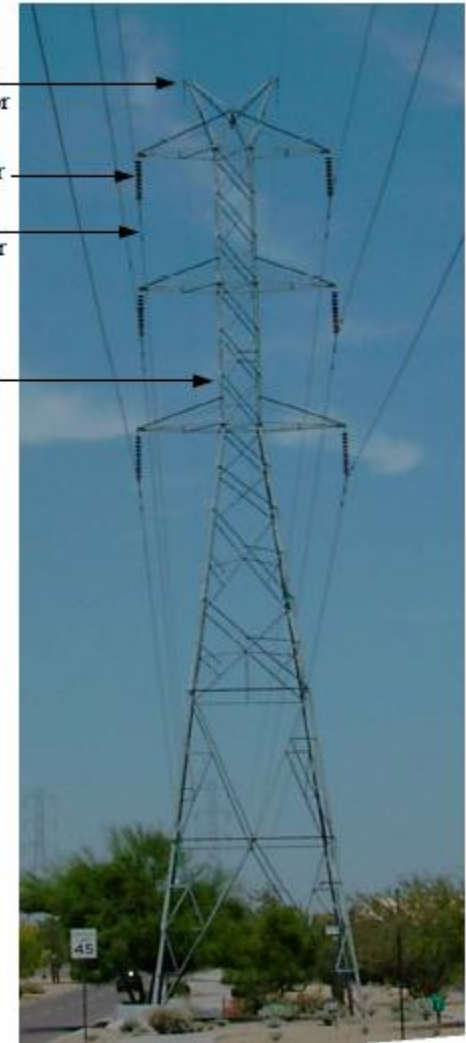
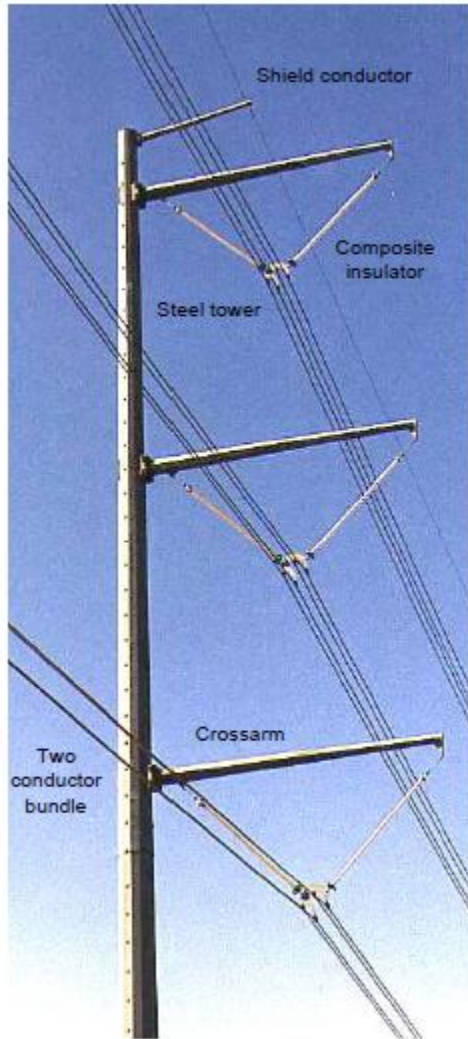
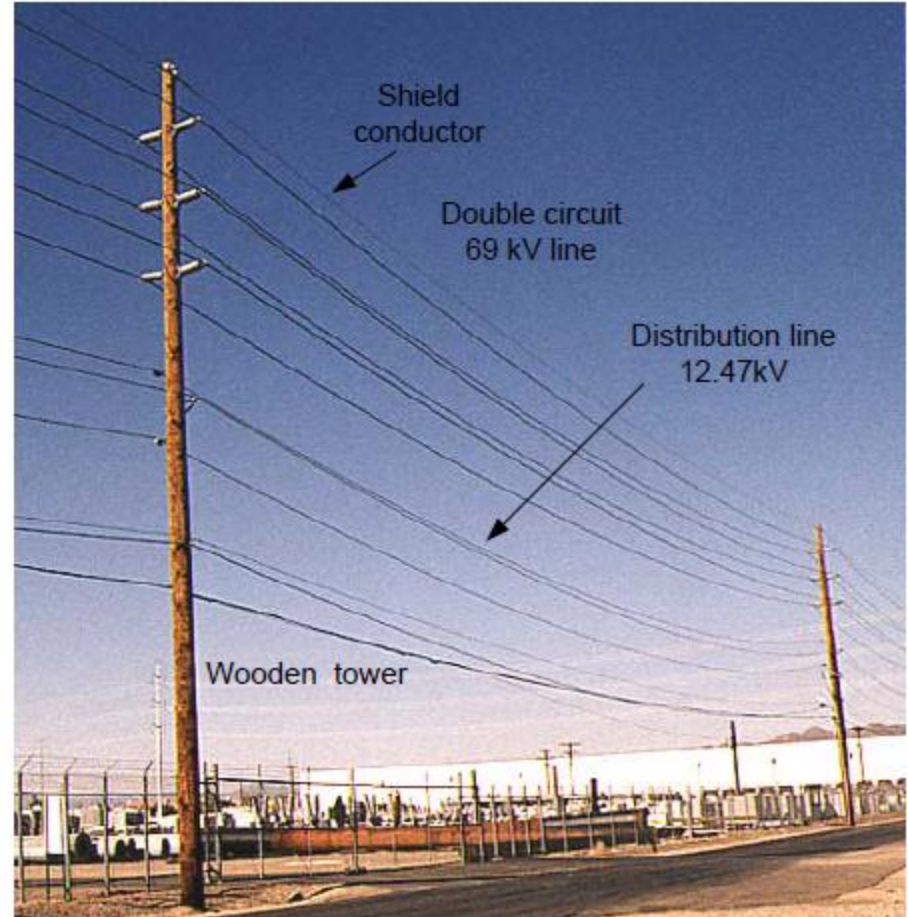


ELG4125: Power Transmission Lines

The most common methods for transfer of electric power are: Overhead AC; Underground AC; Overhead DC; Underground DC

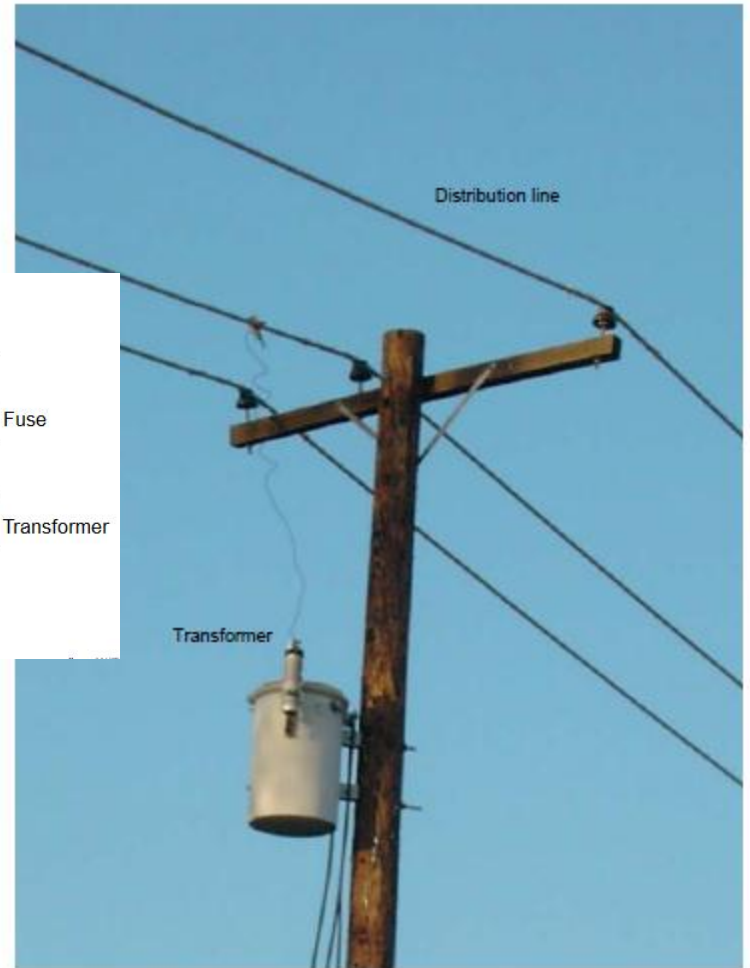
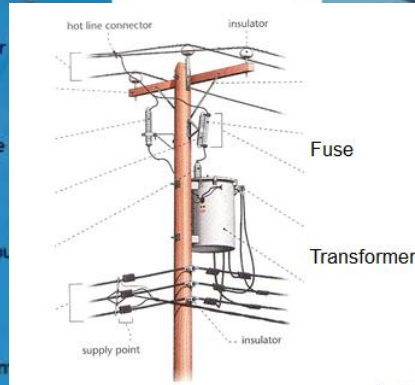
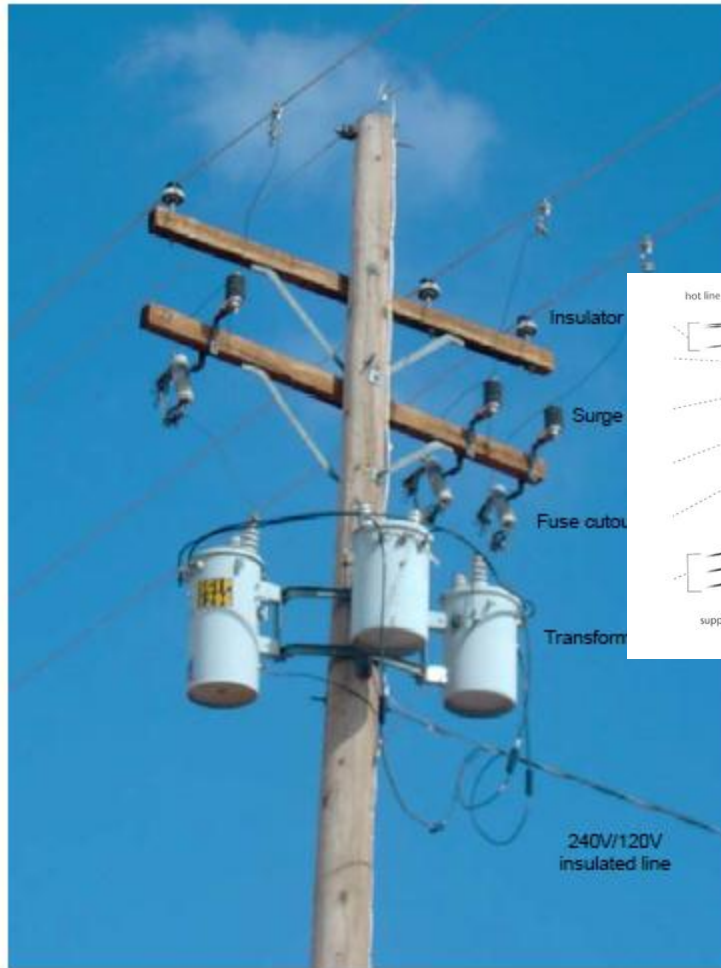


Distribution Lines

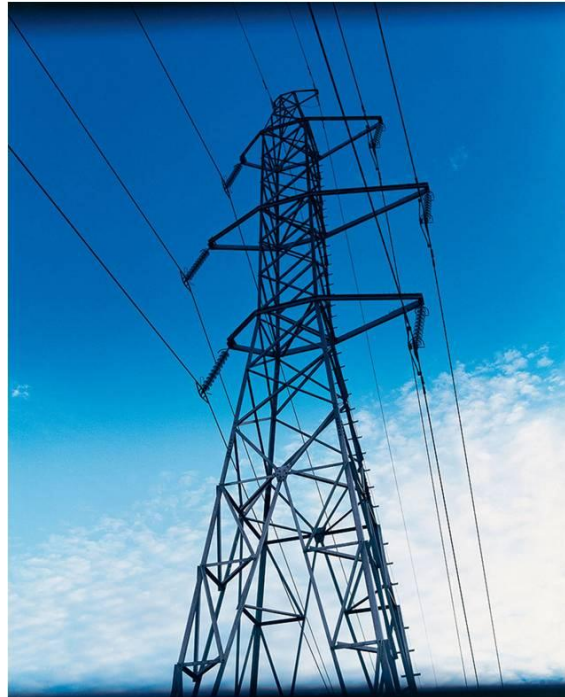
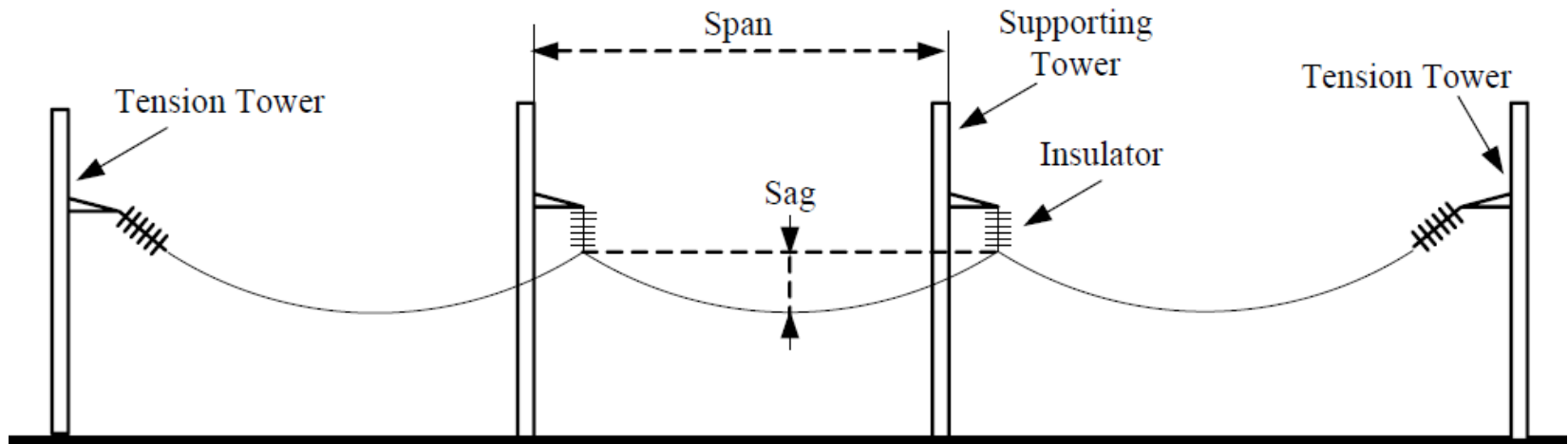


Distribution Line

Distribution Lines and Transformers



Transmission Lines

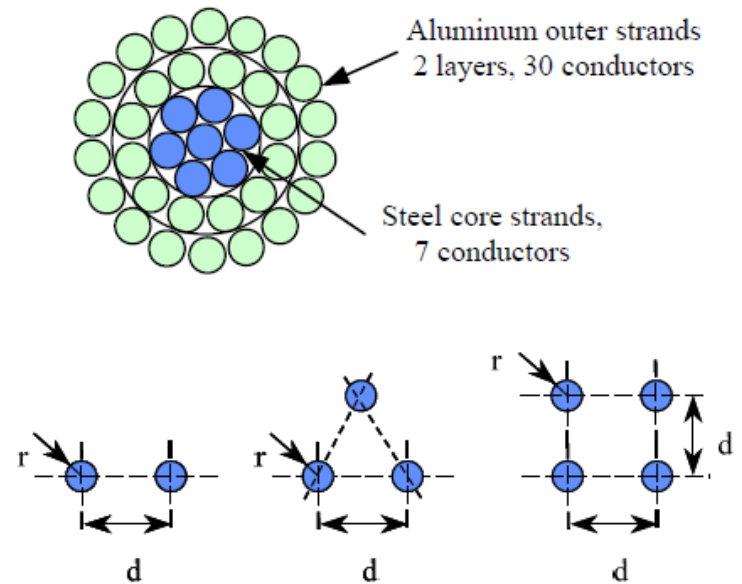


Types of Conductors

Aluminum has replaced copper as the most common conductor metal for overhead transmission (**Why?**). In general, the types of conductors are: solid; stranded; and hollow conductors.

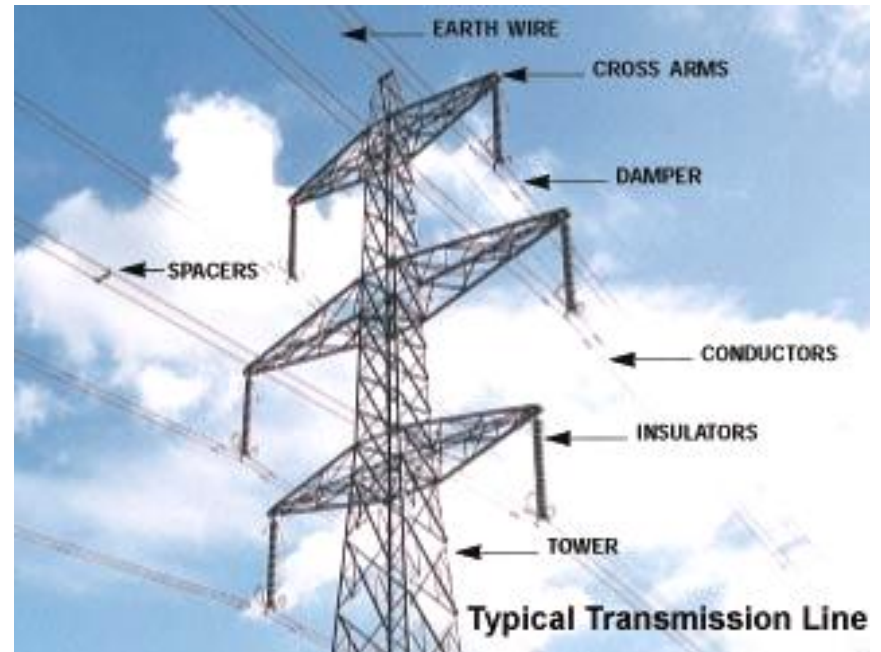
- **Aluminum Conductor Steel Reinforced (ACSR);**
- **All Aluminum Conductor (AAC);**
and
- **All Aluminum Alloy Conductor (AAAC).**

- **ACSR Conductor**



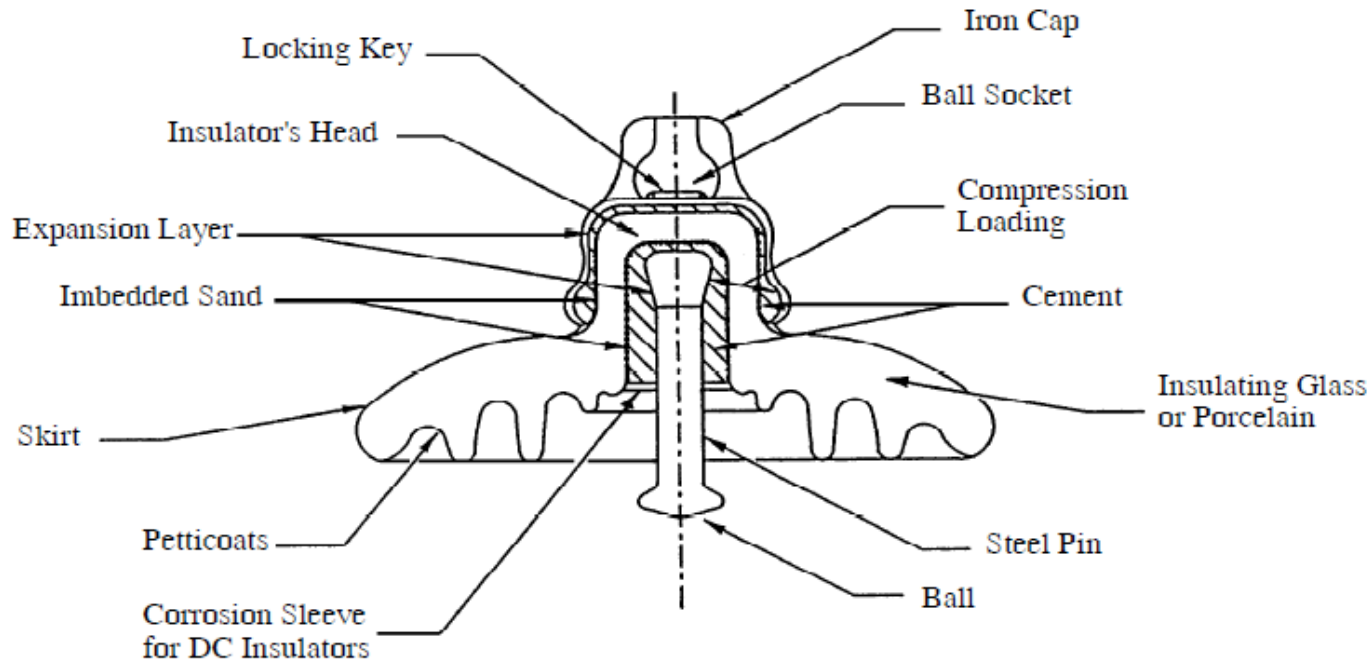
Bundled Conductors in Transmission Lines

Advantages: Reduced corona loss due to larger cross-sectional area; reduced interference with telecommunication systems; improved voltage regulation.



Insulators

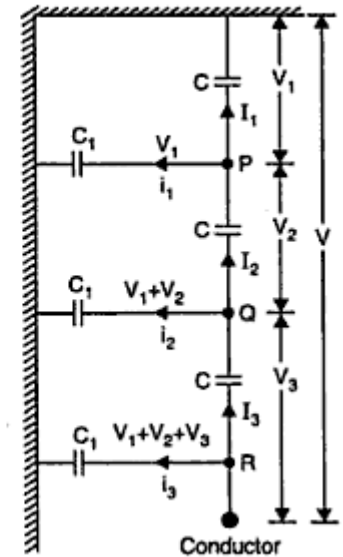
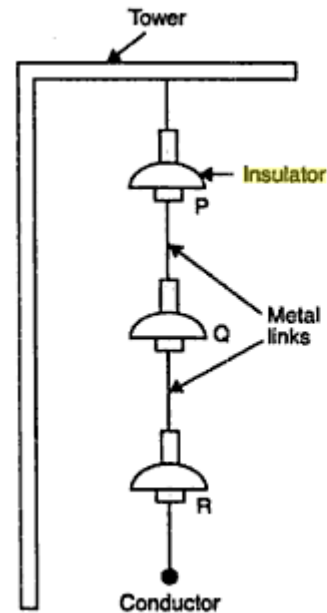
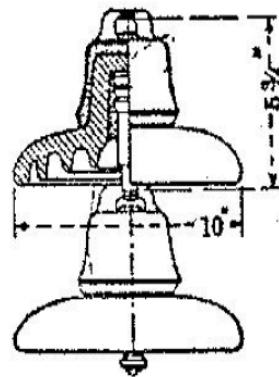
The insulators used for overhead transmission lines are: Pin; suspension; strain; and shackle. The following figure shows a suspension type (for above 33 kV).



Insulator Chain

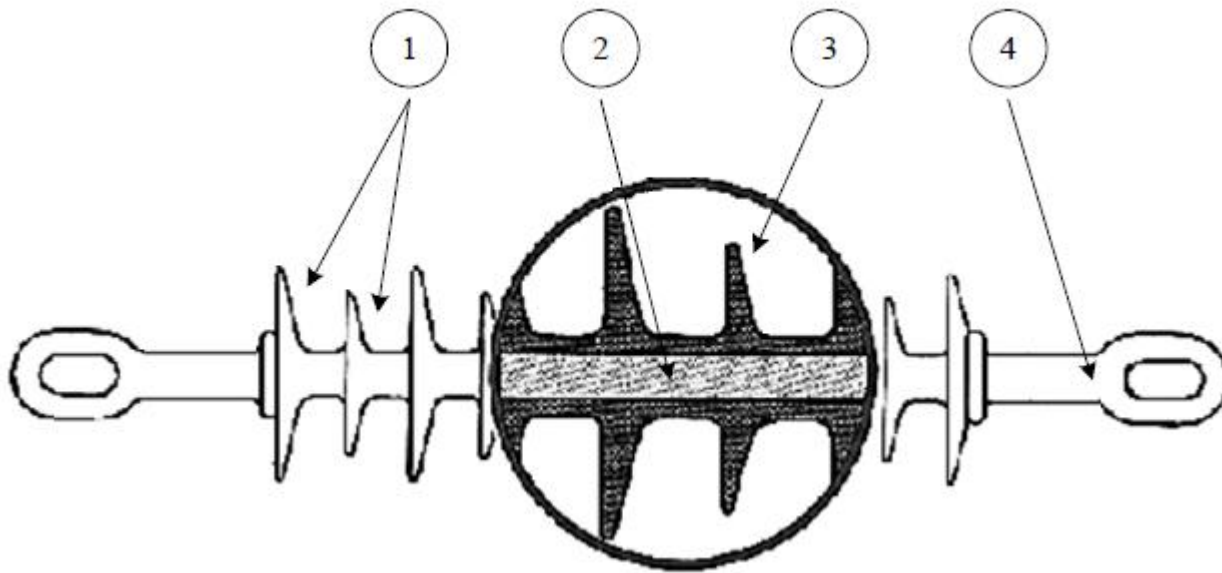
Number of separate discs are joined with each other by using metal links to form a string. The insulator string is suspended from the cross arm of the support.

Line Voltage	Number of Insulators per String
69 kV	4-6
115 kV	7-9
138 kV	8-10
230 kV	12
345 kV	18
500 kV	24
765 kV	30-35



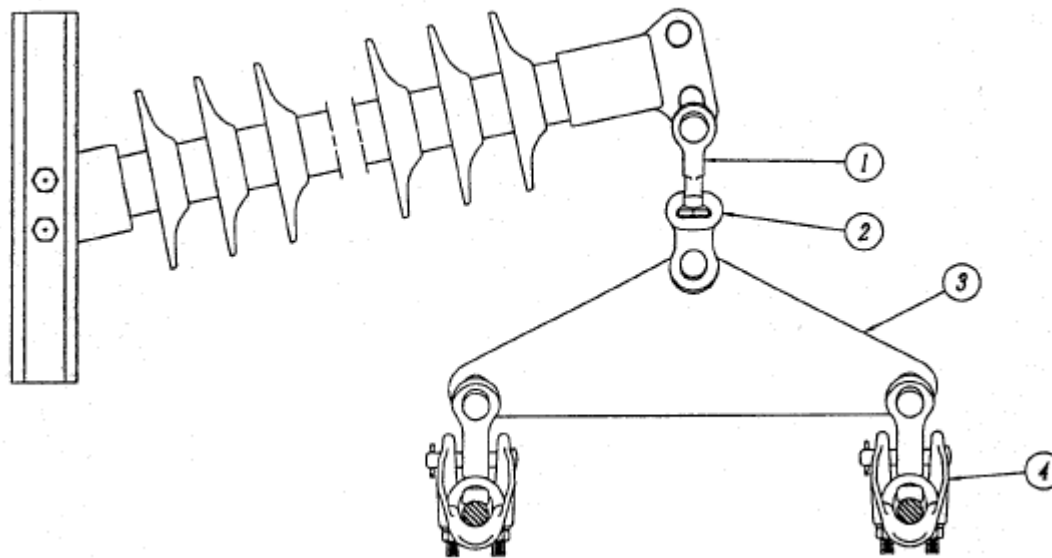
Composite Insulator

1. Sheds to prevent bridging by ice and snow.
2. Fibreglass reinforced resin rod.
3. Rubber weather shed.
4. Forced steel end fitting.



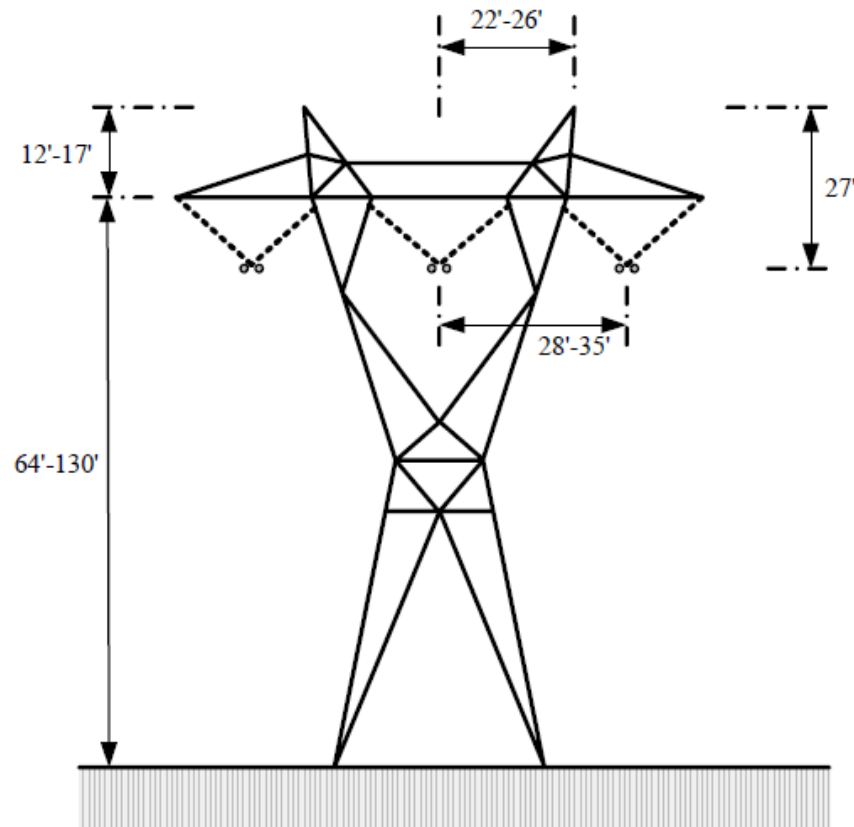
Line Post for Holding Two Lines

- (1) Clevis ball; (2) Socket for the clevis; (3) Yoke plate; (3) Suspension clamp.



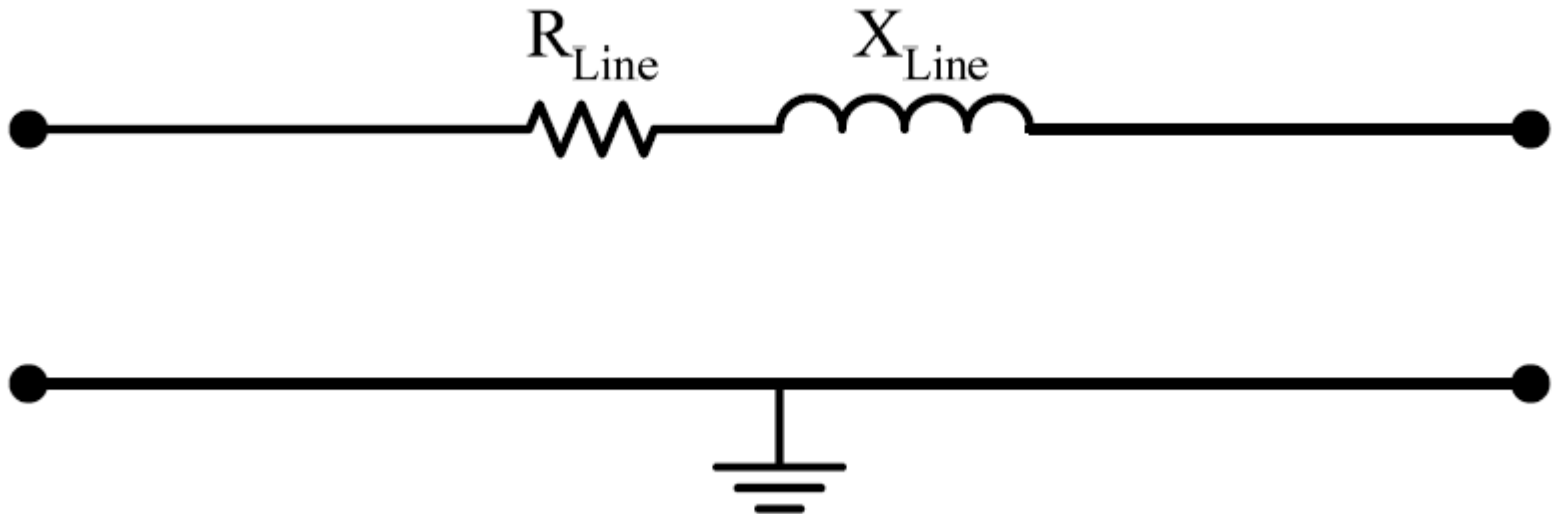
Support Structures

Wooden poles; tubular poles; RCC poles (above 33 kV); Latticed steel towers (above 66 kV, see below) where double circuit transmission lines can be set on the same tower.

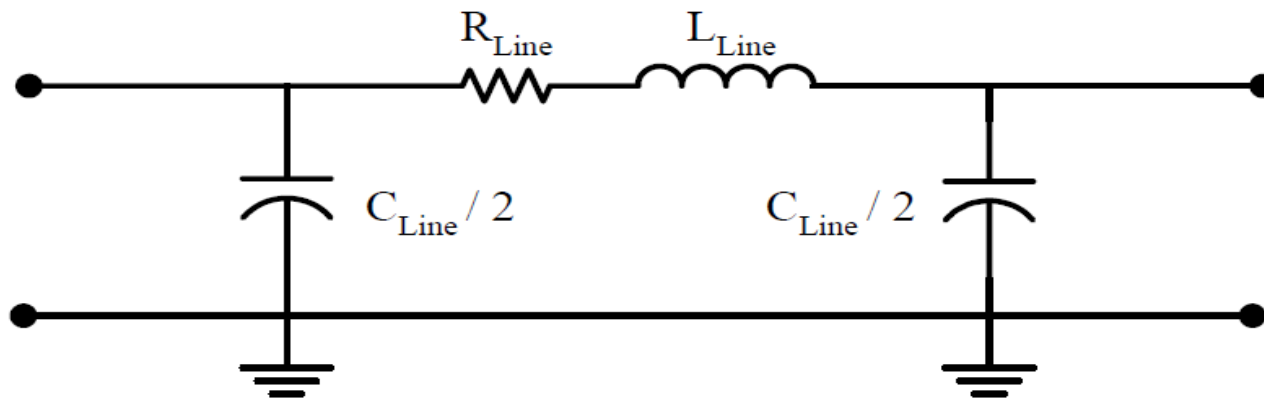


Transmission Line Model

- A transmission line is a distributed element in which voltage and current depend on both time and space.
- A property of a distributed system is that waves can travel both in a forward and reverse direction.
- The voltage at any given point is the superposition of the forward and reverse traveling waves.
- The following circuit models a short transmission line.



- The R in this element represents the "conductor loss", mainly due to temperature, spiraling, frequency, and frequency (skin effect).
- The G in this element represents the "dielectric loss" (due to loss in the insulator: dirt, salt, moisture, and other contaminants) and due to corona loss (meteorological conditions: particularly rain and conductor surface irregularities).
- When we include R and G in the model, we have a lossy transmission line.
- If we assume there is no loss, we can reduce the model to an ideal! "lossless transmission line" consisting of only inductance and capacitance.



Resistance

The DC resistance of a conductor is given by

$$R_{DC} = \frac{\rho l}{A}$$

Where l is the length of conductor; A is cross-sectional area, ρ is the resistivity of the conductor. The DC resistance per meter of the conductor is

$$R_{DC} = \frac{\rho}{A}(\Omega/\text{m})$$

The resistivity of a conductor is a property of the material that the conductor is made from. It varies with both type and temperature of the material. At the same temperature, the resistivity of aluminum is higher than the resistivity of copper.

AC resistance of a conductor is always higher than its DC resistance due to the skin effect forcing more current flow near the outer surface of the conductor. The higher the frequency of current, the more noticeable skin effect would be. At frequencies of our interest (50-60 Hz), however, skin effect is not very strong.

Resistance

The resistivity increases linearly with temperature over normal range of temperatures. If the resistivity at one temperature is known, the resistivity at another temperature can be found from

$$\rho_{T_2} = \rho_{T_1} \frac{M + T_2}{M + T_1}$$

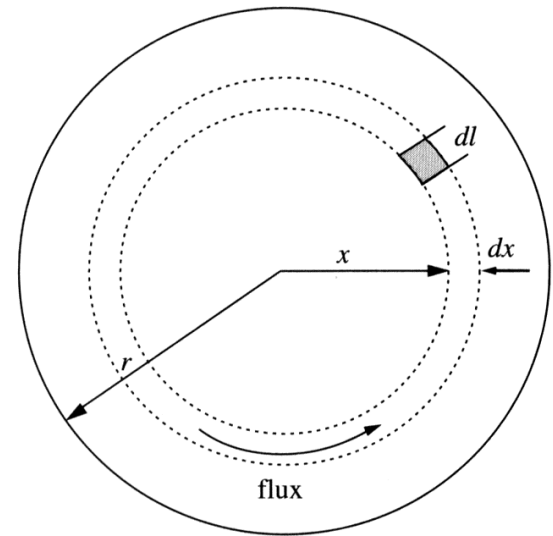
Where T_1 and ρ_{T_1} are temperature 1 in °C and the resistivity at that temperature, T_2 and ρ_{T_2} are temperature 2 in °C and the resistivity at that temperature, and M is the temperature constant.

Material	Resistivity at 20°C [$\Omega \cdot m$]	Temperature constant [°C]
Annealed copper	$1.72 \cdot 10^{-8}$	234.5
Hard-drawn copper	$1.77 \cdot 10^{-8}$	241.5
Aluminum	$2.83 \cdot 10^{-8}$	228.1
Iron	$10.00 \cdot 10^{-8}$	180.0
Silver	$1.59 \cdot 10^{-8}$	243.0

Inductance

The series inductance of a transmission line consists of two components: internal and external inductances, which are due to the magnetic flux inside and outside the conductor respectively. The inductance of a transmission line is defined as the number of flux linkages (Wb-turns) produced per ampere of current flowing through the line:

$$L = \frac{\phi}{I}$$



Consider a conductor of radius r carrying a current I . At a distance x from the center of this conductor, the magnetic field intensity H_x may be found from Ampere's law:

$$\int H_x \cdot dl = I_x$$

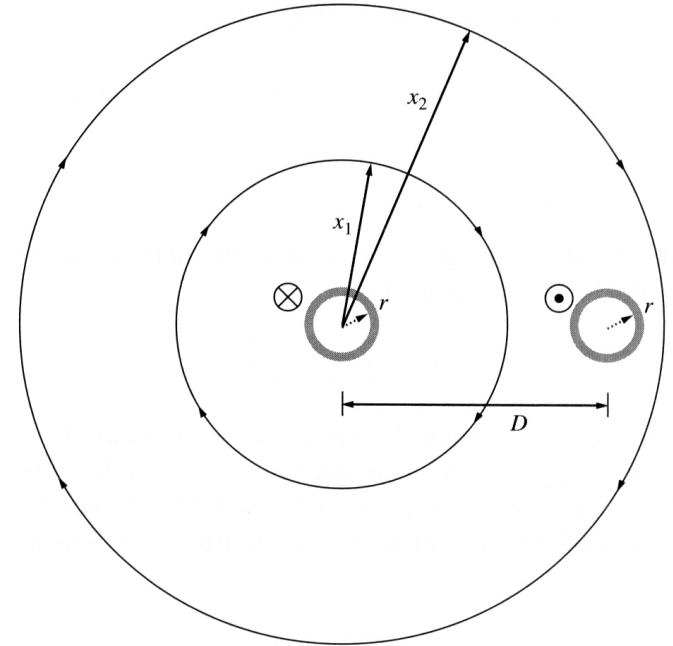
Inductance of a Single-Phase 2-Wire Transmission Line

The inductance of a single-phase line consisting of two conductors of radii r spaced by a distance D and both carrying currents of magnitude I flowing into the page in the left-hand conductor and out of the page in the right-hand conductor.

Considering two circular integration paths, we notice that the line integral along x_1 produces a net magnetic intensity since a non-zero net current is enclosed by x_1 . Therefore:

$$\int H_x \cdot dl = I_x$$

Since the path of radius x_2 encloses both conductors and the currents are equal and opposite, the net current enclosed is 0 and, therefore, there are no contributions to the total inductance from the magnetic fields at distances greater than D .



Inductance of a Single-Phase 2-Wire Transmission Line

The total inductance of a wire per unit length in this transmission line is a sum of the internal inductance and the external inductance between the conductor surface (r) and the separation distance (D):

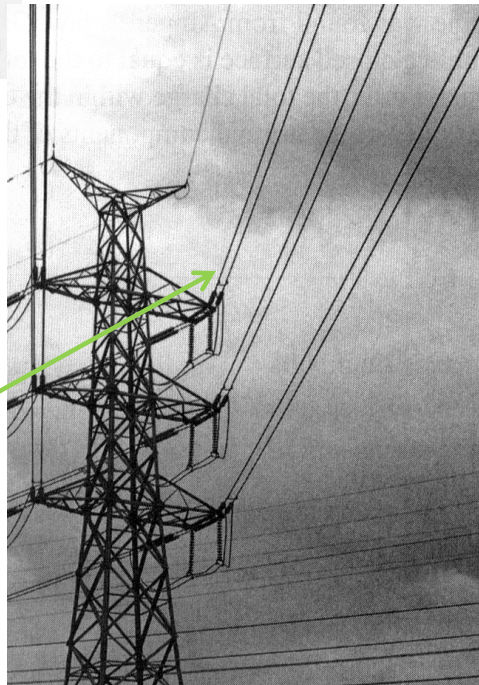
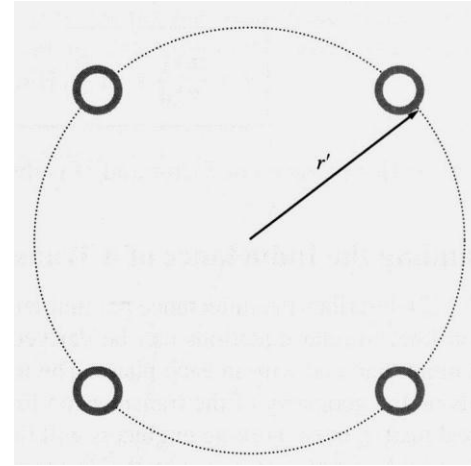
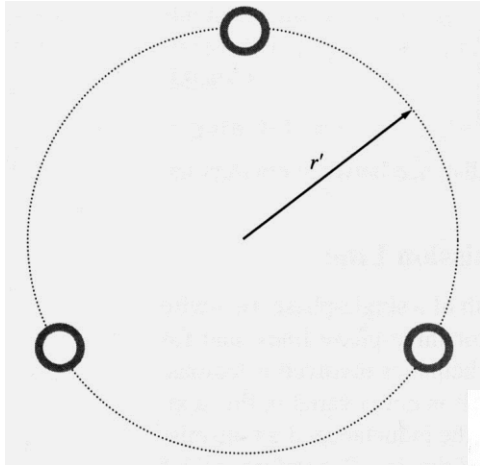
$$L = 2 \times 10^{-7} \ln \frac{D}{r'}$$

By symmetry, the total inductance of the other wire is the same, therefore, the total inductance of a two-wire transmission line is

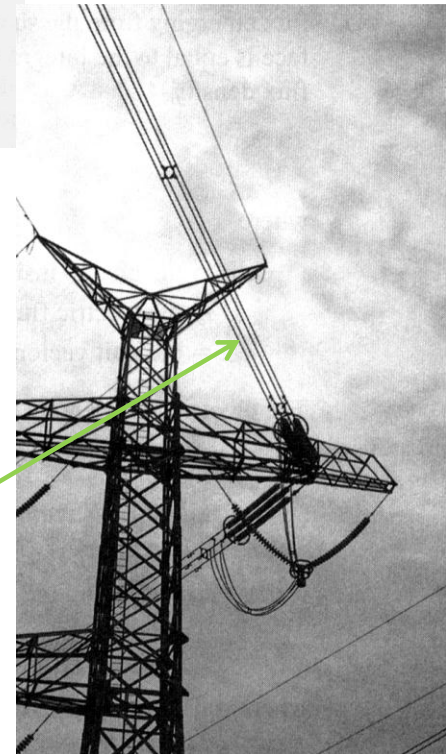
$$L = 4 \times 10^{-7} \ln \frac{D}{r'}$$

Where r' is the effective ($0.7788 r$) radius of each conductor and D is the distance between conductors.

Inductance of a Transmission Line



A two-conductor bundle



A four-conductor bundle

Capacitance

Since a voltage V is applied to a pair of conductors separated by a dielectric (air), charges of equal magnitude but opposite sign will accumulate on the conductors:

$$Q = CV$$

Where C is the capacitance between the pair of conductors.

In AC power systems, a transmission line carries a time-varying voltage different in each phase. This time-varying voltage causes the changes in charges stored on conductors. Changing charges produce a changing current, which will increase the current through the transmission line and affect the power factor and voltage drop of the line. This changing current will flow in a transmission line even if it is open circuited.

Capacitance

The capacitance of the transmission line can be found using the Gauss's law:

$$\oiint D \cdot dA = Q$$

where A specifies a closed surface; dA is the unit vector normal to the surface; q is the charge inside the surface; D is the electric flux density at the surface:

$$D = \varepsilon E$$

where E is the electric field intensity at that point; ε is the permittivity of the material:

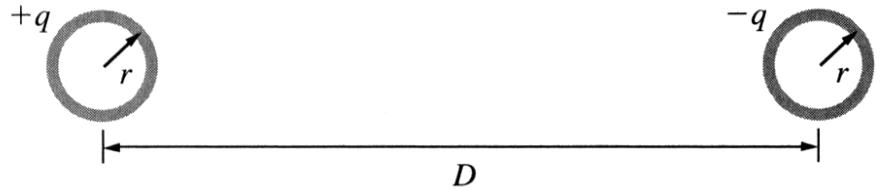
$$\varepsilon = \varepsilon_r \varepsilon_0$$

 *Relative permittivity of the material*

The permittivity of free space $\varepsilon_0 = 8.85 \cdot 10^{-12}$ F/m

Capacitance of a Single Phase Two-Wire Transmission Line

The potential difference due to the charge on conductor a can be found as



$$V_{ab,a} = \frac{q_a}{2\pi\epsilon} \ln \frac{D}{r}$$

Similarly, the potential difference due to the charge on conductor b is

$$V_{ba,b} = \frac{q_b}{2\pi\epsilon} \ln \frac{D}{r}$$

or

$$V_{ab,b} = -\frac{q_a}{2\pi\epsilon} \ln \frac{D}{r}$$

Capacitance of a Single Phase Two-Wire Transmission Line

The total voltage between the lines is

$$V_{ab} = V_{ab,a} + V_{ab,b} = \frac{q_a}{2\pi\epsilon} \ln \frac{D}{r} - \frac{q_b}{2\pi\epsilon} \ln \frac{D}{r}$$

Since $q_a = q_b = q$, the equation reduces to

$$V_{ab} = \frac{q}{\pi\epsilon} \ln \frac{D}{r}$$

The capacitance to ground (F/m) per unit length (line-to-neutral) of this single-phase transmission line will be

$$C_{ab} = \frac{q}{V} = \frac{q}{\frac{q}{\pi\epsilon} \ln \frac{D}{r}} = \frac{2\pi\epsilon}{\ln \frac{D}{r}}$$

Example

An 8000 V, 60 Hz, single-phase, transmission line consists of two hard-drawn aluminum conductors with a radius of 2 cm spaced 1.2 m apart. If the transmission line is 90 km long and the temperature of the conductors is 20°C,

- a. What is the series resistance per kilometer of this line?
- b. What is the series inductance per kilometer of this line?
- c. What is the shunt capacitance per kilometer of this line?
- d. What is the total series reactance of this line?
- e. What is the total shunt admittance of this line?

a. The series resistance of the transmission line is

$$R_{DC} = \frac{\rho l}{A}$$

Ignoring the skin effect, the resistivity of the line at 20°C will be $2.83 \cdot 10^{-8} \Omega\text{-m}$ and the resistance per kilometer of the line is

$$R_{DC} = 0.0225 \Omega/\text{km}$$

Example

b. The series inductance per kilometer of the transmission line is

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

c. The shunt capacitance per kilometer of the transmission line is

$$C_{ab} = \frac{q}{V} = \frac{q}{\frac{q}{\pi \epsilon} \ln \frac{D}{r}} = \frac{2\pi \epsilon}{\ln \frac{D}{r}}$$

d. The series impedance per kilometer of the transmission line is

$$Z = R + jX_L$$

Then the total series impedance of the line is $Z_T = (R + jX_L) \times 90 \text{ km}$

e. The shunt admittance per kilometer of the transmission line is $Y_C = j2\pi f C$

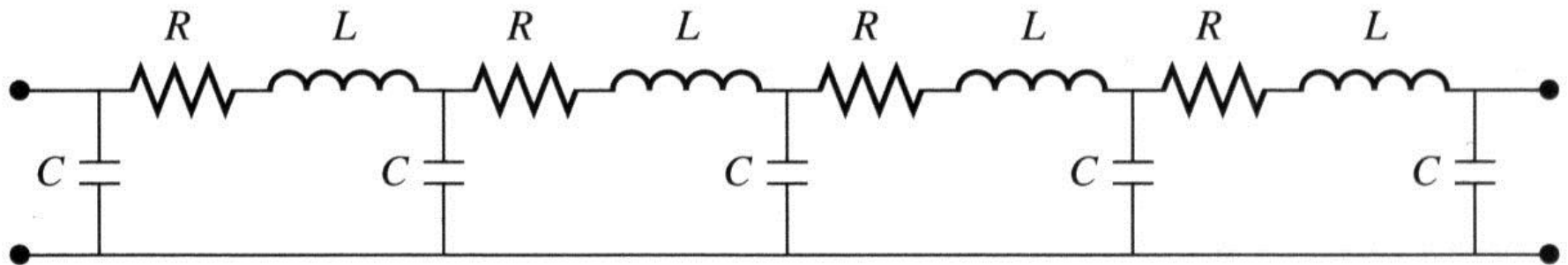
The total shunt admittance will be $Y_T = (j2\pi f C) \times 90 \text{ km}$

The corresponding shunt capacitive reactance is $Z_T = \frac{1}{Y_T}$

Transmission Line Models

Unlike the electric machines studied so far, transmission lines are characterized by their distributed parameters: distributed resistance, inductance, and capacitance.

The distributed series and shunt elements of the transmission line make it harder to model. Such parameters may be approximated by many small discrete resistors, capacitors, and inductors.



However, this approach is not very practical, since it would require to solve for voltages and currents at all nodes along the line. We could also solve the exact differential equations for a line but this is also not very practical for large power systems with many lines.

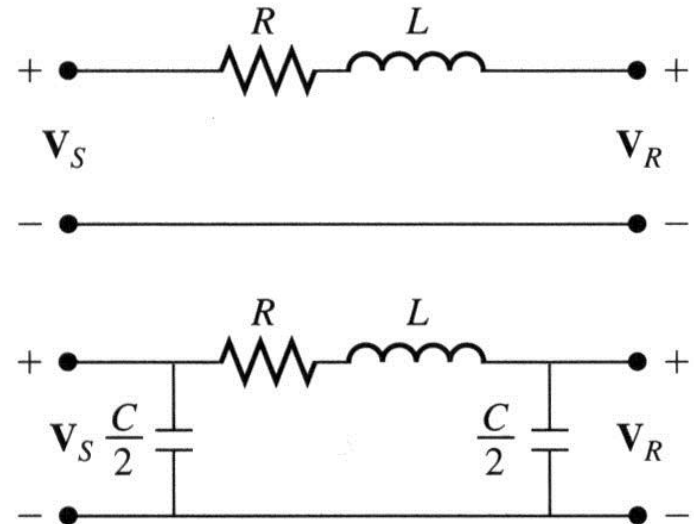
Transmission Line Models

Fortunately, certain simplifications can be used. Overhead transmission lines shorter than 80 km (50 miles) can be modeled as a series resistance and inductance, since the shunt capacitance can be neglected over short distances.

The inductive reactance at 60 Hz for – overhead lines – is typically much larger than the resistance of the line.

For medium-length lines (80-240 km), shunt capacitance should be taken into account. However, it can be modeled by two capacitors of a half of the line capacitance each.

Lines longer than 240 km (150 miles) are long transmission lines and are to be discussed later.



Limits Affecting Maximum Power Transfer

Thermal

- limit is due to heating of conductor and hence depends heavily on ambient conditions.
- For many lines, sagging is the limiting constraint.
- Newer conductors limit can limit sag. For example, in 2004 ORNL working with 3M announced lines with a core consisting of ceramic Nextel fibers. These lines can operate at 200 °C.
- Trees grow, and will eventually hit lines if they are planted under the line.

Angle

- while the maximum power transfer occurs when line angle difference is 90 degrees, actual limit is substantially less due to multiple lines in the system

Voltage

- as power transfers increases, reactive losses increase as I^2X . As reactive power increases the voltage falls, resulting in a potentially cascading voltage collapse.

Safety of Transmission Lines

- How safe can people safely live to power line? It depends on the voltage and current through the power lines.
- The electromagnetic radiation is directly proportional to the current level through the power lines. The magnitude of the magnetic field produced by a straight power line is:

$$B = \frac{\mu_0 \times i}{4\pi r}$$

where B is the magnitude of the magnetic field in Tesla (T); μ_0 is the magnetic permeability of free space; i is the current (A); r is the distance from the conductor (m).

If T unit is multiplied by 10000, then the unit will be in mG (milligauss). The Swedish maximum allowable B is 2.5 mG.

Power Line Hazard: Magnetic Field Calculation

- According to the Swedish Standard, what is the minimum distance homes should be placed from a 12.47 kV line rated at 500 A? As 12.47 kV lines are often located in or near neighborhoods. Is the resulted distance practical?

$$B = \frac{\mu_0 \times i}{4\pi r} = \frac{4\pi \times 10^{-7} \times 500}{2\pi r} \times 10,000 = 2.5 \text{ mG}$$

The safe distance, r , is 400 m!

- The 400 m is not practical because city lots are generally less than 100 in length!