\frac{1}{r'} + a \ln\frac{1}{D_{ab}} + a^2\ln\frac{1}{D_{bc}}\right)$$

$$L_c = 2\times10^{-7}\left(\ln\frac{1}{r'} + a^2 \ln\frac{1}{D_{ca}} + a\ln\frac{1}{D_{bc}}\right)$$

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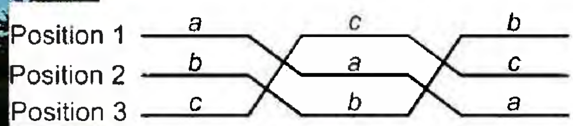
Inductance of Three-Phase Transposed Line (Asymmetrical Spacing)

- Asymmetrical spacing causes flux linkages and inductance for each phase to be different.
- This results in unequal voltages at the receiving end.



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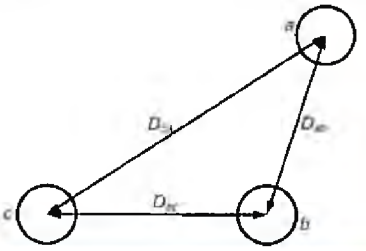
Inductance of Three-Phase Transposed Line (Asymmetrical Spacing)



$$L_a = 2\times10^{-7}\left(\ln\frac{1}{r'} + a^2\ln\frac{1}{D_{ab}} + a\ln\frac{1}{D_{ca}}\right)$$

$$L_b = 2\times10^{-7}\left(\ln\frac{1}{r'} + a\ln\frac{1}{D_{ab}} + a^2\ln\frac{1}{D_{bc}}\right)$$

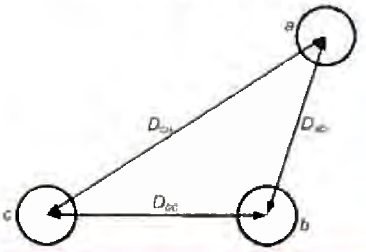
$$L_c = 2\times10^{-7}\left(\ln\frac{1}{r'} + a^2\ln\frac{1}{D_{ca}} + a\ln\frac{1}{D_{bc}}\right)$$

$$L = \frac{L_a + L_b + L_c}{3}$$

Therefore

$$L = \frac{2\times10^{-7}}{3}\left[\ln\left(\frac{1}{r'}\right)^3 + (a + a^2)\left(\ln\frac{1}{D_{ab}} + \ln\frac{1}{D_{bc}} + \ln\frac{1}{D_{bc}}\right)\right]$$

Inductance of Three-Phase Transposed Line (Asymmetrical Spacing)



$$L = \frac{2\times10^{-7}}{3}\left[\ln\left(\frac{1}{r'}\right)^3 + (a + a^2)\left(\ln\frac{1}{D_{ab}} + \ln\frac{1}{D_{bc}} + \ln\frac{1}{D_{bc}}\right)\right]$$

$$a + a^2 = -1$$

$$L = \frac{2\times10^{-7}}{3}\left(3\ln\frac{1}{r'} - \ln\frac{1}{D_{ab}} - \ln\frac{1}{D_{bc}} - \frac{1}{D_{ca}}\right)$$

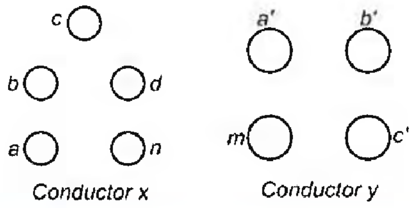
$$L = 2\times10^{-7}\left(\ln\frac{1}{r'} - \ln\frac{1}{(D_{ab}D_{bc}D_{ca})^{1/3}}\right)$$

$$= 2\times10^{-7}\ln\frac{(D_{ab}D_{bc}D_{ca})^{1/3}}{r'}$$

$$GMD = \sqrt[3]{D_{ab}D_{bc}D_{ca}}$$

$$L = 2\times10^{-7}\ln\frac{GMD}{r'}$$

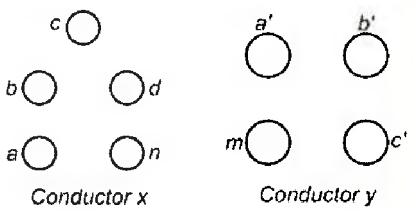
Composite Conductors



$$\lambda_a = 2\times10^{-7}\frac{I}{n}\left(\ln\frac{1}{r_x'}+\ln\frac{1}{D_{ab}}+\ln\frac{1}{D_{ac}}+\cdots+\ln\frac{1}{D_{an}}\right)$$
$$-2\times10^{-7}\frac{I}{m}\left(\ln\frac{1}{D_{aa'}}+\ln\frac{1}{D_{ab'}}+\ln\frac{1}{D_{ac'}}+\cdots+\ln\frac{1}{D_{am'}}\right)$$

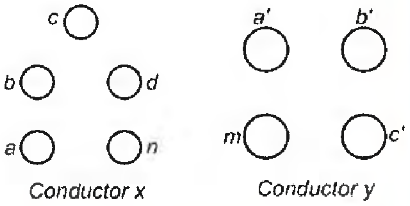
Composite Conductors

$$\lambda_a = 2\times10^{-7}\frac{I}{n}\left(\ln\frac{1}{r_x'}+\ln\frac{1}{D_{ab}}+\ln\frac{1}{D_{ac}}+\cdots+\ln\frac{1}{D_{an}}\right)$$
$$-2\times10^{-7}\frac{I}{m}\left(\ln\frac{1}{D_{aa'}}+\ln\frac{1}{D_{ab'}}+\ln\frac{1}{D_{ac'}}+\cdots+\ln\frac{1}{D_{am'}}\right)$$



$$\lambda_a = 2\times10^{-7}\, I \ln\frac{\sqrt[m]{D_{aa'}D_{ab'}D_{ac'}\cdots D_{am'}}}{\sqrt[n]{r_x' D_{ab}D_{ac}\cdots D_{an}}}$$

Composite Conductors



$$\lambda_a = 2\times10^{-7} I \ln \frac{\sqrt[m]{D_{aa'}D_{ab'}D_{ac'}\cdots D_{am'}}}{\sqrt[n]{r'_x D_{ab}D_{ac}\cdots D_{an}}}$$

$$L_a = \frac{\lambda_a}{(I/n)} = 2n\times10^{-7}\ln\frac{\sqrt[m]{D_{aa'}D_{ab'}D_{ac'}\cdots D_{am'}}}{\sqrt[n]{r'_x D_{ab}D_{ac}\cdots D_{an}}}$$

Similarly,

$$L_b = 2n\times10^{-7}\ln\frac{\sqrt[m]{D_{ba'}D_{bb'}D_{bc'}\cdots D_{bm'}}}{\sqrt[n]{r'_x D_{ab}D_{bc}\cdots D_{bn}}}$$

$$L_c = 2n\times10^{-7}\ln\frac{\sqrt[m]{D_{ca'}D_{cb'}D_{cc'}\cdots D_{cm'}}}{\sqrt[n]{r'_x D_{ac}D_{bc}\cdots D_{cn}}}$$

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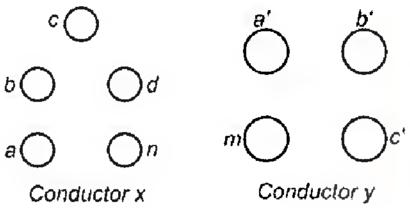
Composite Conductors



$$L_a = \frac{\lambda_a}{(I/n)} = 2n\times10^{-7}\ln\frac{\sqrt[m]{D_{aa'}D_{ab'}D_{ac'}\cdots D_{am'}}}{\sqrt[n]{r'_x D_{ab}D_{ac}\cdots D_{an}}}$$

$$L_{av,x} = \frac{L_a + L_b + L_c + \cdots + L_n}{n}$$

n strands that are electrically parallel:

$$L_x = \frac{L_{av,x}}{n} = \frac{L_a + L_b + L_c + \cdots + L_n}{n^2}$$

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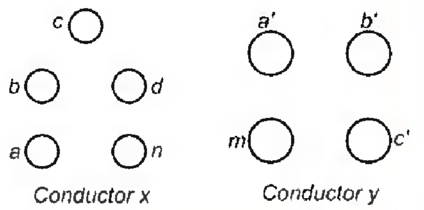
Composite Conductors



$$L_a = \frac{\lambda_a}{(I/n)}$$

$$= 2n \times 10^{-7} \ln \frac{\sqrt[m]{D_{aa'} D_{ab'} D_{ac'} \cdots D_{am'}}}{\sqrt[n]{r'_x D_{ab} D_{ac} \cdots D_{an}}}$$

$$L_x = \frac{L_{av,x}}{n} = \frac{L_a + L_b + L_c + \cdots + L_n}{n^2}$$

Substituting the values of L_a , L_b etc.

$$L_x = 2 \times 10^{-7} \ln \frac{GMD}{GMR_x}$$

Where,

$$GMD = \sqrt[mn]{(D_{aa'} D_{ab'} D_{ac'} \cdots D_{am'}) \cdots\cdots (D_{na'} D_{nb'} D_{nc'} \cdots D_{nm'})}$$

$$GMR_x = \sqrt[n^2]{(r'_x D_{ab} D_{ac} \cdots D_{an}) \cdots\cdots (r'_x D_{na} D_{nb} \cdots D_{nn-1})}$$

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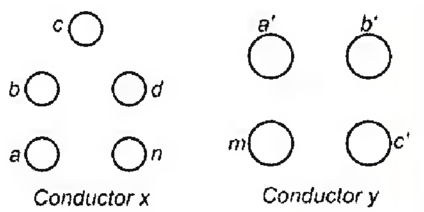
Composite Conductors



$$L_x = 2 \times 10^{-7} \ln \frac{GMD}{GMR_x}$$

Where,

$$GMD = \sqrt[mn]{(D_{aa'} D_{ab'} D_{ac'} \cdots D_{am'}) \cdots\cdots (D_{na'} D_{nb'} D_{nc'} \cdots D_{nm'})}$$

$$GMR_x = \sqrt[n^2]{(r'_x D_{ab} D_{ac} \cdots D_{an}) \cdots\cdots (r'_x D_{na} D_{nb} \cdots D_{nn-1})}$$

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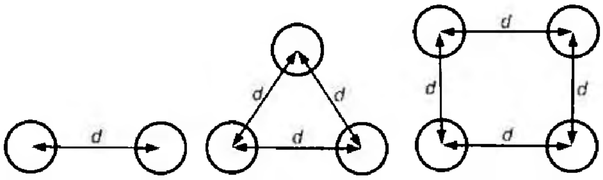
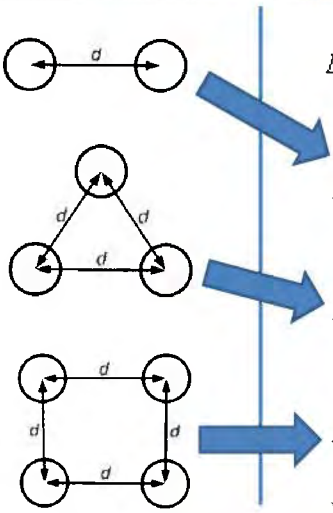
Bundled Conductors



- Extra high voltage lines corona causes problems such as power loss, interference, etc.
- The high voltage surface gradient is reduced considerably by having two or more conductors.
- It also reduces the inductance of lines by reducing voltage drop.

Bundled Conductors



$$L = 2\times10^{-7}\ln\frac{GMD}{D_{s,nb}}$$ where n=2,3 ....

$$D_{s,2b} = \sqrt[4]{(D_s \times d)^2} = \sqrt{D_s \times d}$$

$$D_{s,3b} = \sqrt[9]{(D_s \times d \times d)^3} = \sqrt[3]{D_s \times d^2}$$

$$D_{s,4b} = \sqrt[16]{(D_s \times d \times d \times \sqrt{2}d)^4} = 1.09\sqrt[4]{D_s \times d^3}$$

Where, D_s is the *GMR* of the conductor

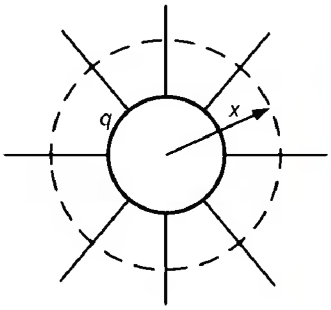
Line Parameters Preview

- Resistance
- Inductance
  - Inductance of single conductor
  - Inductance of three-phase line (symmetrical, asymmetrical spacing, transposition)
  - Composite and bundled conductor

Capacitance of a Straight Conductor

- Capacitance in a transmission line results due to the potential difference between the conductors.
- The conductors get charged in the same way as the parallel plates of a capacitor.
- Capacitance between two parallel conductors depends on the size and the spacing between the conductors.
- Usually the capacitance is neglected for the transmission lines that are less than 80 km (50 miles) long.
- However the capacitance becomes significant for longer lines with higher voltage.

Capacitance of a Straight Conductor

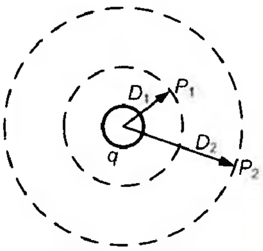


$$C = \frac{q}{V}$$

$$D = \frac{q}{A} = \frac{q}{2\pi x}$$

$$E = \frac{q}{2\pi x \varepsilon_0}$$

Capacitance of a Straight Conductor



$$E = \frac{q}{2\pi x \varepsilon_0}$$

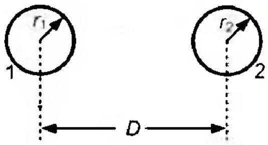
$$E = \frac{q}{2\pi x \varepsilon_0}$$

$$V_{12} = \int_{D_1}^{D_2} E dx$$

$$= \int_{D_1}^{D_2} \frac{q}{2\pi x \varepsilon_0} dx$$

$$= \frac{q}{2\pi \varepsilon_0} \ln \frac{D_2}{D_1}$$

Capacitance of a Single-Phase Line



$$V_{12} = \frac{q}{2\pi\,\varepsilon_0} \ln \frac{D_2}{D_1}$$

Let us assume that conductor 1 carries a charge of q_1 C/m while conductor 2 carries a charge q_2 C/m.

D>> r_1 and r_2 and ground influence also is neglected.

$$V_{12}(q_1) = \frac{q_1}{2\pi\,\varepsilon_0} \ln \frac{D}{r_1}$$

$$V_{12}(q_2) = \frac{q_2}{2\pi\,\varepsilon_0} \ln \frac{r_2}{D}$$

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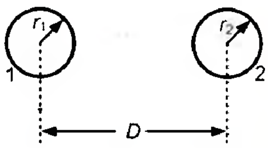
Capacitance of a Single-Phase Line



$$V_{12}(q_1) = \frac{q_1}{2\pi\,\varepsilon_0} \ln \frac{D_2}{r_1}$$

$$V_{12}(q_2) = \frac{q_2}{2\pi\,\varepsilon_0} \ln \frac{r_2}{D}$$

Let principle of superposition

$$V_{12} = V_{12}(q_1) + V_{12}(q_2)$$

$$= \frac{q_1}{2\pi\,\varepsilon_0} \ln \frac{D}{r_1} + \frac{q_2}{2\pi\,\varepsilon_0} \ln \frac{r_2}{D}$$

Assume that q_1 (= $-q_2$) is equal to q

$$V_{12} = \frac{q}{2\pi\,\varepsilon_0} \ln \frac{D}{r_1} - \frac{q}{2\pi\,\varepsilon_0} \ln \frac{r_2}{D}$$

$$= \frac{q}{2\pi\,\varepsilon_0} \ln \frac{D^2}{r_1 r_2}$$

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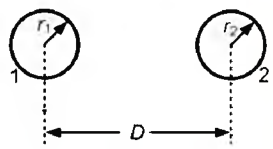
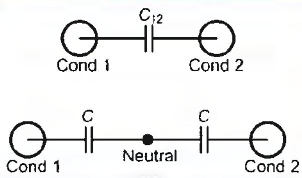
Capacitance of a Single-Phase Line





$$V_{12} = \frac{q}{2\pi\varepsilon_0}\ln\frac{D^2}{r_1 r_2}$$

Assuming $r_1 = r_2 = r$

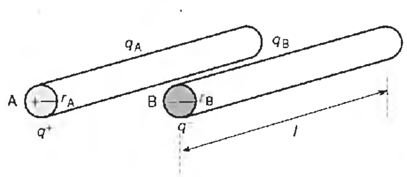
$$V_{12} = \frac{q}{\pi\varepsilon_0}\ln\frac{D}{r}$$

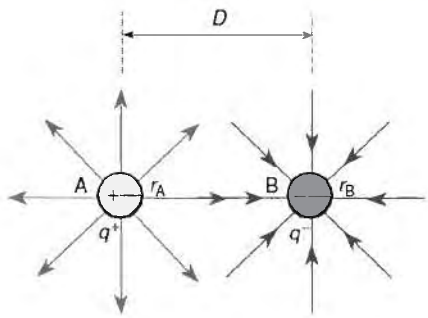
$$C_{12} = \frac{\pi\varepsilon_0}{\ln(D/r)}$$

Capacitance is defined between the conductor and neutral

$$C = 2C_{12} = \frac{2\pi\varepsilon_0}{\ln(D/r)}$$

Capacitance of Single-Phase Line





$$V_{AB-A} = \int_{r_A}^{D} E_A\,dx = \frac{q}{2\pi\varepsilon_0}\ln\left[\frac{D}{r_A}\right]$$

$$V_{AB-B} = \int_{D}^{r_B} E_B\,dx = \frac{-q}{2\pi\varepsilon_0}\ln\left[\frac{r_B}{D}\right]$$

Capacitance of Single-Phase Line

The total voltage is the sum of the generated voltages V_{AB-A} and V_{AB-B}

$$V_{AB} = V_{AB-A} + V_{AB-B} = \frac{q}{2\pi\varepsilon_0} \ln\left[\frac{D}{r_A}\right] - \frac{q}{2\pi\varepsilon_0} \ln\left[\frac{r_B}{D}\right]$$

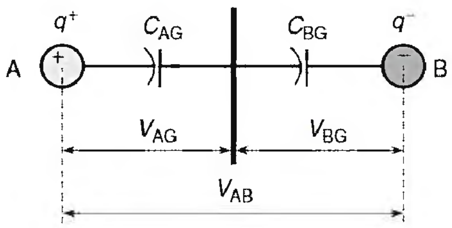
$$= \frac{q}{2\pi\varepsilon_0} \ln\left[\frac{D^2}{r_A r_B}\right]$$

If the conductors have the same radius, $r_A = r_B = r$,

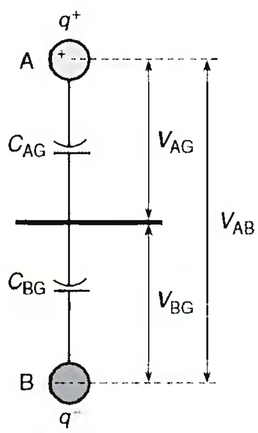
$$V_{AB} = \frac{q}{\pi\varepsilon_0} \ln\left[\frac{D}{r}\right] \text{ (V)}$$

$$C_{AB} = \frac{\pi\varepsilon_0}{\ln\left[\frac{D}{r}\right]} \text{ (F/m)}$$

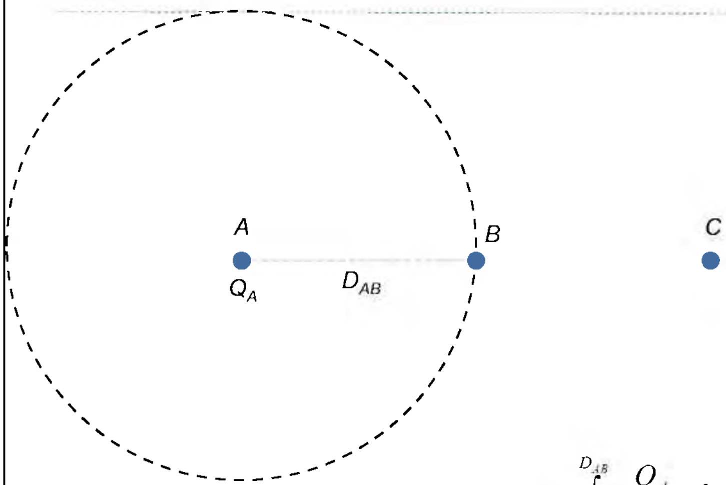
Phase to Neutral Capacitance of Single-Phase Line



$$C_{AG} = \frac{2\pi\varepsilon_0}{\ln\left[\frac{D}{r}\right]} \text{ (F/m)}$$



VAB due to charge QA



$$V_{AB\_A} = \int_{r_A}^{D_{AB}} \frac{Q_A}{2\pi\varepsilon_0 x}dx = \frac{Q_A}{2\pi\varepsilon_0}\ln\frac{D_{AB}}{r_A}$$

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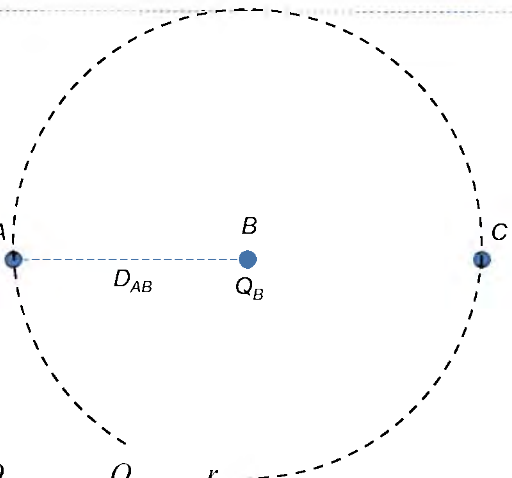
VAB due to charge QB



$$V_{AB\_B} = \int_{D_{AB}}^{R_B} \frac{Q_B}{2\pi\varepsilon_0 x}dx = \frac{Q_B}{2\pi\varepsilon_0}\ln\frac{r_B}{D_{AB}}$$

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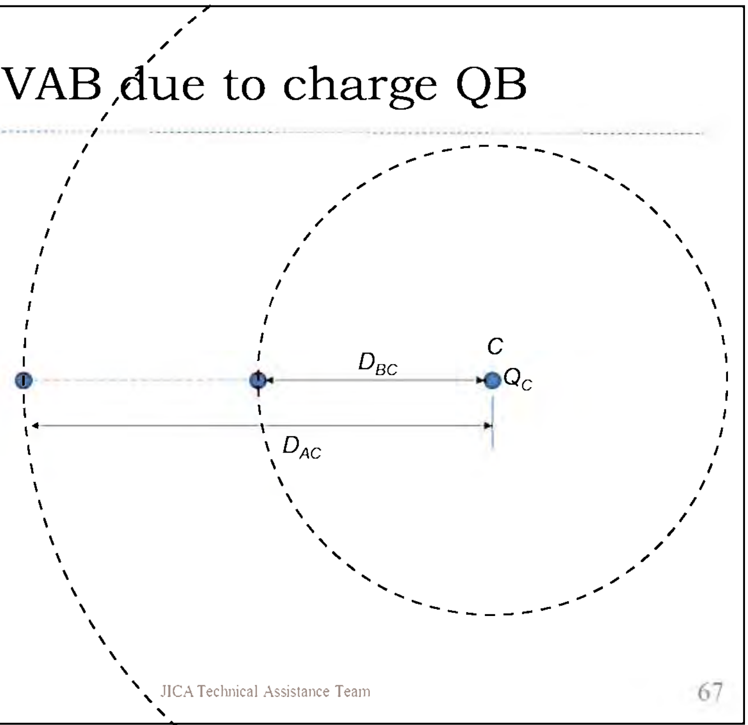
VAB due to charge QB



Voltage Difference between conductor A and B

$V_{AB\_A} = \frac{Q_A}{2\pi\varepsilon_0}\ln\frac{D_{AB}}{r_A}$	$V_{AB\_B} = \frac{Q_B}{2\pi\varepsilon_0}\ln\frac{r_B}{D_{AB}}$	$V_{AB\_C} = \frac{Q_C}{2\pi\varepsilon_0}\ln\frac{D_{AB}}{D_{AC}}$

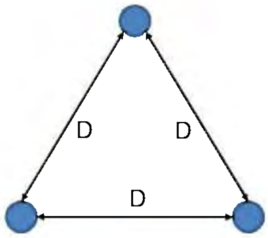
Using the principle of superposition

$$V_{AB} = V_{AB\_A} + V_{AB\_B} + V_{AB\_C}$$
$$= \frac{Q_A}{2\pi\varepsilon_0}\ln\frac{D_{AB}}{r_A} + \frac{Q_B}{2\pi\varepsilon_0}\ln\frac{r_B}{D_{AB}} + \frac{Q_C}{2\pi\varepsilon_0}\ln\frac{D_{BC}}{D_{AC}}$$

Similarly,

$$V_{AC} = \frac{Q_A}{2\pi\varepsilon_0}\ln\frac{D_{AC}}{r_A} + \frac{Q_B}{2\pi\varepsilon_0}\ln\frac{D_{BC}}{D_{AB}} + \frac{Q_C}{2\pi\varepsilon_0}\ln\frac{r_C}{D_{AC}}$$

Symmetric Spacing



$$V_{AB} = \frac{Q_A}{2\pi\varepsilon_0}\ln\frac{D}{r} + \frac{Q_B}{2\pi\varepsilon_0}\ln\frac{r}{D} + \frac{Q_C}{2\pi\varepsilon_0}\ln\frac{D}{D}$$

$$= \frac{1}{2\pi\varepsilon_0}\left(Q_A \ln\frac{D}{r} + Q_B \ln\frac{r}{D}\right)$$

$$V_{AC} = \frac{Q_A}{2\pi\varepsilon_0}\ln\frac{D}{r} + \frac{Q_B}{2\pi\varepsilon_0}\ln\frac{D}{D} + \frac{Q_C}{2\pi\varepsilon_0}\ln\frac{r}{D}$$

$$= \frac{1}{2\pi\varepsilon_0}\left(Q_A \ln\frac{D}{r} + Q_C \ln\frac{r}{D}\right)$$

Phase Voltage

$V_{AB} = \sqrt{3}\, V_{AN} \angle 30^\circ$ and $V_{AC} = -V_{CA} = \sqrt{3}\, V_{AN} \angle -30^\circ$;

Therefore, V_{AN} can be expressed in terms of V_{AB} and V_{AC} as

$$V_{AN} = \frac{V_{AB} + V_{AC}}{3}$$

substituting V_{AB} and V_{AC}

$$V_{AN} = \frac{1}{6\pi\varepsilon_0}\left[\left[q_A \ln\left[\frac{D}{r}\right] + q_B \ln\left[\frac{r}{D}\right]\right] + \left[q_A \ln\left[\frac{D}{r}\right] + q_C \ln\left[\frac{r}{D}\right]\right]\right]$$

Capacitance of Symmetric Three-Phase Line

$$V_{AN} = \frac{1}{6\pi\varepsilon_0}\left[\left[q_A \ln\left[\frac{D}{r}\right] + q_B \ln\left[\frac{r}{D}\right]\right] + \left[q_A \ln\left[\frac{D}{r}\right] + q_C \ln\left[\frac{r}{D}\right]\right]\right]$$

$$= \frac{1}{6\pi\varepsilon_0}\left[2q_A \ln\left[\frac{D}{r}\right] + \left(q_B + q_C\right) \ln\left[\frac{r}{D}\right]\right] \text{ (V)}$$

Under balanced conditions $q_A + q_B + q_C = 0$, or $-q_A = (q_B + q_C)$

$$= \frac{1}{6\pi\varepsilon_0}\left[2q_A \ln\left[\frac{D}{r}\right] - q_A \ln\left[\frac{r}{D}\right]\right] \text{ (V)}$$

$$V_{AN} = \frac{1}{2\pi\varepsilon_0} q_A \ln\left[\frac{D}{r}\right] \text{ (V)}$$

Capacitance of Symmetric Three-Phase Line

$$V_{AN} = \frac{1}{2\pi\varepsilon_0} q_A \ln\left[\frac{D}{r}\right] \text{ (V)}$$

The capacitance per unit length between phase A and neutral

$$C_{AN} = \frac{q_A}{V_{AN}} = \frac{2\pi\varepsilon_0}{\ln\left[\frac{D}{r}\right]} \text{ (F/m)}$$

Three-Phase Asymmetric Transmission Line

V_{AB} on the first, second, and third section of the transposed line

$$V_{AB\ first} = \frac{1}{2\pi\varepsilon_0}\left[q_A \ln\left[\frac{D_{AB}}{r}\right] + q_B \ln\left[\frac{r}{D_{AB}}\right] + q_C \ln\left[\frac{D_{AB}}{D_{AC}}\right]\right] \text{ (V)}$$

$$V_{AB\ second} = \frac{1}{2\pi\varepsilon_0}\left[q_A \ln\left[\frac{D_{BC}}{r}\right] + q_B \ln\left[\frac{r}{D_{BC}}\right] + q_C \ln\left[\frac{D_{AC}}{D_{AB}}\right]\right] \text{ (V)}$$

$$V_{AB\ third} = \frac{1}{2\pi\varepsilon_0}\left[q_A \ln\left[\frac{D_{AC}}{r}\right] + q_B \ln\left[\frac{r}{D_{AC}}\right] + q_C \ln\left[\frac{D_{AB}}{D_{BC}}\right]\right] \text{ (V)}$$

Three-Phase Asymmetric Transmission Line

Similarly, the expressions for V_{AC} on the first, second, and third section of the transposed line

$$V_{AC\ first} = \frac{1}{2\pi\varepsilon_0}\left[q_A \ln\left[\frac{D_{AC}}{r}\right] + q_B \ln\left[\frac{D_{BC}}{D_{AB}}\right] + q_C \ln\left[\frac{r}{D_{AC}}\right]\right]$$

$$V_{AC\ second} = \frac{1}{2\pi\varepsilon_0}\left[q_A \ln\left[\frac{D_{AB}}{r}\right] + q_B \ln\left[\frac{D_{AC}}{D_{BC}}\right] + q_C \ln\left[\frac{r}{D_{AB}}\right]\right]$$

$$V_{AC\ third} = \frac{1}{2\pi\varepsilon_0}\left[q_A \ln\left[\frac{D_{BC}}{r}\right] + q_B \ln\left[\frac{D_{AB}}{D_{AC}}\right] + q_C \ln\left[\frac{r}{D_{BC}}\right]\right]$$

Three-Phase Asymmetric Transmission Line

$$V_{AB\ transp} = \frac{V_{AB\ first} + V_{AB\ second} + V_{AB\ third}}{3}$$

$$= \frac{1}{6\pi\varepsilon_0}\left[q_A \ln\left[\frac{D_{AB}D_{AC}D_{BC}}{r^3}\right] + q_B \ln\left[\frac{r^3}{D_{AB}D_{AC}D_{BC}}\right] + q_C \ln\left[\frac{D_{AC}D_{AC}D_{BC}}{D_{AC}D_{AC}D_{BC}}\right]\right] \text{(V)}$$

$$V_{AC\ transp} = \frac{V_{AC\ first} + V_{AC\ second} + V_{AC\ third}}{3}$$

$$= \frac{1}{6\pi\varepsilon_0}\left[q_A \ln\left[\frac{D_{AB}D_{AC}D_{BC}}{r^3}\right] + q_B \ln\left[\frac{D_{AC}D_{AC}D_{BC}}{D_{AB}D_{AC}D_{BC}}\right] + q_C \ln\left[\frac{r^3}{D_{AC}D_{AC}D_{BC}}\right]\right] \text{(V)}$$

the phase-to-neutral voltage V_{AN} (phase voltage) is

$$V_{AN\ transp} = \frac{V_{AB\ transp} + V_{AC\ transp}}{3}$$

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Capacitance of Three-Phase Asymmetric Transmission Line

$$V_{AN\ transp} = \frac{V_{AB\ transp} + V_{AC\ transp}}{3}$$

$$= \frac{1}{18\pi\varepsilon_0}\left[2\ q_A \ln\left[\frac{D_{AB}D_{AC}D_{BC}}{r^3}\right] + (q_B + q_C) \ln\left[\frac{r^3}{D_{AB}D_{AC}D_{BC}}\right]\right]$$

For a balanced system where $-q_A = (q_B + q_C)$

$$V_{AN\ transp} = \frac{1}{6\pi\varepsilon_0} q_A \ln\left[\frac{D_{AB}D_{AC}D_{BC}}{r^3}\right]$$

$$= \frac{1}{2\pi\varepsilon_0} q_A \ln\left[\frac{\text{GMD}}{r}\right] \text{(V)}$$

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Capacitance of Three-Phase Asymmetric Transmission Line

Finally, the capacitance and capacitive reactance, per unit length, from phase to neutral

$$C_{AN\ transp} = \frac{q_A}{V_{AN\ transp}} = \frac{2\pi\varepsilon_0}{\ln\left[\frac{GMD}{r_e}\right]}\ (F/m)$$

$$X_{AN\ transp} = \frac{1}{2\pi f C_{AN\ transp}} = \frac{1}{4\pi f \varepsilon_0} \ln\left[\frac{GMD}{r_e}\right]\ (\Omega/m)$$

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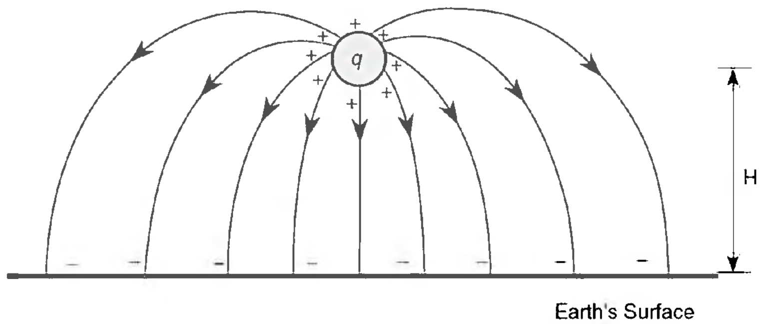
Effect of Earth on Capacitance



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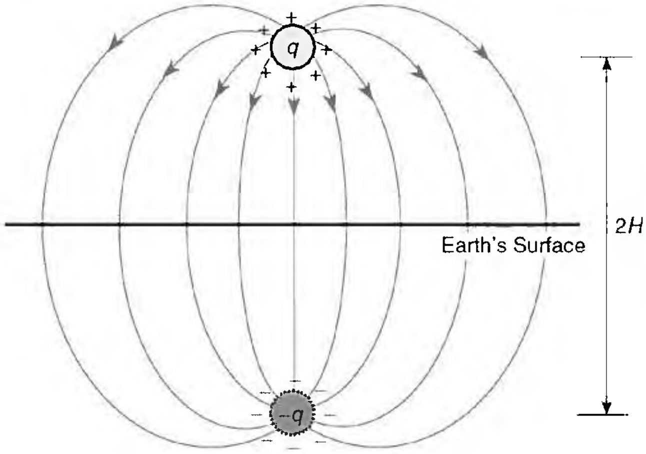
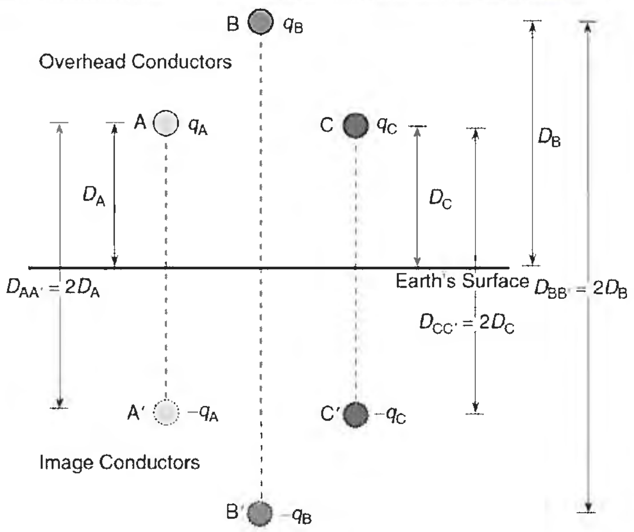
Effect of Earth on Capacitance

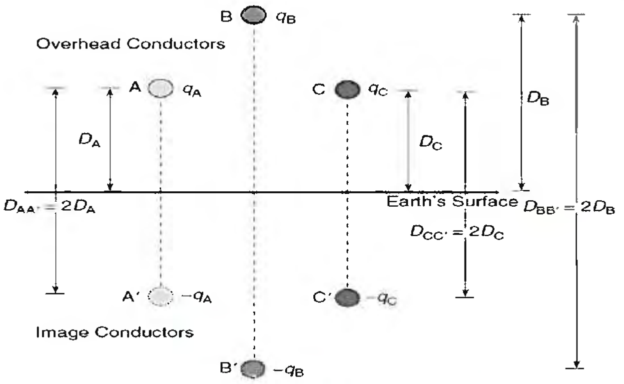


$$C = \frac{2\pi\varepsilon_0}{\ln\left(\frac{2H}{r}\right)}$$

Effect of Earth on Capacitance



Three-Phase Line



$$V_{AB} = \frac{1}{2\pi\varepsilon_0}\begin{bmatrix} q_A \ln\left[\frac{D_{AB}}{r_A}\right] + q_B \ln\left[\frac{r_B}{D_{AB}}\right] + q_C \ln\left[\frac{D_{BC}}{D_{AC}}\right] - \\ -q_A \ln\left[\frac{D_{AB'}}{D_{AA'}}\right] - q_B \ln\left[\frac{D_{BB'}}{D_{AB'}}\right] - q_C \ln\left[\frac{D_{BC'}}{D_{AC'}}\right] \end{bmatrix} \text{(V)}$$

Symmetrical Three Phase Line

$$V_{AB} = \frac{1}{2\pi\varepsilon_0}\begin{bmatrix} q_A \ln\left[\frac{D_{AB}}{r_A}\right] + q_B \ln\left[\frac{r_B}{D_{AB}}\right] + q_C \ln\left[\frac{D_{BC}}{D_{AC}}\right] - \\ -q_A \ln\left[\frac{D_{AB'}}{D_{AA'}}\right] - q_B \ln\left[\frac{D_{BB'}}{D_{AB'}}\right] - q_C \ln\left[\frac{D_{BC'}}{D_{AC'}}\right] \end{bmatrix} \text{(V)}$$

$r = r_A = r_B = r_C$ $D = D_{AB} = D_{BC} = D_{CA}$

$$V_{AB} = \frac{1}{2\pi\varepsilon_0}\left[q_A\left(\ln\left[\frac{D}{r}\right] - \ln\left[\frac{D_{AB'}}{D_{AA'}}\right]\right) + q_B\left(\ln\left[\frac{r}{D}\right] - \ln\left[\frac{D_{BB'}}{D_{AB'}}\right]\right) - q_C \ln\left[\frac{D_{BC'}}{D_{AC'}}\right]\right] \text{(V)}$$

Similarly,

$$V_{AC} = \frac{1}{2\pi\varepsilon_0}\left[q_A\left(\ln\left[\frac{D}{r}\right] - \ln\left[\frac{D_{CA'}}{D_{AA'}}\right]\right) - q_B \ln\left[\frac{D_{CB'}}{D_{AB'}}\right] + q_C\left(\ln\left[\frac{r}{D}\right] - \ln\left[\frac{D_{CC'}}{D_{AC'}}\right]\right)\right] \text{(V)}$$

Capacitance of Symmetrical Three Phase Line

The phase voltage V_{AN}

$$V_{AN} = \frac{V_{AB} + V_{AC}}{3}$$

$$= \frac{1}{2\pi\varepsilon_0} q_A \left(\ln\left[\frac{D}{r}\right] - \ln\left[\frac{\sqrt[3]{D_{AB'} D_{BC'} D_{CA'}}}{\sqrt[3]{D_{AA'} D_{BB'} D_{CC'}}}\right] \right) \text{ (V)}$$

Therefore, the phase capacitance C_{AN}, per unit length, is

$$C_{AN} = \frac{q_A}{V_{AN}} = \frac{2\pi\varepsilon_0}{\ln\left[\frac{D}{r}\right] - \ln\left[\frac{\sqrt[3]{D_{AB'} D_{BC'} D_{CA'}}}{\sqrt[3]{D_{AA'} D_{BB'} D_{CC'}}}\right]} \text{ (F/m)}$$

$$V_{AC} = \frac{1}{2\pi\varepsilon_0}\left[q_A \left(\ln\left[\frac{D}{r}\right] - \ln\left[\frac{D_{CA'}}{D_{AA'}}\right] \right) - q_B \ln\left[\frac{D_{CB'}}{D_{AB'}}\right] + q_C \left(\ln\left[\frac{r}{D}\right] - \ln\left[\frac{D_{CC'}}{D_{AC'}}\right] \right) \right] \text{ (V)}$$

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VI. TRANSMISSION AND DISTRIBUTION SYSTEM

<u>PERFORMANCE OF TRANSMISSION LINE (LINE PARAMETERS-PART 2)</u>

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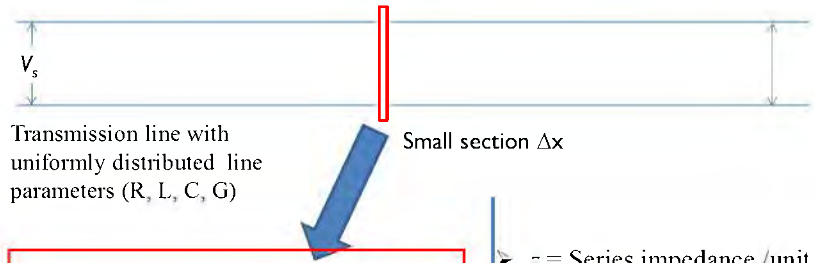
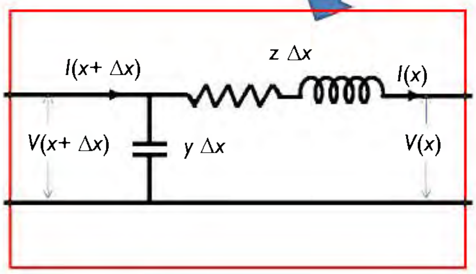
Distributed and Lumped Parameters





- z = Series impedance /unit length/phase
- y = Shunt admittance / unit length/phase
- l = Length of transmission line
- Z = Total series impedance/ phase
- Y = Total shunt impedance/ phase

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Transmission Line Models

- **Short line :** Length less than 80 km.
  - Shunt admittance is neglected
  - Lumped parameter model
- **Medium line:** Length between 80 km to 250 km.
  - Shunt admittance needs to be considered
  - Lumped parameter model
    - Nominal π model
    - Nominal T model
- **Long line:** Length longer than 250 km.
  - Distributed parameter model
  - Shunt admittance effect is important
  - Equivalent π or T equivalent can be derived

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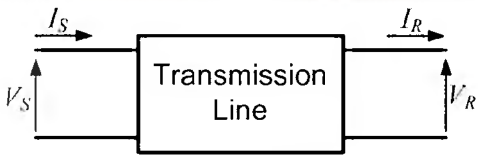
ABCD Parameters of Transmission Line



$$V_S = AV_R + BI_R$$

$$I_S = CV_R + DI_R$$

Matrix Format

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix}$$

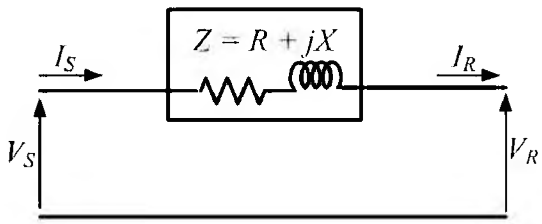
$$A = \left.\frac{V_S}{V_R}\right|_{I_R=0} \quad C = \left.\frac{I_S}{V_R}\right|_{I_R=0}$$

$$B = \left.\frac{V_S}{I_R}\right|_{V_R=0} \quad D = \left.\frac{I_S}{I_R}\right|_{V_R=0}$$

$$AD - BC = 1$$

$$A = D$$

Short Transmission Line



$$V_S = V_R + ZI_R$$

$$I_S = I_R$$

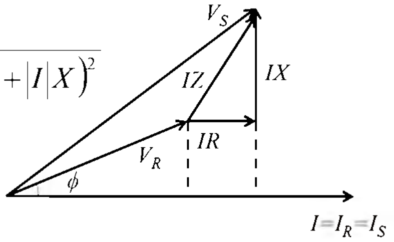
Matrix Format

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix}$$

$A=1$, $B=Z$, $C=0$, $D=1$

Regulation of Short Transmission Line

$$|V_S| = \sqrt{\left(|V_R|\cos\phi + |I|R\right)^2 + \left(|V_R|\sin\phi + |I|X\right)^2}$$



$$V_S = \sqrt{V_R^2\cos^2\phi + I^2R^2 + 2|V_R||I|R\sin\phi + V_R^2\sin^2\phi + I^2X^2 + 2|V_R||I|X\sin\phi}$$

$$V_S = \sqrt{V_R^2 + 2V_R IR\sin\phi + 2V_R IX\sin\phi + I^2\left(R^2 + X^2\right)}$$

$$V_S = V_R\sqrt{1 + \frac{2IR\sin\phi}{V_R} + \frac{2IX\sin\phi}{V_R} + \frac{I^2\left(R^2+X^2\right)}{V_R^2}}$$

← Small quantity

Regulation of Short Transmission Line

$$V_S = V_R\sqrt{1 + \left(\frac{2IR\sin\phi}{V_R} + \frac{2IX\sin\phi}{V_R}\right)}$$

$$V_S = V_R\left(1 + \frac{IR\sin\phi}{V_R} + \frac{IX\sin\phi}{V_R}\right)$$

$$V_S = V_R + IR\sin\phi + IX\sin\phi$$

$$\text{Regulation} = \frac{|V_S| - |V_R|}{V_R}$$

$$\text{Regulation} = \frac{|I|R\sin\phi}{V_R} + \frac{|I|X\sin\phi}{V_R}$$

$$\sqrt{1+x} = \sum_{n=0}^{\infty}\frac{(-1)^n(2n)!}{(1-2n)(n!)^2 4^n}$$

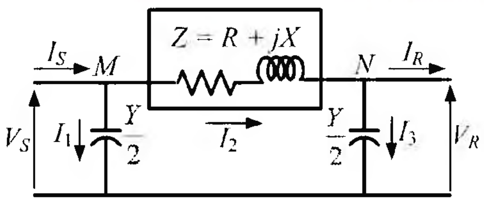
$$= 1 + \frac{x}{2} - \frac{x^2}{8} + \frac{x^3}{16} + \ldots\ldots$$

Medium Transmission Line

- Medium transmission lines are modelled with lumped series impedance and shunt admittance.

  - Nominal π Representation
  - Nominal T Representation

Nominal π Representation



$$V_s = ZI_2 + V_R = Z\left(V_R\frac{Y}{2} + I_R\right) + V_R$$

$$= \left(\frac{YZ}{2} + 1\right)V_R + ZI_R$$

$$I_s = I_1 + I_2 = I_1 + I_3 + I_R$$

$$= \frac{Y}{2}V_s + \frac{Y}{2}V_R + I_R$$

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

$$= Y\left(\frac{YZ}{4} + 1\right)V_R + \left(\frac{YZ}{2} + 1\right)I_R$$

Nominal π Representation

$$V_s = \left(\frac{YZ}{2} + 1\right)V_R + ZI_R$$

$$I_s = Y\left(\frac{YZ}{4} + 1\right)V_R + \left(\frac{YZ}{2} + 1\right)I_R$$

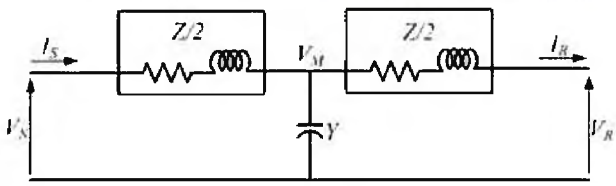
Therefore *A, B, C, D* parameters

$$A = D = \left(\frac{YZ}{2} + 1\right)$$

$$B = Z\,\Omega$$

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

Nominal T Representation



$$V_M = V_R + \frac{Z}{2}I_R \text{ and } I_M = YV_M$$

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

$$V_s = \left(\frac{YZ}{2} + 1\right)V_R + Z\left(\frac{YZ}{4} + 1\right)I_R$$

$$I_S = YV_M + I_R$$

$$= YV_R + \left(\frac{YZ}{2} + 1\right)I_R$$

Nominal T Representation

$$V_s = \left(\frac{YZ}{2} + 1\right)V_R + Z\left(\frac{YZ}{4} + 1\right)I_R$$

$$I_S = YV_R + \left(\frac{YZ}{2} + 1\right)I_R$$

Therefore *A, B, C, D* parameters

$$A = D = \left(\frac{YZ}{2} + 1\right)$$

$$B = Z\left(\frac{YZ}{4} + 1\right)\Omega$$

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

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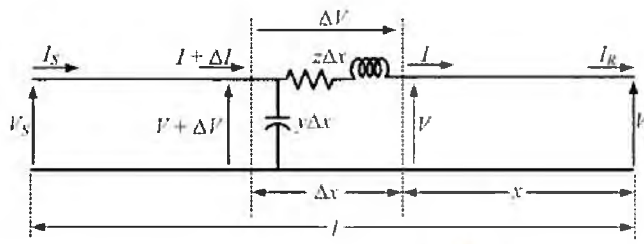
Long Line Model



$$\Delta V = Iz\,\Delta x \Rightarrow \frac{\Delta V}{\Delta x} = Iz \quad \xrightarrow{\Delta x \to 0} \quad \frac{dV}{dx} = Iz$$

$$\Delta I = (V + \Delta V)y\,\Delta x = Vy\,\Delta x + \Delta Vy\,\Delta x \Rightarrow \frac{\Delta I}{\Delta x} = Vy \quad \xrightarrow{\Delta x \to 0} \quad \frac{dI}{dx} = Vy$$

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Long Line Model

$$\frac{dV}{dx} = Iz \qquad \text{And} \qquad \frac{dI}{dx} = Vy$$

Again differentiating with respect to x

$$\frac{d}{dx}\left(\frac{dV}{dx}\right) = z\frac{dI}{dx}$$

$$\frac{d^2V}{dx^2} - yzV = 0$$

Solution of the differential Eqn.

$$V = A_1 e^{x\sqrt{yz}} + A_2 e^{-x\sqrt{yz}}$$

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Long Line Model

$$V = A_1 e^{x\sqrt{yz}} + A_2 e^{-x\sqrt{yz}}$$

Differentiating with respect to x

$$\frac{dV}{dx} = A_1\sqrt{yz}\,e^{x\sqrt{yz}} - A_2\sqrt{yz}\,e^{-x\sqrt{yz}}$$

We know that

$$\frac{dV}{dx} = Iz$$

Therefore

$$I = \frac{1}{z}\left(\frac{dV}{dx}\right) = \frac{A_1}{\sqrt{z/y}}e^{x\sqrt{yz}} - \frac{A_2}{\sqrt{z/y}}e^{-x\sqrt{yz}}$$

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Long Line Model

$$V = A_1 e^{x\sqrt{yz}} + A_2 e^{-x\sqrt{yz}}$$

$$I = \frac{1}{z}\left(\frac{dV}{dx}\right) = \frac{A_1}{\sqrt{z/y}} e^{x\sqrt{yz}} - \frac{A_2}{\sqrt{z/y}} e^{-x\sqrt{yz}}$$

$\gamma = \sqrt{yz}$ which is called the ***propagation constant***

$Z_C = \sqrt{\frac{z}{y}}\ \Omega$ which is called the ***characteristic impedance***

$$V = A_1 e^{\gamma x} + A_2 e^{-\gamma x}$$

$$I = \frac{A_1}{Z_C} e^{\gamma x} - \frac{A_2}{Z_C} e^{-\gamma x}$$

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Long Line Model

$V = A_1 e^{\gamma x} + A_2 e^{-\gamma x}$ And $I = \frac{A_1}{Z_C} e^{\gamma x} - \frac{A_2}{Z_C} e^{-\gamma x}$

At $x = 0$.

$V = V_R$ and $I = I_R$

$$V_R = A_1 + A_2$$

$$I_R = \frac{A_1}{Z_C} - \frac{A_2}{Z_C}$$

Solving for A_1 and A_2

$$A_1 = \frac{V_R + Z_C I_R}{2} \quad \text{and} \quad A_2 = \frac{V_R - Z_C I_R}{2}$$

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Long Line Model

We are interested in terminal conditions: $x = l$ we have $V = V_s$ and $I = I_S$

$$V_S = \frac{V_R + Z_C I_R}{2} e^{\gamma l} + \frac{V_R - Z_C I_R}{2} e^{-\gamma l}$$

$$I_S = \frac{V_R / Z_C + I_R}{2} e^{\gamma l} - \frac{V_R / Z_C - I_R}{2} e^{-\gamma l}$$

$$V_S = \left(\frac{e^{\gamma l} + e^{-\gamma l}}{2} \right) V_R + Z_C \left(\frac{e^{\gamma l} - e^{-\gamma l}}{2} \right) I_R$$

$$I_S = \frac{1}{Z_C} \left(\frac{e^{\gamma l} - e^{-\gamma l}}{2} \right) V_R + \left(\frac{e^{\gamma l} + e^{-\gamma l}}{2} \right) I_R$$

Long Line Model

$$V_S = \left(\frac{e^{\gamma l} + e^{-\gamma l}}{2} \right) V_R + Z_C \left(\frac{e^{\gamma l} - e^{-\gamma l}}{2} \right) I_R$$

$$I_S = \frac{1}{Z_C} \left(\frac{e^{\gamma l} - e^{-\gamma l}}{2} \right) V_R + \left(\frac{e^{\gamma l} + e^{-\gamma l}}{2} \right) I_R$$

$$\frac{e^{\gamma l} - e^{-\gamma l}}{2} = \sinh \gamma l \quad \text{and} \quad \frac{e^{\gamma l} + e^{-\gamma l}}{2} = \cosh \gamma l$$

$$V_S = \cosh(\gamma l) V_R + Z_C \sinh(\gamma l) I_R$$

$$I_S = \frac{1}{Z_C} \sinh(\gamma l) V_R + \cosh(\gamma l) I_R$$

Long Line Model

$$V_S = \cosh(\gamma l)V_R + Z_C \sinh(\gamma l)I_R$$

$$I_S = \frac{1}{Z_C}\sinh(\gamma l)V_R + \cosh(\gamma l)I_R$$

The ABCD parameters of the long transmission line

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

$$B = Z_C \sinh \gamma l$$

$$C = \frac{\sinh \gamma l}{Z_C}$$

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Method to Evaluate Hyperbolic Functions of Complex Number

$$\gamma l = \alpha l + j\beta l$$

1	$\cosh(\alpha l + j\beta l) = \cosh(\alpha l)\cos(\beta l) + j\sinh(\alpha l)\sin(\beta l)$ $\sinh(\alpha l + j\beta l) = \sinh(\alpha l)\cos(\beta l) + j\cosh(\alpha l)\sin(\beta l)$
2	$\cosh(\gamma l) = 1 + \frac{\gamma^2 l^2}{2!} + \frac{\gamma^4 l^4}{2!} + ... \approx \left(1 + \frac{YZ}{2}\right)$ $\sinh(\gamma l) = \gamma l + \frac{\gamma^3 l^3}{3!} + \frac{\gamma^5 l^5}{5!} + ... \approx \sqrt{YZ}\left(1 + \frac{YZ}{6}\right)$
3	$\cosh(\alpha l + j\beta l) = \frac{e^{\alpha l}e^{j\beta l} + e^{-\alpha l}e^{-j\beta l}}{2} = \frac{1}{2}\left(e^{\alpha l}\angle\beta l + e^{-\alpha l}\angle -\beta l\right)$ $\sinh(\alpha l + j\beta l) = \frac{e^{\alpha l}e^{j\beta l} - e^{-\alpha l}e^{-j\beta l}}{2}\frac{1}{2}\left(e^{\alpha l}\angle\beta l - e^{-\alpha l}\angle -\beta l\right)$

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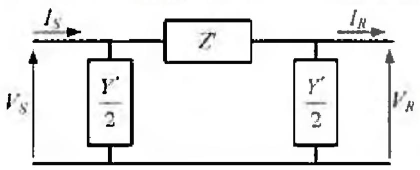
Equivalent π Representation of Long Transmission Line



$$A = D = \left(\frac{Y'Z'}{2} + 1\right)$$

$$B = Z'\,\Omega$$

$$C = Y'\left(\frac{Y'Z'}{4} + 1\right) \text{ mho}$$

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

$$B = Z_C \sinh \gamma l$$

$$C = \frac{\sinh \gamma l}{Z_C}$$

Comparing the ABCD parameters compute Z' and $Y'/2$

Equivalent π Representation of Long Transmission Line

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

$$B = Z_C \sinh \gamma l$$

$$C = \frac{\sinh \gamma l}{Z_C}$$

Compare

$$A = D = \left(\frac{Y'Z'}{2} + 1\right)$$

$$B = Z'\,\Omega$$

$$C = Y'\left(\frac{Y'Z'}{4} + 1\right) \text{ mho}$$

$$Z' = Z_C \sinh \gamma l = \sqrt{\frac{z}{y}} \sinh \gamma l = zl \frac{\sinh \gamma l}{l\sqrt{yz}} = Z \frac{\sinh \gamma l}{\gamma l}$$

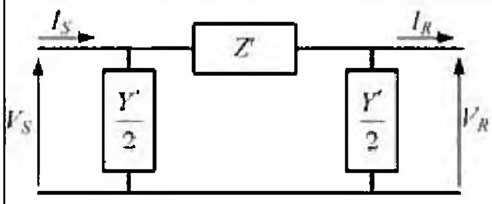
$$\tanh\left(\tfrac{1}{2}x\right) = \frac{\cosh x - 1}{\sinh x}.$$

$$\cosh \gamma l = \frac{Y'Z'}{2} + 1 = \frac{Y'}{2} Z_C \sinh \gamma l + 1$$

Rearranging for $Y'/2$

$$\frac{Y'}{2} = \frac{1}{Z_C}\frac{\cosh \gamma l - 1}{\sinh \gamma l} = \frac{1}{Z_C}\tanh(\gamma l/2) = \sqrt{\frac{y}{z}}\tanh(\gamma l/2) = \frac{yl}{2}\frac{\tanh(\gamma l/2)}{(l/2)\sqrt{yz}} = \frac{Y}{2}\frac{\tanh(\gamma l/2)}{(\gamma l/2)}$$

Equivalent π Representation of Long Transmission Line



$$Z' = Z \frac{\sinh \gamma l}{\gamma l}$$

$$\frac{Y'}{2} = \frac{Y}{2} \frac{\tanh(\gamma l/2)}{(\gamma l/2)}$$

Length (km)	Lumped Parameters		Distributed Parameters	
	Z(Ω)	Y(mho)	Z(Ω)	Y(mho)
100	52.41 < 79°	3.17 X 10^{-4} < 90°	52.27 < 79°	3.17 X 10^{-4} < 89.98°
250	131.032 < 79°	7.93 X 10^{-4} < 90°	128.81 < 79.2°	8.0 X 10^{-4} < 89.9°
500	262.064 < 79°	1.58 X 10^{-3} < 90°	244.61 < 79.8°	1.64 X 10^{-3} < 89.6°

For impedance (z) = 0.1 + j 0.51 Ω/km and admittance (y) = j 3.17 x 10^{-6} mho/km

Ferranti Effect

- In long transmission lines and cables, receiving end voltage becomes greater than sending end during no-load or light load conditions. This effect is known as *Ferranti effect* .
- This occurs due to high charging current.

$$V_S = \cosh(\gamma l)V_R + Z_C \sinh(\gamma l)I_R$$

$$I_R = 0 \Rightarrow V_S = \cosh(\gamma l)V_R$$

$$\text{Therefore } V_R = \frac{V_S}{\cosh(\gamma l)}$$

- Thus V_R will be always greater than zero (during no load).
- Actual value depends on L, C and l.

Lossless Transmission Line

$$V_x = \cosh(\gamma x)V_R + Z_C \sinh(\gamma x) I_R$$

In loss less line, resistance is assumed to be zero

$$Z_C = \sqrt{\frac{R + j\omega L}{j\omega C}}$$

$$R = 0 \quad \Rightarrow \quad Z_C = \sqrt{\frac{j\omega L}{j\omega C}} = \sqrt{\frac{L}{C}}$$

$$\gamma x = \alpha x + j\beta x \quad \Rightarrow \quad \gamma x = j\beta x$$

$$\cosh(\alpha l + j\beta l) = \cosh(\alpha l)\cos(\beta l) + j\sinh(\alpha l)\sin(\beta l)$$

$$\sinh(\alpha l + j\beta l) = \sinh(\alpha l)\cos(\beta l) + j\cosh(\alpha l)\sin(\beta l)$$

$$V_x = \cos(\beta x)V_R + jZ_C \sin(\beta x) I_R$$

Surge Impedance Loading

- *Characteristic impedance* of a line is also called as *surge impedance* for the special case of loss less line.

$$Z_C = \sqrt{\frac{L}{C}} \qquad SIL = P_x = \frac{V_0^2}{Z_C}$$

- The term **surge impedance loading** or ***SIL*** is often used to indicate the nominal capacity of the line.
- The term ***SIL*** or **natural power** is a measure of power delivered by a transmission line when terminated by surge impedance.
- It is convenient to express the power transmitted in terms of per unit of SIL.

Surge Impedance Loading

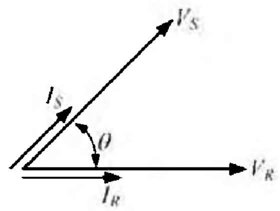
$$V_x = \cos(\beta x) V_R + j Z_C \sin(\beta x) I_R$$
$$I_x = j(1/Z_C)\sin(\beta x) V_R + \cos(\beta x) I_R$$

- If the line is terminated with surge impedance Z_c:

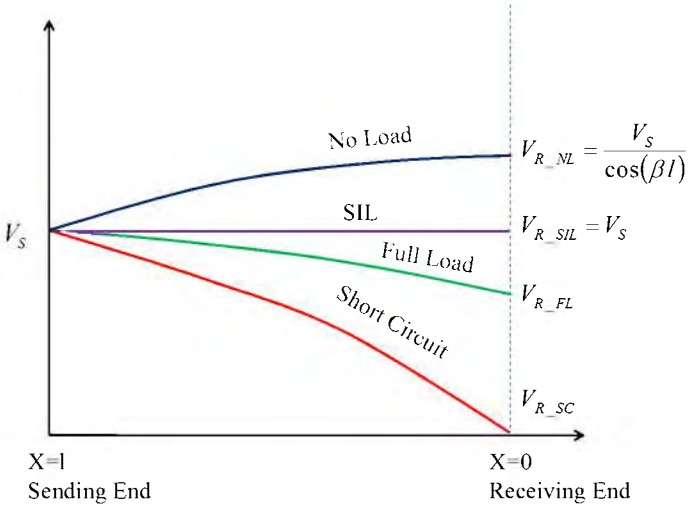
$$V_R = Z_C I_R \quad \Rightarrow \quad Z_C = \frac{V_R}{I_R}$$

$$V_x = V_R(\cos(\beta x) + j\sin(\beta x)) = V_R e^{-j\beta x}$$
$$I_x = I_R(\cos(\beta x) + j\sin(\beta x)) = I_R e^{-j\beta x}$$

$$V_S = V_R e^{-j\beta l}$$
$$I_S = I_R e^{-j\beta l}$$



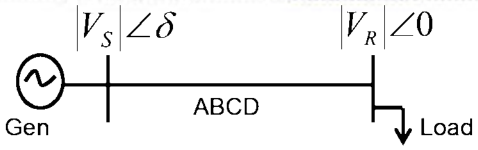
Comparison of Different Loading



Surge Impedance Loading

Voltage Level (kV)	SIL (MW)	Thermal Limit (MVA)
132	50	94
220	132	237
400	515	948
765	2200	4261

Power Transfer Through Transmission Line



$S_S = P_S + jQ_S$ $\qquad$ $S_R = P_R + jQ_R$

$$V_S = AV_R + BI_R \quad \Rightarrow \quad I_R = \frac{V_S}{B} - \frac{AV_R}{B}$$

Let $A = |A|\angle\alpha$ and $B = |B|\angle\beta$

$$I_R = \frac{|V_S|}{|B|}\angle(\delta - \beta) - \frac{|A||V_R|}{|B|}\angle(\alpha - \beta)$$

Power Flow Through Transmission Line

$$I_R^* = \frac{|V_S|}{|B|}\angle(\beta-\delta) - \frac{|A||V_R|}{|B|}\angle(\beta-\alpha)$$

- Complex power $V_R I_R^*$ at receiving end:

$$V_R I_R^* = P_R + jQ_R = \frac{|V_S||V_R|}{|B|}\angle(\beta-\delta) - \frac{|A||V_R|^2}{|B|}\angle(\beta-\alpha)$$

Real Part: $$P_R = \frac{|V_S||V_R|}{|B|}\cos(\beta-\delta) - \frac{|A||V_R|^2}{|B|}\cos(\beta-\alpha)$$

Imaginary Part $$Q_R = \frac{|V_S||V_R|}{|B|}\sin(\beta-\delta) - \frac{|A||V_R|^2}{|B|}\sin(\beta-\alpha)$$

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Power Flow Through Transmission Line

Real Part: $$P_R = \frac{|V_S||V_R|}{|B|}\cos(\beta-\delta) - \frac{|A||V_R|^2}{|B|}\cos(\beta-\alpha)$$

Imaginary Part $$Q_R = \frac{|V_S||V_R|}{|B|}\sin(\beta-\delta) - \frac{|A||V_R|^2}{|B|}\sin(\beta-\alpha)$$

- Maximum power will get transferred, if $\beta=\delta$

$$P_{R\_\max} = \frac{|V_S||V_R|}{|B|} - \frac{|A||V_R|^2}{|B|}\cos(\beta-\alpha)$$

$$Q_{R\_\max} = -\frac{|A||V_R|^2}{|B|}\sin(\beta-\alpha)$$

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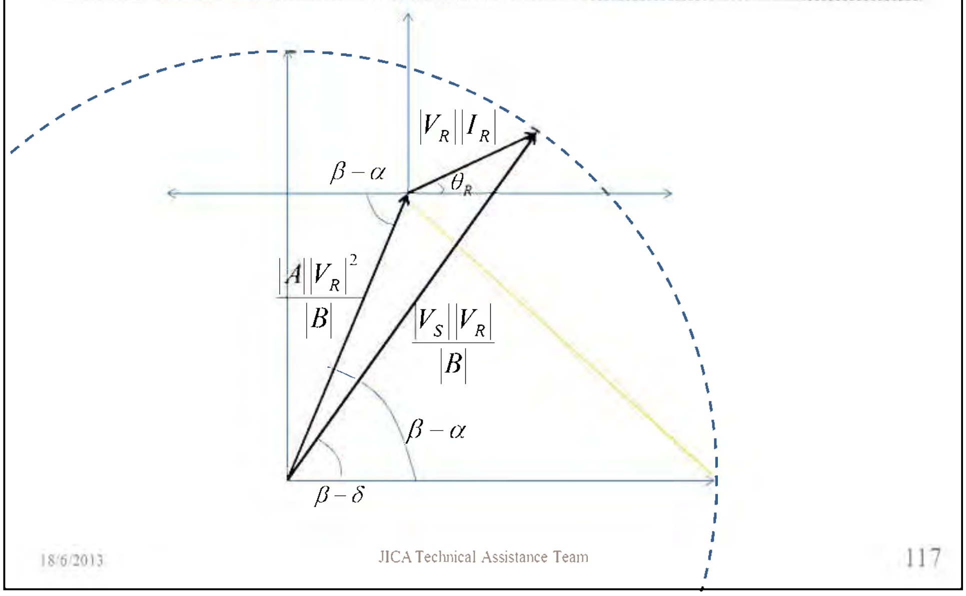
Receiving End Circle Diagram



Maximum Power in Short Line Approximation

$$P_{R\_max} = \frac{|V_S||V_R|}{|B|} - \frac{|A||V_R|^2}{|B|}\cos(\beta-\alpha)$$

For Short line A=1, B=Z, C=0, D=1
Assuming X/R ratio is high enough to neglect resistance

$$A = D = 1\angle 0,\quad B = |Z|\angle\theta,\quad C = 0,\quad \cos\theta = R/|Z|$$

$$P_{R\_max} = \frac{|V_S||V_R|}{|Z|} - \frac{|V_R|^2}{|Z|}\cos(\theta) = \frac{|V_S||V_R|}{|Z|} - \frac{|V_R|^2}{|Z|^2}R$$

$$Q_{R\_max} = -\frac{|A||V_R|^2}{|B|}\sin(\theta)$$

With large X/R Ratio

$$P_R = \frac{|V_S||V_R|}{|B|}\cos(\beta - \delta) - \frac{|A||V_R|^2}{|B|}\cos(\beta - \alpha)$$

$$Q_R = \frac{|V_S||V_R|}{|B|}\sin(\beta - \delta) - \frac{|A||V_R|^2}{|B|}\sin(\beta - \alpha)$$

Generally, $R << X$ then $Z = jX$

$A = D = 1\angle 0,\ \ B = |X|\angle 90,\ \ C = 0,$

$$P_R = \frac{|V_S||V_R|}{|X|}\sin\delta \quad \Rightarrow \quad P_{R\_max} = \frac{|V_S||V_R|}{|X|}$$

$$Q_R = \frac{|V_S||V_R|}{|X|}\cos(\delta) - \frac{|V_R|^2}{|X|} \quad \Rightarrow \quad Q_R = \frac{|V_R|}{|X|}\left(|V_S| - |V_R|\right) = \frac{|V_R|}{|X|}|\Delta V|$$

Sending End Power

$$I_S = CV_R + DI_R \qquad \text{but } I_R = \frac{V_S}{B} - \frac{AV_R}{B}$$

$$I_S = CV_R + \frac{D}{B}V_S - \frac{DA}{B}V_R$$

$$= \frac{D}{B}V_S - \frac{V_R(AD - BC)}{B}$$

$$I_S = \frac{DV_S}{B} - \frac{V_R}{B}$$

- Complex power $V_S I_S^*$ at receiving end:

  Let $A = D = |A|\angle\alpha$ and $B = |B|\angle\beta$

Sending End Power

$$V_S I_S^* = P_S + jQ_S = \frac{|A||V_S|^2}{|B|}\angle(\beta-\alpha) - \frac{|V_S||V_R|}{|B|}\angle(\delta+\beta)$$

Real Part:

$$P_S = \frac{|A||V_S|^2}{|B|}\cos(\beta-\alpha) - \frac{|V_S||V_R|}{|B|}\cos(\delta+\beta)$$

Imaginary Part

$$Q_S = \frac{|A||V_S|^2}{|B|}\sin(\beta-\alpha) - \frac{|V_S||V_R|}{|B|}\sin(\delta+\beta)$$

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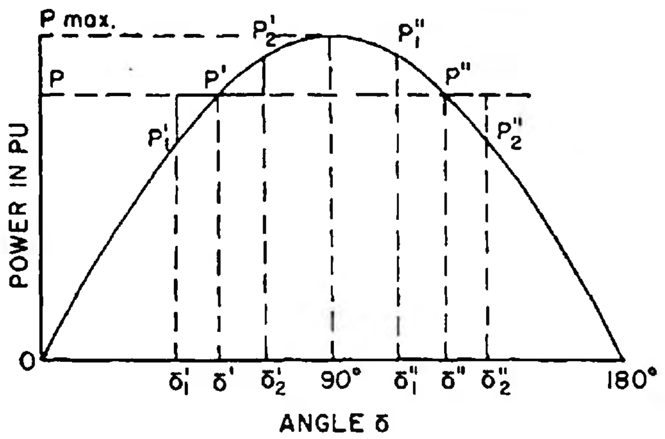
Steady State Stability Limit



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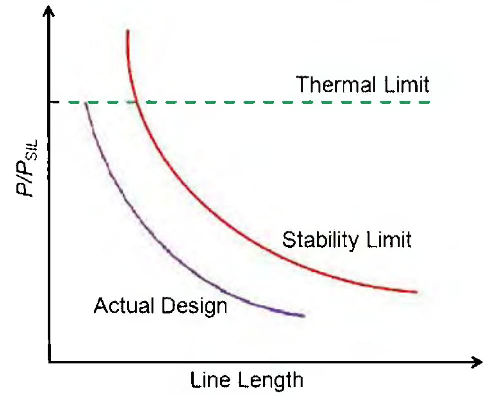
Power Transfer Capability



- Thermal Limit
- Voltage drop limit
- Stability limit

Actual Design

$$P_R = \frac{|V_S||V_R|}{|B|}\sin\delta = \frac{|V_R|^2}{|Z_c \sin(\beta l)|}\sin\delta = SIL\frac{\sin\delta}{\sin(\beta l)}$$

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Main Objectives

- Choice of voltage, choice of conductor, spacing between conductors
- Calculation line constants, regulation and efficiency
- Calculation of Corona Loss
- Choosing number and type of insulators
- Choice of method of grounding
- Calculation of radio interference
- Stability considerations
- Electrostatic and electromagnetic effect
- Insulation coordination
- Protective system

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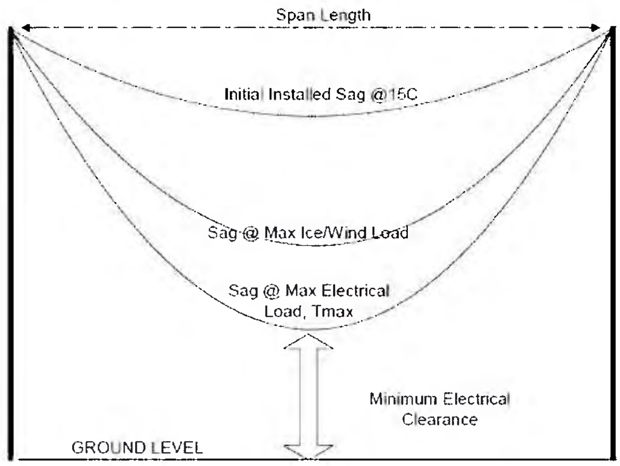
Main Components of Overhead Line

- Conductors
  - Copper
  - Aluminum: ACSR, AAAR, AAC, Expanded ACSR
- Support Structure (Towers)
  - Galvanized steel (for high voltage)
  - Wood, concrete, steel (for low voltage)
- Insulators
  - Porcelain
  - Glass
  - Polymer insulation

Mechanical Design

- Main Factors
  - Selection of line route
  - Types of tower or pole
  - Right of way
  - Ground and conductor clearance
  - Tower spacing, span length
  - Mechanical loadings
    - Weight of conductor per unit length
    - Load due to wind, ice, snow, etc.
    - Temperature
    - Conductor tension
    - Distance between the supports (Span length)

Sag and Tension:



Maximum sag so that clearance to ground and other conductors can be maintained.

Maximum tension so that structures can be designed to withstand it.

Minimum sag to control structure uplift problems.

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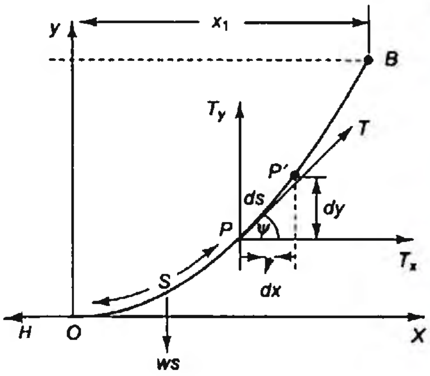
Calculation of Sag and Tension



$$H = T_x$$

$$T_y = ws$$

$$\tan \psi = dy/dx = T_y/T_x = ws/H$$

$$ds^2 = dx^2 + dy^2$$

$$\frac{ds^2}{dx^2} = 1 + \frac{dy^2}{dx^2}$$

$$\frac{ds}{dx} = \sqrt{1 + (dy/dx)^2} \Rightarrow \frac{ds}{dx} = \sqrt{1 + w^2 s^2 / H^2} \Rightarrow dx = \frac{ds}{\sqrt{1 + w^2 s^2 / H^2}}$$

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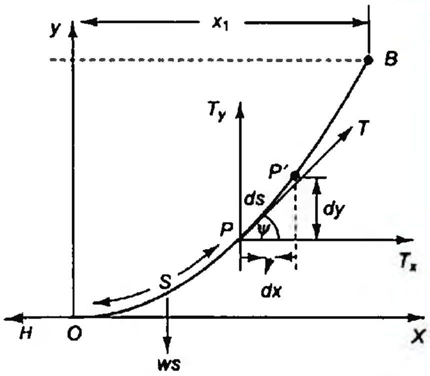
Calculation of Sag and Tension



$$\int dx = \int \frac{ds}{\sqrt{1 + w^2 s^2 / H^2}}$$

Integrating

$$x + c_1 = \frac{H}{w} \sinh^{-1}\left(\frac{ws}{H}\right);$$

At x=0, s=0, therefore c_1=0

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

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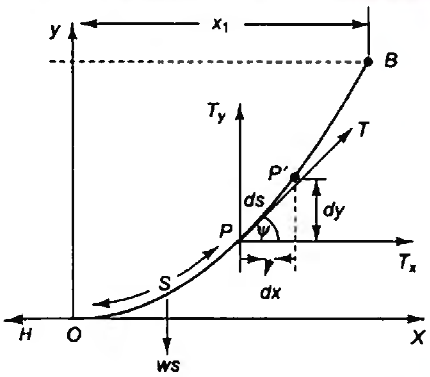
Calculation of Sag and Tension



$$s = \frac{H}{w} \sinh \frac{wx}{H}$$

$$\Downarrow$$

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

Also $\dfrac{dy}{dx} = \dfrac{ws}{H}$

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

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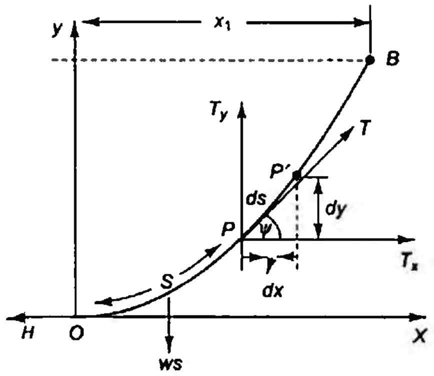
Calculation of Sag and Tension



$$\int dy = \int \sinh \frac{wx}{H}\, dx$$

Integrating

$$y = \frac{H}{w} \cosh\left(\frac{wx}{H}\right) + c_2$$

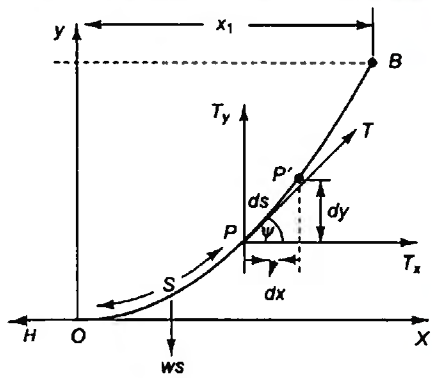
At y=0, x=0, therefore

$$c_2 = -\frac{H}{w}$$

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

$$y = \frac{H}{w}\left(\cosh \frac{wx}{H} - 1\right)$$

Calculation of Sag and Tension



For tension at point P,

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

$$= H^2 + w^2 s^2$$

We know $s = \frac{H}{w} \sinh \frac{wx}{H}$

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

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

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

$$T = H \cosh \frac{wx}{H}$$

Support at Same Heights

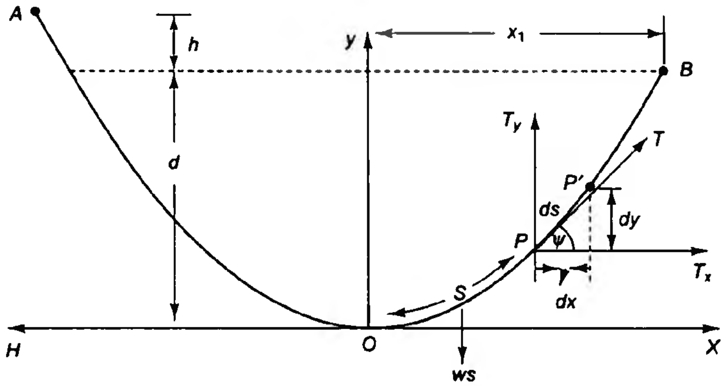
If the towers at same height and span is $2l$, i.e. half span is l

$$s = \frac{H}{w}\sinh\frac{wx}{H} \Rightarrow S = \frac{H}{w}\sinh\left(\frac{wl}{H}\right)$$

$$y = \frac{H}{w}\left(\cosh\frac{wx}{H} - 1\right) \Rightarrow d = \frac{H}{w}\left(\cosh\frac{wl}{H} - 1\right)$$

$$T = H\cosh\frac{wx}{H} \Rightarrow H\cosh\frac{wl}{H}$$

Supports at Different Heights



Supports at Different Heights

For tower B → $y_B = \frac{H}{w}\left(\cosh\frac{wx_1}{H} - 1\right)$ | $y = \frac{H}{w}\left(\cosh\frac{wx}{H} - 1\right)$

For tower A → $y_A = d + h = \frac{H}{w}\left(\cosh\frac{w(2l - x_1)}{H} - 1\right)$

Therefore, difference in tower heights

$$h = \frac{H}{w}\left(\cosh\frac{w(2l - x_1)}{H} - \cosh\frac{wx_1}{H}\right)$$

$$= \frac{2H}{w}\sinh\frac{wl}{H}\sinh\frac{w(l - x_1)}{H}$$

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Approximate Formulae for Sag and Tension

$H\cosh\frac{wl}{H}$ → $T \approx H\left(1 + \frac{w^2l^2}{2H^2}\right)$ → $T \approx H$

$d = \frac{H}{w}\left(\cosh\frac{wl}{H} - 1\right)$ → $d \approx \frac{H}{w}\left(1 + \frac{w^2l^2}{2H^2} - 1\right)$ → $d \approx \frac{wl^2}{2H}$

$S = \frac{H}{w}\sinh\left(\frac{wl}{H}\right)$ → $S \approx \frac{H}{w}\left(\frac{wl}{H} + \frac{w^3l^3}{6H^3}\right)$ → $S \approx l + \frac{w^2l^3}{6H^2}$

$T \approx H$ → $d \approx \frac{wl^2}{2T}$ and $S \approx l + \frac{w^2l^3}{6T^2}$

$\sinh x = x + \frac{x^3}{3!} + \frac{x^5}{5!} + \frac{x^7}{7!} + \cdots$ and $\cosh x = 1 + \frac{x^2}{2!} + \frac{x^4}{4!} + \frac{x^6}{6!} + \cdots$

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Parabolic Approximation

- In case of short spans (distribution lines) with small sag (less than 10%), the curve can be considered as parabola.
  - Sag less than 6% could give only 0.5% error
  - Sag between 6-10 % could give only 2% error

$$y = \frac{H}{w}\left(\cosh\frac{wx}{H} - 1\right) \approx \frac{H}{w}\left(1 + \frac{w^2x^2}{2H^2} - 1\right) \Rightarrow y \approx \frac{wx^2}{2H}$$

$$y \approx \frac{wx^2}{2T} \qquad T \approx H$$

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Effect of Ice Covering and Wind

- If the ice thickness is more than 0.5 cm then it is considered.
- Effect of ice covering (w_i) is to increase the weight of conductor (w_c) , and thus increases the vertical sag.
- If r is radius of conductor and t is thickness of ice layer.

$$V_i = \pi(r+t)^2 - \pi r^2$$
$$= \pi(r^2 + 2rt + t^2 - r^2)$$
$$= \pi(t^2 + 2rt)\ \text{m}^3$$

If ρ is the density of ice

$$W_i = \pi\rho(t^2 + 2rt) \quad \text{kg/m}$$

Therefore, total weight (W_T)

$$W_T = W_c + W_i$$

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Effect of Ice Covering and Wind

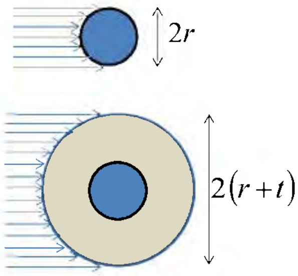
- The wind pressure acts on the conductor in horizontal direction. Assume that wind blows uniformaly.
- If p is the wind pressure, wind loading (w_w)

Conductor alone $\quad w_w = 2rp \text{ kg/m}$

Conductor + Ice $\quad w_w = 2(r+t)p \text{ kg/m}$

- The wind pressure depends on the velocity of the wind.

$$p = 0.006 v^2 \text{ kg/m}^2$$



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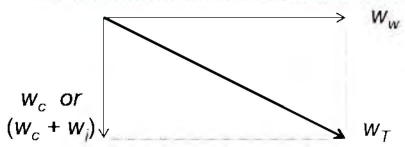
Effect of Ice Covering and Wind



- The resultant weight of the conductor is:

Conductor alone $\quad w_T = \sqrt{w_c^2 + w_w^2} \text{ kg/m}$

Conductor + Ice $\quad w_T = \sqrt{(w_c + w_i)^2 + w_w^2} \text{ kg/m}$

- The angle at which loading is acting is:

Conductor alone $\quad \phi = \tan^{-1}(w_w / w_c)$

Conductor + Ice $\quad \phi = \tan^{-1}(w_w / (w_c + w_i))$

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Stringing Chart

- The curves of sag and tension with temperature variation are called the *Stringing Charts*.
- Stringing chart is helpful in providing sag and tension at any temperature, if the sag and tension is know at any particular temperature.
- They are useful in erecting line conductors at specified temperature and loading conditions.
- At high temperature, sag is more and tension is less whereas at low temperature sag is less but tension is more.

Stringing Chart

w	Load per unit length
f	Stress (tension per mm^2)
S	Conductor length (half span)
d	Sag
θ	Temperature
A	Area of cross section of conductor
α	Coefficient of linear expansion
E	Young's modulus

- Subscripts 1 and 2 denote temperatures at maximum load conditions and under stringing conditions (installation or erection of transmission line).

Stringing Chart

- For short spans
- $d \approx \dfrac{w\,l^2}{2T}$ and $S \approx l + \dfrac{w^2\,l^3}{6\,T^2}$ ⟹ $T = A\,f$ ⟹ $S = l + \dfrac{w^2 l^3}{6A^2 f^2}$
- At temperature θ_1

$$S_1 = l + \frac{w_1^{\,2} l^3}{6A^2 f_1^{\,2}} \quad \text{and} \quad d_1 = \frac{w_1\, l^2}{2A\, f_1}$$

- At temperature θ_2

$$S_2 = l + \frac{w_2^{\,2} l^3}{6A^2 f_2^{\,2}} \quad \text{and} \quad d_2 = \frac{w_2\, l^2}{2A\, f_2}$$

Stringing Chart

- Due to increase in temperature from θ_1 to θ_2, increase in length is:

$$(\theta_2 - \theta_1)\alpha\, S \approx (\theta_2 - \theta_1)\alpha\, l \quad ⟸ \quad \Delta l = l_o\, \alpha\, \Delta\theta$$

- There is another effect increase in temperature from θ_1 to θ_2, decrease tension or stress from f_1 to f_2:

$$\left(\frac{f_1 - f_2}{E}\right) S \approx \left(\frac{f_1 - f_2}{E}\right) l \quad ⟸ \quad \Delta l = \frac{\Delta f\, l_0}{E}$$

- Therefore new length is:

$$S_2 = S_1 + (\theta_2 - \theta_1)\alpha\, l - \left(\frac{f_1 - f_2}{E}\right) l$$

Stringing Chart

$$l + \frac{w_2^{\,2} l^3}{6A^2 f_2^{\,2}} = l + \frac{w_1^{\,2} l^3}{6A^2 f_1^{\,2}} + (\theta_2 - \theta_1)\alpha\, l - \left(\frac{f_1 - f_2}{E}\right) l$$

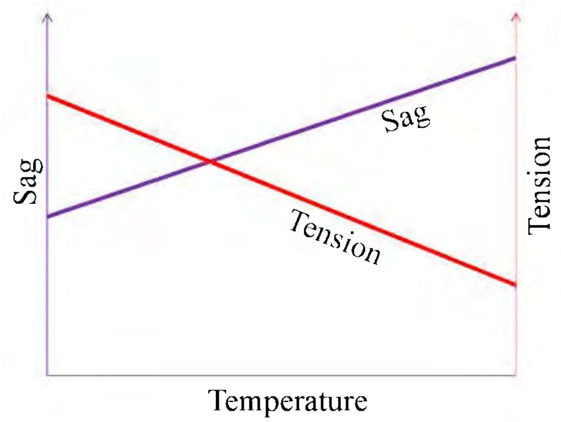
- Simplifying

$$\frac{w_2^{\,2} l^2 E}{6A^2} = f_2^2\left(f_2 - f_1 + \frac{w_1^{\,2} l^2 E}{6A^2 f_1^{\,2}} + (\theta_2 - \theta_1)\alpha\, E\right)$$

- This is cubic equation in f2 which can be solved using mathematical algorithm. Then the sag is:

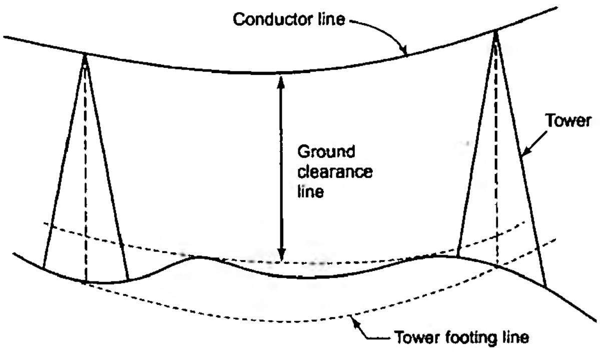
$$d_2 = \frac{w_2\, l^2}{2A\, f_2}$$

Stringing Chart



Sag Template

- It is plot of curve used for locating the tower positions.



- Nowadays, this is done using sophisticated software programs, which take input such as cost of tower, foundation requirements, soil quality, etc.

Ruling or Equivalent Span

- There are several situations span length is not same.
- Therefore, tension in each span will be different.
- This is not possible in case of suspension type insulator, because it will swing to equalize the tension.
- Therefore, the uniform tension in each span is calculated by defining the equivalent span (or ruling span).

$$L_e = \sqrt{\frac{L_1^3 + L_2^3 + L_2^3 + \cdots + L_n^3}{L_1 + L_2 + L_3 + \cdots + L_n}}$$

- L_e is the equivalent or ruling span
- L_i is the each individual span in line

Ruling or Equivalent Span

- Also approximate ruling span is:

$$L_e = L_{avg} + \frac{2}{3}\left(L_{max} + L_{avg}\right)$$

  - L_{avg} is the average span in line
  - L_{max} is the maximum span in line

- The *ruling span* is then used to calculate the horizontal component of tension, which is to be applied to all the spans between the anchor points. Then the sag at each span is computed using

$$d_i = \frac{w l_i^2}{2H}$$

- Span should not be more than twice the *ruling span* or less than half the *ruling span*.

- In addition to Horizontal swing due to wind pressure, there are two types of vertical vibrations:
  - Aeolian or resonant vibrations
    - It is caused by vortex phenomena in light winds.
    - Low magnitude (up to 5 cm) and high frequency (5-40 Hz)
    - Less harmful because of small magnitude
    - These vibrations are common in conductor and more or less always present.
    - The *Armour rods* or *dampers* are used to damp these vibrations.

Armour rods

Stock-bridge dampers

Conductor Vibrations

- Galloping (or dancing conductors)
  - Generally happened due to asymmetrical layer of ice formation.
  - When this asymmetrical ice coated conductor exposed to light winds (particularly when the slope of ground is higher).
  - High magnitude (up to 6 m) and low frequency (0.25-2 Hz).
  - These vibration may cause flashover between the conductors.
  - To avoid this flashover horizontal configuration is preferred.
  - Also if conductor is perfectly circular the effect can be minimized.
  - The stranded conductors can be wrapped up with PVC to make conductor perfectly circular.

Insulators for Overhead Line

- *Insulators* are used to insulate towers from the live conductors
- The insulators are attached to the tower and support the line conductors.
- Important characteristics:
  - It should be completely homogeneous materials without voids and impurities.
  - Leakage current through it should be minimum.
  - Breakdown strength of the material should be high and it should withstand over-voltages and normal working voltages.
  - It should be mechanically strong to bear the conductor load and should have longer life.

Insulator Ratings

- Three voltages ratings
  - Working voltage
  - Puncture voltage
  - Flashover voltage

- Flashover voltage is less than puncture.

$$\text{Safety Factor} = \frac{\text{Flashover Voltage}}{\text{Working Voltage}}$$

Insulators for Overhead Line

- Porcelain:
  - Porcelain is widely used as it is cheap.
  - It is thoroughly vitrified to remove voids and glazed before use to keep surface free of dust and moisture.
  - Breakdown strength is around 6-12 kV/mm

- Glass:
  - Toughened glass is another choice having higher dielectric strength (120 kV/mm), mechanical strength and life.
  - Flaws can be detected easily by visual inspection.
  - Main disadvantage is moisture rapidly condenses on the surface giving high surface leakage current.

Insulators for Overhead Line

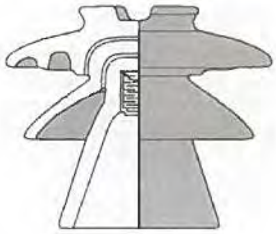
- Polymeric Insulation:
  - Silicone rubber and EPDM (Ethylene propylene diene monomer) are used for insulation purpose.
  - Low cost, light weight, higher life, improved dielectric performance under contamination or pollution.
  - They are used in combination with fiber glass rod.
  - These are under field trials and may take time to be used extensively.
  - Tracking and erosion of the shed material, which led to pollution and caused flashover.
  - Chalking and crazing of the insulator's surface, which resulted in increased contaminant collection, arcing, and flashover.

Types of Insulators

- Pin type insulators
- Suspension type insulators
- Strain type insulators

- Shackle insulator
- Post type insulators
- Composite polymeric insulators

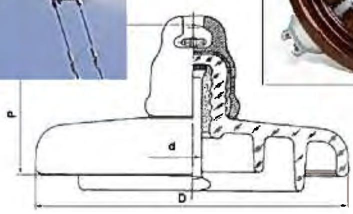
Pin Type Insulator



- Supported on steel bolt or pin which is firmly supported on cross-arm.
- Conductor is tied to insulator on groove by annealed binding wire.
- Generally used for 11 kV and 33 kV lines.
- They can be made in one piece up to 33 kV and two pieces for higher voltages.
- Pin type insulators are uneconomical for higher voltages.
- The leakage or creep age distance is from line to pin radially along the surface.

Suspension Type Insulators

- Consists of one or more insulating units hung from cross arm and conductor is connected at lowest unit.
- String is free to swing (lower mechanical stresses); thus long cross arms are required.
- Economical voltages above 33 kV. Each typical unit is designed for 11 kV.



- Failed unit can be changed without changing whole string.
- V shaped insulator strings can also be used to avoid the swings.
- 400 -> 19 units -> 3.84 m

Strain Type Insulator

- The insulators are similar to suspension type insulator but used in horizontal position.
- Generally used at the towers with dead end, angle towers, and road and river crossings.
- They can take tension off the conductors. When tension is very high two or more are used in parallel.

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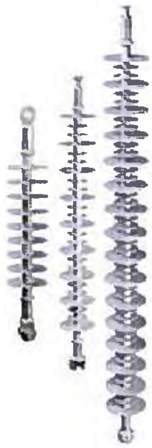
Shackle, Post and Polymeric insulators

Shackle insulators or spool insulators

Post type insulators



Polymeric insulators

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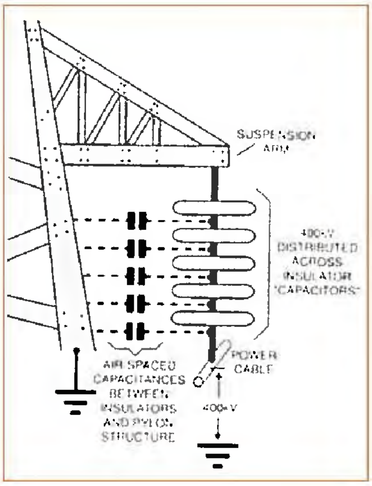
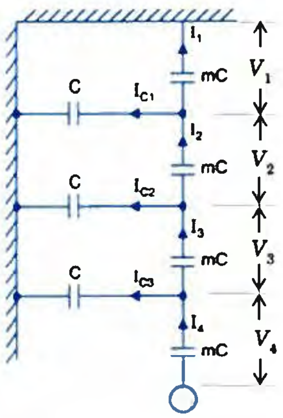
Potential Distribution over String



- Capacitance of disc: Capacitance between metal work of the insulator units; some times called as mutual capacitance.
- Capacitance to ground: capacitance between metal work of insulator to tower.

$$m = \frac{\text{Capacitance per insulator}}{\text{Capacitance to ground}} = \frac{mC}{C}$$

Potential Distribution over the String



$$m = \frac{\text{Capacitance per insulator}}{\text{Capacitance to ground}} = \frac{mC}{C}$$

- If V is voltage across the conductor and ground. We have:

$$V = V_1 + V_2 + V_3 + V_4$$

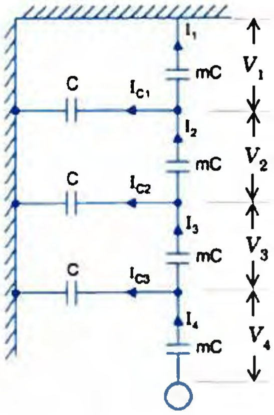
Also $I_2 = I_1 + I_{c_1}$

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

$$V_2 = \frac{V_1}{m}(m+1) = \frac{m+1}{m}V_1$$

$$V_2 = V_1\left[1 + \frac{1}{m}\right]$$

Potential Distribution over the String



- Similarly, $I_3 = I_2 + I_{c_2}$

$$V_3 m\omega C = V_2 m\omega C + (V_1 + V_2)\omega C$$

$$V_3 m\omega C = V_2 \omega C(m+1) + V_1 \omega C$$

Substituting $V_2 = \frac{m+1}{m} V_1$

$$V_3 m\omega C = \frac{m+1}{m} V_1 \omega C(m+1) + V_1 \omega C$$

$$= V_1 \omega C \left[\frac{(m+1)^2}{m} + 1\right]$$

$$V_3 = V_1 \left[\frac{m^2 + 3m + 1}{m^2}\right]$$

$$V_3 = V_1 \left[1 + \frac{3}{m} + \frac{1}{m^2}\right]$$

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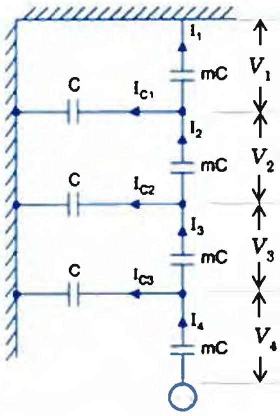
Potential Distribution over the String



- Similarly, $I_4 = I_3 + I_{c_3}$

$$V_4 m\omega C = V_1 \omega C \left[\frac{m^2 + 3m + 1}{m}\right] + \omega C\,[V_1 + V_2 + V_3]$$

$$= V_1 \omega C \left[\frac{m^2 + 3m + 1}{m}\right]$$

$$+ \omega C \left[V_1 + \frac{m+1}{m} V_1 + \frac{m^2 + 3m + 1}{m^2} V_1\right]$$

$$V_4 = V_1 \cdot \left[\frac{m^2 + 3m + 1}{m^2} + \frac{3m^2 + 4m + 1}{m^3}\right]$$

$$V_4 = V_1 \left[1 + \frac{6}{m} + \frac{5}{m^2} + \frac{1}{m^3}\right]$$

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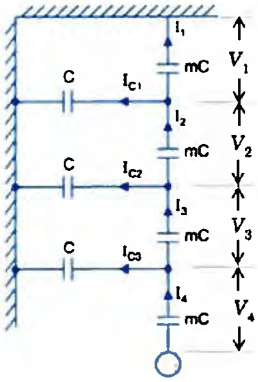
String Efficiency



- Let m = 5

$$V_2 = V_1\left[1+\frac{1}{m}\right] \Rightarrow V_2 = 1.2V_1$$

$$V_3 = V_1\left[1+\frac{3}{m}+\frac{1}{m^2}\right] \Rightarrow V_2 = 1.64V_1$$

$$V_4 = V_1\left[1+\frac{6}{m}+\frac{5}{m^2}+\frac{1}{m^3}\right] \Rightarrow V_2 = 2.41V_1$$

$$String\ Effciency = \frac{Voltage\ Across\ String}{n \times Voltage\ across\ unit\ adjacent\ to\ line} \times 100$$

$$= \frac{(1+1.2+1.64+2.41)V_1}{4 \times 2.41V_1} \times 100 = 63.8\%$$

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Methods of Equalizing the Potential

- Methods to improve string efficiency
  - Selection of *m*
  - Grading of units
  - Static shielding or guard rings

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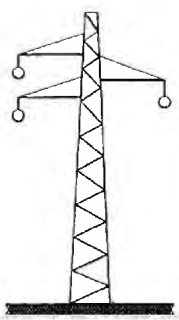
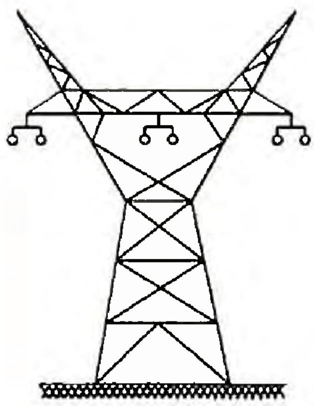
Line Support

- **Wooden Poles**
  - Cheapest, used for small spans (30-40m)
  - Tendency to rot at ground and life can not be predicted.
- **Reinforced concrete poles**
  - Long life and low maintenance
  - High cost of transport because of weight
- **Tubular steel poles**
  - Longer spans than wooden, longer life, light weight, high strength
  - Need galvanization
- **Lattice steel towers**
  - Economical for long spans, tall supports and HV transmission
  - Galvanized and painted

Typical Towers





- Main stem
- Cross arms
- Insulator
- Guy wire (Optional)

Type of Towers

- Type A tower (Tangent tower with suspension string)
  - Used on straight runs and up to 2^0 line diversions
- Type B tower (small angle tower with tension string)
  - Used for line diversions from 2^0 to 15^0
- Type C tower (Medium angle tower with tension string)
  - Used for line diversions from 15^0 to 30^0
- Type D tower (Large angle tower with tension string)
  - Used for line diversions from 30^0 to 60^0
- Type E tower (Dead End tower with tension string)
  - Used for line termination and starting
- Special tower
  - Suspension tower: (Span about 1000m) for river or mountain crossing
  - Transposition tower: Transposition of line

Innovative Designs



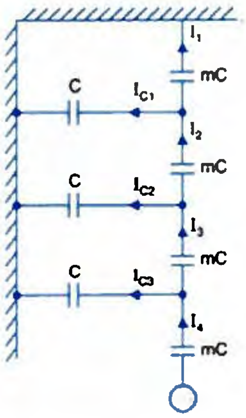

VI. TRANSMISSION AND DISTRIBUTION SYSTEM

OVERHEAD TRANSMISSION LINES ELECTRICAL DESIGN

Methods of Equalizing the Potential

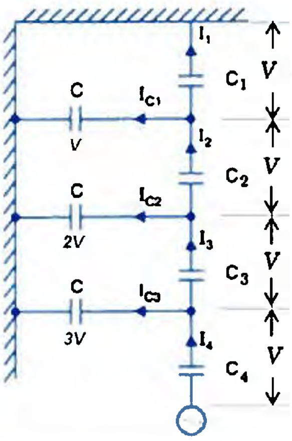
- Methods to improve string efficiency
  - Selection of *m*
  - Grading of units
  - Static shielding or guard rings

Selection of m



- If the value of *m* is increased, which can be achieved by increasing the cross-arm length.
- Increased cross-arm length decreases the capacitance between earth and metallic connections.
- However increasing cross-arm length is not economical after certain distance.
- Theoretically, one can achieve equal voltage distribution when *m* is infinity.
- It is found that value of *m* greater than 10 is not economical.

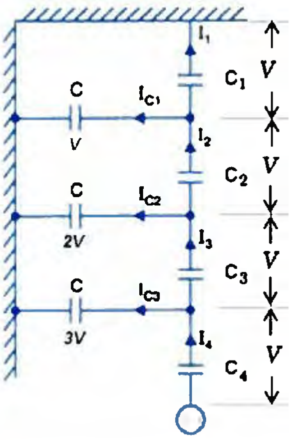
Grading of Units



- Voltage across capacitor is inversely proportional to the capacitance for given current.
- By correct grading of capacitances complete equality voltage can be achieved.
- We have,

$$I_2 = I_{C1} + I_1$$
$$\omega C_2 V = \omega C V + \omega C_1 V$$
$$C_2 = (C + C_1)$$

Grading of Units



$$I_3 = I_{C2} + I_2$$

$$\omega C_3 V = 2\omega C V + \omega C_2 V$$

$$But \;\; C_2 = (C + C_1)$$

$$\omega C_3 V = 2\omega C V + \omega (C + C_1) V$$

$$C_3 = 3C + C_1$$

$$C_3 = C_1 + (1+2)C$$

Generalized case:

$$C_n = C_1 + (1 + 2 + 3 + \cdots + (n-1))C$$

Therefore, if $C_1 = 5C$, then

$$C_2 = 6C,\; C_3 = 8C,\; C_4 = 11C, \;\; \text{and so on}$$

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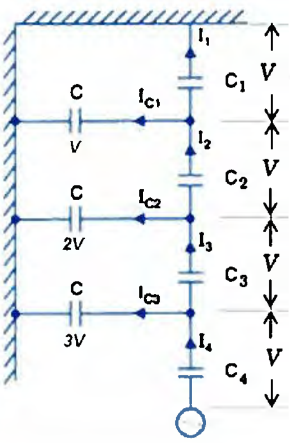
Grading of Units



- Thus if capacitance of one unit is fixed other capacitances can be easily determined.
- This requires units of different capacities, which is uneconomical and impractical.
- Therefore this method is usually not employed except for very high voltage lines.
- In that case, string is graded in groups, ma be two/three.

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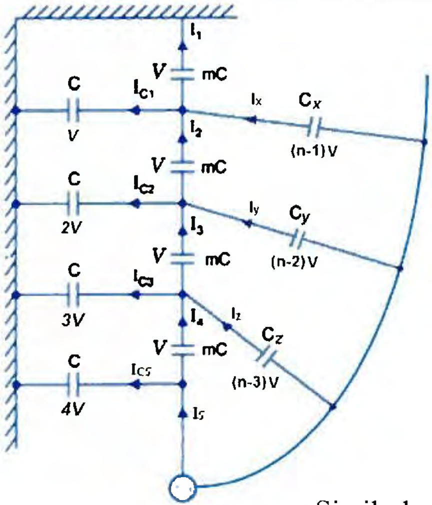
Static Shielding



$$I_2 + I_x = I_1 + I_{C1}$$
$$I_3 + I_y = I_2 + I_{C2}$$
$$I_4 + I_z = I_3 + I_{C3}$$

Voltages can be equal if

$$I_x = I_{C1}$$
$$\omega Cx(n-1)V = \omega CV$$
$$C_x = \frac{C}{(n-1)}$$

Also, $I_y = I_{C2}$

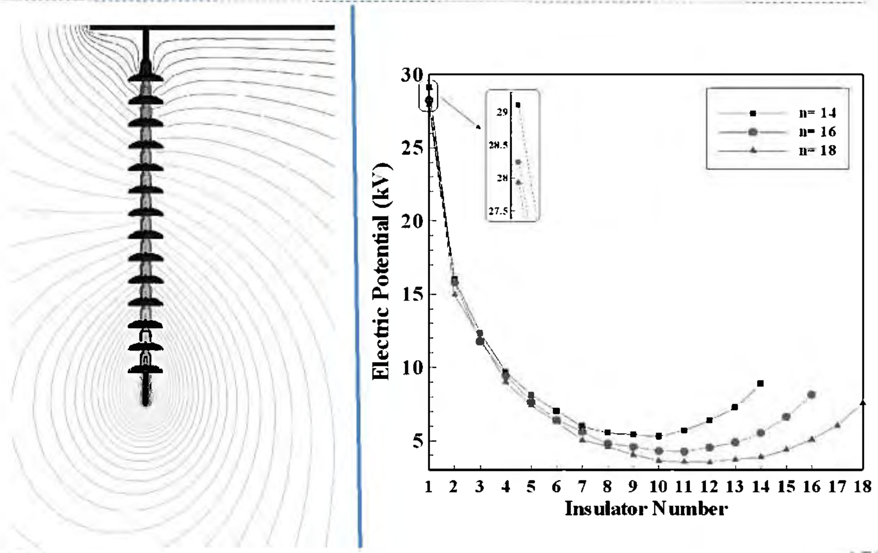
$$\omega Cy(n-2)V = 2\omega CV$$
$$C_y = \frac{2C}{(n-2)}$$

Similarly, $C_Z = \frac{3C}{(n-3)}$ and $C_p = \frac{pC}{(n-p)}$

Static Shielding

- In practice, it is very difficult to achieve the condition of equal voltages.
- However the partial advantage can be gained by this method (*guard ring*) and used normally.
- Further, when the horn gap is also used, it also protect the insulator from the flashover.

Numerical Method (FEM, BEM, FDM, etc.)



VI. TRANSMISSION AND DISTRIBUTION SYSTEM

OVERHEAD TRANSMISSION LINES
CORONA

What is Corona?

- " Corona is a luminous discharge due to ionization of the air surrounding an electrode, caused by a voltage gradient exceeding a certain critical value."

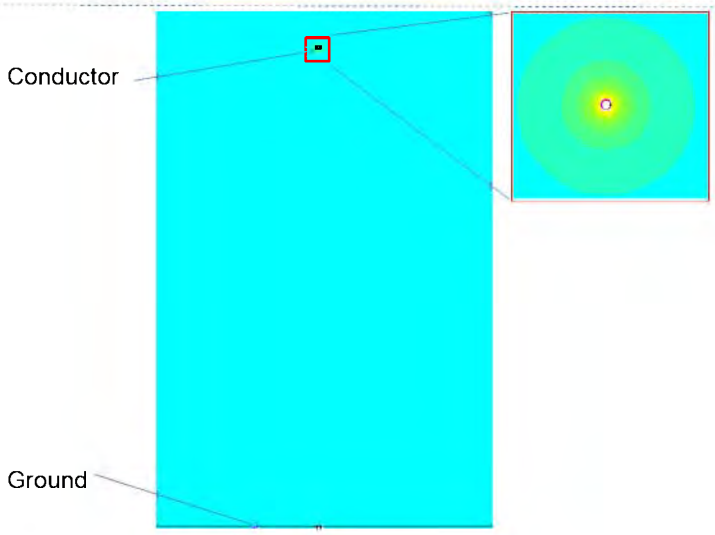
Why Corona is Important?

- Corona from conductors may cause audible noise and radio noise.
- Audible noise from conductors may violate noise standards.
- Radio noise from conductors may interfere with communications systems.
- Corona loss may be significant when compared with resistive loss of conductors.
- Corona can cause possible damage to polymeric insulators.
- Therefore, corona free lines needs to be designed which requires an understanding of factors that affect corona

Partial Discharge

- The breakdown of a gas takes place when a self sustained discharge or ionization process is set in.
- This takes place when the electric field stress exceeds a certain critical value.
- In the case of uniform field this condition is satisfied at all the points and there will be complete breakdown by forming an arc between the electrodes.
- For air breakdown strength (at 25^0C and 760 mm Hg) is 30 kV/cm for DC and 30 kV/cm (peak) for AC.
- However, if the electric field is highly non-uniform the breakdown condition may not be all over the gap.

Non-Uniform Field



Corona

- Therefore in non-uniform field, some region of dielectric experiences higher field strength than the critical value, while other region field stress is well below critical value.
- Thus, self sustained discharge condition will be valid only in the strong field region giving rise to partial discharge called corona.
- This associated with a glow (bluish or violet tuffs, streamers, and/or glow) and a hissing sound and when it takes place in air ozone, oxides of nitrogen and nitric acid (in the presence of moisture) are formed.
- Light is produced by recombination of nitrogen atom with free electrons.

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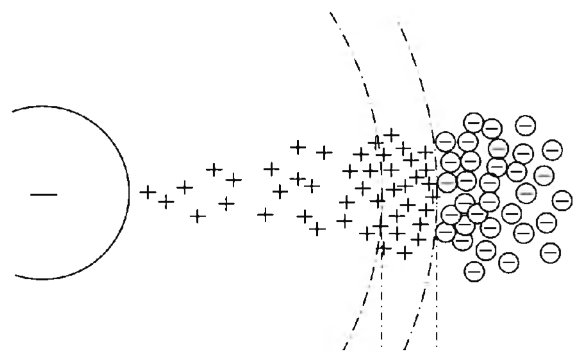
Mechanism of Corona Formation

- Conductors at Negative DC voltage



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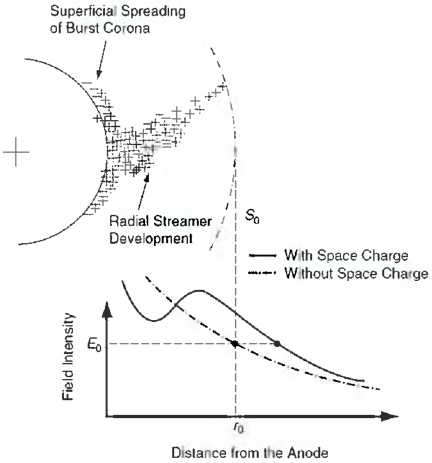
Mechanism of Corona Formation

- Conductors at Positive DC voltage



Mechanism of Corona Formation

- Conductors at AC voltage:
  - In positive half cycle:
    - when voltage exceeds corona inception value, ionization starts and intensity progressively increases till peak.
    - Electrons quickly reach conductor but before positive ions reach other electrode polarity changes.
    - Some positive ions remain virtually cutoff from both electrodes.
  - In negative half cycle:
    - In negative half cycle corona again starts when voltage exceeds corona inception value.
    - Electrons spreads out from the conductor and neutralize the stranded ions.

Mechanism of Corona Formation

- Conductors at AC voltage:
  - In this way, in every cycle some space charge need to be neutralized and result will be loss in charges from the source.
  - The energy continuously lost in the corona space.
  - Recombination of opposite charges will release energy in the surrounding air, which is heated up.

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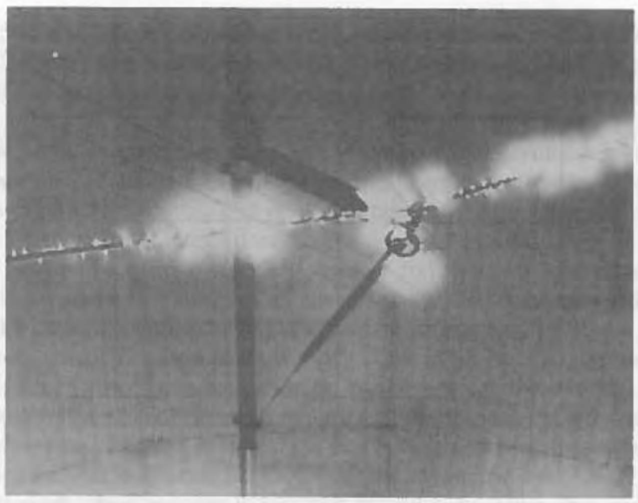
Corona (Laboratory Testing)



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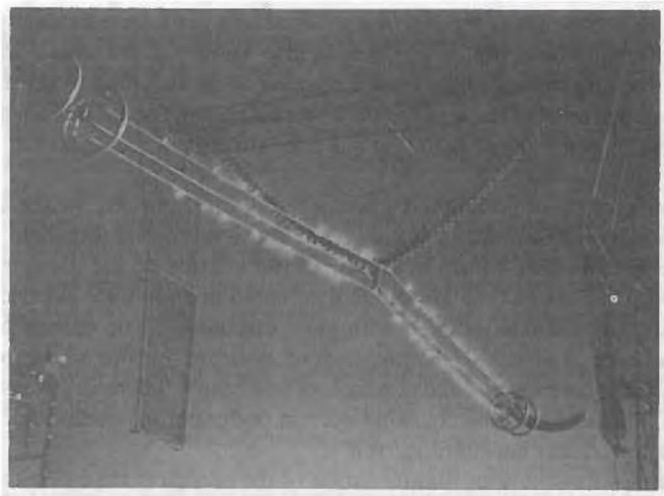
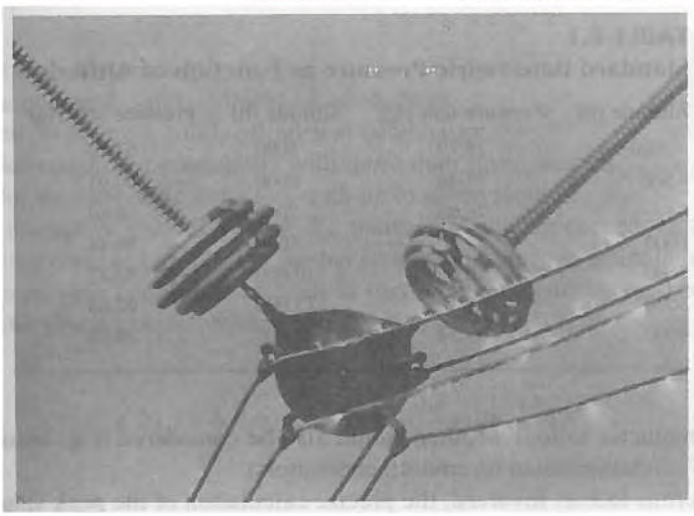
Corona (Laboratory Testing)



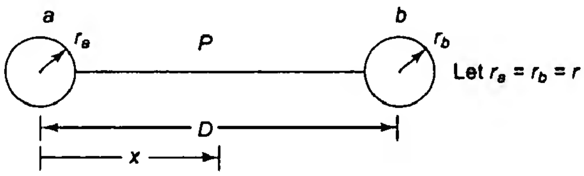
Corona (Testing)



Corona

Critical Disruptive Voltage

- The minimum potential difference required between the conductor to start ionization is called *critical disruptive voltage* or *corona inception voltage*



$$E_x = \frac{q}{2\pi \epsilon_0 x} + \frac{q}{2\pi \epsilon_0 (D-x)} = \frac{q}{2\pi \epsilon_0}\left[\frac{1}{x} + \frac{1}{D-x}\right]$$

$$= \frac{q}{2\pi \epsilon_0} \frac{D}{x(D-x)}$$

Critical Disruptive Voltage

Potential Difference between the conductor

$$V = -\int_{D-r}^{r} E_x\, dx = \int_{r}^{D-r} \frac{q}{2\pi \epsilon_0}\left[\frac{1}{x} + \frac{1}{D-x}\right] dx$$

$$= \frac{q}{\pi \epsilon_0} \ln D/r \quad \Rightarrow \quad q = \frac{\pi \epsilon_0 V}{\ln D/r}$$

Therefore,

$$E_x = \frac{q}{2\pi \epsilon_0} \frac{D}{x(D-x)} \quad \Rightarrow \quad E_x = \frac{\pi \epsilon_0 V}{\ln D/r} \frac{1}{2\pi \epsilon_0} \frac{D}{x(D-x)}$$

$$= \frac{V}{2 \ln D/r} \frac{D}{x(D-x)}$$

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Critical Disruptive Voltage

$$E_x = \frac{V}{2 \ln D/r} \frac{D}{x(D-x)}$$

- Above expression is for single phase line and $V' = V/2$

$$E_x = \frac{V' D}{x(D-x) \ln D/r}$$

- Now this can be used to single phase with $V' = V/2$ or for three phase line $V' = V/\sqrt{3}$

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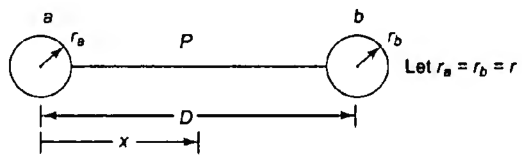
Critical Disruptive Voltage



$$E_x = \frac{V' D}{x(D - x) \ln D/r}$$

- Gradient increase a x decreases and will be maximum at conductor surface i.e. $x=r$

$$g_{max} = E_r = E_{max} = \frac{V'D}{r(D - r) \ln D/r} \cong \frac{V'}{r \ln D/r}$$

- Therefore, $V' = rg_{max} \ln D/r$

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Critical Disruptive Voltage

$$V' = rg_{max} \ln D/r$$

- When g_{max} reaches g_0 (breakdown strength of air) air breaks down.

g_0 = 30 kV/cm. For AC voltages $g_0 = \frac{30}{\sqrt{2}}$ = 21.2 kV (rms)/cm

Above g_0 is for fair (standard) whether conditions, at any other condition

$$g_0' = g_0 \delta$$

where $\delta = \frac{p}{273+t} \cdot \frac{273+25}{760} = 0.392 \frac{p}{273+t}$

δ is the relative air density or air density correction factor

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Critical Disruptive Voltage

- The *critical disruptive voltage* or *corona inception voltage* is then given by

$$V_d = r\, g_0\, \delta \ln \frac{D}{r} \quad \text{kV}$$

- Here, the assumption is conductor is solid having smooth surface, however in practical cases (like ACSR), conductor will not be having smooth surface. To account for surface irregularities a factor m_0 is used. Thus,

$$V_d = r\, g_0\, \delta\, m_0 \ln D/r \quad \text{kV}$$

m_0 = surface irregularity factor or stranding factor

Critical Disruptive Voltage

- Surface irregularity factor depends on state of cross section of conductor and state of its surface.
- It also considers dust and dirt on the conductor surface.
- The value of m_0 lies between 0.8 to 1.
  - m_0 = 1 for smooth, polished, and round conductors
  - m_0 = 0.92 – 0.98 for rough surfaced conductors
  - m_0 = 0.8 – 0.88 for stranded conductors
- Now when *d* and *r* expressed in cm.

$$V_d = (30\ \delta\, m_0)\ [r \ln(D/r)] \quad \text{kV (Peak)}$$
$$V_d = (21.1\ \delta\, m_0)\ [r \ln(D/r)] \quad \text{kV (rms)}$$

Critical Disruptive Voltage

$$V_c = g_{\max}\left(r \ln\frac{D}{r}\right)$$

Fair (or standard) whether conditions and solid conductor with smooth surface → $g_{max} = g_0$; g_0 = 30 kV/Cm (Peak), g_0 = 21.1 kV/Cm (rms) → $V_c = g_0\left(r \ln\frac{D}{r}\right)$

Other (or foul) whether conditions than standard and solid conductor with smooth surface → $g_{max} = \delta\, g_0$; $\delta = 0.392\frac{p}{273+t}$ → $V_c = g_0\,\delta\left(r \ln\frac{D}{r}\right)$

Other whether conditions than standard and conductor with irregular surface (ACSR) → $g_{max} = m_0\,\delta\, g_0$; The value m_0 is 0.8 to 1 → $V_c = m_0 g_0\,\delta\left(r \ln\frac{D}{r}\right)$

Visual Critical Disruptive Voltage

- At the critical disruptive voltage corona starts, but it will not be visible. It requires further ionization by collision.
- If the voltage is further increased at some point corona becomes visible. This voltage is called as *visual critical disruptive voltage* or *visual corona inception voltage*.
- The voltage gradient (g_v) for visual corona is given by [*Peek*]:

$$g_v = g_0\,\delta\left(1+\frac{0.301}{\sqrt{r\,\delta}}\right) \text{ kV/cm}$$

- Therefore, $V_d = g_v\, m_v\, r \ln(D/r)$ kV

$$V_d = g_0\,\delta\left(1+\frac{0.301}{\sqrt{r\,\delta}}\right) m_v\left[r \ln(D/r)\right] \text{ kV}$$

Visual Critical Disruptive Voltage

- Surface irregularity factor (m_v) is different from m_0.
- Local corona: For conductor with irregular surface, visual corona occurs at different point than whole surface called as *local corona.*
  - $m_v = 0.72$ for local visual corona on stranded conductor
  - $m_v = 0.82$ for general (or decided) corona on stranded conductor
  - $m_v = 1$ for smooth and polished conductor
- Now when *d* and *r* expressed in cm.

$$V_d = 30\,\delta \left(1 + \frac{0.301}{\sqrt{r\,\delta}}\right) m_v \left[r \ln(D/r)\right] \quad \text{kV (Peak)}$$

$$V_d = 21.1\,\delta \left(1 + \frac{0.301}{\sqrt{r\,\delta}}\right) m_v \left[r \ln(D/r)\right] \quad \text{kV (rms)}$$

Visual Critical Disruptive Voltage

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$$V_d = 21.1\,\delta \left(1 + \frac{0.301}{\sqrt{r\,\delta}}\right) m_v \left[r \ln(D/r)\right] \quad \text{kV (rms)}$$

Critical Disruptive Voltage

$$V_c = g_{\max}\left(r \ln \frac{D}{r}\right)$$

Critical Disruptive Voltage or corona inception voltage → $g_{max} = m_0\, \delta\, g_0$ The value m_0 is 0.8 to 1 → $V_c = m_0 g_0\, \delta \left(r \ln \frac{D}{r}\right)$

Visual critical disruptive voltage or visual corona inception voltage → $g_v = g_0\, \delta \left(1 + \frac{0.301}{\sqrt{r\,\delta}}\right)$ in kV/cm → $V_d = m_v\, g_v \left[r \,\ln\left(\frac{D}{r}\right)\right]$

Corona Loss

- The ionized charges near the conductor surface take energy from the supply system and thus there is loss of some energy due to corona.
- Peek's Empirical relation for corona in fair whether condition

$$P_c = 241 \times 10^{-5} \times \frac{f+25}{\delta}\sqrt{\frac{r}{d}}\left(V_p - V_c\right)^2 \quad \text{kW/phase/km}$$

Where V_P phase to neutral operating voltage in kV and f is frequency.

- For storm or foul whether condition voltage is 0.8 V_c

$$P_c = 241 \times 10^{-5} \times \frac{f+25}{\delta}\sqrt{\frac{r}{d}}\left(V_p - 0.8V_c\right)^2 \quad \text{kW/phase/km}$$

This relation is correct results when 1) Corona loss is predominant 2) Frequency lies between 25 and 125 Hz 3)Ration of $V_p/V_c > 1.8$ 4) radius of conductor is greater than 0.25 cm.

Corona Loss

- When the ratio $V_p/V_c < 1.8$ Peterson's formula gives good results

$$P_c = \frac{1.11066 \times 10^{-4} f V^2}{(\ln(d/r))^2} F \quad \text{kW/Phase/km}$$

- Here F is corona factor determined by test depends on V_p/V_c.

V_p/V_c	1	1.4	1.6
F	0.05	0.3	1

Factors Affecting Corona

- Atmospheric factors
  - Temperature
  - Pressure
  - Dust and dirt
  - Rain, snow, fog
- Electrical factor
  - Frequency
  - Supply voltage
- Line configuration
  - Conductor configuration
  - Profile of conductor
  - Diameter of conductor
  - Surface condition
  - Number of conductor per phase
  - Heating of conductor by load current
  - Conductor spacing

Factors Affecting Corona

- Atmospheric Factors

$$\delta = \frac{p}{273+t} \cdot \frac{273+25}{760} = 0.392 \frac{p}{273+t}$$

$$V_c = m_0 g_0 \delta \left(r \ln \frac{D}{r} \right)$$

$$P_c = 241 \times 10^{-5} \times \frac{f+25}{\delta} \sqrt{\frac{r}{d}} (V_p - V_c)^2 \quad \text{kW/phase/km}$$

  - Temperature:
  - Pressure:
  - Dust, dirt:
  - Rain, snow, fog:

Factors Affecting Corona

- Electrical Factor

$$\delta = \frac{p}{273+t} \cdot \frac{273+25}{760} = 0.392 \frac{p}{273+t}$$

$$V_c = m_0 g_0 \delta \left(r \ln \frac{D}{r} \right)$$

$$P_c = 241 \times 10^{-5} \times \frac{f+25}{\delta} \sqrt{\frac{r}{d}} (V_p - V_c)^2 \quad \text{kW/phase/km}$$

  - Frequency
  - Voltage

Factors Affecting Corona

- Line configuration

$$V_c = m_0 g_0 \delta \left(r \ln \frac{D}{r} \right)$$

$$P_c = 241 \times 10^{-5} \times \frac{f + 25}{\delta} \sqrt{\frac{r}{d}} (V_p - V_c)^2 \quad \text{kW/phase/km}$$

- Conductor configuration
- Diameter of conductor
- Number of conductor per phase
- Conductor spacing
- Profile of conductor
- Surface condition
- Heating of conductor by load current

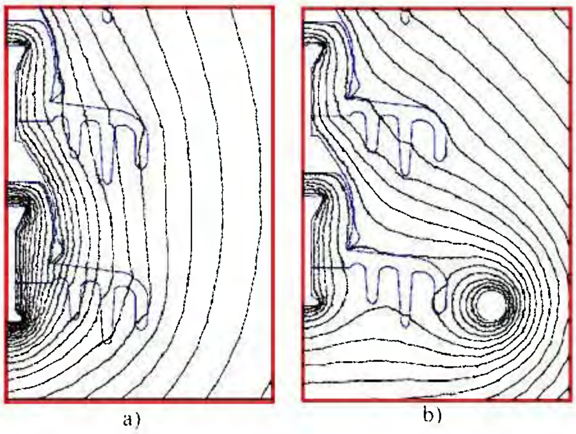
Merits and Demerits of Corona

- Merits
  - Act as safety valve during lightning and switching surges.
  - The waves gets dissipated as corona loss.
  - Other applications:
    - Van de Graaff generator, Electrostatic precipitator, Electro printing, Ionization counting, Electrostatic deposition
- Demerits
  - Corona loss reduces efficiency.
  - Ionized air around the conductor works as conducting medium increases effective diameter of conductor.
  - This increases capacitance and decrease surge impedance loading.
  - Interference with communication lines.

Prevention of Corona

- Economic consideration, it is advisable to build the line corona free for all the whether. Modern practice is to build corona free line in fair whether condition.
- To prevent corona loss, critical disruptive voltage higher the phase voltage.
  - Increasing conductor spacing
  - Increasing radius of conductor (Expanded ACSR)
  - Use of bundled conductors
  - Spacing between bundled conductor
  - Homogenous Insulators:
  - Elimination of sharp points:
  - Using Corona rings:
  - Surface Treatments:

Corona Ring



a) contour plots without corona ring
b) contour plots with corona ring

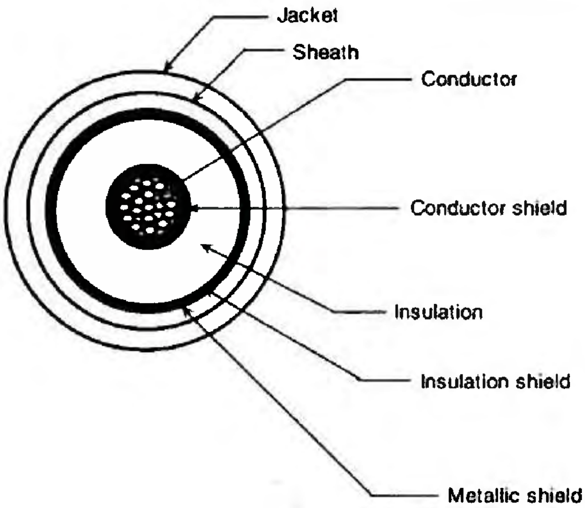
... POWER SYSTEM ENGINEERING

UNDERGROUND CABLES

Advantage of Underground Cables

- Underground cables are technically advantages than the overhead lines
  - Not exposed to environmental conditions
  - Inductance is lower in cable so voltage drop is less
- However, high erection cost, low heat dissipation and high charging current makes it uneconomical for long distance transmission
- Cables are preferred in following conditions:
  - Public safety involved and low interference is required
  - Large populated cities
  - Scenic beauty of city is important
  - Submarine crossing, and substation and transformer connections

Components of Power Cable



Components of Power Cable

- *Conductor* for carrying current
- *Conductor shield* to provide smooth radial electric field
- *Insulation* to insulate high voltage conductor
- *Insulation shield (optional)* to provide smooth radial electric field. Also act as hermitic seal of cable.
- *Metallic sheath and/or plastic jacket* for mechanical protection. Metal sheath protect cable from water ingress.
- *Metal wire armoring (optional)* for mechanical protection

Materials Used in Cables

- Conductors
  - Copper or aluminum
  - Stranded for flexibility
  - Size is decided by required ampacity
  - Temperature rise should be in limit to avoid degradation of the insulation
- Insulation Material
  - Paper (impregnated)
  - PVC (polyvinyl cloride)
  - Thermoset materials (XLPE, TR-XLPE, EPR)
  - Liquid and gaseous insulation

Insulation: Paper

- Dry paper is excellent insulator but losses the property quickly if it becomes wet.
- Dry paper is hygroscopic, so it must be sealed from air contact.
- Thus, it is sheathed with water resistant materials.
- Performance is improved by impregnating with mineral oil.
- It has relative permittivity of 3.6 and can withstand 20kV/mm.
- Ratings: 80^0C continuous loading, 130^0C short time overload and 200^0C for short circuit.
- Requires special jointing mechanism to ensure the appropriate sealing.
- Weight of cable is also higher as compared to PVC and XLPE

Insulation: Thermoset Materials

- These are also synthetic materials which do not soften, flow or get distorted when subjected to heat and pressure.
- XLPE (Cross linked polyethylene)
  - Long chains of polyethylene molecules are linked by carbon atoms.
  - Better electrical properties than PVC.
  - Extensively used for medium and high voltage cables (up to 500 kV).
  - Can be used up to 90^{0}C conductor temperature and worked upto -40^{0}C.
  - It has relative permittivity of 2.5 and can withstand 18 kV/mm.
  - Good mechanical strength and lighter in weight
- TR-XLPE (tree retardant XLPE): It contains special additive which resists tree formation.
- EPR (Ethylene propylene rubber): Higher thermal rating, thus higher ampacity. Dielectric properties are lesser than XLPE

Insulation: Liquid and Gaseous Insulation

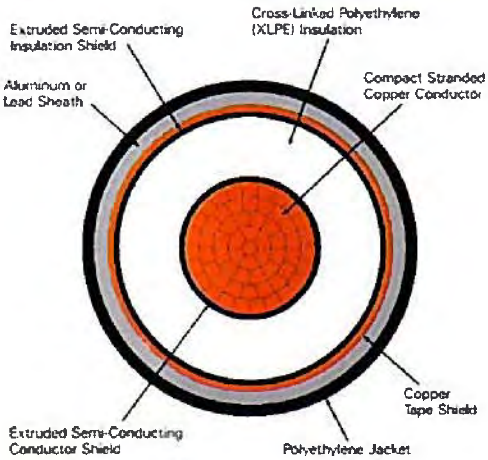
- In solid insulation voids are main problem which starts the partial discharge and may lead to breakdown.
- Void formation can be prevented by
  - Filling the cable with an insulating gas (N or SF6) at high pressure.
  - Use of low viscosity oil under (mineral oil) pressure.
- This results in much higher safe electric stresses and also high permissible operating temperature.

- temp

Different types of cable

- Belted
- Screened
- Pressure cables

Cable Structure



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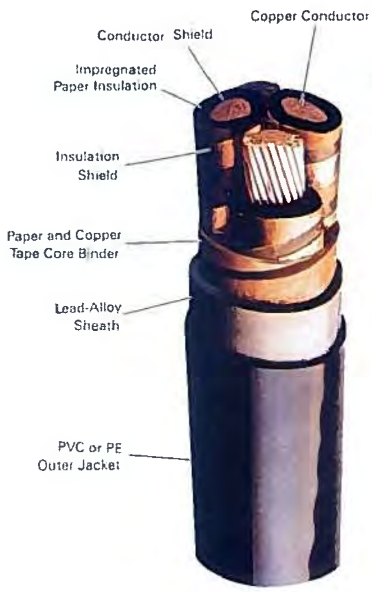
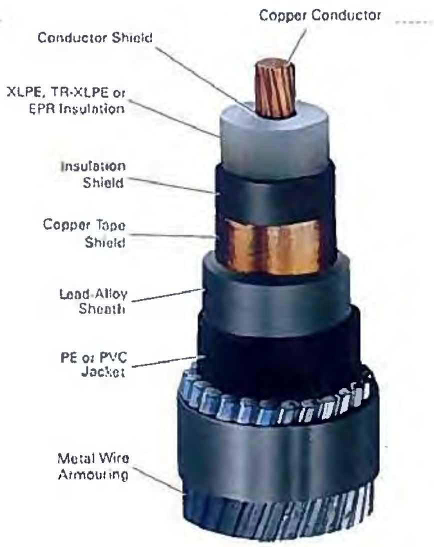


Paper-Insulated Lead-Covered Cables (PILC)



Sub- Marine Cable

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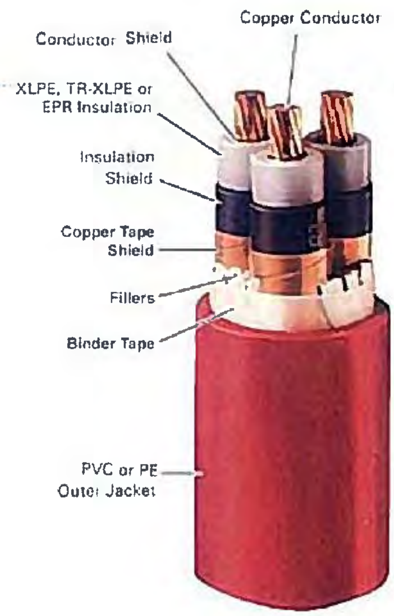

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Materials of Cable Component

Conductor	Insulation	Shield	Sheath	Jacket	Armor
•Copper or •Aluminum (Stranded)	•Paper •PVC •XLPE •TR-XLPE •EPR •Vulcanized rubber •Polythene	•Semiconducting (Insulation with carbon impregnation) •Aluminum Copper (tape)	•Lead •Aluminum	•PVC •Polythene •Nylon •Neoprene	•Galvanized steel

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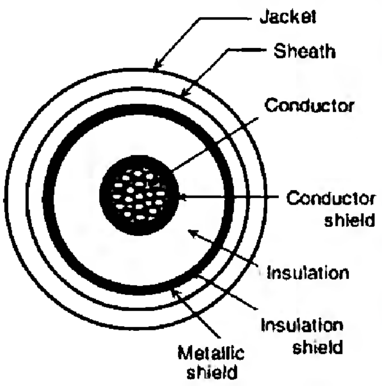
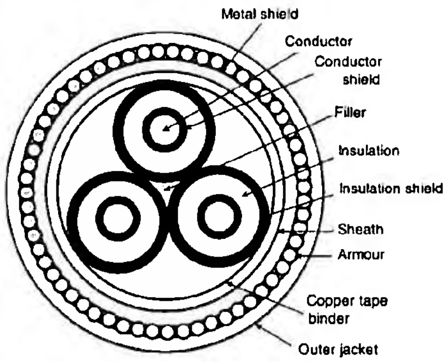
Single Core and Three Core Cables

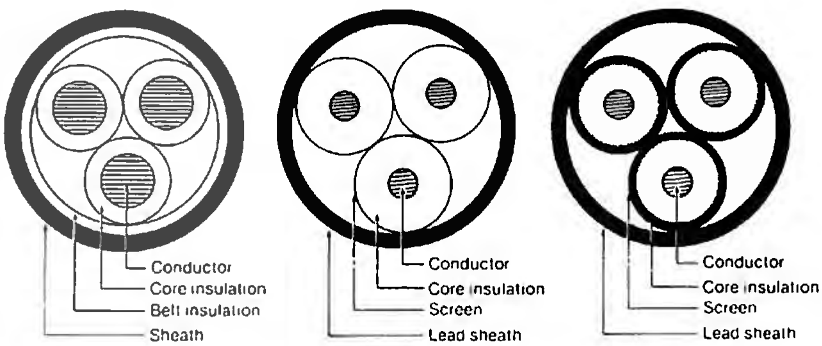


Single Core Cable



Three Core Cable
(Below 66 kV)

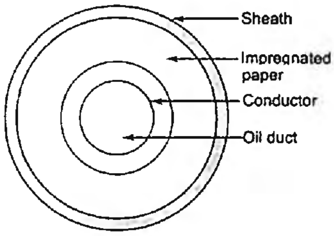
Belted and Screened or shielded Cable

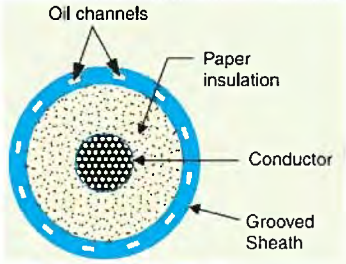


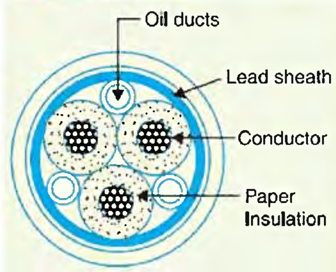
Belted **H-Type Screened** **S.L. Type Screened**

- Belted cables are used up to 11 kV.
- There are two types of screened cables H-Type (Hochstadter) and S.L. type (Separate lead). Used up to 33 kV

Pressurized Cable (Oil filled & oil pressure)

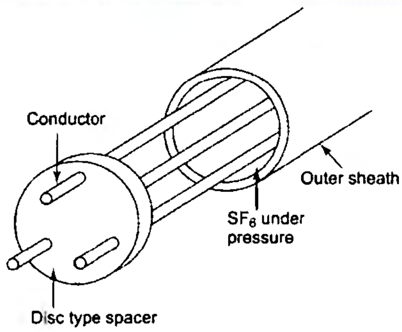






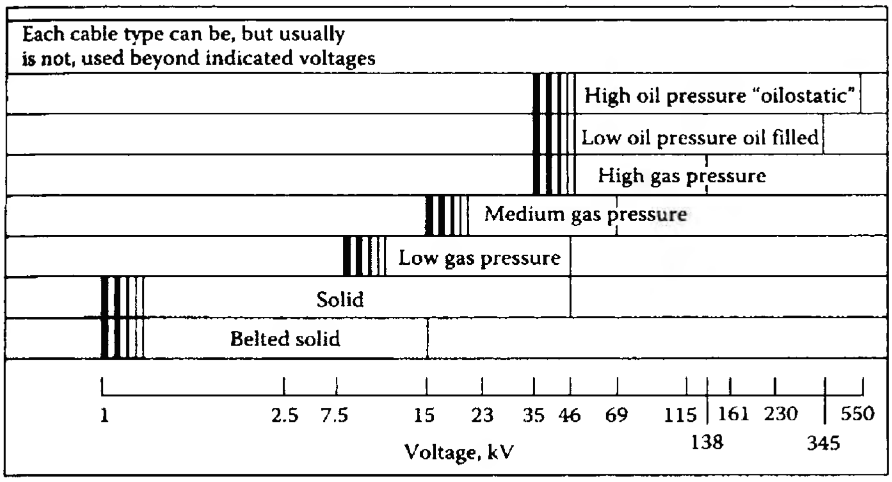
- Above 220 kV, It is necessary to avoid void formation.
- Voids are generally formed by cyclic heating and cooling and can be prevented by use of oil under pressure.
- Oil channel is made by spiral steel tape.

Gas Pressurized and Gas Filled Cables



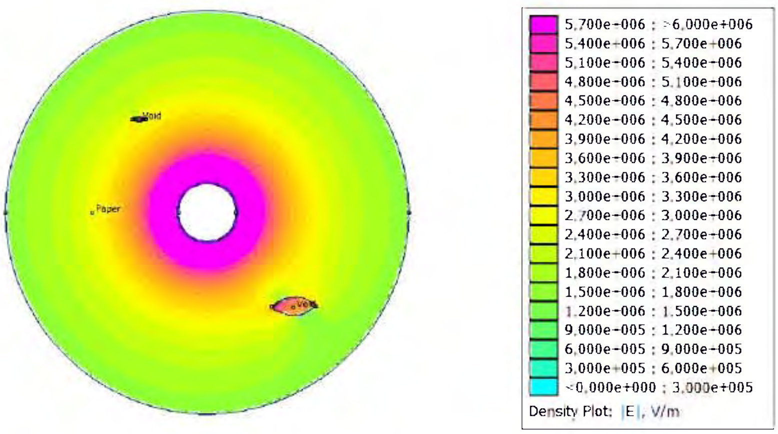
- Mainly two types: 1. impregnated gas pressure cable 2. gas filled cables.
- More revolutionary are the cables incorporating cryogenic cooler.
- Used up to 132 kV to 500 kV

Operating Range of the Cables

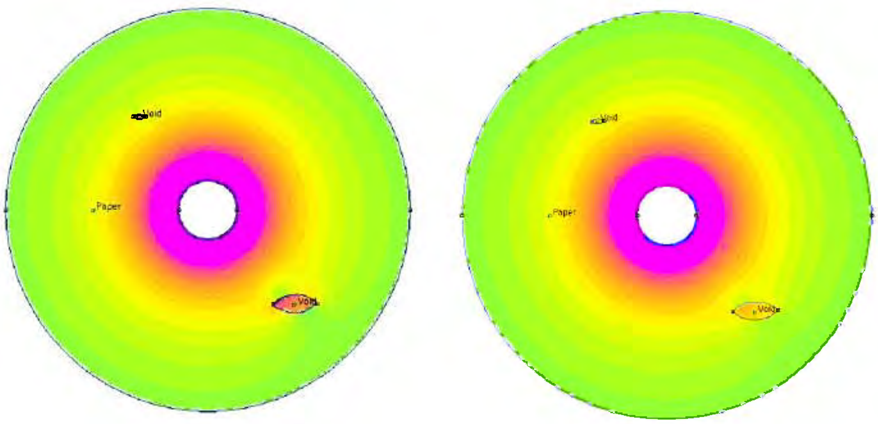


Recommended voltage ranges for various of paper-insulated paper cables.

Electric Field Intensity with Voids



Effect of Void Permittivity



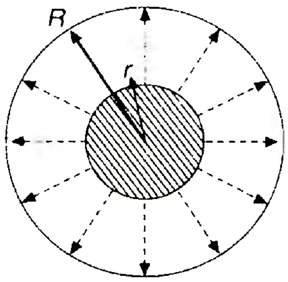
Air Voids

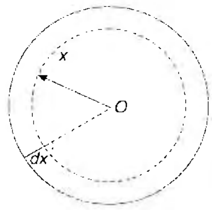
Voids filled with oil

Electrical Characteristics of Cables

- Insulation resistance
- Conductor inductance
- Cable capacitance
- Electrical stress inside insulation
  - Grading of cable
    - Capacitance grading
    - Inter-sheath grading
- Dielectric losses and tan delta (loss tangent)
- Sheath and armor losses

Insulation Resistance





- Resistance of small section *dx* is: $dR_x = \frac{\rho dx}{2\pi x l}$
- Therefore insulation resistance is $R_i = \frac{\rho}{2\pi l}\int_r^R \frac{dx}{x} = \frac{\rho}{2\pi l} \ln \frac{R}{r}$ ohm
- Insulation per unit length $R_i = \frac{\rho}{2\pi} \ln \frac{R}{r}$ ohm/m

Conductor Inductance

- For single core cable:

$$L = 2 \times 10^{-7} \ln \left(\frac{D}{r'}\right) \text{ H/metre}$$

D = separation distance between phase conductors
r' = 0.7788r
r = radius of the conductor

- For three core cable:

$$L = 2 \times 10^{-7} \ln \left(\frac{D}{r'}\right) \text{ H/metre}$$

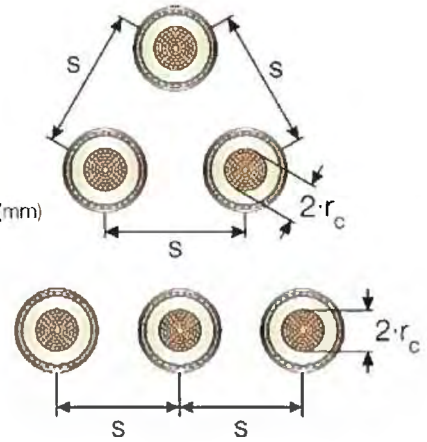
D = separation distance between cores
r' = 0.7788r

Inductance of Cable

Formula for inductance

$$L = 0.05 + 0.2 \cdot \ln\left(\frac{K \cdot s}{r_c}\right) \ [mH/km]$$

Where trefoil formation: K = 1
flat formation: K = 1.26
s = distance between conductor axes (mm)
r_C = conductor radius (mm)

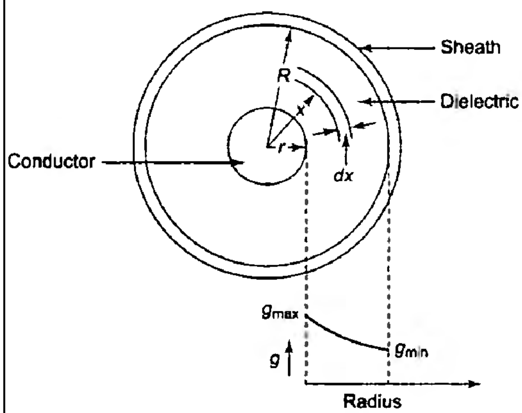


Formula for inductive reactance

$$X = 2\pi f \cdot \frac{L}{1000} \ [\Omega/km]$$

Where f = frequency (Hz)
L = inductance (mH/km)

Capacitance of Cable



$$g = \frac{q}{2\pi k x} \ \text{V/m}$$

Therefore, voltage is

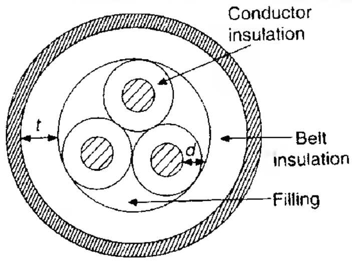
$$V = \int_r^R g \cdot dx = \int_r^R \frac{q}{2\pi k x} dx$$

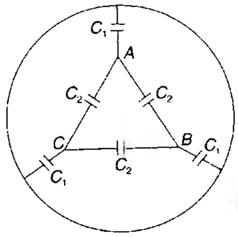
$$V = \frac{q}{2\pi k} \ln\frac{R}{r}$$

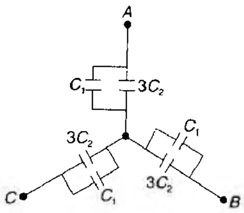
Therefore, capacitance between core to sheath

$$c = \frac{2\pi k_0 k_r}{\ln R/r} \ \text{F/m}$$

Capacitance of Three Core Belted Cable





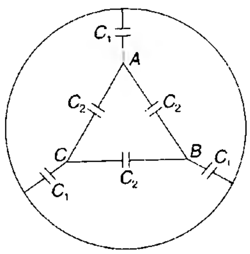


$C_0\ (=C_1\ +\ 3C_2)$

$$C_0 = \frac{0.0298\varepsilon_r}{\log_{10}\left(1+\dfrac{T+t}{d}\left(3.84-1.70\dfrac{t}{T}+0.52\dfrac{t^2}{T^2}\right)\right)}\quad \mu\text{F/km}$$

where ε_r is the relative permittivity of the insulation, t the thickness of belt insulation, d the diameter of the conductor and T the conductor insulation thickness.

How to find C1 and C2



Take following measurements:

1. All the three conductors joined together and measure the capacitance between sheath and conductors.

   $C_x = 3C_1$ ⇨ $C_1 = C_x/3$

1. Connect two conductors and sheath together and measure the capacitance between sheath and remaining conductors

   $C_y = 2C_2 + C_1$

   ⇨ $C_2 = \dfrac{C_y}{2} - \dfrac{C_1}{2} = \dfrac{C_y}{2} - \dfrac{C_x}{6}$

Therefore $C_0 = C_1 + 3C_2 = \dfrac{C_x}{3} + 3\left(\dfrac{C_y}{2} - \dfrac{C_x}{6}\right) = \dfrac{3C_y}{2} - \dfrac{C_x}{6}$

Electric Stress in The Cable

$$V = \frac{q}{2\pi\varepsilon} \ln \frac{R}{r} \Rightarrow \frac{q}{2\pi\varepsilon} = \frac{V}{\ln (R/r)}$$

$$E_x = \frac{q}{2\pi\varepsilon x} \Rightarrow E_x = \frac{V}{x \ln (R/r)}$$

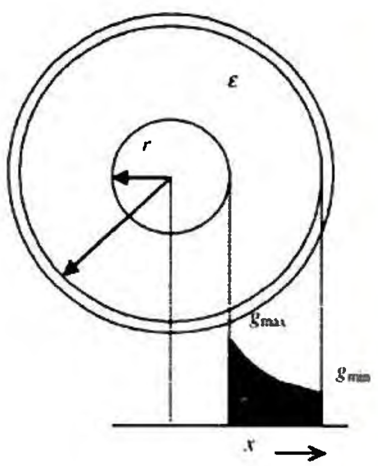
- Maximum stress occurs at the surface of conductor

$$E_{max} = \frac{V}{r \ln (R/r)}$$

- Minimum stress occurs at the sheath surface

$$E_{min} = \frac{V}{R \ln (R/r)}$$

Electric Stress in The Cable



$$E_{max} = \frac{V}{r \ln (R/r)}$$

- Optimal radius minimum stress

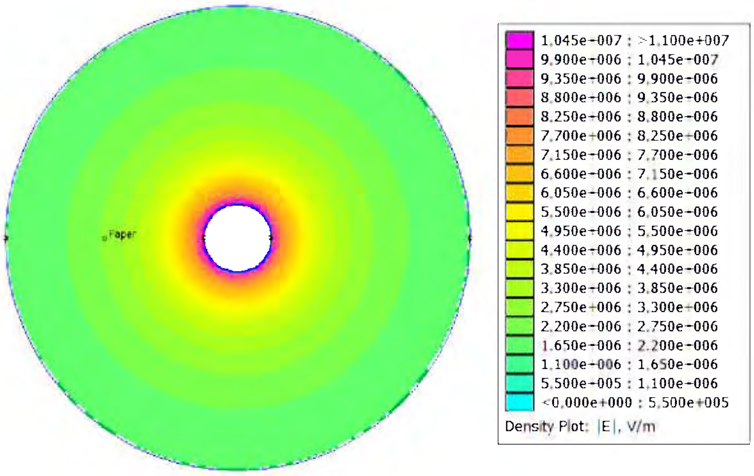
$$\frac{dE_{max}}{dr} = 0$$

$$r \times \frac{r}{R} \times \left(-\frac{R}{r^2}\right) + \ln \frac{R}{r} = 0$$

$$\ln \frac{R}{r} = 1 \quad \text{or} \quad \frac{R}{r} = e$$

$$E_{max} = \frac{V}{r} = \frac{Ve}{R} \qquad R = 2.718r$$

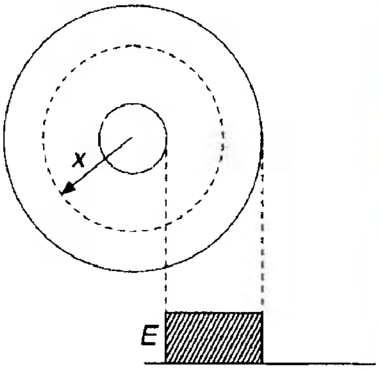
Electric Stress in The Cable



Grading of Cables

- Electric field inside the cable is not uniform, maximum at conductor surface and minimum at the sheath.
- Thus insulation material is not properly utilized.
- The insulation near conductor surface is stressed more while there is very less stress at the outer diameter of cable.
- Grading is used to decrease difference between E_{max} and E_{min}.
- Grading can be broadly classified into two categories.
  - Capacitance Grading
  - Intersheath Grading

Capacitance Grading



Ideal condition for stress in cable

$$E_x = \frac{q}{2\pi\varepsilon x} = k$$

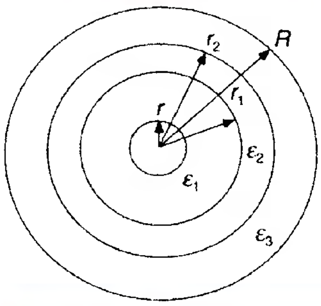
There fore the permittivity is

$$\varepsilon = \frac{k_1}{x}$$

This can not be realized in practice since it requires infinite number of dielectric materials with varying permittivity

In practice, this can be realized by two or three layers of the dielectric materials.

Capacitance Grading (With Same Safety Factor)



- While designing cable $E_{max} = \frac{G}{F}$
- Let dielectric strengths of material is G1 G2 and G3 corresponding to ε1, ε2, and ε3 and F is safety factor same for all materials.

Layer 1 (ε_1)	Layer 1 (ε_2)	Layer 1 (ε_3)
$\frac{q}{2\pi\varepsilon_1 r} = \frac{G_1}{F}$	$\frac{q}{2\pi\varepsilon_2 r_1} = \frac{G_2}{F}$	$\frac{q}{2\pi\varepsilon_3 r_2} = \frac{G_3}{F}$

Capacitance Grading (With Same Safety Factor)

$$q = 2\pi\varepsilon_1 r\frac{G_1}{F} = 2\pi\varepsilon_2 r_1\frac{G_2}{F} = 2\pi\varepsilon_3 r_2\frac{G_3}{F}$$

$$\varepsilon_1 r G_1 = \varepsilon_2 r_1 G_2 = \varepsilon_3 r_2 G_3$$

- Since $r < r_1 < r_2$ ⇒ $\varepsilon_1 G_1 > \varepsilon_2 G_2 > \varepsilon_3 G_3$
- Therefore material having highest product of permittivity and dielectric strength should be kept near to the conductor. The operating voltage of Cable is given by

$$V = \int_r^{r_1} E_1\,dx + \int_{r_1}^{r_2} E_2\,dx + \int_{r_2}^{R} E_3\,dx$$

$$= \frac{q}{2\pi}\left(\frac{1}{\varepsilon_1}\ln\frac{r_1}{r} + \frac{1}{\varepsilon_2}\ln\frac{r_2}{r_1} + \frac{1}{\varepsilon_3}\ln\frac{R}{r_2}\right)$$

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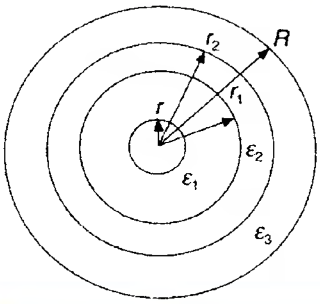
Capacitance Grading (With Same Maximum Stress)



- If the materials are subjected to same maximum stress at the r , r_1, *and* r_2

Layer 1 (ε_1)	Layer 1 (ε_2)	Layer 1 (ε_3)
$E_{max} = \frac{q}{2\pi\varepsilon_1 r}$	$E_{max} = \frac{q}{2\pi\varepsilon_2 r_1}$	$E_{max} = \frac{q}{2\pi\varepsilon_3 r_2}$

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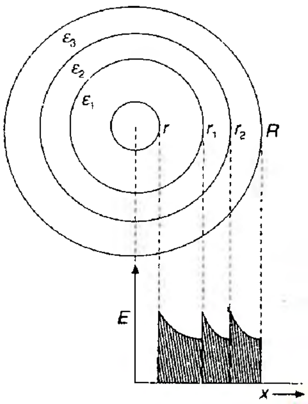

$$E_{max} = \frac{q}{2\pi\varepsilon_1 r} = \frac{q}{2\pi\varepsilon_2 r_1} = \frac{q}{2\pi\varepsilon_3 r_2}$$

$$\varepsilon_1 r = \varepsilon_2 r_1 = \varepsilon_3 r_2$$

- Since $r < r_1 < r_2$ ⇒ $\varepsilon_1 > \varepsilon_2 > \varepsilon_3$
- Therefore same maximum stress material having highest permittivity needs to be kept at surface of conductor.

$$V = E_{max}\left(r \ln\frac{r_1}{r} + r_1 \ln\frac{r_2}{r_1} + r_2 \ln\frac{R}{r_2}\right) \text{ volt}$$

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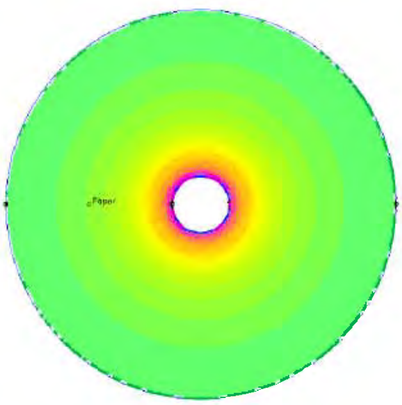
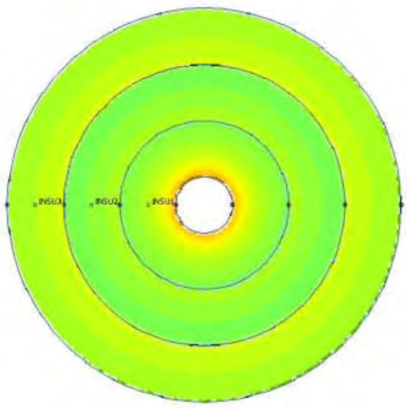
Capacitance Grading



Without grading



With capacitance grading

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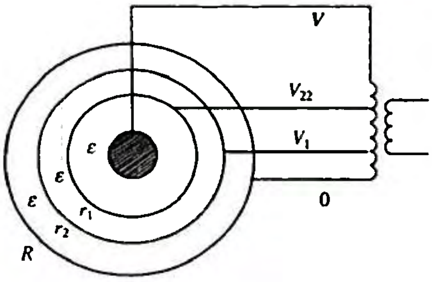
Intersheath Grading



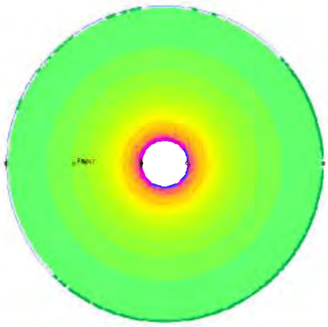
- Metal Sheaths having radii r_1 and r_2 are kept at potential V_1 and V_2 using auxiliary transformer .

Layer 1 (V)	Layer 1 (V_1)	Layer 1 (V_2)
$E_{max} = \frac{V - V_2}{r \ln (r_1/r)}$	$E_{max} = \frac{V_2 - V_1}{r_1 \ln (r_2/r_1)}$	$E_{max} = \frac{V_1}{r_2 \ln (R/r_2)}$

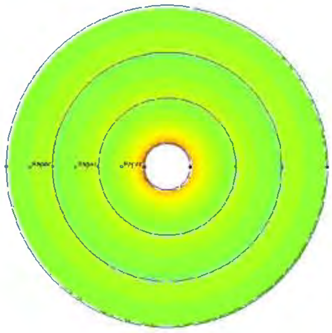
Intersheath Grading

- Since the material is same, the maximum stress is also same:

$$\frac{V - V_2}{r \ln (r_1/r)} = \frac{V_2 - V_1}{r_1 \ln (r_2/r_1)} = \frac{V_1}{r_2 \ln (R/r_2)}$$

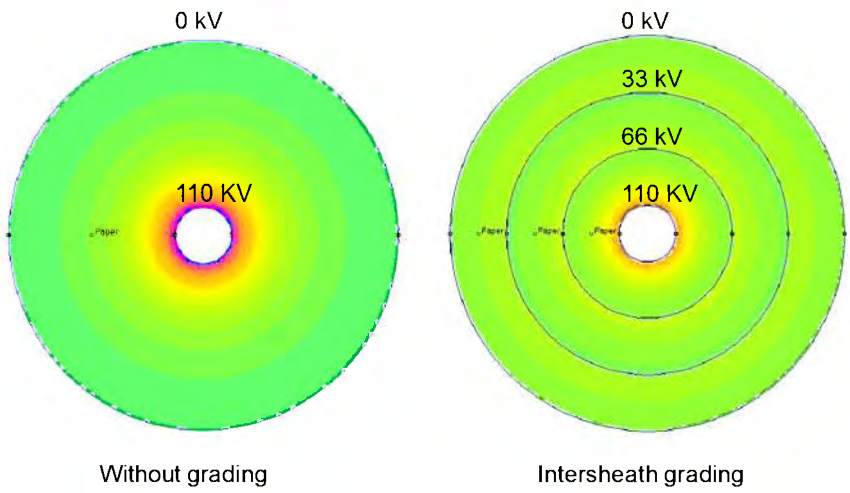


Without grading



Intersheath grading

Intersheath Grading



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Grading of Cable

- Generally not used for following reasons:
  - Non-availability of material with varying permittivity materials
  - Change in permittivity with time
  - Damage of intersheath during cable laying
  - Charging current through the intersheath can damage the cable due to overheating
  - Resonance due to cable capacitance and transformers inductance

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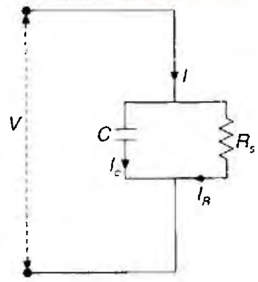
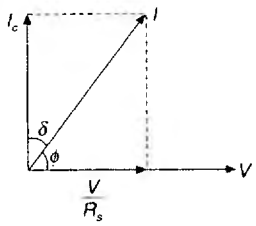
Dielectric Losses or Loss Tangent





Power loss in leakage resistance

$$P_l = \frac{V^2}{R_s}$$

For small angle δ

$$\delta \approx \tan\,\delta \approx \sin\,\delta \approx \sin\,(90 - \phi) = \cos\,\phi$$

From phasor diagram

$$\frac{V/R_s}{V\omega C} = \tan\,\delta \;\Rightarrow\; \frac{V}{R_s} = V\omega C\,\tan\,\delta$$

Therefore, dielectric power loss:

$$P_l = V^2\omega C\,\tan\,\delta = V^2\omega C\delta \text{ watt}$$

Loss Tangent of Different Materials

Material	Tan δ
Impregnated Paper	0.01
Oil filled paper insulation	0.004
PVC	0.1
XLPE	0.0004

- The loss angle depends on the temperature.
- Roughly it follows ‘V’ curve, i.e. Loss angle will be minimum at certain temperature.

Other Topics

- Breakdowns in Cable Insulation
  - Intrinsic Breakdown or puncture:
  - Thermal Breakdown:
  - Tracking:
- Sheath and armour losses

Underground Cable System

Japanese Technical Assistance
on Strengthening Institutional Capacity
of National Development Agency (ADN)
in Democratic of Timor-Leste

-- POWER --

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Syllabus

No.	Contents
1	Introduction
2	Power Station (Diesel)
3	Substation
4	Transmission and Distribution System
5	Power System Study
6	Power Flow Analysis
7	Renewable Energy (Photovoltaic Power)
8	Protecting System
9	Power System Operation and Control
10	Others

The contents may be changed depending on conditions.
I would like to discuss about the contents with Mr. Miguel and YOU.

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