ELEC-E8432 An Introduction to Hydrogen Economy

Lecture 1

Power System and power transmission

Matti Lehtonen

Power system

- Power system consists of electrical networks, which connect generating units and loads, or load centers
- Because of economy of scale, power has been produced in large units
- Another reason is that often generation locations are centers are from
- To enable long distance transmission, high voltages are required. Power=Voltage*Current. Current magnitude defines conductor size. To keep current in reasonable limits, high voltage is thus needed.
- Another reason is voltage drop in the line. This is measured in volts
- Power systems have several voltage levels connected by transformers:
- Transmission network (400 kV in Finland) several 1000´s of km
- Subtransmission 110 kV feeding load centers and big industry
- Distribution networks: Medium voltage 20 kV and low voltage 0.4 kV

Transmission And Distribution Networks

Power generating stations
- generator (10,5 kV, 20 kV)
- Step-up transformer (20/400 kV)

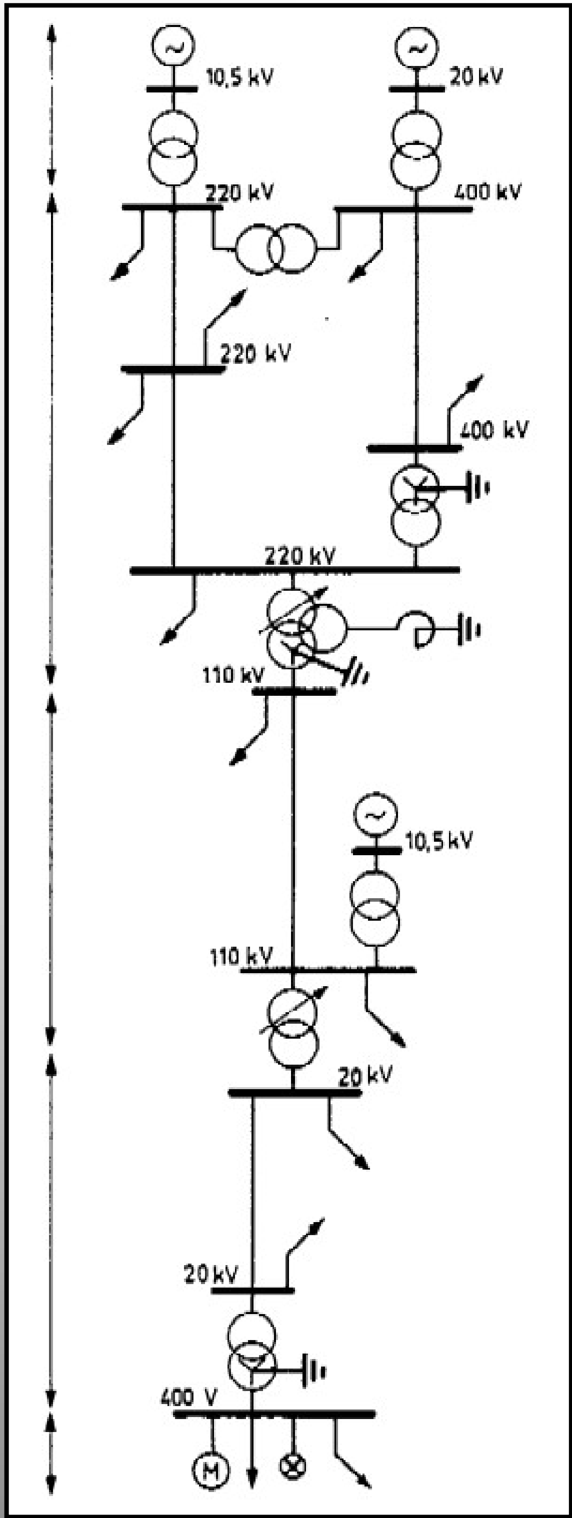
Transmission system
- transformers (400/220 kV)
- 400 and 220 kV lines
- Switching stations (400, 220 kV)

High voltage distribution system

- 110 kV lines
- Transformer stations (110/20 kV)
- Industrial loads

Medium voltage distribution system
- 20 kV lines
- 20/0.4 kV secondary substations
- Large customer connections

Low voltage network
- 0,4 kV lines and customer connections



Integration of power systems

- To enable cost efficient power systems, the transmission networks are connected between countries, here the power can be produced at the cheapest location at the moment
- Another reason is the reserve generation capacity, which can be shared between neighboring countries
- A bigger system also enables larger generation units to be connected in the systems. A good example is large nuclear power plants.
- An example of the system interconnection is the Nordic power system presented in the next slide.

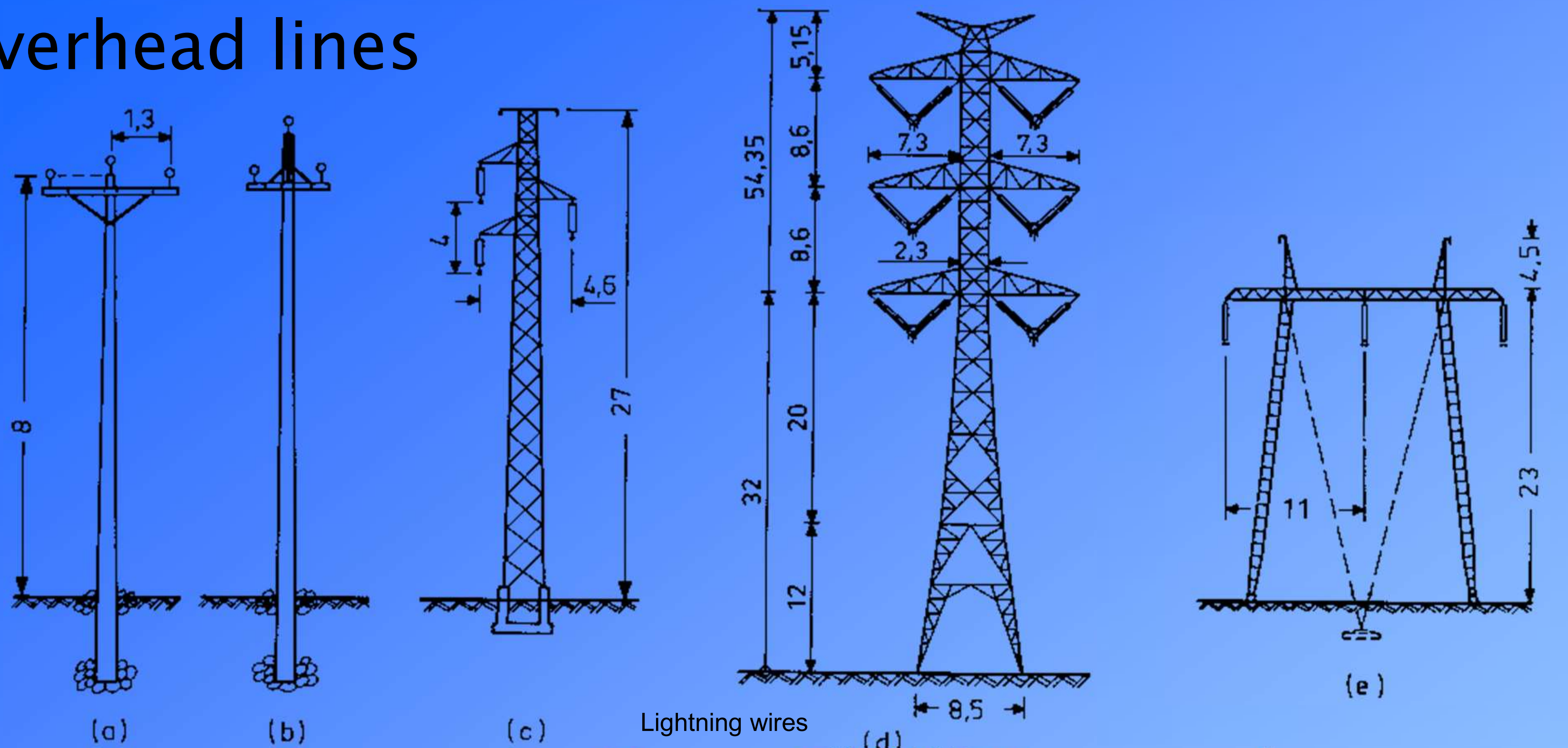
NORDIC TRANSMISSION SYSTEM

Nordel

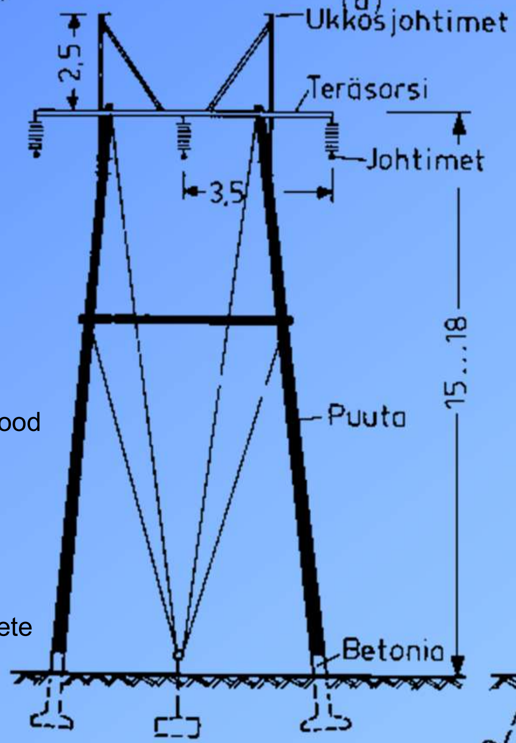
OVERHEAD LINES

- Let us next consider the overhead lines used in transmission networks and in medium voltage distribution systems.
- These lines have bare conductors, thus there is no insulation covering the conductors
- The conductors are attached to the power line towers of poles by insulators.
- At higher voltage levels these insulators are of suspension type. They are composed of a string of insulator discs connected in series.

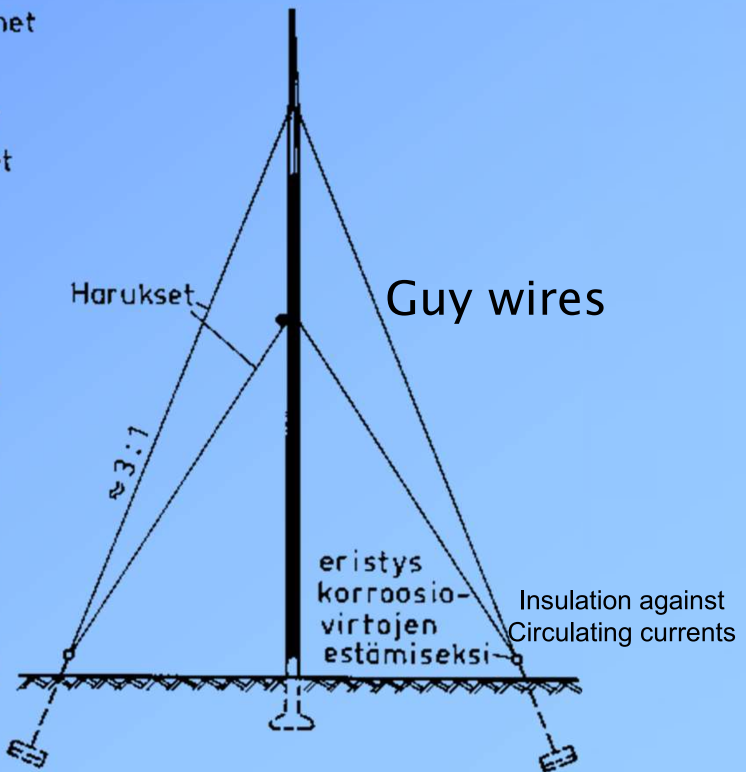
Overhead lines

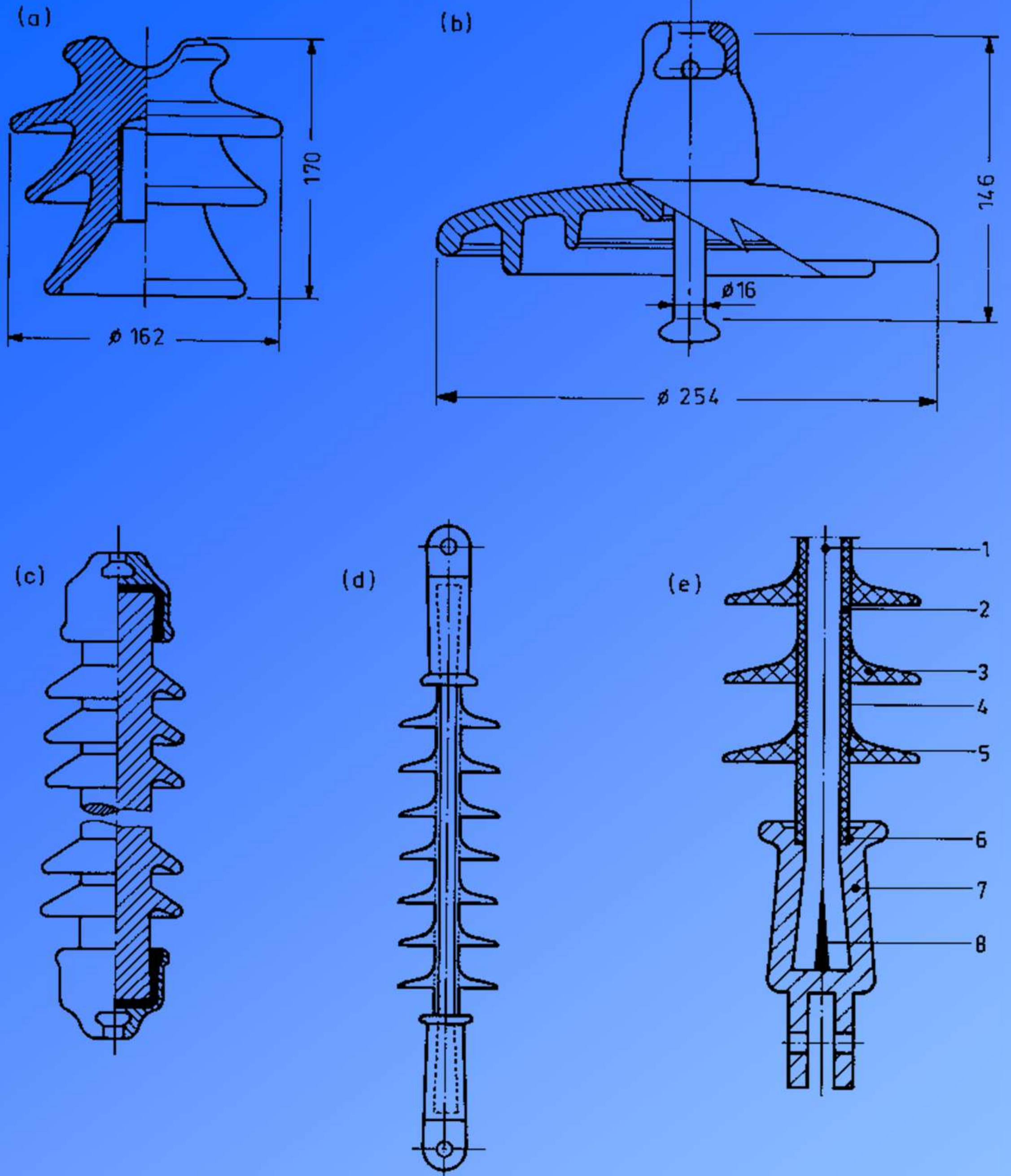


a) ja b) 20 kV wood poles
c) Free standing 110 kV steel tower, I–strings
d) Free standing 440 kV steel tower, V–strings
e) 400 kV steel tower with guy wires

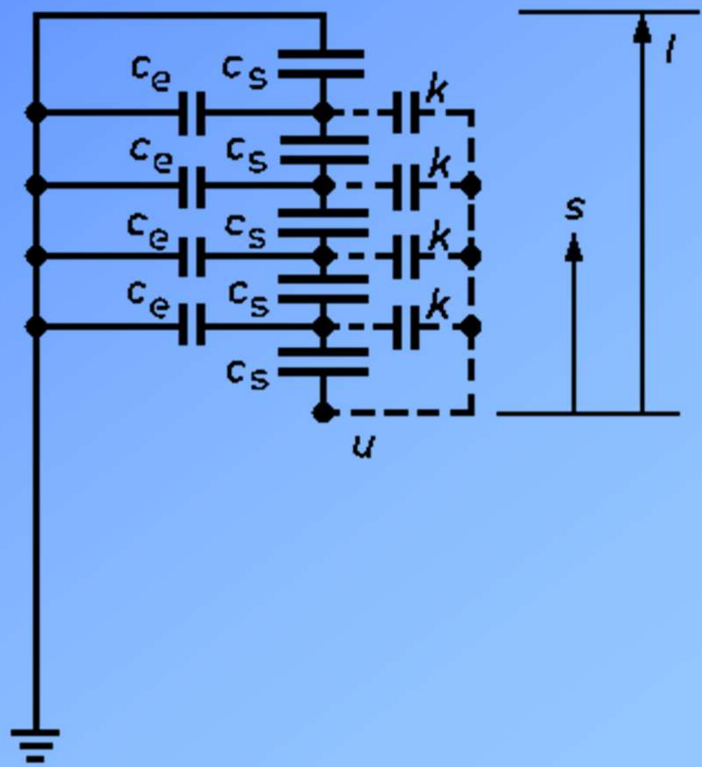


110 kV wood pole with guy wires

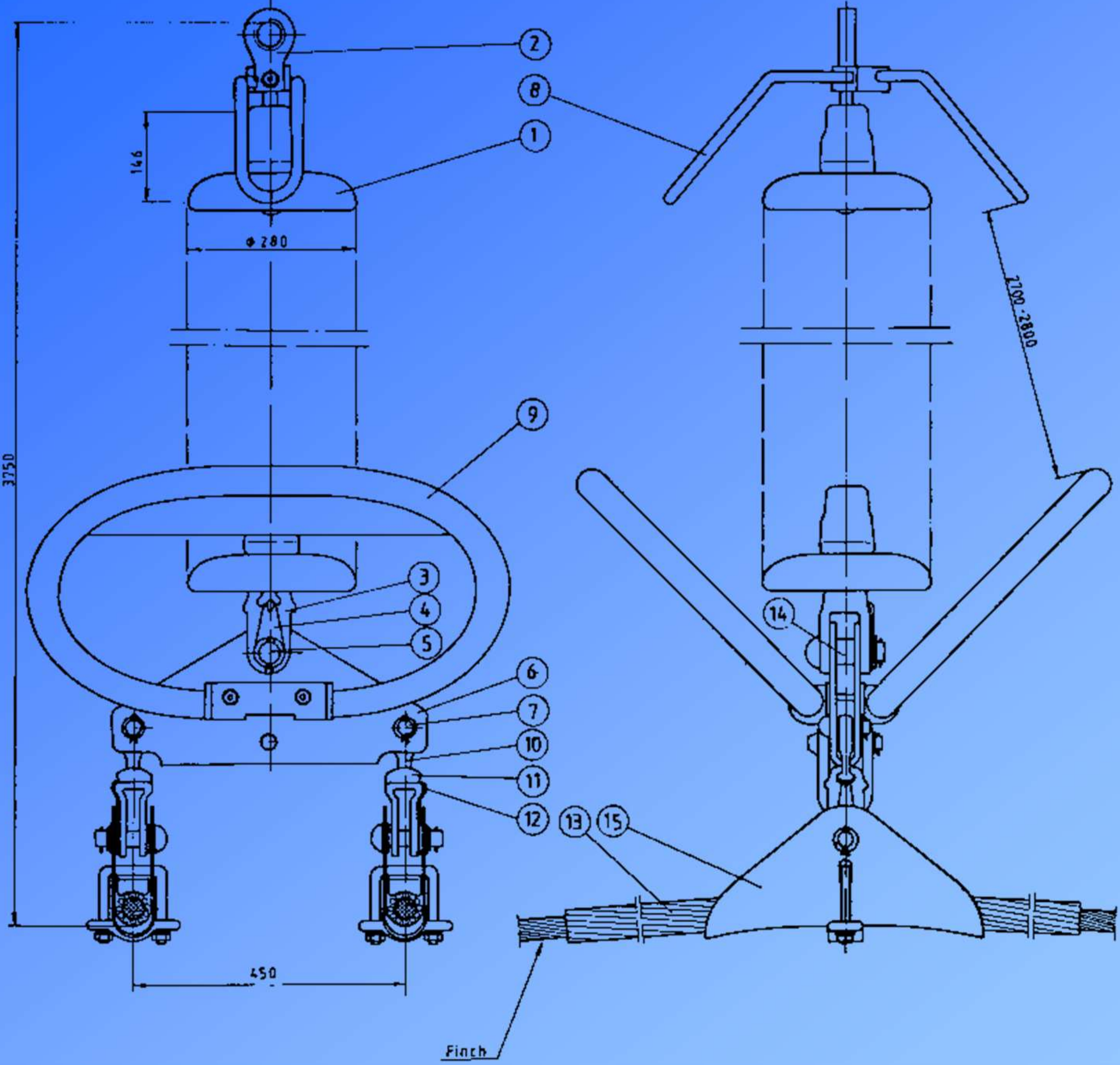




Capacitances of insulator string



OH-line insulators. a) pin insulator, b) disc insulator, c) long rod type d) multi-material type, e) and the cross-section: 1 fiber glass rod, 2 silicon plating, 3 silicon discs, 4, 5, 6 junctions, 7 terminal piece, 8 filling piece.



400 kV insulator string and its accessories: 1 insulator, 8 upper protective horn, 9 lower protective horn, 13 protective layer, 15 conductor support

High Voltage Overhead Lines

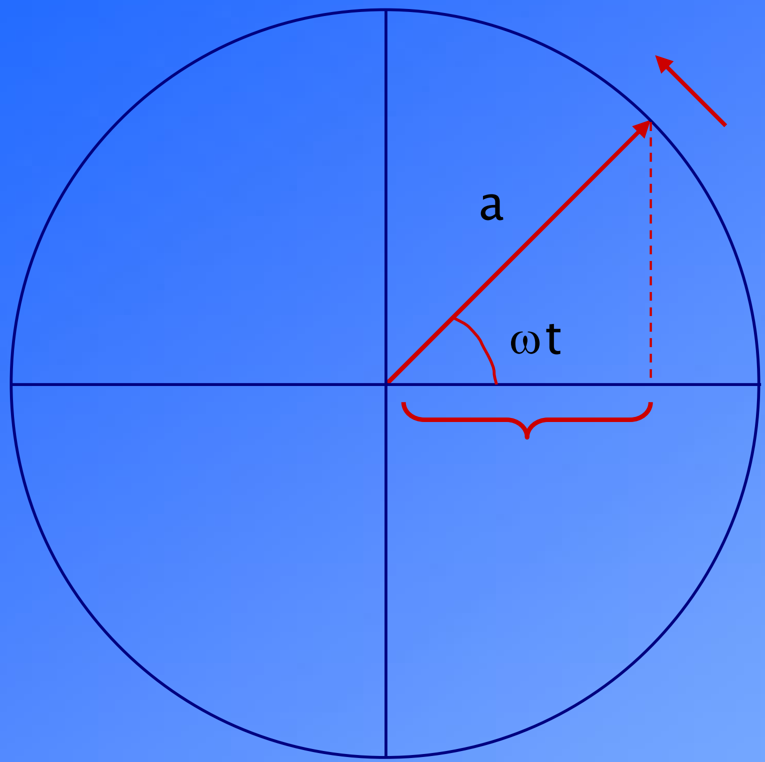
In Finland towers with guy wires in sparsely populated areas
And free standing towers in city areas. Oldest lines are built
In 1920s.

110 kV – 400 kV lines are used
in Fingrid transmission system.
Some 110 kV lines for local
HV distribution by areal
Distribution companies

3-phase system

- In alternating current (AC) system, the voltages and currents follow sinusoidal wave form
- The power system utilizes three-phase system, where the phase shift of the power cycle between phases is 120 degrees. This means that the sum of voltages and currents in the three phases is zero. The benefit of this arrangement is that no return wire is needed for the load currents.
- The nominal voltage of the system (400 kV, 110 kV, etc) is the voltage between phases – this is called line voltage
- Voltage between phase and neutral is 58% of line voltage
- In normal situation, the neutral is at zero potential

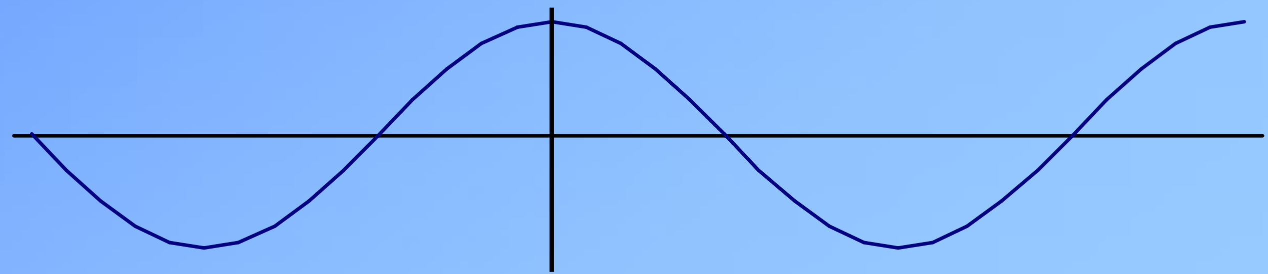
Alternating current & phasors



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

$$\omega = \text{angular freq} = 2\pi f$$

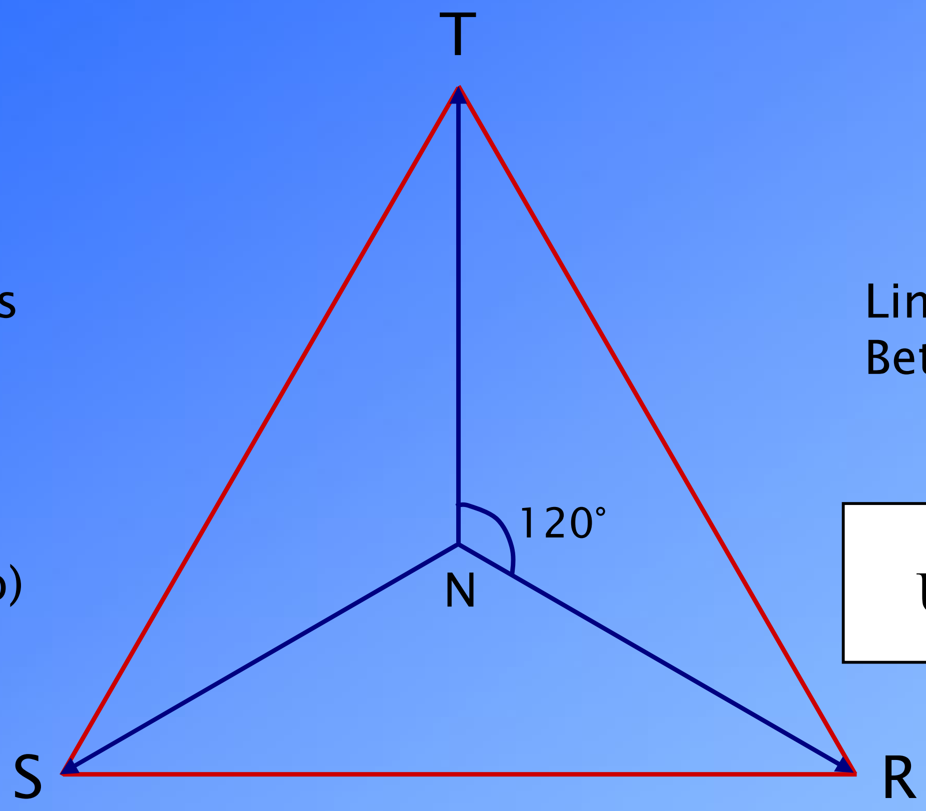
$$\text{Rms value } U = \frac{a}{\sqrt{2}}$$



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}

Powers in a 3-phase system

- The powers in AC network are divided in real power P, reactive power Q, and apparent power S
- Only real power P provides work or useful energy to the load. Q is oscillating between the source and load, and in average does not provide work when integrated over a power cycle. S is a square sum of P and Q and defines the dimensioning of power system for power flows.
- Loads use both P and Q. Q is needed by electrical motors to create magnetic field and enable their operation. P and Q depend on voltage, current and phase angle between them.
- Q is used by inductances L and can be produced by capacitances C. Thus, reactive power flows of Q can be compensated by capacitors.

Powers in a 3-ph system

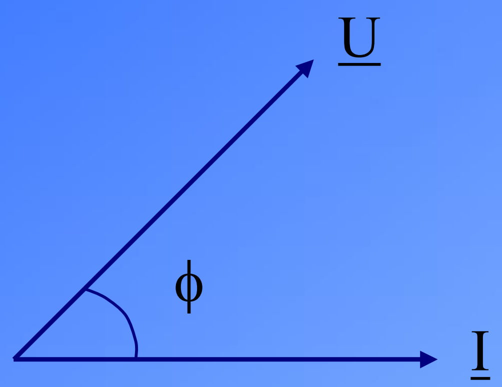
$$S = 3\,U_P\,I = \sqrt{3}\;U_L\,I$$

$$P = S\cos\phi$$

$$Q = S\sin\phi$$

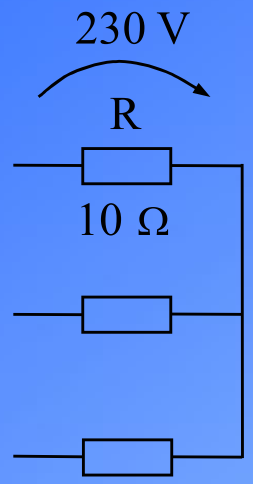
$$S = \sqrt{P^2 + Q^2}$$

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



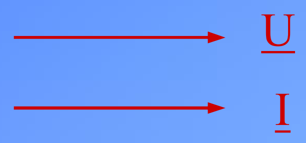
P/S = cosϕ is power factor

a)



Resistance R

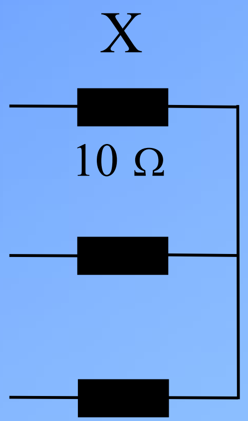
$$U = RI \Rightarrow I = 23\text{ A}$$



$\phi = 0°$

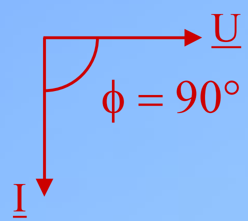
$$P = 3U_p I\cos\phi$$
$$= 3\cdot 230\cdot\cos 0°\cdot 23\text{W} = 15{,}9\text{kW}$$
$$Q = 3U_p I\sin\phi = 0$$

b)



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

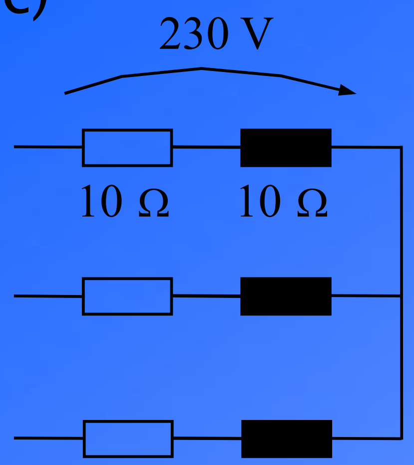
I = 23 A ($\underline{U} = \underline{X}\underline{I}$)



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

Powers in a 3-ph system (continued)

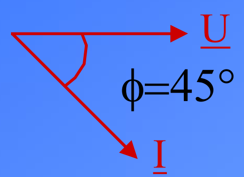
c)



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

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

$$= 16{,}26\angle -45^\circ A$$



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

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

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

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

Another way

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

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

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

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

Computation usually using line voltages

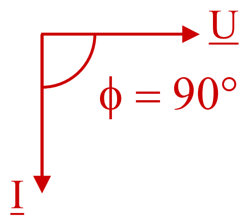
$$\Rightarrow S = 3\,U_P I_P^*$$

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

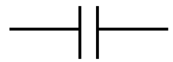
Reactance (ind)

L

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

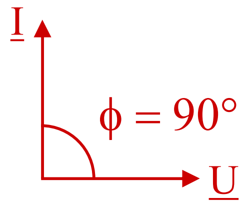


Capacitance



C

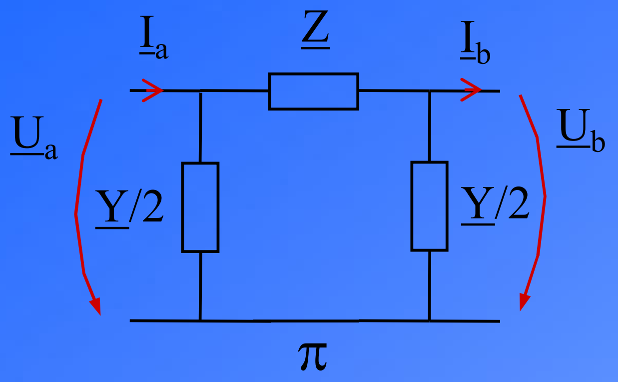
$$\underline{X} = \frac{1}{j\omega C} = -j\frac{1}{\omega C}$$

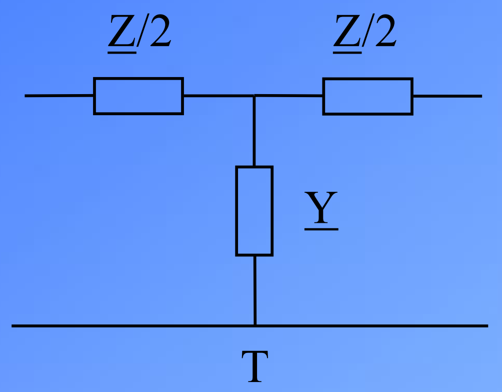


Modelling power lines

- Power lines have two series components, resistance R and reactance X, where X is the product of angular frequency $\omega = 2\pi f$ and inductance L (f is power system frequency)
- Series resistance R causes power losses when load current flows in the line. Series X consumes reactive power.
- Power lines have two shunt components between phase and neutral (earth): Conductance G caused by resistive leakage currents and capacitive admittance Y caused by capacitances. Resistive leakage currents are very small, but capacitive currents affect the reactive power balance of the network and must be taken into account for voltage control

Modelling lines





$\omega = 2\pi f$
f=50 Hz

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

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

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

Long lines

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

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

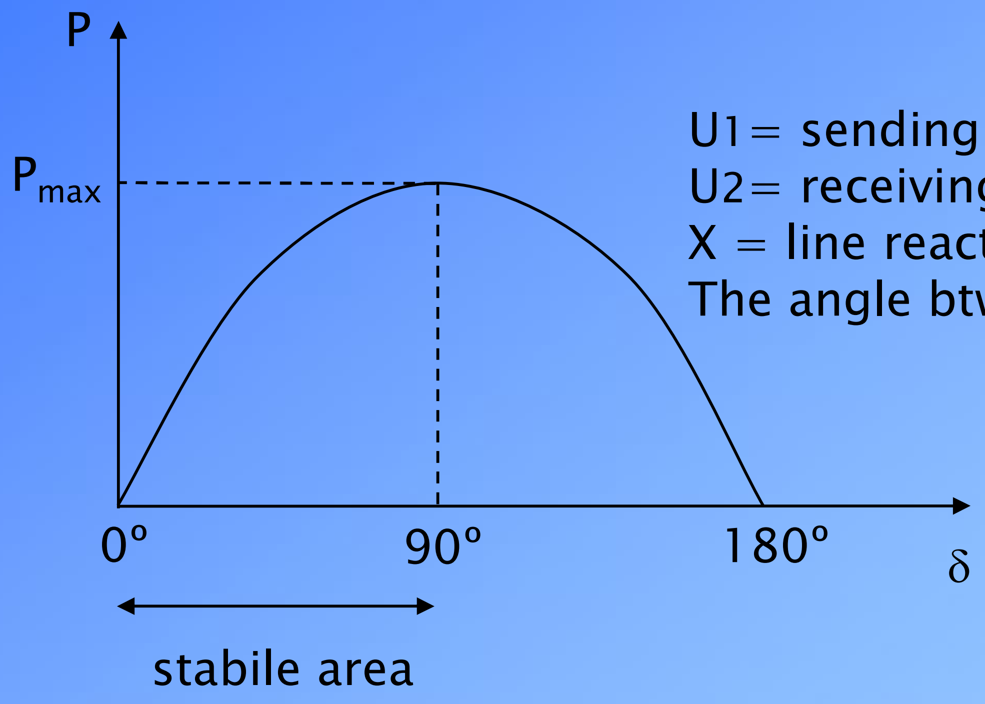
$$\underline{Z}_c = \sqrt{(r + j\omega l)/(g + j\omega c)}$$

Power transmission

- Power transmission capacity of a line can be modelled by power-angle equation (next slide). When phase angle between sending end voltage and receiving end voltage is increased, power transmission is also increased until 90 degrees, which gives the theoretical limit of maximum power transmission.
- In practice, some margin must be left for network disturbances. Hence the practical maximum of power-angle is about 45 degrees.
- The way to increase power transmission capacity is to increase U or decrease X (=line series reactance)

Power transmission – Power–Angle Equation

$$P = \frac{U_1\, U_2}{X} \sin\delta$$



U1 = sending end voltage
U2 = receiving end voltage
X = line reactance
The angle btw U1,U2 is δ

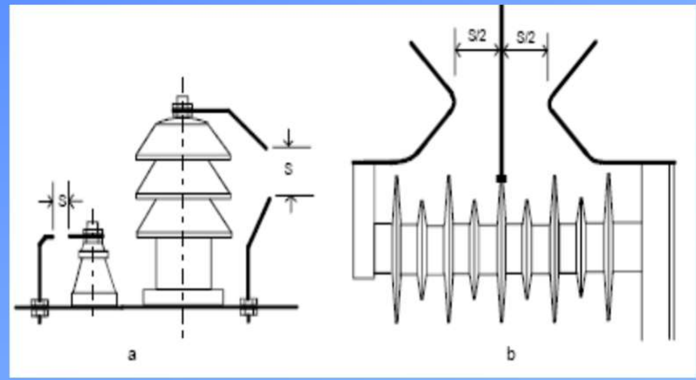
Limit power of static stability

Surge Arresters

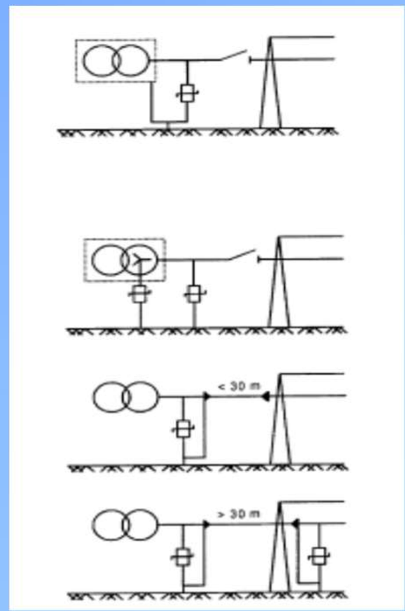
- Surge arresters SA are used to protect power system components against short time overvoltages
- The are used for fast overvoltage transients due to lightnings and switching actions
- In normal operation SA are isolators, but turn conducting when protective voltage level of component is exceeded
- There must be enough margin between insulation level of components and protective level of SA
- SA must be located close to the protected equipment, which usually is a transformer or a cable

Overvoltage protection

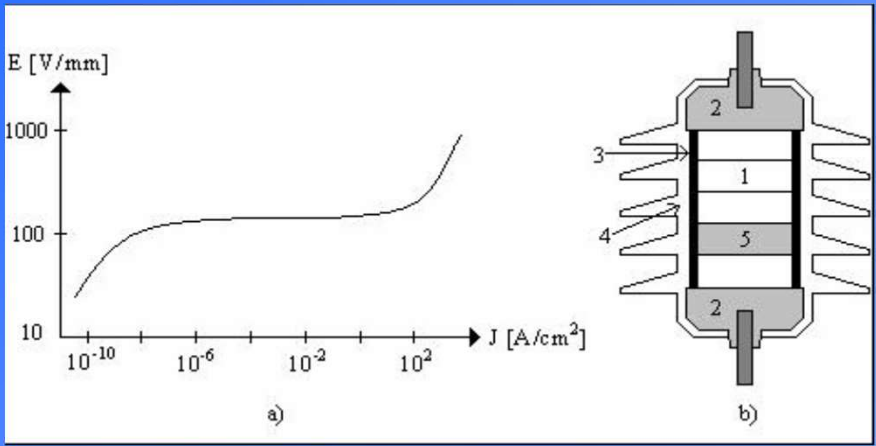
- **Surge Arresters and Spark Gaps**
  - Limit the overvoltages below the withstand level of insulation
  - Used at Trasformers and places where cables are connected to overhead lines
  - Must be located as close to the protected device as possible



a) Single gap, b) Double gap with bird spike



Surge Arresters

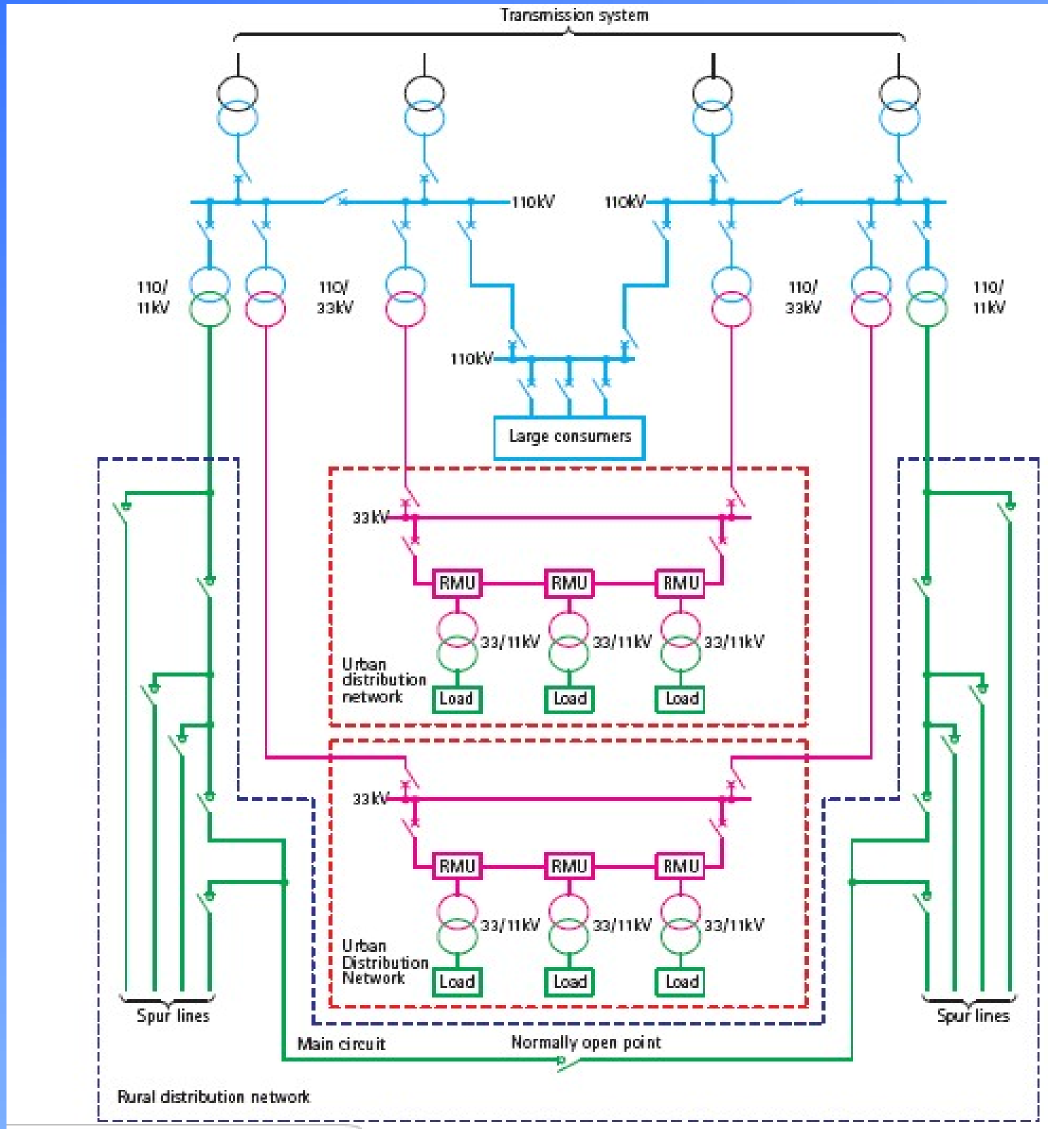


Voltage – current characteristics of ZnO (a) and construction (b). 1: ZnO element, 2: connecting electrodes, 3: supporting cylinder, 4: outer cover, 5: metallic spacer

HV and MV distribution networks

A network with both 110/33 kV urban system and 110/11 kV rural distribution.

In addition, own 110 kV lines for big industrial loads.



Transmission capacity of power lines

- Power angle limits the transmission capacity of long high voltage lines
- In case of short transmission lines or distribution networks, the capacity is limited by allowed maximum load current or maximum voltage drop caused by the load current in the line series impedance

POWER TRANSFORMERS

- Power transformers connect different voltage levels
- They are built around magnetic iron core, having separate windings for low voltage side and high voltage side.
- Interturn insulation is usual made by paper tape. Insulation between windings is based on mineral oil, which also works as coolant

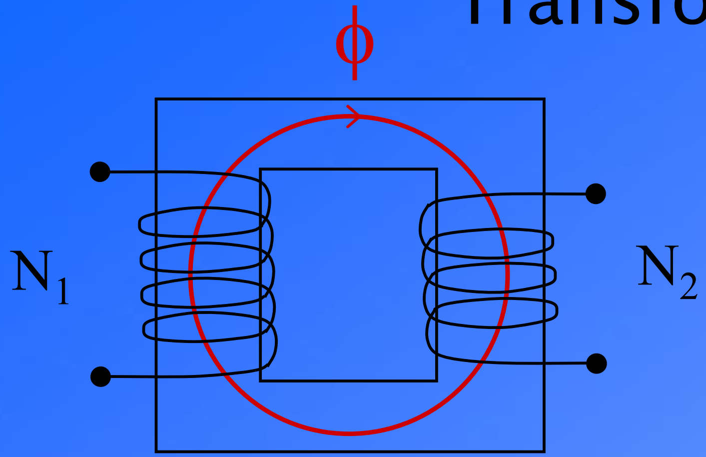
Power transformers

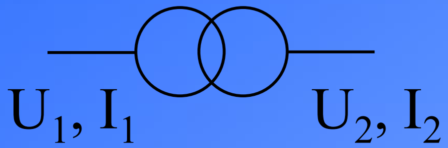
Transformer parts:

- bushings
- Radiators for cooling
- on-load tap-changer
- Oil expansion tank
- Control and supervision equipment

110 kV / 20 kV primary transformer

Transformer operation principle





Voltage per turn is constant

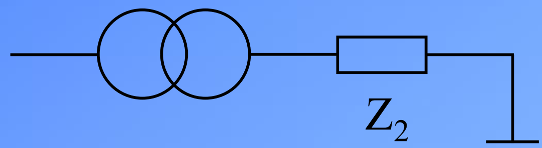
$$\frac{U_1}{U_2} = \frac{N_1}{N_2}$$

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 at primary side ?



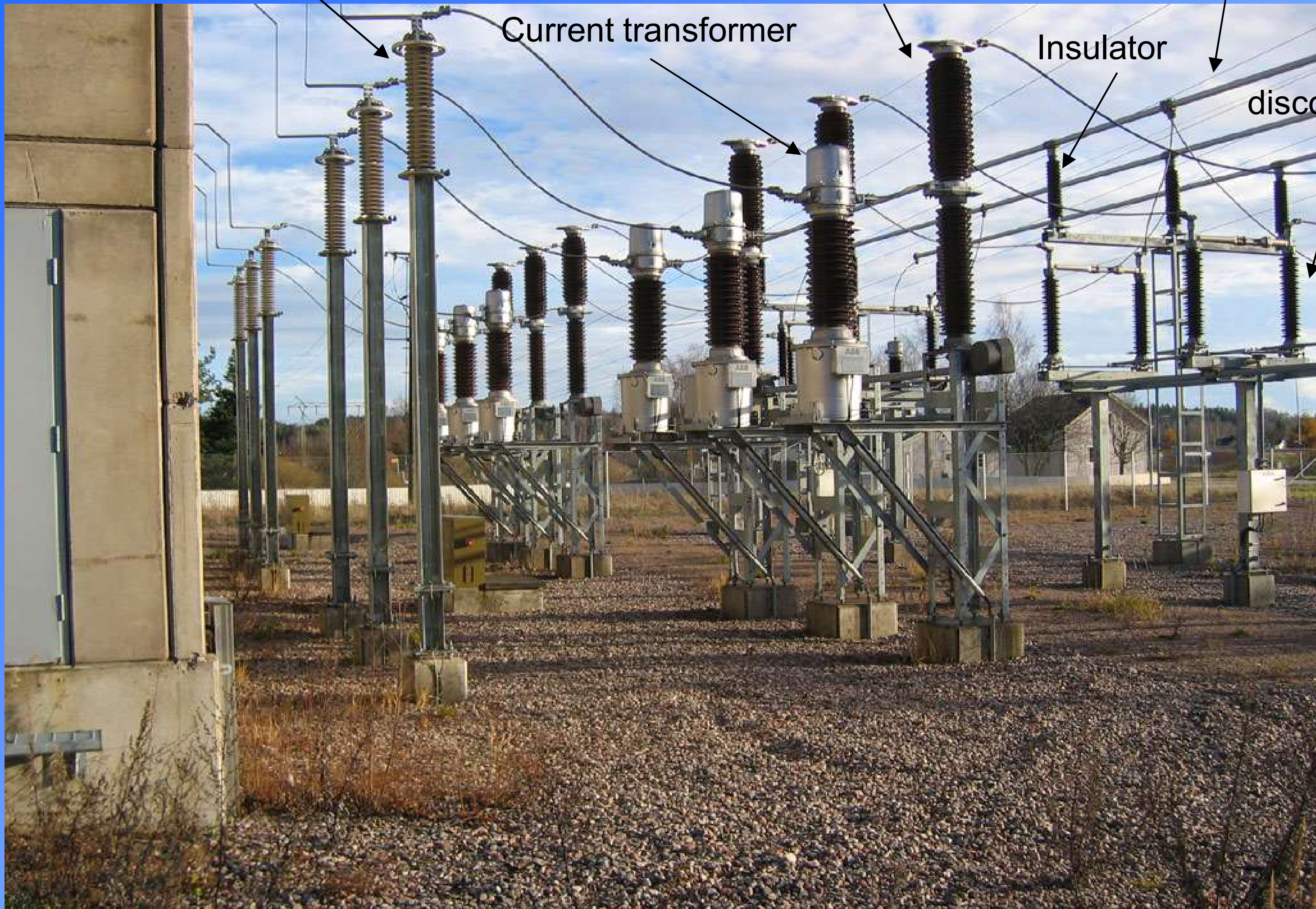
at secondary $Z_2 = \frac{U_2}{I_2}$

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

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

U=voltage, I=current,Z=impedance

Equipment at switching stations



Equipment at switching stations

Current transformers

Surge arresters

110kV circuit breaker

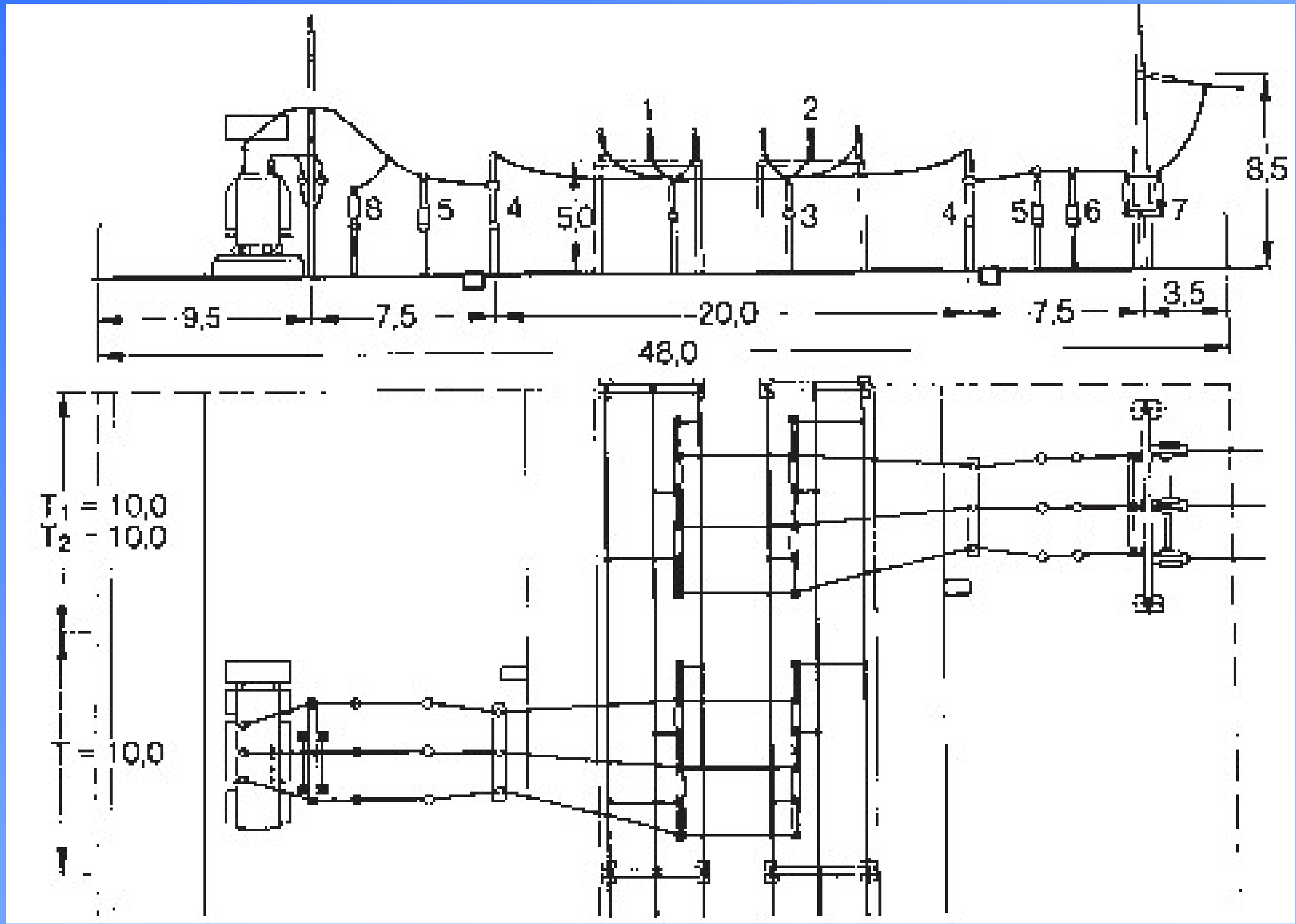
Transformer bushings

Equipment at switching stations

Switching station lay-out

123kV 2-busbar system

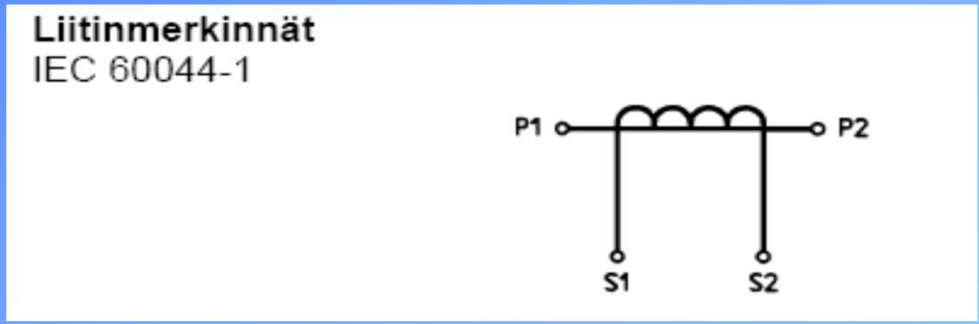
1. Busbar (KK) I
2. KK II
3. Busbar disconnectors
4. Circuit Breaker
5. Current transformer
6. Voltage transforme
7. Line disconnector
8. Surge Arresters

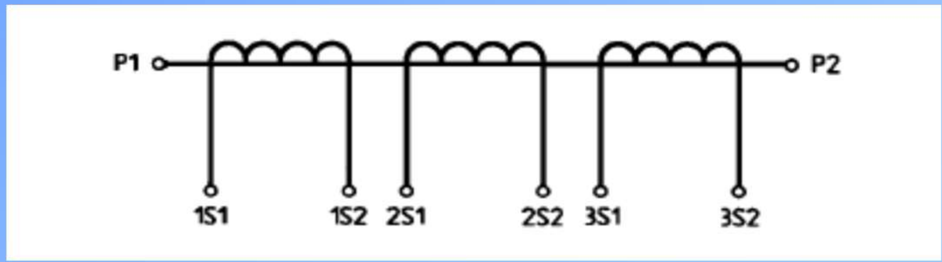


Current transformers

Current transformers

- Down scales the currents in primary side to lower level suitable for measurement intrumentation and protective relays
- Measurement cores and protection cores
- Rated values according to standards

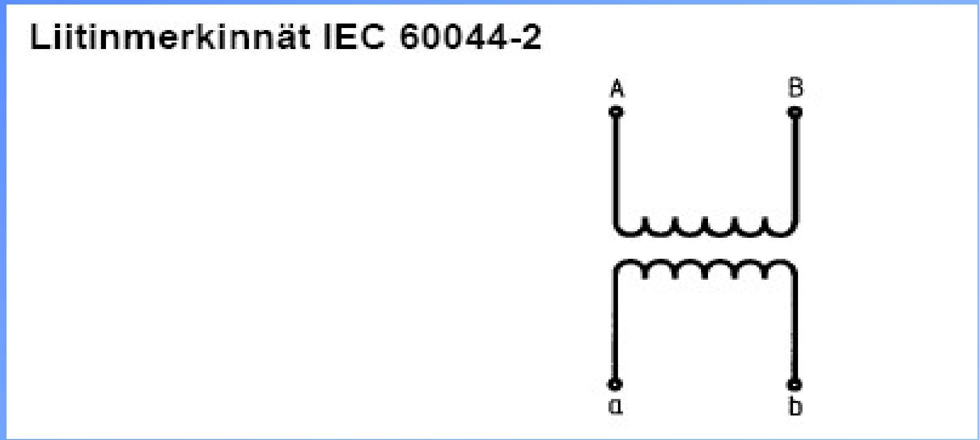


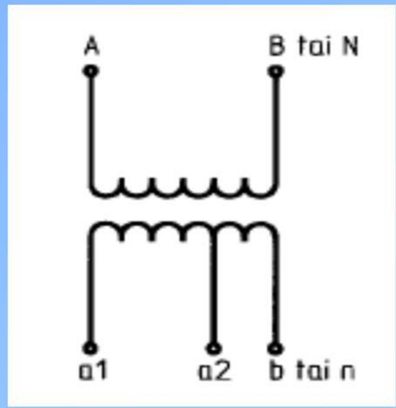


Rated primary currents:
10 - 12,5 - 15 - 20 - 25 - 30 - 40 - 50 - 60 - 75 A
And their 10, 100, 1000 etc … multiples.
Secondaries: 1 A, 2 A and 5 A

Voltage (Potential) transformers

- Isolation from grid voltage and down scaling
- Windings separately for measurement and protection
- Rated values standardized





20 kV overhead lines and CC lines

Bare conductor

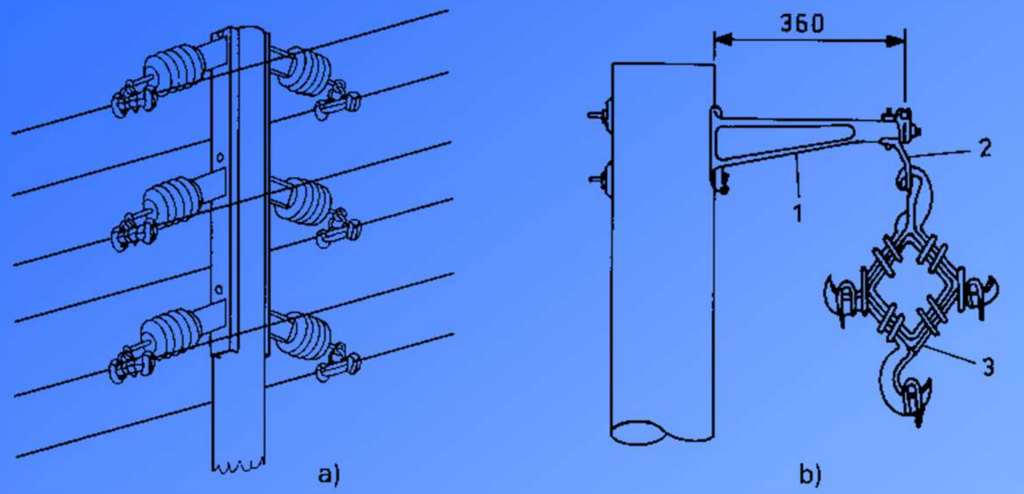
20 kV overhead line is usually built with bare conductors. In a three phase system we have 3 conductor on a lateral or triangle form, attached on insulators mounted on metallic cross-arms. The towers mostly are of wood, impregnated by CCA, C or creosote.

20 kV CC line (Covered Conductor) has a thin insulation cover on phases. The spacing of phases is smaller.

CC-line tolerates short contact between phases and phase with trees without immediate outages.

CC conductor

CC-lines



Covered conductor lines a) SAX-line (also called PAS), b) SAMI-line (Sekko/Hendrix). 1 support, 2 spacer link, 3 spacer.

- narrower line corridors
- phases contacting ⇒ no disturbance
- tree contact: no immediate disurbance, but damage in a few days
- detection of a broken conductor difficult

- power not able to move
  - welds conductors broken ?
  - arcing horns

After possible fault circumstance line must be patrolled !

Distribution network structures

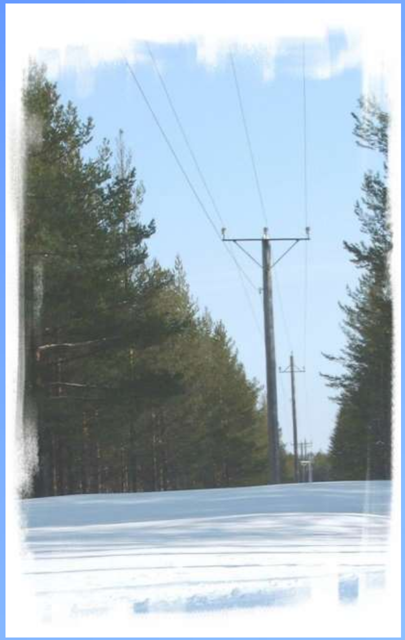
Medium Voltage Overhead lines (1/3)

- 3-phases, 20 kV
  - No zero or neutral wire
- Looped, but radial operated
  - Disconnecting switches, some in remote control
  - Back-up connections at least at back bone line
- Ungrounded or compensated neutral
- Protective relays + circuit breakers at primary subs.
- Typical length 20…30 km (Lapland even100 km…)
- Typical load only a few megawatts

Distribution network structures

•MV Networks (2/3)

- Overhead lines
  - Steel/Aluminum wires 25…201 mm^2
  - costs 10…20 k€/km
- CC-lines
  - Thin insulation, not full insulation strength
  - Narrow corridor, often double or triple circuit
  - 20…30 % more expensive than bare conductor OH-line



Distribution network structures

MV-Networks (3/3)

- Underground cables
  - Full insulation, PEX (XLPE)
  - Cross-sections 120…240 mm^2
  - price 30…50 k€/km depending on soil (excavation)
  - Trend when cutting dowm outages in rural area
- Air cable SAXKA – ony little used

UG Cable

MV air cable

Cable structures

Cable construction

Conductor

Conductor screen

- semiconducting

Insulation (PEX)

Insulation screen

- semiconducting

Water sealing

Protective screen

- Grounded

Outer jacket (PE)

Messenger/ground wire

Twisted 3 phases

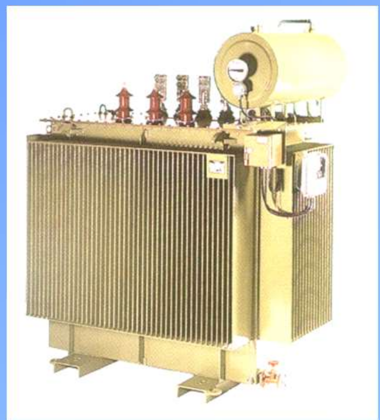
RAKENNE

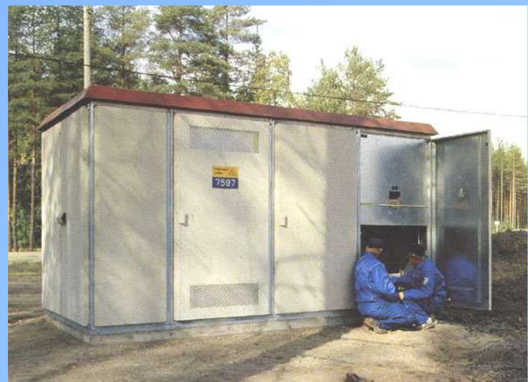
Johdin	25 mm²: Vesitiivis yksilankainen alumiinijohdin 50 … 185 mm²: Vesitiivis pyöreä tiivistetty alumiinijohdin
Johdinsuoja	Puolijohtava muovi
Eristys	PEX-muovi
Hohtosuoja	Puolijohtava muovi
Vesitiivistys	Veden vaikutuksesta paisuva puolijohtava nauha
Kosketussuoja	Alumiini-muovilaminaatti, joka toimii samalla poikittaissuuntaisena
Vaihevaippa	Säänkestävä musta PE-muovi
Kannatin	Vesitiivis pyöreä muutamalankainen sinkitty
Kannattimen eristys	Säänkestävä musta PE-muovi
Kertaus	Kolme vaipattua vaihetta kerrattu kannattimen ympärille

Distribution network structures

Secondary substations

- Connected to 20 kV line by a disconnecting switch
  - Surge arrester or spark gap to protect transformer
  - In OH-lines, transformers pole mounted, 1- or 2-poles
  - In UGC networks a cabin
- Low Voltage switchgear
  - In pole station just fuse boxes
  - In cabins a switchgear with fuses
- Transformer body connected to protective ground



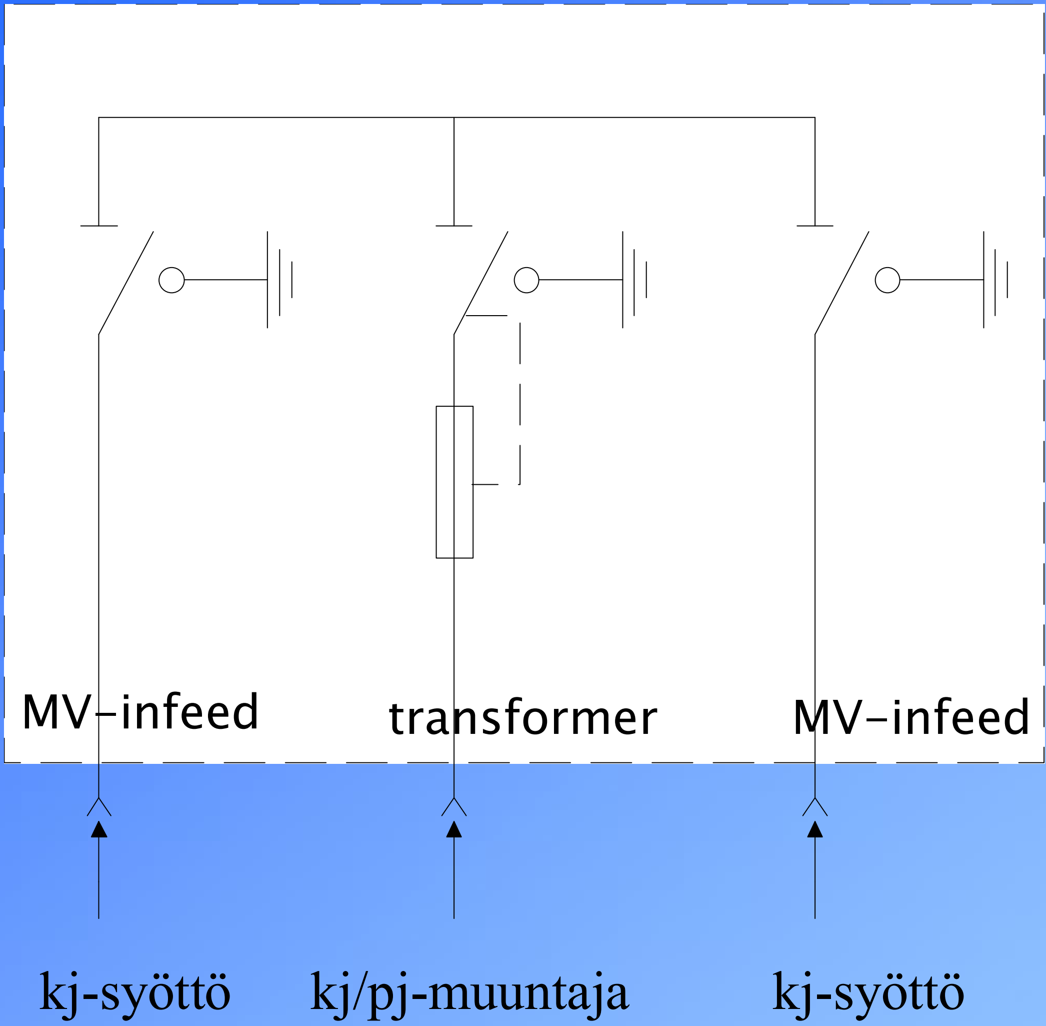


Secondary substations

- **Transformers**
  - Pole mounted 16…100 kVA
    - Oil insulated
    - No expansion tank
  - Normal transformers 30…3150 kVA
    - Oil filled
    - With expansion tank
    - Off load tap changers ± 5 %
  - Dry type transformers 315…2000 kVA
    - Fire safe
  - Hermetically close transformers 50…1000 kVA
    - Oil and air separated, less moisture accumulation ⇒ slower aging

Transformer stations

Ring main unit (RMU)



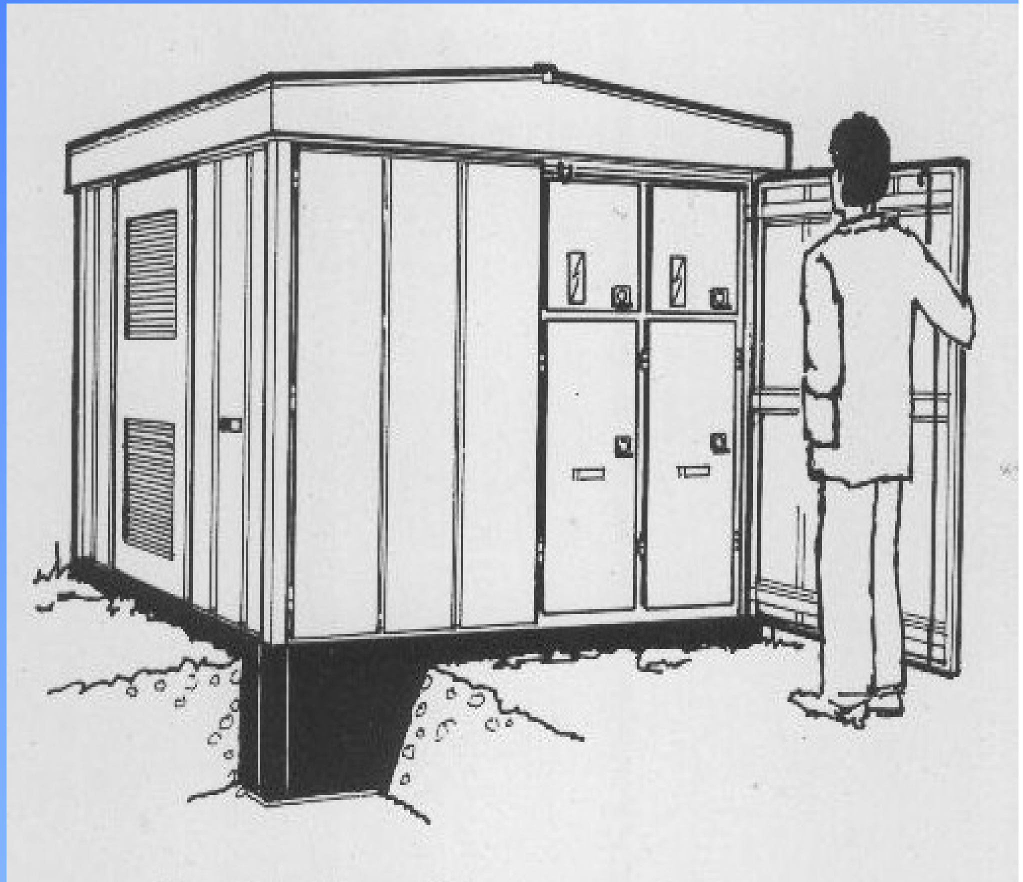
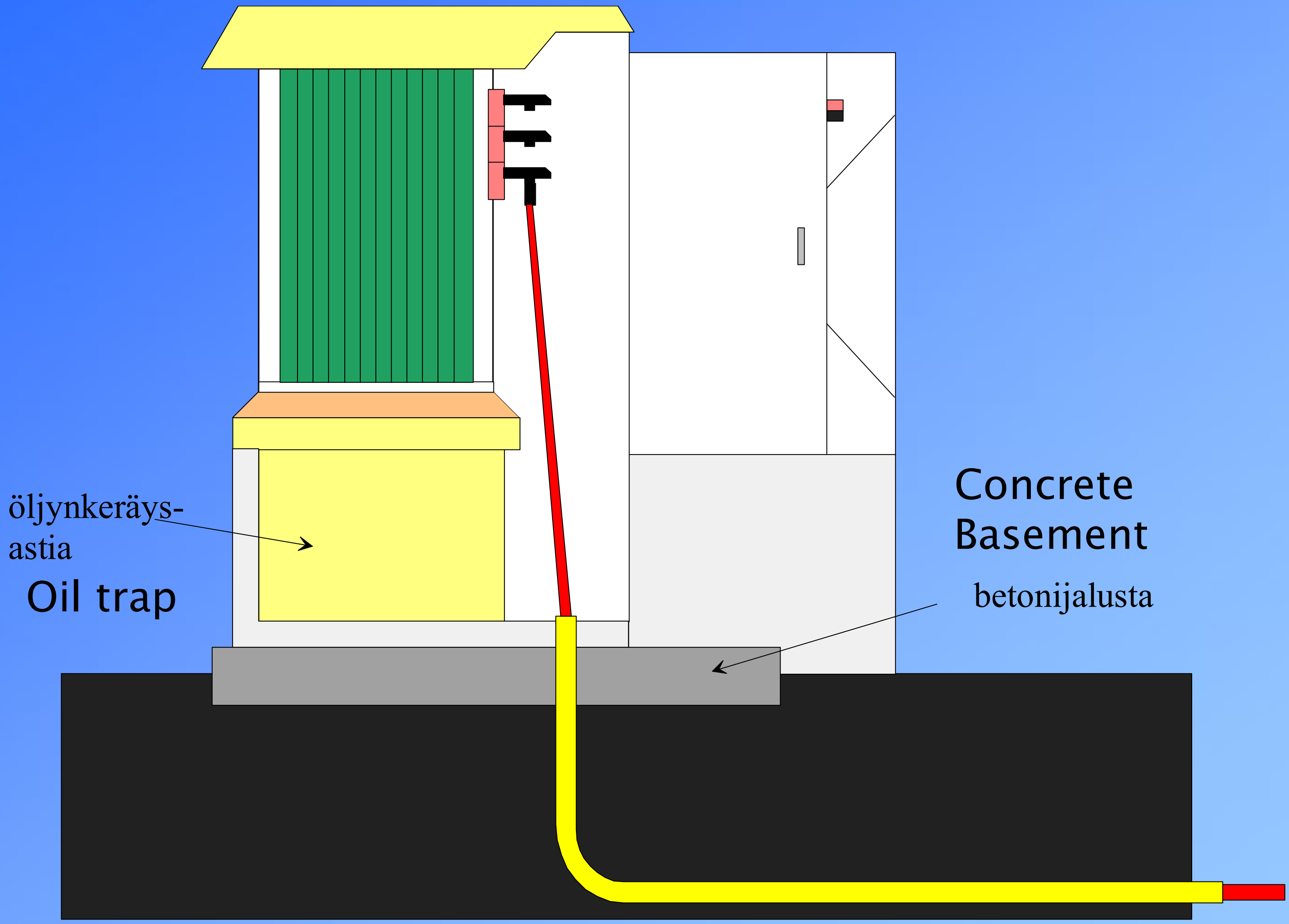


Figure 10.5 Typical prefabricated pad-mounted MV/LV substation

Secondary substations

- Small cabin (transformer 50 – 315 kVA) "dog house"



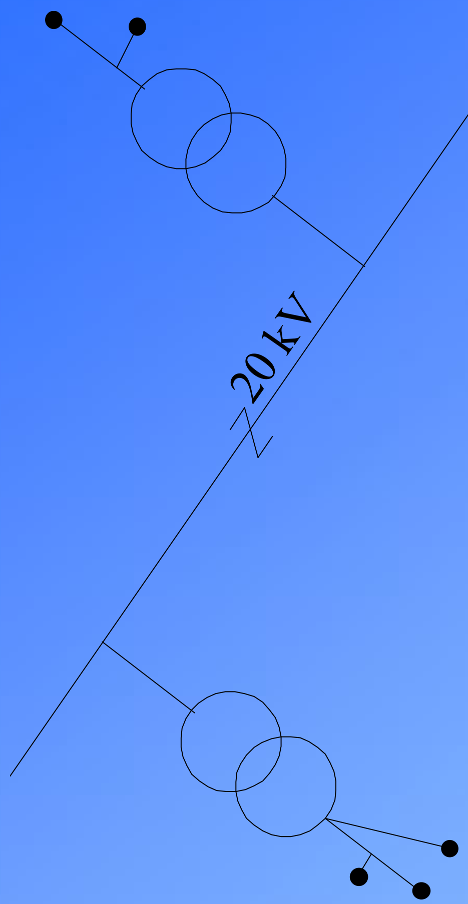
400/1000 V ABC-line (AMKA)

- AMKA – a Air Bundle Cable, where three phase conductors are twisted around the messenger. Messenger works as a PEN-conductor. (combined neutral wire and protective earth conductor).
- AMKA is attached to wood poles and usually used in rural and suburban areas.
- The height of the line is over 4 meters and distance from roads at minimum 5.5 meters.

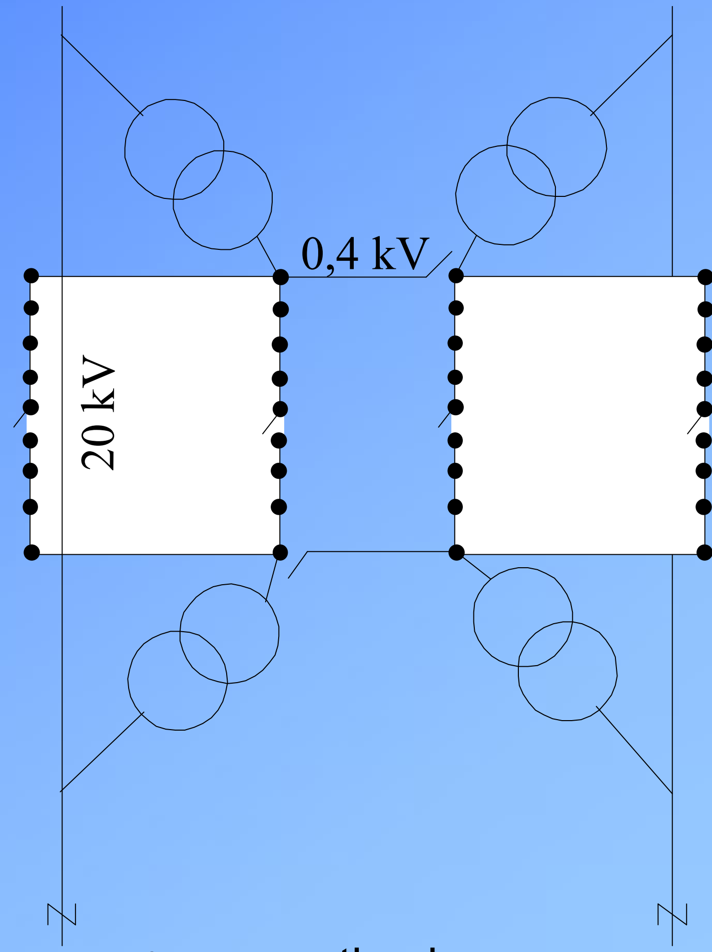
- Rated voltage 0.6/1 kV
- Max temperatures
  - Continuous 70 degrees
  - In short circuit 135 degrees

Phase marks

Secondary substations and low voltage networks



Rural



Urban