ELEC-E8413

POWER SYSTEMS

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ELEC-E8413 power systems

Lectures

Lecture 1	Network components Referring, p.u. computation
Lecture 2	p.u. computation Load flows
Lecture 3	Power stations Load modeling
Lecture 4	Stability
Lecture 5	Faults
Lecture 6	P and Q control
Lecture 7	Power Quality
Lecture 8	High voltage engineering
Lecture 9	Substation equipment Transformers
Lecture 10	Lines
Lecture 11	Protection
Lecture 12	Earthings, hazard voltages

Course materials

- **Course books:**
- 7 B. M. Weedy , B. J. Cory , N. Jenkins, J. B. Ekanayake, G. Strbac, “Electric Power Systems” fifth edition, December 26, 2012 , ISBN-10: 047068268X, ISBN-13: 978-0470682685.
- John J. Grainger, William D. Stevenson, Jr., “Power System Analysis, ” Singapore, 1994. ISBN-10: 0070612935, ISBN-13: 978-0070612938.
- Harrison, John Anthony, "The essence of electric power systems" Prentice Hall, 1996, ISBN 0133975142, 9780133975147
- Kirtley, James, "Electrical Power Principles: Sources, Conversion, Distribution & Use", Wiley, 2010. ISBN: 9780470686362. (Available at Aalto ebrary) http://site.ebrary.com/lib/aalto/docDetail.action?docID=10411610
- **Books in Finnish: Liisa Haarla & Jarmo Elovaara, Sähköverkot 1&2, Otatieto**
- **Slides and exercise materials available in MyCourses**

Transmission and distribution systems

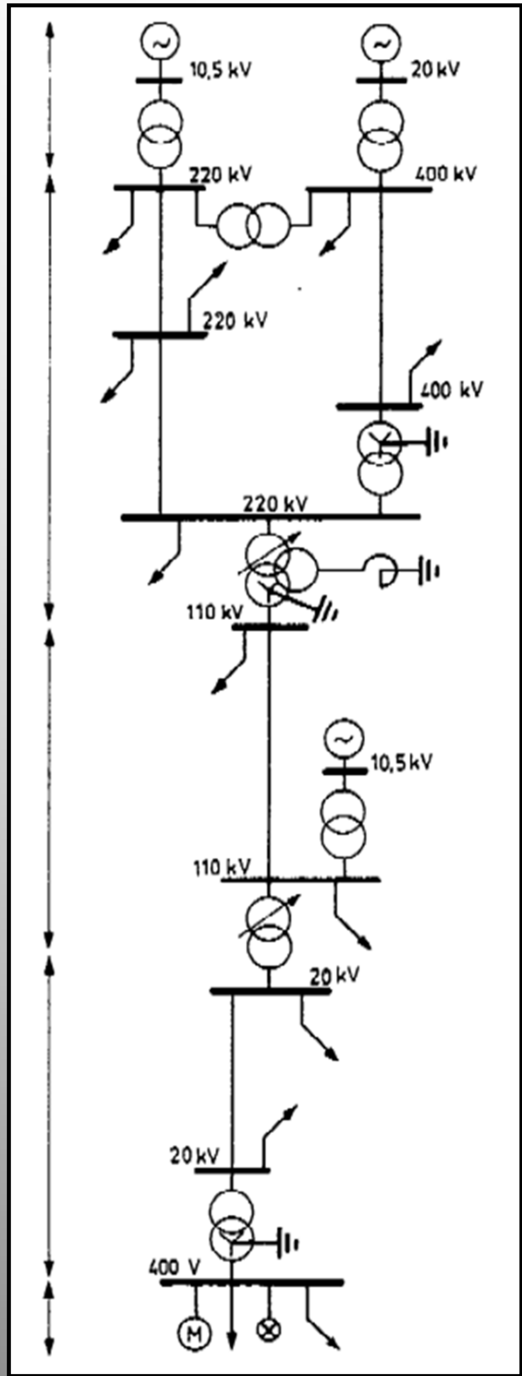
Power station
- generator (10,5 kV, 20 kV)
- generator transformer (20/400 kV)

Transmission system
- transformers (400/220 kV)
- 400, 220 (ja 110) kV lines
- switching station (220 kV)
- transformer station (400/220 kV)

Subtransmission system
- 110 kV lines
- primary substation (110/20 kV)

Medium voltage distribution
- 20 kV lines

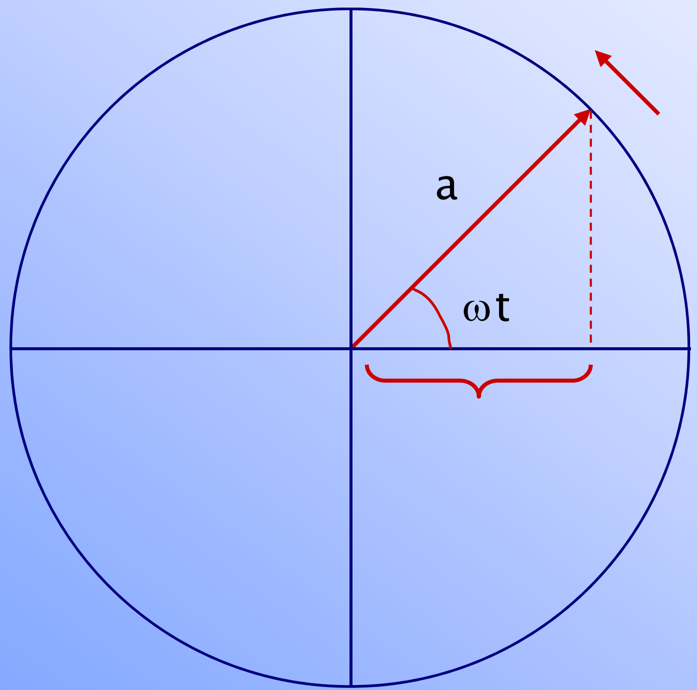
Low voltage distribution
- 0,4 kV lines and customers



Nordic transmission system

Nordel

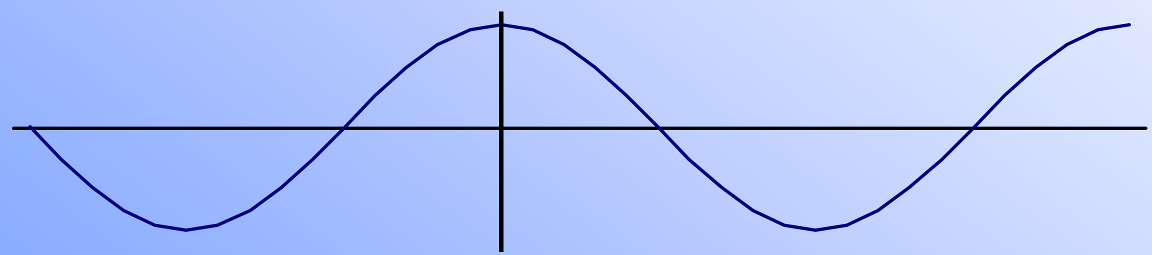
Alternating current & phasors



$u(t) = a \cos \omega t$

ω = angular freq = $2\pi f$

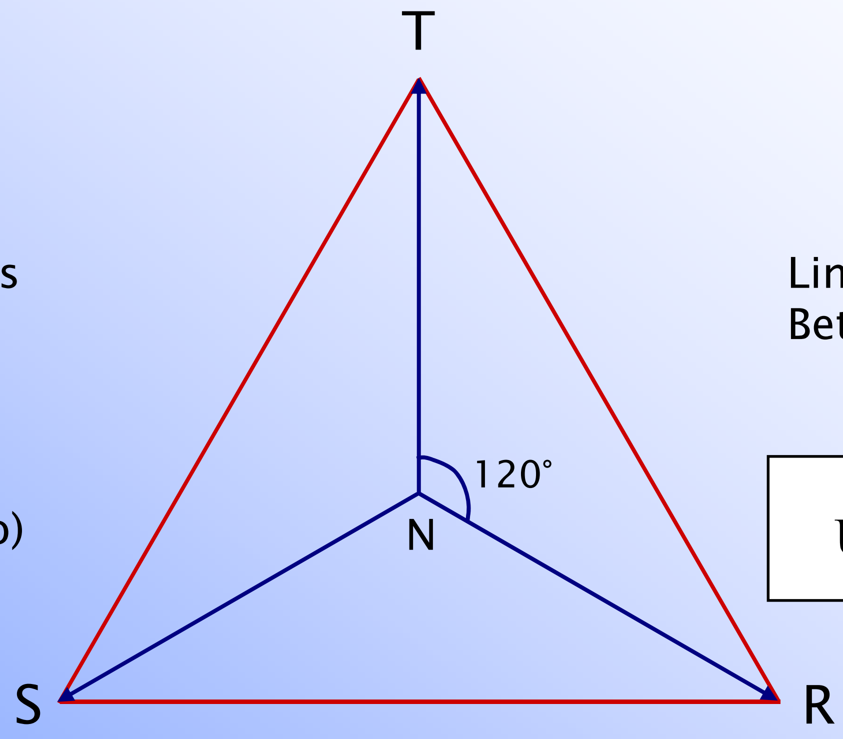
Rms value $U = \dfrac{a}{\sqrt{2}}$



3-phase system

Phase voltage is
Between phase
And neutral N

Neutral is in
Ground (= zero)
potential



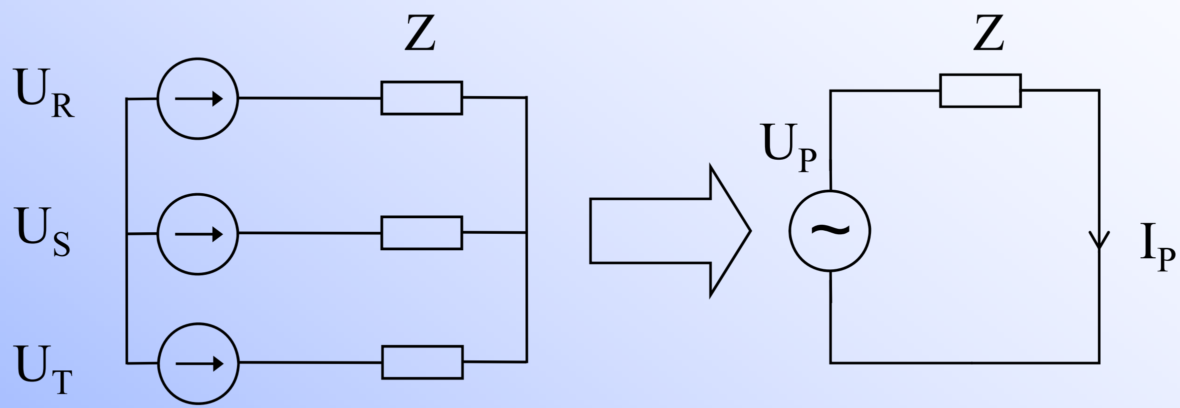
Line voltage is
Between phases

$$U_L = \sqrt{3}\ U_P$$

Phase voltage U_P U_R U_S U_T

Line voltage U_L U_{RS} U_{ST} U_{TR}

Single line diagram of a 3-ph system



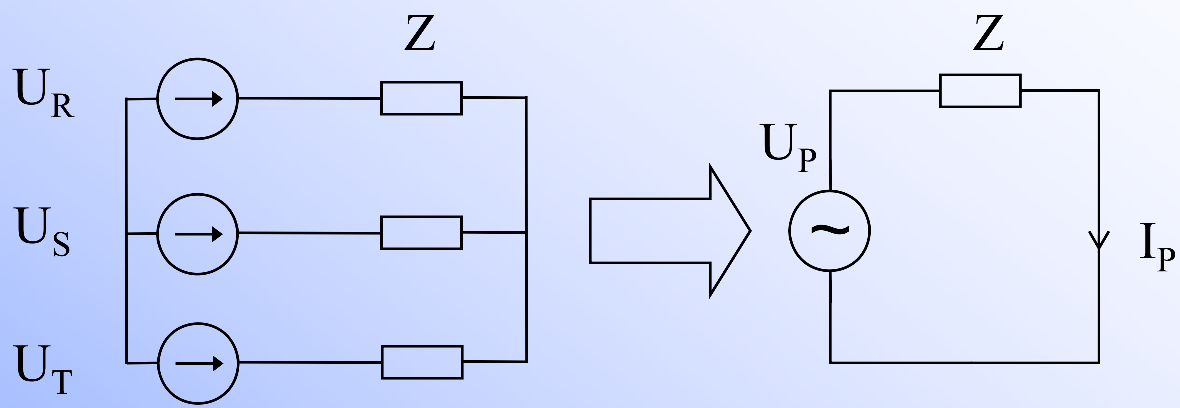
In a three phase system, phase quatities Up and Ip cancel when summed

Hence the voltages and currents in neutrals behind the load and source are zero

A single line diagram of a three phase system is made by connecting neutrals

Hence only one phase is analysed, and the other two exhibit similar behavior

Powers & single line diagram of a 3-ph system



Power: $S = 3\,U_P\,I_P = \sqrt{3}\;U_L\,I_P$

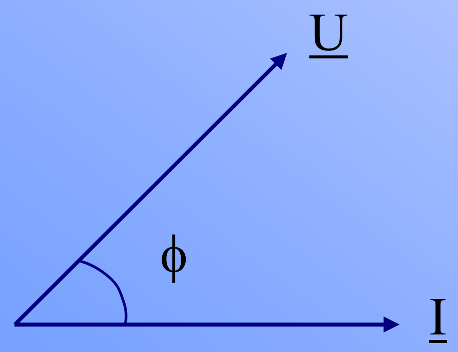
Impedance Z :

$$Z = \frac{U_P}{I_P} = U_P \cdot \frac{3\,U_P}{S}$$

$$= \frac{3\,U_P^2}{S} = \frac{U_L^2}{S}$$

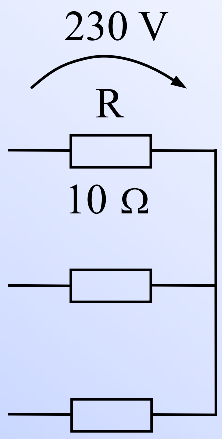
Powers in a 3-ph system

$$S = 3\,U_P\,I = \sqrt{3}\,U_L\,I$$
$$P = S\cos\phi$$
$$Q = S\sin\phi$$
$$S = \sqrt{P^2 + Q^2}$$
$$\underline{S} = P + jQ$$



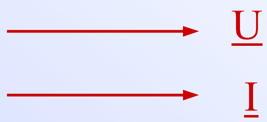
P/S = cosϕ is power factor

a)



Resistance R

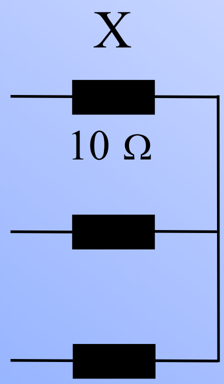
$$U = RI \Rightarrow I = 23\text{ A}$$



$\phi = 0°$

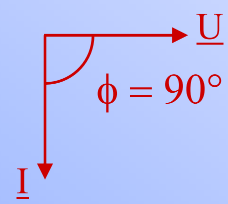
$$P = 3U_pI\cos\phi$$
$$= 3\cdot 230\cdot\cos 0°\cdot 23\text{W} = 15{,}9\text{kW}$$
$$Q = 3U_pI\sin\phi = 0$$

b)



Reactance $\underline{X} = j\omega L$

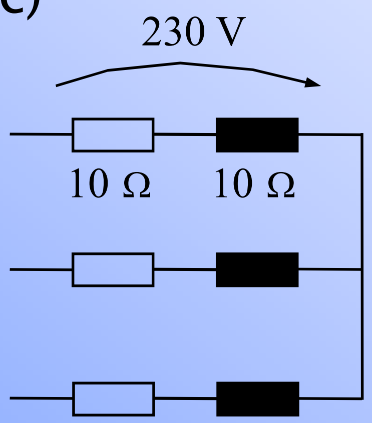
$I = 23$ A $\quad (\underline{U} = \underline{XI})$



$$P = 3U_pI\cos 90^0 = 0$$
$$Q = 3U_pI\sin 90^0 = 3*230*23\text{ var} = 15{,}9\text{ kVAr}$$

Powers in a 3-ph system (continued)

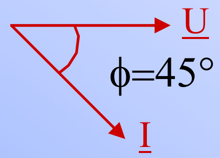
c)



$$\underline{Z} = R + jX = 10 + j10 = 14{,}1\angle 45°$$

$$\underline{U} = \underline{Z}\underline{I} \Rightarrow \underline{I} = \frac{\underline{U}}{\underline{Z}} = \frac{230\angle 0°}{14{,}1\angle 45°}$$

$$= 16{,}26\angle -45° A$$



$$P = 3\,U_p I \cos\phi = 3 \cdot 230 \cdot 16{,}26 \cdot \cos 45° = 7{,}9\text{ kW}$$

$$Q = 3\,U_p I \sin\phi = 3 \cdot 230 \cdot 16{,}26 \cdot \sin 45° = 7{,}9\text{ kVAr}$$

$$S = 3\,U_p I = 3 \cdot 230 \cdot 16{,}26 = 11{,}2\text{ kVA}$$

$$S = \sqrt{P^2 + Q^2} = 11{,}2\text{ kVA}$$

Another way

$$S = 3\,U_P I_P^* = 3\,U_P\angle 0° \cdot I_P\angle 45° = 3\,U_P I_P\angle 45°$$

$$= 3 \cdot 230 \cdot 16{,}26\angle 45°\text{ VA} = 11{,}2\angle 45°\text{ kVA}$$

$$= 7{,}9 + j7{,}9\text{ kVA}$$

$$\begin{cases} \underline{U} = U\angle 0° \\ \underline{I} = I\angle -\phi \\ \underline{I}^* = I\angle\phi \end{cases}$$

Computation usually using line voltages

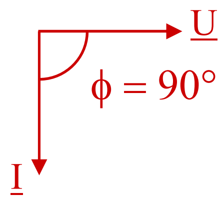
$$\Rightarrow S = 3\,U_P I_P^*$$

$$S = \sqrt{3}\,U_L I_P^*$$

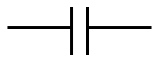
Reactance (ind)

L

$$\underline{X} = j\omega L$$

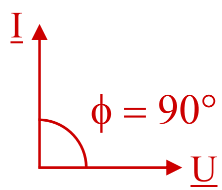


Capacitance



C

$$\underline{X} = \frac{1}{j\omega C} = -j\frac{1}{\omega C}$$



EXAMPLE: RESISTIVE-INDUCTIVE LOAD

In a 0.4 kV three phase system there is a load, which takes 10 A with power factor cosϕ = 0.9. Calculate real power P, reactive power Q and apparent power S.

U_L=400 V ⇔ $U_P = \frac{400}{\sqrt{3}} V = 230\, V$

Power per phase: P=$U_P I_P$ cosϕ= 230 * 10 * 0.9 W = 2070 W = 2.07 kW

Three phase power: P = 3 $U_P I_P$ cosϕ = 6.2 kW

Using line voltages

$P = \sqrt{3}\, U_L I_P \cos \emptyset = \sqrt{3} * 400 * 10 * 0.9$ W = 6.2 kW

Three phase reactive power: P = 3 $U_P I_P$ sinϕ = 3 kvar (ϕ = 26 deg)

Using line voltages

$Q = \sqrt{3}\, U_L I_P \sin \emptyset = \sqrt{3} * 400 * 10 * 0.44$ var = 3 kvar

Example (continued)

In a 0.4 kV three phase system there is a load, which takes 10 A with power factor $\cos\phi = 0.9$. Calculate real power P, reactive power Q and apparent power S.

$$P = \sqrt{3}\, U_L I_P \cos\emptyset = \sqrt{3} * 400 * 10 * 0.9 \text{ W} = 6.2 \text{ kW}$$

$$Q = \sqrt{3}\, U_L I_P \sin\emptyset = \sqrt{3} * 400 * 10 * 0.44 \text{ var} = 3 \text{ kvar}$$

Apparent power S:

$$S = P + jQ = 6.2 + j3\ kVA$$

$$S = \sqrt{P^2 + Q^2} = 6.9\ kVA$$

$$S = \sqrt{3}\, U_L I_P = \sqrt{3} * 400 * 10\ VA = 6.9\ kVA$$

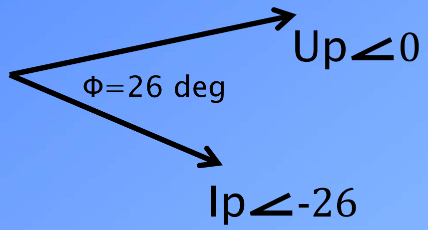
Example (continued)

In a 0.4 kV three phase system there is a load, which takes 10 A with power factor cosϕ = 0.9. Calculate real power P, reactive power Q and apparent power S.

$$P = \sqrt{3}\, U_L I_P \cos\emptyset = \sqrt{3} * 400 * 10 * 0.9 \text{ W} = 6.2 \text{ kW}$$

$$Q = \sqrt{3}\, U_L I_P \sin\emptyset = \sqrt{3} * 400 * 10 * 0.44 \text{ var} = 3 \text{ kvar}$$

Apparent power S:



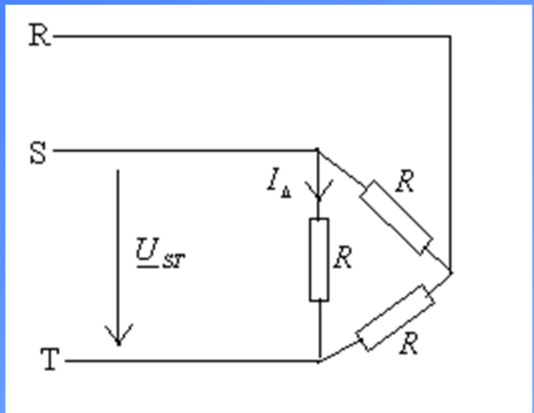
$$S = 3\ U_P\, {I_P}^* = 3 * 230 \angle 0^0 * 10\angle 26^0\ VA = 6.9\angle 26^0\ kVA$$

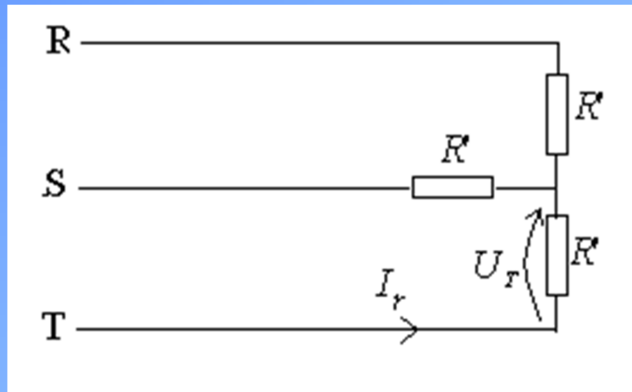
$$S = \sqrt{3}\ U_L\, {I_P}^* = \sqrt{3} * 400 \angle 0^0 * 10\angle 26^0\ VA = 6.9\angle 26^0\ kVA$$

$$S = 6.9\angle 26^0\ kVA = 6.9\cos 26^0\ kW + j6.9 sin 26^0\ kvar = 6.2kW + j3kvar$$

DELTA AND STAR CONNECTIONS

In 3-phase system loads and equipment (like generator or transformer windings) can be connected either in delta (between phases) or star (between phase and neutral)





Power in delta and star connection

Let consider a set of three 10 Ω resistors connected in star or delta in low voltage network.

In star connection, the voltage of resistors is 230 V ⇔ I = U/R = 23A

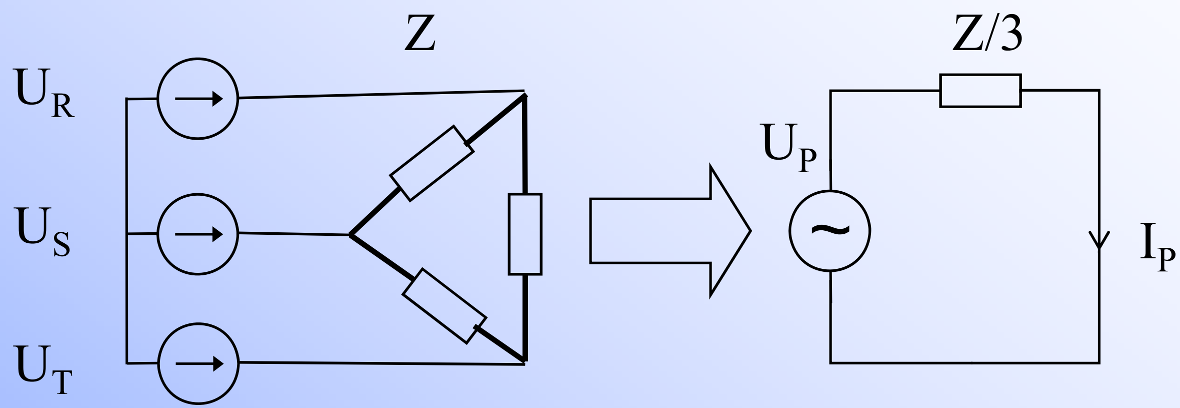
Three phase power P = 3UI = 3*230*23 W = 16 kW

In delta connection, the voltage of resistors is 400 V ⇔ I = U/R = 40A

Three phase power P = 3UI = 3*400*40 W = 48 kW

In delta-connection both the current and the voltage is $\sqrt{3}$- fold, and hence the power will be 3-fold compared to star connection.

Delta-Star transformation in a 3-ph system



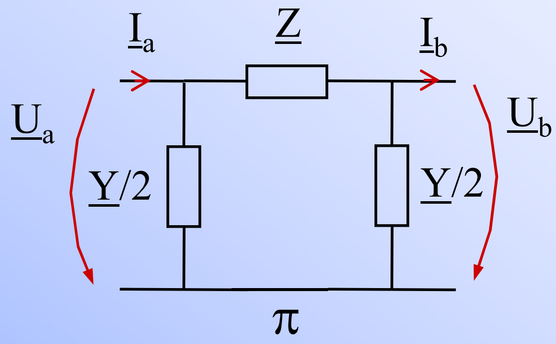
In three phase systems, the analytical solutions are made using single line diagrams where impedances are between phase and neutral, i.e. in star

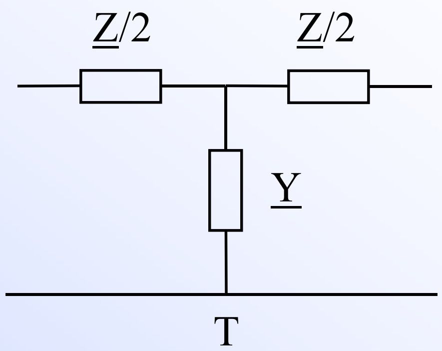
Hence, the delta connection must be transformed to star.

This is done by dividing the impedances by three.

(proof: the powers are the same in both cases)

Lines





$$\underline{Z} = (r + j\omega l)\, s$$

$$\underline{Y} = (g + j\omega c)\, s$$

- s = length
- r = resistance / s
- l = inductance / s
- g = conductance / s
- c = capacitance / s

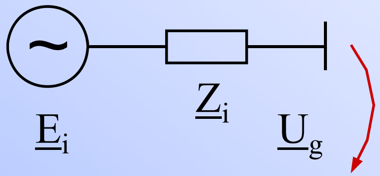
Long lines

$$\begin{bmatrix} \underline{U}_a \\ \underline{I}_a \end{bmatrix} = \begin{bmatrix} \cos \underline{\beta}\, s & j\underline{Z}_c \sin \underline{\beta}\, s \\ j\dfrac{1}{\underline{Z}_c} \sin \underline{\beta}\, s & \cos \underline{\beta}\, s \end{bmatrix} \begin{bmatrix} \underline{U}_b \\ \underline{I}_b \end{bmatrix}$$

$$\underline{\beta} = \sqrt{(r + j\omega l) \cdot (g + j\omega c)}$$

$$\underline{Z}_c = \sqrt{(r + j\omega l)/(g + j\omega c)}$$

Generators



$$\underline{Z}_i = R + jX_d$$

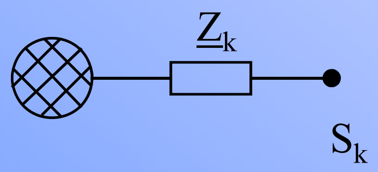
$$X_d = x_d \frac{U_N^2}{S_N}$$

$$x_d > x_d' > x_d''$$

synchronous, transient, subtransient reactance

Feeding transmission grid

S_k = short circuit power MVA

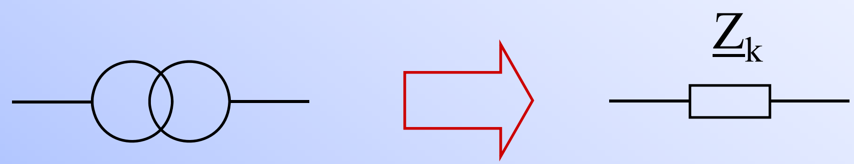


$$\underline{Z}_k \approx jX_k$$

$$X_k = \frac{U^2}{S_k}$$

U_N = rated voltage (kV)
S_N = rated power (MVA)
x_d = p.u. synchronous reactance

Transformer

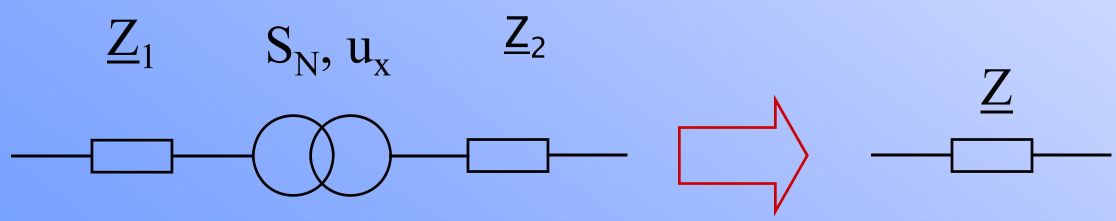


U_N = rated voltage (kV)
S_N = rated power (MVA)
u_x = p.u. short circuit reactance

$$\underline{Z}_k = R_k + jX_k$$

$$R_k = u_r \frac{U_N^2}{S_N}$$

$$X_k = u_x \frac{U_N^2}{S_N}$$

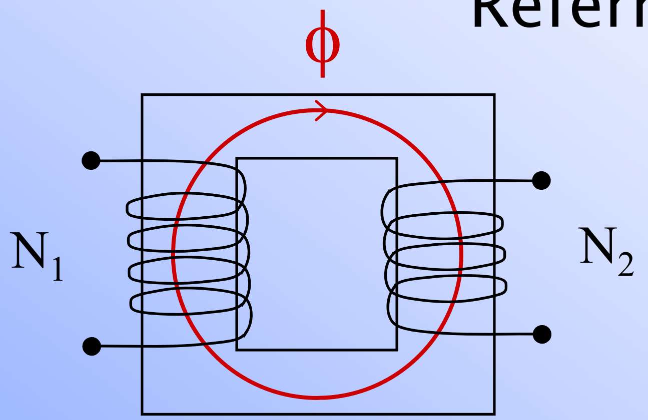


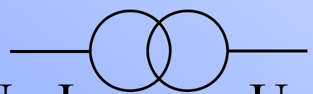
μ =transforming ratio

$$\mu = \frac{U_{1n}}{U_{2n}}$$

$$\underline{Z} = \underline{Z}_1 + ju_x \frac{U_{1n}^2}{S_N} + \mu^2 \cdot \underline{Z}_2$$

Referring over a transformer





Voltage over a turn is constant

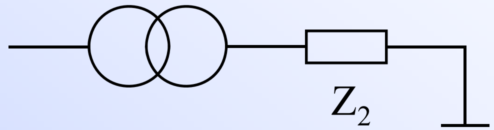
$$\frac{U_1}{U_2} = \frac{N_1}{N_2}$$

Power is constant

$$S = \sqrt{3}\, U_2 I_2 = \sqrt{3}\, U_1 I_1$$

$$\Rightarrow \frac{I_1}{I_2} = \frac{U_2}{U_1} = \frac{N_2}{N_1}$$

Secondary impedance Z_2 referred to primary ?



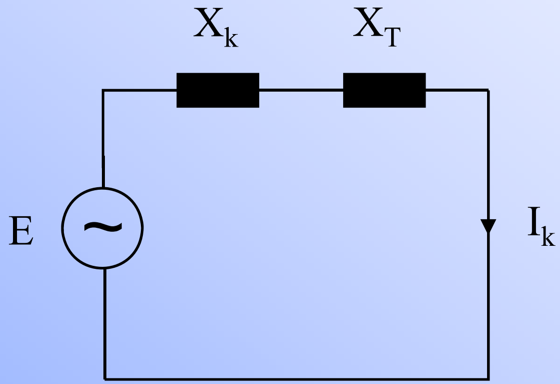
in secondary $Z_2 = \frac{U_2}{I_2}$

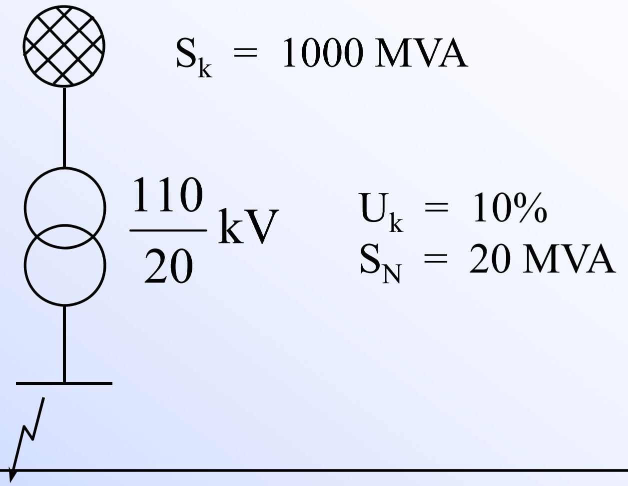
in primary $Z_2' = \frac{U_1}{I_1} = \frac{U_2 \cdot \frac{N_1}{N_2}}{I_2 \cdot \frac{N_2}{N_1}} = \left(\frac{N_1}{N_2}\right)^2 \cdot Z_2$

usually we write $\frac{N_1}{N_2} = \frac{U_{1n}}{U_{2n}}$

Referring over a transformer

An example





$$X_k = \frac{U_1^{\,2}}{S_k} = \frac{110^2}{1000} = 12{,}1\,\Omega \qquad (110\,\text{kV})$$

$$X_T = u_k \frac{U_2^{\,2}}{S_N} = 0{,}1 \cdot \frac{20^2}{20} = 2\,\Omega \qquad (20\,\text{kV})$$

20 kV level $\quad E = \frac{U_2}{\sqrt{3}}$

$$I_{k_2} = \frac{U_2}{\sqrt{3}\left(X_k{}' + X_T\right)} = \frac{20\,\text{kV}}{\sqrt{3}\left(\left(\frac{20}{110}\right)^2 \cdot 12{,}1 + 2\right)\Omega} = \underline{\underline{4{,}81\,\text{kA}}}$$

110 kV level $\quad E = \frac{U_1}{\sqrt{3}}$

$$I_{k_1} = \frac{U_1}{\sqrt{3}\left(X_k + X_T{}'\right)} = \frac{110\,\text{kV}}{\sqrt{3}\left(12{,}1 + \left(\frac{110}{20}\right)^2 \cdot 2\right)\Omega} = \underline{\underline{0{,}875\,\text{kA}}}$$

check :

$$I_{k_1} = \frac{U_{2n}}{U_{1n}} I_{k_2} = \frac{20}{110} \cdot 4{,}81\,\text{kA} = 0{,}875\,\text{kA}$$

Referring and p.u. values

1. Referring over a transformer (from U_1 to U_2)

$$U_1' = (U_{2n}/U_{1n}) \cdot U_1$$
$$I_1' = (U_{1n}/U_{2n}) \cdot I_1$$
$$Z_1' = (U_{2n}/U_{1n})^2 \cdot Z_1$$

Referring is easy when only two voltage levels

2. In case of several voltage levels p.u. computation

Select for the base values some base power S_b and voltage of one selected voltage level U_b

⇨ Other base voltages by transforming ratios:

$$U_{2b} = (U_{2n}/U_{1n}) \cdot U_{1b}$$

⇨ Current base value by base power and base voltage:

$$I_b = S_b / \sqrt{3}\, U_b$$

⇨ Impedance base value by base power and base voltage:

$$Z_b = U_b^{\,2} / S_b$$

3-ph power as a p.u. value using the equation $\underline{s} = \underline{u}\underline{i}^*$
Other computation as with single line diagram

Calculations using p.u. values

The actual U(kV), I(A), Z(Ω), S (MVA), P(MW), Q(Mvar) values are first scaled by corresponding base values of the voltage level in question

$$u = U/U_b \qquad i = I / I_b \qquad z = Z/Z_b \qquad s = S / S_b$$

As the result we have per unit (p.u.) values. Now all the different voltage Levels have been transformed to the same general domain and no any Referring over transformers is needed any more.

The calculations are done with single line diagram. For 3ph powers $\underline{s} = \underline{ui}^*$

Once the calculations are done, we have the results in the form of Dimensionless p.u. values.

Finally the results are transformed back to actual physical values by Multiplying the p.u. values by the base values of the concerned voltage level.

$$U = uU_b \qquad I = iI_b \qquad Z = zZ_b \qquad S = sS_b$$