TSTE26 Powergrid and technology for renewable production

Lecture 3
Electric power system

Lars Eriksson
FSISY

LINKÖPING UNIVERSITY

Outline

Electric Power Systems, A first course by Ned Mohan

- Chapter 2 Review of basic electric circuits (available as preview on the internet)
- Chapter 4 AC transmission lines (pdf in Lisam)

Symbols and Conventions

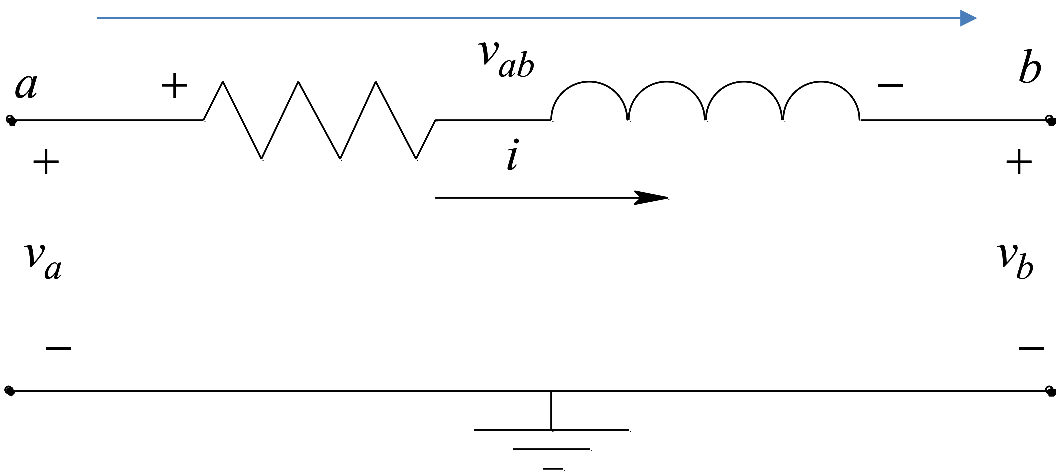


Fig. 2-1 Convention for voltages and currents.

a – Sender

b – Receiver

Phasors

$$v(t) = \sqrt{2}\, V \cos \omega t$$

$$i(t) = \sqrt{2}\, I \cos(\omega t - \phi)$$

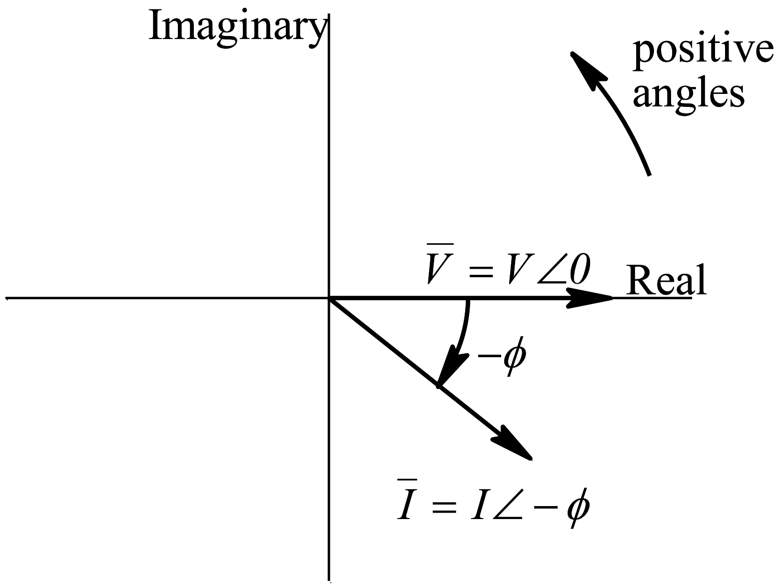


Fig. 2-2 Phasor diagram.

Inductance:
Voltage comes before current

Capacitance:
Current comes before voltage

Phasor Analysis (RMS)

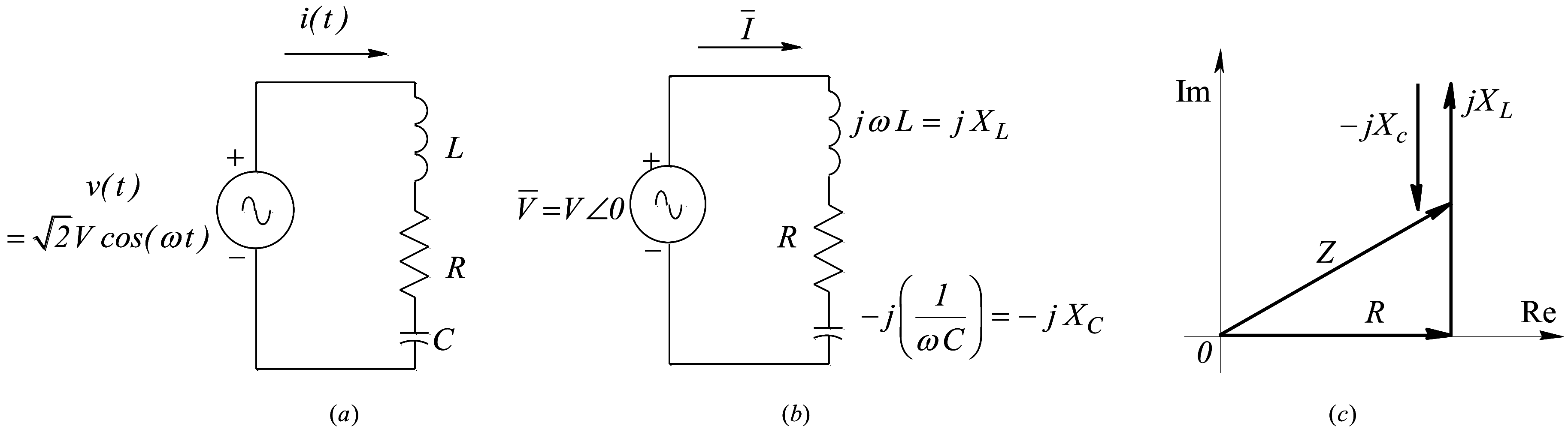


Fig. 2-3 A circuit (a) in time-domain and (b) in phasor-domain; (c) impedance triangle.

$$u_L = L\frac{di}{dt} \qquad \bar{U}_L = j\omega L\bar{I}$$

$$u_C(t) = u_C(t_1) + \frac{1}{C}\int_{t_1}^{t} i(t)dt \qquad \bar{U}_c = \frac{1}{j\omega C}\bar{I}$$

Instantaneous Power Flow

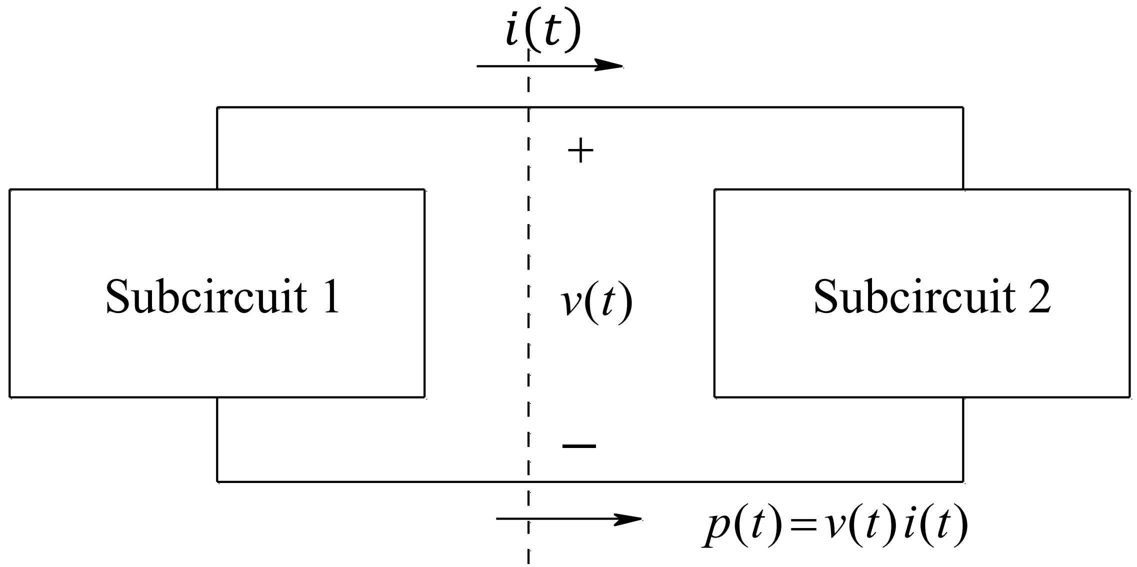
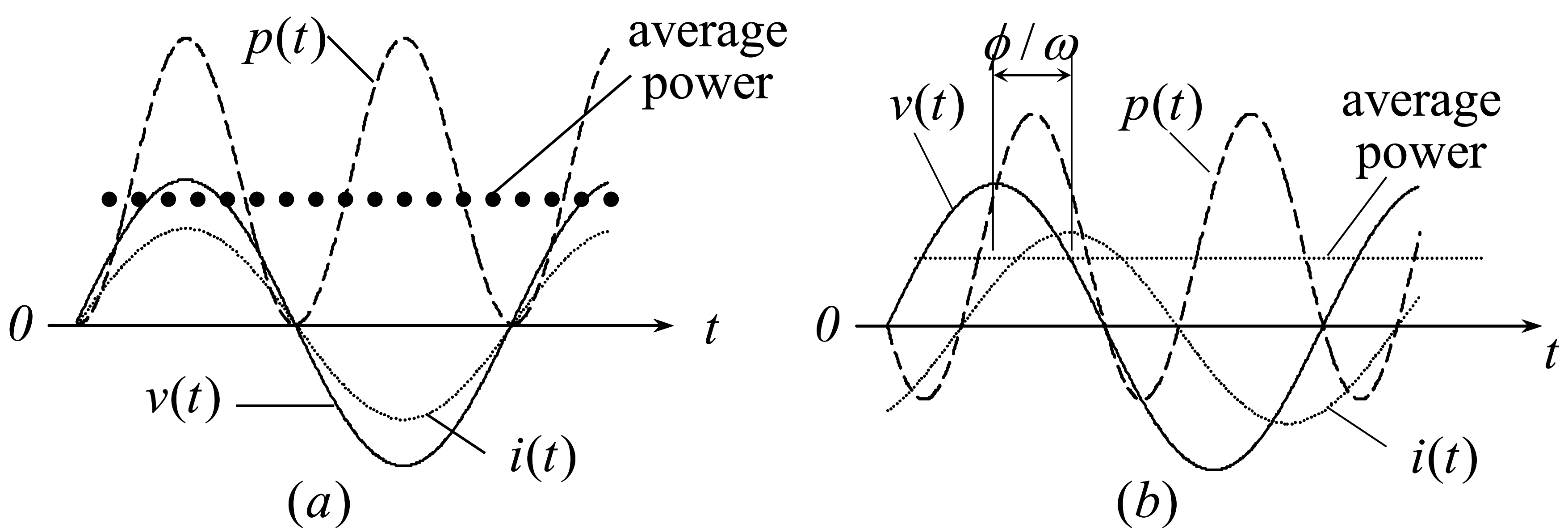


Figure 2-6 A generic circuit divided into two sub-circuits.

LINKÖPING UNIVERSITY

Real(Active) Power



$$(a)\quad p(t)=\sqrt{2}V\cos\omega t\cdot\sqrt{2}I\cos\omega t=2VIcos^{2}\omega t=VI+VI\cos 2\omega t$$

$$(b)\quad p(t)=\sqrt{2}V\cos\omega t\cdot\sqrt{2}I\cos(\omega t-\phi)=VI\cos\phi+VI\cos(2\omega t-\phi)$$

P, Q, VA and Power Factor

$$\bar{S} = \overline{VI}^{*} = \bar{V} \cdot conj(\bar{I})$$

$$\bar{S} = P + jQ$$

$$P = V\,I\cos\phi$$

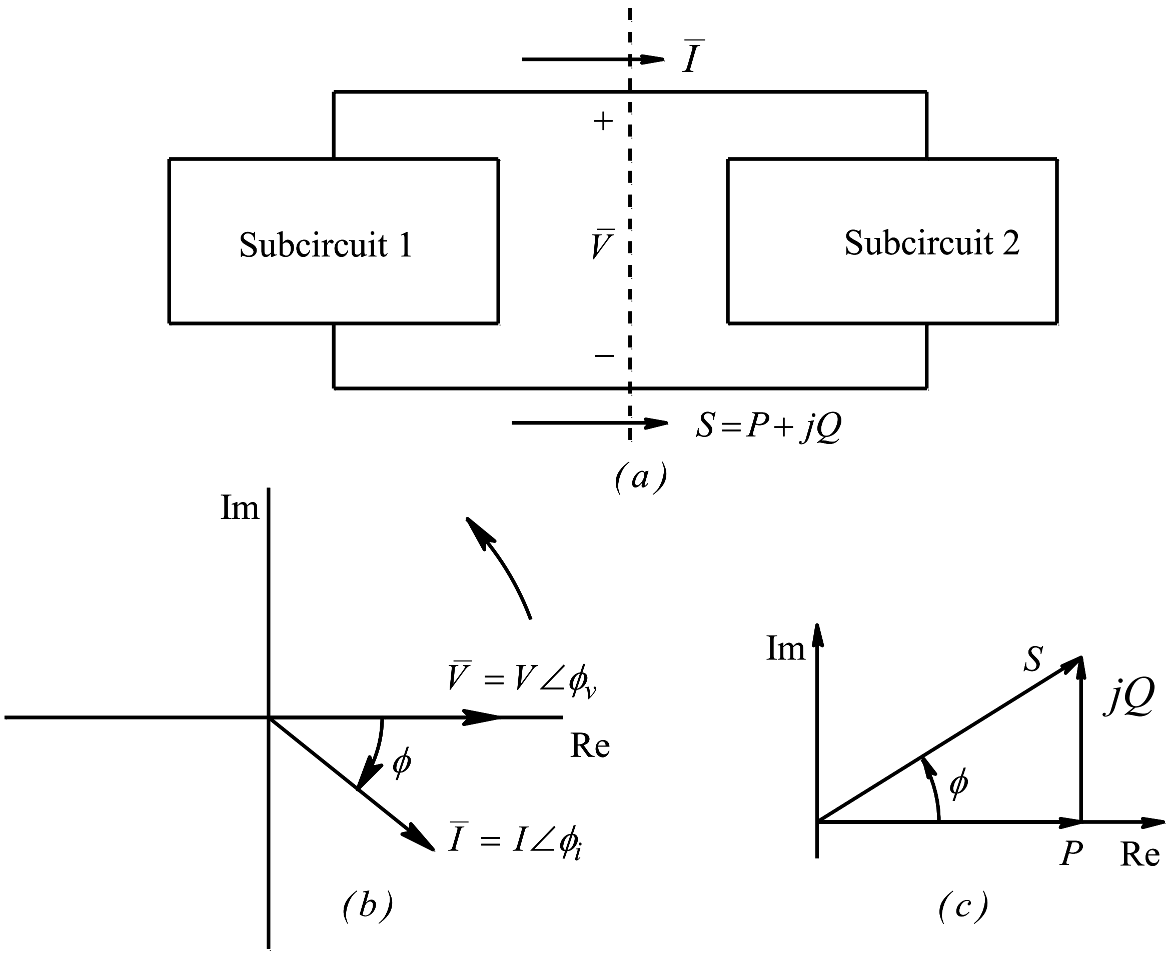
$$Q = V\,I\sin\phi$$

$$|S| = \sqrt{P^2 + Q^2}$$

$$\phi = \phi_v - \phi_i$$

$$\phi = \tan^{-1}\left(\frac{Q}{P}\right)$$

$$\text{Power Factor} = \frac{P}{VI} = \cos\phi$$



Circuit calculation example

$V_1 = 120\angle 0°\ V$

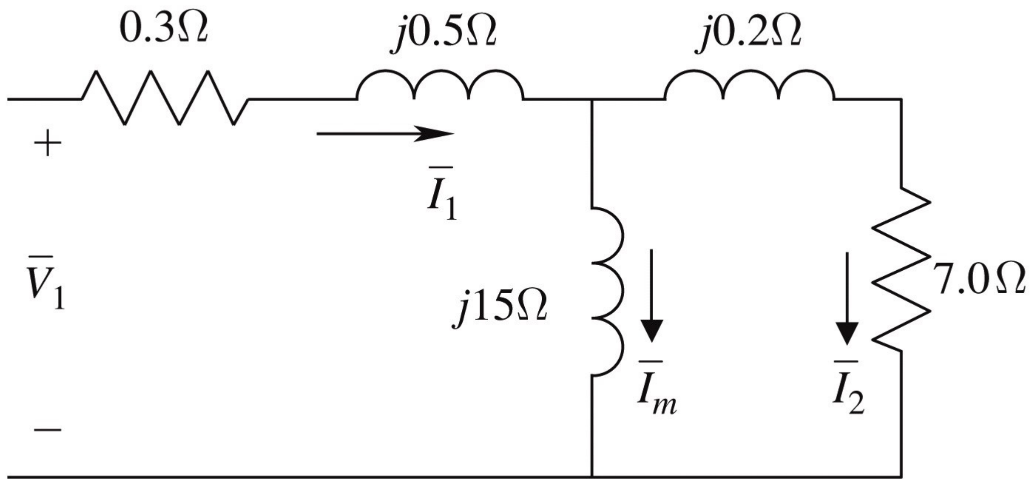


Figure 2.5

a) Calculate the input impedance $\bar{Z}_{in}$ and $\bar{I}_1$ (Example 2.2)
b) Calculate P, Q, S and the power factor (Example 2.3)

Circuit calculation example - solution

```
Z1 =0.3+0.5j;
Zm = 15j;
Z2 = 7+0.2j;
Zin = Z1+Zm*Z2/(Zm+Z2) %5.9+j3.3 ohm

V1 = 120;
I1 = V1/Zin %15.5-j8.6A

I2 = I1*Zm/(Zm+Z2)
Im=I1-I2
Sm = Zm*Im*conj(Im)
S2 = Z2*I2*conj(I2)
S1 = Z1*I1*conj(I1)

S = S1+S2+Sm %1858+j1031 VA
P = real(S)
Q = imag(S)

Sxx = Zin*I1*conj(I1) %alternative solution

pf = cosd(atand(Q/P))
```

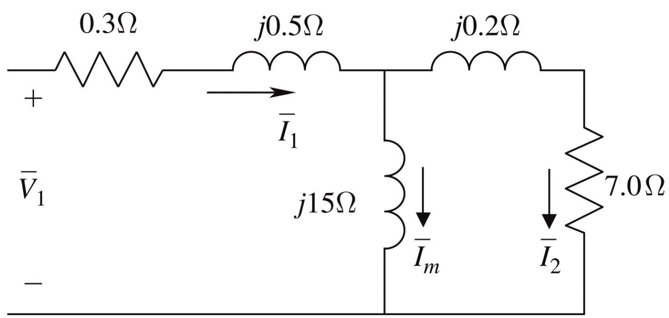


Figure 2.5

Example of Power Factor Correction

$V_1 = 120\,V$

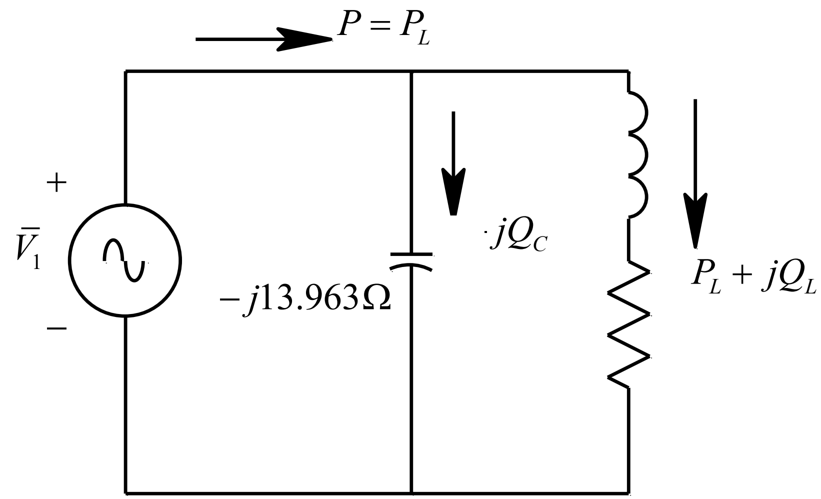


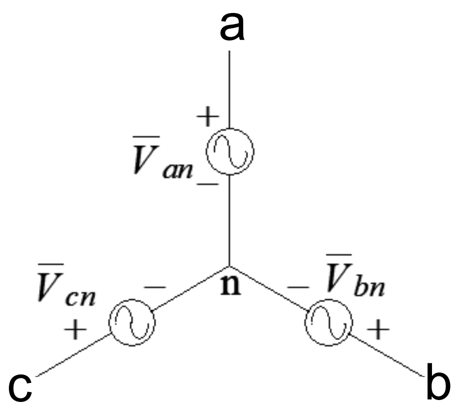
Fig. 2-9 Power factor correction in Example 2-5.

$$P_L + jQ_L = (1858 + j1031)VA$$

Unity power factor, $\cos\phi = 1$

$$Q_L = -Q_c = -\frac{V_1^2}{X_c}$$

Three-Phase Voltages



$\bar{V}_{an}$ the voltage between phase a and the neutral (n)

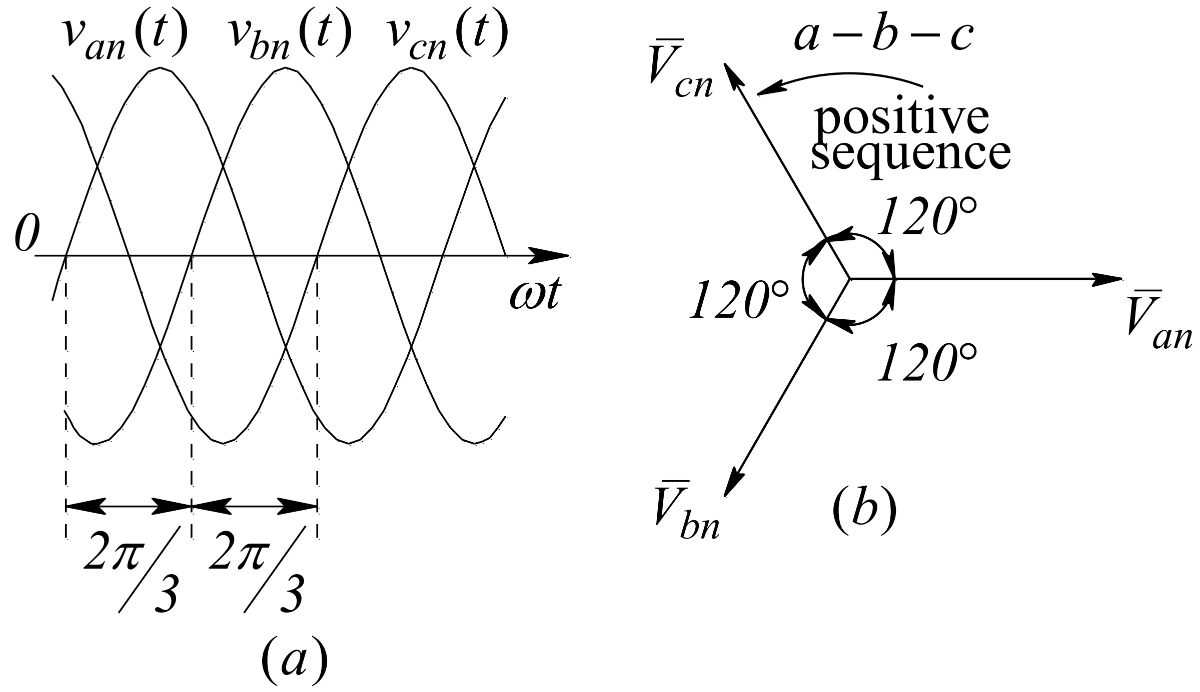


Fig. 2-11 Three-phase voltages in time and phasor domain.

$$v_{an} = \sqrt{2}V\cos(\omega t)$$
$$v_{bn} = \sqrt{2}V\cos(\omega t - 120°)$$
$$v_{cn} = \sqrt{2}V\cos(\omega t - 240°)$$

$$\bar{V}_{an} = V\angle 0°$$
$$\bar{V}_{bn} = V\angle -120°$$
$$\bar{V}_{cn} = V\angle -240°$$

V_{an} is the RMS phase to neutral voltage

Balanced Three-Phase Circuit Analysis

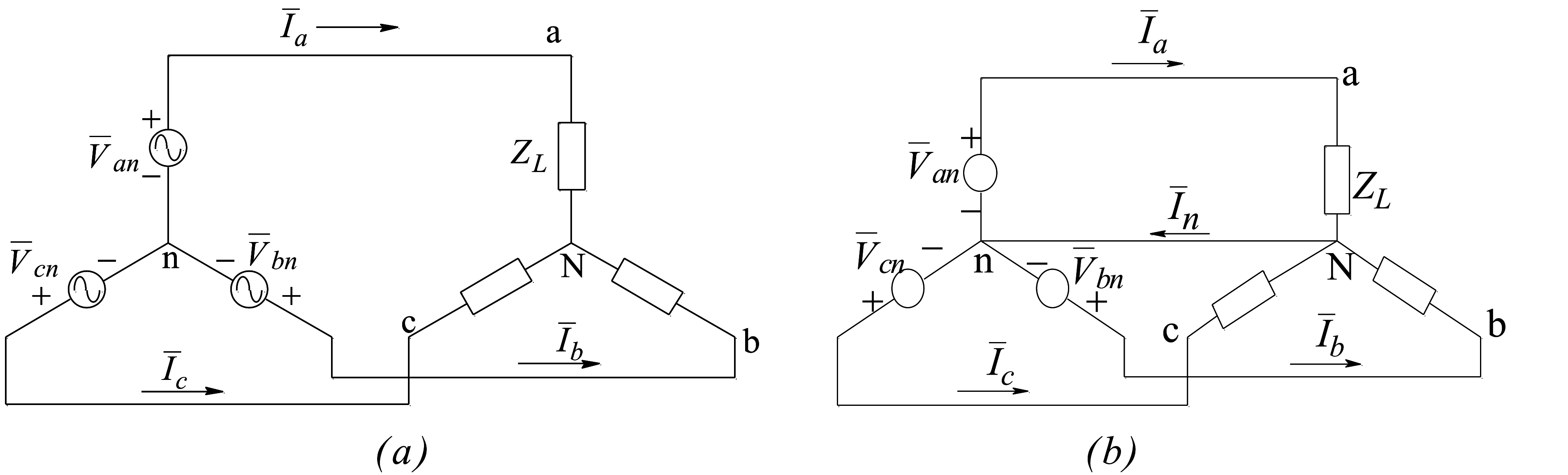


Fig. 2-12 Balanced wye-connected, three-phase circuit.

If the source is symmetrical 3-phase and the load same in all phases.

- $V_n = V_N$
- $I_n = 0 \rightarrow I_a + I_b + I_c = 0$

Per-Phase Analysis

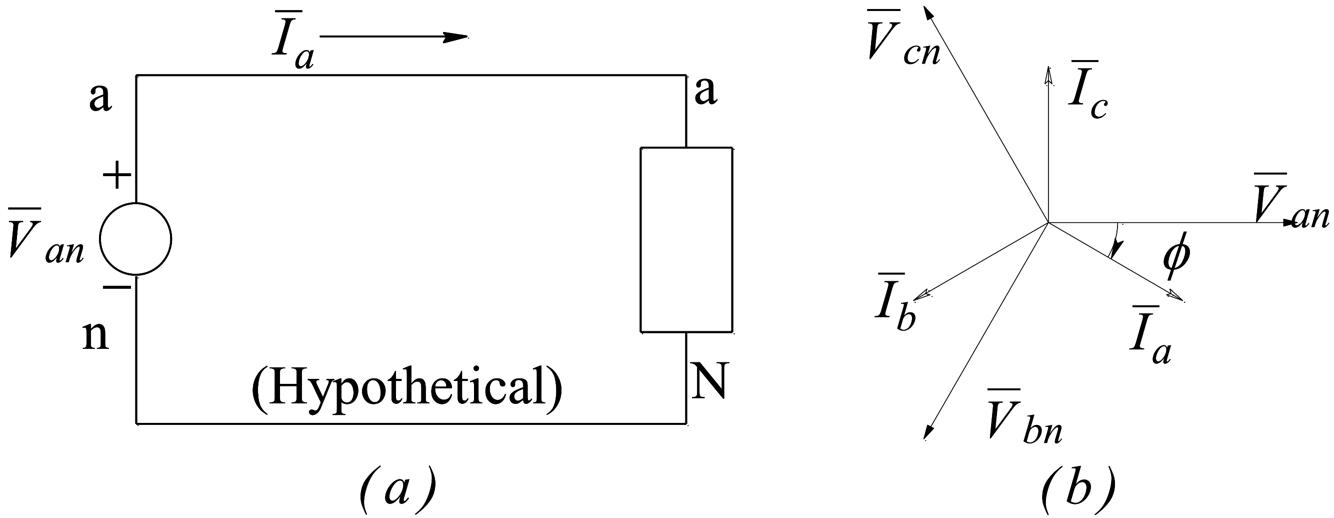
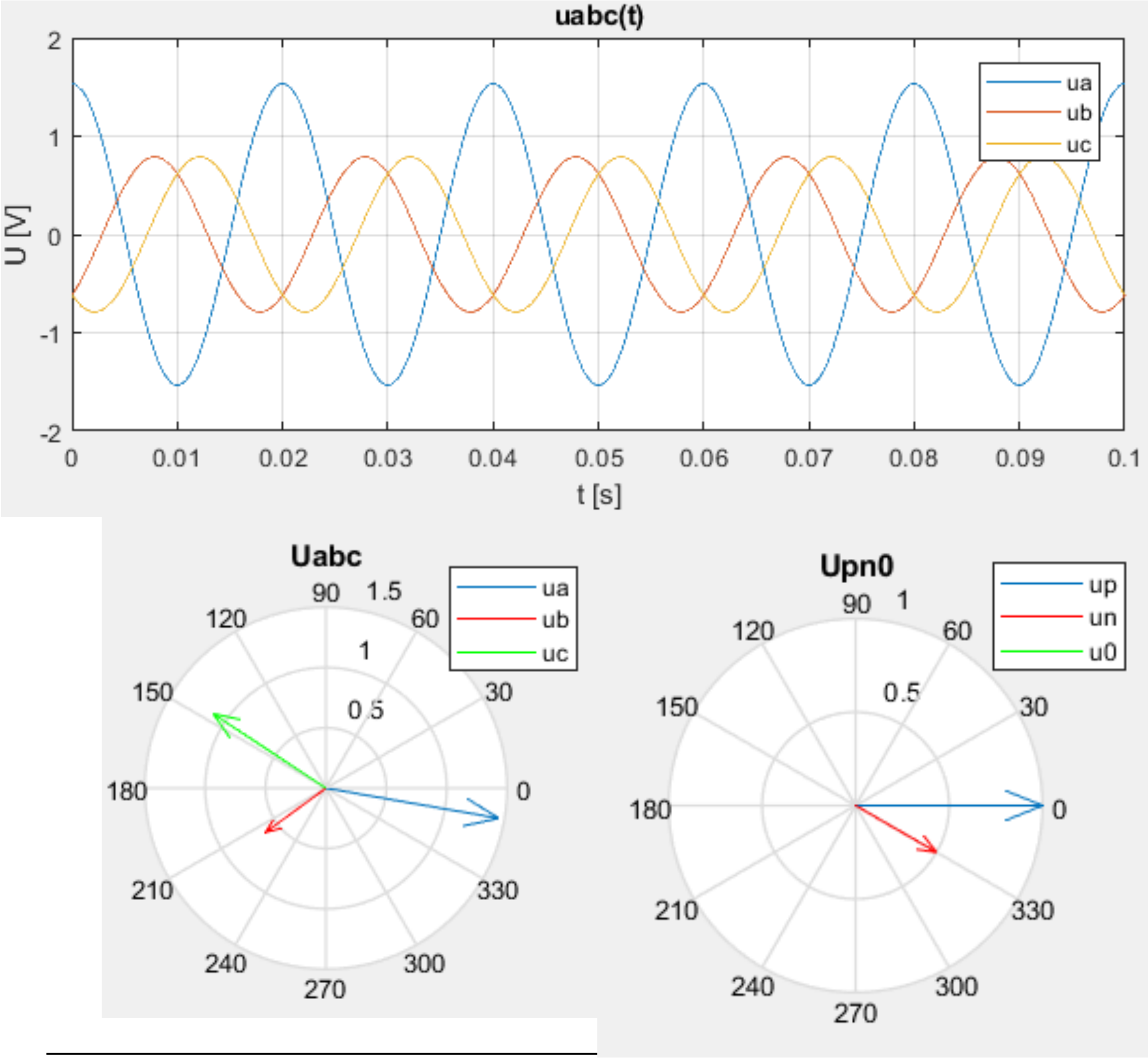


Fig. 2-13 Per-phase circuit and the corresponding phasor diagram.

For symmetrical load analysis of one phase is enough!

Positive/Negative/Zero sequence



Arbitrary 3-phase voltages (or currents) can be composed by:

- **Positive sequence**: 3-phases 120° displaced: a-b-c
  Symmetrical
- **Negative sequence**: 3-phases 120° reversely displaced: a-c-b
  Backwards rotation
- **Zero sequence**: 3-phases in-phase a+b+c ≠ 0
  Current in neutral

Symmetrical components

Positive/Negative/Zero sequence

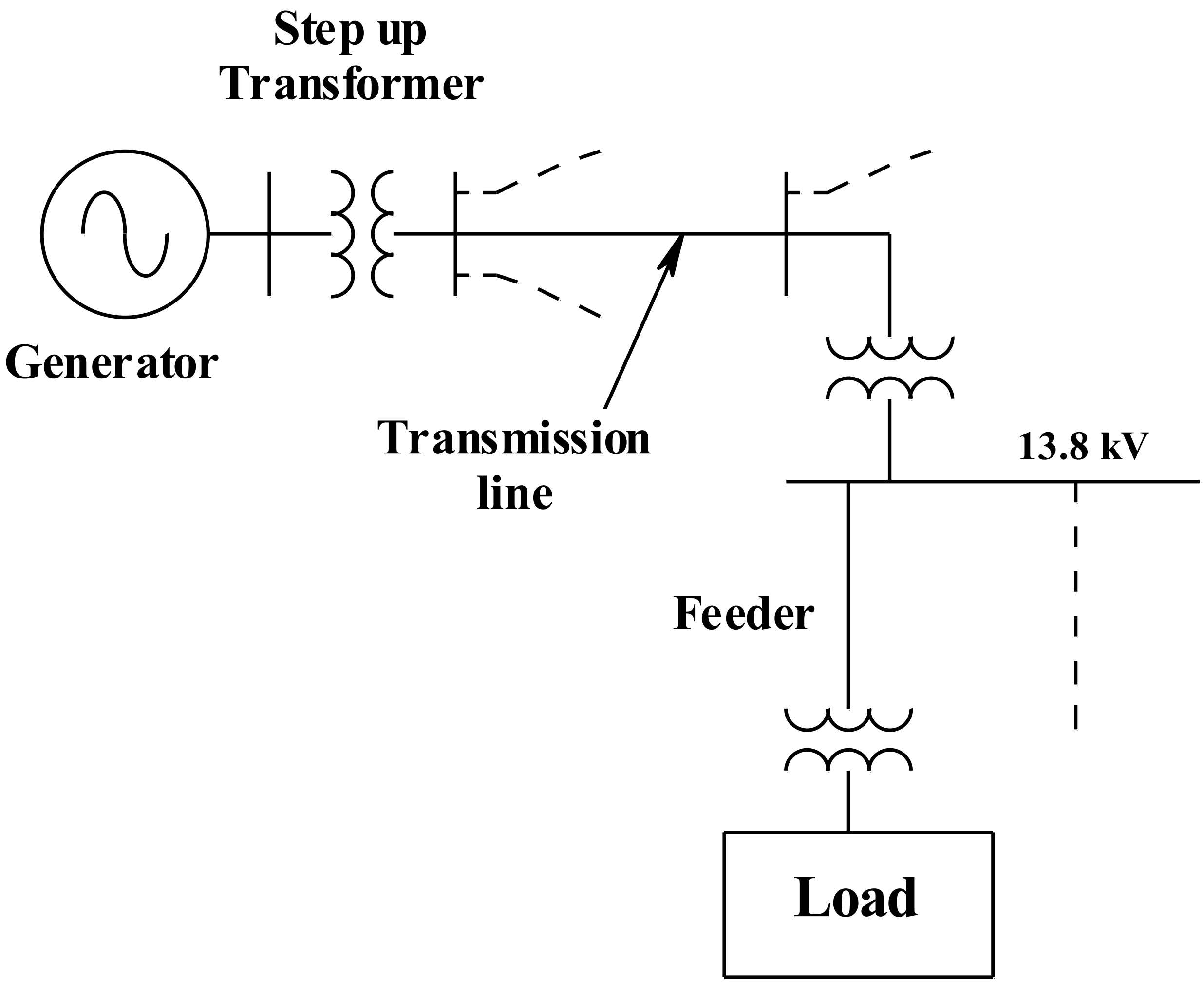
$$\mathbf{V}_{abc} = \begin{bmatrix} \vec{V}_a \\ \vec{V}_b \\ \vec{V}_c \end{bmatrix} = \begin{bmatrix} V_a \angle \theta_a \\ V_b \angle \theta_b \\ V_c \angle \theta_c \end{bmatrix} \quad , \quad \mathbf{V}_{+-0(a)} = \begin{bmatrix} \vec{V}_a^+ \\ \vec{V}_a^- \\ \vec{V}_a^0 \end{bmatrix} = \begin{bmatrix} V_a^+ \angle \theta_a^+ \\ V_a^- \angle \theta_a^- \\ V_a^0 \angle \theta_a^0 \end{bmatrix}$$

$$[T_{+-0}] = \frac{1}{3} \begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \\ 1 & 1 & 1 \end{bmatrix} \quad \alpha = e^{j2\pi/3} = 1\angle 120^\circ$$

$$\mathbf{V}_{+-0(a)} = [T_{+-0}] \, \mathbf{V}_{abc}$$

- Circuit analysis can now be done separately for positive, negative and zero sequence considering a 1-phase system
- Inverse transformation to abc

One-line (Single-line) Diagram



Phase-Phase (Line-Line) Voltages

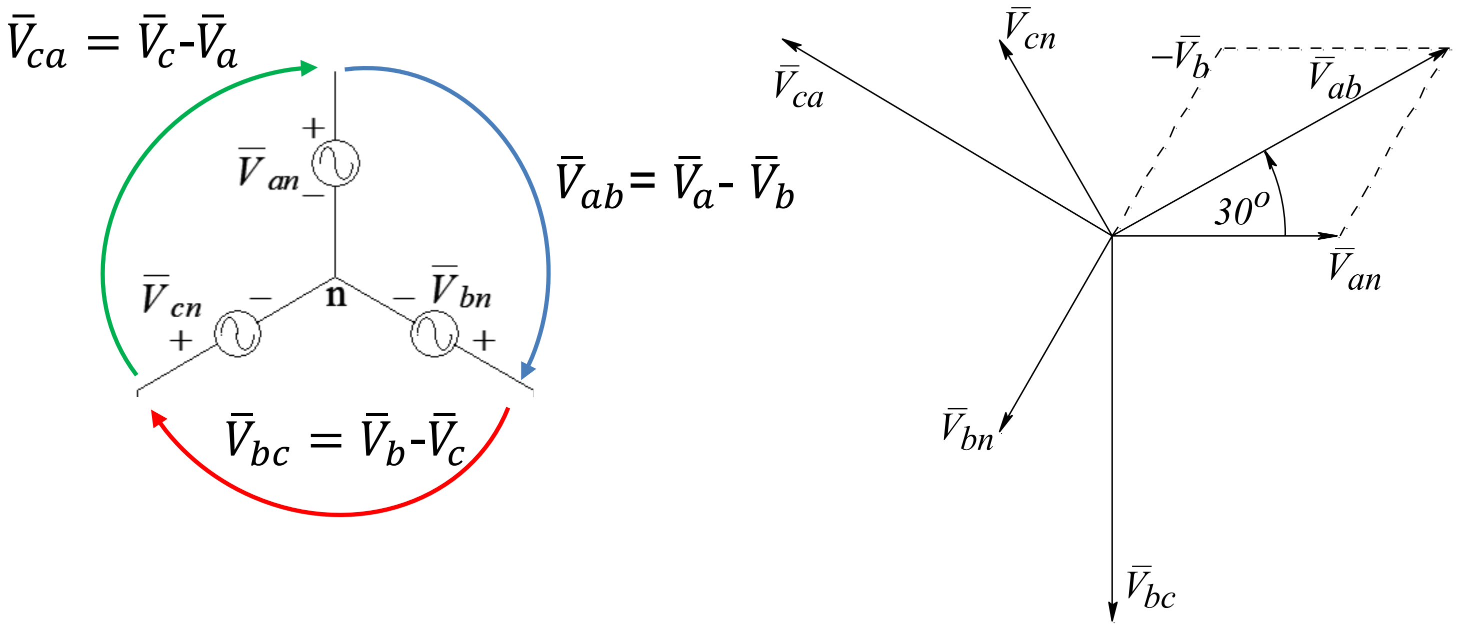


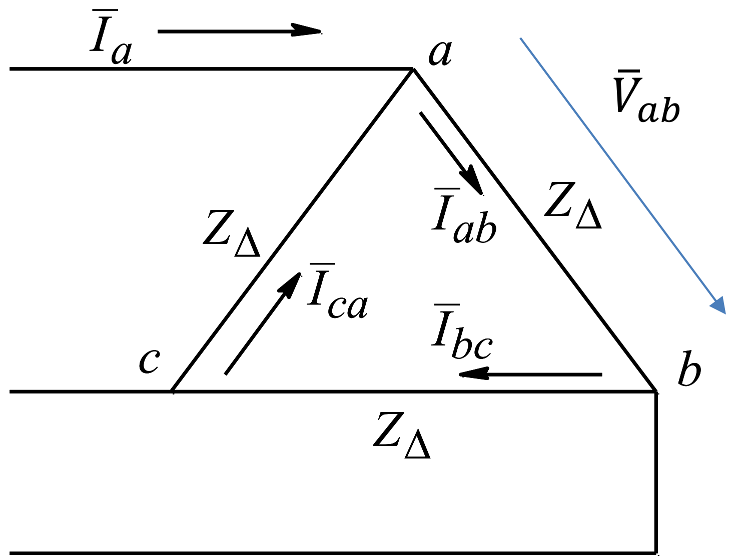
Fig. 2-15 Line-to-line voltages in a three-phase circuit.

Under symmetrical conditions:

$$if\ \bar{V}_{an} = V\angle 0°$$

$$\bar{V}_{ab} = \sqrt{3} \cdot V\angle 30°$$

Delta Connection



Under symmetrical conditions:

$$\bar{I}_{ab} = \mathrm{I}\angle 0°$$

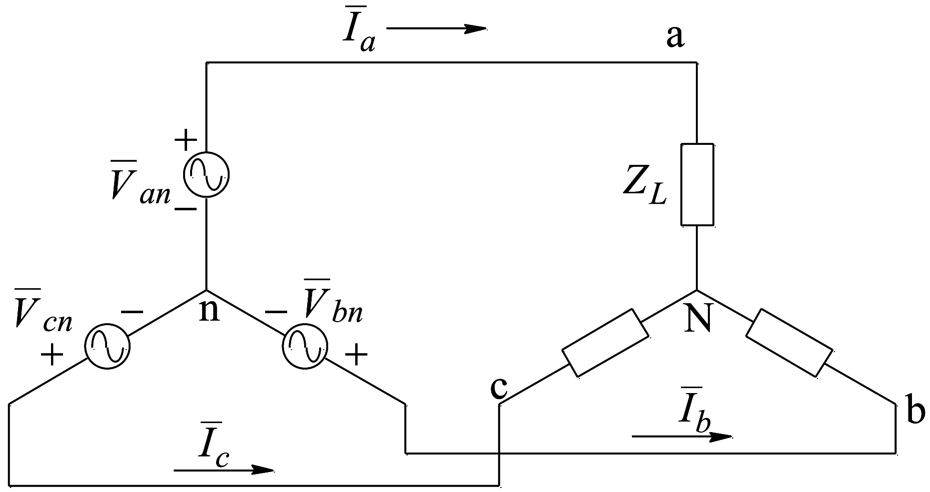
$$\bar{I}_{ca} = \mathrm{I}\angle - 240°$$

$$\bar{I}_a = \bar{I}_{ab} - \bar{I}_{ca} = \sqrt{3} \cdot I\angle - 30°$$

Power balance:

$$3\bar{V}_{an} \cdot \bar{I}_a^* = 3\bar{V}_{ab} \cdot \bar{I}_{ab}^*$$

3-phase power



(a)

Fig. 2-12 Balanced wye-conne

$$P_{3ph} = 3V_{ph}I\cos\phi$$

$$Q_{3ph} = 3V_{ph}I\, sin\,\phi$$

$$S_{3ph} = 3V_{ph}I$$

$$Power\ factor = \frac{P_{3ph}}{S_{3ph}} = \frac{3V_{ph}I\cos\phi}{3V_{ph}I} = \cos\phi$$

$$V_{ph-ph} = \sqrt{3}\cdot V_{ph}$$

$\bar{V}_{ph-ph} = \bar{V}$, the normal voltage for describing a 3-phase system

$$P_{3ph} + jQ_{3ph} = \sqrt{3}\cdot \bar{V}_{ph-ph}\cdot \bar{I}^* = \sqrt{3}\cdot \bar{V}\cdot \bar{I}^*$$

Per Unit Quantities

$$R_{base}, X_{base}, Z_{base} = \frac{V_{base}}{I_{base}} \quad \text{(in } \Omega \text{)} \qquad (2\text{-}48)$$

$$G_{base}, B_{base}, Y_{base} = \frac{I_{base}}{V_{base}} \quad \text{(in ℧)} \qquad (2\text{-}49)$$

$$P_{base}, Q_{base}, (VA)_{base} = V_{base} I_{base} \quad \text{(in Watt, VAR, or VA)} \qquad (2\text{-}50)$$

In terms of these base quantities, the per-unit quantities can be specified as

$$\text{Per-Unit Value} = \frac{\text{actual value}}{\text{base value}} \qquad (2\text{-}51)$$

Per Unit Quantities, 3ph

U_{base} =Phase-phase voltage

$$S_{base} = \sqrt{3}U_{base}\ I_{base}$$

$$Z_{base} = \frac{U_{ph}}{I} = \frac{U_{base}}{\sqrt{3}I_{base}} = \frac{U_{Base}^2}{S_{base}}$$

$$\text{Per-Unit Value} = \frac{\text{actual value}}{\text{base value}}$$

Per unit example

a) Compute the base current I_{base} and the base impedance Z_{base} given $V_{LL,base} = 208 \text{ and}$ $S_{3ph,base} = 5.4\ kVA$.

b) Compute the line current when the voltage is $0.9\angle 0°\ pu$ and the impedance is $0.5\angle - 60°\ pu.$

Per unit example - solution

$a)\quad V_{LL,base} = 208\,V$

$$V_{ph,base} = \frac{208}{\sqrt{3}} = 120\,V$$

$$S_{3ph,base} = 5.4\,kVA$$

$$S_{ph,base} = \frac{5.4}{3} = 1.8\,kVA$$

$$I_{base} = \frac{S_{ph,base}}{V_{ph,base}} = \frac{S_{3ph,base}}{\sqrt{3}V_{LL,base}} = 15\,A$$

$$Z_{base} = \frac{V_{ph,base}}{I_{base}} = \frac{V_{LL,base}^2}{S_{3ph,base}} = 8\,ohm$$

$b)\quad \bar{v} = 0.9\angle 0°\,pu$

$\bar{z} = 0.5\angle -60°\,pu$

$\bar{\imath} = \frac{\bar{v}}{\bar{z}}$ [pu] = 0.99+j1.56

$|\bar{\imath}| = 1.8\,pu$

$\bar{I} = \bar{\imath} \cdot I_{base}$[A] = 1.35+j23.4A =

= 27 ∠60°A

AC Transmission lines

LINKÖPING
UNIVERSITY

Transmission Network in Nordic

Transmission lines:

220-400 kV

Regional lines:

40-130 kV

Distribution lines:

10-20 kV

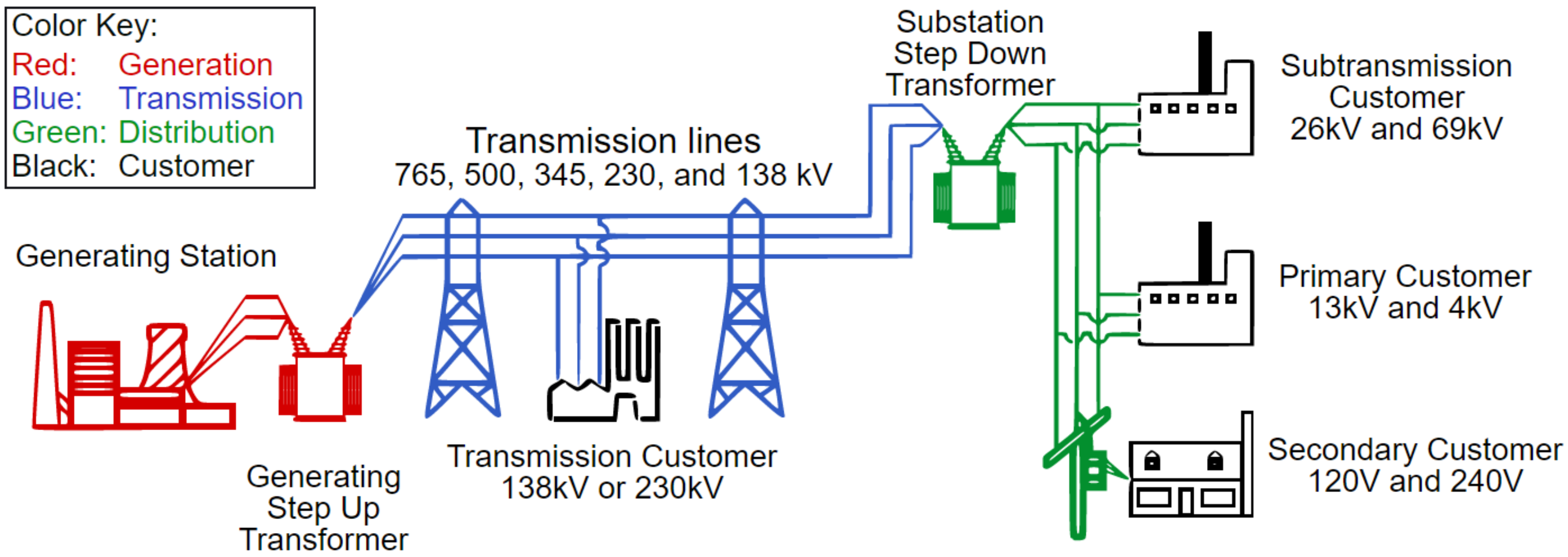
Nätstation

nnätsstation

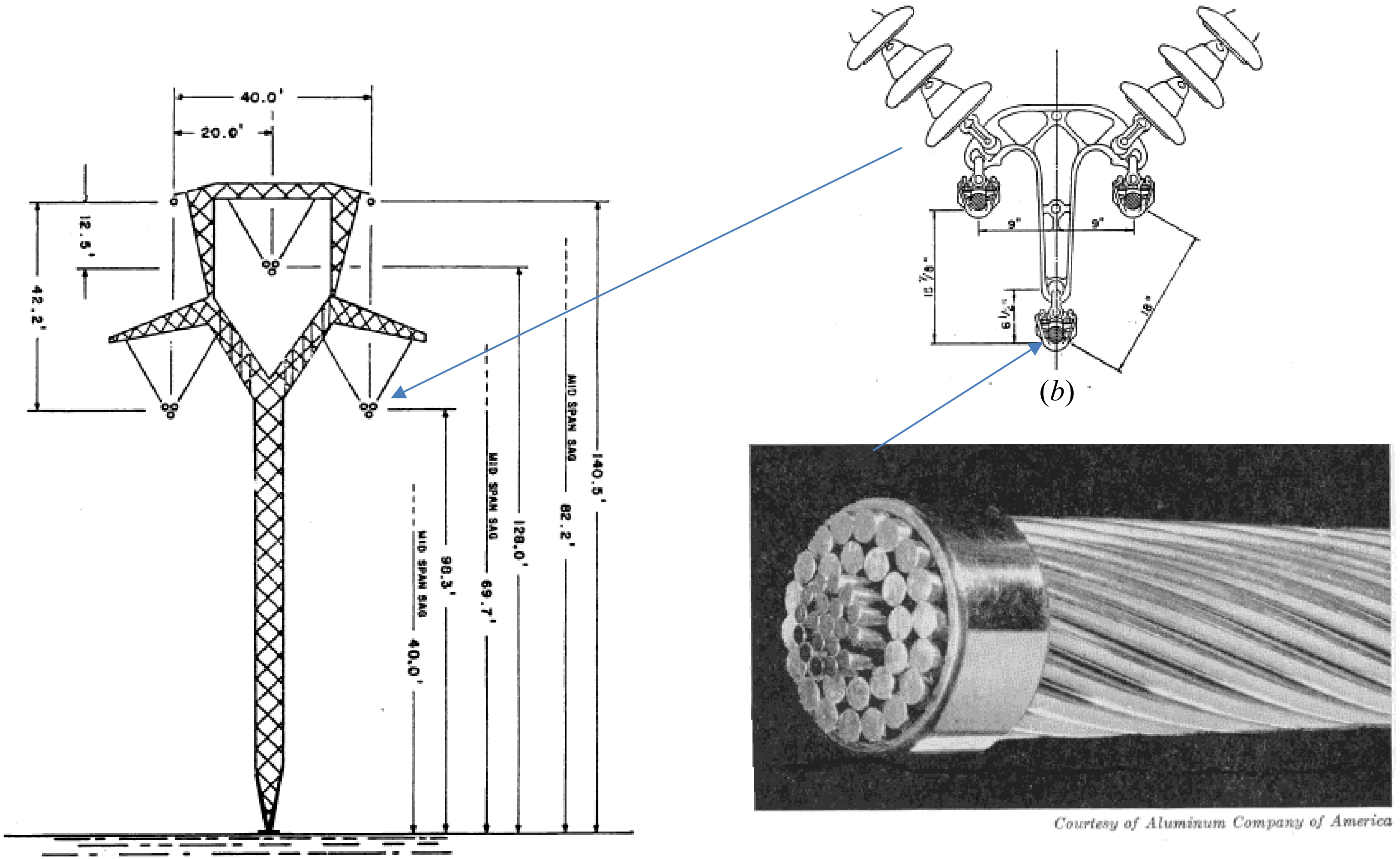
Images:
Svenska kraftnät
Vattenfall

Overhead AC Transmission Lines

- Distribution Lines
  - 10 kV, 36 kV
- Transmission Line Voltages (Web link: SVK)
  - 115 kV, 230 kV, 345 kV, 500 kV and 765 kV
- Three-Phase



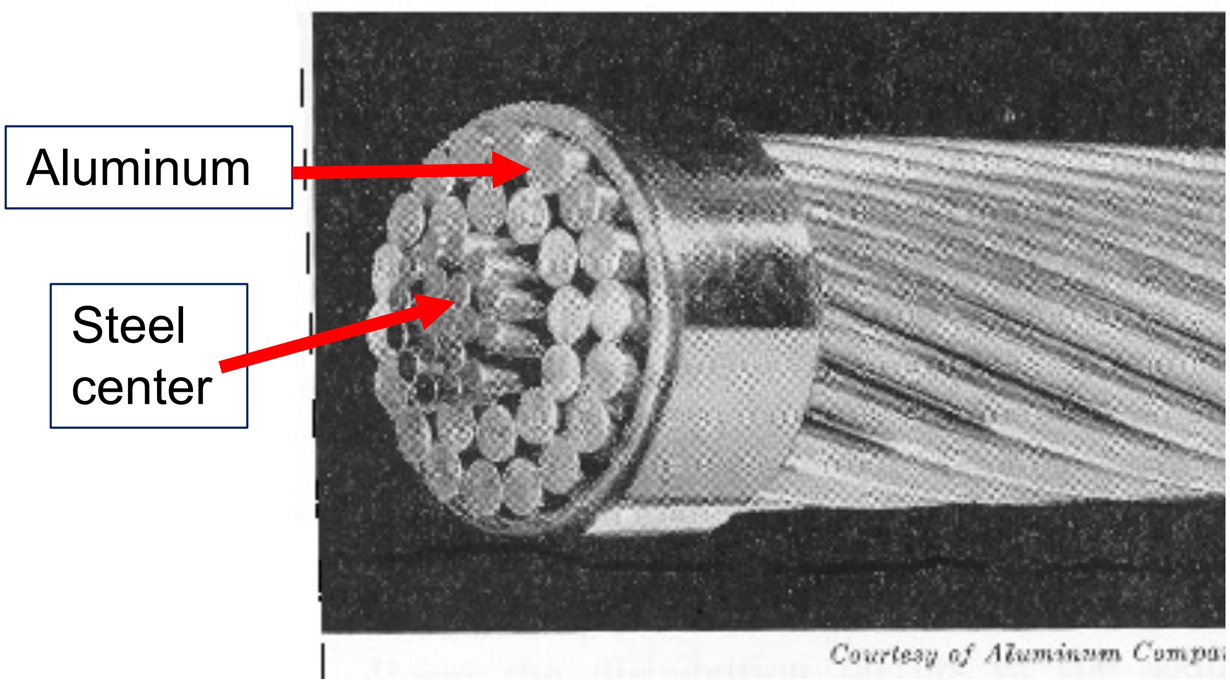
Transmission Tower, Conductor and Bundling

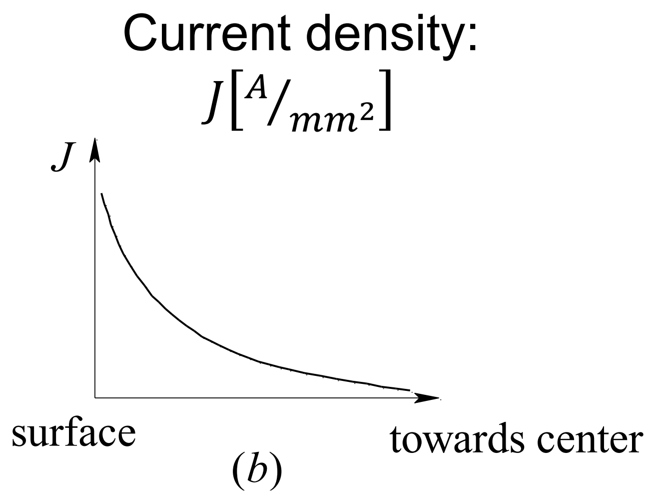


(a) (c)

Fig. 4-1 500-kV transmission line (Source: University of Minnesota EMTP course).

Conductors:



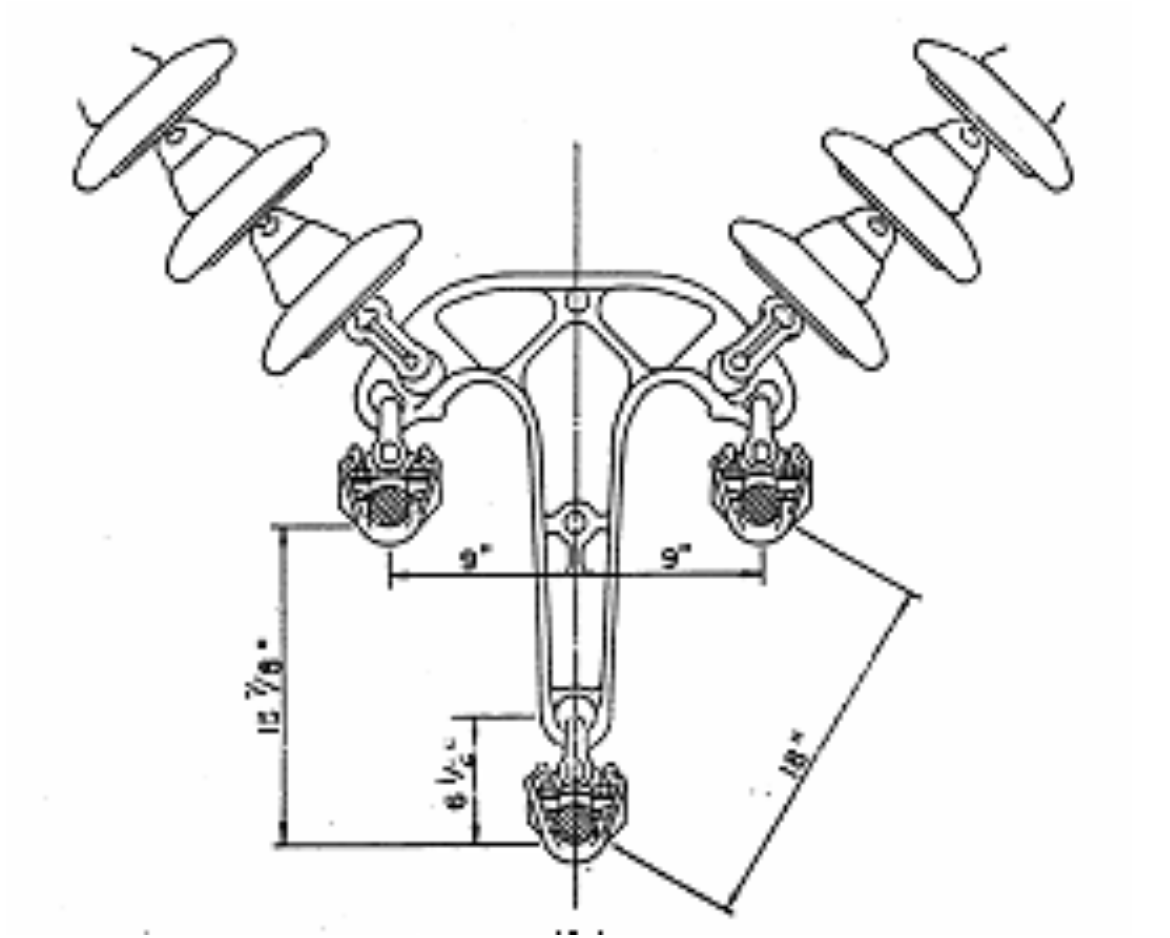


- ACSR, **A**luminum **C**onductor, **S**teel **R**einforced
- Skin effect = current confined to the surface
  - Aluminum in the outer part for low resistance
  - Steel in the center for mechanical strength

LINKÖPING UNIVERSITY

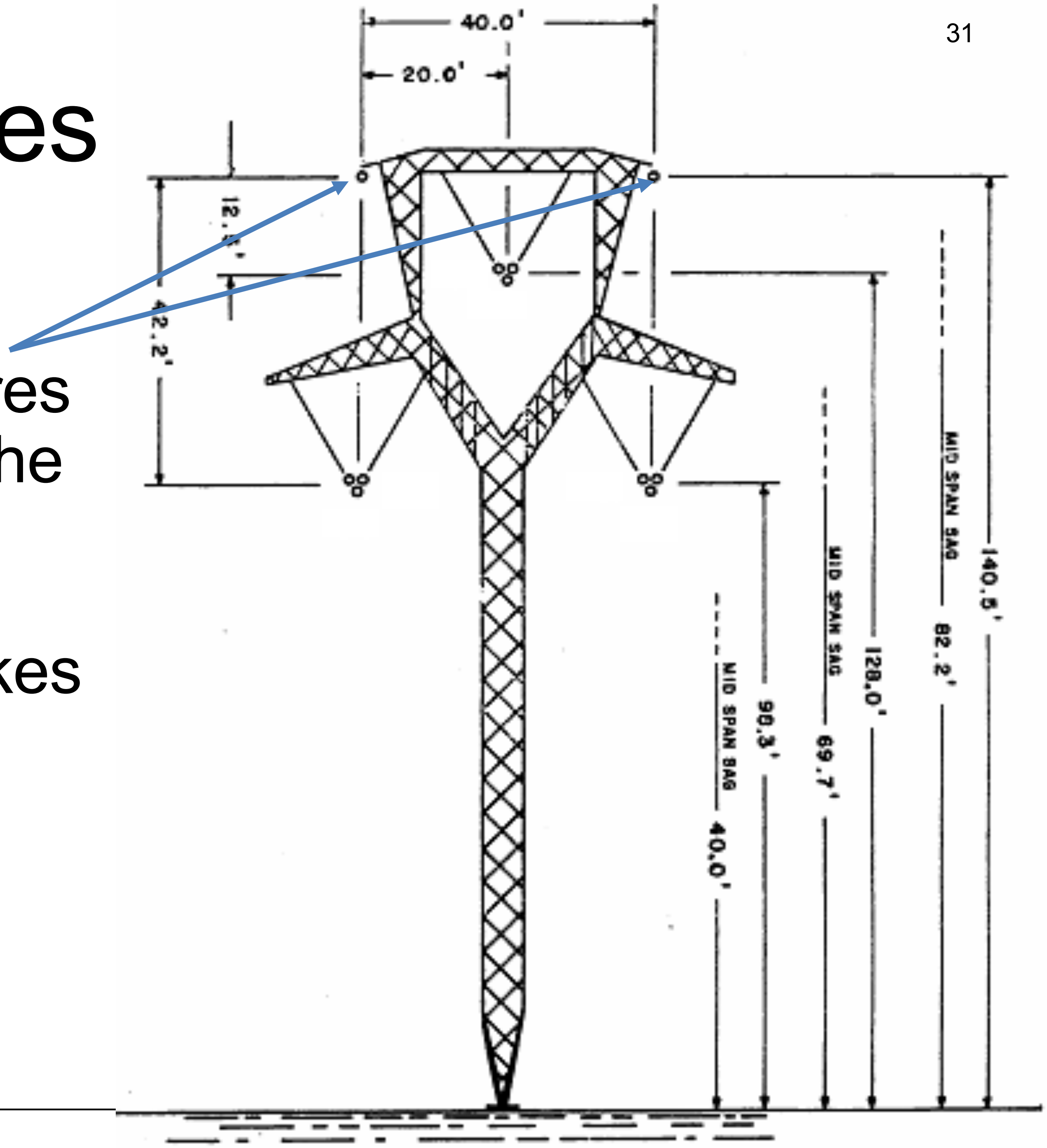
Bundling:

- To reduce electric field at the conductor surface
- Less than 16 kV/cm
- 345 kV Lines
  - 2 conductor-bundle at 18 inches
- 500 kV Lines
  - 3 conductor bundle at 18 inches

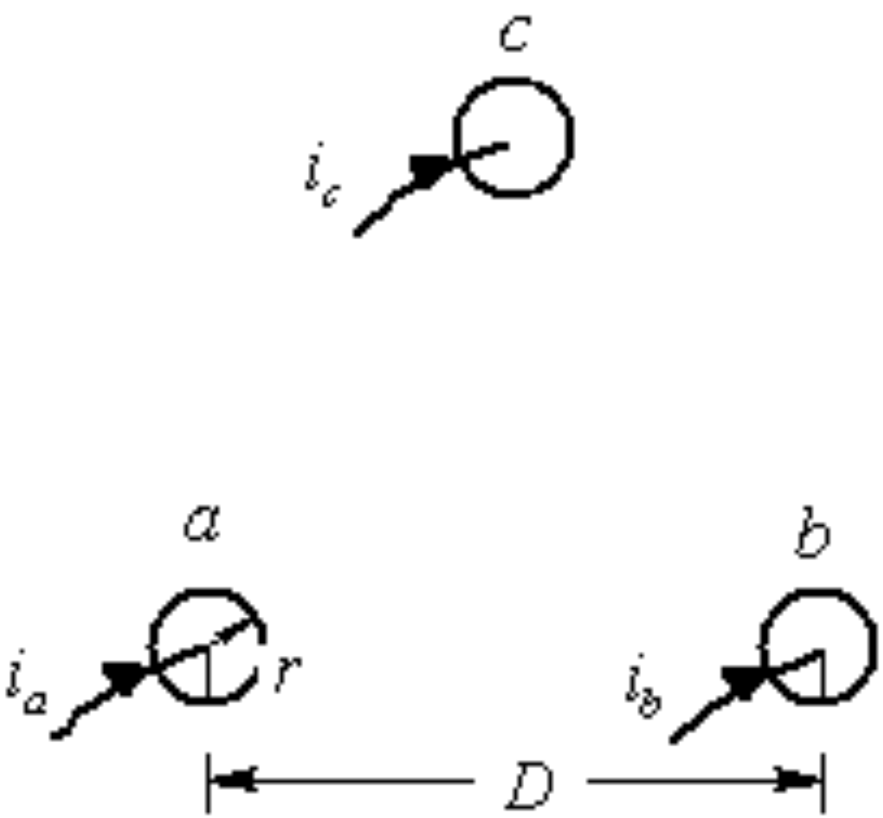


Shield Wires

- Grounded wires at the top of the tower
- Shielding of Lightning strikes



Transmission Line Inductance

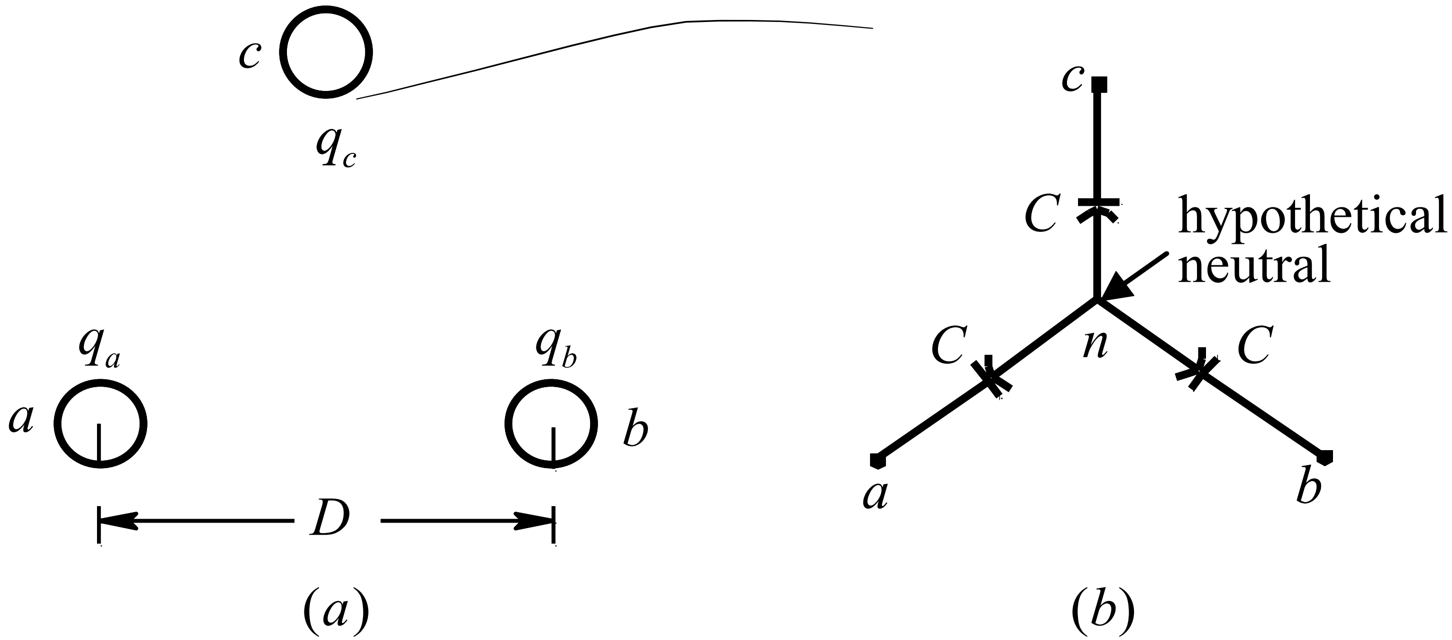


$$i_a + i_b + i_c = 0$$

$$L = \left(\frac{\mu_0}{2\pi}\right) \ln \frac{D}{r}$$

GMD $D = \sqrt[3]{D_1 D_2 D_3}$

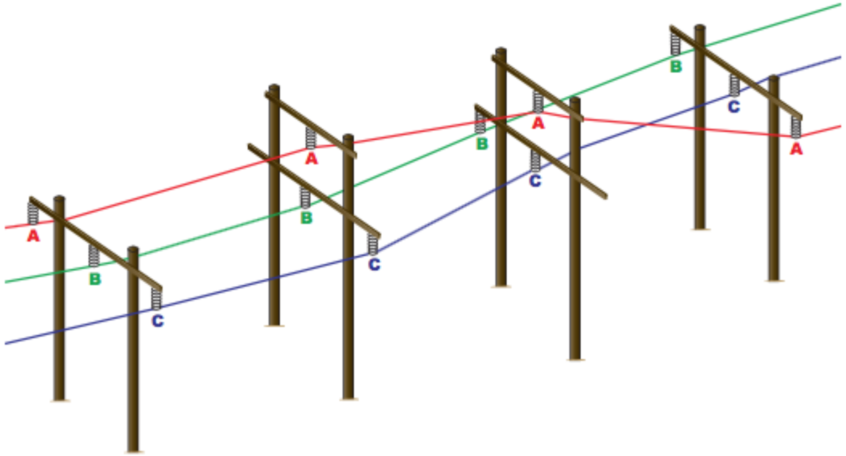
Transmission Line Capacitance

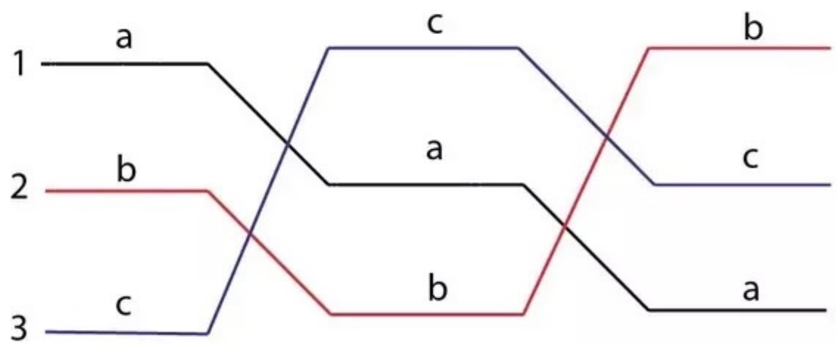


$$C = \frac{2\pi\varepsilon_0}{\ln\frac{D}{r}}$$

$$D = \sqrt[3]{D_1 D_2 D_3}$$

Transposition

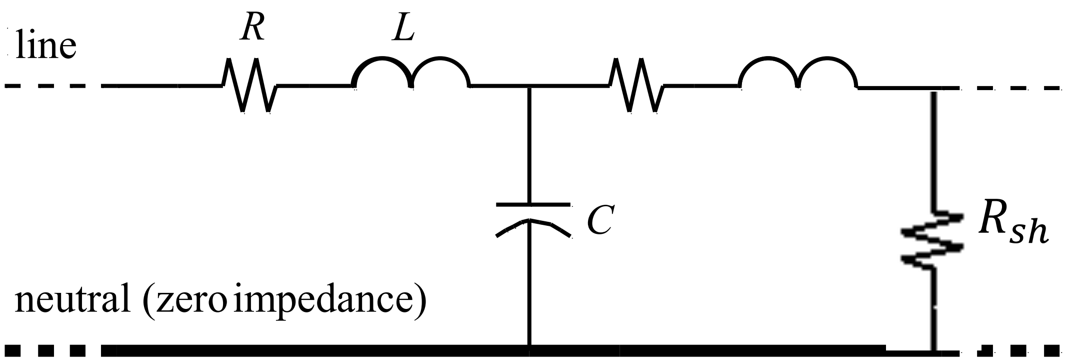




Transposition of the Conductors

- Conductors in different positions gets different L and C
- Transposition neutralizes the difference over the length of the line

Transmission Line Parameters:



- Distributed Parameters per km
- Analyzed on a per-phase basis

$\bar{U} = \bar{Z} \cdot \bar{I}$ $\quad$ $Impedance$: $\bar{Z} = R + jX\ [ohm]$

$Reactance\ (ind)$: $X_L = \omega L\ [ohm]$ $\quad$ $Reactance\ (cap)$: $X_C = \dfrac{-1}{\omega C}\ [ohm]$

$\bar{I} = \bar{Y} \cdot \bar{U}$ $\quad$ Admittance: $\bar{Y} = \frac{1}{\bar{Z}} = G + jB\ [mho\ or\ S]$

$Conductance$: $G = \dfrac{1}{R_{sh}}\ [mho]$ $\quad$ $Susceptance$: $B = \dfrac{-1}{X_C} = \omega C\ [mho]$

Typical Parameters for various Voltage Transmission Lines

Table 4-1

Transmission Line Parameters with Bundled Conductors (except at 230 kV) at 60 Hz [2, 6]

Nominal Voltage	$R(\Omega/km)$	$\omega L(\Omega/km)$	ωC ($\mu mho/km$
230 kV	0.055	0.489	3.373
345 kV	0.037	0.376	4.518
500 kV	0.029	0.326	5.220
765 kV	0.013	0.339	4.988

$Reactance\ (ind)$: $X_L = \omega L$ $\quad$ $Susceptance$: $B = \omega C$

Voltage Profile With Surge Impedance Loading (SIL)

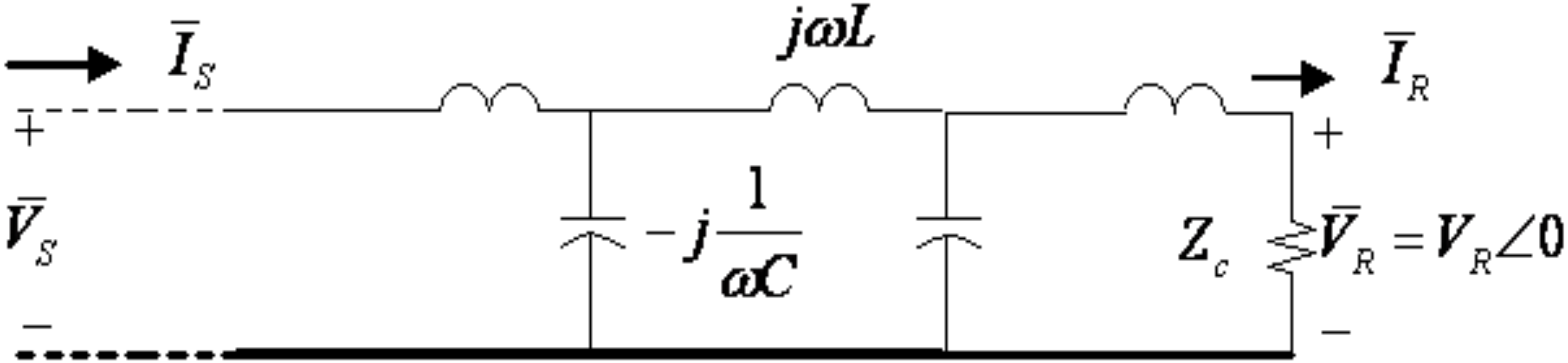
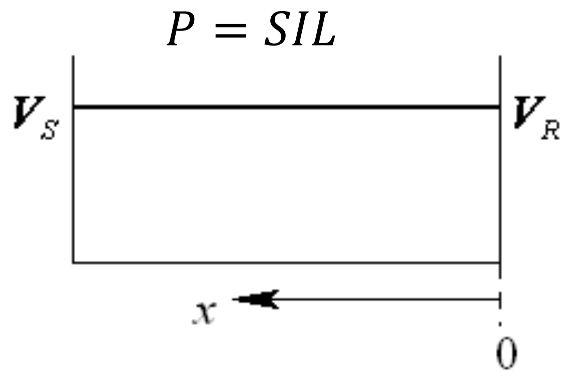


Fig. 4-10 Per-phase transmission line terminated with a resistance equal to Z_c.

Reactive power balance:

$$\omega L I_x^2 = V_x^2 \omega C$$



Surge impedance:

$$Z_c = \sqrt{\frac{L}{C}}$$

$$SIL = \frac{V_{LL}^2}{Z_c}$$

Typical Surge Impedances and SIL for various Voltage Transmission Lines

Table 4-2

Surge Impedance and Three-Phase Surge Impedance Loading [2, 6]

Nominal Voltage	$Z_c (\Omega)$	$SIL\,(MW)$
230 kV	375	140 MW
345 kV	280	425 MW
500 kV	250	1000 MW
765 kV	255	2300 MW

Loadability of Transmission Lines

Table 4-3

Loadability of Transmission Lines [6]

Line Length (km)	Limiting Factor	Multiple of SIL
0 - 80	Thermal	> 3
80 - 240	5% Voltage Drop	1.5 - 3
240 - 480	Stability	1.0 – 1.5

TSTE26
Lars Eriksson

www.liu.se