ELK322E
POWER TRANSMISSION SYSTEMS

Chapter 4.1.2: MODELLING OF POWER TRANSMISSION LINES

Inductance and capacitance of the lines

POWER TRANSMISSION SYSTEMS

4.1 Introduction

- Transmission lines carry electric energy from the generation stations to the sub-stations.
- They can carry AC or DC or a combination of both. Also, electric current can be carried by either overhead or underground transmission lines.
- Transmission lines vary from a few kilometers long in an urban environment to over 1000 km for lines carrying power from remote hydroelectric plants.
- They may differ greatly in the amount of power carried.

Types of Transmission Lines:

- Overhead Transmission Lines
- Sub-transmission Lines
- Under Ground Transmission lines

- The main characteristics that distinguish transmission lines from distribution lines are that they are operated at relatively high voltages.
- They transmit large quantities of power, and they may transmit the power over large distances.
- **For overhead transmission line** transmission voltage levels vary from 115 kV up to 765 kV. The voltages that are in the range of 345-765 kV are classified as EHVs.
- The voltages above 765 kV are considered as the ultrahigh voltages (UHVs).
- **Sub-transmision Lines** carry voltages reduced from the major transmission line system. Typically, 34.5 kV to 115 kV, this power is sent to regional distribution substations.

•Some utilities categorize sub-transmision lines as transmission lines.

•**Underground transmission lines** are more common in populated areas. They may be buried with no protection, or placed in conduit, trenches, or tunnels.

HVDC Transmission

• The DC voltage transmission tower has lines in pairs rather than in threes (for 3-phase current) as in AC voltage lines.

•One line is the positive current line and the other is the negative current line.

•A Bipolar DC System has one conductor having positive potential with respect to the ground, and a second conductor operating at an equal negative potential.

•A monopolar dc system has only one conductor with return path through the earth.

Despite alternating-current being the dominant mode for electric power transmission, in a number of applications HVDC is often the preferred option.

•Undersea cables.

•Endpoint-to-endpoint long bulk power transmission without intermediate 'taps', for example, in remote areas.

•Increasing the capacity of an existing power-grid in situations where additional wires are difficult or expensive to install.

•Because for a given power rating the constant voltage in a DC line is lower than the peak voltage in an AC line. This voltage determines the insulation thickness and conductor spacing.

•Reducing the profile of wiring and pylons for a given power transmission capacity. HVDC can carry more power per conductor.

•Connection of certain generating plant to the distribution grid.

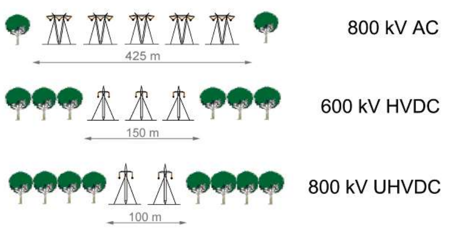
•Stabilizing a predominantly AC power-grid.

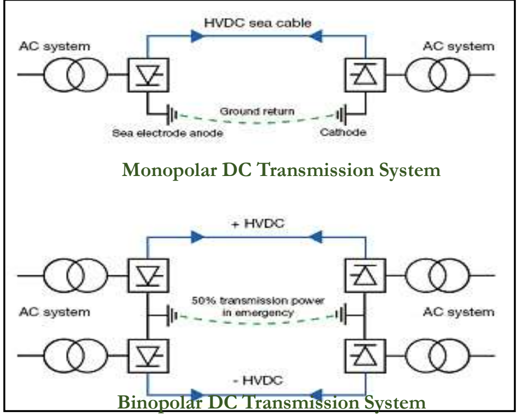
•Allowing power transmission between unsynchronized AC distribution systems. Avoids difficulties of synchronizing two systems.

Dis-advanges of using DC transmissions.

- Economic for only long distance
- Lack of devices for excellent switching
- No simple devices to change voltage level.

Less environmental damage with HVDC Transmission





Monopolar DC Transmission System

Binopolar DC Transmission System

4.2. Modeling of Power Transmission Lines

•The function of overhead transmission line is to transmit bulk power to load centers and large industrial users beyond the primary distribution lines.

•The decision to build a transmission system results from planning studies to determine how best to meet the system requirements.

•The following factors have to be considered at the planning stage of a power transmission system.

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- Transmission voltage level,
- Conductor type and size,
- Voltage control and line regulations,
- Corona and losses,
- Power flow and system stability,
- System Protection,
- System grounding,
- Insulation coordination,

Mechanical design:

- Sag and stress, calculations,
- Conductor composition,
- Conductor spacing,
- Insulator and conductor hardware selection,

Structural Design

4.2.1 Types of Conductor

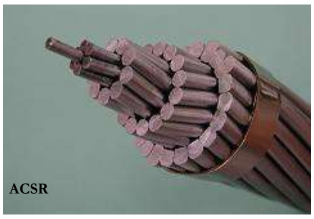
•Conventional Conductors

•**AAC**: All-aluminum conductors

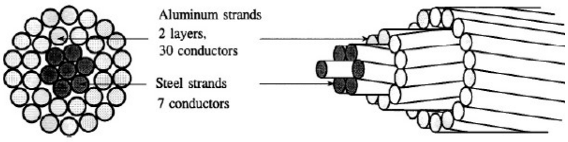
• **AAAC**: All-aluminum-alloy conductors

•**ACSR**: Aluminum conductor steel reinforced.

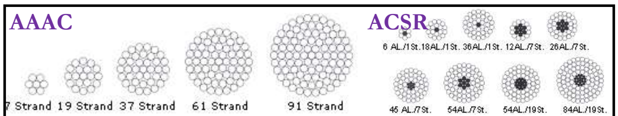
•**ACAR**: Aluminum conductor alloy reinforced.



- The most common conductor type is the aluminum conductor steel reinforced (ACSR), which has been in use for more than 80 years.
- By varying the relative cross-sectional areas of steel and aluminum, the conductor can be made stronger at the expense of conductivity, or it can be made more conductive at the expense of strength where it's not required.



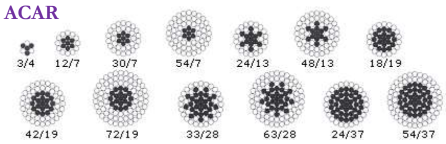
Stranded aluminum conductor with stranded steel core (ACSR).



AAAC: Used as bare overhead conductor for primary and secondary distribution. Designed utilizing a highstrength aluminum alloy to achieve a high strength-to-weight ratio; affords better sag characteristics. Aluminum alloy gives AAAC higher resistance to corrosion than ACSR.

ACSR: Used as bare overhead transmission cable and as primary and secondary distribution cable. ACSR offers optimal strength for line design. Variable steel core stranding enables desired strength to be achieved without sacrificing ampacity.

ACAR: Used as bare overhead transmission cable and as primary and secondary distribution cable. A good strength-to-weight ratio makes ACAR applicable where both ampacity and strength are prime considerations in line design. For equal weight ACAR offers higher strength and ampacity than ACSR.



(a).Conductor Resistance

- Although conductor resistance is small enough so that it does not appreciably contribute to voltage drop, it is of considerable interest in systems analysis because it causes I^2R losses.
- The dc resistance of a conductor,
- $R_{dc} = \rho\ (l/A)$.
- Where, ρ is the conductor resistivity,
- l is the length of the conductor
- and A is the cross-sectional area of the conductor.

However, values of resistivity are given for a specified temperature (20o C), and resistivity changes approximately linearly with temperature.

- As temperature rises, the resistance increases linearly, according to the following equation:

$$R_2 = R_1 \left(\frac{T + t_2}{T + t_1} \right)$$

- Where; R1 at t1, R2 at t2, T: constant changing with type of conductor.

- In addition, the resistance to AC is usually higher than the resistance to DC because AC causes current distribution in the conductor to be non-uniform; typically, more current tends to flow at the surface of the conductor than in the interior. This phenomenon is known a ''**Skin Effect**''.
- **Skin Effect** increases the resistance of the conductor.

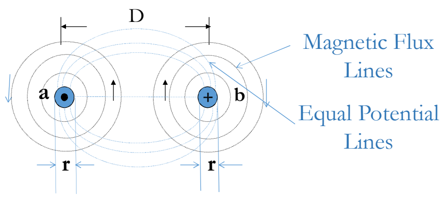
(b). Inductance and Inductive Reactance of the Line

•The inductive reactance is by far the most dominating impedance element.

•The inductance depends on the size of the conductors, the spacing between the conductors, transposition, the arrangement of conductors and the material of each conductor.

•Several arrangements are used in modern transmission systems.

Inductance of Single-Phase Overhead Lines



•A change in current causes a change in Flux
•This results in an induced voltage in the circuit
•This induced voltage is called IX voltage drop
•The voltage drop in the single phase line due to loop impedance;

•$V=2L[R+J0.2794 \log_{10} (Dm/Ds)]=j\omega Li$

The inductance of the conductor is:

$$L=2*10\exp(-7) \ln (Dm/Ds)], (H/m)$$

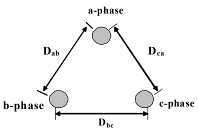
The inductive Reactance is:

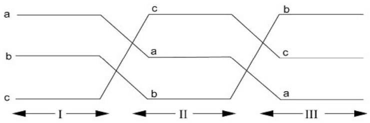
$$X_L=2\pi fL=2.02*10\exp(-3) *f* \ln (Dm/Ds)]$$

$$X_L=4.657*10\exp(-3) *f* \log (Dm/Ds)]$$

Where;
Dm: GMD-Equivelent or geometric mean distance between conductor centers. Calculated according to placement of the conductors.
Ds: GMR-Geometric mean radius or self GMD of one conductor (taken from a table).

Inductance of a three phase line



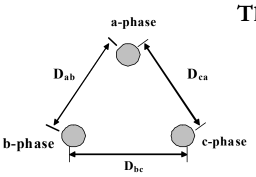


Transposition of Line Conductors

•There is a need for equalizing the mutual inductances.

•One means for doing this is to construct transpositions or rotations of overhead line wires.

• A transposition is a physical rotation of the conductors, arranged so that each conductor is moved to occupy the next physical position in a regular sequence such as *a-b-c*, *b-c-a*, *c-a-b*.



The average inductance per-phase

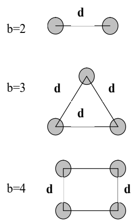
$$L = 2x10^{-7} \ln \frac{D_{eq}}{D_s} \quad (H/m)$$

$$D_{eq} = D_m = (D_{ab} x D_{bc} x D_{ca})^{1/3}$$

- *Deq* is the equivalent spacing to calculate average value of inductance and capacitance.
- *Ds* is the Geometric Mean Radius (GMR) and usually taken from manufacturer table for individual conductor but needs to be calculated for bundle conductor.

Bundled Conductors

•**Bundled Conductors** are used above 345 kV instead of using one large conductor two or more conductors of approximately the same total cross sections are used for a phase.



- For bundled conductor GMR can be calculated as follow.
- *For b=2* $D_S^b = \sqrt{Dsxd}$

  For b=3 $D_S^b = \sqrt[3]{Ds\ x\ d^2}$

  For b=4 $D_S^b = \sqrt[4]{(Ds\ x\ d^3)}$ x1.09

- **Advantage using bundled conductors**
- Reduce line impedance
- Increase corona critical voltage level
- More power may be carried per-unit mass of the conductor.
- **Disadvantage**
  - Increased wind and ice loading.
  - More complicated
  - Increased cost

Inductive reactance of the line per-phase pu length will be:

$$X_L = 2\pi f L \ (\Omega)$$

Tower Design

- Tower height
- Base width
- Top damper widt
- Cross arms lengtl

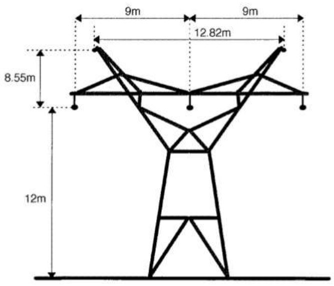


Fig. Typical 765 KV Tower Structure

LINE CAPACITANCE

- The line capacitance is a leakage (or charging) path for the ac line currents.
- The capacitance of a transmission line is the result of the potential differences between the conductors themselves as well as potential differences between the conductors and ground.
- Charges on conductors arise, and the capacitance is the charge per unit potential difference.
- The charges on the conductors are time varying.
- The time variation of the charges results in what is called line-charging currents.

Capacitance and Capacitive reactance of Three Phase Overhead Lines

The line to neutral capacitance:

$$C_n = \frac{2\pi\varepsilon}{\ln(Deq/r)} \quad (F/m) to\ neutral$$

Where,

- D is the distance between the conductor centers and the ground, r is the radius of the conductor, and $\varepsilon=\varepsilon_0\varepsilon_r$, and $\varepsilon_r=1$ for air and $\varepsilon_0=8.85x10^{-12}$ (F/m).
- Capacitive inductance will be:

$X_c=(1/2\pi f C_n)$ (Ω/km), line to ground.

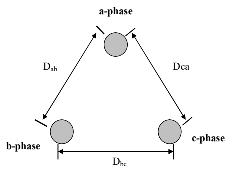
Example1:

The conductors of a three phase line are ACSR Drake. The length of the line 280 km and the operating voltage is 220kV. The conductors are arranged as in Fig., and $D_{ab}=D_{ca}=20'$ $D_{bc}=38'$ and $D_s=0.0373$ft and r=0.0462ft from the table.

- **Solution**:

$$L=2x10^{-7}\ln\frac{D_{eq}}{D_s} \quad (H/m)$$

$$D_{eq} = D_m = (D_{ab} x D_{bc} x D_{ca})^{1/3}$$



- Deq= 24.8 ft

L=13x10-7(H/m),→ XL=0.41 (Ω/km).

$$C_n = \frac{2\pi\varepsilon}{\ln(D/r)} \quad (F/m) to\ neutral$$

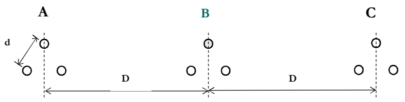
- ***Cn****=8.847x10-12 (F/m).*
- *then the capacitive reactance of the line*

Xc*=284.4x106 (Ω/km)*

- **The charging current** to due the capacitance to ground:
- ***Ich****=V/Xc=0.426 (A/km)*;
- For the whole line
- *(**Ich**)L=0.426x280= 119A* (leakage to ground).
- Related reactive power: ***Qc****=45.3 MVAr,*

Example 2: Calculate the per phase inductance and reactance of a balanced 3phase, 50 Hz, line with horizontal phase spacing of (*D=10m*) using three conductor bundling with a spacing between conductors in the bundle of (d=0.333m). And *Ds*=0.0466ft from the table for a conductor *Ds*=0.0466x0.308m=0.014m.

$$D^3{}_s = \sqrt[3]{D_s x d^2}$$



$$D_{eq} = D_m = (D_{ab} x D_{bc} x D_{ca})^{1/3}$$ **Deq=12.6m**

$$L = 2x10^{-7} \ln \frac{D_{eq}}{D_s} \quad (H/m)$$ L=9.736x10^{-7} (H/m)

4.13 SUMMARY

Although computer programs are usually available or written rather easily for calculating inductance of all kinds of lines, some understanding of the development of the equations used is rewarding from the standpoint of appreciating the effect of variables in designing a line. However, tabulated values such as those in Tables A.3 and A.4 make the calculations quite simple except for parallel-circuit lines. Table A.3 also lists resistance.

The important equation for inductance per phase of single-circuit three-phase lines is given here for convenience:

$$L = 2 \times 10^{-7} \ln \frac{D_{eq}}{D_s} \text{ H/m per phase} \qquad (4.61)$$

Inductive reactance in ohms per kilometer at 60 Hz is found by multiplying inductance in henrys per meter by $2\pi 60 \times 1000$:

$$X_L = 0.0754 \times \ln \frac{D_{eq}}{D_s} \ \Omega/\text{km per phase} \qquad (4.62)$$

or

$$X_L = 0.1213 \times \ln \frac{D_{eq}}{D_s} \ \Omega/\text{mi per phase} \qquad (4.63)$$

Both D_{eq} and D_s must be in the same units, usually feet. If the line has one conductor per phase, D_s is found directly from tables. For bundled conductors D_s^b, as defined in Sec. 4.12, is substituted for D_s. For both single-conductor and bundled-conductor lines

$$D_{eq} = \sqrt[3]{D_{ab} D_{bc} D_{ca}} \qquad (4.64)$$

For bundled-conductor lines D_{ab}, D_{bc}, and D_{ca} are distances between the centers of the bundles of phases a, b, and c.

For lines with one conductor per phase it is convenient to determine X_L from tables by adding X_a for the conductor as found in Table A.3 to X_d as found in Table A.4 corresponding to D_{eq}.

The important equation for capacitance to neutral for a single-circuit, three-phase line is

$$C_n = \frac{2\pi k}{\ln \frac{D_{eq}}{D_{sC}}} \text{ F/m to neutral} \qquad (5.44)$$

D_{sC} is the outside radius r of the conductor for a line consisting of one conductor per phase. For overhead lines k is 8.854×10^{-12} since k_r for air is 1.0. Capacitive reactance is ohm-meters is $1/2\pi f C$, where C is in farads per meter. So, at 60 Hz

$$X_C = 4.77 \times 10^4 \ln \frac{D_{eq}}{D_{sC}} \ \Omega \cdot \text{km to neutral} \qquad (5.45)$$

or upon dividing by 1.609 km/mi, we have

$$X_C = 2.965 \times 10^4 \ln \frac{D_{eq}}{D_{sC}} \ \Omega \cdot \text{mi to neutral} \qquad (5.46)$$

Values for capacitive susceptance in siemens per kilometer and siemens per mile are the reciprocals of Eqs. (5.45) and (5.46), respectively.

Both D_{eq} and D_{sC} must be in the same units, usually feet. For bundled conductors D_{sC}^b is substituted for D_{sC}. For both single- and bundled-conductor lines

$$D_{eq} = \sqrt[3]{D_{ab} D_{bc} D_{ca}} \qquad (5.47)$$

For bundled-conductor lines D_{ab}, D_{bc}, and D_{ca} are distances between the centers of the bundles of phases a, b, and c.

For lines with one conductor per phase it is convenient to determine X_C by adding X'_a for the conductor as found in Table A.3 to X'_d as found in Table A.5 corresponding to D_{eq}.

Inductance, capacitance, and the associated reactances of parallel-circuit lines are found by following the procedure of Example 5.4.

PROBLEMS

5.1. A three-phase transmission line has flat horizontal spacing with 2 m between adjacent conductors. At a certain instant the charge on one of the outside conductors is 60 μC/km, and the charge on the center conductor and on the other outside conductor is -30 μC/km. The radius of each conductor is 0.8 cm. Neglect the effect of the ground and find the voltage drop between the two identically charged conductors at the instant specified.

Problem: A 60-Hz three-phase line composed of one ACSR Bluejay conductor per phase has flat horizontal spacing of 11m between adjacent conductors. Compare the inductive reactance in ohms per kilometer per phase of this line with that of a line using a two-conductor bundle of ACSR 26/7 conductors having the same total cross-sectional area of aluminum as the single-conductor line and 11-m spacing measured from the center of the bundles. The spacing between conductors in the bundle is 40 cm.

Solution:

$$D_{eq} = \sqrt[3]{11 \times 11 \times 22} = 13.86 \text{ m}$$

Bluejay:

$$D_s = 0.0415\left(2.54 \times 12 \times 10^{-2}\right) = 0.0126 \text{ m}$$

$$X = 2 \times 10^{-7} \times 10^3 \times 377 \ln\frac{13.86}{0.0126} = 0.528\ \Omega/\text{km}$$

Dove is the conductor for bundling:

$$D_s = 0.0314\left(2.54 \times 12 \times 10^{-2}\right) = 0.00957 \text{ m}$$

$$D_s^b = \sqrt{0.00957 \times 0.4} = 0.0619 \text{ m}$$

$$X = 2 \times 10^{-7} \times 10^3 \times 377 \ln\frac{13.86}{0.0619} = 0.408\ \Omega/\text{km}$$

A 60-Hz three-phase line composed of one ACSR *Bluejay* conductor per phase has flat horizontal spaicng of 11 m between adjacent conductors. Compare the capacitive reactance in ohm-kilometers per phase of this line with that of a line using a two-conductor bundle of ACSR 26/7 conductors having the same total cross-sectional area of aluminum as the single-conductor line and the 11 m spacing measured between bundles. The spacing between conductors in the bundle is 40 cm.

Solution:

$$D_{eq} = \sqrt{11 \times 11 \times 22} = 13.86 \text{ m}$$

$$\textit{Bluejay}: r = 1.259 \times 2.54/2 \times 10^{-2} = 0.016 \text{ m}$$

$$X_C = 4.77 \times 10^4 \ln\frac{13.86}{0.016} = 322,650\ \Omega \cdot \text{km}$$

2-conductor bundle,

$$r = 0.927 \times 2.54/2 \times 10^{-2} = 0.01177$$

$$D_{sC}^b = \sqrt{rd} = \sqrt{0.0177 \times 0.4} = 0.0842 \text{ m}$$

$$X_C = 4.77 \times 10^4 \ln\frac{13.86}{0.0842} = 243,440\ \Omega \cdot \text{km}$$

References:

[1] T GÖNEN, ' Modern Power System Analysis'.
[2] WD Stevonson, 'Element of Power System Analysis'