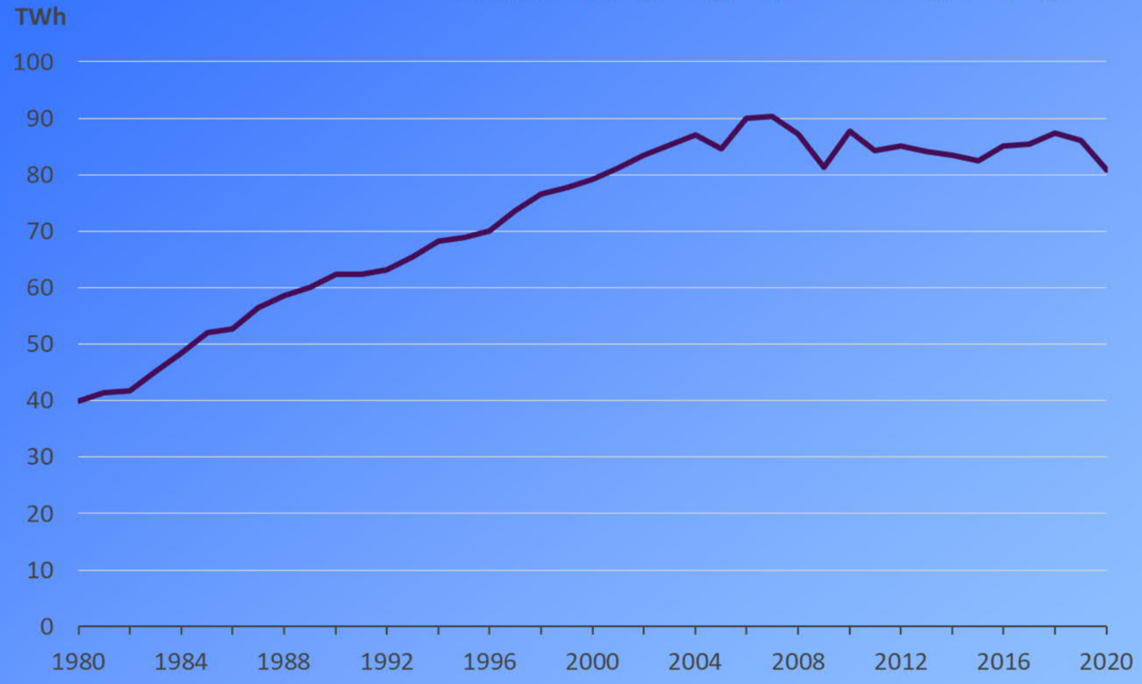
ELEC-E8422 Introduction to Electrical Energy Systems

Lecture 2

Basic Components of Power Systems

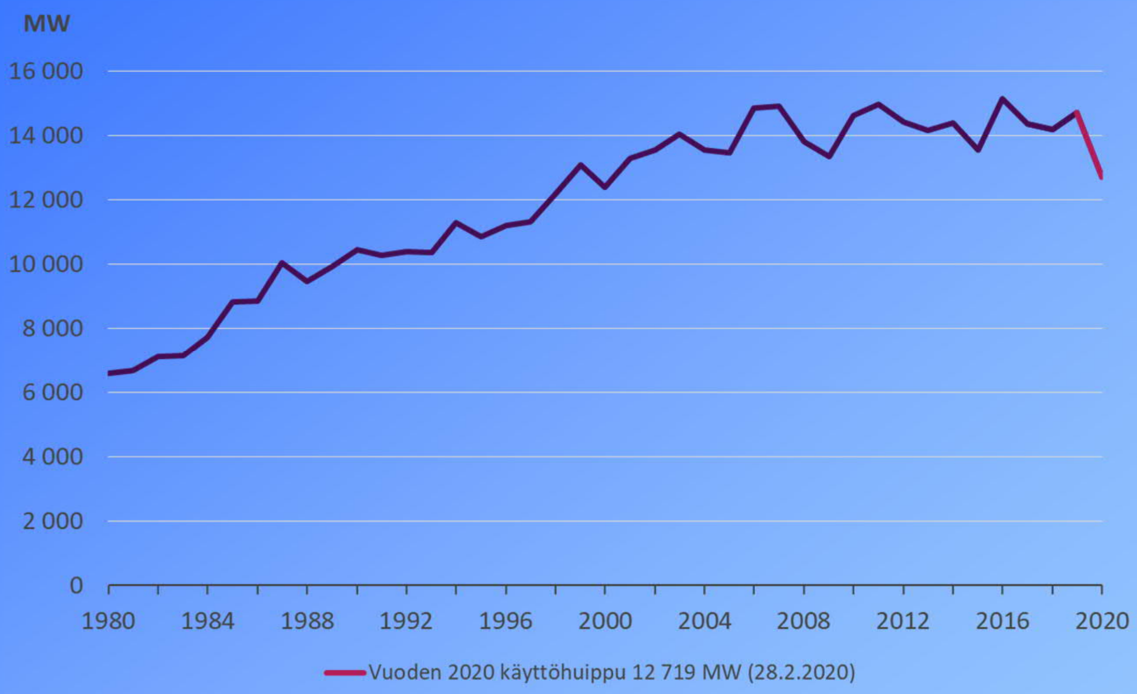
Matti Lehtonen

Use of Electricity in Finland in 1980-2020

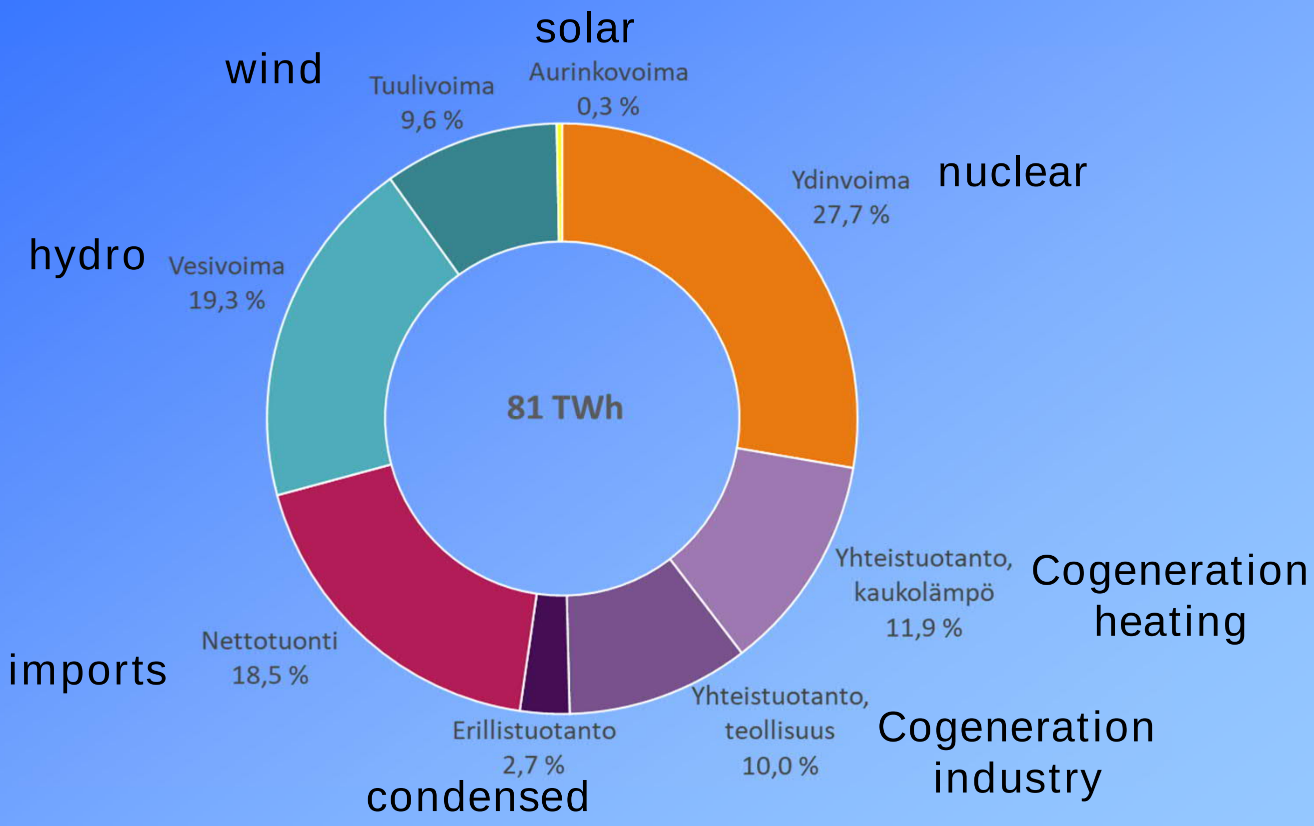


- Sähkönkäyttö vuonna 2020
  81 TWh

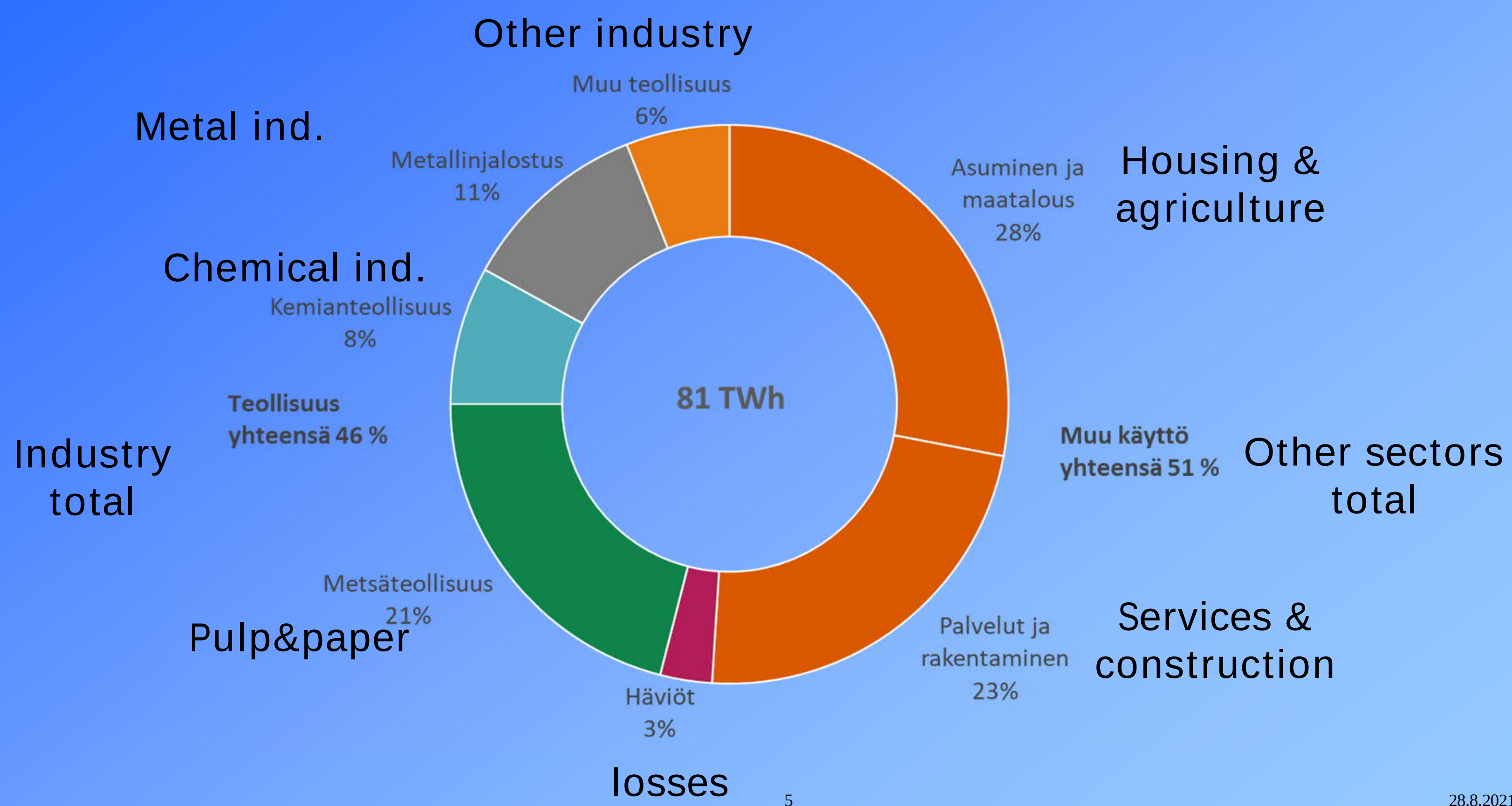
Maximum hourly demand (MW)



POWER PURCHASE 2020



ELECTRICITY USE 2020



Transmission And Distribution Networks

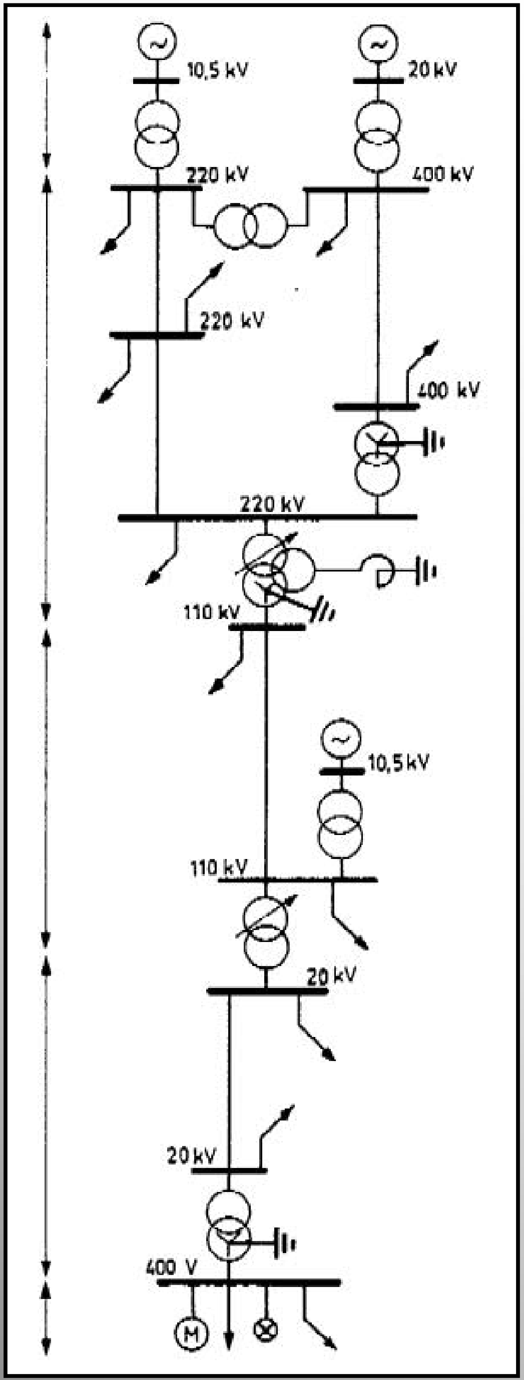
Power generating stations
- generator (10,5 kV, 20 kV)
- Step-up transformer (20/400 kV)

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



NORDIC TRANSMISSION SYSTEM

Nordel

POWER GENERATING STATIONS
conventional steam power plants

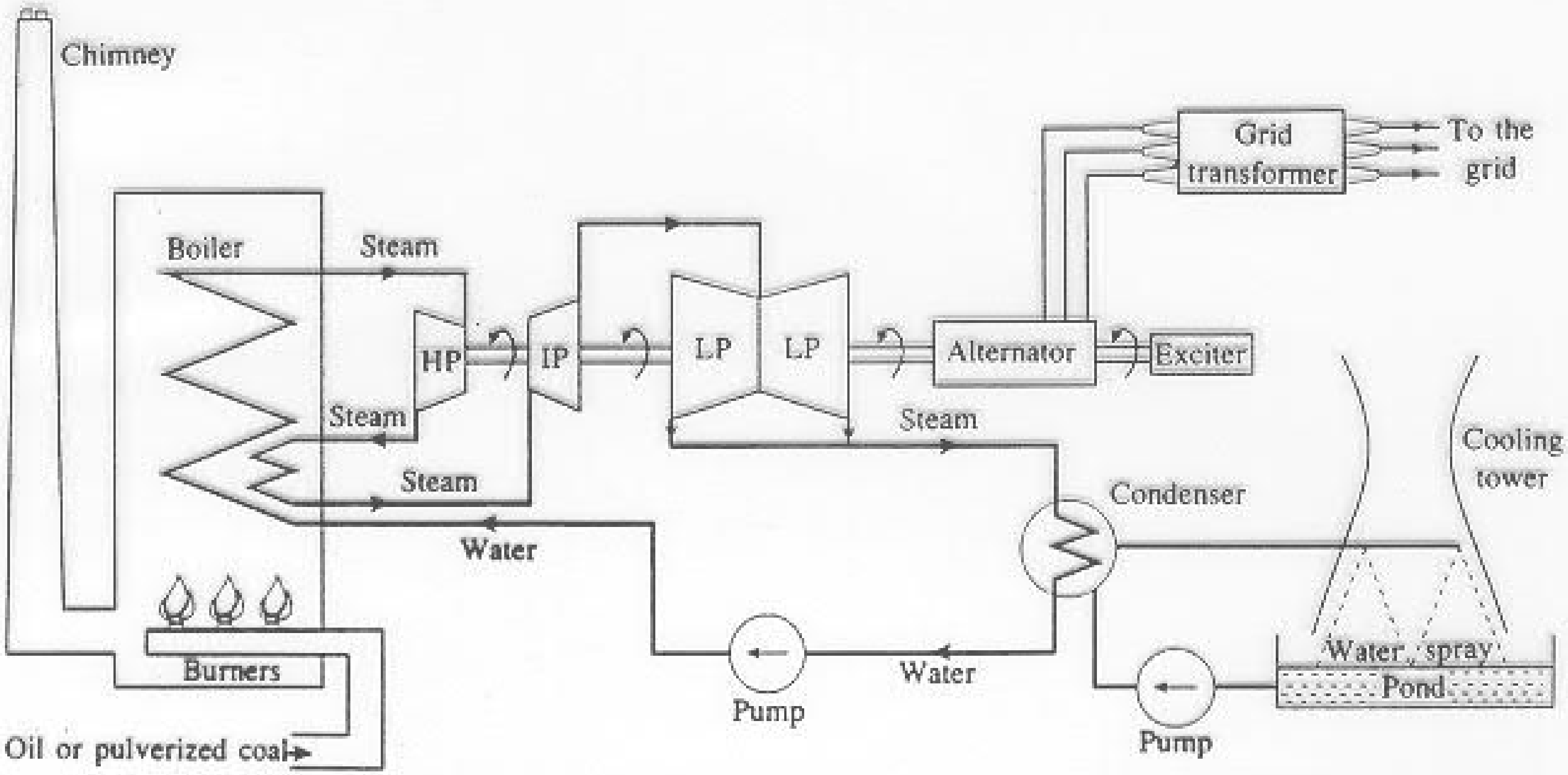


Figure 7.1 Schematic diagram of a coal- or oil-burning power station. HP, IP and LP are the high-pressure, intermediate-pressure and low-pressure turbines respectively

POWER GENERATING STATIONS

conventional steam power plants

Steam produced by coal, oil or peat

Efficiency at maximum about 40%

Base-load or intermediate generation

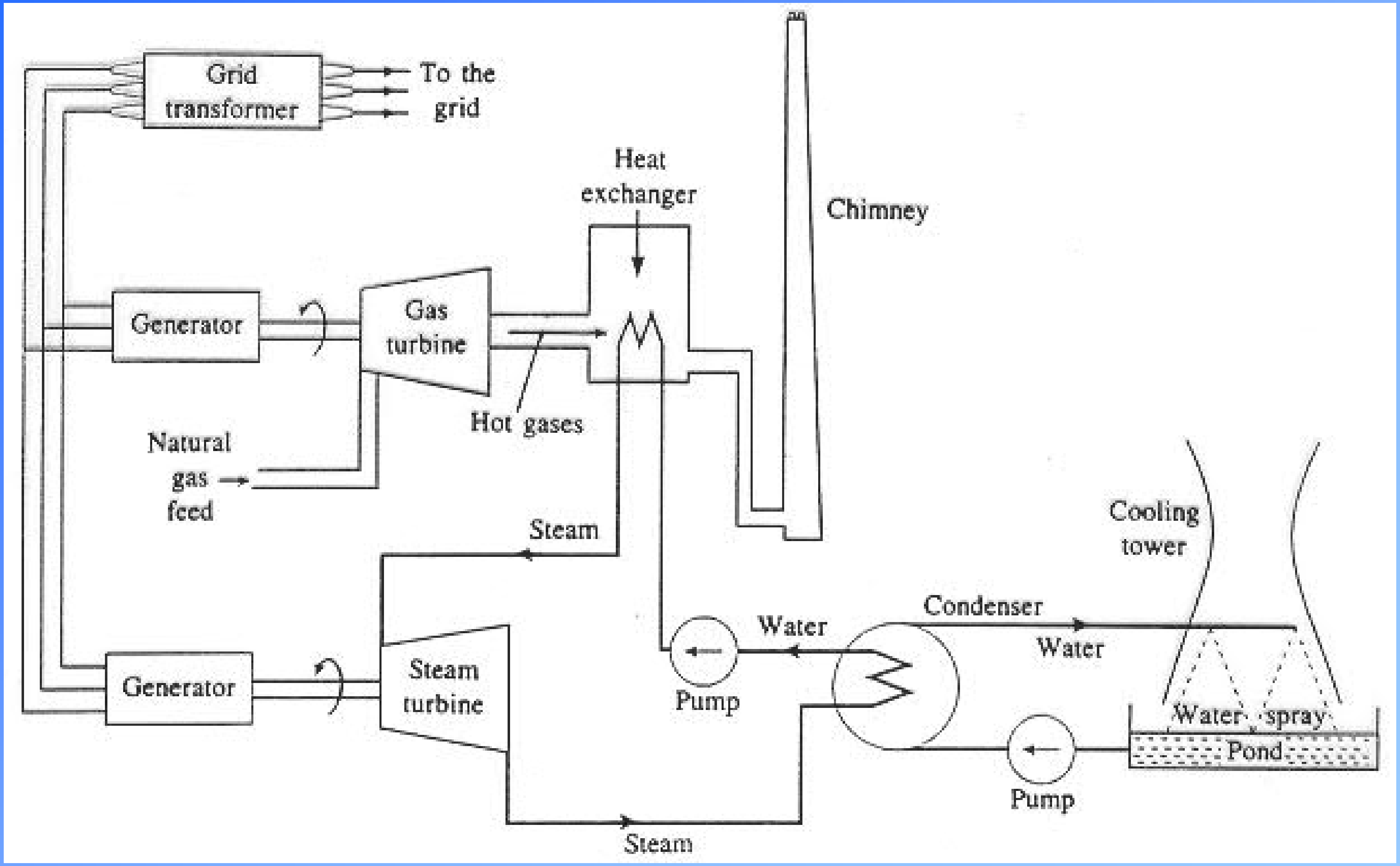
High environmental impact due to CO_2, SO_2 and NO_x

Efficiency increased if waste heat energy is used for district heating

$\Rightarrow$condenser replaced by heat exchanger

$\Rightarrow$”back-pressure power plant ”

POWER GENERATING STATIONS
combined-cycle power stations



POWER GENERATING STATIONS
combined-cycle power stations

One generator driven by a gas turbine, one with steam

The exhaust heat of gas turbine is utilised in steam production

The emission of SO_2 and NOx better controlled than in conventional plants (gasification)

In back-pressure connection, thermal efficiency is very high; yield of electricity and heat about 50/50

POWER GENERATING STATIONS
Nuclear power plants

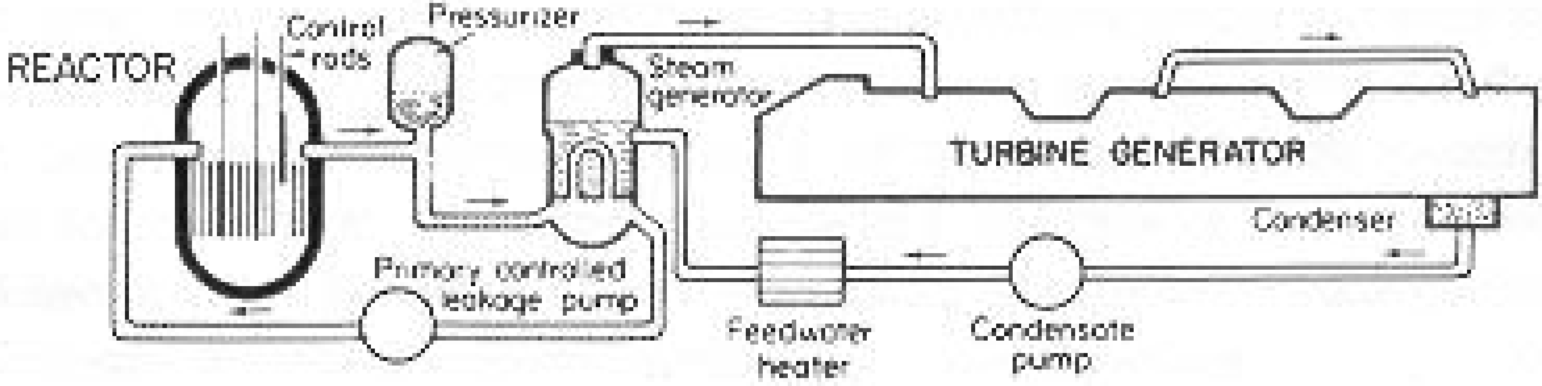


Figure 1.17 Schematic diagram of a pressurized water reactor. (*Permission of Edison Electric Institute.*)

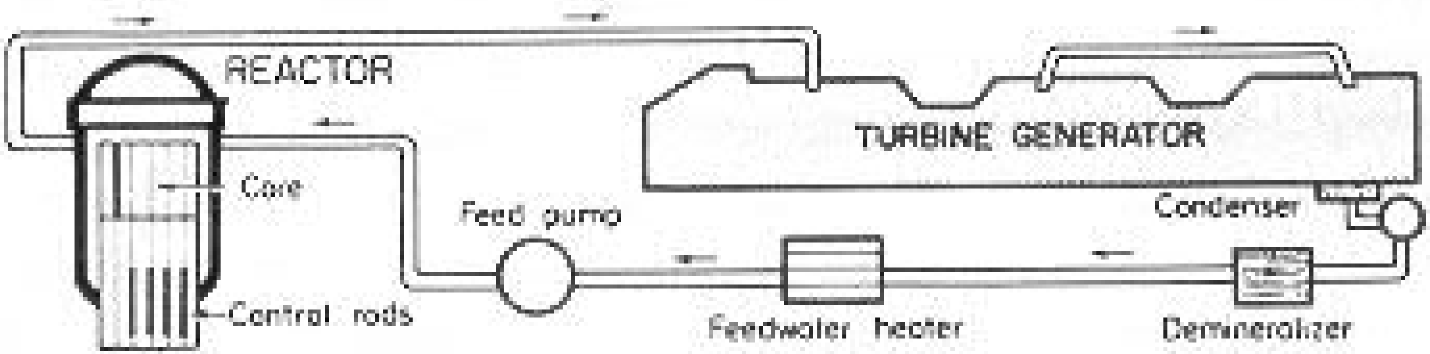


Figure 1.18 Schematic diagram of a boiling water reactor. (*Permission of Edison Electric Institute.*)

POWER GENERATING STATIONS
Nuclear power plants

Conventional steam plants beyond the heat producing reactor

High investments – low fuel costs => base load production

No emissions of CO_2 , SO_2, or NO_x

Open questions: final treatment of used fuel

Present plants based on fission of uranium-235 (0,7% of all U)

Fast-breeder reactors: uranium-238 converted to plutonium

Fusion energy: D+T= He+n or D+D=T+H or D+D=He+n

POWER GENERATING STATIONS
Hydro power plants

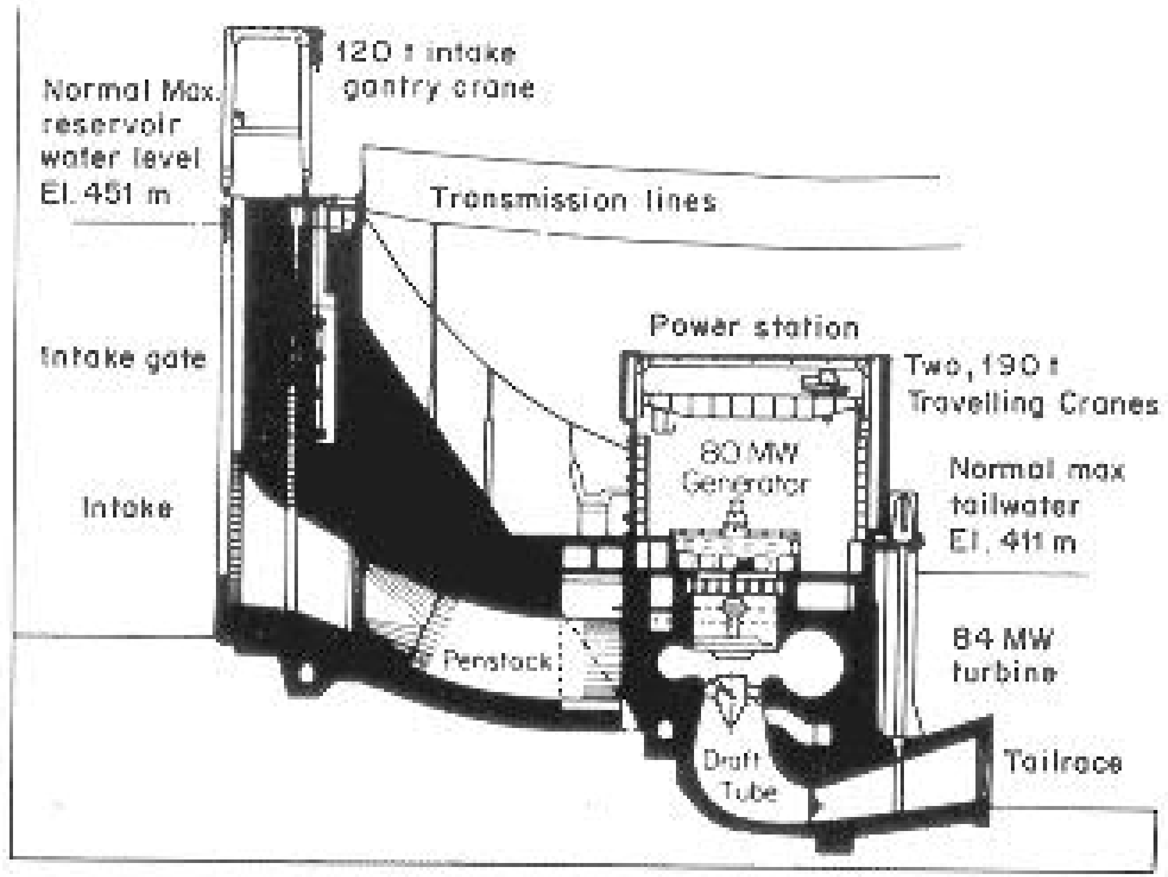


Figure 1.12 Hydroelectric scheme—Kainji, Nigeria. Section through the intake dam and power house. The scheme comprises an initial four 80 MW Kaplan turbine sets with the later installation of eight more sets. Running speed 115.4 rev/min. This is a large-flow scheme with penstocks 9 m in diameter. (*Permission of Engineering.*)

POWER GENERATING STATIONS
Hydro power plants

High investments, but no fuel costs

Variation of water flows: reservoir often needed

Limitations of operation:
⇒flood control
⇒limited variation of water level

Very good properties for generated power control
=> used for production / demand balance control

No emissions of CO_2 , SO_2, or NO_x

Properties of different power plant types

Hydro power

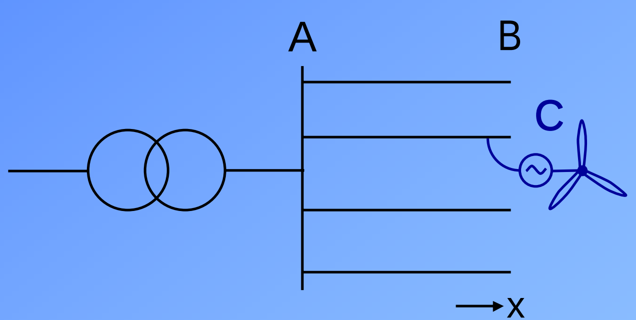
- high investments
- variable inflow
  - reservoirs needed
- good power control properties
- limitations of utilisation
  - flood control
  - water level variation limits
- as reservoir natural or artificial lakes

Solar power

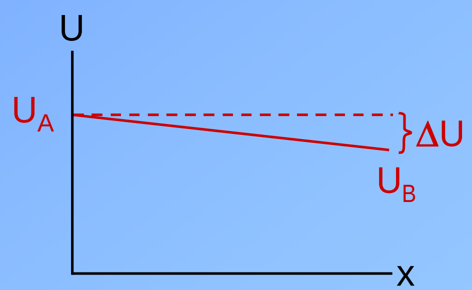
- small efficiency of the cell n. 15 % and high price (x 10)
- amount of light a problem in Finland

Wind power

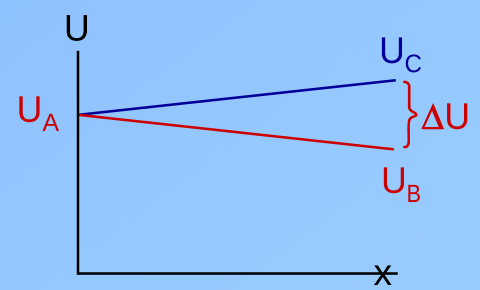
- economic size ~ 4 - 5 MW
- large wind parks 100 - 1000 MW
- network connection sometimes troublesome



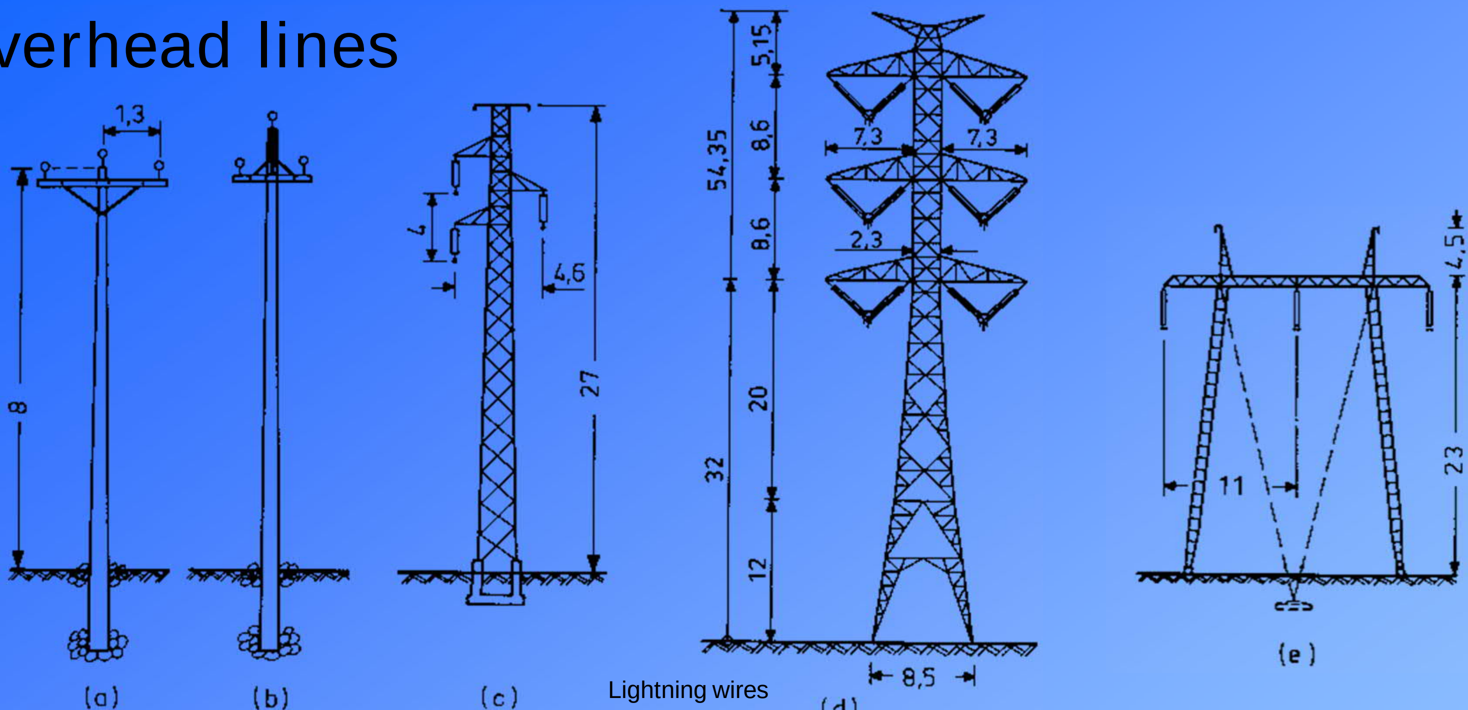
Network voltage normally



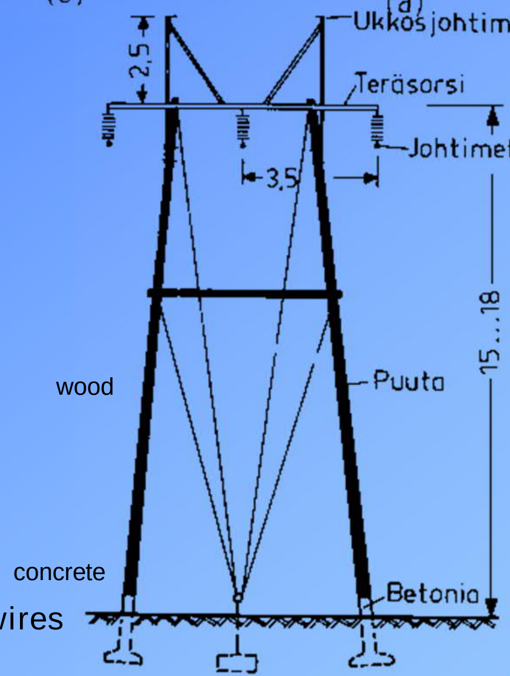
And if wind power in C



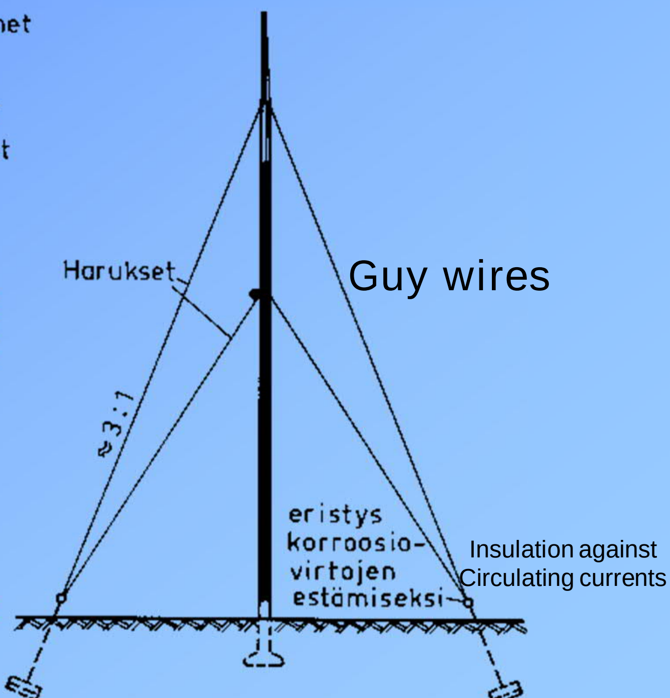
Overhead lines

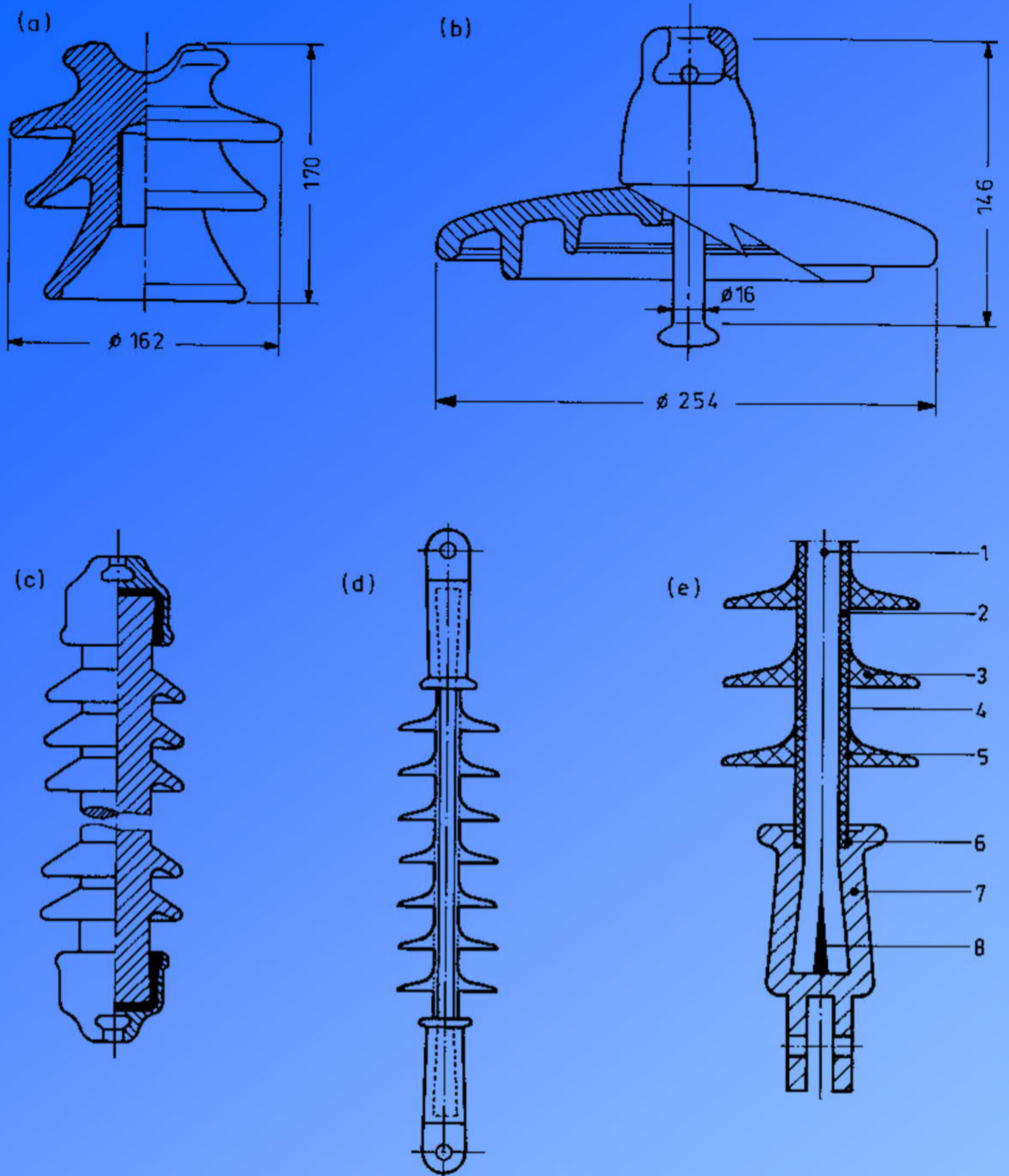


a) ja b) 20 kV wood poles
c) Free standing 110 kV steel tower, I-strings
d) Free standing 440 kV steel tower, V-strings
e) 400 kV steel tower with guy wires

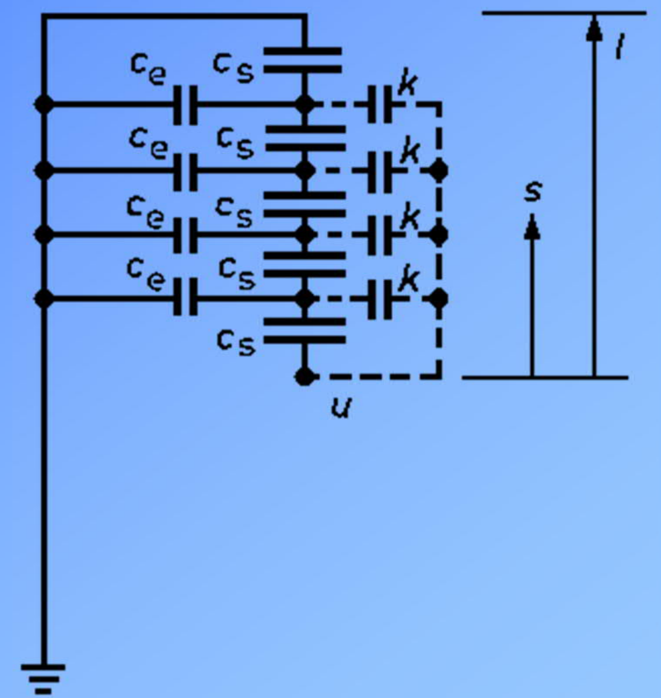


110 kV wood pole with guy wires

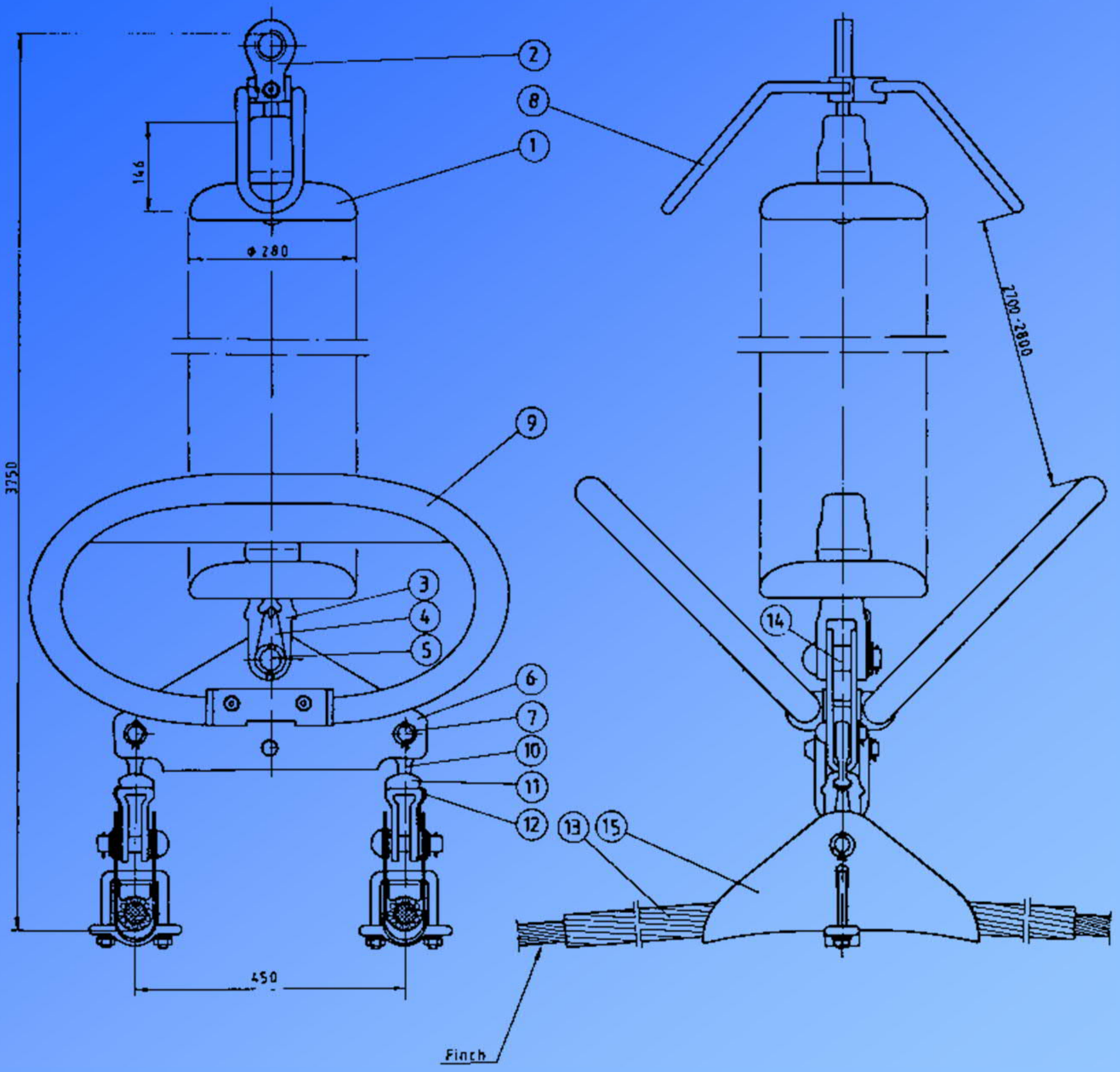




Capacitances of insulator string



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

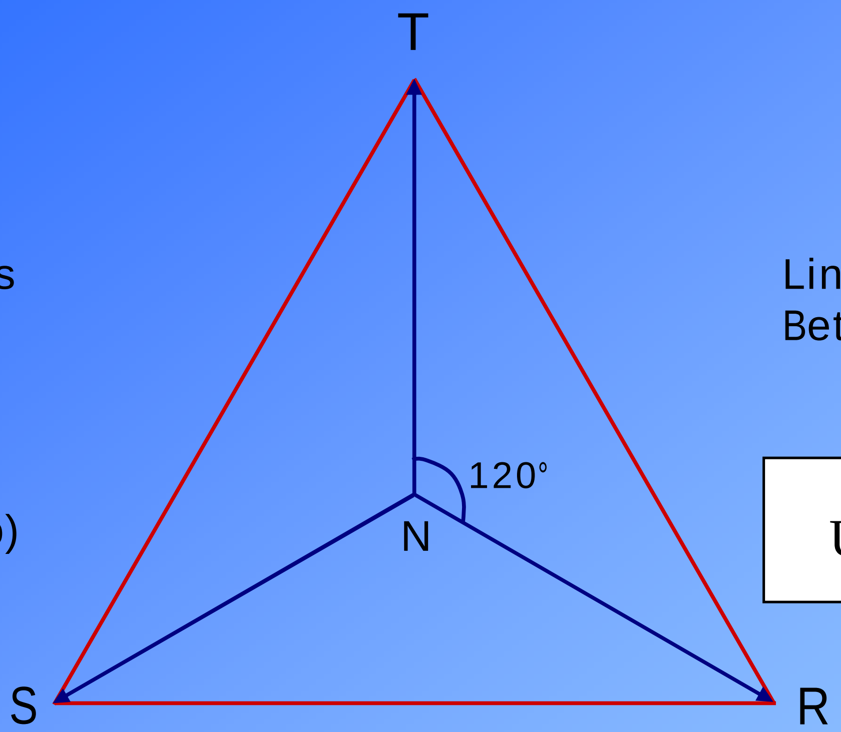
In Finland towers with guy wires in sparsely populated areas
And free standing towers in city areas. Oldest lines are built
In 1920s.

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

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-ph system

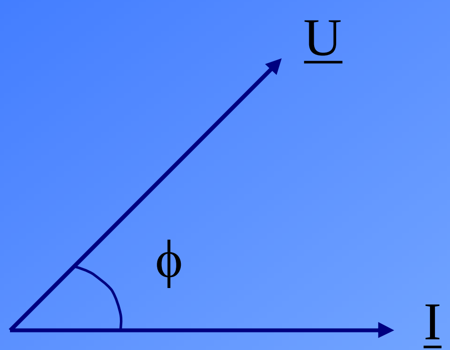
$$S = 3\,U_P\,I = \sqrt{3}\,U_L\,I$$

$$P = S\cos\phi$$

$$Q = S\sin\phi$$

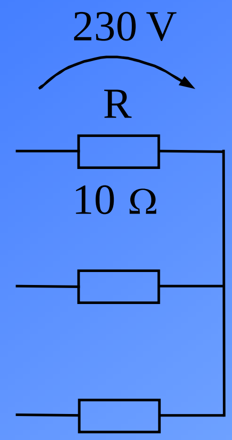
$$S = \sqrt{P^2 + Q^2}$$

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



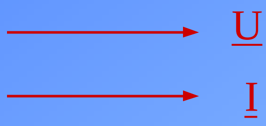
P/S = cosϕ is power factor

a)



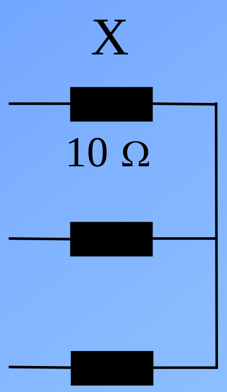
Resistance R

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



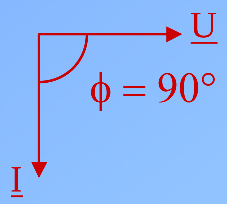
$$P = 3U_p I\cos\phi$$
$$= 3\cdot 230\cdot\cos 0°\cdot 23\,\text{W} = 15{,}9\,\text{kW}$$
$$Q = 3U_p I\sin\phi = 0$$

b)



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

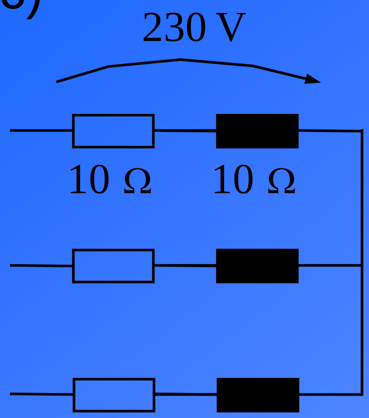
$I = 23\,\text{A}$ $\quad(\underline{U} = \underline{X}\underline{I})$



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

Powers in a 3-ph system (continued)

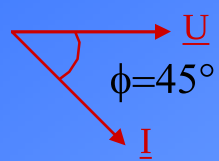
c)



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

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

$$= 16{,}26\angle -45°\,A$$



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

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

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

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

<u>Another way</u>

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

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

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

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

Computation usually using line voltages

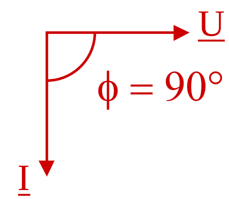
$$\Rightarrow S = 3\,U_P I_P^*$$

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

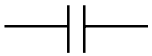
Reactance (ind)

L

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

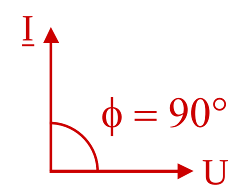


Capacitance

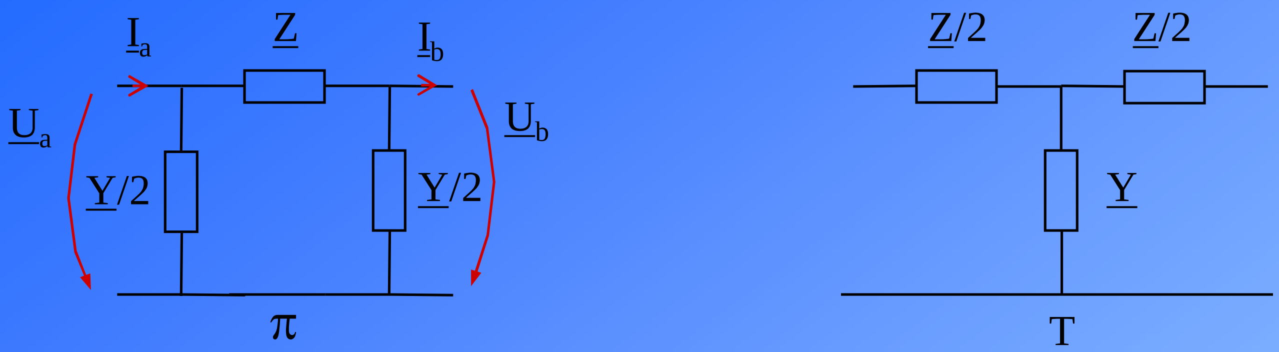


C

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



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

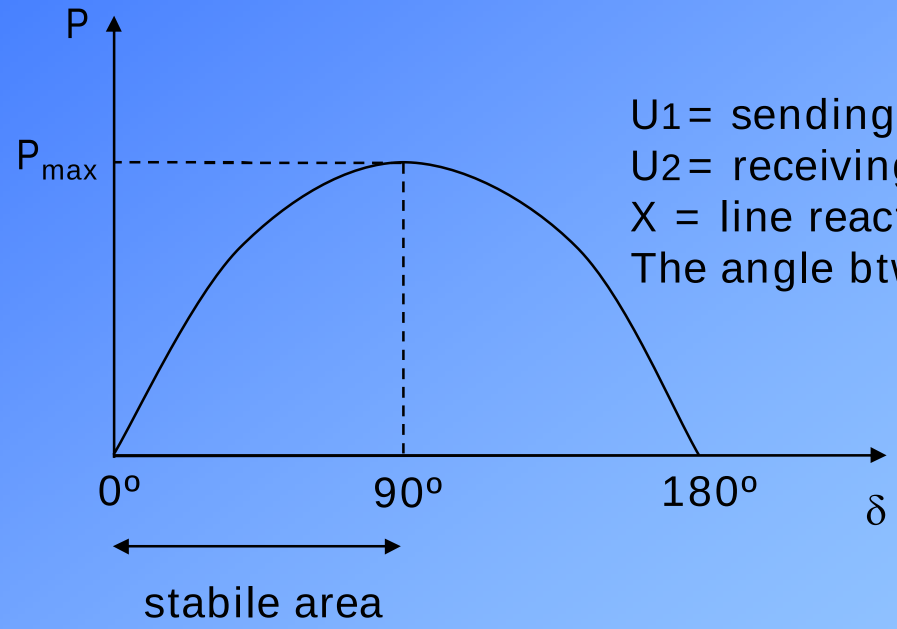
$$\begin{bmatrix} \underline{U}_a \\ \underline{I}_a \end{bmatrix} = \begin{bmatrix} \cos \underline{\beta}\, s & j\underline{Z}_c \sin \underline{\beta}\, s \\ j\dfrac{1}{\underline{Z}_c} \sin \underline{\beta}\, s & \cos \underline{\beta}\, s \end{bmatrix} \begin{bmatrix} \underline{U}_b \\ \underline{I}_b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

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

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

Power transmission – Power-Angle Equation

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



U_1 = sending end voltage
U_2 = receiving end voltage
X = line reactance
The angle btw U1,U2 is δ

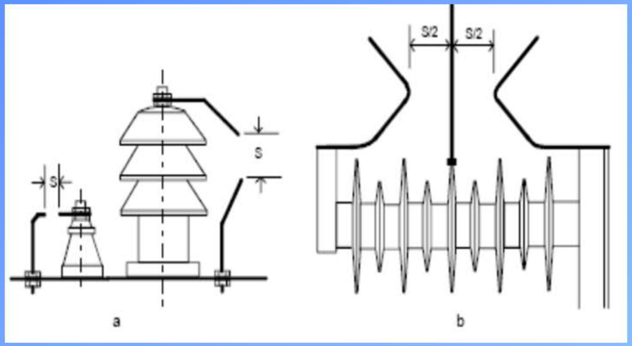
Limit power of static stability

Surge Arresters

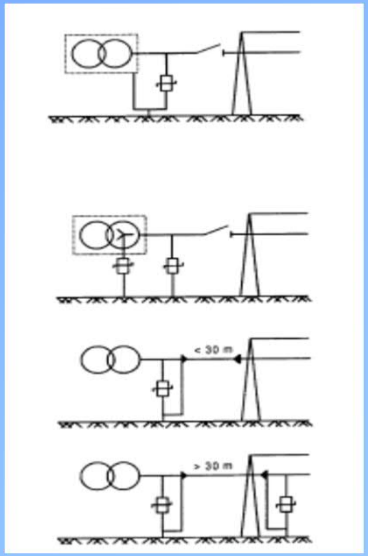
- Used for fast overvoltage transients due to lightnings and switching actions
- In normal operation are isolators, but quickly turn to conducting when protective voltage level of voltage is exceeded
- There must be enough margin between insulation level of components and protective level of SA
- SA must be located close to the protected equipment, which usually is a transformer or a cable

Overvoltage protection

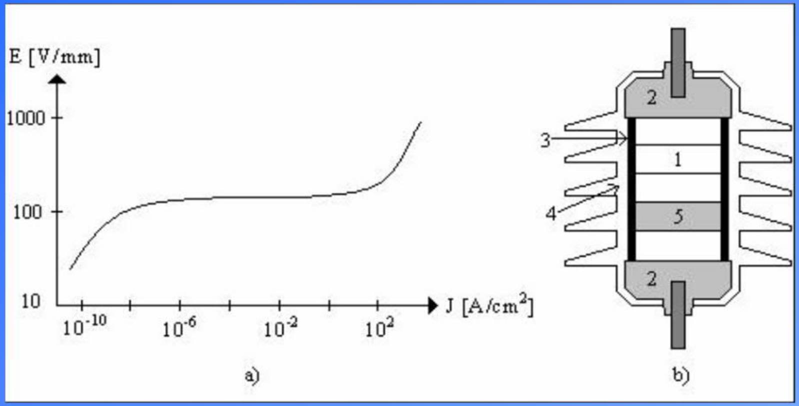
- **Surge Arresters and Spark Gaps**
  - Limit the overvoltages below the withstand level of insulation
  - Used at Trasformers and places where cables are connected to overhead lines
  - Must be located as close to the protected device as possible



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

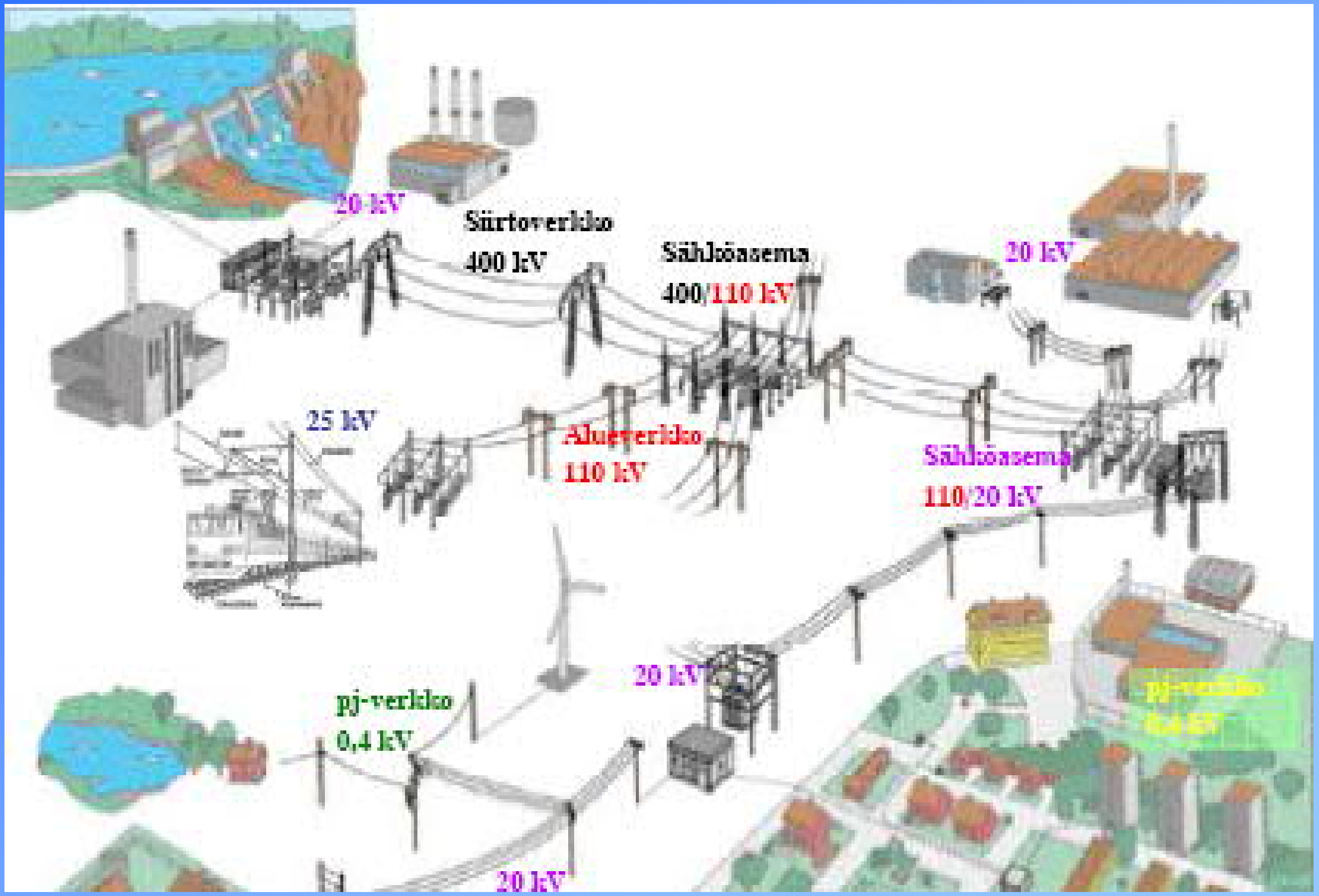


Surge Arresters



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

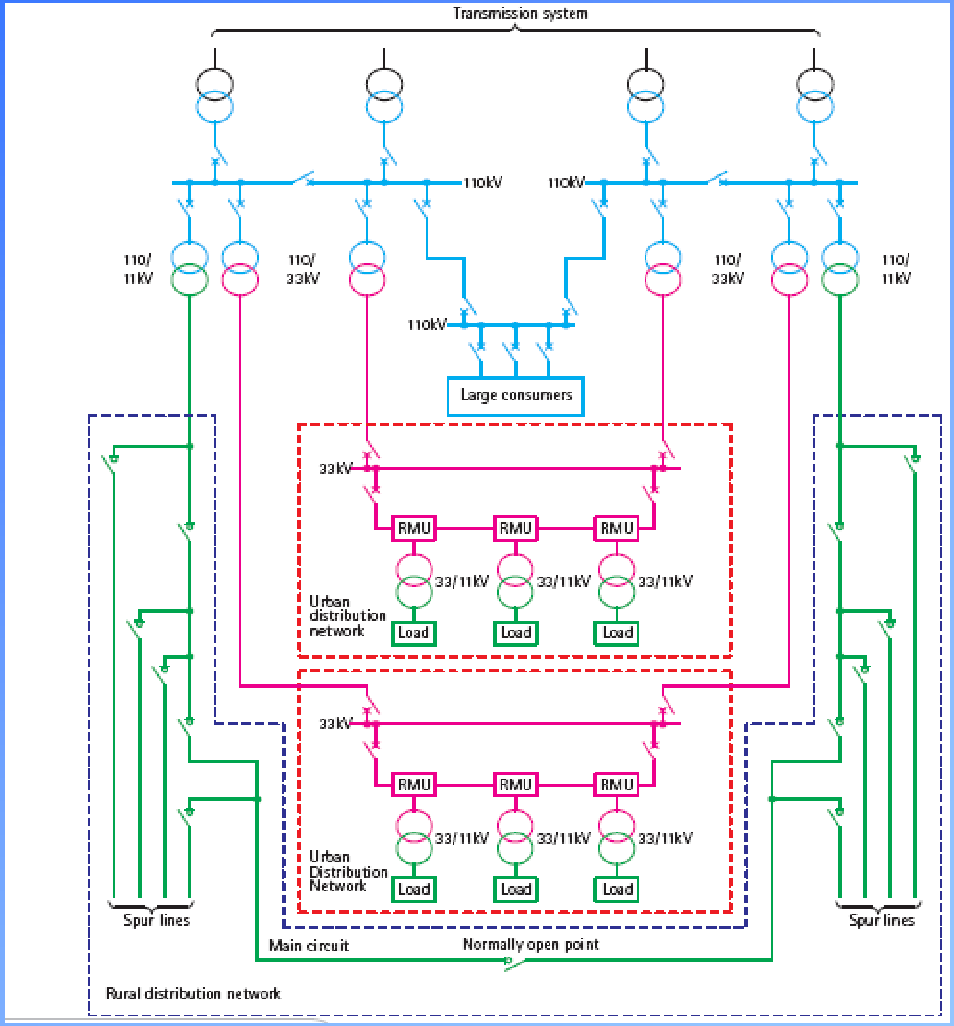
Power system



HV and MV 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.



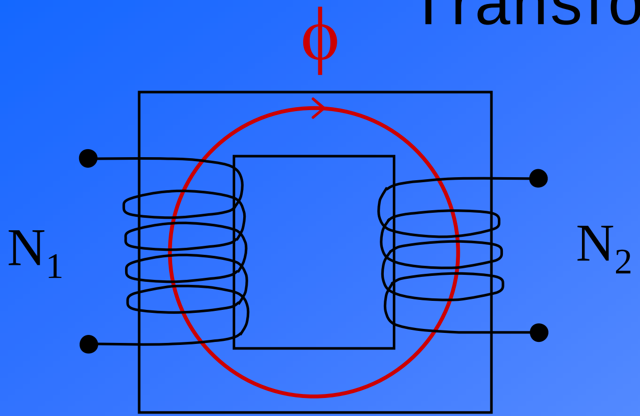
Power transformers

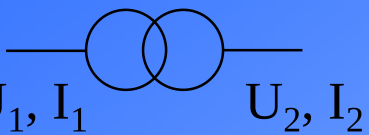
Transformer parts:

- 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

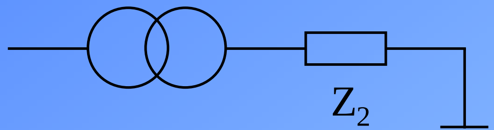
$$\frac{U_1}{U_2} = \frac{N_1}{N_2}$$

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 ?

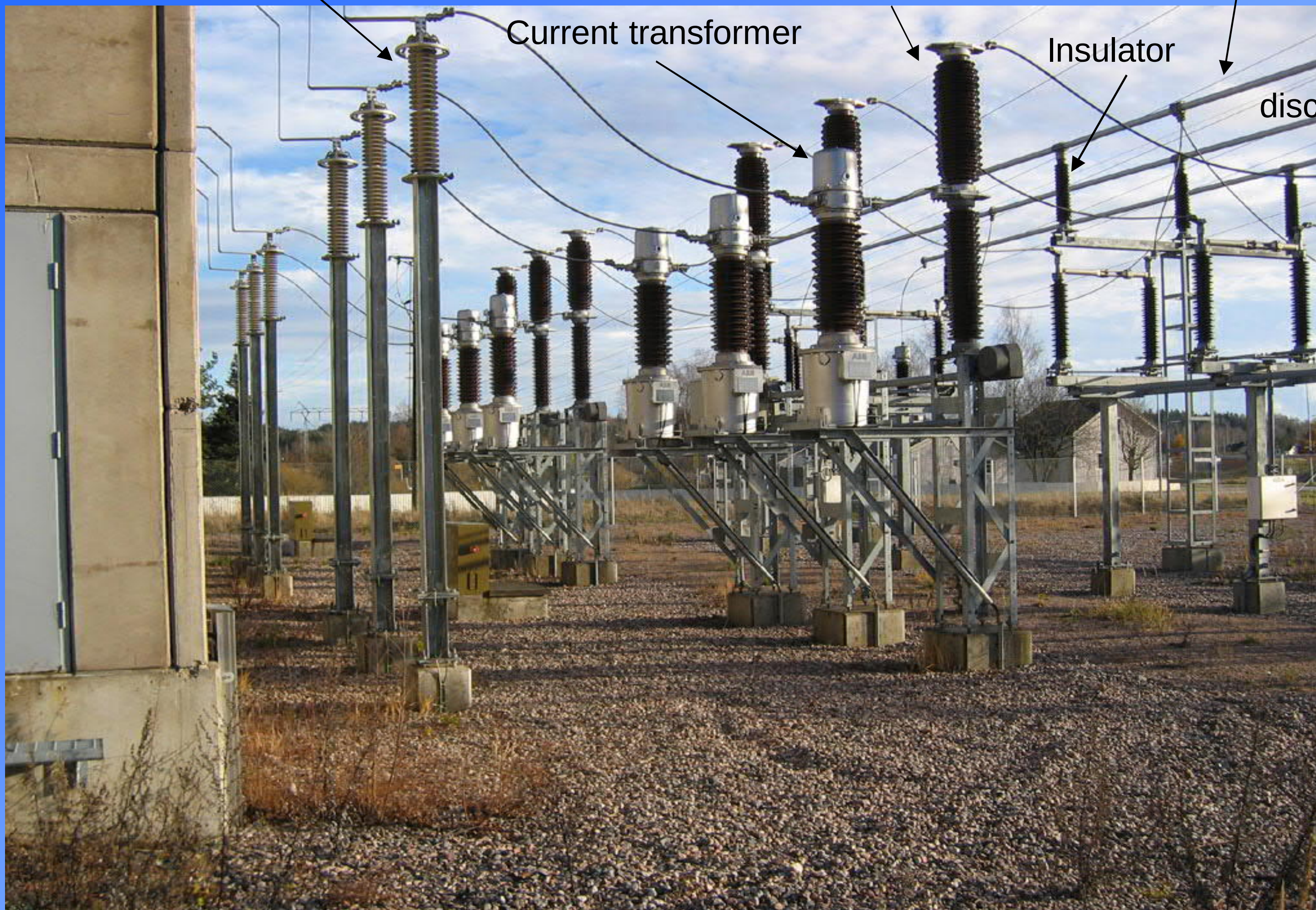


at secondary $Z_2 = \frac{U_2}{I_2}$

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

Equipment at switching stations



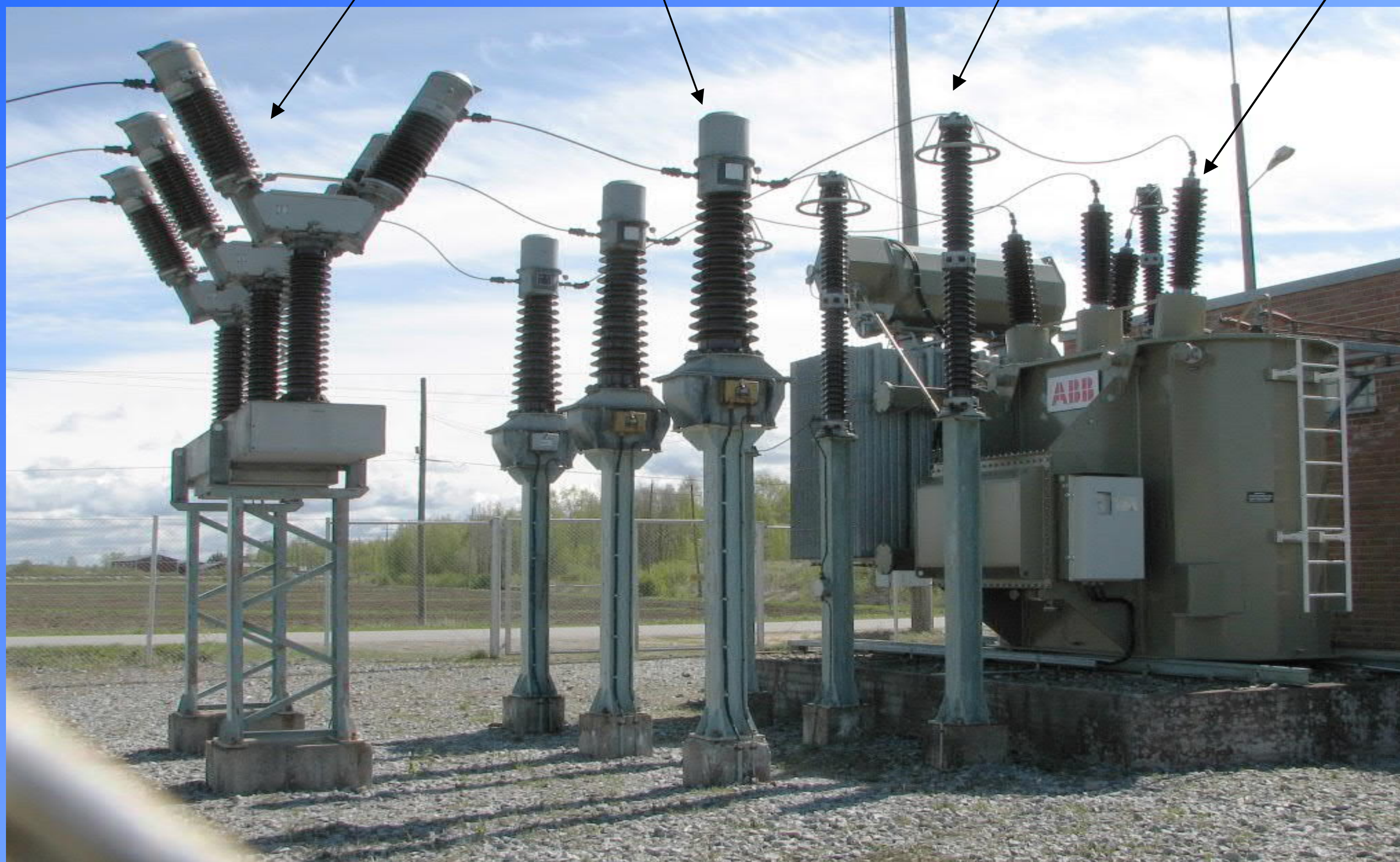
Equipment at switching stations

Current transformers

Surge arresters

110kV circuit breaker

Transformer bushings

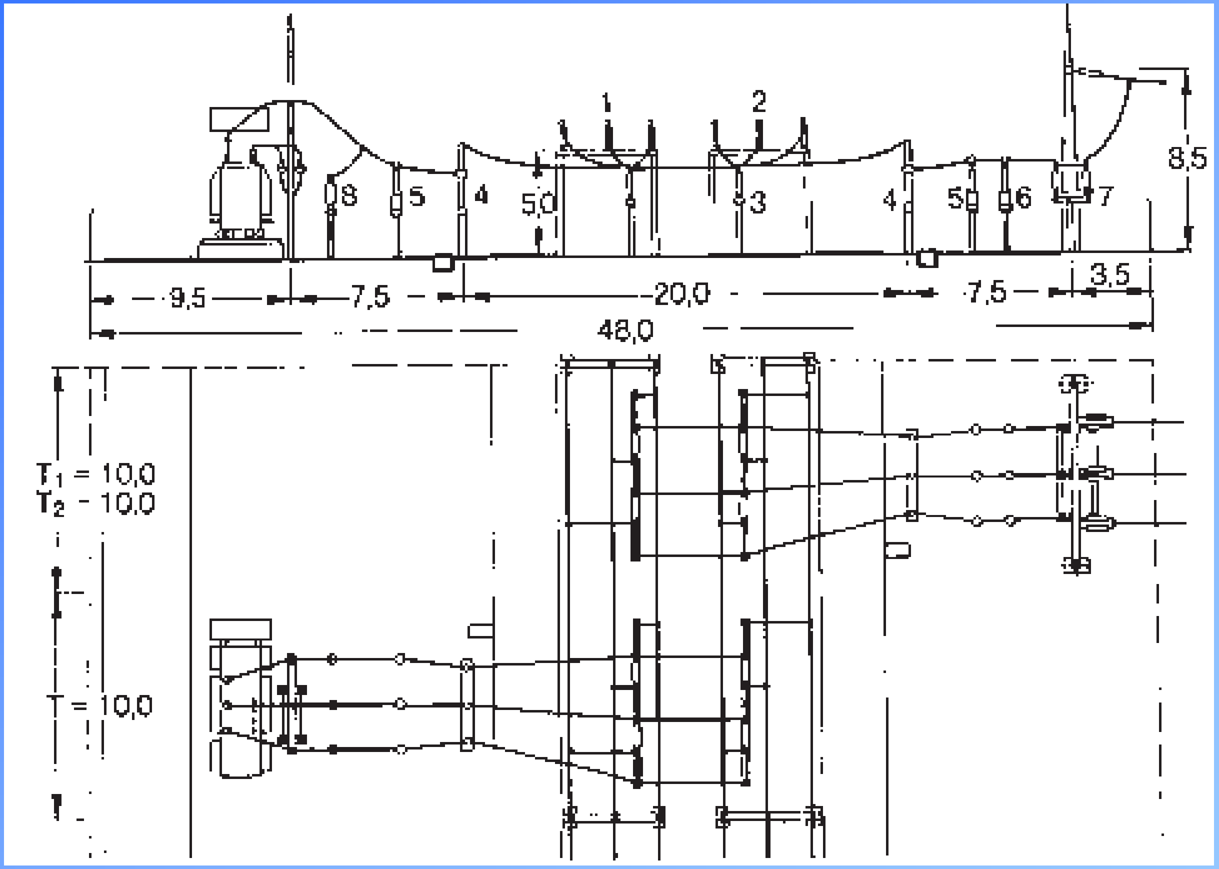


Equipment at switching stations

Switching station lay-out

123kV 2-busbar system

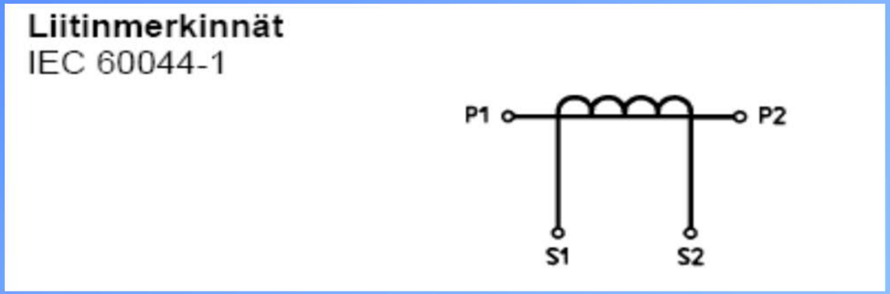
1. Busbar (KK) I
2. KK II
3. Busbar disconnectors
4. Circuit Breaker
5. Current transformer
6. Voltage transforme
7. Line disconnector
8. Surge Arresters

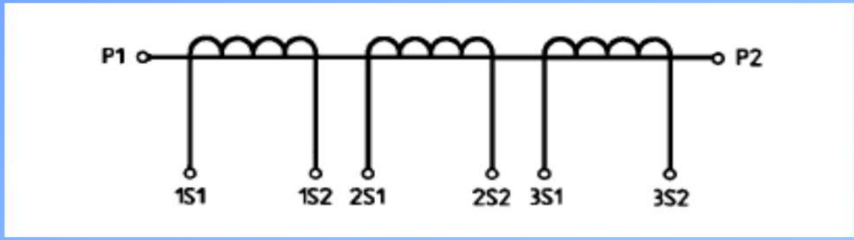


Current transformers

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

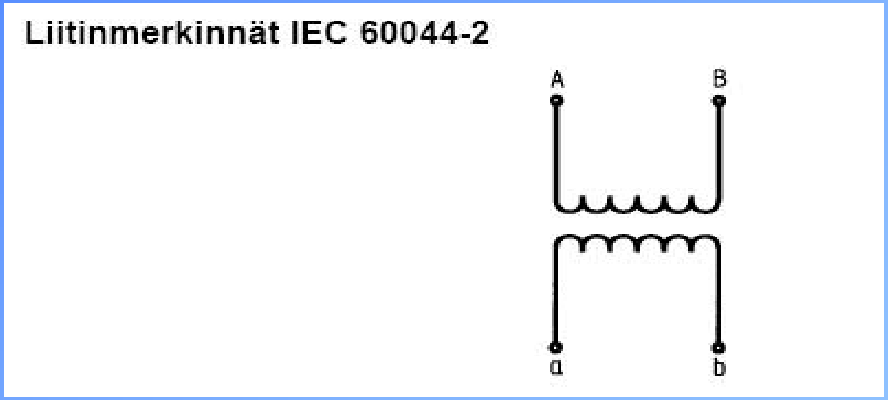


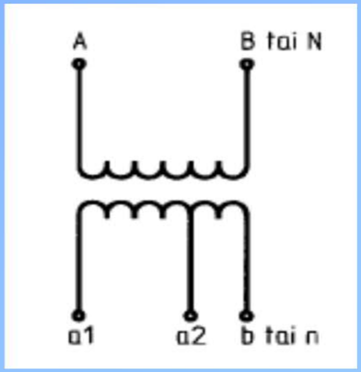


Rated primary currents:
10 - 12,5 - 15 - 20 - 25 - 30 - 40 - 50 - 60 - 75 A
And their 10, 100, 1000 etc … multiples.
Secondaries: 1 A, 2 A and 5 A

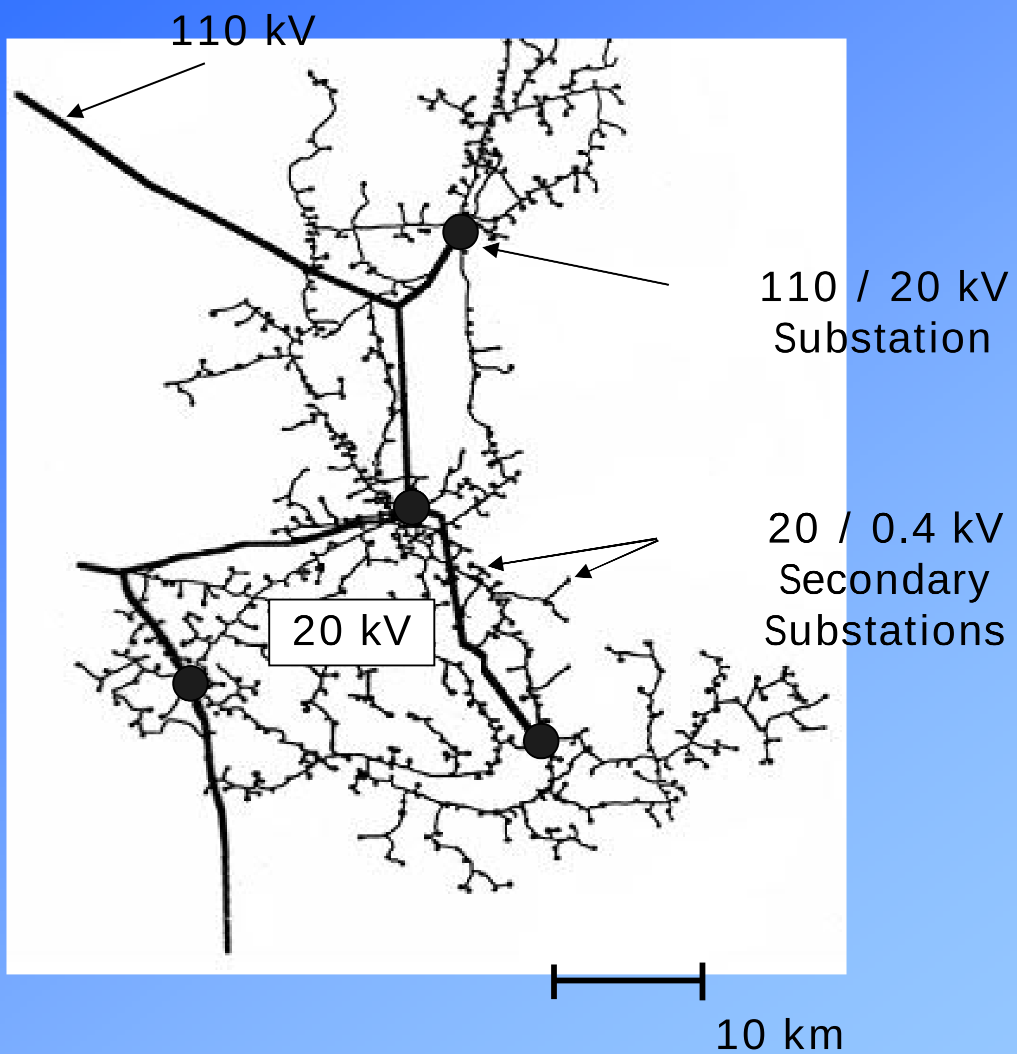
Voltage (Potential) transformers

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





Distribution networks ”on map”



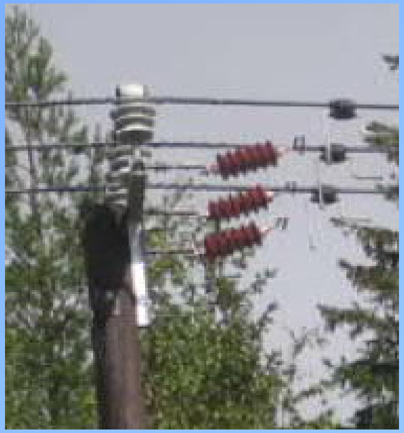
20 kV overhead lines and CC lines

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.

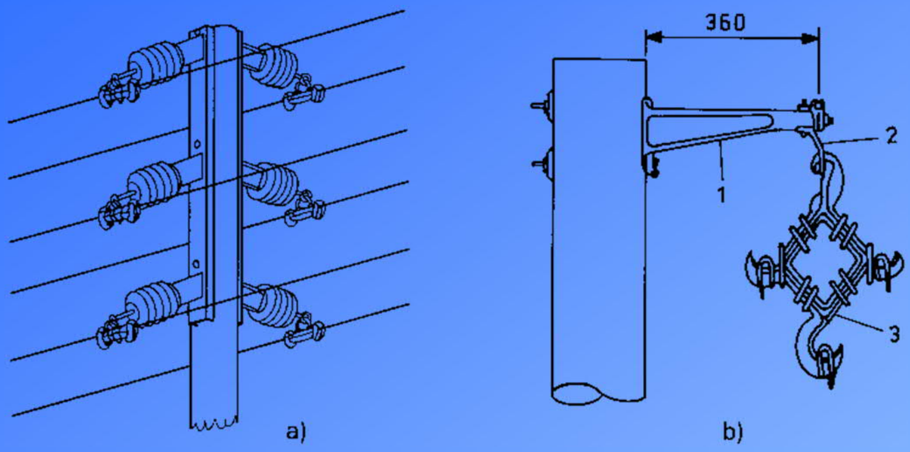
20 kV CC line (Covered Conductor) has a thin insulation cover on phases. The spacing of phases is smaller.

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 $\Rightarrow$ 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

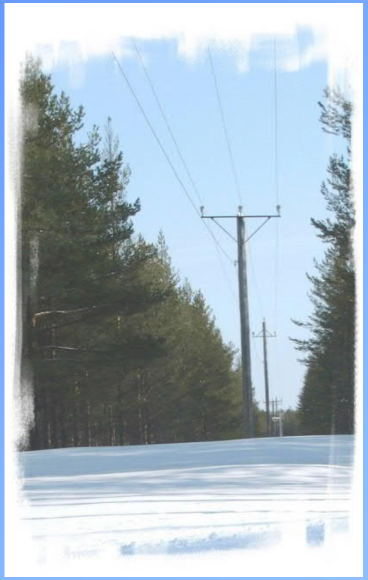
Medium Voltage Overhead lines (1/3)

- 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

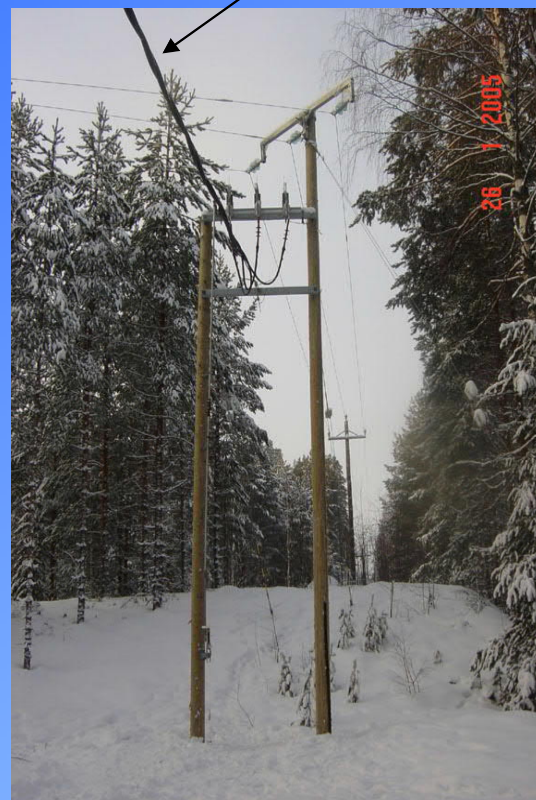
UG Cable

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

Air cable



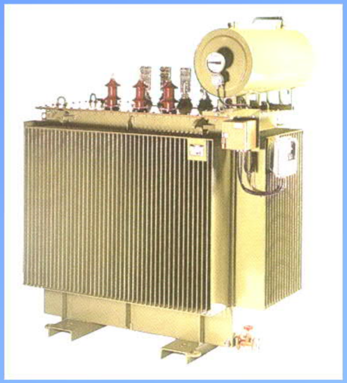
RAKENNE

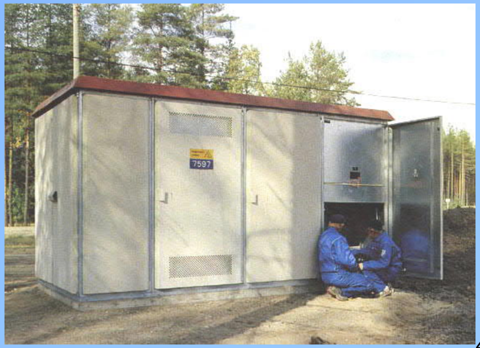
Johdin	25 mm²: Vesitiivis yksilankainen alumiinijohdin 50 … 185 mm²: Vesitiivis pyöreä tiivistetty alumiinijohdin
Johdinsuoja	Puolijohtava muovi
Eristys	PEX-muovi
Hohtosuoja	Puolijohtava muovi
Vesitiivistys	Veden vaikutuksesta paisuva puolijohtava nauha
Kosketussuoja	Alumiini-muovilaminaatti, joka toimii 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)

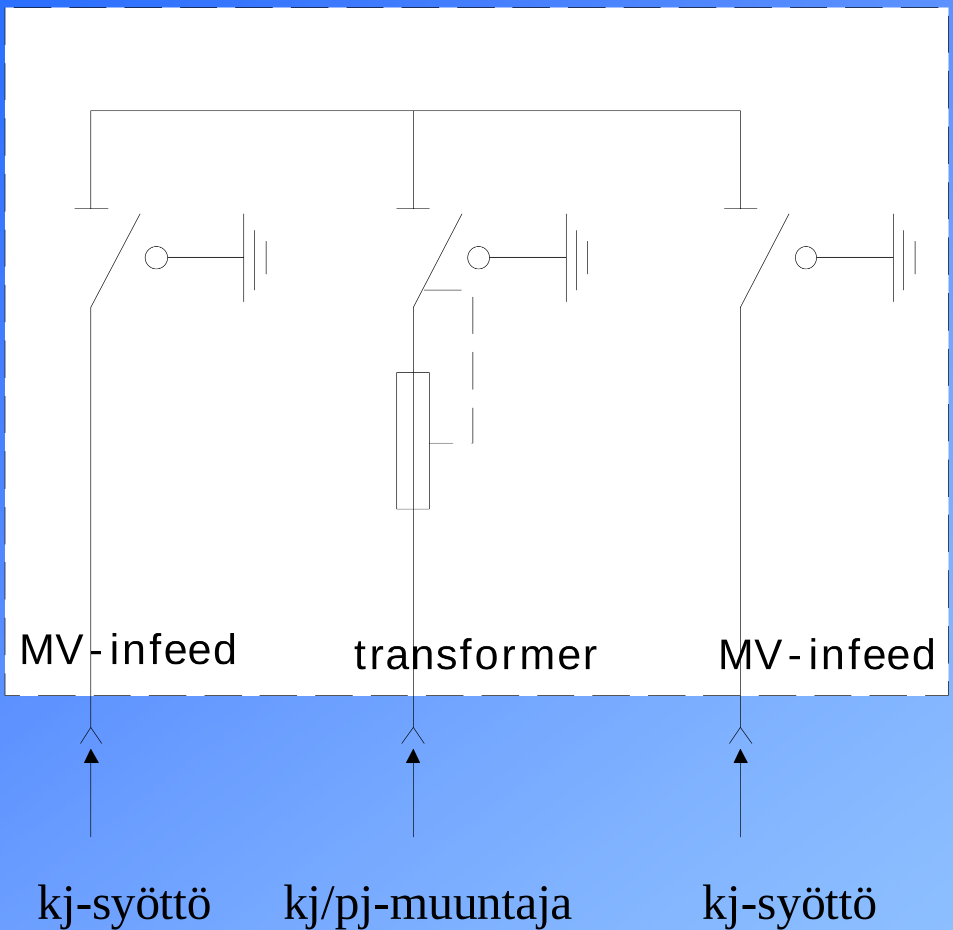
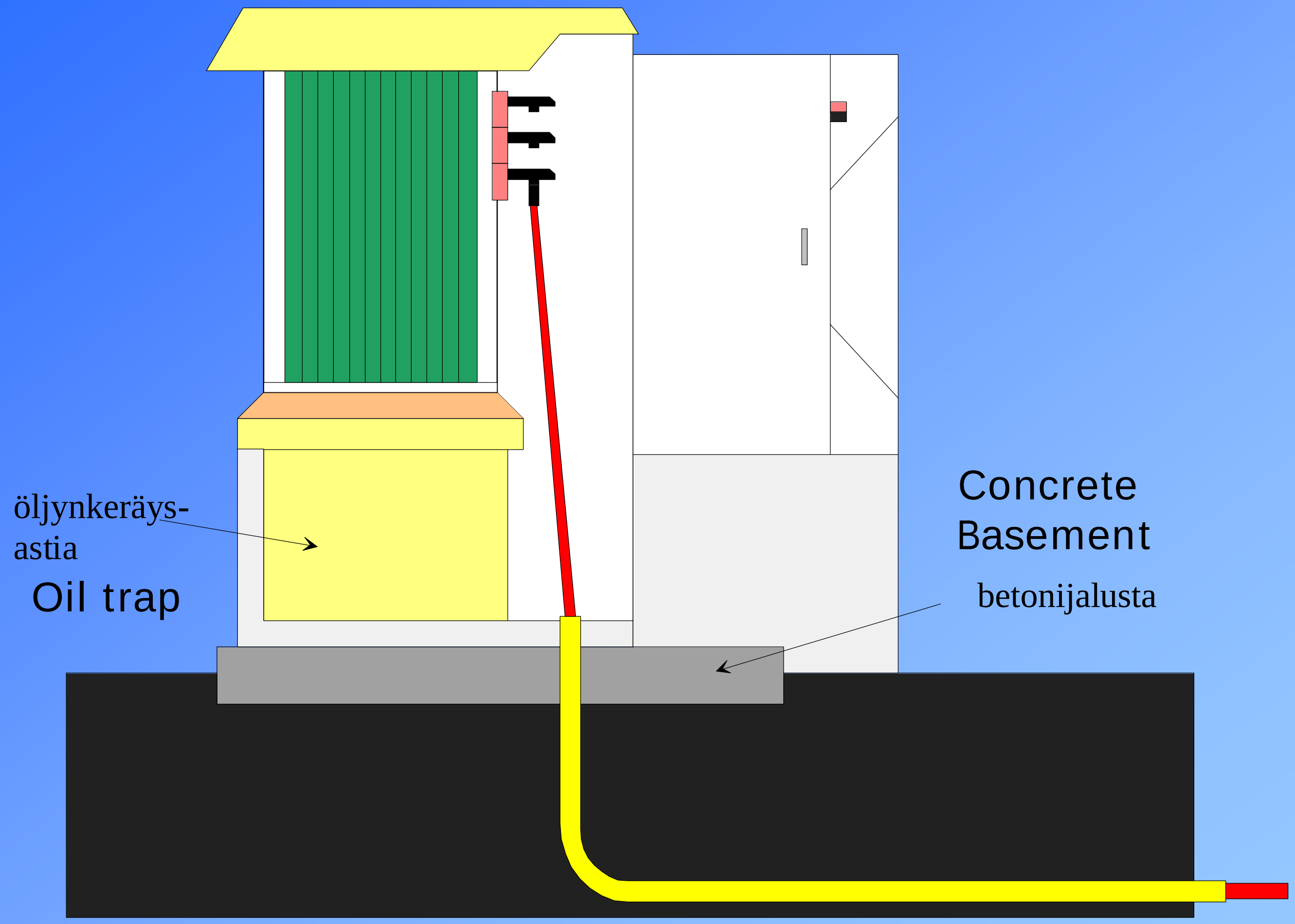


Figure 10.5 Typical prefabricated pad-mounted MV/LV substation

Secondary substations

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

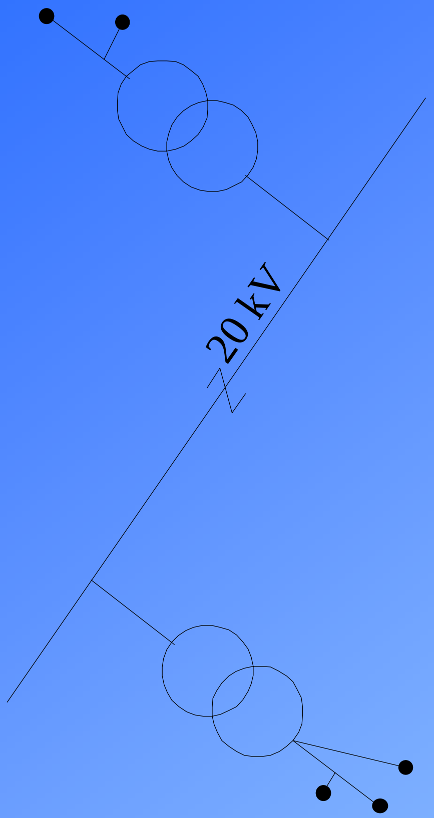


400/1000 V ABC-line (AMKA)

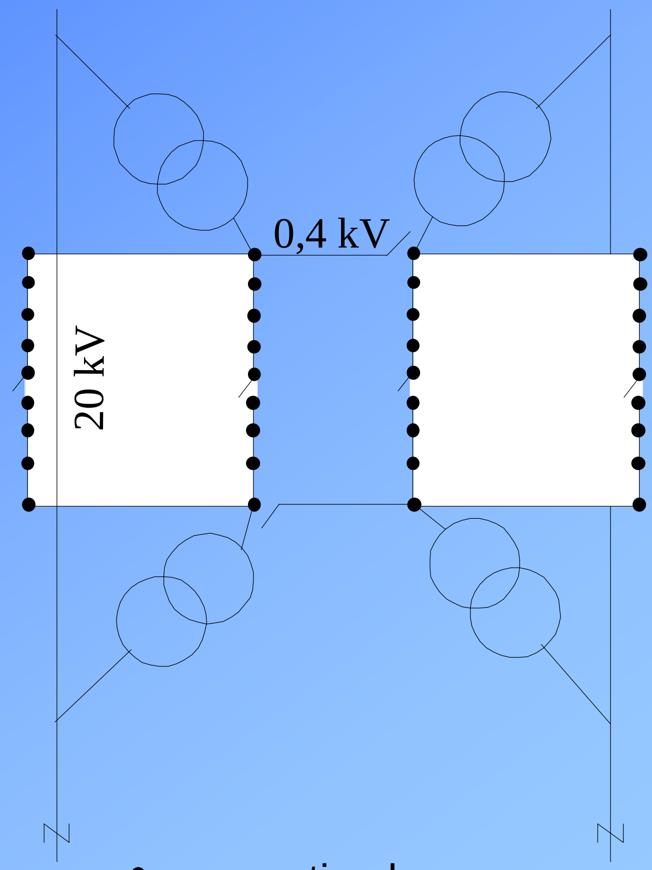
- AMKA – a Air Bundle Cable, where three phase conductors are twisted around the messenger. Messenger works as a PEN-conductor. (combined neutral wire and protective earth conductor).
- AMKA is attached to wood poles and usually used in rural and suburban areas.
- The height of the line is over 4 meters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

Secondary substations



Rural



Urban

Secondary substations, low voltage networks

LV-UGC
LV-ABC
MV line