**ESF II project of the University of West Bohemia in Pilsen**

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EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research,
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MINISTRY OF EDUCATION,
YOUTH AND SPORTS

ZÁPADOČESKÁ UNIVERZITA V PLZNI

# Power transformers

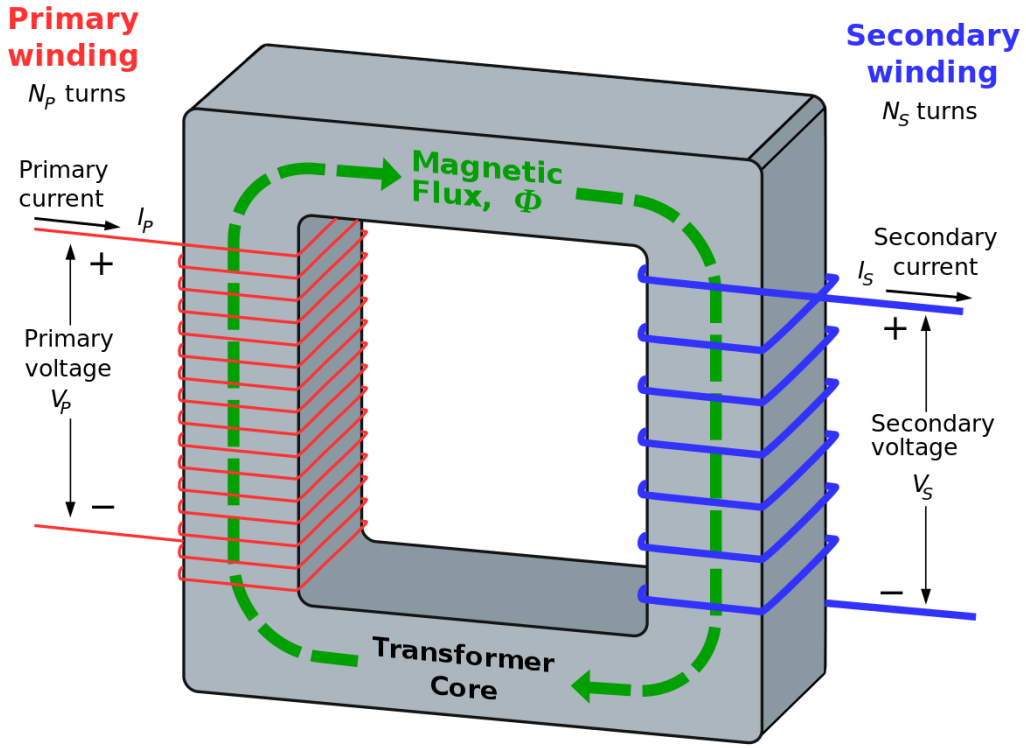
Miloslava Tesařová

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# Principle of a transformer




$$u_i = N\frac{d\phi}{dt} .$$

$$u_i = N\, d(\Phi_{max} \sin\omega t)/dt$$

$$u_i = N\omega\Phi_{max} \cos ?t$$

$$U_{max} = N\omega\Phi_{max}$$

$$\omega = 2\pi f$$

$$U_i = \sqrt{2}\,\pi N f \Phi$$

$$Ui = 4{,}44\, Nf\, \Phi$$

Ui – induced voltage (RMS value)
N – winding turns
Φ - magnetic flux

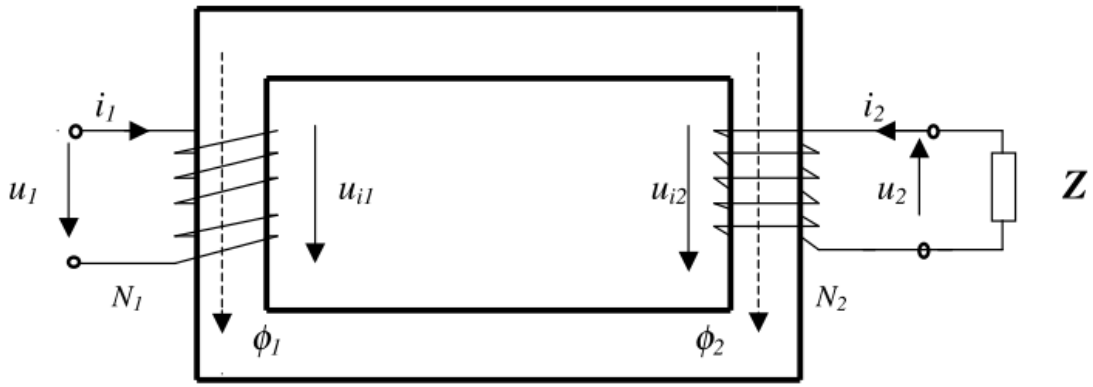
# Transformer ratio

**Transformer ratio :**

**= ration of induced voltages on primary and secondary sides**

$$U_1 = U_{i1} = \sqrt{2}\,\pi f \Phi N_1$$
$$U_2 = U_{i2} = \sqrt{2}\,\pi f \Phi N_2$$

$$P = \frac{U_1}{U_2} = \frac{U_{i1}}{U_{i2}} = \frac{N_1}{N_2}$$

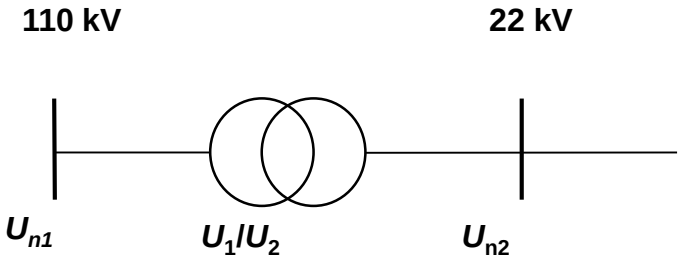



**With neglecting transformer losses: primary input = secondary output**

**$U_1$ x $I_1$ = $U_2$ x $I_2$** $\Rightarrow$ **$U_1$ / $U_2$ = $I_2$ / $I_1$** $\Rightarrow$ $P = \frac{I_2}{I_1}$

# Transformer ratio

**These transformer ratios are defined:**




## a) Nominal ratio

- transformer nominal voltage ratio, e.g. 110/23 kV

$$P = U_1 / U_2$$

- nominal secondary voltage $U_2$ of a transformer, connecting higher voltage level to lower one, is 5% higher than network nominal voltage Un2 (it compensates for voltage drop along a transformer and leads to keeping voltage in permitted band in downstream grid)

## b) Fictitious ratio

- nominal voltage ratio of connected networks, e.g. 110/22 kV

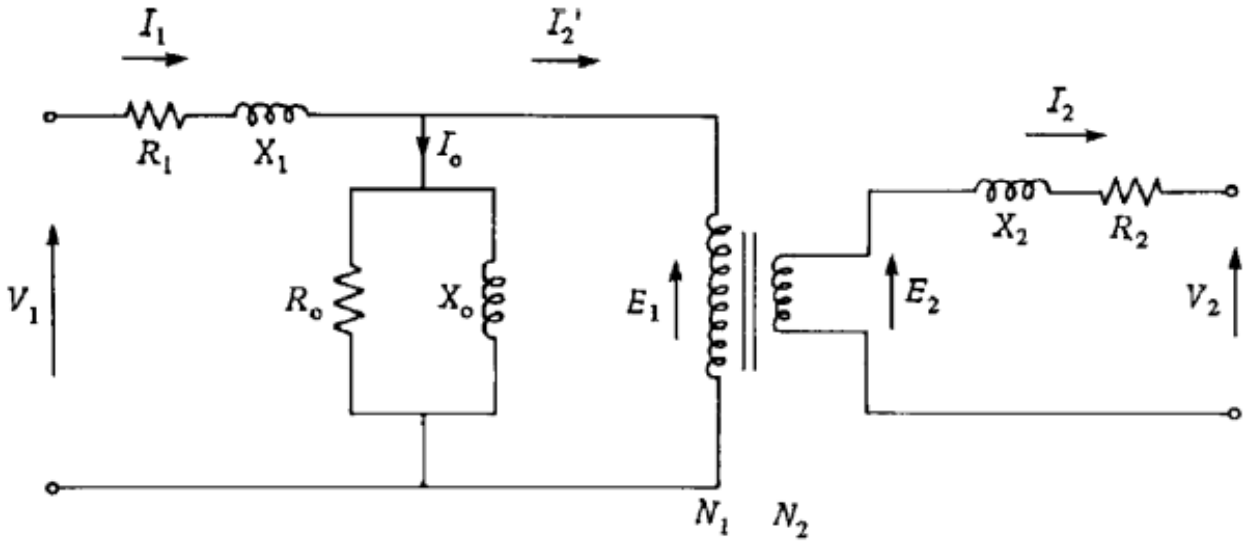
$$P = U_{n1} / U_{n2}$$

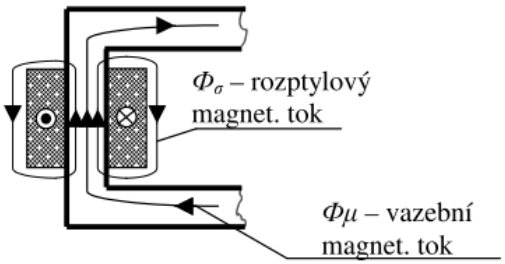
## c) Actual ratio

- ratio of turns set by transformer tap changer

$$P = N_1 / N_2$$

# Transformer equivalent circuit




$V_1$ = primary terminal voltage
$E_1$ = primary induced emf (theoretical)
$V_2$ = secondary terminal voltage
$E_2$ = secondary induced emf (theoretical)

$E_1/N_1 = E_2/N_2$ $\qquad$ $V_1/N_1 - V_2/N_2$

$I_o$ = vector sum of primary magnetizing and core loss currents
$I_1$ = total primary current ($I_o + I_2'$)
$I_2$ = secondary load current
$I_2'$ = load component of total primary current (reflected secondary current)

$X_o$ & $R_o$ = magnetizing and core loss reactive and resistive components
$X_1$ & $R_1$ = primary winding reactive leakage and coil resistance
$X_2$ & $R_2$ = secondary winding reactance and resistance

$N_1$ = primary coil number of turns
$N_2$ = secondary coil number of turns

## Transformer nameplate

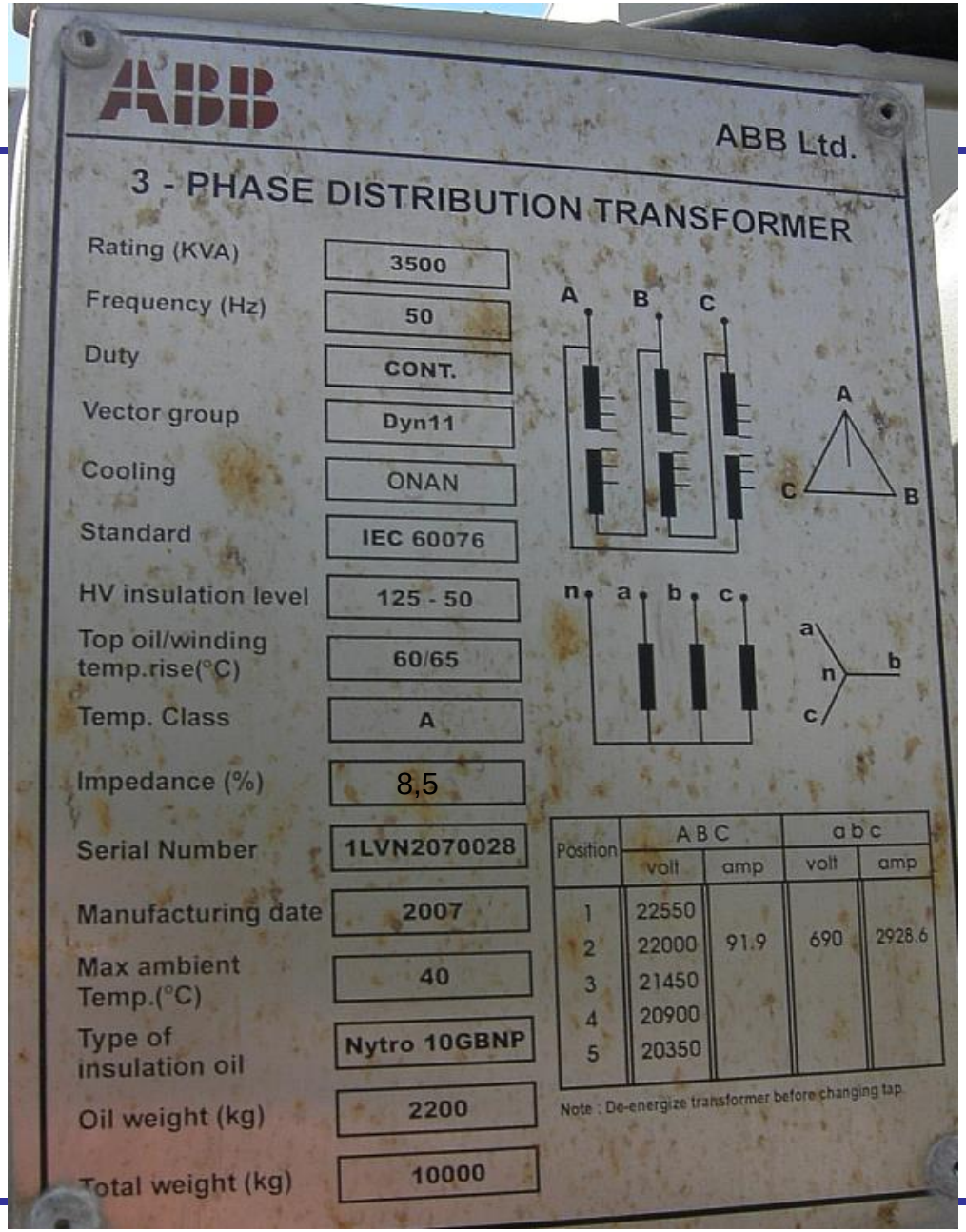
**Trafo 22 / 0,69 kV**
**$S_{nT}$ = 3500 kVA**

**Regulation steps on primary side:**
**+ 1x2,5% Un**
**- 3x2,5% Un**

**impedance = 8,5 %**

**3-phase transformer**
**ONAN**

**Two-winding transformer Dyn 11**



# Transformer parameters

**Nominal voltages (primary, secondary)**
**Transformer ratio, tapping (voltage regulation steps)**

**Nominal Output**

**MV/LV up to 2,5 MVA**
**110/22 kV up to 63 MVA**

**(Short circuit) impedance $u_{k\%}$**

**No-load current $i_{0\%}$**

**Power losses – load loss (cooper loss, loss in windings) $\Delta P_k$**
**- no-load loss (iron loss) $\Delta P_0$**

**Transformer winding connections and phasor relationships (clock hour number)**

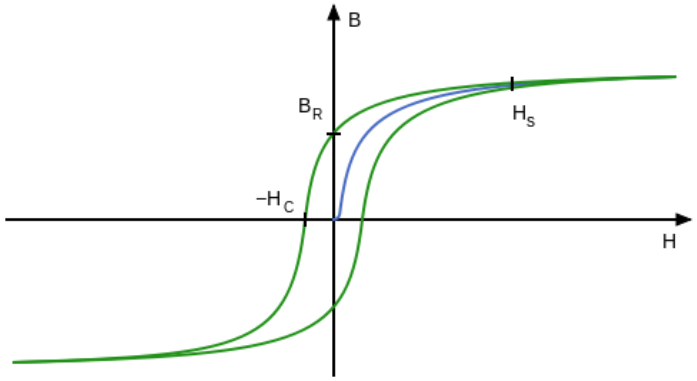
| | |
|---|---|
| **EHV/HV, HV/HV** | **YNynd** |
| **HV/MV** | **YNd1(d) or YNyn0(d)** |
| **MV/MV, MV/LV** | **Dyn** |
| **MV/LV up to 400 kVA** | **Yyn0 or YZn1** |

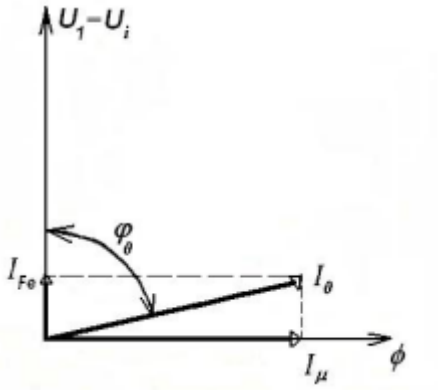
# Transformer parameters

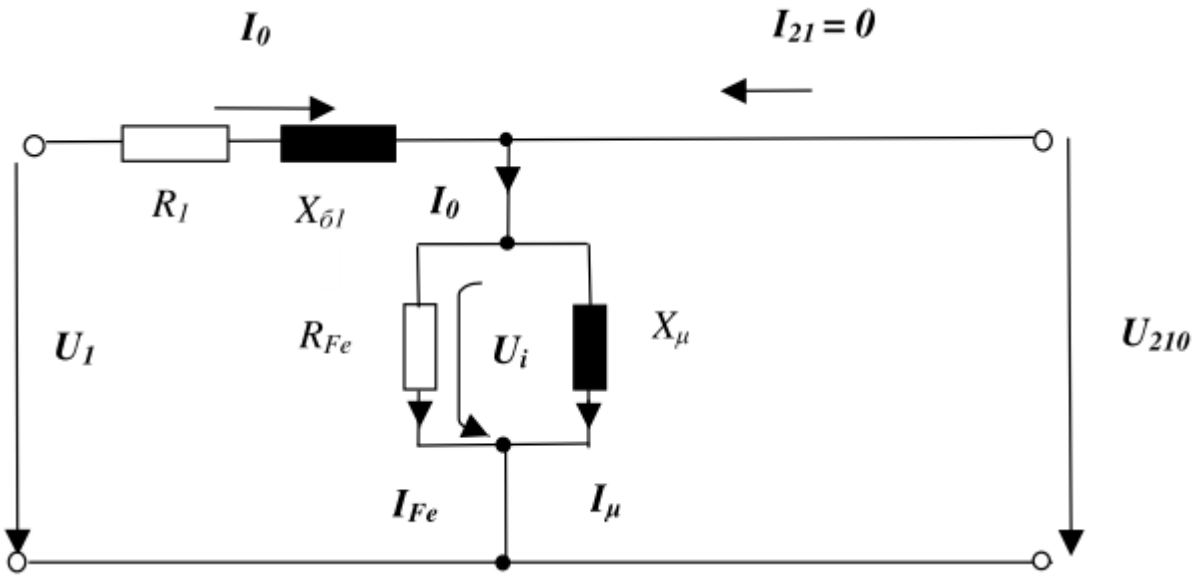
**No-load current $i_{0\%}$ - up to 1% In**

**No-load loss $\Delta P_0$**

- **– Joule's resistance loss in primary winding caused by $I_0$ (negligible)**
- **- loss in iron (magnetic circuit)**
  - **– eddy currents ($I_{Fe}$) and hysteresis**



# Transformer parameters

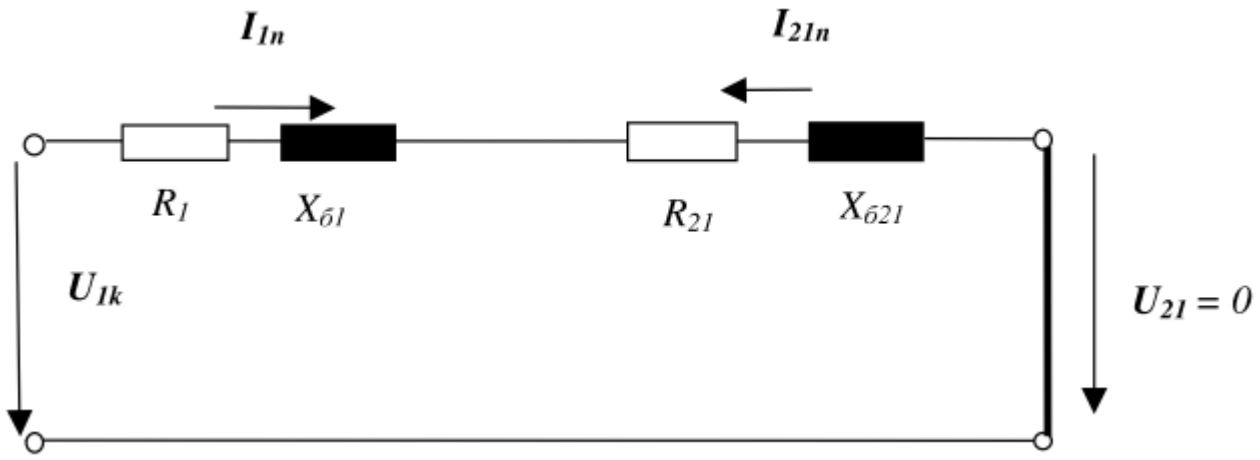
**(Short circuit) impedance $u_{k\%}$**

$u_{k\%} = U_{k1} / U_{n1f}$ pro $R_T << X_T$ $u_{k\%} = U_{k1} / U_{n1f} = (Z_T \cdot In) / U_{n1f}$

| | |
|---|---|
| **MV/LV** | **4 – 6 %** |
| **huge trafas** | **cca 8 – 15 %** |

**Load loss $\Delta P_k$**

**– Joule's resistance loss in primary and secondary winding**



# Transformer losses

**No-load loss $\Delta P_0$ (in iron)**

$$\Delta P_0 = 3 \cdot G \cdot U_f^2 = G \cdot U^2$$

**Loss reduction –**

**- construction of core (lamination, sheet thickness up to 0,5 mm) the thinner the laminations, the lower the eddy currents)**

**- material of core (cold-rolled, grain-oriented steel sheets, amorphous materials)**

**Materials of magnetic cores**

- **Warm rolled FeSi sheets (up to 1960)**
- **cold-rolled, grain-oriented steel sheets**
- **cold-rolled, grain-oriented steel sheets, thickness cca 0,2 mm**
- **amorphous materials (Fe, Si, B alloy, rapid chilling of liquid metal avoids crystal growth) thickness cca 0,02 mm , only 1/3 loss in comparison to above mentioned sheets**

# Transformer losses

**Load loss $\Delta P_k$ (in windings) – about 3 - 4 x higher than $\Delta P_0$**

$$\Delta P_{kn} = 3 \cdot R \cdot I_n^2$$

**Total power loss dependant upon transformer loading – cca 1% Sn**

$$\Delta P_{celk} = \Delta P_0 + \Delta P_k \cdot \left( \frac{I}{I_n} \right)^2 ,$$

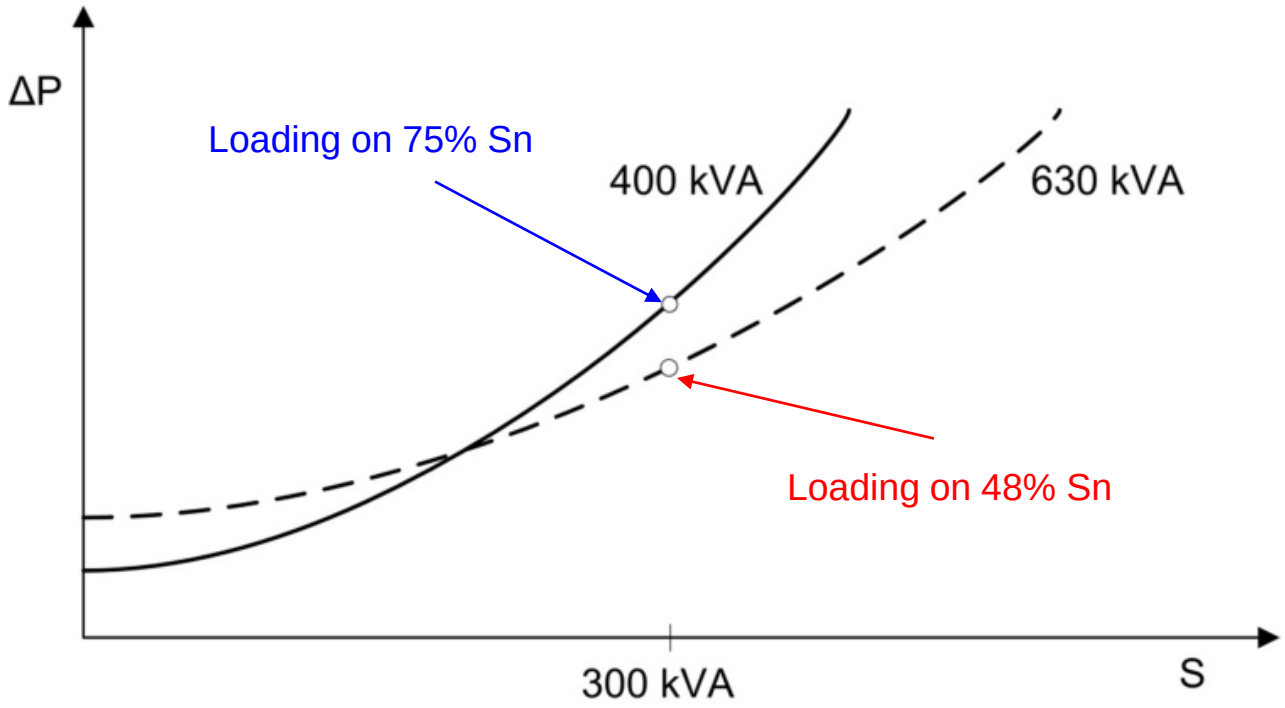
In – nominal current of a transformer
I – actual current flowing true transformer

| DTR 22/0,42 kV 400 kVA | TR se standardními ztrátami | TR s redukovanými ztrátami |
|---|---|---|
| $P_o$ (W) | 930 | 610 |
| $P_k$ (W) | 6000 | 4600 |
| | standard losses | reduced losses |

# Transformer losses

**Optimal transformer loading**

**- cca 70% Sn and lower**



# Transformer losses

**Reactive losses**

$$\Delta Q_{celk} = \Delta Q_0 + \Delta Q_k \cdot \left( \frac{I}{I_n} \right)^2$$

**No-load reactive losses $\Delta Q_0$ (in magnetizing reactance)**

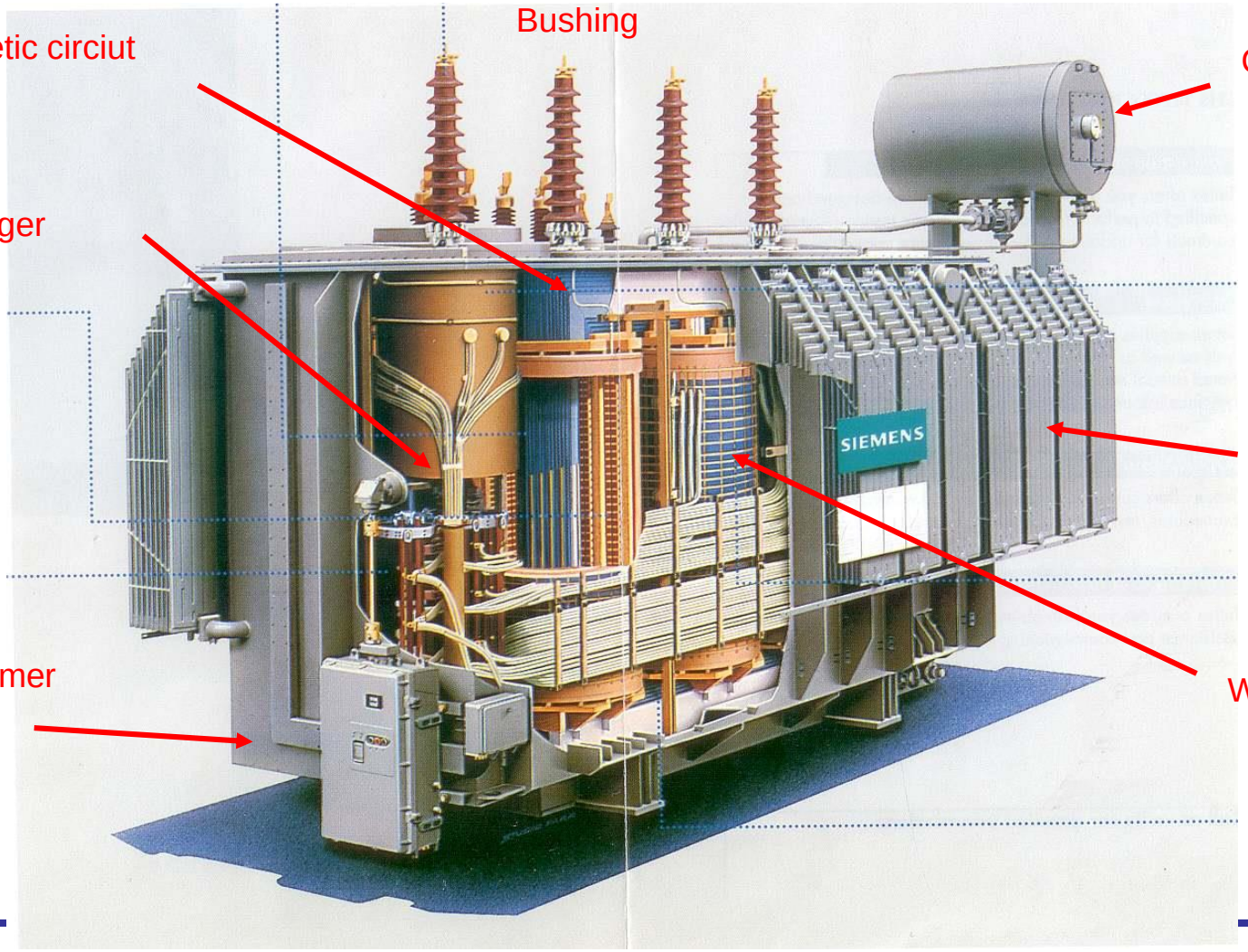
$$\Delta Q_0 = 3 \cdot U_f \cdot I_0 = \sqrt{3} \cdot U_n \cdot I_0 = \sqrt{3} \cdot U_n \cdot i_0 \cdot I_n = \sqrt{3} \cdot U_n \cdot i_0 \cdot \frac{S_n}{\sqrt{3} \cdot U_n} = i_0 \cdot S_n$$

**Load reactive losses $\Delta Q_k$ (in leakage reactances)**

$$\Delta Q_{kn} = 3 \cdot X_\sigma \cdot I_n^2 = 3 \cdot \frac{U_{kf}}{I_n} \cdot I_n^2 = 3 \cdot u_k \cdot U_{nf} \cdot I_n = u_k \cdot S_n$$

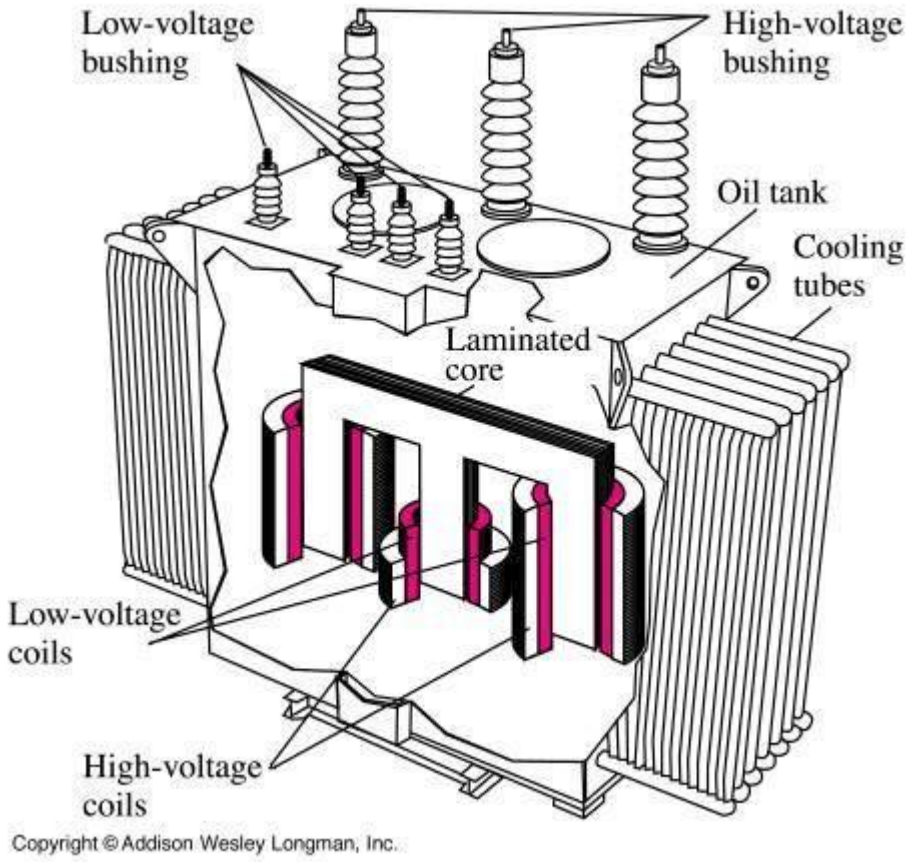
**In comparison to transformers produced before 30 - 40 years, reactive losses of transformers used in present are 10 - 20%.**

# Transformer 110 kV / vn

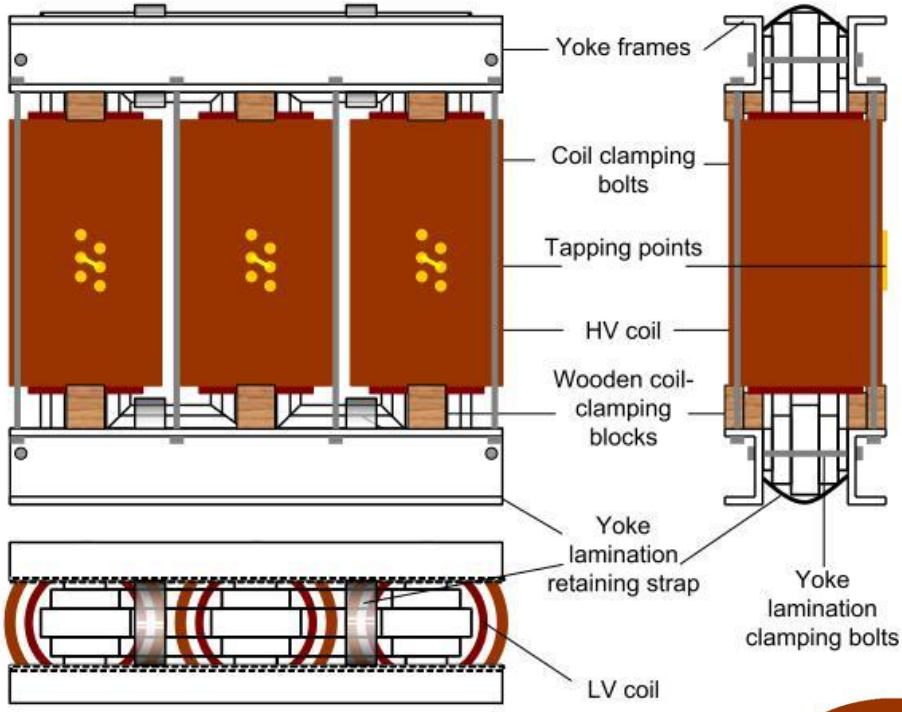


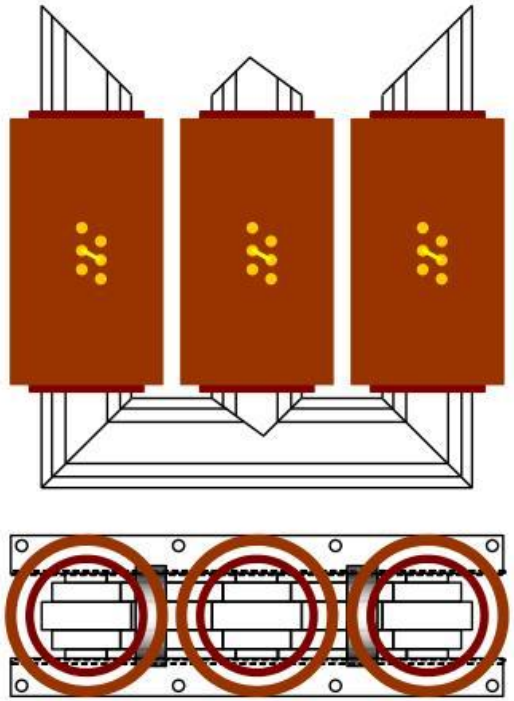
# Transformer construction

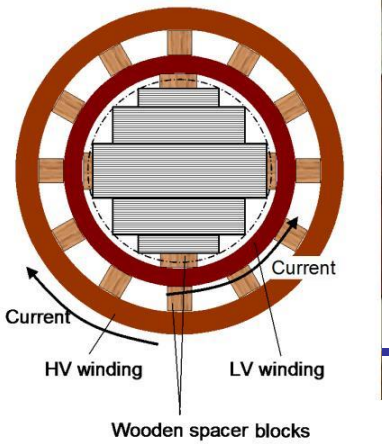
Oil transformer MV/LV



# Transformer construction

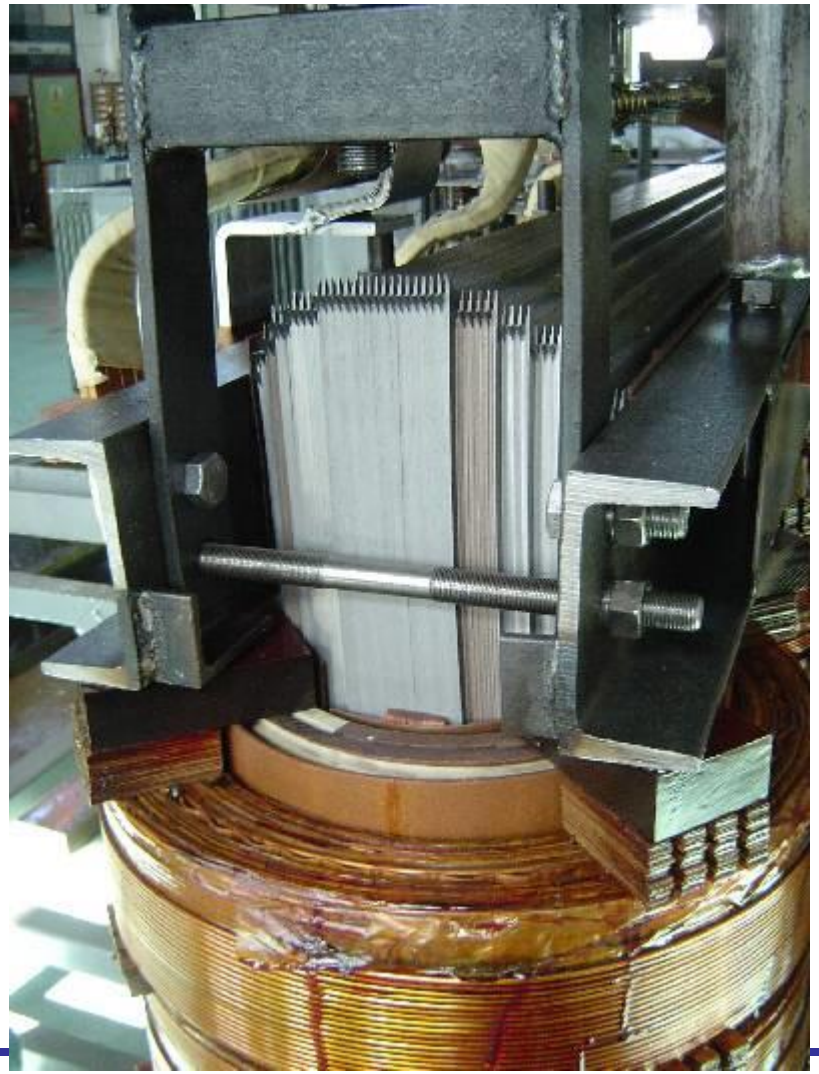




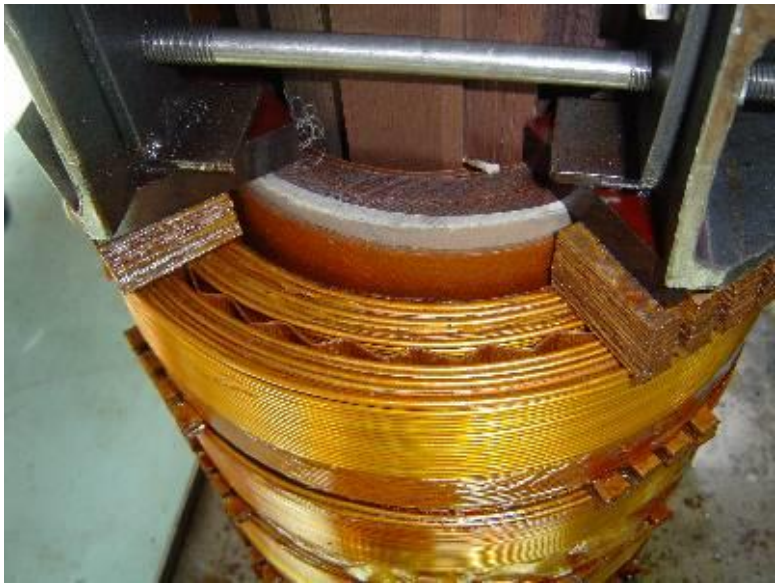
# Transformer construction





# Transformer construction







# Transformer cooling

## Cooling classification

**1st letter – primary cooling medium (winding cooling)**
**2nd letter – way of primary cooling medium circulation**
**3rd letter – secondary cooling medium (tank cooling)**
**4th letter – way of secondary cooling medium circulation**

**Kind of cooling medium**

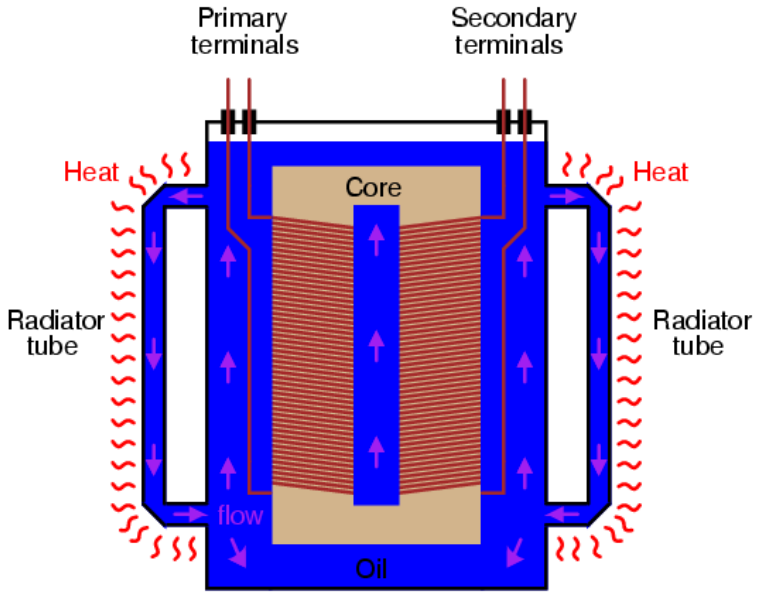
| | |
|---|---|
| O | oil |
| A | air |
| W | water |

**Kind of circulation**

| | |
|---|---|
| N | natural circulation |
| F | forced circulation (pump, cooling air fan) |

**ONAN - oil-immersed transformer with natural oil circulati**
**naturally to surrounding air**
**application: MV/LV transformers**

**ONAF - oil-immersed transformer with natural oil circulati**
**radiators dissipating heat to surrounding air**
**application: huge EHV/HV, HV/MV transformers**

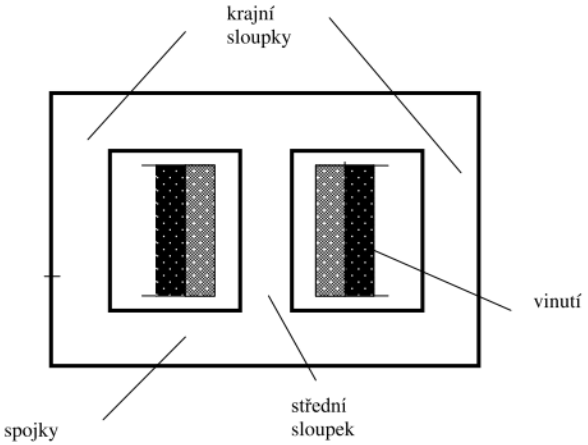



**Added fans to radiators increase loading of a transformer about 40%.**

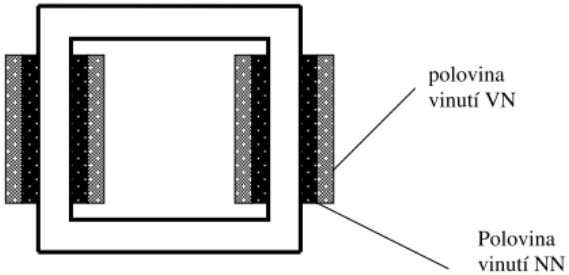
# Transformer division

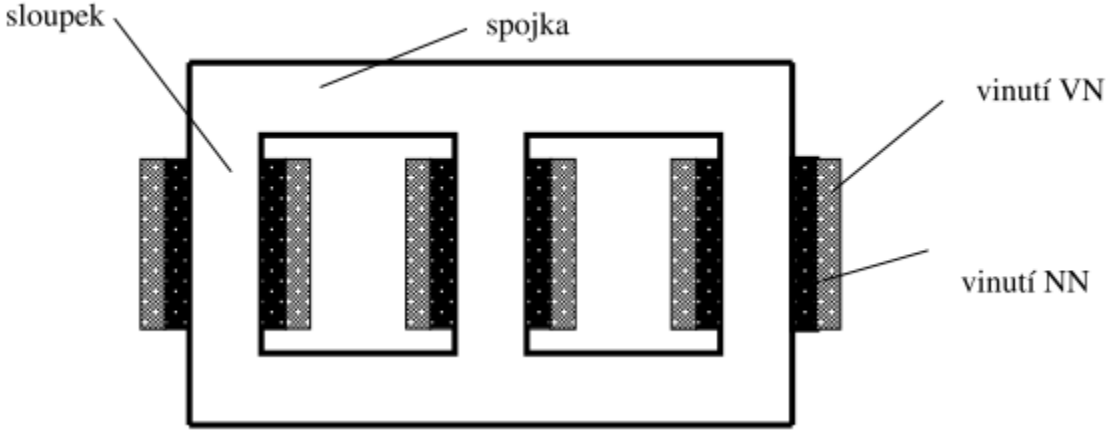
**According to magnetic core arrangement**

**– sheel-type**




**- core-type**



# Transformer division

**According to insulation medium**

- **– oil-type – huge outputs, more effective cooling**
- **– dry-type – lower outputs, they can be installed on the floor, in the roof, less fire hazard**





# Transformer division

**According to location**

- **– outdoor – huge outputs výkony**
- **– indoor – lower outputs, $CO_2$ extinguishing systems, ventilation, separation of switchgears**





# Transformer division

**According to location**

- **– outdoor – huge outputs výkony**
- **– indoor – lower outputs, $CO_2$ extinguishing systems, ventilation, separation of switchgears**



**outdoor two-pole trafostation**



**kiosk trafostation with 2 transformers**

# Transformer division

**According to number of phases – 3-phase TR**
**- 1-phase TR**

**- huge 3-phase transformers can be designed as three 1-phase transformers**

**According to their connection into the power system**

- **step-down transformers**
- **step-up transformers (they connect generators to power system)**

**So called block transformers – between generator and power system (G and TR are connected usually by metal-enclosed conductors)**

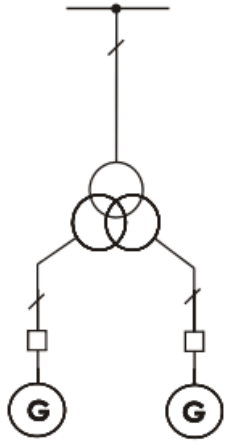
**According to winding number**

**– two-winding (primary and secondary winding)**

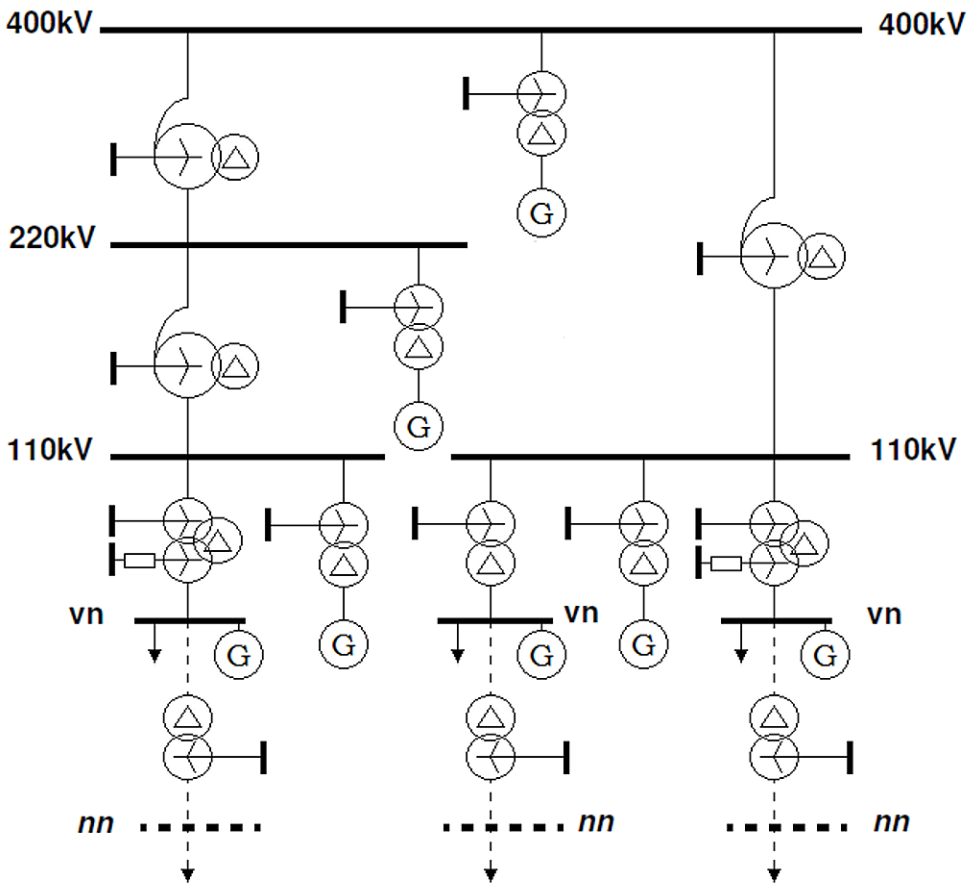
**- three-winding**

- **double secondary transformers , e.g. power plants**
- **transformers with tertiary winding , e.g. TR 110/22 kV tertiary winding D (reduction of unsymetry)**

**- autotransformer, e.g. EHV/HV**

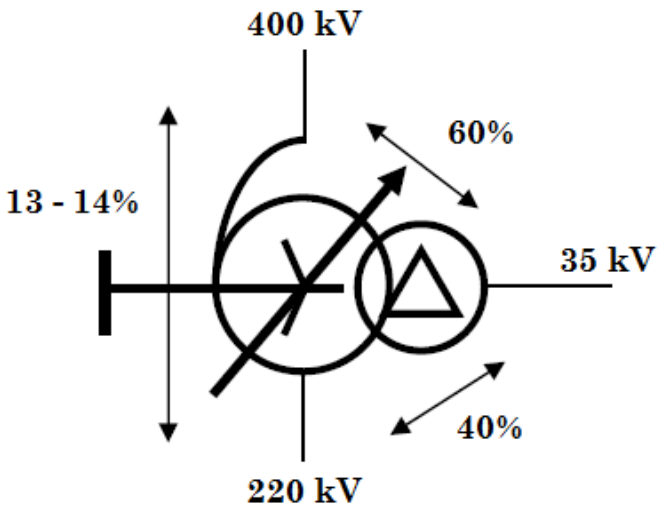


# Transformer concept of Czech power system

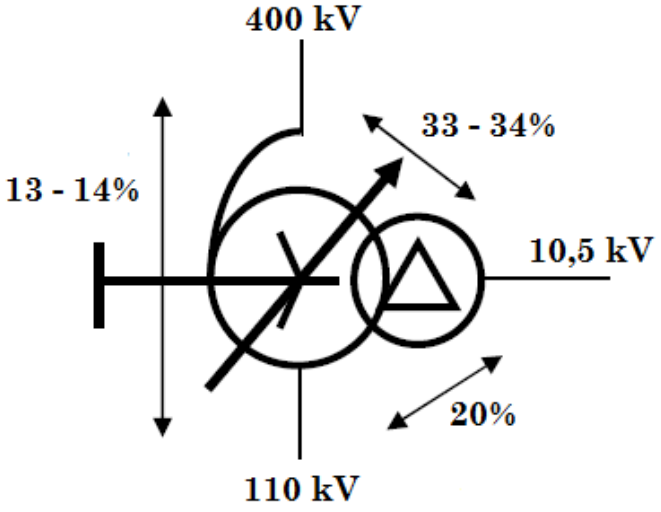


# Transformer concept of Czech power system

**400/220 kV transformers**

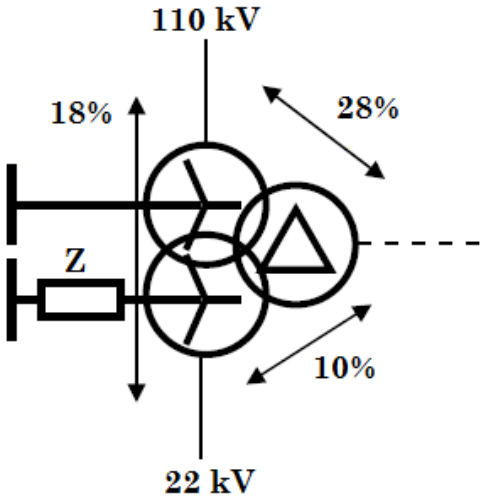



**400 (220)/110 kV transformers**

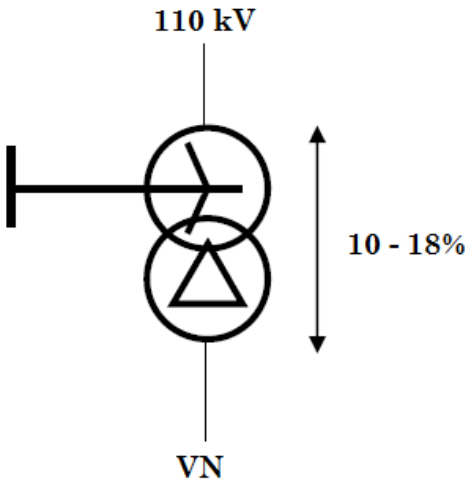


# Transformer concept of Czech power system

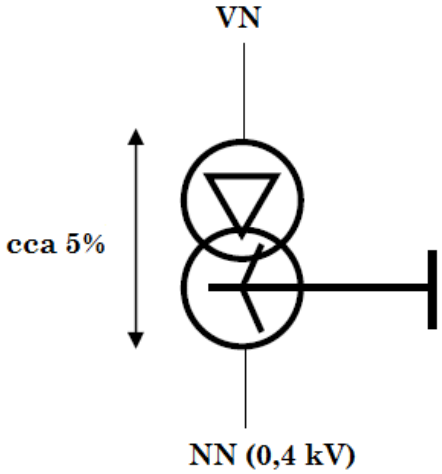
**110/22 kV transformers**



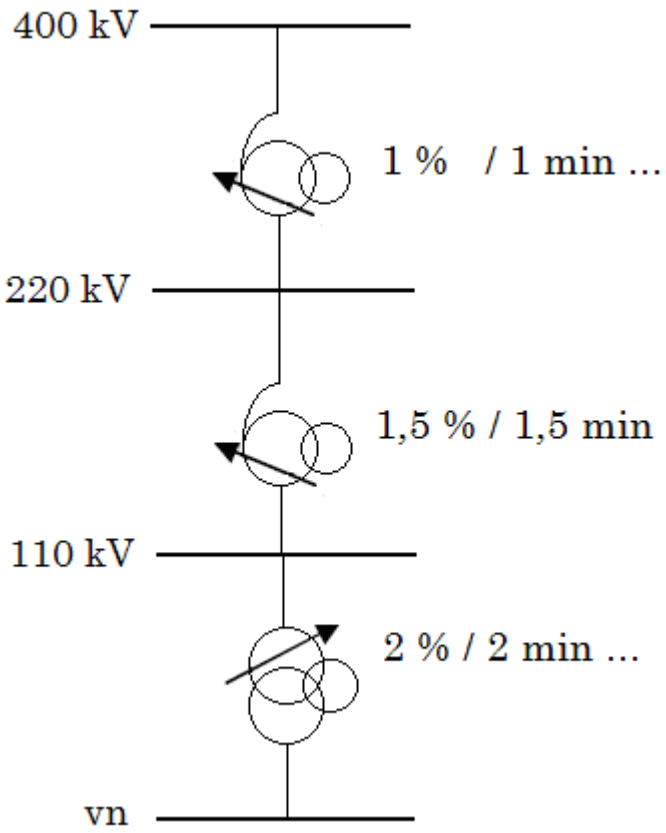

**Transformers of industrial consumers**




**Distrubution transformers**



# Transformer concept of Czech power system



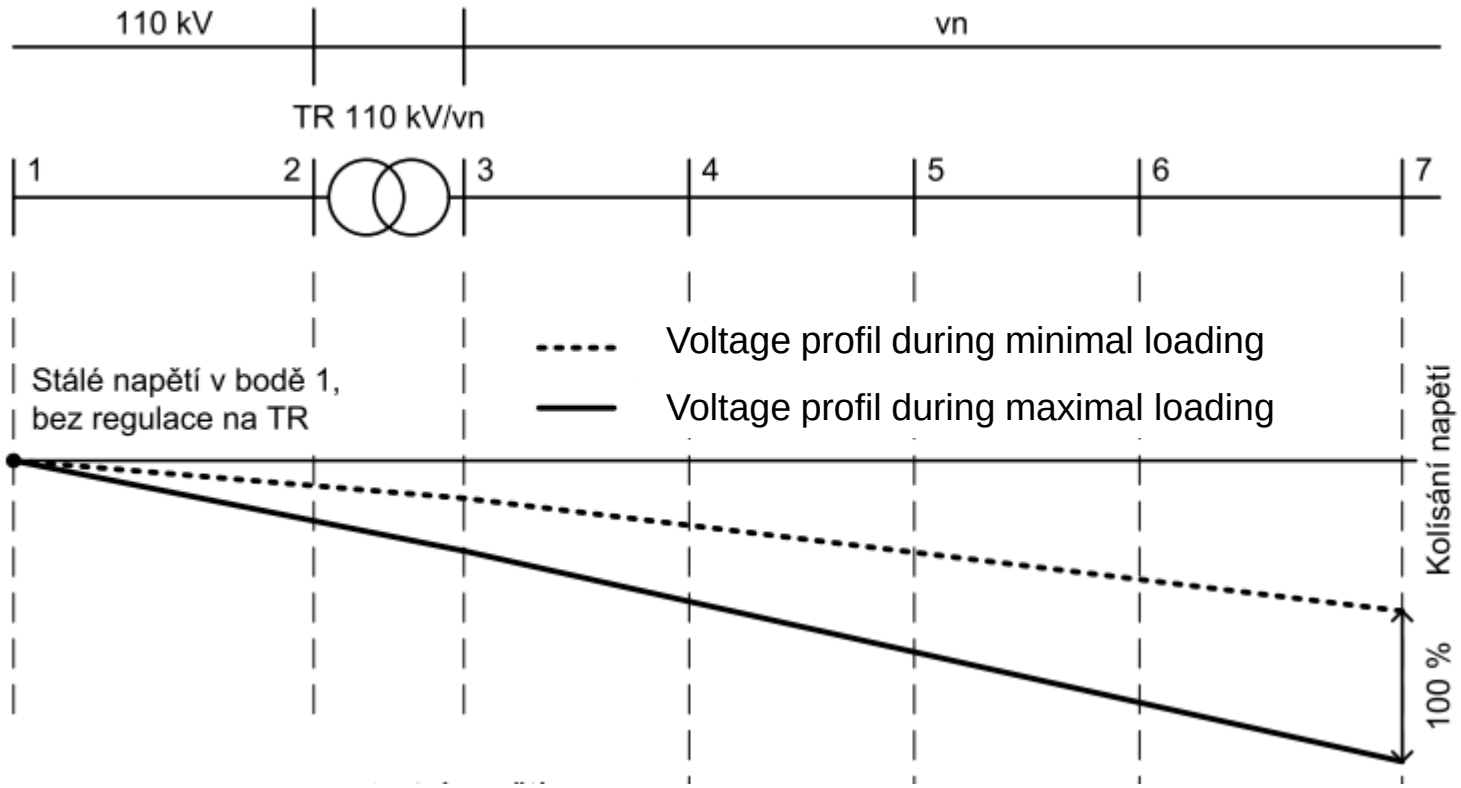

**Voltage regulation step and timing**

**Trafo 110 kV ± 8x2% / 23 kV**

**Principal tap – ratio 110 / 23 kV**

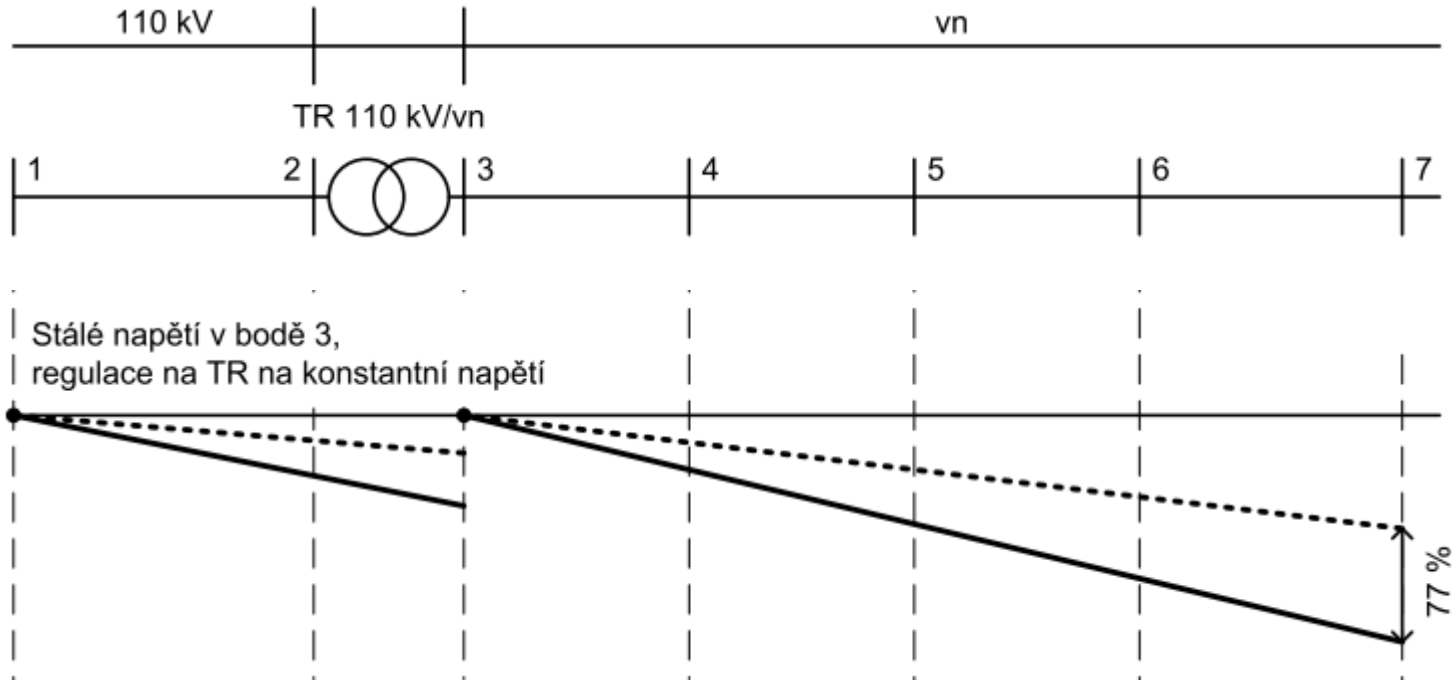
# Voltage regulation in DS

Without any voltage regulation



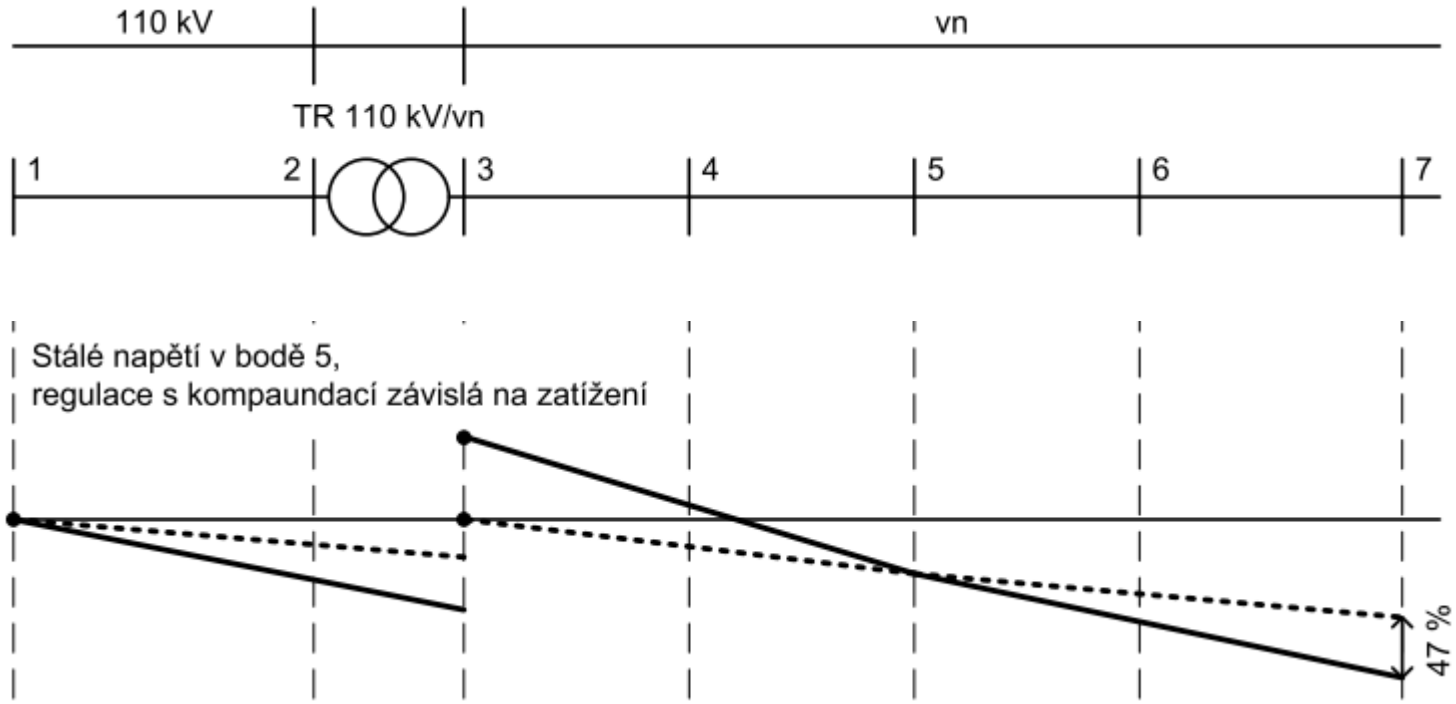
# Voltage regulation in DS

Voltage regulation – constant voltage in MV substation (bus 3)
- Constant volatge 23,1 kV, i.e. 105 % Un



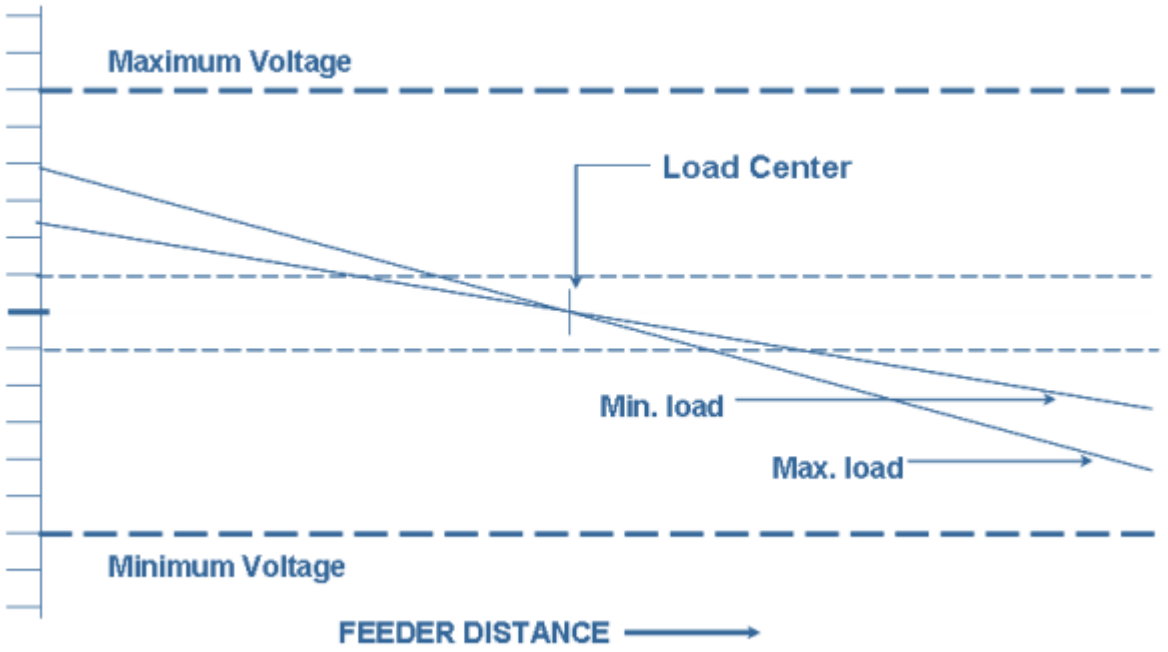
# Voltage regulation in DS

Voltage regulation – variable voltage in MV substation (bus 3) in dependance on network loading (line drop compensation)

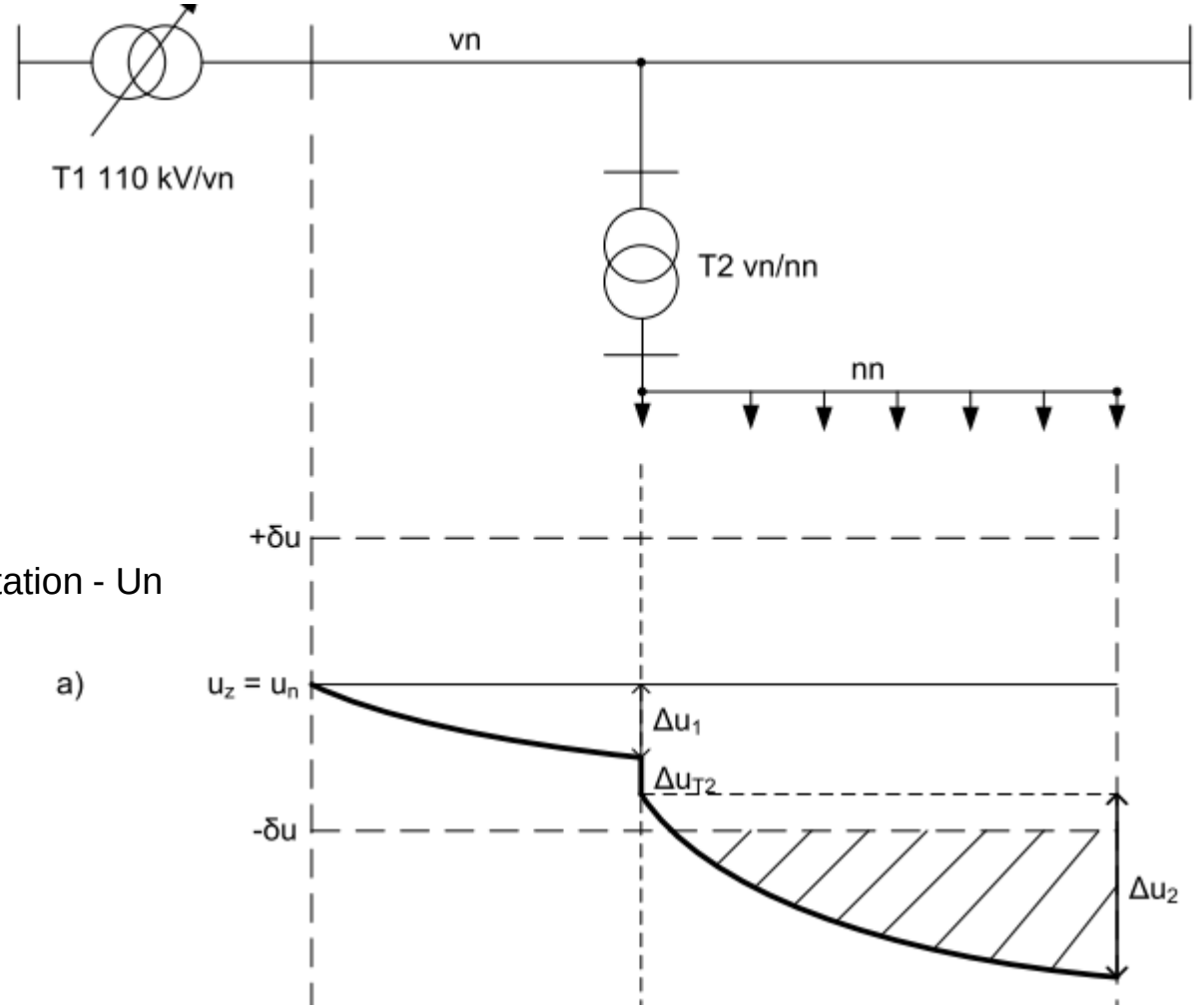


# Voltage regulation in DS

Voltage regulation – variable voltage in MV substation (bus 3) in dependance on network loading (line drop compensation)



# Voltage regulation in DS

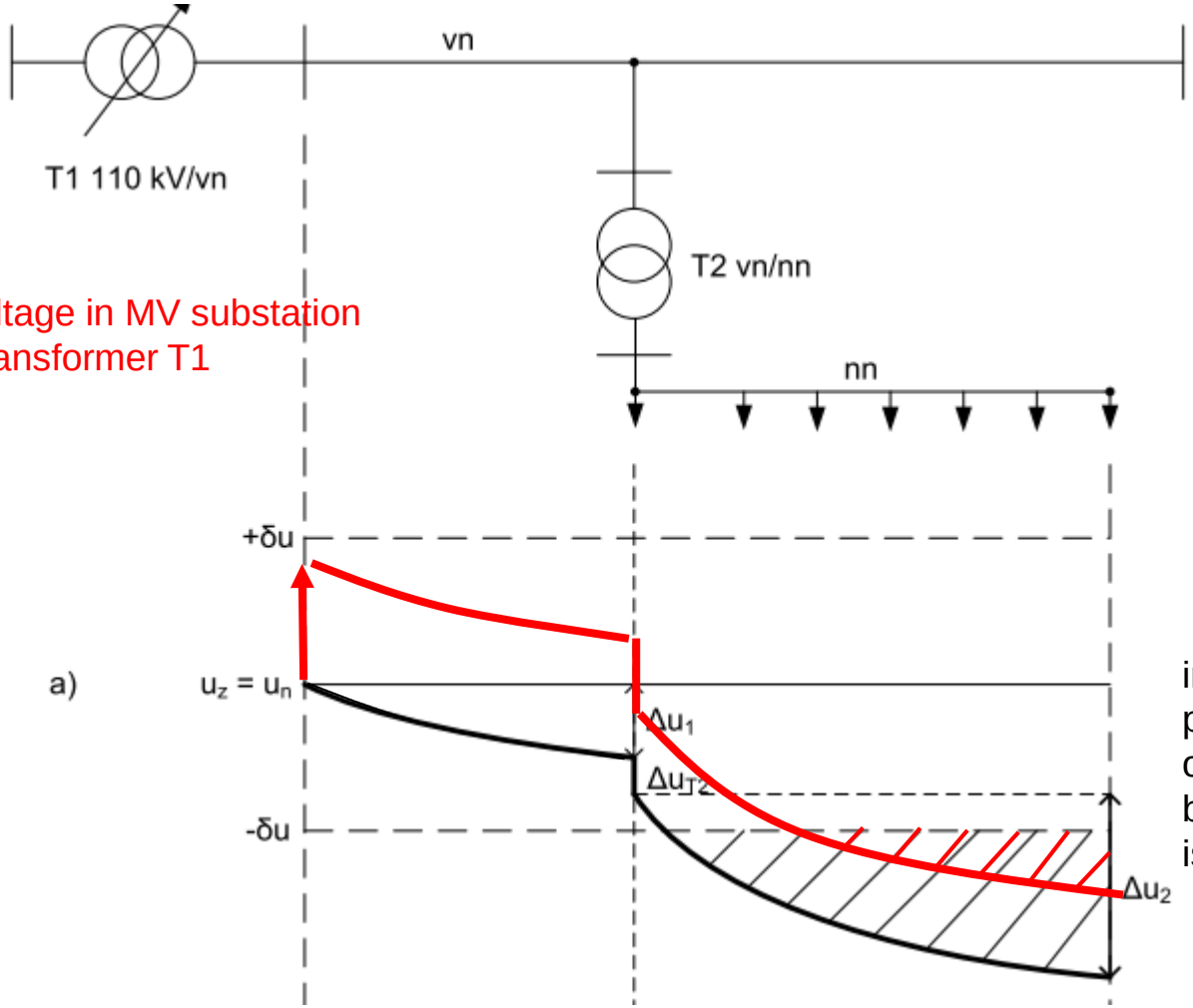



In MV substation - Un

in LV network
is undervoltage

# Voltage regulation in DS

To increase voltage in MV substation
by means of transformer T1

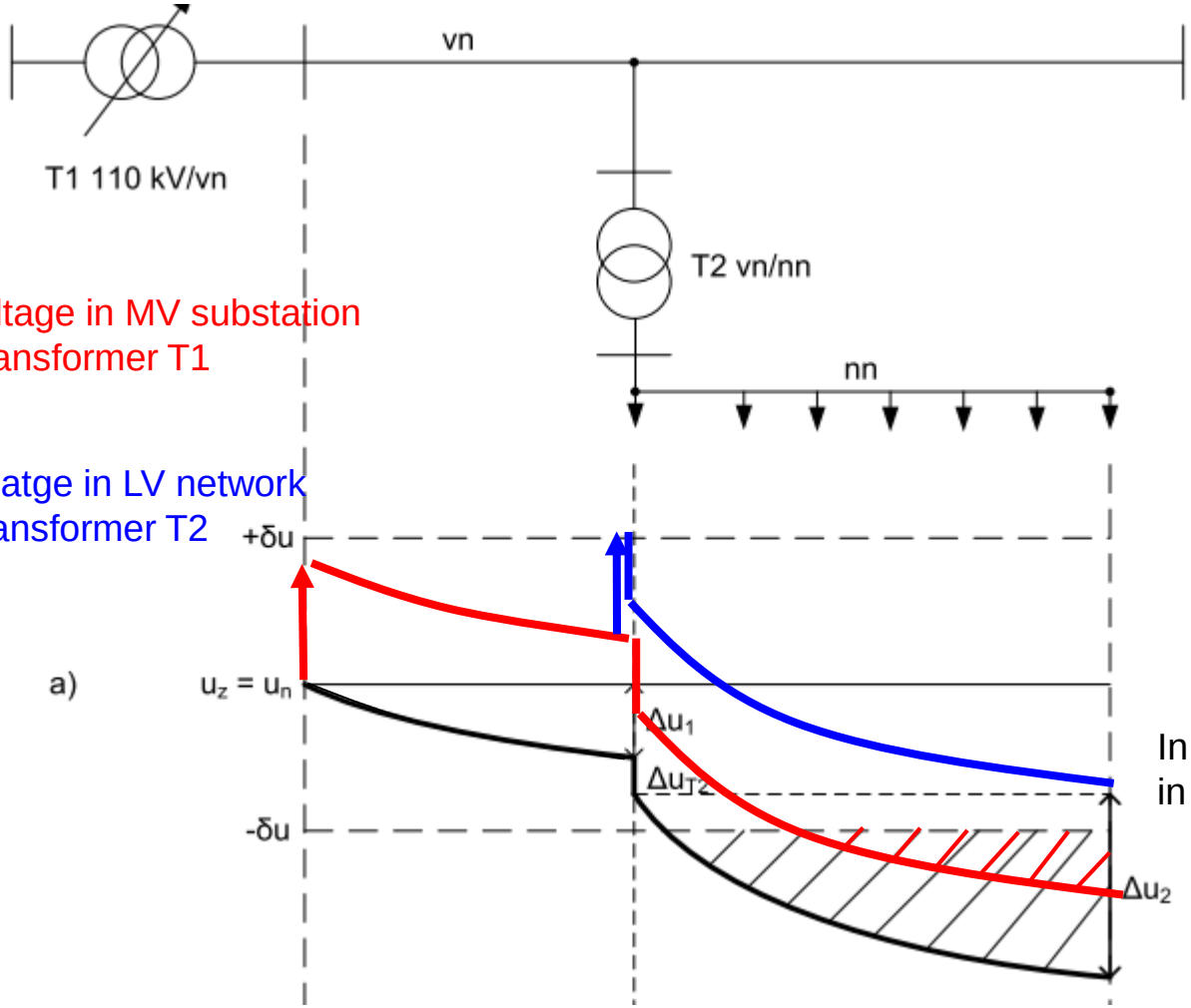



in LV network
partial improvement
of voltage conditions,
but in some parts
is still undervoltage

# Voltage regulation in DS

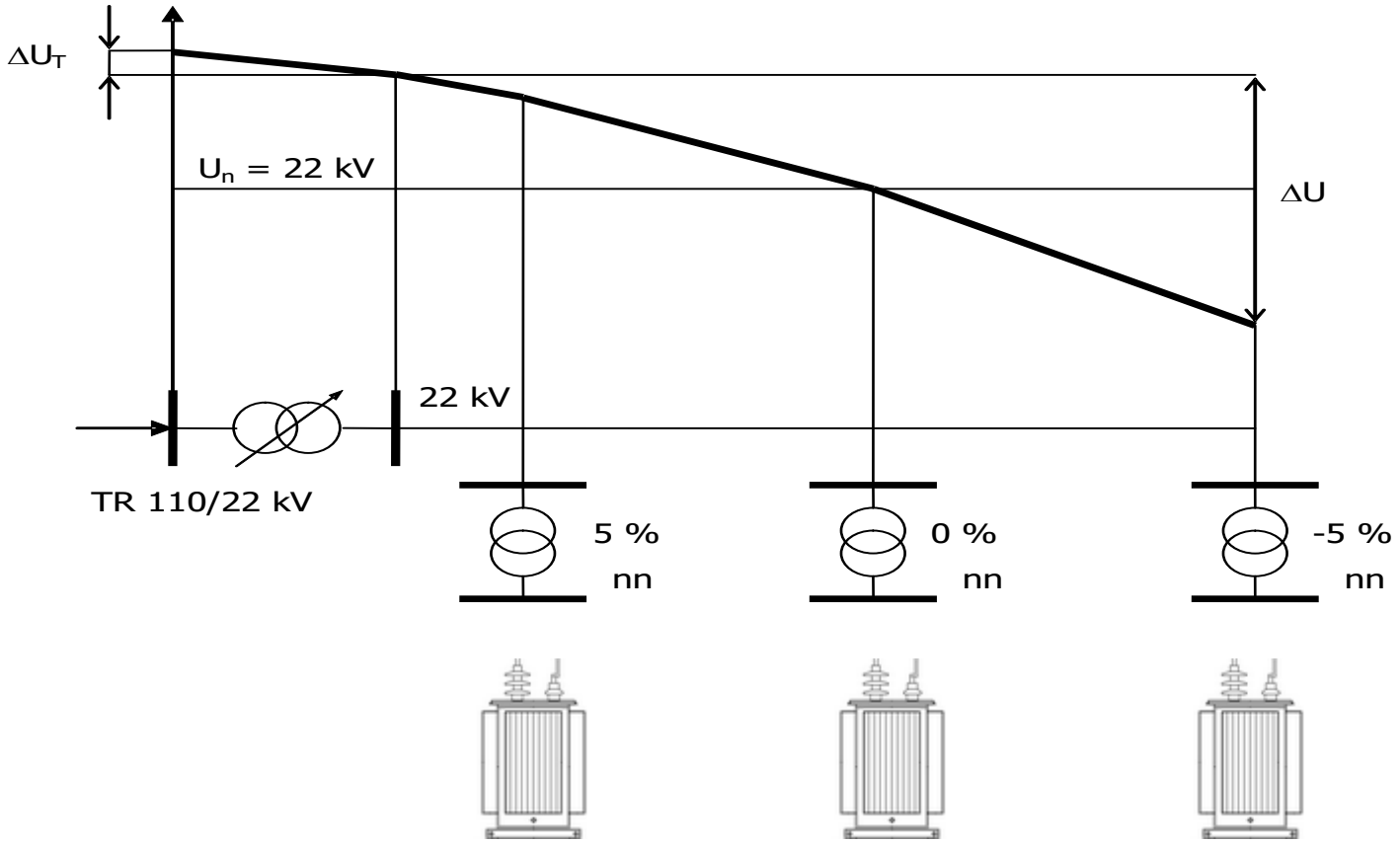
To increase voltage in MV substation
by means of transformer T1

To increase volatge in LV network
by means of transformer T2




In LV network is voltage
in permissible band - OK

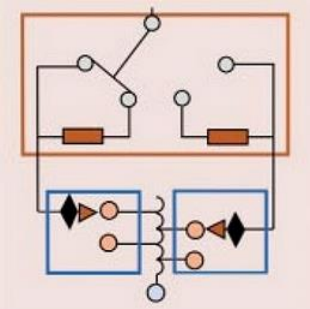
# Voltage regulation in DS

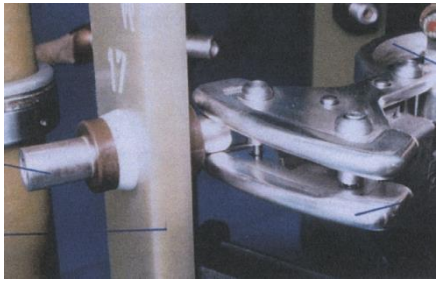


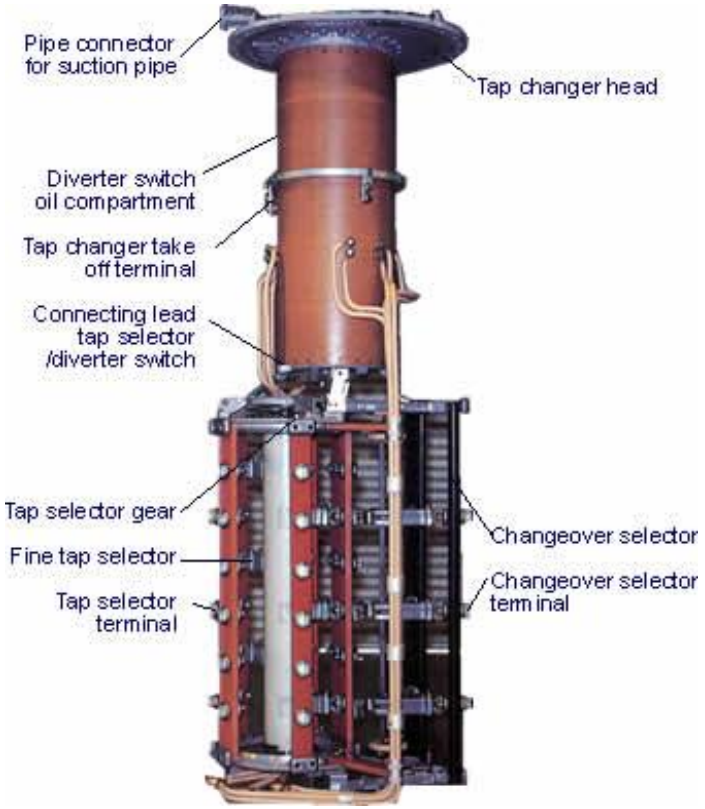
# Voltage regulation

## OLTC (on-load tap changer) transformers

- manipulation with tap changer without transformer switch-off
- EHV/HV, 110 kV/MV
- rarely MV/LV – cca 3 times expensive !







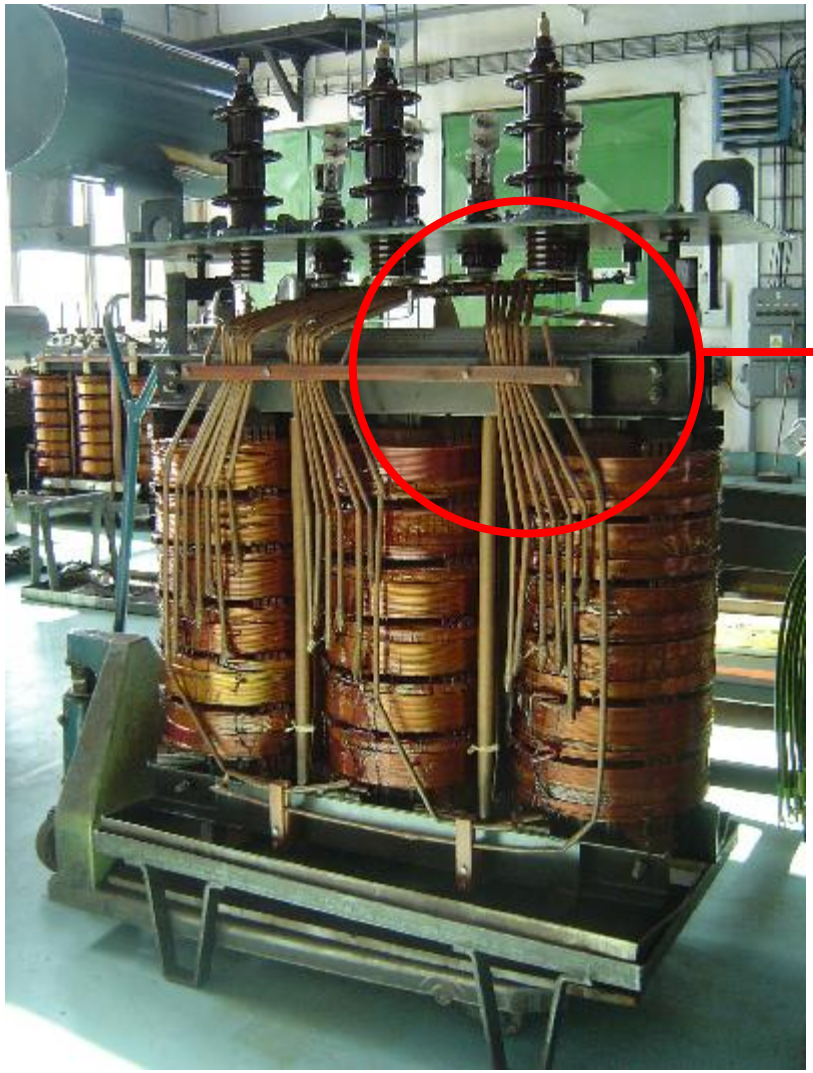

## Off-load tap changer transformers

- manipulation with tap changer only if transformer is switch-off
- MV/MV and MV/LV

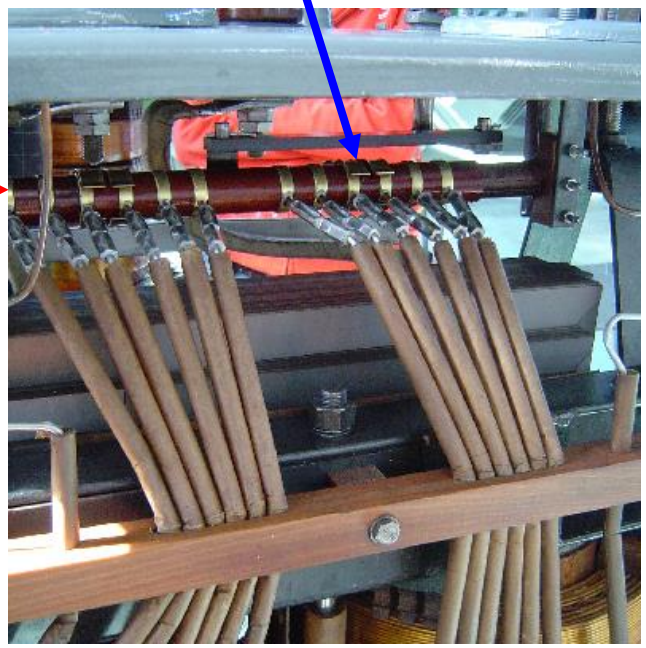


# Transformers MV/LV

## Tap changer



Tap selector



# Transformers MV/LV

## Tap setting on distribution transformers





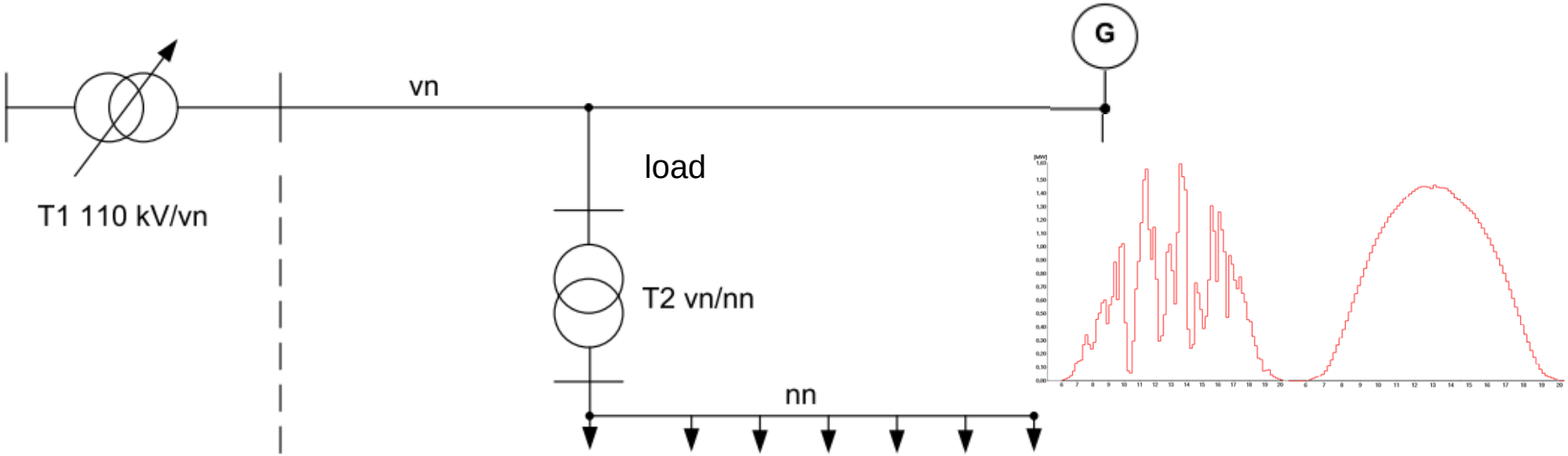
Tap selector
external part



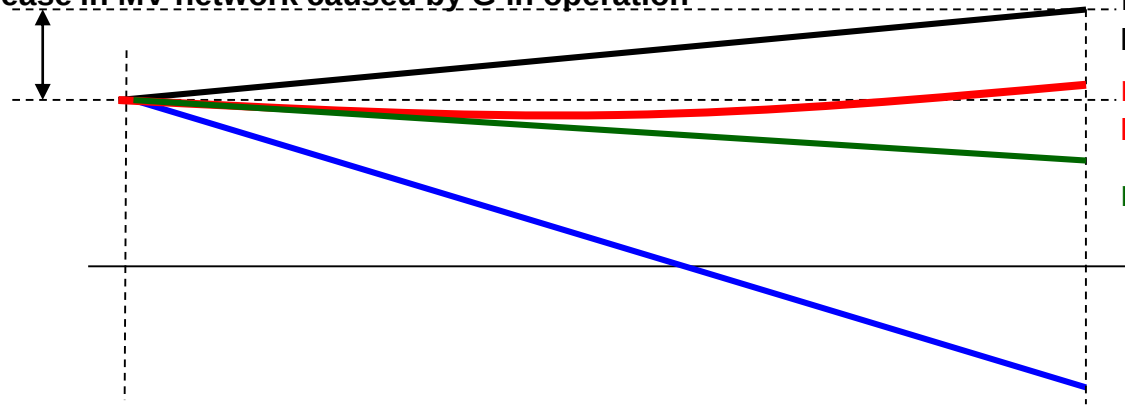
Older distribution transformers



# Changes in DS – distributed generation




**Voltage increase in MV network caused by G in operation**
**max. 2% Un**



No load, G in operation
**Back flow into upstream network**

min. load, G in operation
**Pload < Pgen ⇒ back flow**

min. load, G out of operation

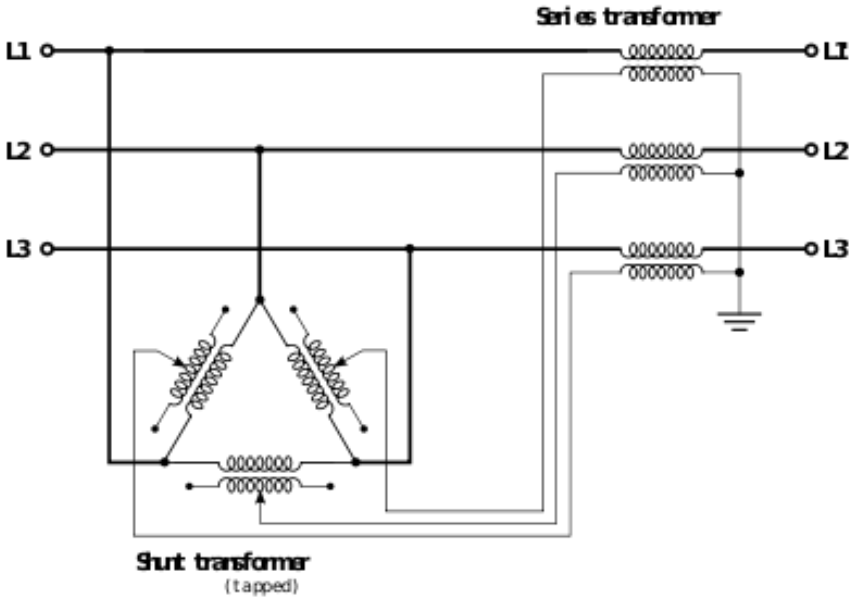
max. load, G out of operation

Similar situation in LV networks – voltage regulation more complicated

# Trends - PST

**Transmission system**

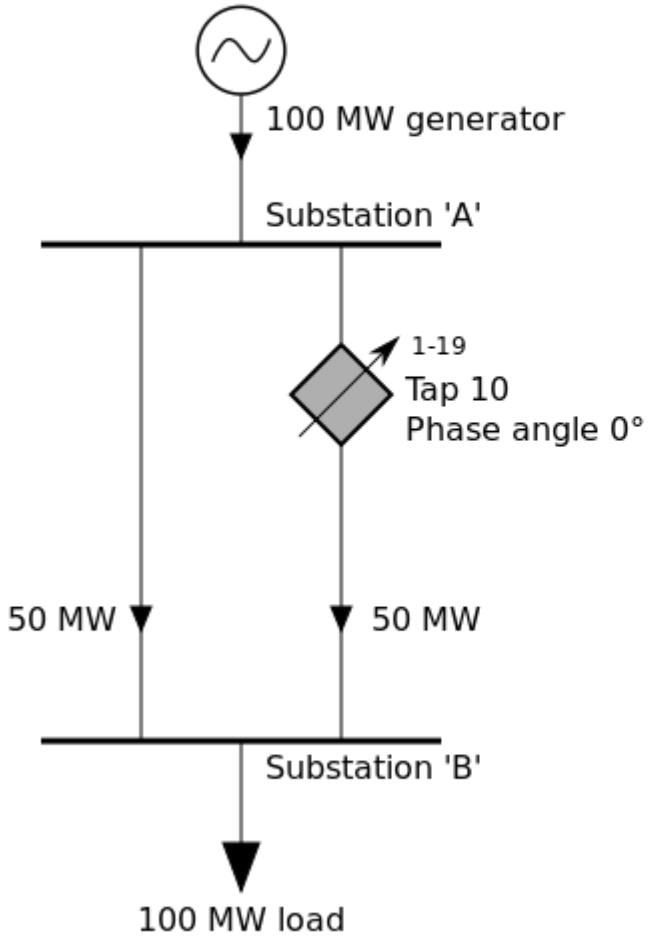
**Phase shift transformers (PST)**



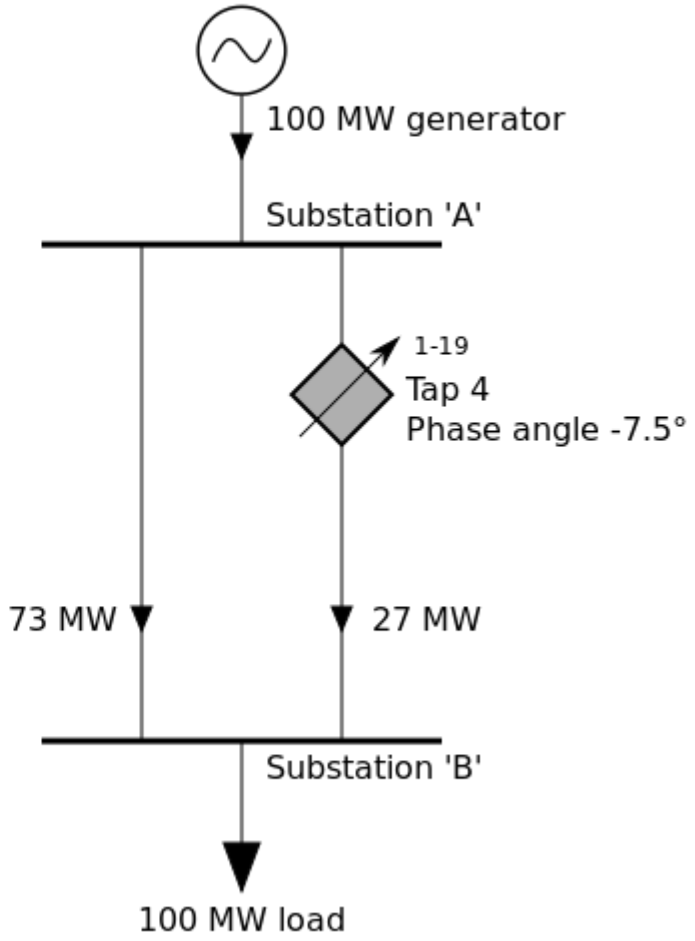



# Trends - PST

**Quadrature booster on centre tap**

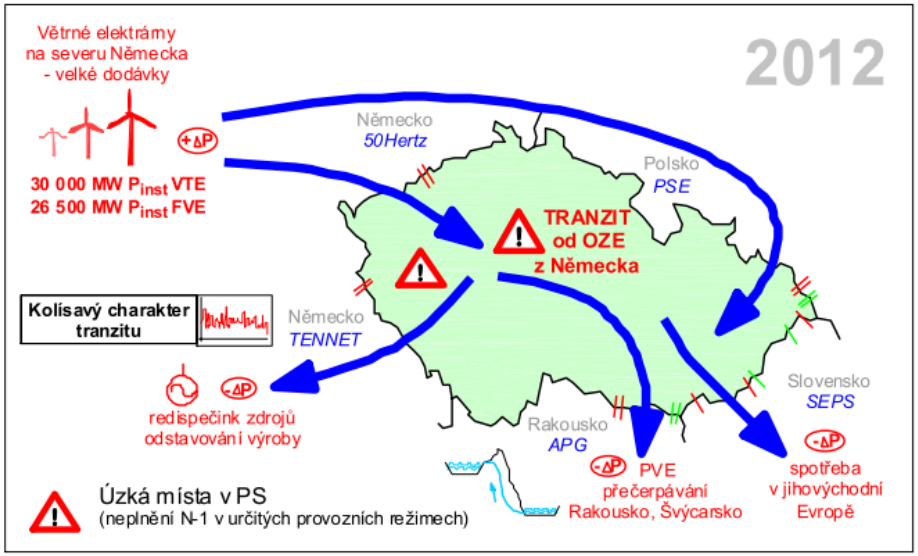


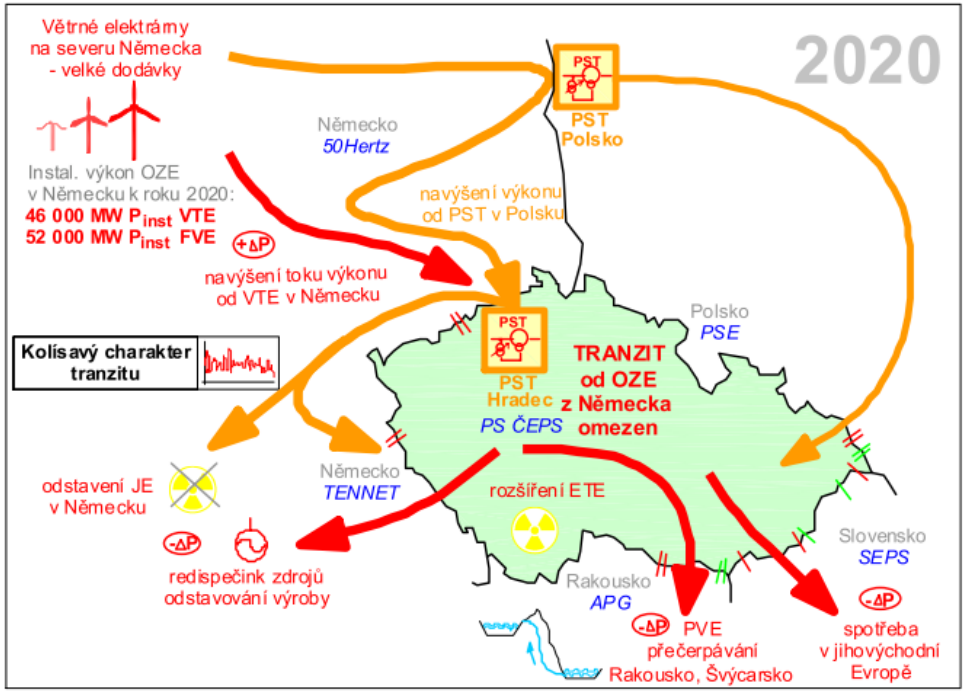

**Quadrature booster on 'buck' tap**



# Trends - PST

**Impact of PST on power distribution in the Central Europe region**



# Trends – distribution system

**- OLTC (on-load tap changer) MV/LV transformers**

- **Oil air-tight storage transformers**
  - **– air- tight tank**
  - **- flexible tank without conservator**
  - **- elimination of air infiltration (humidity and O2)**

**- LV side – secondary winding - metal leaf**





*OLTC transformer Siemens (air-tight tank)*