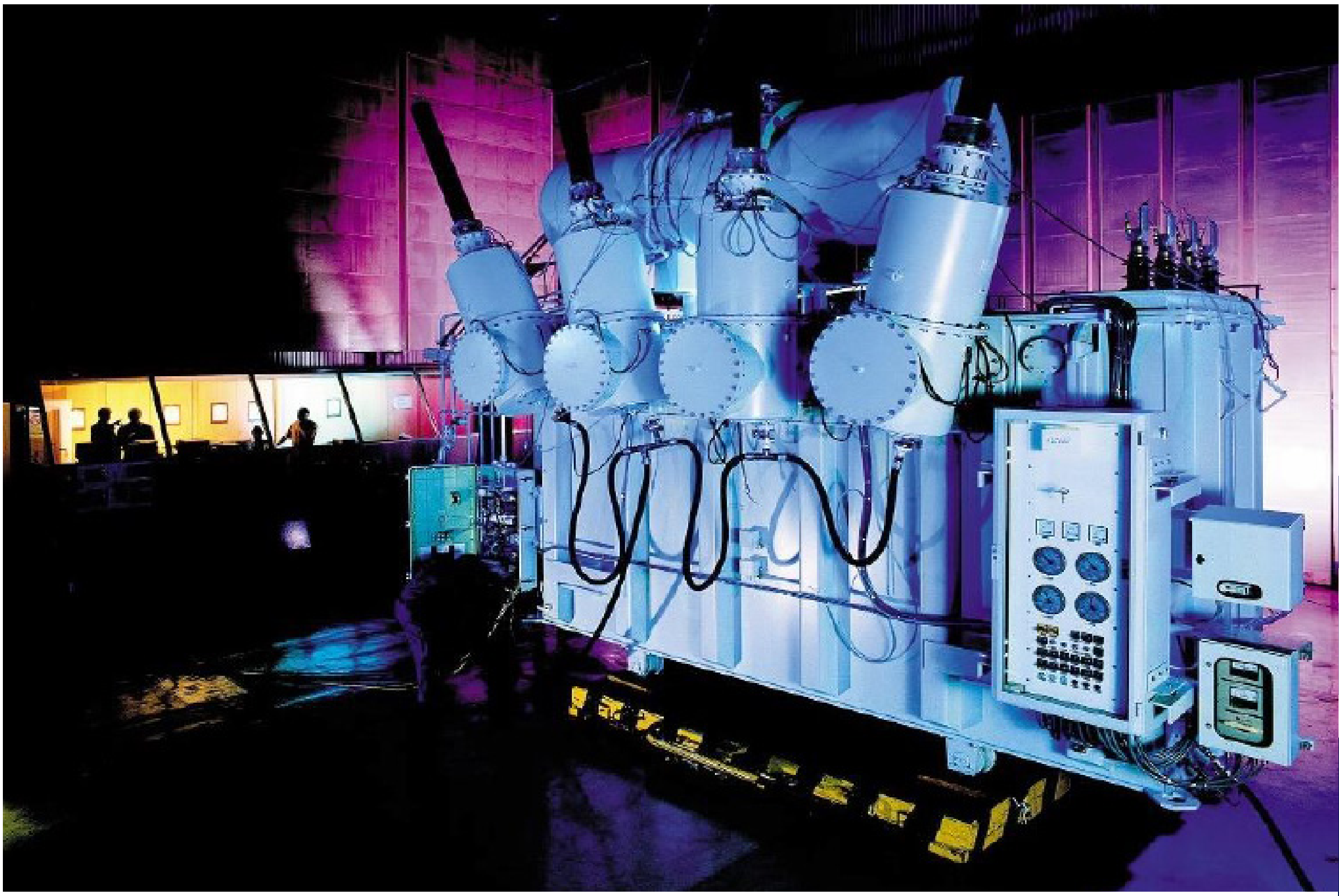
Transformers



Zoltán Kvasznicza

Transformers

Pécs

2019

The Transformers course material was developed under the project EFOP 3.4.3-16-2016-00005 "Innovative university in a modern city: open-minded, value-driven and inclusive approach in a 21st century higher education model".

SZÉCHENYI 2020

PÉCSI TUDOMÁNYEGYETEM
UNIVERSITY OF PÉCS

Zoltán Kvasznicza

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A Transformers tananyag az EFOP-3.4.3-16-2016-00005 azonosító számú, „Korszerű egyetem a modern városban: Értékközpontúság, nyitottság és befogadó szemlélet egy 21. századi felsőoktatási modellben” című projekt keretében valósul meg.

EFOP-3.4.3-16-2016-00005 Korszerű egyetem a modern városban:
Értékközpontúság, nyitottság és befogadó szemlélet
egy 21. századi felsőoktatási modellben

SZÉCHENYI 2020

MAGYARORSZÁG KORMÁNYA

Európai Unió
Európai Szociális Alap

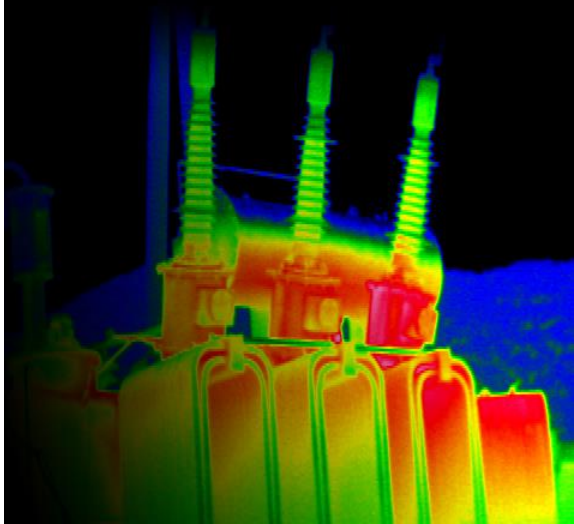
BEFEKTETÉS A JÖVŐBE

University of Pécs
Faculty of Engineering and Information Technology

Eletric Energy Converters I.

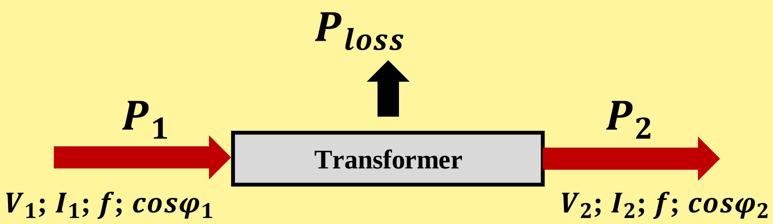
Transformers

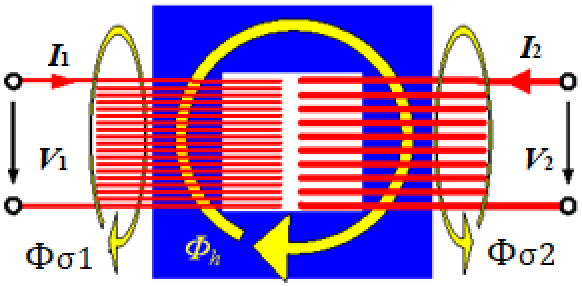
Written by:
Dr. Kvasznicza Zoltán



INTRODUCTION

A transformer is an electrical machine that transfers electrical power with a given alternating voltage and current to a power with other alternating voltage and current at a given frequency with the help of magnetic field.



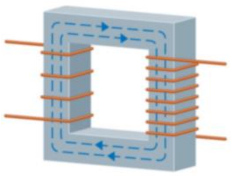


Properties:

- **contains no moving parts,**
- **works on the basis of the transformer electromotive force,**
- **can be applied for alternating voltage,**
- **has a good efficiency,**
- **is not suitable to modify frequency.**

Notice:

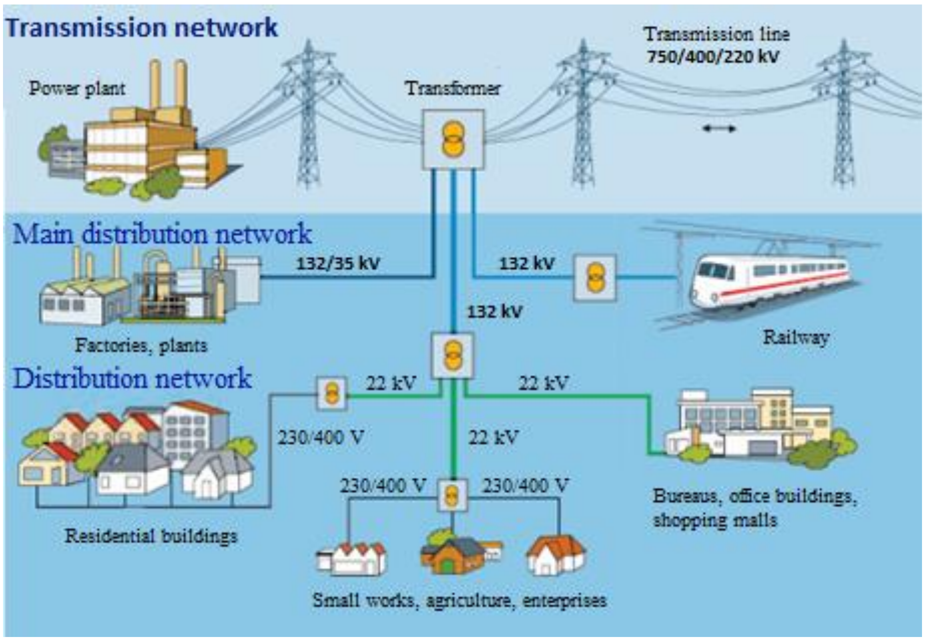
- *The medium applied for transferring energy is the magnetic field → enables galvanic separation as well.*
- *In case of a special construction it can be used for modifying the number of phases.*



INTRODUCTION

For industrial purposes transformers with powers ranging from several VAs to several thousands of MVAs are built.

CAUSES OF APPLYING POWER TRANSFORMERS



PRODUCTION

In traditional systems electrical energy is produced by electrical synchronous generators with voltage levels of the order of magnitude of 11 kV.

TRANSPORT

Locations of the production (power plants) and the usage (consumers) of electrical energy are not identical. Reduction of transport loss ($\sim I^2$; $\sim R$) can be achieved by reducing current, however this requires the increase of the voltage level.

USAGE

Usage of electrical energy by the consumers at the voltage level applied during production as well as during transport would be costly and dangerous → protection of the consumers enables the usage of only rather low voltages.

PRINCIPLE OF CONSTRUCTION

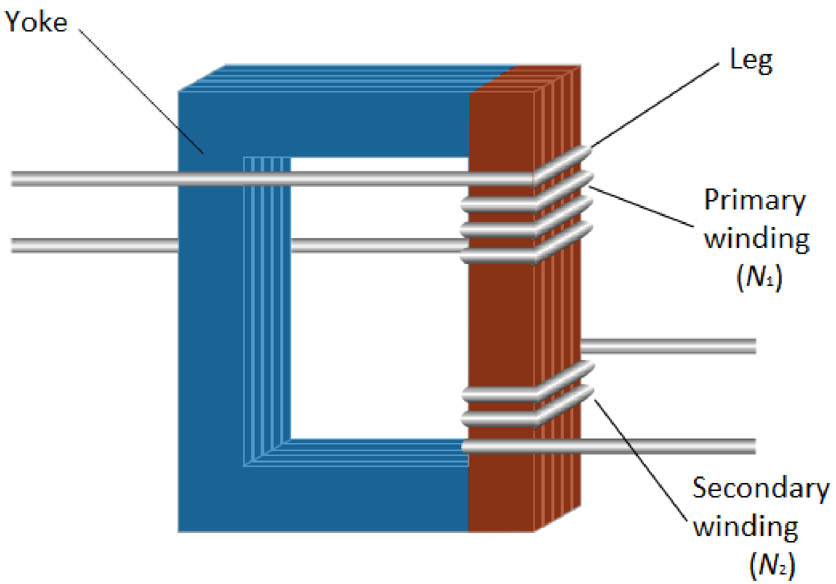
A transformer consists of a closed, laminated IRON CORE made of well magnetizable iron material and WINDINGS.

IRON CORE

Serves for conducting and closing the alternating magnetic field.

LEG: Part of the core surrounded by the windings.

YOKE: Other part of the core between the ends of the legs.



WINDING

PRIMARY WINDING: The primary winding with number of turns of N_1 takes energy from the network.

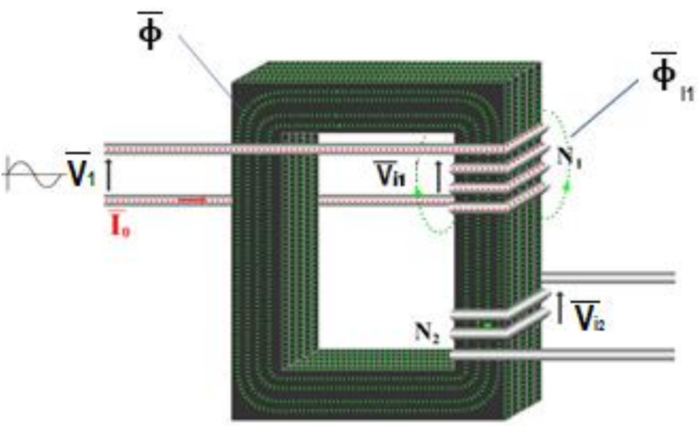
SECUNDARY WINDING: The secondary winding with number of turns of N_2 puts out power.

Notice:

role of the two windings can be interchangeable, thus in many cases the windings are distinguished by their voltage:

- *WINDING WITH HIGHER VOLTAGE*
- *WINDING WITH LOWER VOLTAGE*

WORKING PRINCIPLE OF SINGLE-PHASE TRANSFORMERS
NO-LOAD CONDITION



$\bar{V}_1$

Sinusoidal alternating voltage with frequency f_1 is connected to the primary winding.

$\bar{I}_0$; $\bar{\Theta}_1$

A The no-load current flowing in the closed primary circuit produces an excitation of $\bar{I}_0 N_1$.

$\bar{\Phi}$; $\bar{\Phi}_l$

In the closed core conducting the magnetic lines of force well an alternating magnetic field builds up ($\phi = \phi_{max} sin\omega t$).

$\bar{\Phi}_{l1}$ Primer Leakage flux of the primary winding

- Its lines of force close outside of the core and it comes to several tenths % of the main flux because of the high magnetic resistance outside.
- It links only with the primary winding, it keeps away from the secondary winding → loss

$\bar{V}_{l1}$

It is induced by $\bar{\Phi}_{l1}$ in the primary winding.

$\bar{\Phi}$ Main flux

- $\phi = \phi_{max} sin\omega t$
- Its lines of force stay within the core having low magnetic resistance.
- It links with the primary as well as the secondary winding → energy conversation.

$\bar{V}_{i1}$; $\bar{V}_{i2}$

The alternating magnetic field links with the turns of both windings and induces voltage in them.

NO-LOAD CONDITION

The main flux ($\Phi = \Phi_{max}\sin\omega t$) induces voltage in the turns of the primary winding (N_1) as well as in the turns of the secondary winding (N_2)

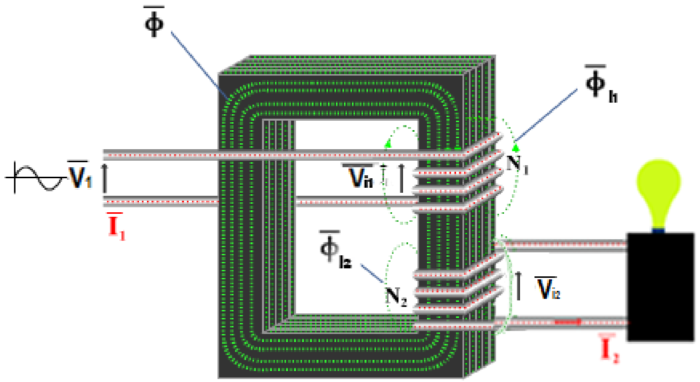
CALCULATION OF THE INDUCED VOLTAGE

	PRIMARY WINDING	SECONDARY WINDING
Time function	$V_{i1}(t) = N_1\frac{d\phi(t)}{dt} = N_1\phi_m\frac{d\sin\omega t}{dt} = = \omega N_1\phi_m\cos\omega t = 2\pi f N_1\phi_m\cos\omega t$	$V_{i2}(t) = N_2\frac{d\phi(t)}{dt} = N_2\phi_m\frac{d\sin\omega t}{dt} = = \omega N_2\phi_m\cos\omega t = 2\pi f N_2\phi_m\cos\omega t$
Complex form	$\overline{V}_{i1} = N_1\frac{d\overline{\phi}}{dt} = j\omega N_1\overline{\phi}$	$\overline{V}_{i2} = N_2\frac{d\overline{\phi}}{dt} = j\omega N_2\overline{\phi}$
Root-mean-square value	$V_{i1rms} = \frac{2\pi}{\sqrt{2}}fN_1\phi_m = 4,44fN_1\phi_m$	$V_{i2rms} = \frac{2\pi}{\sqrt{2}}fN_2\phi_m = 4,44fN_2\phi_m$

Ratio calculated from the induced voltages: $a = \frac{V_{i1rms}}{V_{i2rms}} = \frac{4,44fN_1\phi_m}{4,44\,fN_2\phi_m} = \frac{N_1}{N_2}$

Notice: Apart from the main flux the leakage flux Φl_1 induces voltage in the primary winding as well and the current causes voltage drop on the ohmic resistance of this winding. Resultant of these three voltages keeps the balance with the primary terminal voltage.

LOAD CONDITION



When connecting a consumer to the secondary winding of the transformer having been operating in no-load condition before the induced voltage (V_{i2}) is utilized as a voltage source.

In the secondary circuit V_{i2} lets to flow a current with a magnitude and phase displacement determined by the consumer.

The load current flowing through the turns of the winding produces an excitation weakening the main flux (Lenz's law).

$$\phi \approx constant$$

Because of the constraint for maintaining the equilibrium between the voltages of the primary circuit the flux can not vary.

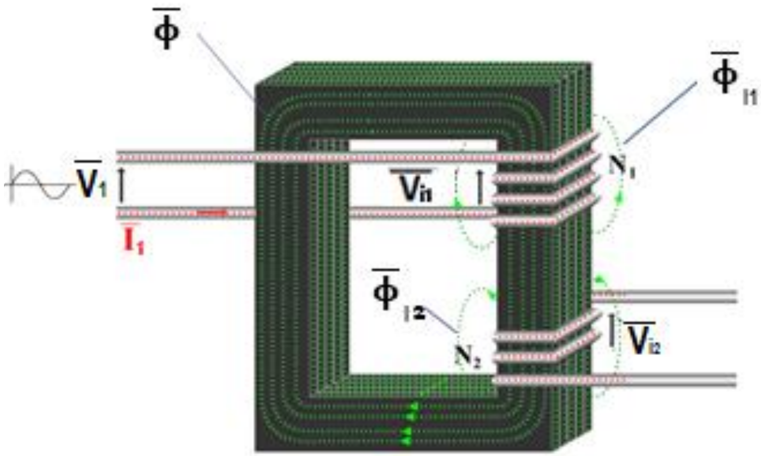
$$\overline{I}_0 \rightarrow \overline{I}_1$$

Current of the primary winding increases and the primary excitation increases as well from $\overline{I}_0 N_1$ to $\overline{I}_0 N_0$ to an extent required for compensating the flux reducing effect of the excitation $\overline{I}_2 N_2$ apart from producing the main flux.

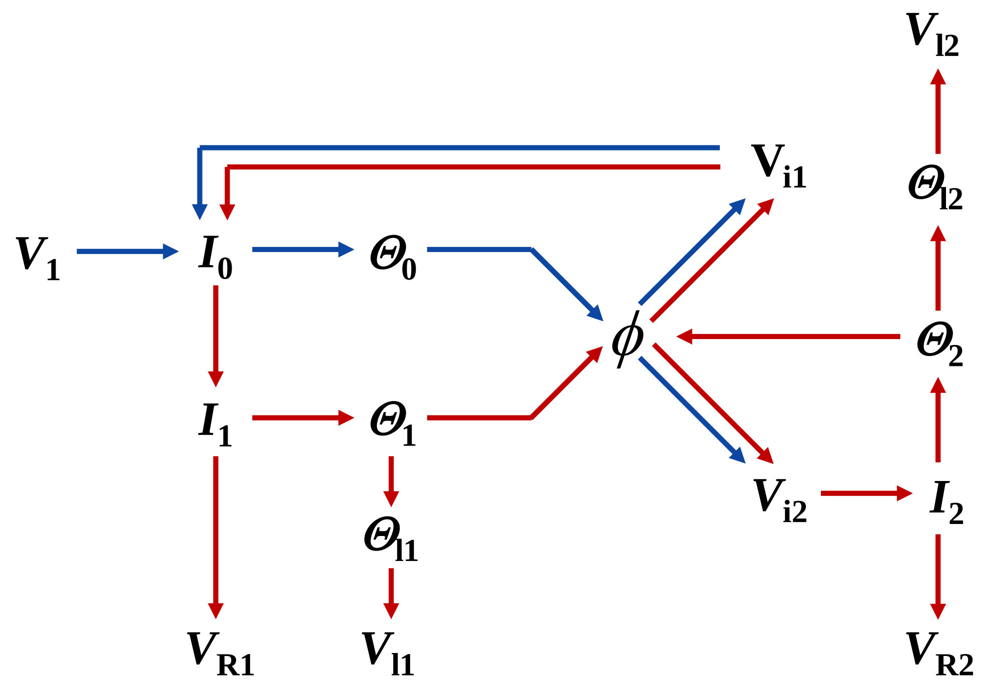
CONCLUSION

If a transformer is loaded with a consumer then not only the secondary current begins to conduct current but the primary current varies as well so that the main flux and the induced voltage remain nearly as before.

LOAD CONDITION



WORKING SCHEME



Notice:

- *In a loaded transformer not only I_1 produces leakage flux Φ_{l1} but I_2 as well. Lines of force of the secondary leakage flux link only with the turns of the secondary winding and close outside of the core → voltages produced by them are small.*
- *Current (I_2) causes voltage drop on the resistance of the secondary winding (R_2)*

LOAD CONDITION

LAW OF THE EQUILIBRIUM OF EXCITATIONS

$$\bar{I}_1 N_1 \quad -\bar{I}_2 N_2 \quad = \quad \bar{I}_0 N_1$$

Increased primary excitation in load condition

Secondary counter-excitation in load condition

Excitation in the primary circuit producing the main flux Φ in no-load condition.

The excitations at both sides have to be identical, since the resultant excitation in load condition and in no-load condition produces the same main flux.

DISCUSSION OF THE CURRENT RELATIONS

The rated current corresponding o the rated power of the transformer is about 10-18 times higher than the no-load current.

$$\bar{I}_1 N_1 - \bar{I}_2 N_2 = \bar{I}_0 N_1$$

(the term $\bar{I}_0 N_1$ is crossed out)

Calculating with absolute values

$$I_1 N_1 - I_2 N_2 \approx 0$$

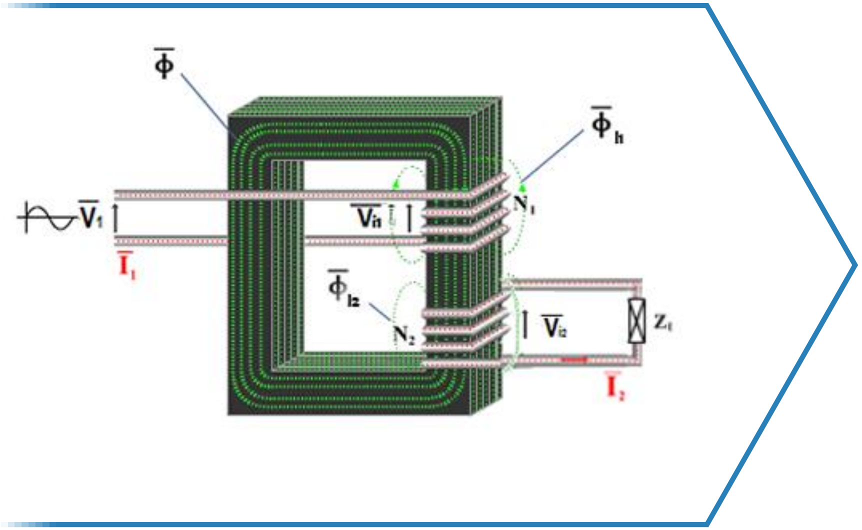
Relation with ratio: $a = \dfrac{V_{i1}}{V_{i2}} = \dfrac{N_1}{N_2} = \dfrac{I_2}{I_1}$

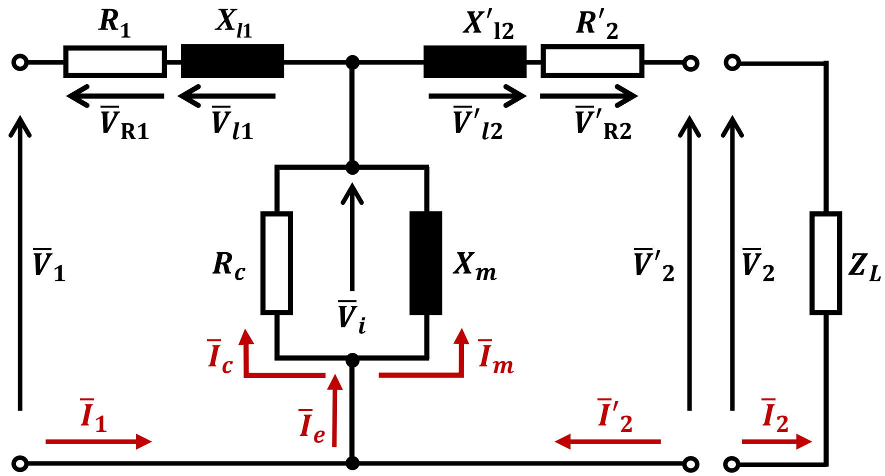
EQUIVALENT CIRCUIT DIAGRAM OF TRANSFORMERS

For the discussion of the operational properties of transformers it will be replaced with a circuit containing passive elements for the sake of an easier understanding of the phenomena taking place in this electrical machine.

Considering voltages, currents and powers this equivalent circuit behaves like the real transformer with some negligations.

Idea of abstraction



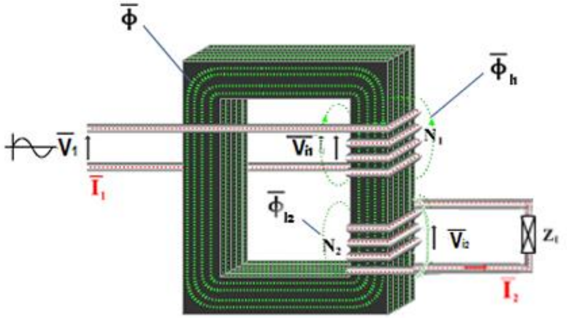


Precondition: The numbers of turns in the primary and secondary windings are the same

$$N_1 = N_2 \Rightarrow a = 1$$

EQUIVALENT CIRCUIT DIAGRAM OF TRANSFORMERS

Fluxes and voltages induced by them in transformers operating with load



ϕ main flux produced by the difference between the primary ($\bar{I}_1 N_1$) and secondary excitations ($\bar{I}_2 N_2$):

$$\bar{V}_{i1} = N_1 \frac{d\bar{\phi}}{dt} = j\omega N_1 \bar{\phi}$$

$$\bar{V}_{i2} = N_2 \frac{d\bar{\phi}}{dt} = j\omega N_2 \bar{\phi}$$

ϕ_{l1} leakage flux of the primary winding produced only by the primary excitation ($\bar{I}_1 N_1$) and induces voltage only in the primary winding

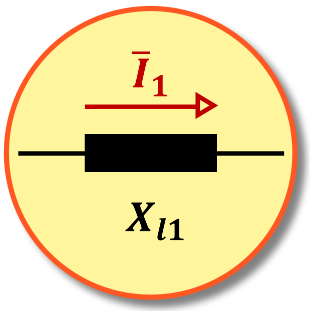
$$\bar{V}_{l1} = \frac{d\bar{\psi}_{l1w}}{dt} = L_{l1} \frac{d\bar{I}_1}{dt} = j\omega L_{l1} \bar{I}_1 = jX_{l1} \bar{I}_1$$

where ψ_{l1w} – leakage flux of the primary winding

$L_{l1} = N_1^2 \Lambda_{l1}$ – primary leakage inductance

Λ_{l1} – magnetic conductance of the primary leakage flux

X_{l1} – primary leakage reactance



ϕ_{l2} leakage flux of the secondary winding produced only by the secondary excitation ($\bar{I}_2 N_2$) and induces voltage only in the secondary winding:

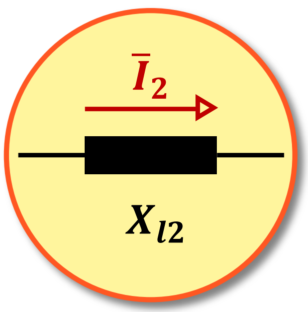
$$\bar{V}_{l2} = \frac{d\bar{\psi}_{l2w}}{dt} = L_{l2} \frac{d\bar{I}_2}{dt} = j\omega L_{l2} \bar{I}_2 = jX_{l2} \bar{I}_2$$

where ψ_{l2w} – leakage flux of the secondary winding

$L_{l2} = N_2^2 \Lambda_{l2}$ – secondary leakage inductance

Λ_{l2} – magnetic conductance of the secondary leakage flux

X_{l2} – secondary leakage reactance



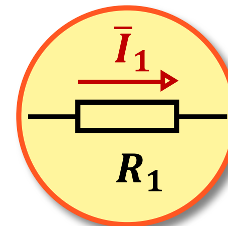
EQUIVALENT CIRCUIT DIAGRAM OF TRANSFORMERS

Resistances of the windings and voltage drops along them

As every real coil the primary and secondary windings have ohmic resistance as well.

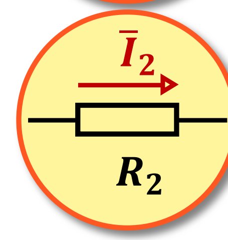
Primary winding

- **resistance of the primary winding**
- **Voltage drop $\bar{V}_{R1} = \bar{I}_1 R_1$ produced by resistance the current $\bar{I}_1$**



Secondary winding

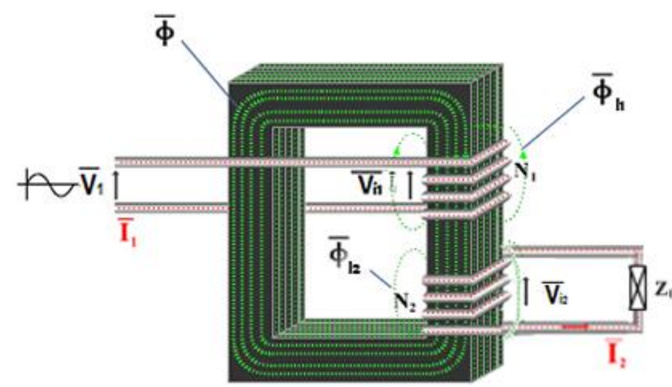
- **resistance of the secondary winding**
- **Voltage drop $\bar{V}_{R2} = \bar{I}_2 R_2$ produced by resistance the current $\bar{I}_2$**



Producing an “idealized” coil:

Xl_1 and Xl_2 leakage reactances corresponding to the leakage fluxes and resistances R_1 and R_2 are removed from the windings.

A transformer built up with idealized windings



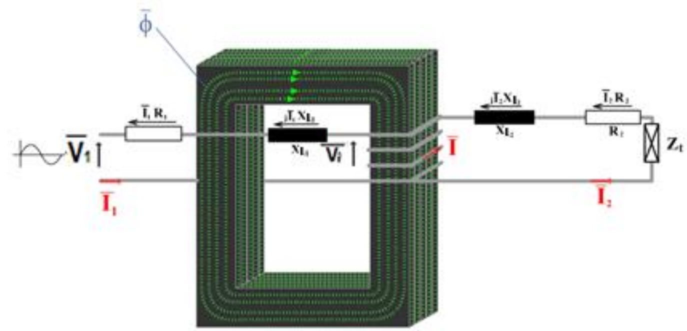
Notice: Windings of the remaining transformer have no ohmic loss and leakage flux, however the useful flux keeps causing loss in the core.

EQUIVALENT CIRCUIT DIAGRAM OF TRANSFORMERS

Replacement of the “idealized” windings:

The number of turns of both windings are the same ($N_1 = N_2$) as well as their induced voltages ($\overline{V}_{i1} = V_{i2}$)

The windings can be connected by turns and can be replaced with a single coil.



Current of the common coil: $\overline{I}_e = \overline{I}_1 - \overline{I}_2$

where $\overline{I}_2$ is the current with the actual direction

Notice: The exciting current equals to the difference between the primary and the actual secondary current and is nearly independent from the load and slightly differs from I_0.

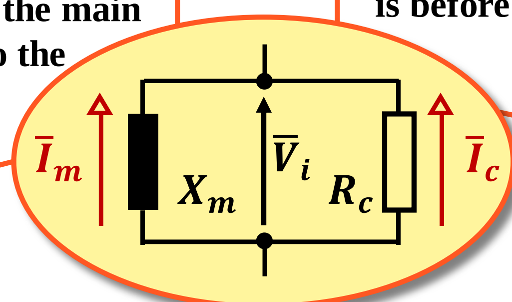
Components of the excitation current: $\overline{I}_e = \overline{I}_m + \overline{I}_c$

REACTIVE COMPONENT

ACTIVE COMPONENT

Maintains the flux inducing the voltage $\overline{V}_1$ in the coil. It is called magnetizing current and has the same phase displacement as the main flux and has a delay of 90° related to the voltage $\overline{V}_{i1}$.

Covers the core loss developing in the core. It has the same phase displacement as $\overline{V}_{i1}$ and is before the main flux by 90 °.



REDUCTION

Until now transformers with numbers of turns $N_1 = N_2$, i.e. with a ratio of $a = 1$, have been discussed..

Taks: To extend the validity of the equivalent circuit to transformers with ratios:

$$a = \frac{V_{i1}}{V_{i2}} = \frac{N_1}{N_2} \neq 1$$

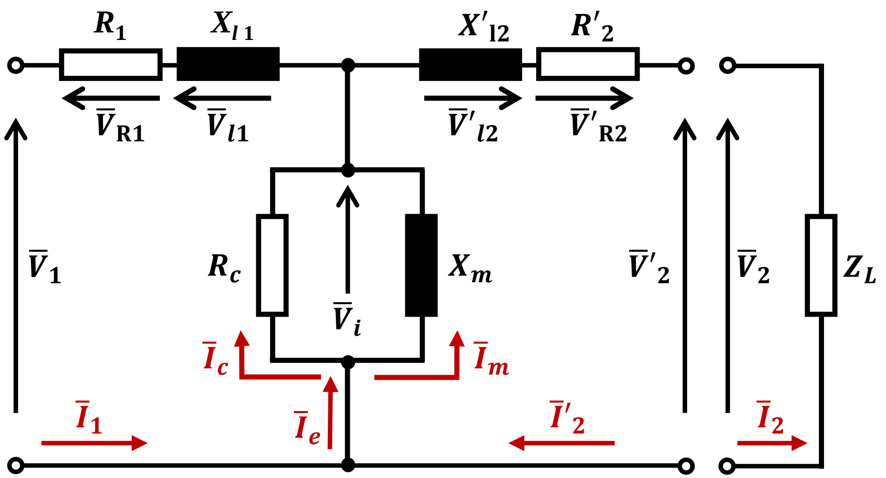
Solution: Secondary values of the given transformer with the ratio of $a = \frac{N_1}{N_2} \neq 1$ have to be recalculated (reduced) to an imaginary transformer with a ratio of 1:1 ($N_1 = aN_2 = N'_2$).

PRECONDITION OF THE REDUCTION

- excitations have to remain unmodified,
- powers and losses have to remain unmodified.

Precondition	Before reduction		After reduction	Reduced value
unmodified	N_2		N'_2	$N'_2 = aN_2 \quad = N_1$
	V_{i2}		V'_{i2}	$V'_{i2} = aV_{i2} \quad = V_{i1}$
excitation	$N_2 I_2$	=	$N'_2 I'_2$	$I'_2 = \frac{N_2}{N_1} I_2 \quad = \frac{I_2}{a}$
loss	$I_2^2 R_2$	=	$(I'_2)^2 R'_2$	$R'_2 = \left(\frac{I_2}{I'_2}\right)^2 R_2 = a^2 R_2$
reactive power	$I_2^2 X_{l2}$	=	$(I'_2)^2 X'_{l2}$	$X'_{l2} = \left(\frac{I_2}{I'_2}\right)^2 X_{l2} = a^2 X_{l2}$
power	$V_2 I_2$	=	$V'_2 I'_2$	$V'_2 = \frac{I_2}{I'_2} V_2 \quad = aV_2$

EQUIVALENT CIRCUIT OF UNIVERSAL VALIDITY



Explanation of the direction of $\overline{I}'_2$:
the so called positive consumer direction is used, where the sign of the absorbed power is positive and that of the generated power is negative.

Actual direction of $\overline{I}_2$:
direction of the current flowing in the secondary winding of the real transformer.

Vector equations formulated on the basis of the equivalent circuit diagram:

$$\overline{V}_1 = \overline{V}_i + \overline{V}_{l\,1} + \overline{V}_{R1} = \overline{V}_i + j\overline{I}_1 X_{l\,1} + \overline{I}_1 R_1$$
$$\overline{V}'_2 = \overline{V}_i + \overline{V}'_{l2} + \overline{V}'_{R2} = \overline{V}_i + j\overline{I}'_2 X'_{l2} + \overline{I}'_2 R'_2$$

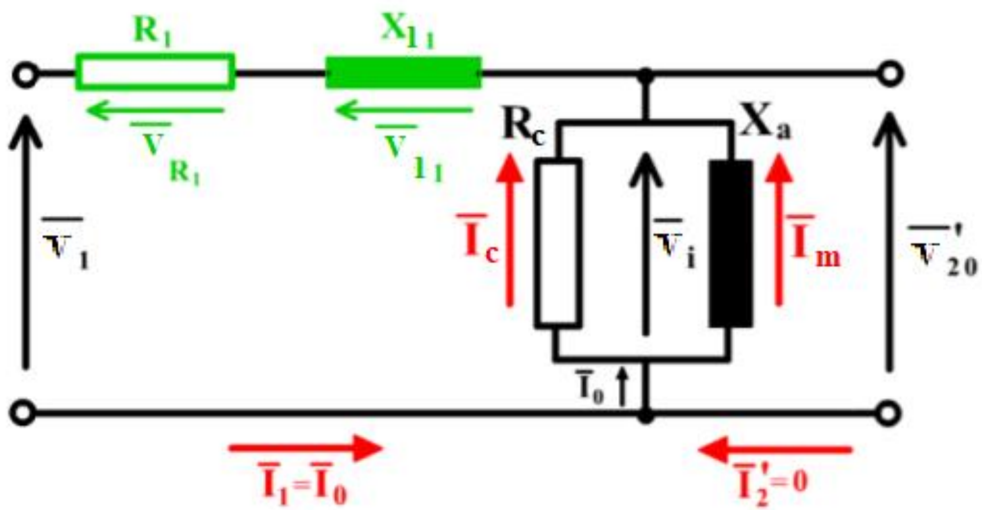
Orders of magnitude of the elements of the equivalent circuit diagram:

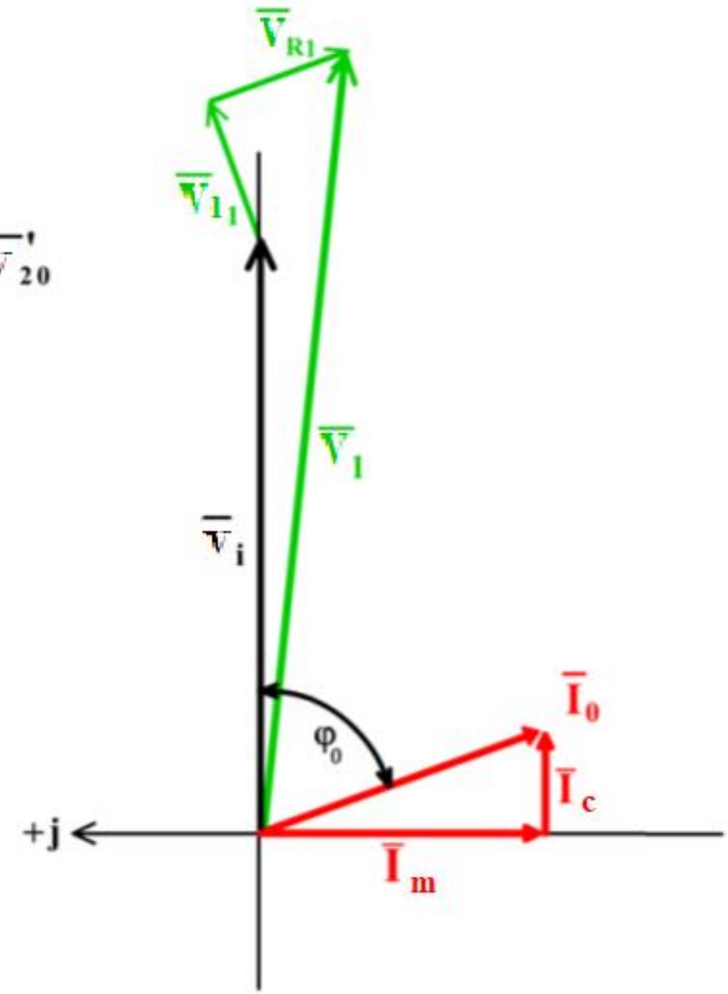
In case of transformers with powers in the order of magnitude of several MVAs: $R_1 \approx R'_2 : X_{l\,1} \approx X'_{l2} : X_m : R_c = 1 : 2 : 10^3 : 10^4$

In case of lower powers: $R_1 \approx R'_2 : X_{l\,1} \approx X'_{l2} : X_m : R_c = 1 : 1 : 10^2 : 10^3$

NO-LOAD OPERATION

In case of no-load operation of the transformer the primary winding is connected to rated voltage while the secondary circuit is not loaded (open) .





1. $\overline{I}'_2 = 0$

2. $\overline{V}'_{20} = \overline{V}'_{i2} = \overline{V}_{i1} = \overline{V}_1$

3. $\overline{V}_1 = \overline{V}_{R_1} + \overline{V}_{11} + \overline{V}_i$

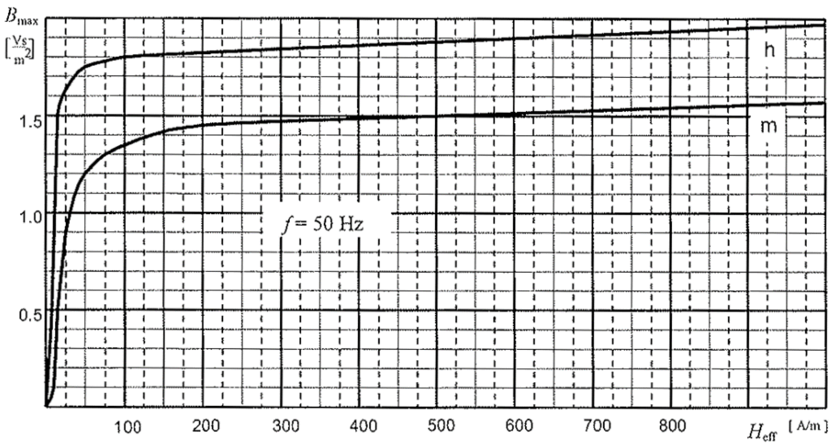
4. $\overline{V}_1 = \overline{I}_0 R_1 + j\overline{I}_0 X_{11} + \overline{V}_i$

NO-LOAD OPERATION – MAGNETIZING CURRENT

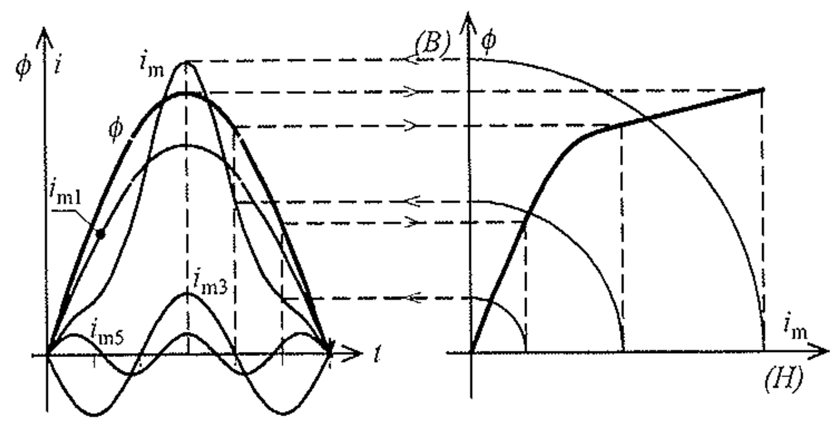
If the network voltage $\overline{V}_1$ – and respectively the induced voltage being in equilibrium with the former one – are sinusoidal, then the MAIN FLUX IS SINUSOIDAL AS WELL ($\overline{V}_{i1} = N_1 \frac{d\overline{\phi}}{dt}$) however it is delayed by a quarter period behind $\overline{V}_{i1}$

In the magnetic circuit of the transformer the magnetizing current has to produce the main flux.

Is characterized with the B(H) characteristic curve being non-linear considering the core (value of the relative permeability is variable), saturating with hystheresis.



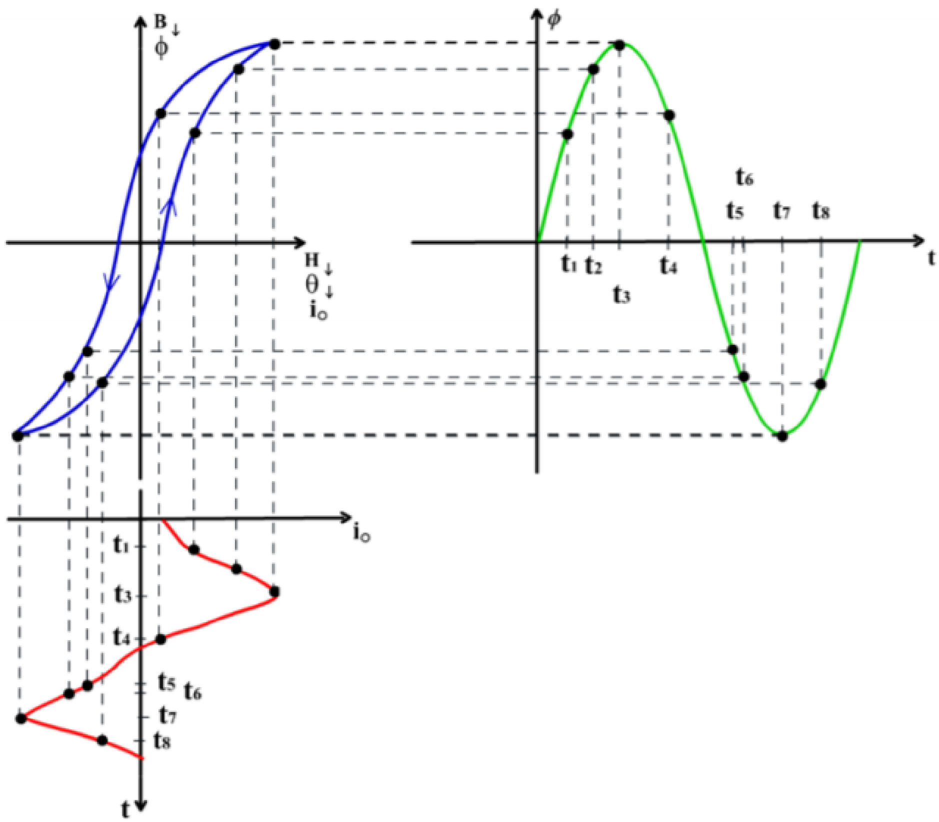
Because of the saturation of the iron the time function of the magnetizing current differs from the sinusoidal shape. Its harmonic content depends on the quality of the material of the core and on the saturation state of the magnetic circuit.



PLOTTING THE TIME FUNCTION OF THE NO-LOAD CURRENT

Properties of the no-load current:

- $\overline{I}_0 = \overline{I}_m + \overline{I}_c$, where $I_m \gg I_c$ (their ratio 10:1)
- The magnetizing current determines the magnitude and time function of the no-load current:
  - non-sinusoidal signal shape → significant harmonic content (i_3 is dominant),
  - the third harmonic is necessary for producing the sinusoidal alternating main flux,
  - in case of single-phase transformers harmonic currents can flow.



NO-LOAD OPERATION – CHARACTERISTIC CURVES

$I_0 = f(V_0)$

Magnetizing characteristic curve of the core, since:

No-load current I_0 → Excitation $I_0 N_1$ → Field strenght H ($NI = \Sigma Hl$) → Alternating magnetic field $B;\ V_0$

$P_0 = f(V_0)$

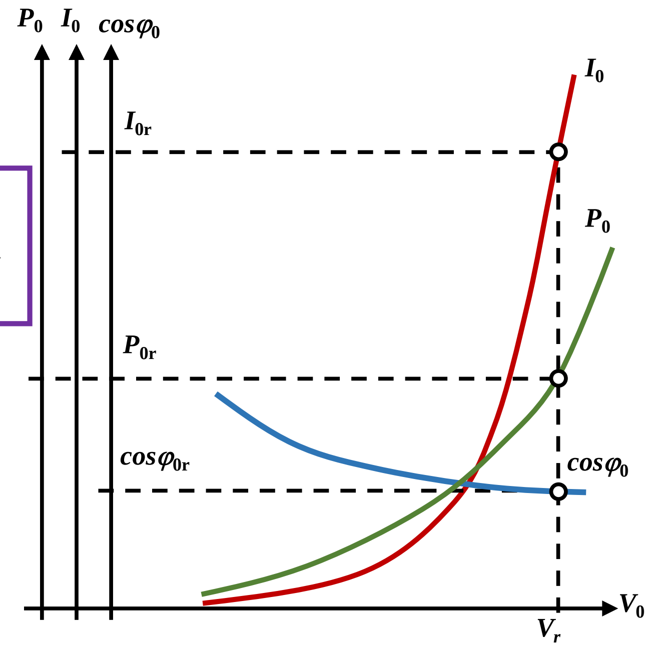
The shape of the characteristic curve is a quadratic parabola with good approximation.

Components of the no-load loss $P_0 = P_{0\,iron} + P_{0\,wind}$

$\sim B^2$ $\sim I_0^2 \ll$

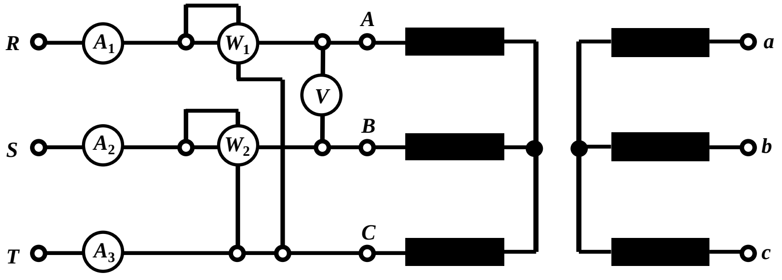
$cos\varphi_0 = f(V_0)$

Can be calculated from the corresponding data: $V_0;\ I_0;\ P_0$



Measurement of no-load characteristic curves

While the terminals of one winding of the transformer are open, the other winding is supplied with a variable, sinusoidal voltage with rated frequency, the value of which voltage is increased in several steps from a low value to about 1.05 V_n.



NO-LOAD OPERATION – CHARACTERISTIC CURVES

Calculation of the elements of the equivalent circuit – of the bridging branch – with the use of rated data.

- **R_v ohmic resistance**
  It models the core loss developing in the core

$$P_{0c} = I_c V_i = \frac{V_i^2}{R_c} \Rightarrow R_c = \frac{V_i^2}{P_{0c}} \approx \frac{V_0^2}{P_0}$$

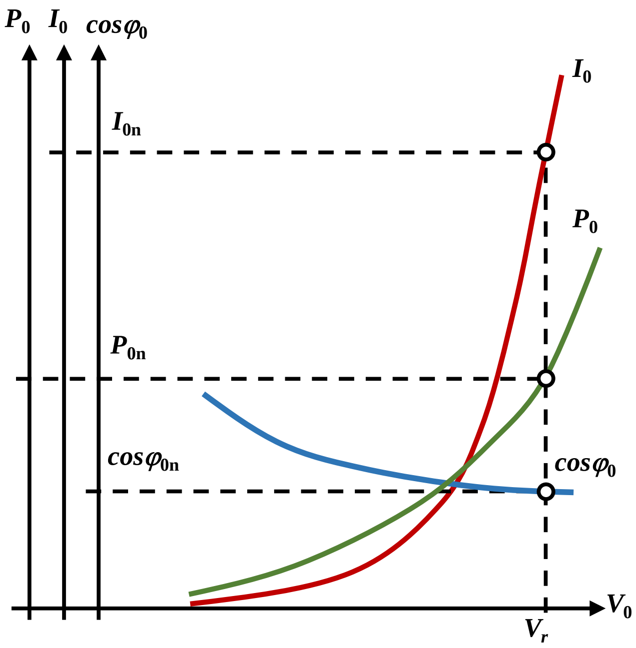
- **X_m main field resistance**
  It models the reactive power required for producing the main field (main flux).

$$Q_0 = I_m V_i = \frac{V_i^2}{X_m} \Rightarrow X_m = \frac{V_i^2}{Q_0} \approx \frac{V_0^2}{Q_0}$$

where:

$$Q_0 = \sqrt{S_0^2 - P_0^2} \qquad S_0 = V_r I_{0r}$$

- **Deviation of no-load characteristic curves from the calculated ones refer to failures in the transformer core:**
  - **quality problems of the lamination**
  - **damages of the plate insulation**
  - **asymmetry of the core (3 phases)**
  - **inaccuracies in matching**
  - **etc.**



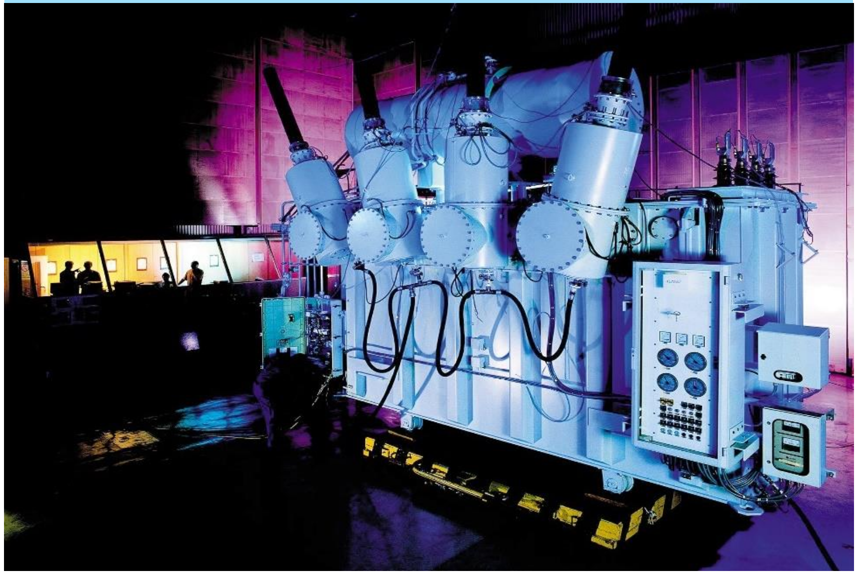
LOAD CONDITIONS AND VECTOR DIAGRAMS

SHORT-CIRCUIT CONDITIONS OF TRANSFORMERS

Two different terms correspond to this operation condition

SHORT-CIRCUITED OPERATION CONDITION
(Short-circuit for measurement)

For measurement purposes the transformer short-circuited on the secondary side is supplied with decreased primary voltage so that in the windings the current does nor surpass significantly the rated value.



SHORT-CIRCUIT

(Short-circuit during operation)

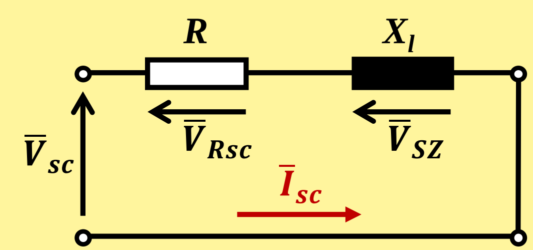
An operation condition different from the normal operation of the transformer connected to the rated voltage, where the secondary terminals get into contact with each-other or the grounding through low resistance through malfunction.

SHORT-CIRCUIT CONDITIONS – SIMPLIFIED EQUIVALENT CIRCUIT

Purpose of the short-circuit measurement:

- Determination of the elements of the equivalent circuit $(R = R_1 + R_2'; \ X_l = X_{l\,1} + X_{l2}')$
- Calculation of the voltage drops and the drop (ε_{sc})

Equivalent circuit diagram



Properties of this operation condition:

- Secondary terminals are short-circuited → $\overline{V}_2 = 0$
- Supply with decreased voltages: $\downarrow V_1 = V_{sc}$ Windings are loaded with rated currents already at a low voltage. → $\phi \downarrow$ (evanescently low)

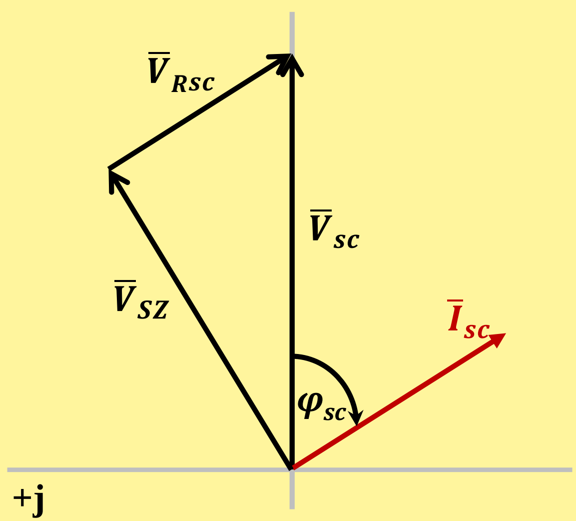
Vector equations:

- Current equation: $\overline{I}_1 = \overline{I}_2' = \overline{I}_{sc}$
- Voltage equation: $\overline{V}_{sc} = \overline{V}_{Rsc} + \overline{V}_{SZ} = \overline{I}_{sc}R + j\overline{I}_{sc}X_l = \overline{I}_{sc}\overline{Z}_{sc}$

where: $\overline{Z}_{sc}$ is the short-circuit impedance of the transformer

$$\overline{Z}_{sc} = (R_1 + R_2') + j(X_{l\,1} + X_{l2}') = R + jX_l$$

$$Z_{sc} = \sqrt{R^2 + X_l^2}$$



LOAD CONDITIONS AND VECTOR DIAGRAMS

SHORT-CIRCUIT CONDITION – DROP (ε_Z)

Rated short-circuit voltage (V_{scr})

The voltage at which rated current flows in the windings of the transformer:

$$V_{scr} = I_r Z_{sc} \Longrightarrow I_r = \frac{V_{scr}}{Z_{sc}}$$

Drop (ε_{sc})

Value of the rated short-circuit voltage related to the rated voltage:

$$\varepsilon_{sc} = \frac{V_{scr}}{V_r} = \frac{I_r Z_{sc}}{V_r}$$

Notice:

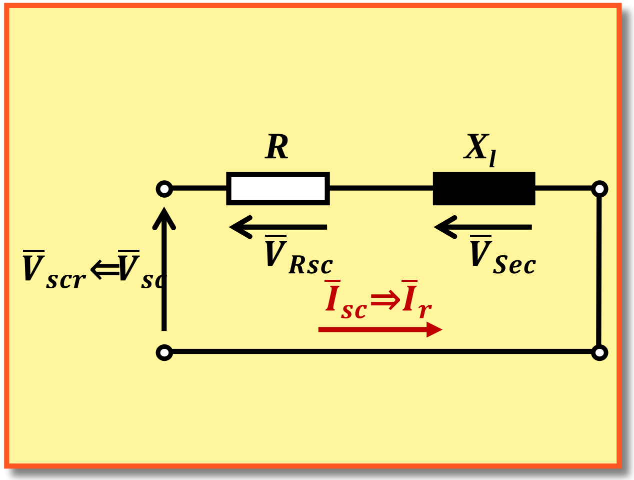
- *$V_r = V_{1r}$ if the primary winding of the transformer is supplied and $V_r = V_{2r}$ if the secondary winding is supplied*,
- *drop can be calculated in percent form, then its value is $\varepsilon_Z \approx 3 \ldots 8\%$.*

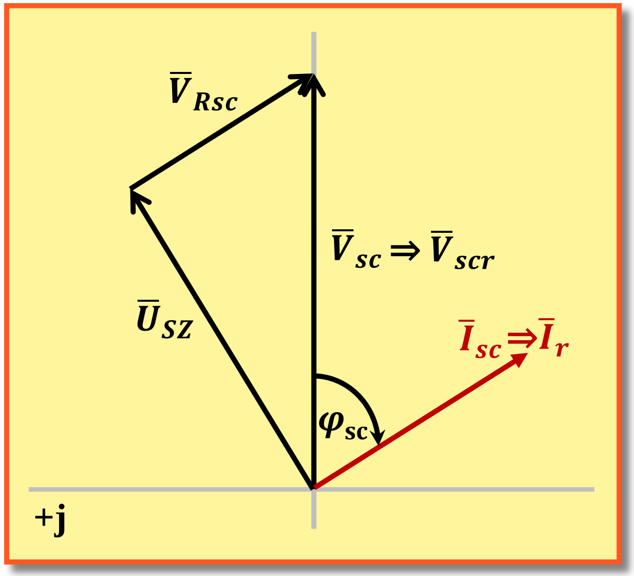
Ohmic and reactive component of drop

$$\varepsilon_{Rsc} = \frac{I_r R}{V_r} = \frac{V_{Rsc}}{V_r} = \frac{V_{scr} cos\varphi_{sc}}{V_r} = \varepsilon_{sc} cos\varphi_{sc}$$

$$\varepsilon_{SZ} = \frac{I_r X_l}{V_r} = \frac{V_{sz}}{V_r} = \frac{V_{scr} sin\varphi_{sc}}{V_r} = \varepsilon_{sc} sin\varphi_{sc}$$

$$\varepsilon_{sc} = \sqrt{\varepsilon_{Rsc}^2 + \varepsilon_{sz}^2}$$





SHORT-CIRCUIT CONDITION – CHARACTERISTIC CURVES

$V_{sc} = f(I_{sc})$

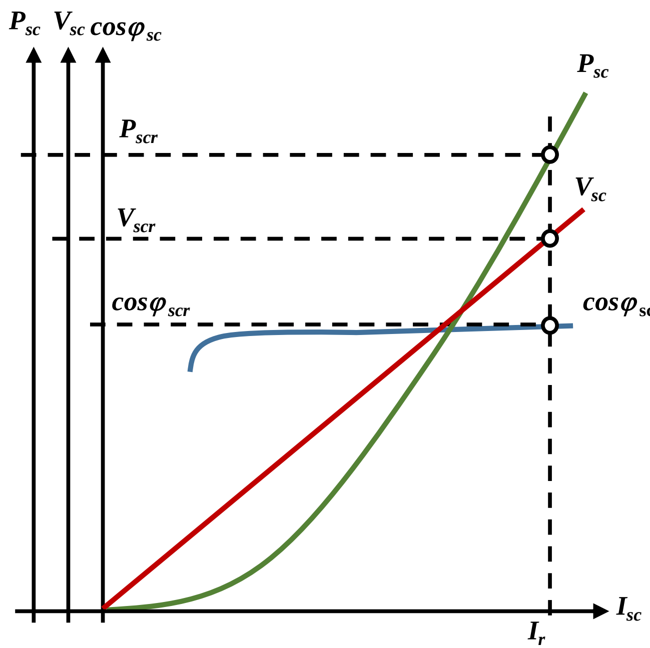
Relation between the short-circuit voltage and current is linear, the core is not saturated thank to the low voltage.

$P_{sc} = f(I_{sc})$

Power input is determined by the loss in the windings proportional to the square of the current, since the core loss proportional to the square of the flux density can be neglected thank to the low voltage.

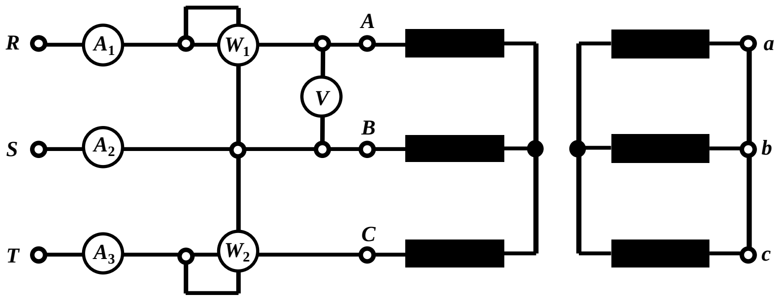
$\cos\varphi_{sc} = f(I_{sc})$

Can be calculated from the data $V_{sc}; I_{sc}; P_{sc}$ has a constant value in the original I_{sc} function.



Measurement of the short-circuit characteristic curves

While one winding of the transformer is short-circuited the other winding is supplied with a variable, sinusoidal voltage with rated frequency, the value of which voltage can be increased in several steps from zero until the current increases to a value of about (1,05…1,1) I_n.



SHORT-CIRCUIT CONDITION – CHARACTERISTIC CURVES

Calculation of the elements of the equivalent circuit with the use of rated data.

- **Resultant of the resistances of the windings:**

$$R_1 + R_2' = \frac{P_{scr}}{I_{1r}^2},$$ **if the secondary side is reduced to the primary side**

$$R_1' + R_2 = \frac{P_{scr}}{I_{2r}^2},$$ **if the primary side is reduced to the secondary side**

Notice: Resistance of the windings depends on the temperature. Thus when determining the rated winding loss the temperature has to be stated as well. Resistance R_h of a coil with a temperature of τ_h can be recalculated to other temperatures (according to standard prescriptions $\tau = 75°C$).

$$R_{75} = R_h \frac{235 + 75}{235 + \tau_h}$$

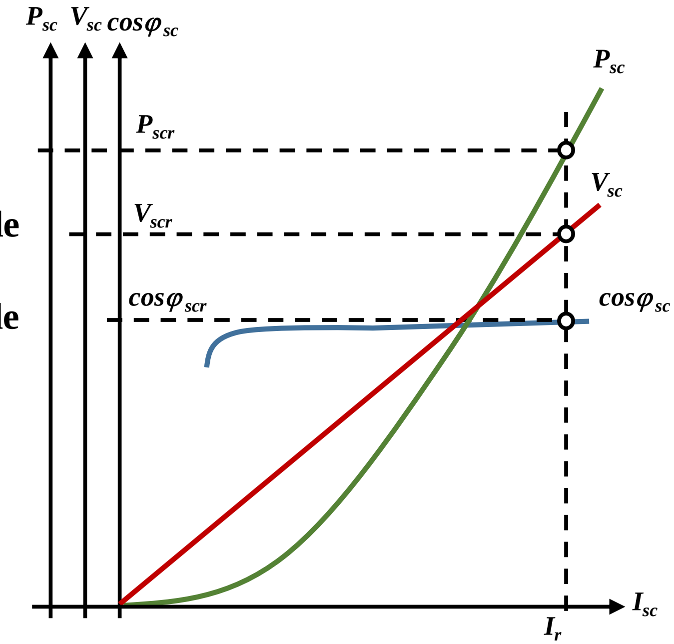
- **Resultant reactance:**

$$X_{l1} + X_{l2}' = \frac{Q_{scr}}{I_{1r}^2},$$ **if the secondary side is reduced to the primary side**

$$X_{l1}' + X_{l2} = \frac{Q_{scr}}{I_{2r}^2},$$ **if the primary side is reduced to the secondary side**

where: $$Q_{scr} = \sqrt{S_{scr}^2 - P_{scr}^2}$$

$$S_{scr} = V_{scr} I_r$$



SHORT-CIRCUIT – SHORT-CIRCUIT DURING OPERATION

A short-circuit arising as a result of a malfunction – at a supply with rated voltage – is on only for a short period until the operation of the protection on the mains.

Properties:

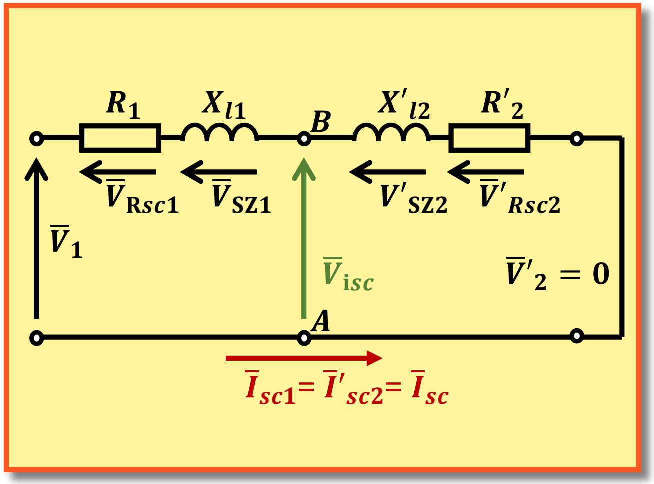
- **Primary side is connected to rated voltage, $V_1 = V_{1r}$**
- **Secondary terminals is short-circuited, $V_2' = 0$**

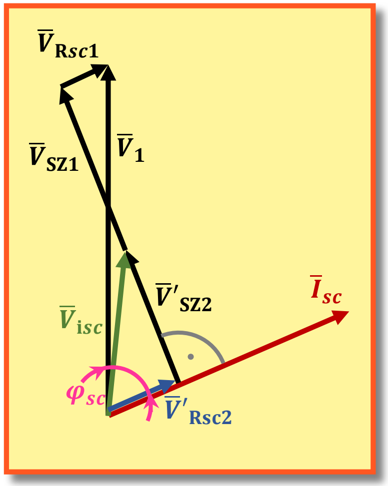
$$I_1 = I_2' = I_{sc} \approx (10 \dots 30)I_r$$

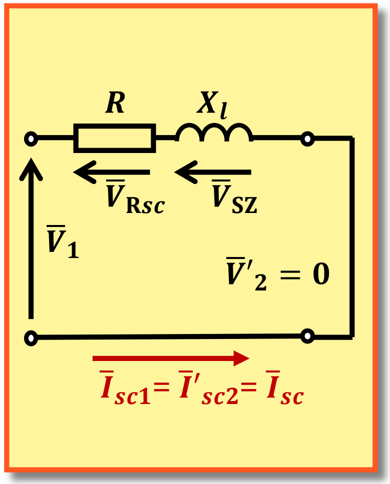
- **The main flux and V_i decrease to about the half of their values at rated load condition.**

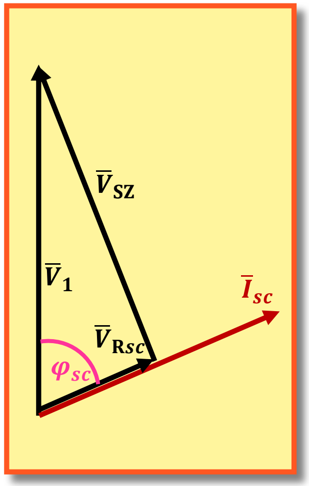
In case of a short-circuit the principal of the equilibrium of the flux is not valid.

Equivalent circuit and vector diagrams:





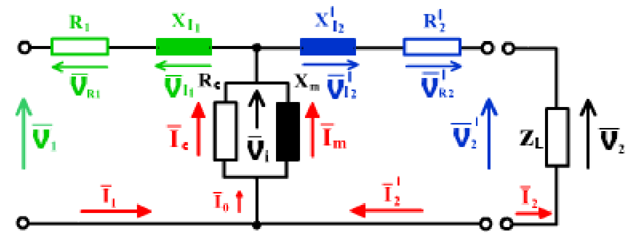




Notice: In case of a sudden short-circuit a transient phenomenon appears as well, the time function of which depends on the time of the beginning of the short-circuit.

LOAD CONDITIONS AND VECTOR DIAGRAMS
TRANSFORMER LOADED WITH CONSUMER

Operational properties of a transformer working with load depend on the characteristics of the transformer itself on one hand and on the characteristics of the load connected to it on the other hand.



Vector equations

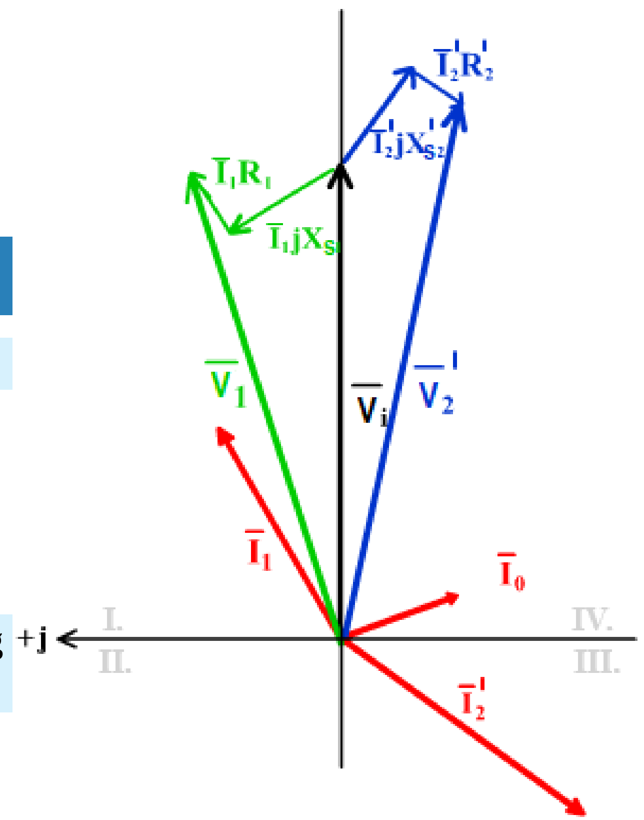
- $\bar{I}_1 + \bar{I}'_2 = \bar{I}_e \approx \bar{I}_0$
- $\bar{I}_e = \bar{I}_c + \bar{I}_m$
- $\bar{V}_1 = \bar{V}_i + j\bar{I}_1 X_{l1} + \bar{I}_1 R_1 = \bar{V}_i + \bar{V}_{l1} + \bar{V}_{R1}$
- $\bar{V}'_2 = \bar{V}_i + j\bar{I}'_2 X'_{l2} + \bar{I}'_2 R'_2 = \bar{V}_i + \bar{V}'_{l2} + \bar{V}'_{R2}$

Typical loads

- **Ohmic-inductive consumer**

  Current $\bar{I}_2$ flowing as a result of $\bar{V}_2$ will delay related to the voltage (plane IV), HOWEVER according to the POSITIVE DIRECTION SYSTEM the current of the transformer as a current source is opposite to this (plane II).
- **Consumer of capacitive art (e.g. a cable network operating without load)**

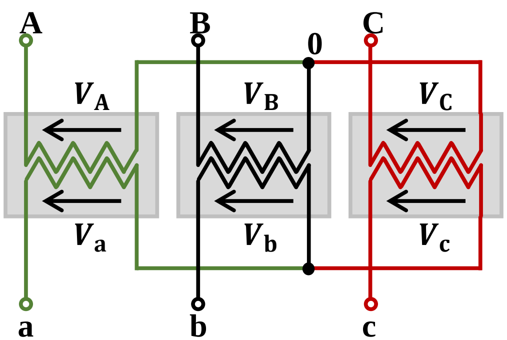
  Current of the consumer noun related to the voltage (plane I), the current supplying it has an opposite sense (plane III).

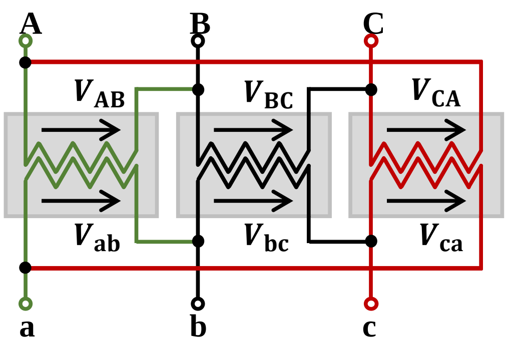


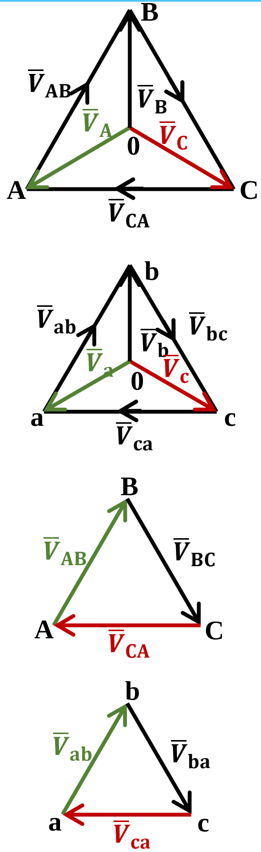
WORKING PRINCIPLE OF THREE-PHASE TRANSFORMERS

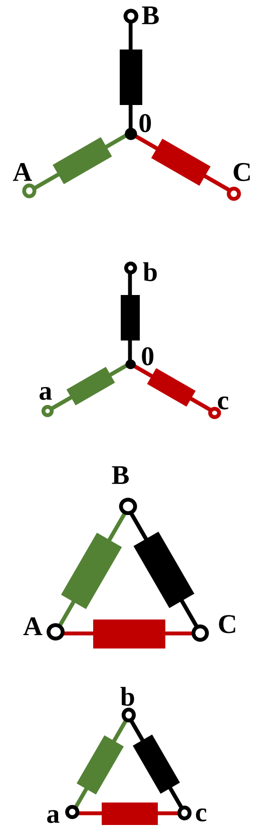
Generation and consumption of electrical power take place mainly in three-phase systems. These systems are characterized by three alternating voltages delayed in phase by one third period related to each-other.

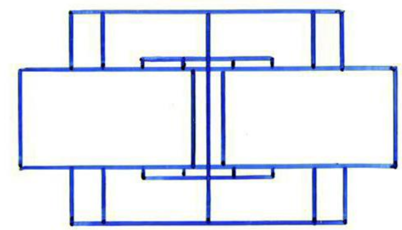
Production of a three-phase voltage system with three single-phase transformers

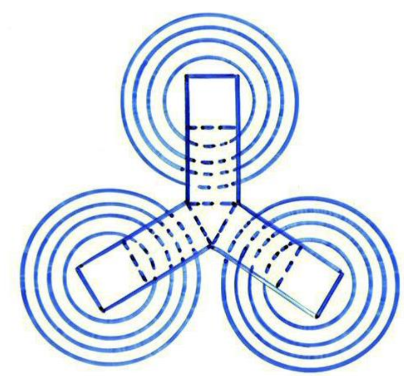












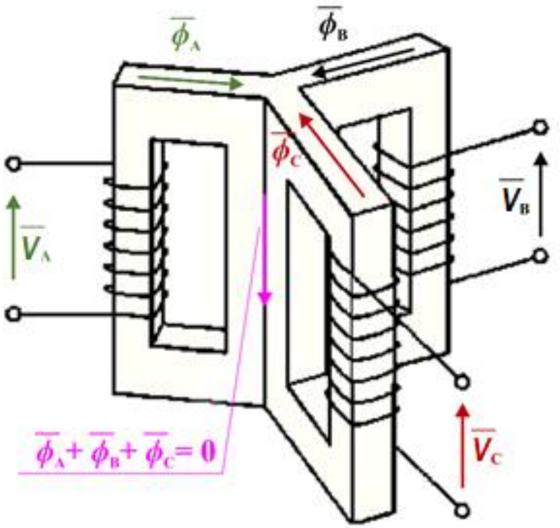
Disadvantages of these connections:

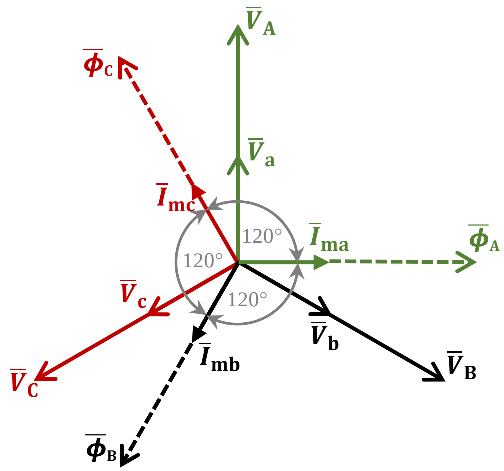
- expensive
- Low efficiency

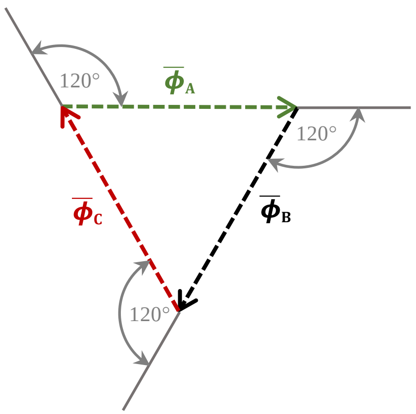
The three single-phase transformers are built into a single unit by joining the cores.

WORKING PRINCIPLE OF THREE-PHASE TRANSFORMERS

Investigation of the fluxes of the transformers built into a single unit



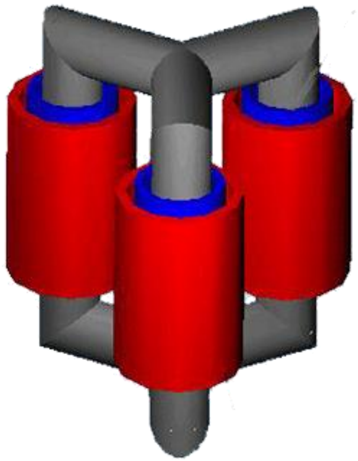




Phase voltages of the three windings have identical magnitudes and delay by angles of 120°-120°-120° related to each-other.

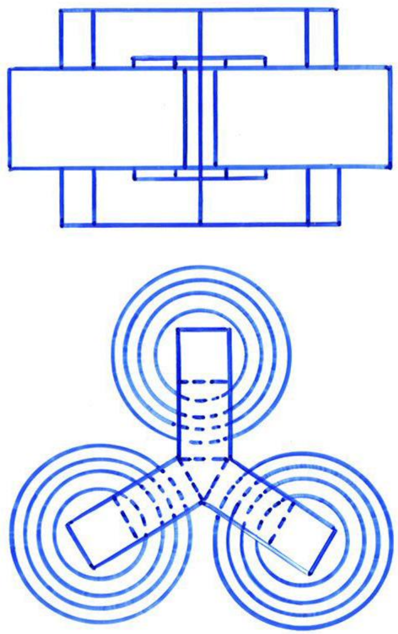
Main fluxes of the three cores have identical magnitudes as well and delay from each-other by one third period.

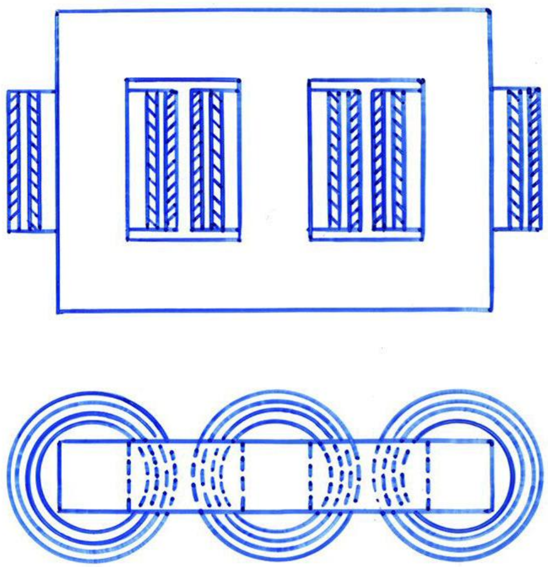
There is no flux in the joint vertical leg: $\overline{\phi}_A + \overline{\phi}_B + \overline{\phi}_C = 0$, thus it can be omitted.



THREE-PHASE CORE TYPE TRANSFORMERS

Because of ease of manufacture the core is built in one plane and the primary and secondary windings of the three phases are put on three legs.





Magnetic circuit related properties of three-phase core type transformers

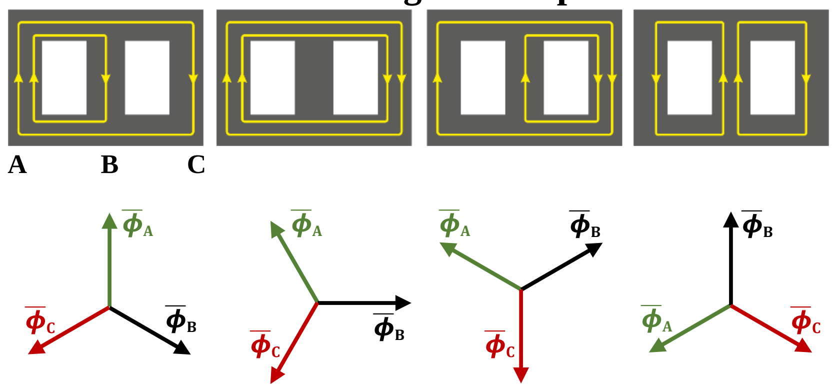
- **Because of the construction of the core the main fluxes of the phases can not be independent from each-other, their sum must always be zero.**
- **The core having three legs is not symmetrical related to the magnetic field.**

ASYMMETRY OF THE NO-LOAD CURRENTS OF THREE-PHASE CORE TYPE TRANSFORMERS

For producing the fluxes with identical magnitudes in each core legs for magnetizing the magnetic circuit of the medium leg requires less excitation – because of the asymmetry of the core – than in case of the two lateral legs.

One of the magnetic circuits corresponding to the lateral legs has the same length as that of the medium circuit, however the other is longer.

Every magnetic circuit is coupled with the windings of two phases.



The no-load currents of the three phases are asymmetric as well:

$$I_{0B} < I_{0A} = I_{0C}$$

Their vector resultant at the star point is not zero.

The two magnetic circuits of the medium leg have the same lengths.

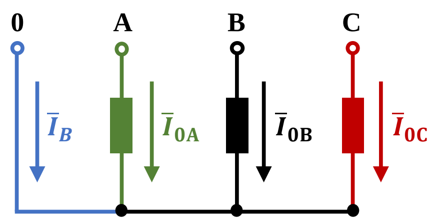
A balancing current ($\bar{I}_b$) flows with a magnitude ensuring that the resultant of the currents is zero.

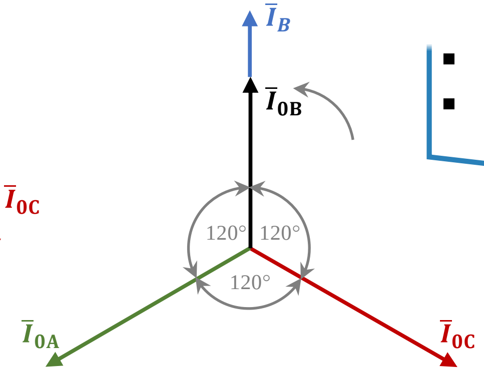
Notice: No-load current of the medium phase is lower than those of the lateral ones by 20-40%.

WORKING PRINCIPLE OF THREE-PHASE TRANSFORMERS

ASYMMETRY OF THE NO-LOAD CURRENTS OF THREE-PHASE CORE TYPE TRANSFORMERS

▪ The primary side is star-connected with led-out neutral wire

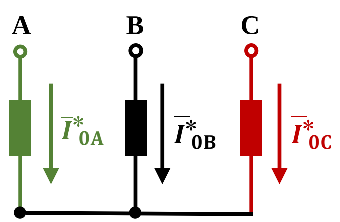


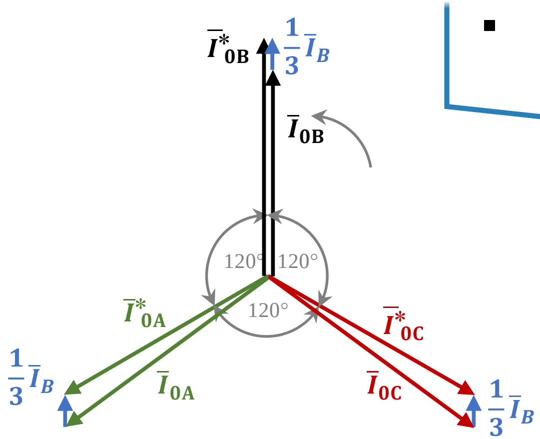


- The balancing current flows out on the neutral wire.
- $\bar{I}_B = \bar{I}_{0A} + \bar{I}_{0B} + \bar{I}_{0C}$

It causes voltage drop along the impedances of the primary network.

▪ The primary side is star-connected without led-out neutral wire





- Because of the lack of neutral wire I_B flows in the primary phase windings.

- Phase current are distorted to an extent ensuring their resultant to be zero:

$$\bar{I}^*_{0A} = \bar{I}_{0A} + \frac{1}{3}\bar{I}_B$$

$$\bar{I}^*_{0B} = \bar{I}_{0B} + \frac{1}{3}\bar{I}_B$$

$$\bar{I}^*_{0C} = \bar{I}_{0C} + \frac{1}{3}\bar{I}_B$$

- Current system composed by $\bar{I}^*_{0A}$; $\bar{I}^*_{0B}$; $\bar{I}^*_{0C}$ is not symmetrical but their resultant is zero.

ASYMMETRY OF THE NO-LOAD CURRENTS OF THREE-PHASE CORE TYPE TRANSFORMERS

Build-up of yoke fluxes

$$\bar{I}_{0A}^{*} = \bar{I}_{0A} + \frac{1}{3}\bar{I}_B$$
$$\bar{I}_{0B}^{*} = \bar{I}_{0B} + \frac{1}{3}\bar{I}_B$$
$$\bar{I}_{0C}^{*} = \bar{I}_{0C} + \frac{1}{3}\bar{I}_B$$

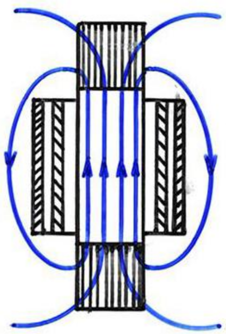
In each primary phase coil a current component $\frac{1}{3}\bar{I}_B$ develops as well.

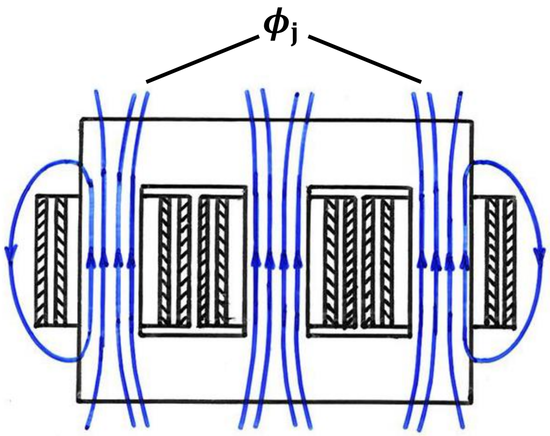
Apart from the three-phase flux so called yoke fluxes (ϕ_y) develop in each leg because of the current components $\frac{1}{3}\bar{I}_B$.

Properties of the yoke fluxes

- They have the same direction in every time moment so that they can not close in cores with three legs.
- They induce voltages with the same phase displacement in each phase coil.
- Voltages induced by the main flux are superposed by those induced by the yoke fluxes.

Magnitude and phase displacement of the phase voltages between the coil terminals and the star point change.





Method of eliminating the effect of the yoke fluxes

- applying yoke turns
- delta connection of the primary side.

CHANGES IN THE VOLTAGES OF A TRANSFORMER AS A RESULT OF THE LOAD

Changes of the voltage is a property of transformers during their operation.

It shows the effect of the load on the magnitude and phase displacement of the secondary terminal voltage at constant primary voltage.

Consumers are interested in the magnitude of the voltage. For a normal operation V_r ±7,5% has to be maintained.

Definition of voltage change($\Delta\overline{V}'_2$)

Voltage change is the difference between the no-load terminal voltage ($\overline{V}'_{20}$) of the transformer supplied with a rated primary voltage supposed to be constant and the terminal voltage at load ($\overline{V}'_2$).

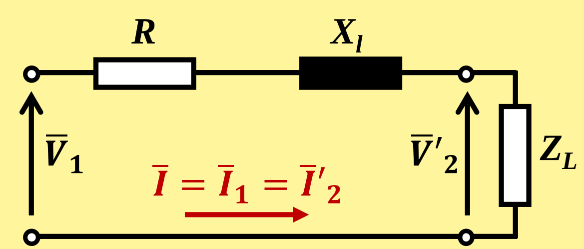
$$\Delta\overline{V}'_2 = \overline{V}'_{20} - \overline{V}'_2$$

Notice: Voltage change can be calculated with r.m.s. value as well described by the difference between the absolute values of the component vectors.

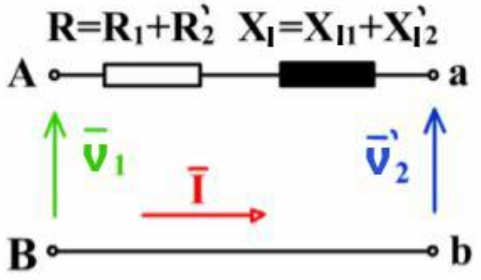
$$\Delta V'_2 = V'_{20} - V'_2$$

Equivalent circuit diagram applied for the discussion of the voltage changes

For the qualitative discussion meeting the requirements of the operation: Simplified equivalent circuit



CHANGES IN THE VOLTAGES OF A TRANSFORMER AS A RESULT OF THE LOAD



$\bar{I}=\bar{I}_1=\bar{I}'_2$

$\bar{V}_1=\bar{I}(R+jX)+\bar{V}'_2=\bar{V}'_2+\bar{Z}_{sc}\cdot\bar{I}$

$$\Delta V'_2=\bar{V}'_{20}-\bar{V}'_2$$

$\Delta V'_2$ calculated from two parts:

$\Delta V'_2=I'_2\cdot Z_{sc}\cdot\cos(\varphi_{sc}-\varphi_2)=IR\cos\varphi_2+IX_l\cdot\sin\varphi_2$

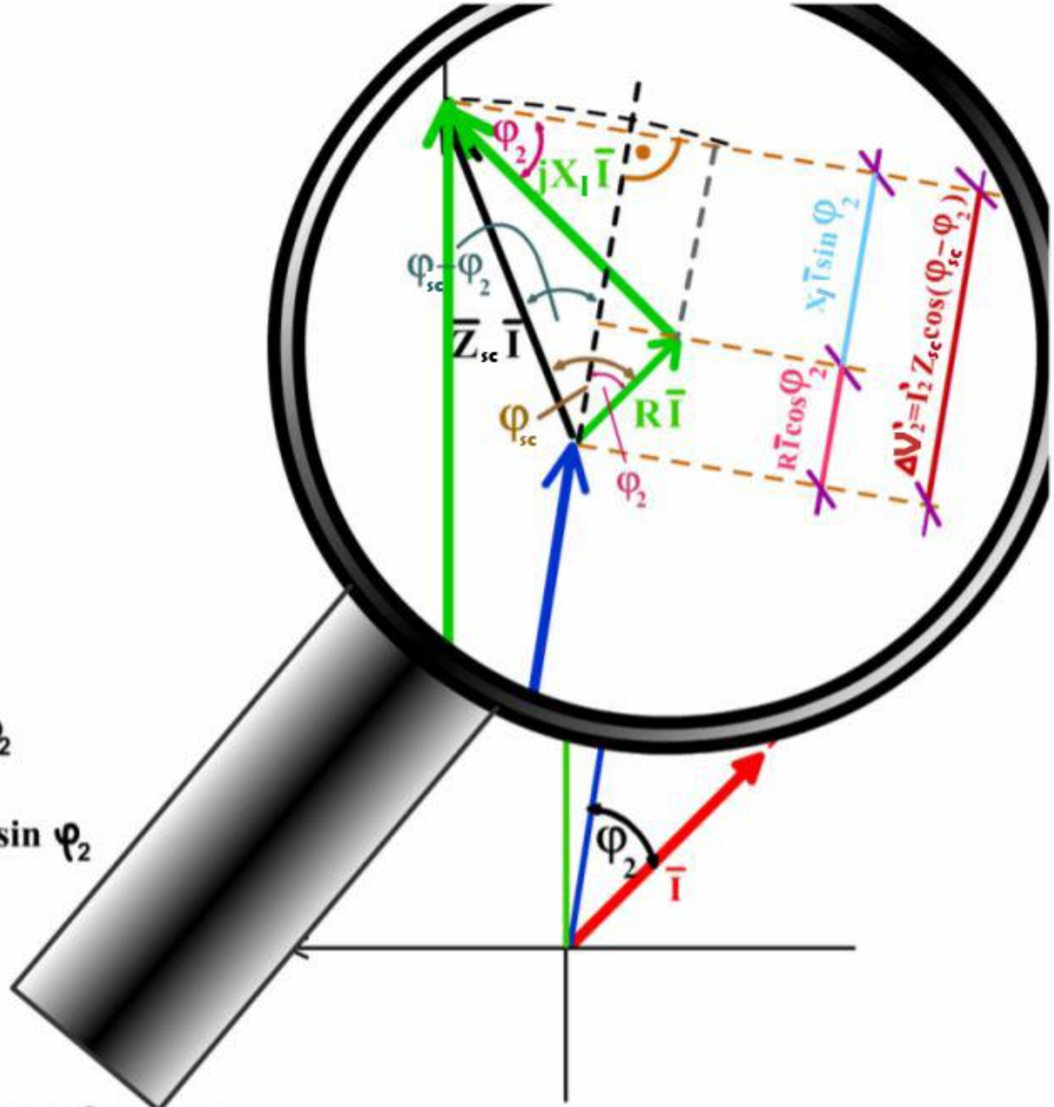
percentage voltage change:

$$\varepsilon=\frac{I'_2\cdot Z_{sc}}{V'_{2r}}\cos(\varphi_{sc}-\varphi_2)=\frac{IR}{V'_{2r}}\cos\varphi_2+\frac{IX_l}{V'_{2r}}\sin\varphi_2$$

with rated current:

$$\varepsilon=\frac{I'_{2r}\cdot Z}{'_{2r}}\cos(\varphi-\varphi_2)=\varepsilon_z\cos(\varphi-\varphi_2)$$

$$\varepsilon=\frac{I'_{2r}\cdot R}{V'_{2r}}\cos\varphi_2+\frac{I'_{2r}\cdot X_l}{V'_{2r}}\sin\varphi_2=\varepsilon_{sc}\cos\varphi_2+\varepsilon_{sz}\sin\varphi_2$$



CHANGES IN THE VOLTAGES OF A TRANSFORMER AS A RESULT OF THE LOAD

▪ Calculation of the secondary voltage

$$V_2' = V_{20}' - \Delta V_2' = V_{20}' - IZ_{sc}\cos(\varphi_{sc} - \varphi_2)$$
$$V_2' = V_{20}' - \Delta V_2' = V_{20}' - (IR\cos\varphi_2 + IX_l \sin\varphi_2)$$

▪ Change in the voltage depending on the phase angle (meeting the condition $I_1 = I_2' = I =$ constant)

$V_2' = f(\varphi_2)$ Typical values of :

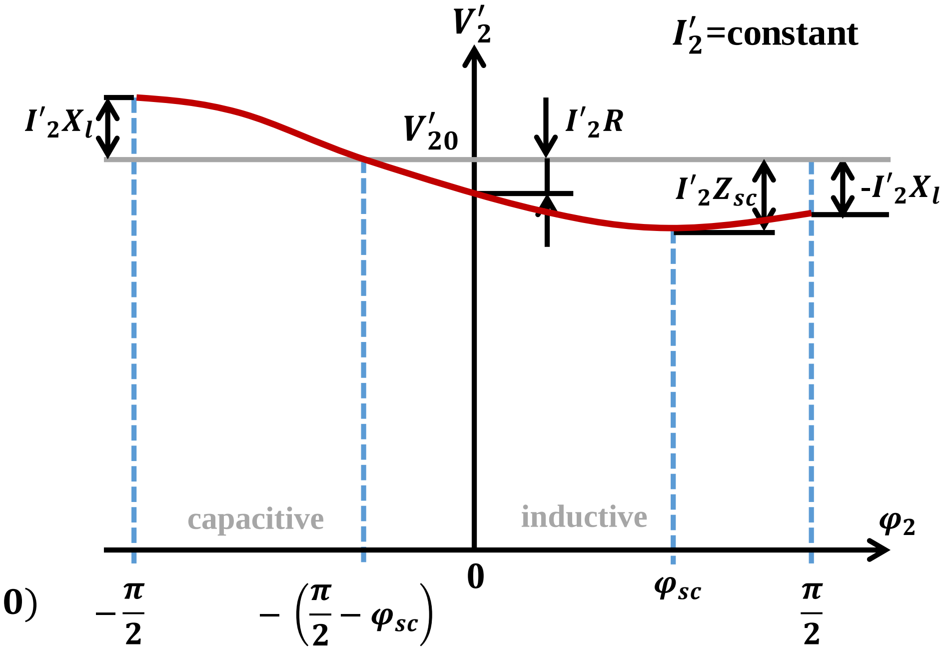
$\varphi_2 = 0$ (ohmic load) $\quad V_2' = V_{20}' - IR$

$\varphi_2 = \frac{\pi}{2}$ (inductive load) $\quad V_2' = V_{20}' - IX_l$

$\varphi_2 = -\frac{\pi}{2}$ (capacitive load) $\quad V_2' = V_{20}' + IX_l$

$\varphi_2 = \varphi_{sc}$ (max. voltage alteration) $\quad V_2' = V_{20}' - IZ_{sc}$

$\varphi_{sc} - \varphi_2 = \frac{\pi}{2} \Rightarrow \varphi_2 = -\left(\frac{\pi}{2} - \varphi_{sc}\right) \quad V_2' = V_{20}'(\Delta V_2' = 0)$

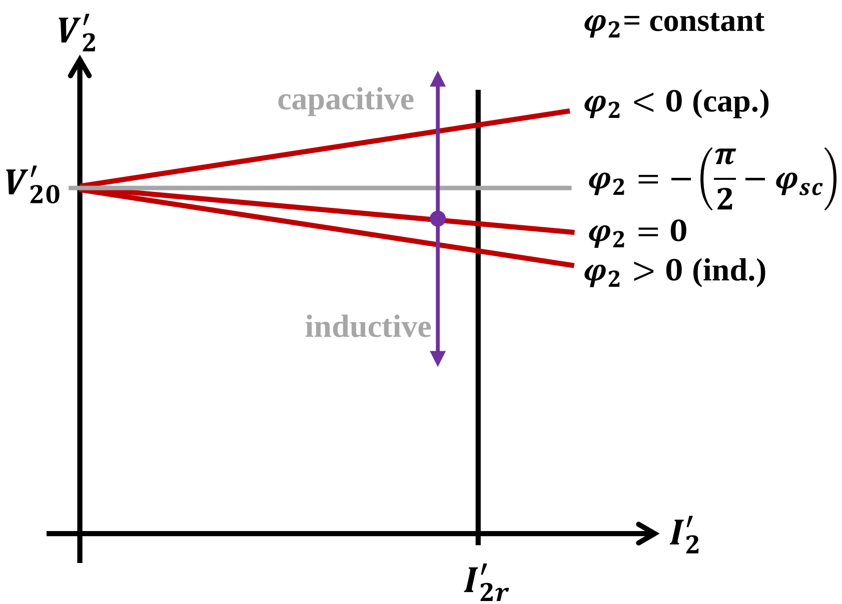


Calculation of the secondary voltage

$$V_2' = V_{20}' - \Delta V_2' = V_{20}' - IZ_{sc}\cos(\varphi_{sc} - \varphi_2)$$
$$V_2' = V_{20}' - \Delta V_2' = V_{20}' - (IR\cos\varphi_2 + IX_l sin\varphi_2)$$

Changes in the voltage depending on the load current (meeting the condition of φ_2= constant)

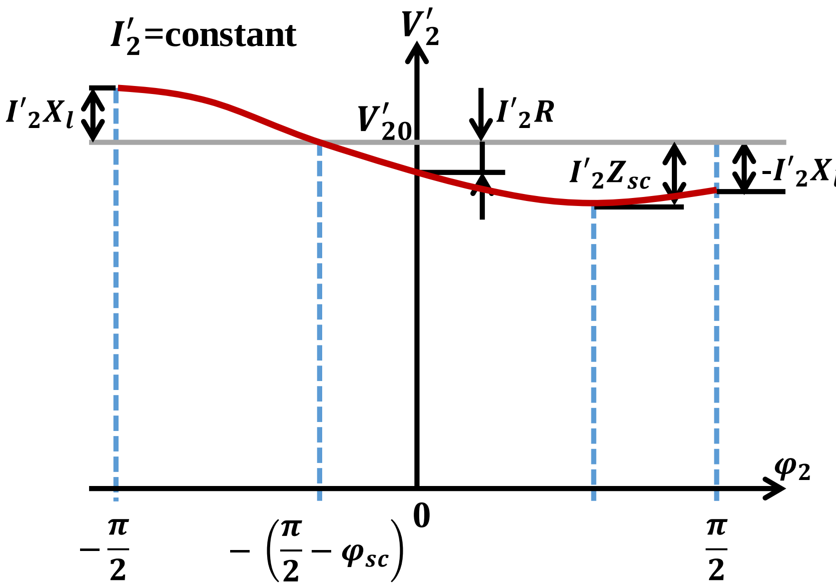
- In case of a constant load angle the secondary terminal voltage changes linear depending on the load current.
- The secondary voltage decreases:
  - In case of ohmic load ($\varphi_2 = 0$): $V_2' = V_{20}' - IR$
  - In case of inductive load($\varphi_2 > 0$): $V_2' = V_{20}' - IZ_{sc}\cos(\varphi_{sc} - \varphi_2)$
  - Voltage drop is maximum if $\varphi_2 = \varphi_{sc}$ $V_2' = V_{20}' - IZ_{sc}$
  - In case of capacitive load($\varphi_2 < 0$), if $$-(\frac{\pi}{2} - \varphi_z) < \varphi_2 < 0$$
- The secondary voltage increases:
  - In case of capacitive load($\varphi_2 < 0$), if $$\varphi_2 < -\left(\frac{\pi}{2} - \varphi_z\right)$$

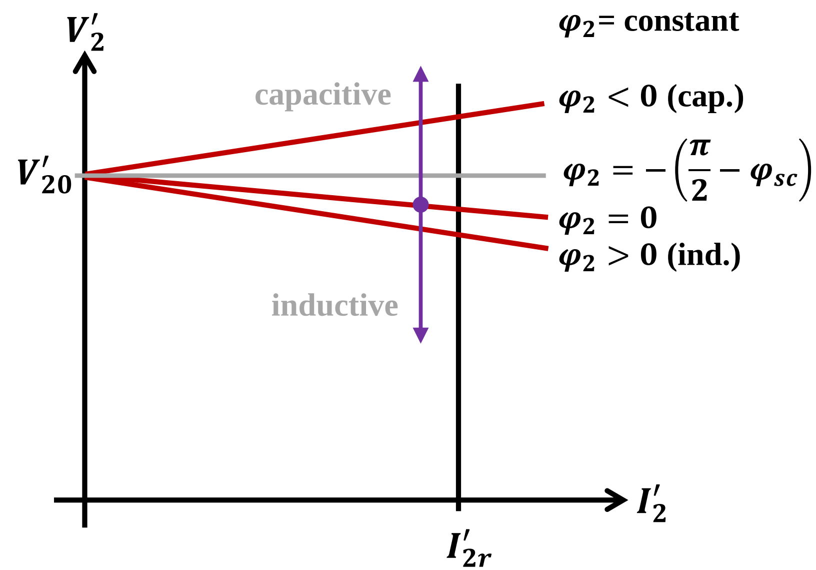


▪ Calculation of the secondary voltage

$$V'_2 = V'_{20} - \Delta V'_2 = V'_{20} - I\, Z_{sc} \cos(\varphi_{sc} - \varphi_2)$$

$$V'_2 = V'_{20} - \Delta V'_2 = V'_{20} - (I\, R \cos \varphi_2 + I\, X_l \sin \varphi_2)$$





SUMMARY

Changes in the voltage of a transformer as a result of the load is determined by:

- **Magnitude ($\bar{I} = \bar{I}_1 = \bar{I}'_2$) and phase displacement(φ_2) of the load current**
- **Short-circuit impedance (Z_{sc}) and short-circuit phase displacement(φ_z) of the transformer.**

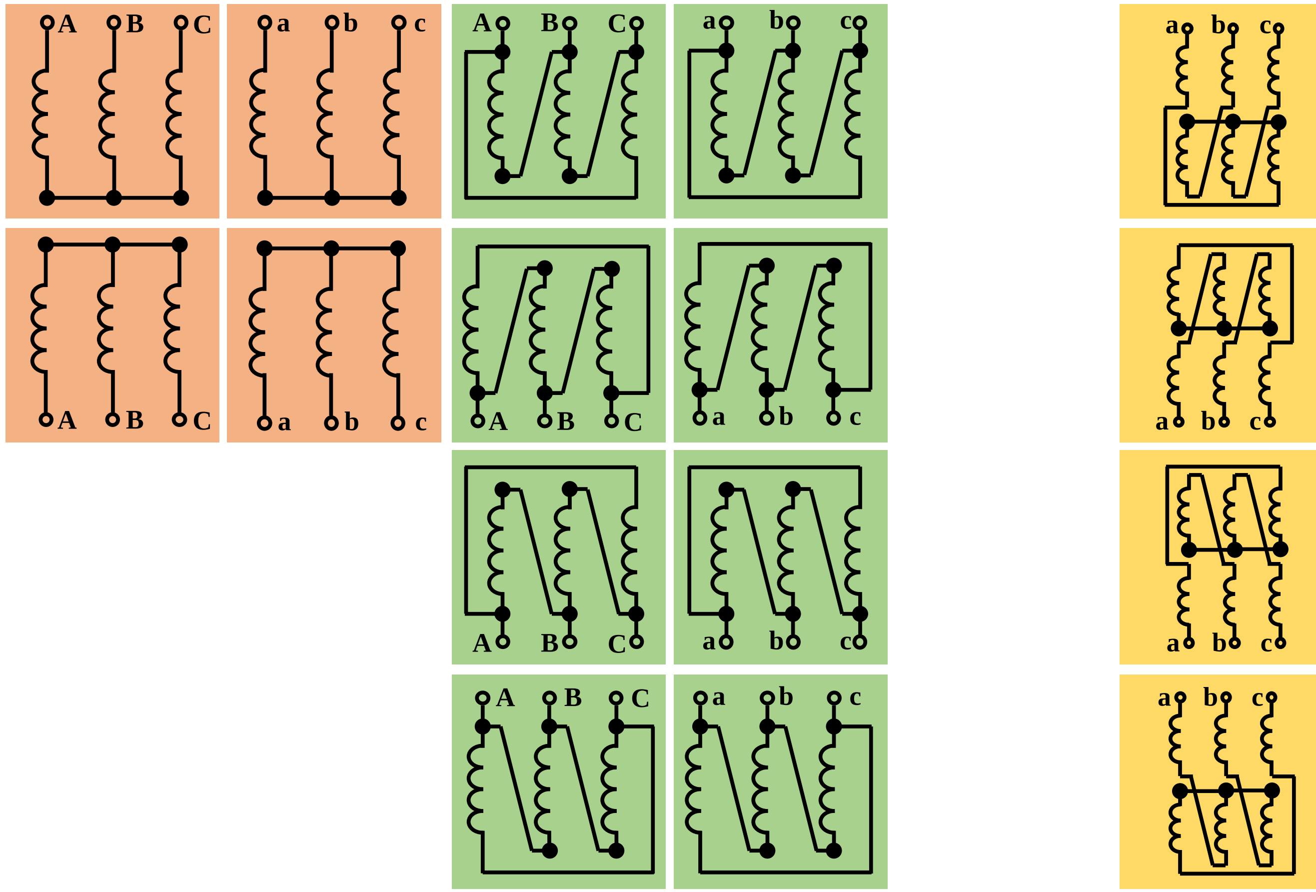
ARTS OF CONNECTION OF THREE-PHASE TRANSFORMERS

Windings of three-phase transformers can basically have three types of connections

Description	STAR CONNECTION		DELTA CONNECTION		ZIG-ZAG CONNECTION
Marking of the conneciton	Y	y	D	d	z

Connections

Star and zig-zag connections can have a lead-out star point. Its marking: E.g. y_0; z_0

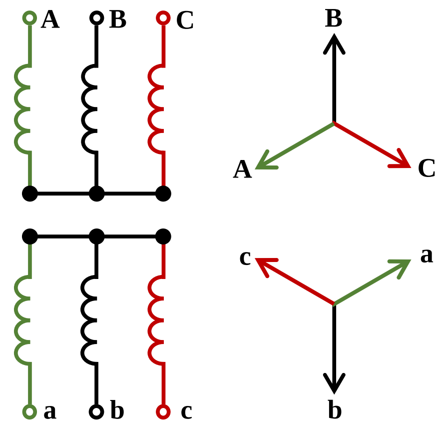


With combinations of different connections the windings of three-phase transformers can have unnecessarily many variations of connections. → Variants proposed for manufacture are defined by standards among them those to be preferred.

ARTS OF CONNECTION OF THREE-PHASE TRANSFORMERS

Basis of the classification of three-phase transformers into connection groups:

NUMBER OF CONNECTION
Definition: Voltages of the side with lower voltages have a delay by NUMBER OF CONNECTION x 30° related to the corresponding voltages at the side with higher voltages.



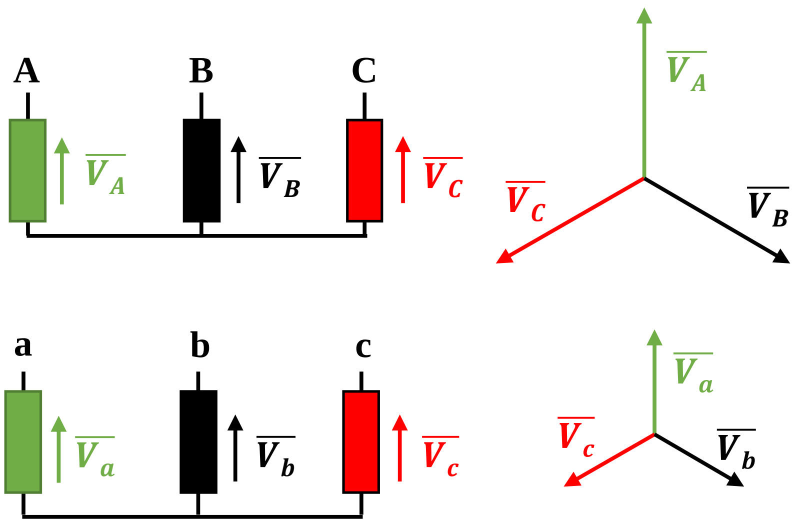
Notice: Three-phase transformers with different connections can belong to the same group. Their common property is the same number of connection.

Standard marking of connection of three-phase transformers

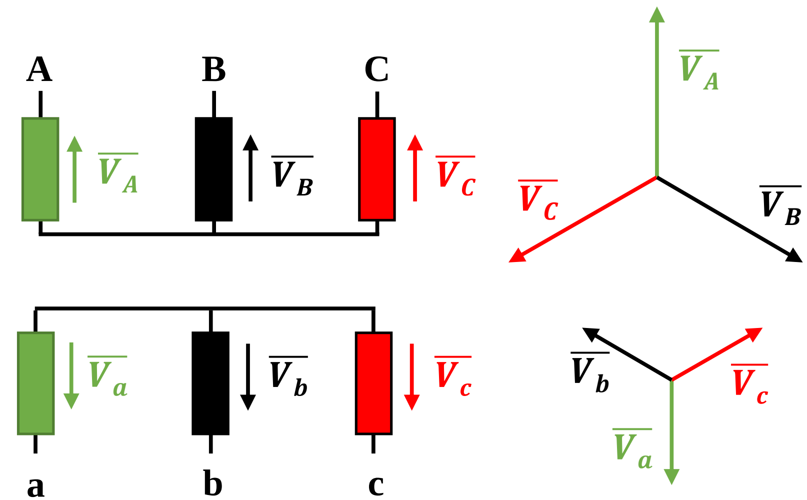
	MARKING OF THE CONNECTION OF THE SIDE WITH HIGHER VOLTAGES	MARKING OF THE CONNECTION OF THE SIDE WITH LOWER VOLTAGES	NUMBER OF CONNECITON
For example:	**D** The side with higher voltages have delta connection.	**y_0** The side with lower voltages have star connection with lead-out star point.	**5** Every phase voltage of the side with y connection has a delay of 5x30°=150° related to the corresponding imaginary phase voltage of the side with **D** connection.

ARTS OF CONNECTION OF THREE-PHASE TRANSFORMERS

Transformers with Yy0; $Yy_0 0$ connections



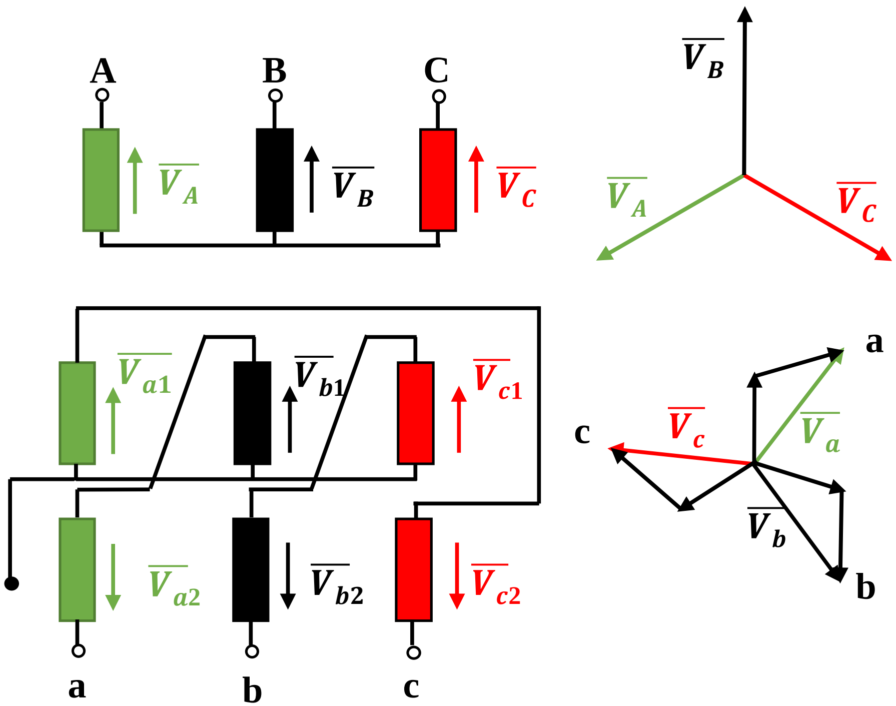
Transformers with Yy6; $Yy_0 6$ connections



- **Proposed by the standard for manufacture.**
- **Application:**
  - **up to a power limit of several 100 kVA,**
  - **the neutral wire can be loaded with max. 10%.**

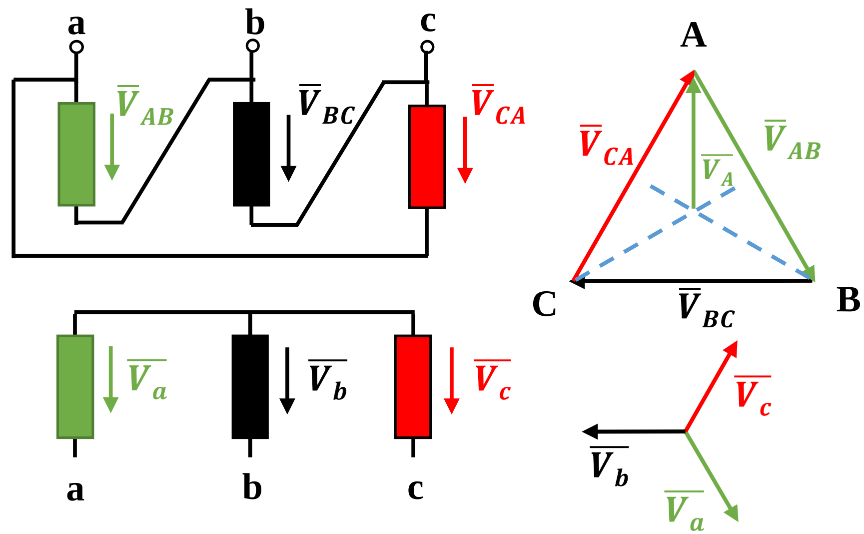
ARTS OF CONNECTION OF THREE-PHASE TRANSFORMERS

Transformers with $Yz_0 5$ connection



- **Application:**
  - up to a power of 100 kVA
  - the neutral wire can be full loaded

Transformers with $Dy_0 5$; Dy5 connection

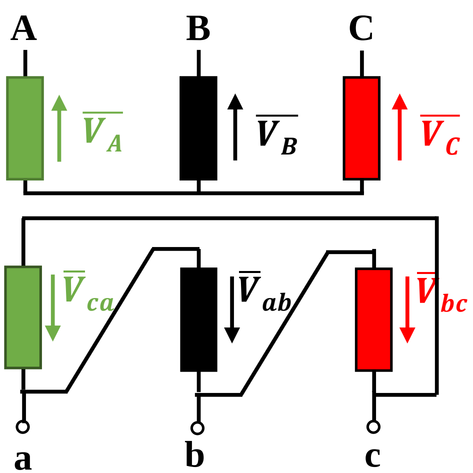


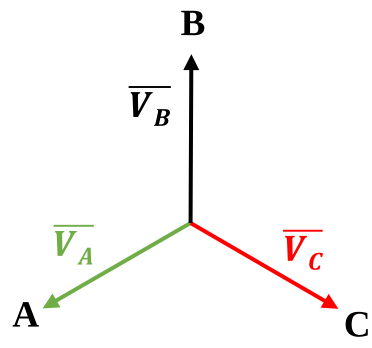
- **Application:**
  - as high power distribution transformers
  - the neutral wire can be full loaded

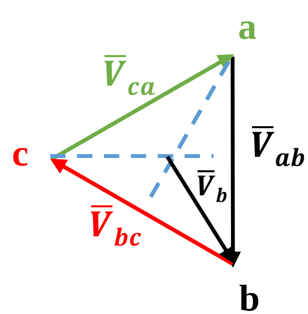
Three-phase transformers with Yz_0 5 and Dy_0 5 connections are proposed for manufacture.

ARTS OF CONNECTION OF THREE-PHASE TRANSFORMERS

Transformers with Yd5 connection







- Application:
  - transformers of power plants, substations
- proposed for manufacture by the standard.

Voltage ratio of three-phase transformers

Ratio calculated from line voltages:

$$a = \frac{V_{1line}}{V_{2line}}$$

Relation with the ratio of turns

E.g. in case of a transformer with Yd5 connection:

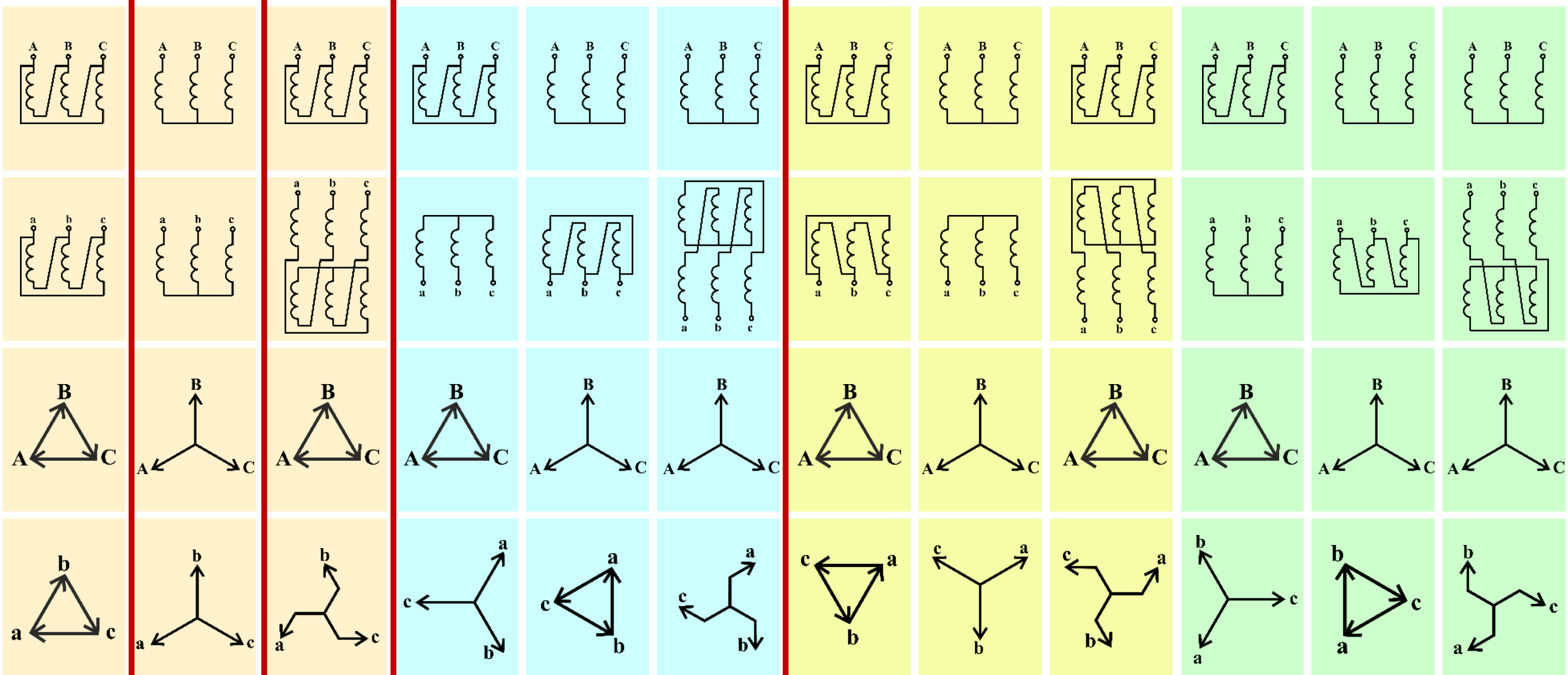
$$a = \frac{V_{1line}}{V_{2line}} = \frac{\sqrt{3}\,cN_1}{cN_2} = \sqrt{3}\frac{N_1}{N_2}$$

- cN_1: Phase voltage of the Y connection
- cN_2: Line (and phase) voltage of the d connection
- N_1: Number of turns of the Y connection
- N_2: Number of turns of the d connection

ARTS OF CONNECTION OF THREE-PHASE TRANSFORMERS

Three-phase transformer connections applied in the practice

	0			5			6			11		
Marking of connection	Dd0	Yy0	Dz0	Dy5	Yd5	Yz5	Dd6	Yy6	Dz6	Dy11	Yd11	Yz11
Connection High voltage side												
Connection Low voltage side												
Vector diagram High voltage side												
Vector diagram Low voltage side												
$\frac{V_1^*}{V_2}$	$\frac{N_1}{N_2}$	$\frac{N_1}{N_2}$	$\frac{2N_1}{3N_2}$	$\frac{N_1}{\sqrt{3}\,N_2}$	$\frac{\sqrt{3}\,N_1}{N_2}$	$\frac{2N_1}{\sqrt{3}\,N_2}$	$\frac{N_1}{N_2}$	$\frac{N_1}{N_2}$	$\frac{2N_1}{3N_2}$	$\frac{N_1}{\sqrt{3}\,N_2}$	$\frac{\sqrt{3}\,N_1}{N_2}$	$\frac{2N_1}{\sqrt{3}\,N_2}$



UNEVEN LOAD OF THREE-PHASE TRANSFORMERS

Transformer under test:

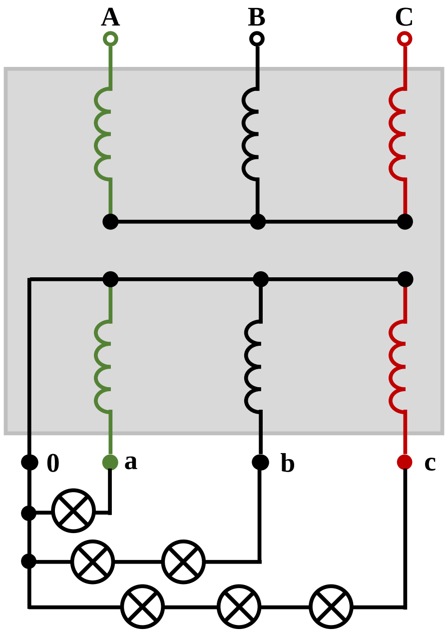
Core type transformer with star/star connection with lead-out star point

Field of application:

For the supply of small consumers and lighting networks, where the three-phase consumers are connected to the line voltage of 400 V and the single-phase consumers to the phase voltage of 230 V.

Problem:

Current flows in the neutral wire of the network, the phases are unevenly loaded if consumers with different power values are connected between the phase wires and the neutral wire.



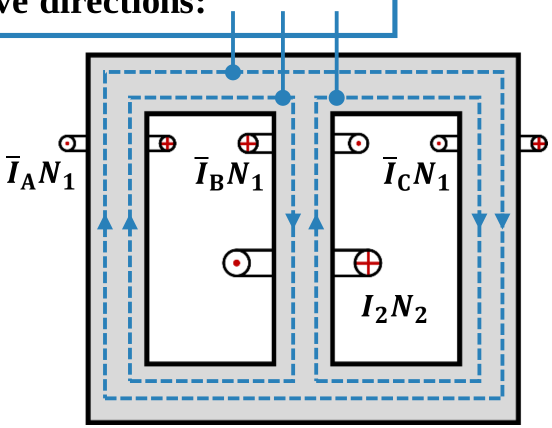
Test:

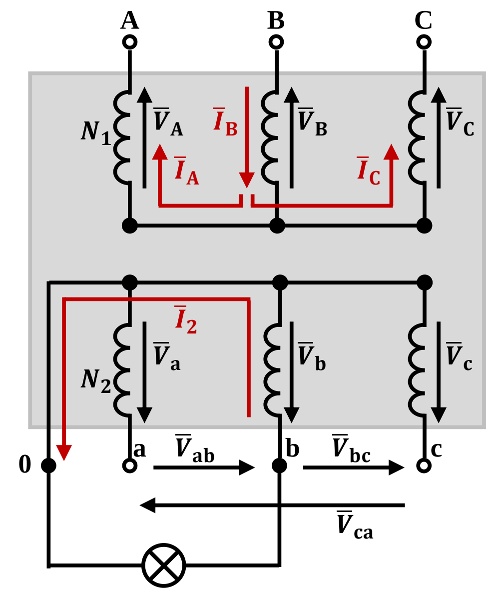
Effect of the uneven load is tested at a limitation case where only the secondary winding on the medium leg is loaded, the other two at the lateral legs have no load (one side load).

UNEVEN LOAD OF THREE-PHASE TRANSFORMERS

Test of the equilibrium of the excitations on the legs:

Magnetic circuits and their chosen positive directions: 1 2 3





Sum of the excitations in the magnetic circuits of the main fluxes are always zero independently from the load:

1) $\bar{I}_A N_1 - \bar{I}_c N_1 = 0$

2) $\bar{I}_A N_1 + \bar{I}_B N_1 - \bar{I}_2 N_2 = 0$

3) $-\bar{I}_B N_1 - \bar{I}_c N_1 + I_2 N_2 = 0$

The nodal rule:

4) $-\bar{I}_A + \bar{I}_B - \bar{I}_C = 0$

$$\bar{I}_B = \frac{2}{3}\bar{I}_2\frac{N_2}{N_1}$$

$$\bar{I}_A = \frac{1}{3}\bar{I}_2\frac{N_2}{N_1}$$

$$\bar{I}_C = \frac{1}{3}\bar{I}_2\frac{N_2}{N_1}$$

UNEVEN LOAD OF THREE-PHASE TRANSFORMERS

Calculating the resultant excitation of the legs

- excitation of the two lateral legs:

$$\bar{I}_A N_1 = \bar{I}_C N_1 = \frac{1}{3}\bar{I}_2 \frac{N_2}{N_1} N_1 = \frac{1}{3}\bar{I}_2 N_2$$

- excitation of the leg in the middle:

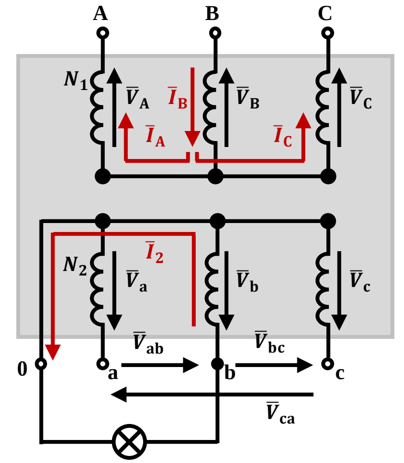
$$\bar{I}_2 N_2 - \bar{I}_B N_1 = \bar{I}_2 N_2 - \frac{2}{3}\bar{I}_2 \frac{N_2}{N_1} N_1 = \frac{1}{3}\bar{I}_2 N_2$$

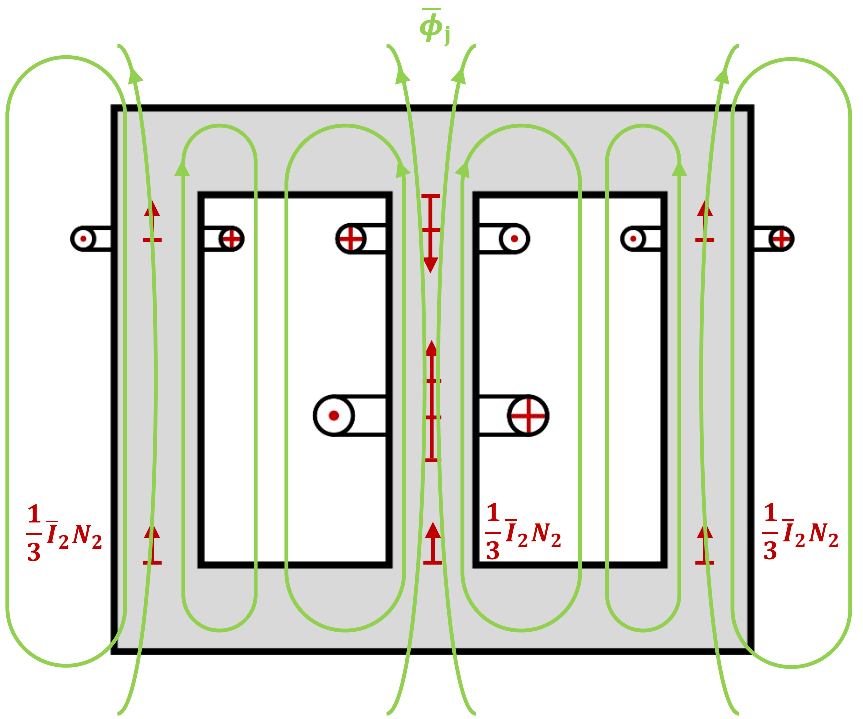
Uneven excitations

In every three legs unbalanced excitations are present with the same magnitude $\left(\frac{1}{3} I_2 N_2\right)$ and direction (pointing upward).

Yoke fluxes

- They are in the same phase displacement with each-other in the three yokes.
- A part of the fluxes leaves the core at the yokes and closes in their vicinity.
- Their magnitude depends on the excitation and conductivity of the magnetic circuits.

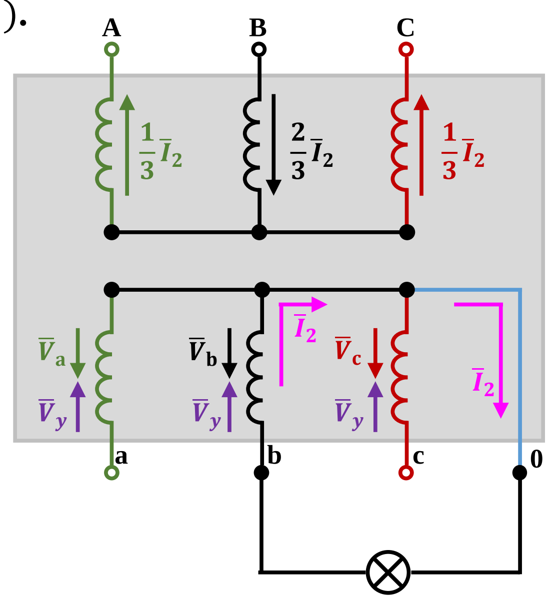




UNEVEN LOAD OF THREE-PHASE TRANSFORMERS

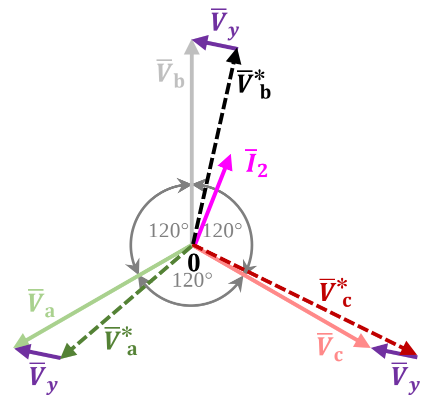
Effect of the yoke fluxes:

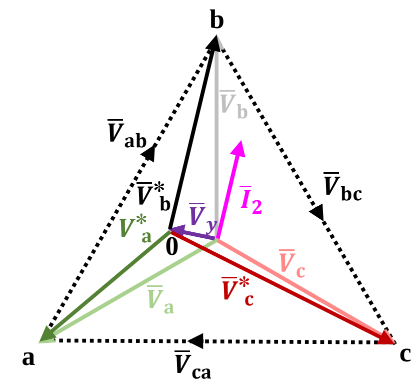
- **They induce additional voltages ($\overline{V}_y$), with the same magnitude and phase displacement in the phase windings, the phase displacement of which is determined by the art of the load($\overline{I}_2$).**



These additional voltages are superposed on the voltages ($\overline{V}_a$; $\overline{V}_b$; $\overline{V}_c$) induced by the main fluxes and distort the symmetrical voltage system.

$$\overline{V}_a^* = \overline{V}_a - \overline{V}_y$$
$$\overline{V}_b^* = \overline{V}_b - \overline{V}_y$$
$$\overline{V}_c^* = \overline{V}_c - \overline{V}_y$$



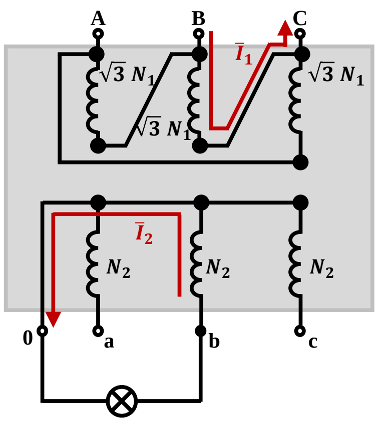


- **They increase the core loss.**
- **They cause eddy current loss in the metal parts around the core.**

UNEVEN LOAD OF THREE-PHASE TRANSFORMERS

Solutions for preventing uneven excitations caused by uneven loads

Transformer with $Yy_0 \Rightarrow Dy_0$ connetion

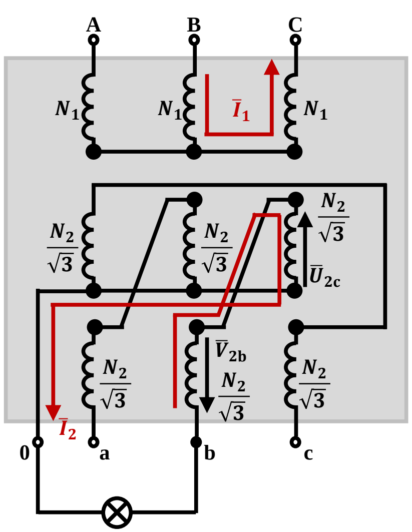


- Current flows only in the primary winding of the leg with its secondary winding loaded ⇒ excitations are in equilibrium ⇒ ~~ϕ_y~~.
- For maintaining the voltage conditions of the Yy_0 connection – assuming a primary network with the same voltage – the number of turns of the primary winding has to be increased to $\sqrt{3}N_1$ in case of Yy_0 connection.

	Yy_0	Dy_0
$a = \frac{V_{1line}}{V_{2line}}$	$\frac{\sqrt{3}cN_1}{\sqrt{3}cN_2} = \frac{N_1}{N_2}$	$\frac{cN_1}{\sqrt{3}cN_2} = \frac{N_1}{\sqrt{3}N_2}$

- Application: In case of high power transformers

Transformer with $Yy_0 \Rightarrow Yz_0$ connetion



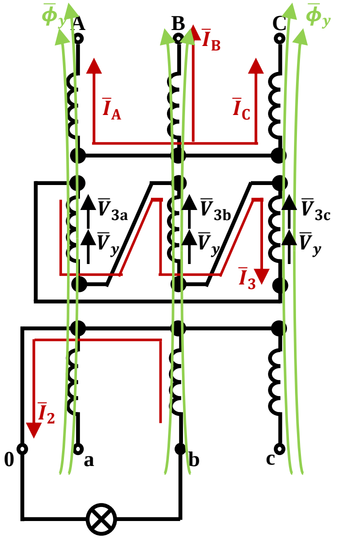
- Current flows in the primary and secondary windings of the same two legs ⇒ excitations are in equilibrium in each leg separately ⇒ ~~ϕ_y~~.
- For maintaining the voltage conditions of the Yy_0 connection – assuming the same primary voltage – the number of turns of the secondary winding of Yz_0 connection has to be increased to $\frac{2}{\sqrt{3}}N_2$

	Yy_0	Yz_0
$a = \frac{V_{1line}}{V_{2line}}$	$\frac{\sqrt{3}cN_1}{\sqrt{3}cN_2} = \frac{N_1}{N_2}$	$\frac{\sqrt{3}cN_1}{\sqrt{3}\sqrt{3}c\frac{N_2}{2}} = \frac{2}{\sqrt{3}}\frac{N_1}{N_2}$

- Application:Transformers with lower powers, higher ratio and relatively high primary voltages.

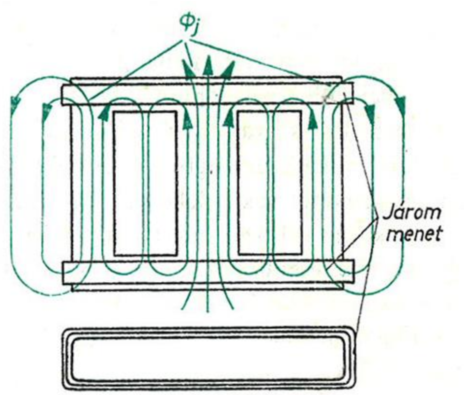
Solutions for decreasing yoke fluxes caused by uneven loads

Transformer with Yy_0 connection with compensating coil (tertiary winding)



- A third, closed winding system placed onto the legs, in which short-circuit current flow produced by the yoke fluxes decreasing these yoke fluxes (Lenz's law).
- Vector resultant of the voltages induced by the main fluxes in this tertiary winding system is zero, they do not produce any current.
- Application: An expensive solution because of building in the third coil, is applied rarely.

Transformer with Yy_0 connection with yoke turn



- An electrically conductive frame surrounds the three legs above and under the windings each.
- Physics of its operation is identical with that of the tertiary winding system.
- It is not a perfect solution so that the neutral wire can only be loaded with $0,25\ I_{2r}$.

PARALLEL OPERATION OF TRANSFORMERS

Two or more transformers are working in parallel if they take power from the same network through their primary terminals and supply the same consumer system through their secondary terminals.

When is it necessary to connect two or more transformers parallel?

- **If a power has to be transported from the primary side to the secondary side higher than the power of the transformer.**
- **Extension of the network ⇒ increase of power.**
- **Because of reliability reasons, during maintenance, repair.**
- **Because of economic considerations.**

PARALLEL OPERATION OF TRANSFORMERS

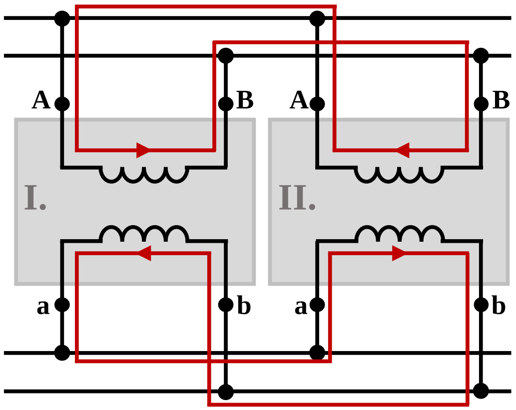
Requirements of parallel operation

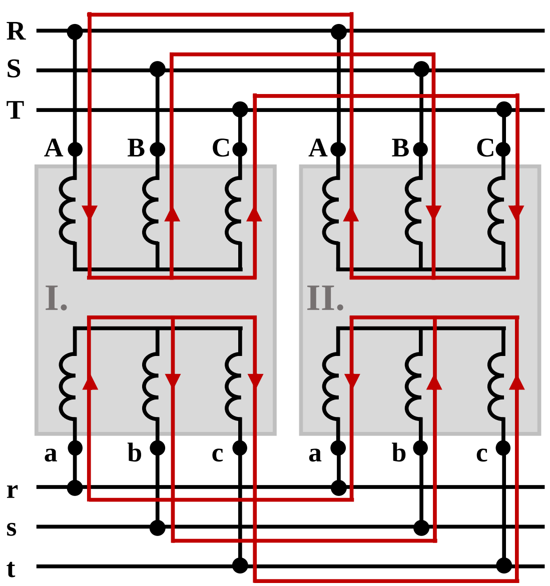
No equalizing current is allowed to flow between parallel connected transformers either under no-load or load conditions.

Equalizing current does not take part in power transmission, it does not do useful work. It causes unnecessary loss in the windings and decreases the loadability.

PRECONDITIONS OF PARALLEL OPERATION UNDER NO-LOAD CONDITION
These preconditions have to be met if the secondary is not loaded.

Notice: It can be considered as a basic precondition of the parallel connection that the rated primary voltage of the transformers is identical with voltage of the joint network.





PARALLEL OPERATION OF TRANSFORMERS

Requirements of parallel operation

The power that has to be transferred from the primary network to the secondary one has to be distributed between the parallel connected transformers according the ratio of their rated powers.

Thus they are loaded to the same extent.

LOAD RELATED PRECONDITIONS OF PARALLEL OPERATION
Load of the secondary side can cause failures.

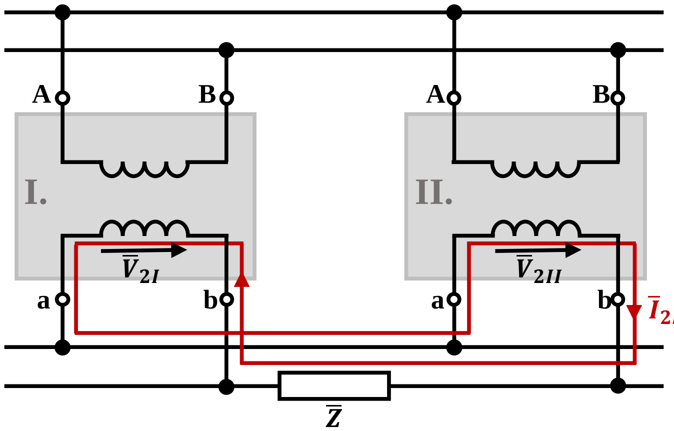
PARALLEL OPERATION OF TRANSFORMERS

No-load related preconditions of the parallel operation

Mash equation established for the circuit of the equalizing current at the secondary side:

$$-\bar{V}_{2I} + \bar{V}_{2II} + \bar{I}_{2b}\bar{Z} = 0$$

where: $\bar{V}_{2I}$; $\bar{V}_{2II}$ are the secondary voltages of the transformer
$\bar{I}_{2b}$ is the balancing current of the secondary side
$\bar{Z}$ is the impedance in the circuit of $\bar{I}_{2b}$



The balancing current:

$$\bar{I}_{2b} = \frac{\bar{V}_{2I} - \bar{V}_{2II}}{\bar{Z}}$$

no equalizing current flows if

$$\bar{V}_{2I} = \bar{V}_{2II}$$

This vector equation means that no equalizing current flows in the secondary circuit, if the induced voltages at the secondary side have the same magnitude and phase displacement.

Notice: The above figure shows the parallel connection of two single-phase transformers, however it can be interpreted so that they are one phase of two three-phase transformers each.

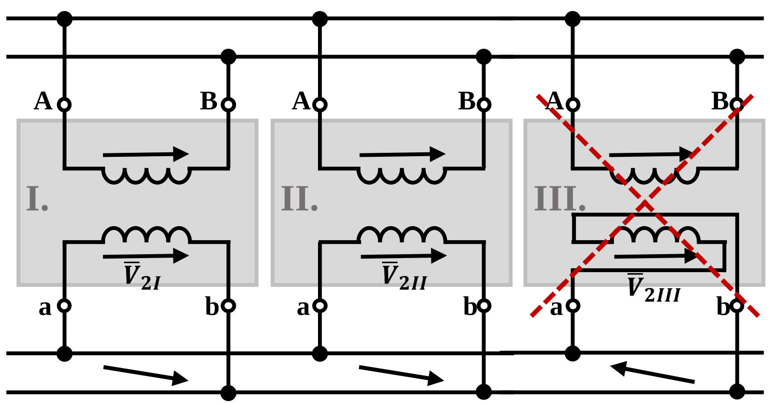
PARALLEL OPERATION OF TRANSFORMERS

No-load related preconditions of the parallel operation

Assuming a joint network for ensuring secondary voltages with the same magnitudes…

**Voltage ratio of parallel connected transformers have to be identical.
Max. allowed deviation : ± 0,5%**

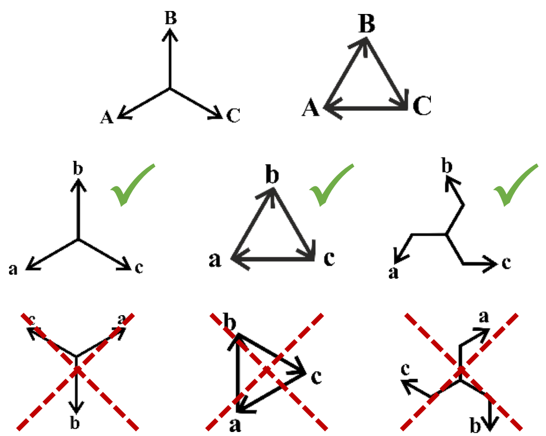
For ensuring the same phase displacement of the secondary voltages…



In case of single-phase transformers the properly marked winding terminals have to be connected the same way to the primary and secondary networks.

Primary coil

Secondary coil



In case of three-phase transformers:

- **numbers of their connection markings,**
- **And the phase sequence must be identical.**

PARALLEL OPERATION OF TRANSFORMERS

No-load related preconditions of the parallel operation

Mash equations established based on the simplified equivalent circuits:

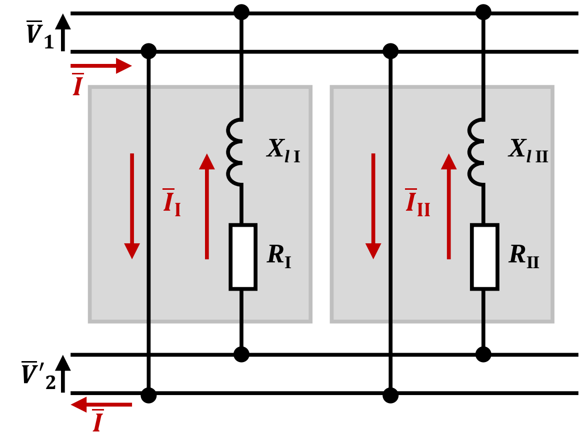
$$\overline{V}_1 = \overline{V}'_2 + \overline{I}_I \overline{Z}_{ZI}$$

$$\overline{V}_1 = \overline{V}'_2 + \overline{I}_{II} \overline{Z}_{ZII}$$

$$\frac{\overline{I}_I}{\overline{I}_{II}} = \frac{\overline{Z}_{ZII}}{\overline{Z}_{ZI}} = \frac{Z_{ZII}}{Z_{ZI}} \frac{e^{j\varphi_{ZII}}}{e^{j\varphi_{ZI}}}$$

this determines the magnitude of the load currents (referring to $\frac{Z_{ZII}}{Z_{ZI}}$)

this determines the phase displacement of the currents related to each-other (referring to $\frac{e^{j\varphi_{ZII}}}{e^{j\varphi_{ZI}}}$)



The parallel connection has the highest utilization,

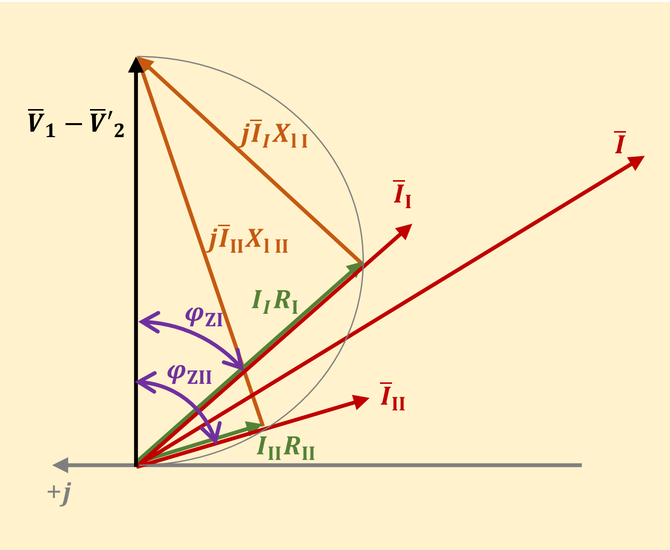
if $\varphi_{ZI} = \varphi_{ZII}$, **then** $I = I_I + I_{II} \geq |\overline{I} = \overline{I}_I + \overline{I}_{II}|$

$$\frac{R_I}{X_{l\,I}} \approx \frac{R_{II}}{X_{l\,II}}$$

Short-circuit phase angle of the transformers is determined by the ratio of their ohmic resistances and leakage reactances.

The R/X_l depends on the measures: $R/X_l \Downarrow$, if $S_r \Uparrow$

Ratio of the rated power of the transformers connected in parallel should not be higher than 3:1.



PARALLEL OPERATION OF TRANSFORMERS

Load related preconditions of the parallel operation

In idealized case: $\varphi_{ZI} = \varphi_{ZII}$, then calculated with absolute values

$$I = I_I + I_{II}$$

$$\frac{I_I}{I_{II}} = \frac{Z_{ZII}}{Z_{ZI}}$$

Objective is that the load (current) of the transformers be proportional to their rated powers:

$$\frac{I_I}{I_{II}} = \frac{S_{rI}}{S_{rII}} = \frac{V_{1r} I_{rI}}{V_{1r} I_{rII}} = \frac{Z_{ZII}}{Z_{ZI}}$$

$$I_{rI} Z_{ZI} = I_{rII} Z_{ZII}$$

$$\varepsilon_{scI} = \varepsilon_{scII}$$

Drops of parallel connected transformers should possibly be identical. The deviation should not be higher than ± 10%.

Effect of drops on the loadability

$$I_I Z_{scI} = I_{II} Z_{scII}$$

$$\underbrace{\frac{I_{rI}}{I_{rI}} \frac{Z_{ZI}}{V_{1r}}}_{\varepsilon_{scI}} I_I = \underbrace{\frac{I_{rII}}{I_{rII}} \frac{Z_{ZII}}{V_{1r}}}_{\varepsilon_{scII}} I_{II}$$

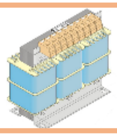
$$\frac{I_I}{I_{II}} = \frac{\varepsilon_{scII}}{\varepsilon_{scI}} \frac{I_{rI}}{I_{rII}}$$

If transformers with different drops are connected parallel then their loadability is influenced reversely by the ratio of their drops. The one with lower drop carries the higher load.

EFFICIENCY OF TRANSFORMERS

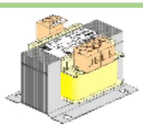
General interpretation of power efficiency: $\eta = \frac{\text{OUTPUT POWER}}{\text{INPUT POWER}}$

Powers of transformers



$$P_1 = \sqrt{3} V_1 I_1 cos\varphi_1$$

$$P_2 = \sqrt{3} V_2 I_2 cos\varphi_2$$



$$P_1 = V_1 I_1 cos\varphi_1$$

$$P_2 = V_2 I_2 cos\varphi_2$$

ENERGY CONVERSION

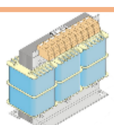
$P_{winding}$

They vary proportionally to the square of the currents flowing in the primary and secondary windings.
Noitce: Assuming that V= constant;
$cos\varphi$ = constant they vary nearly proportionally to the square of the power

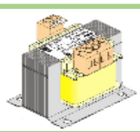
P_{core}

- Is constant independently from the load.
- Its component:
  - Hystheresis loss: $P_h = \sigma_h f B^{1,6 \dots 2} m_{core}$
  - Eddy current loss: $P_{summ} = \sigma_{summ} \Delta^2 f^2 B_{max}^2 m_{core}$

Efficiency of transformers



$$\eta = \frac{\sqrt{3} V_2 I_2 cos\varphi_2}{\sqrt{3} V_1 I_1 cos\varphi_1} = \frac{\sqrt{3} V_2 I_2 cos\varphi_2}{\sqrt{3} V_2 I_2 cos\varphi_2 + P_{core} + P_{coil}}$$ (In case of symmetrical load)



$$\eta = \frac{V_2 I_2 cos\varphi_2}{V_1 I_1 cos\varphi_1} = \frac{V_2 I_2 cos\varphi_2}{V_2 I_2 cos\varphi_2 + P_{core} + P_{coil}}$$

RATED EFFICIENCY (η_r)

Ratio of the output and input powers of the transformer operating with rated load.

The transformer operated at the rated voltage given on its data plate and rated current flows in the winding. For every art of connection and any side:

$$S_r = \sqrt{3} V_{r1} I_{r1} = \sqrt{3} V_{r2} I_{2r}$$

The input power is maximum the rated one (no overload), the output power is decreased by the losses. Value of the apparent power calculated from the rated values, however assuming cosφ = 1 we calculate with active powers.

Rated efficiency calculated with active powers

η_r	TRANSFORMERS	
	Single-phase	**Three-phase**
	$\dfrac{V_r I_r - P_{core} - P_{wr}}{V_r I_r}$	$\dfrac{\sqrt{3} V_r I_r - P_{core} - P_{wr}}{\sqrt{3} V_r I_r}$

Notice: In general the rated efficiency of transformers is very good η_r=95…99% (higher values relate to units with higher powers).

OPERATING EFFICIENCY

Efficiency value calculated from the voltage, current and power factor belonging to the given load during the operation of the transformer.

Properties determining the operating efficiency

- **Core loss;** $P_{core} = \text{constant}$

During operation the supply voltage does not vary, it is of rated value $\left(V_{r\,-7,5\%}^{\,+7,5\%}\right). \Rightarrow \quad P_{core} = \text{constant}$

- **Winding (coil) loss;** $P_w \sim I_w^2$

In the knowledge of the rated coil loss: $\frac{P_{w\,r}}{P_w} = \left(\frac{I_r}{I_w}\right)^2 \Rightarrow P_w = P_{w\,r}\left(\frac{I_w}{I_r}\right)^2 = P_{w\,r}\beta^2$

load current flowing through the transformer (I_w)

β ($\frac{I_w}{I_r}$)

- **Input power;** P_1

$$P_1 = V_r I_w \cos\varphi = V_r\, I_r \frac{I_w}{I_r} \cos\varphi = S_r \beta \cos\varphi$$

Load current (I_w), S_r ($V_r I_r$), β ($\frac{I_w}{I_r}$), **power factor** ($\cos\varphi$)

Operating efficiency : $\eta = \frac{P_1 - P_{core} - P_w}{P_1} = \frac{S_r\beta\cos\varphi - P_{core} - P_{w\,r}\beta^2}{S_r\beta\cos\varphi}$

MAXIMUM EFFICIENCY

At which load conditions is the efficiency maximum?

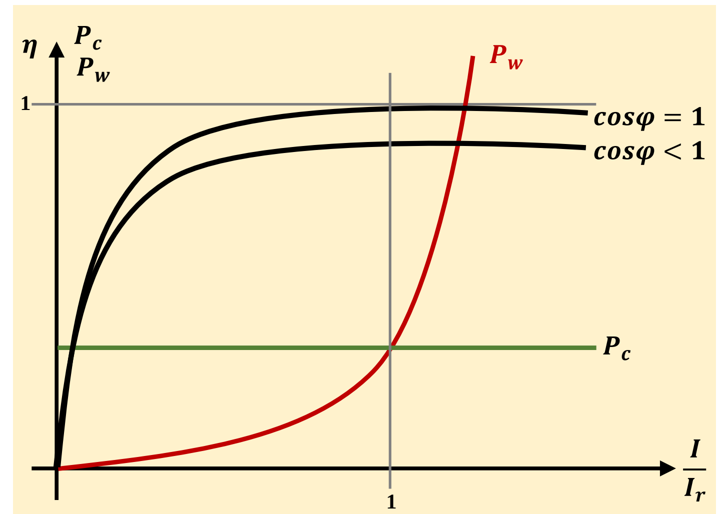
Efficiency function calculated with losses:

Neglecting the exciting current: $I_1^2 R_1 + I_2'^2 R_2' = I_1^2 (R_1 + R_2') = I_1^2 R$

In case of a constant voltage:

P_{core}=constant

$$\eta = \frac{V_1 I_1 cos\varphi_1 - P_c - P_w}{V_1 I_1 cos\varphi_1} = \frac{V_1 cos\varphi_1 - \left(\frac{P_c}{I_1} + \frac{I_1^2}{I_1} R\right)}{V_1 cos\varphi_1}$$



Assuming constant voltage and cosφ = 1 the maximum of the efficiency function has a maximum, where all losses have minimum.

$$\frac{d\left(\frac{P_c}{I_1} + I_1 R\right)}{dI_1} \Rightarrow 0 - \frac{P_c}{I_1^2} + R = 0$$

$P_c = I_1^2 R = P_w$	**Efficiency is maximum at the load, at which the coil and core loss are the same.**

Notice:

- *A transformer designed for $P_w = P_c$ would be too big and expensive. In the reality design is performed for thermal load, when $P_w > P_c$.*
- *Efficiency depends on the power factor as well:*
  - *Maximum efficiency – in case of constant current – is at cosφ = 1.*
  - *Inductive loads decrease the value of cosφ → the value of η decreases as well.*

ANALYSIS OF THE EFFICIENCY FUNCTION

In case of a well dimensioned transformer its efficiency has its maximum within the most frequently used power range.

FOR EXAMPLE:

Transformers frequently operated without load or with low load (e.g. for lighting).

Well utilized transformers operated near to rated power, (e.g. in power plants).

$\eta_{\max}$

- **At low load,**
- **At no load the core loss is determinant,**
- **Decrease of the core loss: higher core cross section using cold-rolled plate material with low loss.**

- **At rated load,**
- **In ideal case:** $\frac{P_w}{P_c} = 1$,

In the reality: $\frac{P_w}{P_c} = 2 \ldots 2,5$.

ANNUAL EFFICIENCY

Annual efficiency ≡ enery efficiency
Refers to the ratio, how much energy the transformer converts during a year at how high loss.

Calculation example of the annual efficiency :

- **A three-phase transformer is connected to the network all the year (i.e. 365 days) → 8760 hours.**
- **Its secondary side is loaded at rated power during h hours.**

$$\eta_{\text{annual}} = \frac{h\sqrt{3}V_{2r}I_{2r}cos\varphi_2}{h\sqrt{3}V_{2r}I_{2r}cos\varphi_2 + 8760P_c + hP_{w\,r}}$$

The useful work (numerator: $h\sqrt{3}V_{2r}I_{2r}cos\varphi_2$)

work of the core loss during the whole year ($8760P_c$)

Work of $P_{w\,r}$ during h hours ($hP_{w\,r}$)

Measurement of the annual efficiency :

With kilowatt-hours meters

Utilization of the annual efficiency :

- **For calculating the economicalness,**
- **For characterizing the operation.**

CORE

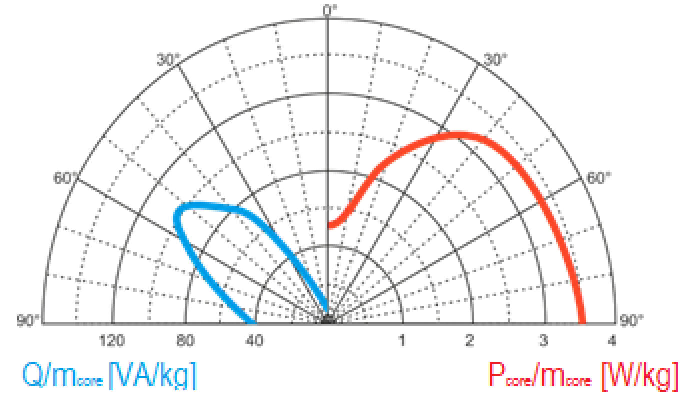
Its role: Establishing flux coupling between the primary and secondary windings with good efficiency (with low loss).

Its material:

- Contradicting requirements :

Good magnetic properties, (magnetizability, high permeability)	High specific resistivity

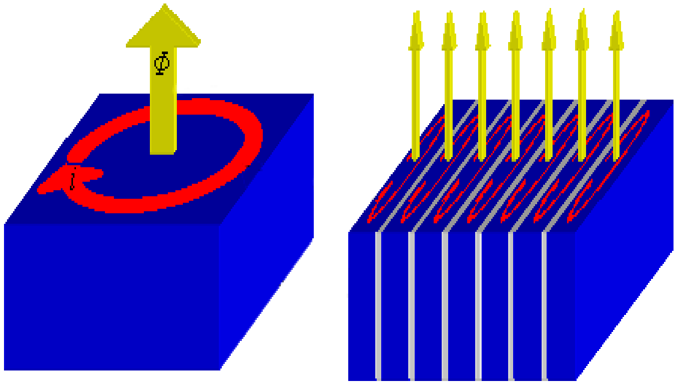
- Cold-rolled iron plate manufactured with heat treatment (recrystallizing heating at 800-1000°C) and with low carbon content and directional particle structure. In the direction of rolling it has low loss and high magnetic permeability.



- Its thickness: 0.35 mm.
- Silicon alloyage to 2.5…4% → for increasing specific resistivity.

Its structure: Plates insulated from each-other. As an effect of heat the silicon content of the plates and the magnesium content of a material called "carlite" create an adhesive magnesium-silicate layer with a thickness of 2-4 µm on the surface of the plates.

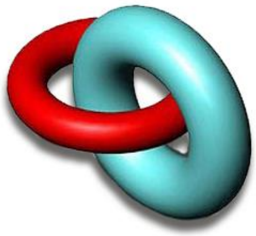
Decrease of the eddy current loss.

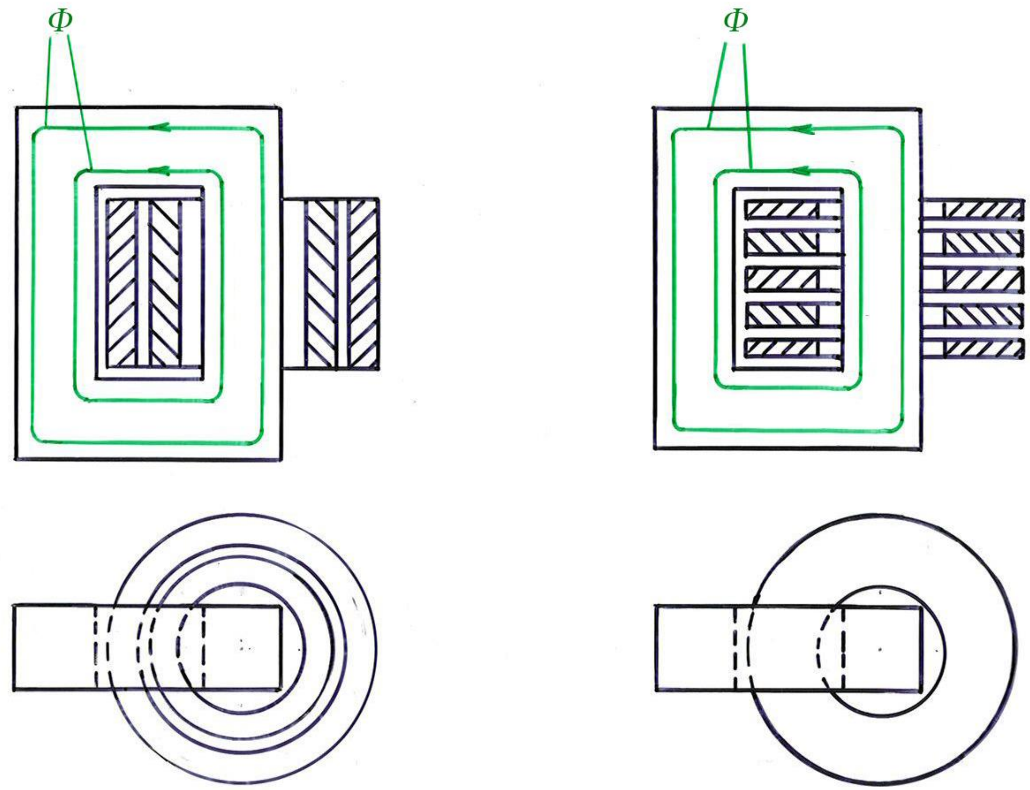


Types of cores of single-phase transformers

Chain-link type core

The core and windings connect to each-other like two links of a chain.

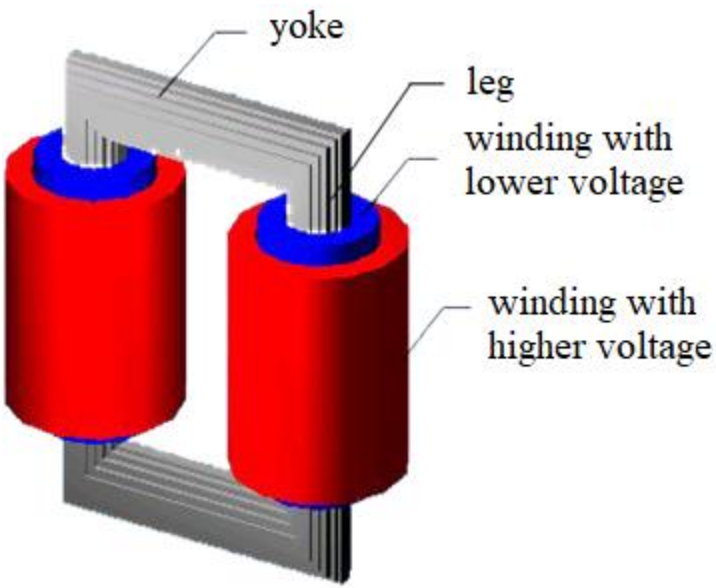


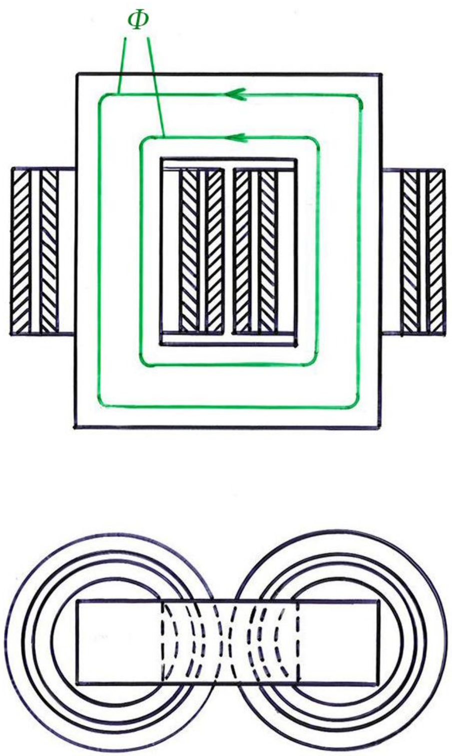


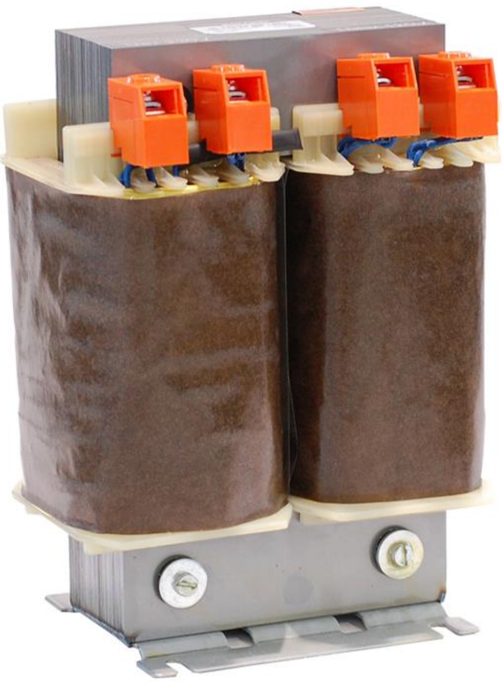
Notice: In case of chain-link only the vertical part of the core surrounded by the coils can be regarded as leg, all other parts are yokes.

Types of cores of single-phase transformers

Core type core





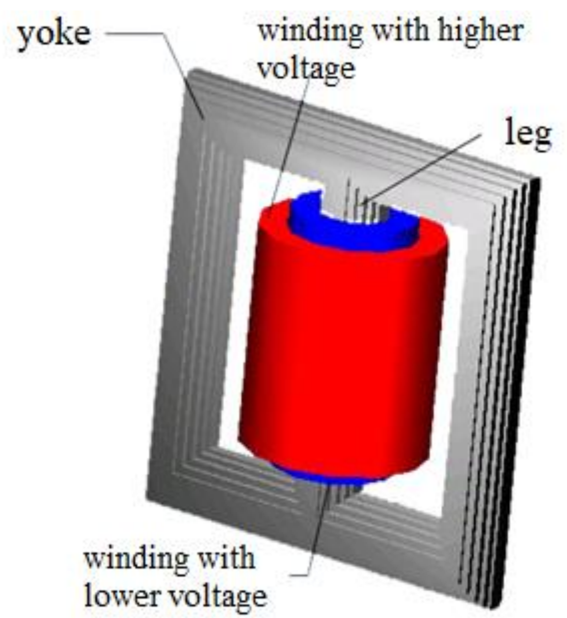


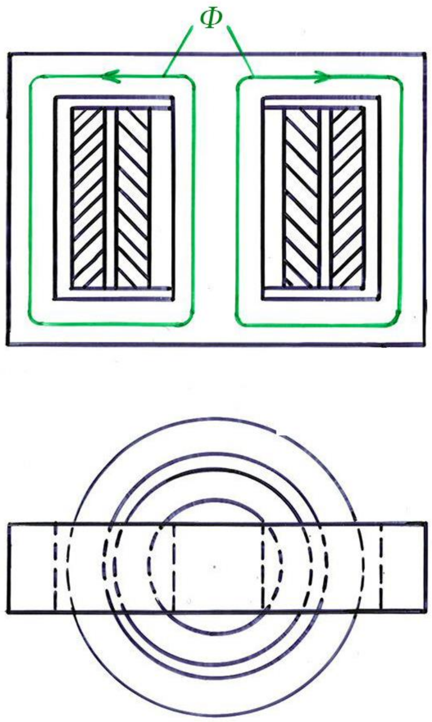
- **Has two legs surrounded with windings.**
- **Possible winding positions:**
  - **One leg supports the primary, the other the secondary winding.** — **High insulation safety but high magnetic leakage.**
  - **Windings are split on both legs.** — **Lower leakage flux but more expensive.**

TYPES OF CORES

Types of cores of single-phase transformers

Shell type core

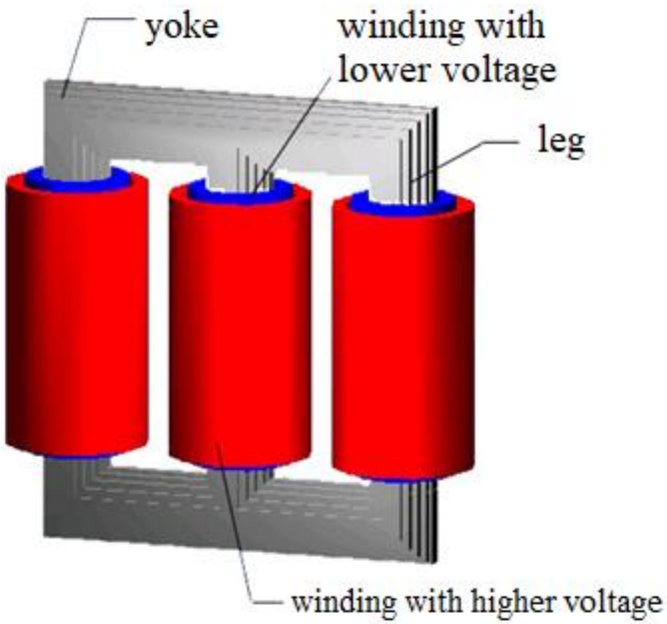


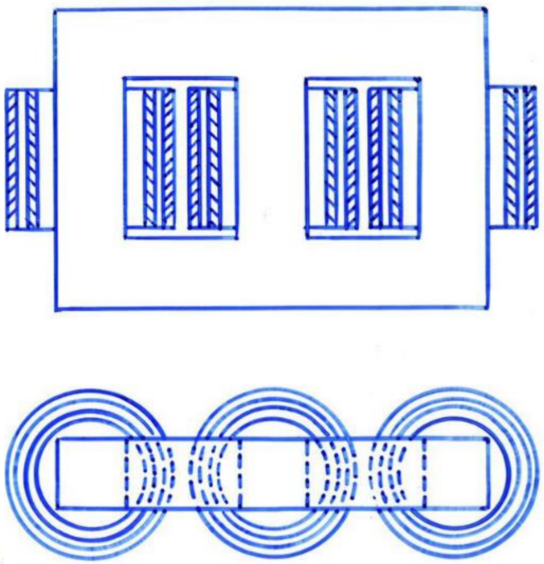


- **Measures of the windings are identical with those of the chain-link type.**
- **Cross-section of the yokes has to be dimensioned to half flux.** → **Lower medium iron length and lower iron weight in turn.** → **Lower core loss.**
- **This is the most frequently applied single-phase transformer type.**

Types of cores of three-phase transformers

Core of core



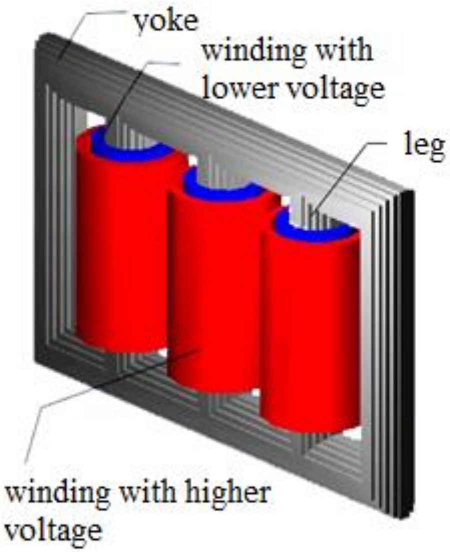


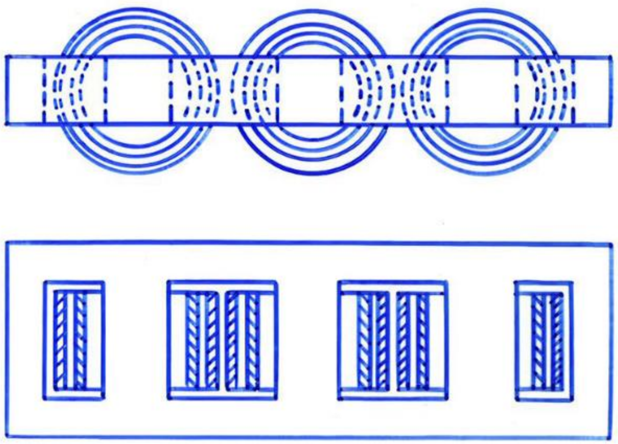
- **This is the most frequently applied three-phase transformer type.**

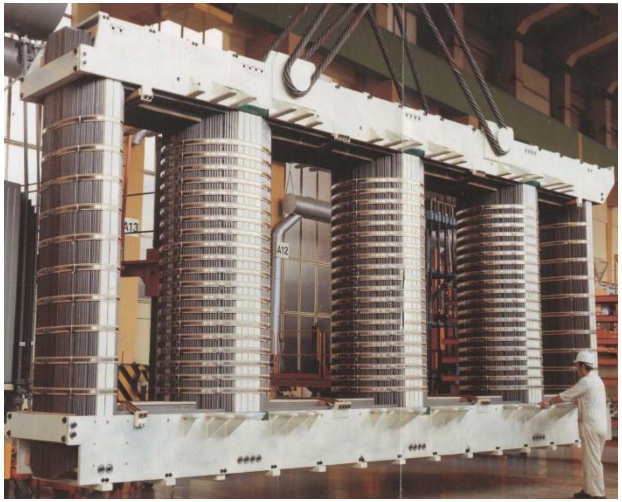
TYPES OF CORES

Types of cores of three-phase transformers

Core type with five legs





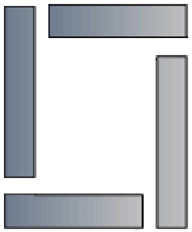


- **Fluxes of all three legs with windings close in two directions.** → **Yokes can have lower cross-section.**
- **In case of symmetrical supply and load the lateral, vertical yokes conduct no fluxes. Sensor coils placed on them can be used for sensing asymmetry.**
- **Unlike core type transformers the fluxes of the phases of transformers with five legs are practically independent from each-other.**

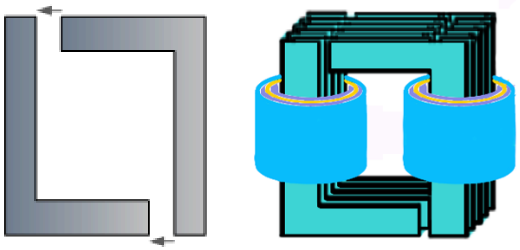
LAMINATION OF THE CORE

Plates of single-phase core type cores

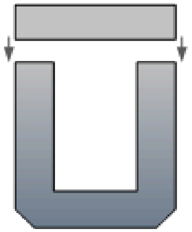
Band lamination



L-L type lamination

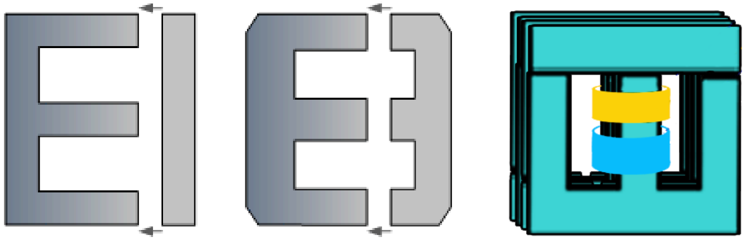


U-I type lamination

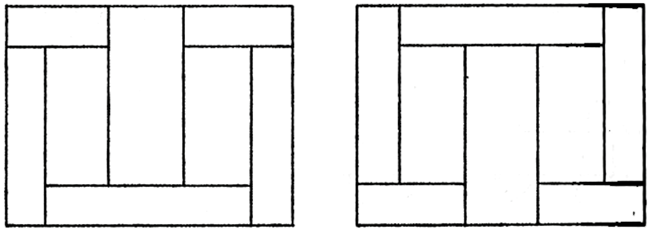


Plates of single-phase shell type cores (with low power)

E-I and E-E lamination



Band lamination

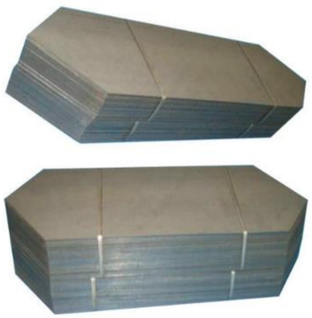


Notice:

- *In case of cold-rolled plates an excess loss develops, because the flux flows in different direction as well than that of the rolling (e.g. at the corners).*
- *Formerly hot-rolled plates were applied with a thickness of 0.35 mm with a silicone content of 3-4.5% and with lacquer or ceramic insulation.*

LAMINATION OF THE CORE

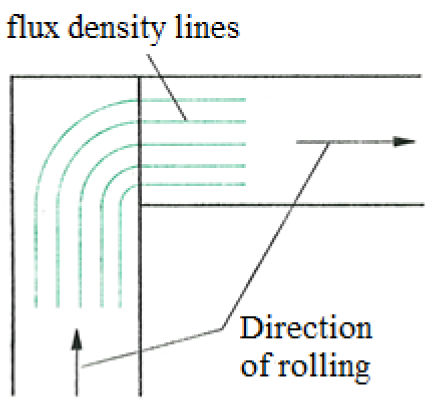
Application of cold-rolled plates



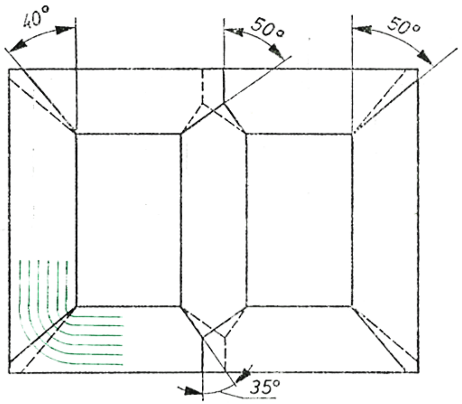
Application of cold-rolled plates are advantageous when the direction of the rolling and the flux is identical.

Problem of joining

90° joining



45° joining

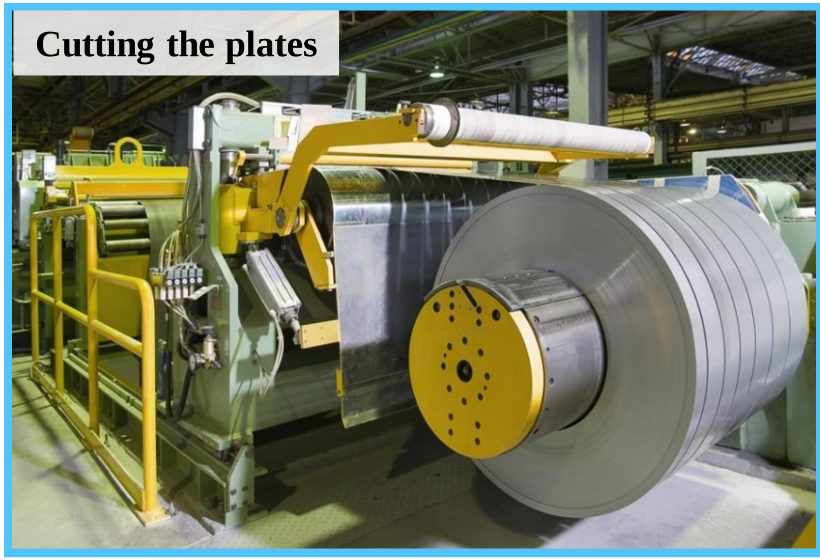


- **Excess loss develops at the corners.**

- **Loss can be reduced with 45° joining.**
- **Because of overlapping the real angles are: 35°; 45°; and 50°.**

LAMINATION OF THE CORE

Steps of manufacturing core

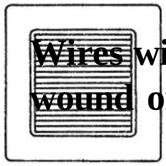


LAMINATION OF THE CORE

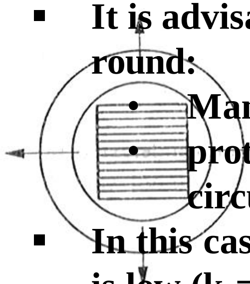
Forming the core cross-section

In case of lower powers (several kVAs)

Quadratic cross-section:



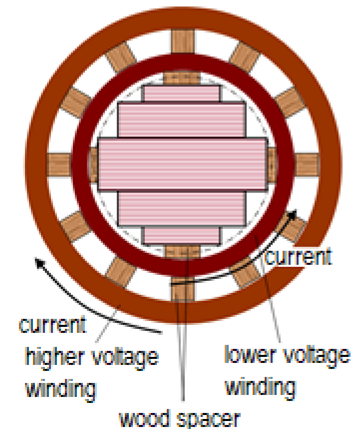
- **Wires with low cross-section are wound onto the form.**



- **It is advisable to make the windings round:**
  - **Manufacturing advantages,**
  - **protection against forces at short-circuits.**
- **In this case the geometrical space factor is low (k_g=0,636).**

In case of higher powers (MVAs)

Stepped cross-section:



/circumference
g ≈ 0,85…0,908),
wires length,
pensive
cture (plate bands
ferent widths).

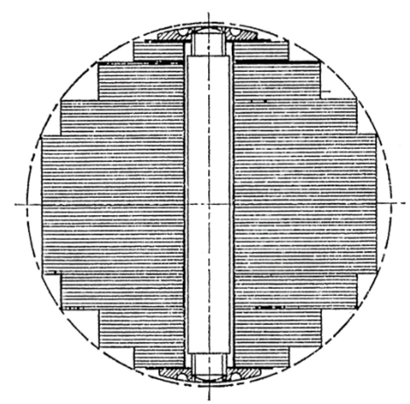
Pressing and fixing the plates

Legs:

- **wedging to the coil insulation (S_r<<),**
- **gluing + screw joint (S_r >>).**

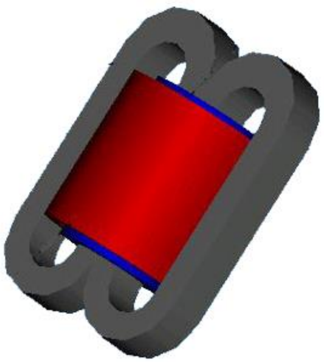
Yokes:

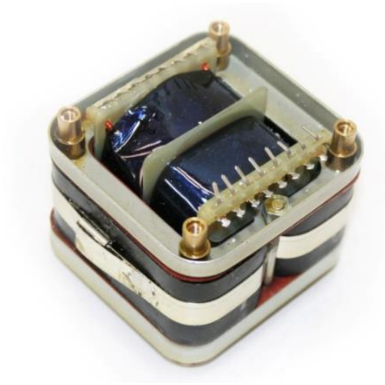
- **hardwood clamp beams,**
- **welded steel structure.**



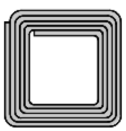
LAMINATION OF THE CORE

Wound cores

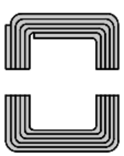




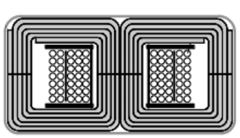
Steps of forming the core:



- **Forming packs: With winding and heat treatment of cold-rolled bands.**



- **Cutting the glued packs into halves, grinding and polishing cut surfaces.**



- **Fixing into the winding on the form.**
- **Fixing and pressing the structure.**

Application: Up to a power of 10 kVA.

WINDINGS

Material of the wires of windings:

- electrolytic copper
- aluminum of high purity (Al 99.99)

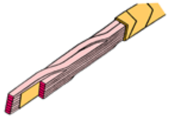
Wire cross-sections:

- round (up to ~2,5 mm^2)
- rectangular (in case of higher cross-sections)
- twisting several elementary wires

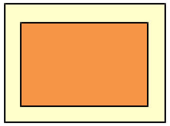
Insulation of the wires:

- enamel on synthetic material basis
- paper (oil insulated transformers)
- foil of synthetic material (r.g. myofler), hostaphan (dry transformers)

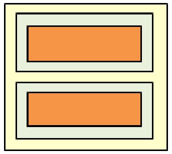
Structures of wires:



- CTC - Continuously Transposed Conductor



- PICC - Paper Insulated Copper Conductor

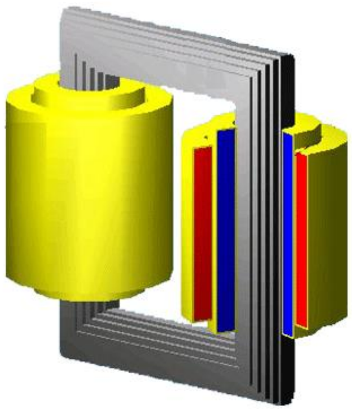


- BPICC – Bunch Paper Insulated Copper Conductor

STRUCTURE OF TRANSFORMERS
GEOMETRIC LAYOUT OF WINDINGS

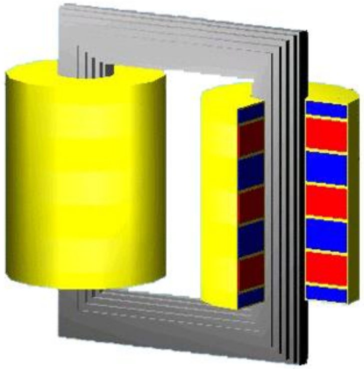
Cylinder type winding layout

- Primary and secondary windings alternate perpendicular to the axis of the leg.
- Turns near to each-other are placed on the entire leg length.
- Because of insulation considerations the winding with lower voltage is placed nearer to the leg.



Disk-type winding layout

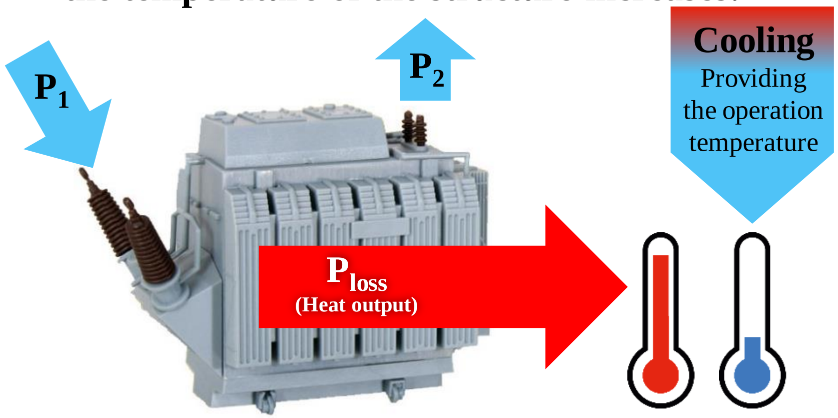
- Primary and secondary windings alternate in the direction of the axis of the leg.
- Discs of the low and high voltage windings split into several parts are placed alternately.
- Because of insulation considerations the disks of the winding with lower voltage is placed nearer to the yokes.

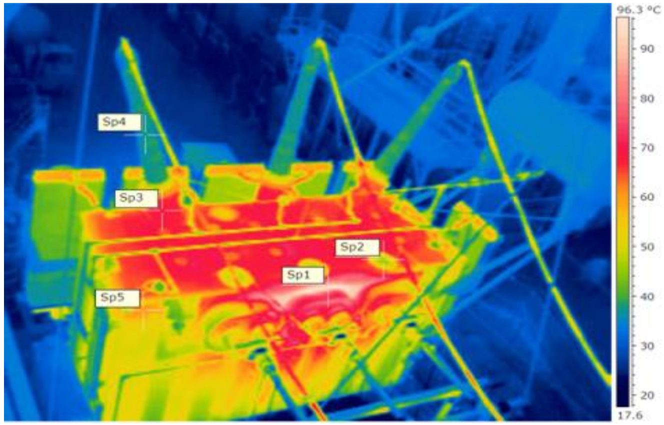


COOLING OF TRANSFORMERS

Effect of the power loss developing during energy conversion:

- **Thermal energy flows to toward the parts with lower temperature,**
- **the temperature of the structure increases.**





Cooling media

For preventing the increase of the temperature of the transformer the cooling medium takes over the thermal energy from the active parts when being in contact with them.

Air

Is applied in case of so-called dry transformers with low powers.

Oil

- **Double role: Insulation and cooling.**
- **Dieletric constant of oil: 2,5.**
- **Dieletric strength of oil > 50kV (RMS).**
- **Disadvantage: Flammable and oxidize when in contact with air (taring) → for preventing this: Application of synthetic oil (e.g. chlorinated diphenile) (dielectric constant:4.5).**
- **Application: For higher powers > 20 kVA.**

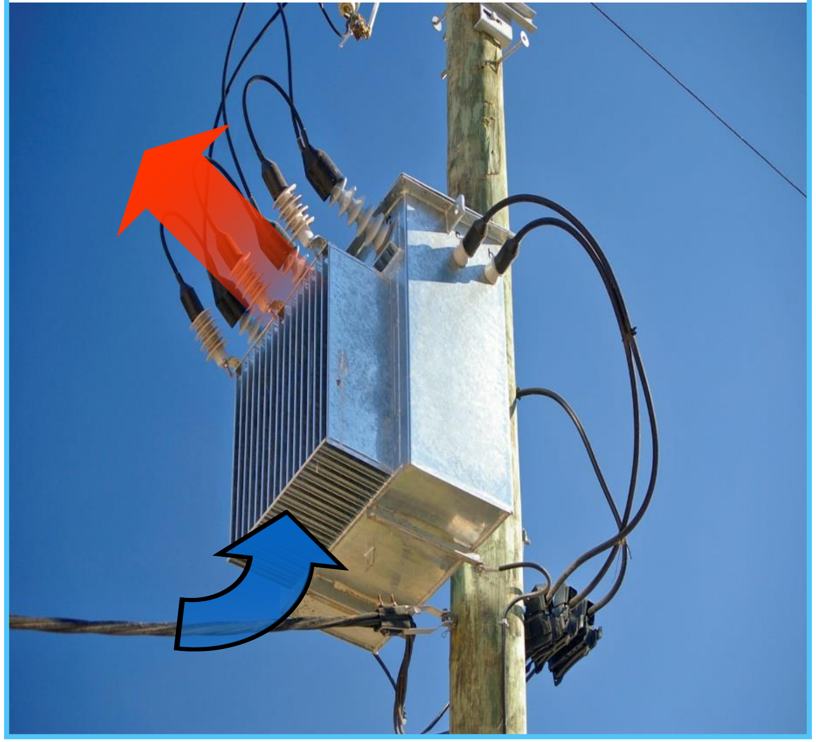
COOLING OF TRANSFORMERS

Method of cool medium transport

Heat transport is realized by the flow of the cool medium (e.g.).

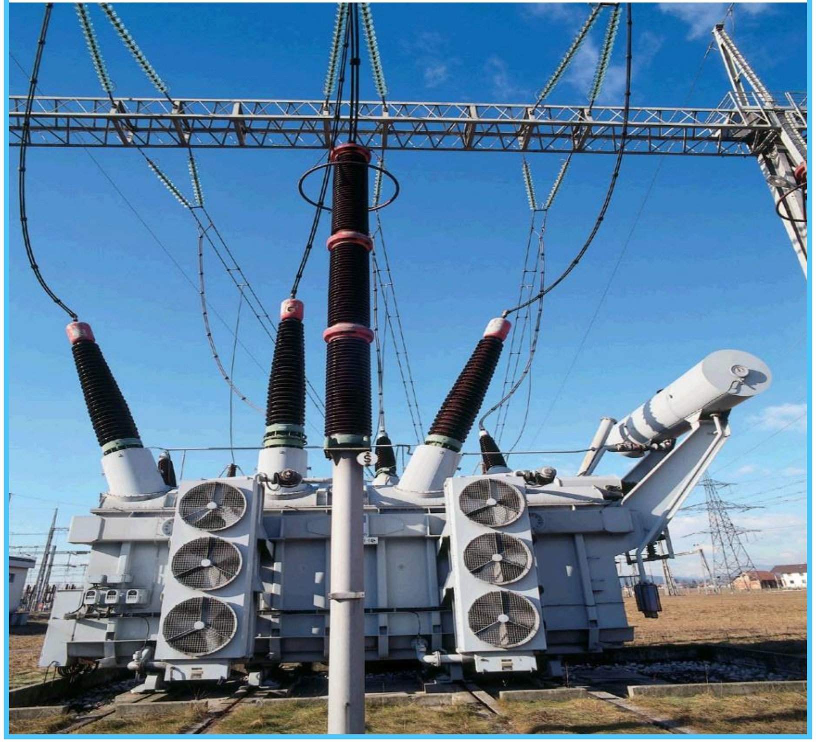
Natural cooling

Flow of the cooling medium is caused by the different specific weight of the cooling medium caused the difference in local temperatures (free thermal flow).



Artificial cooling

Movement of the cooling medium is ensured by an outer unit (e.g. fan, pump).



COOLING OF TRANSFORMERS – COOLING SYSTEMS

Transportation of the heat amount developing in the coils and core of the transformer can be realized directly or applying several cooling circuits.

System with a single cooling circuit

The cooling medium (air) flows freely through the transformer directly from the ambient medium, then returns freely to the ambient medium (open cooling circuit).

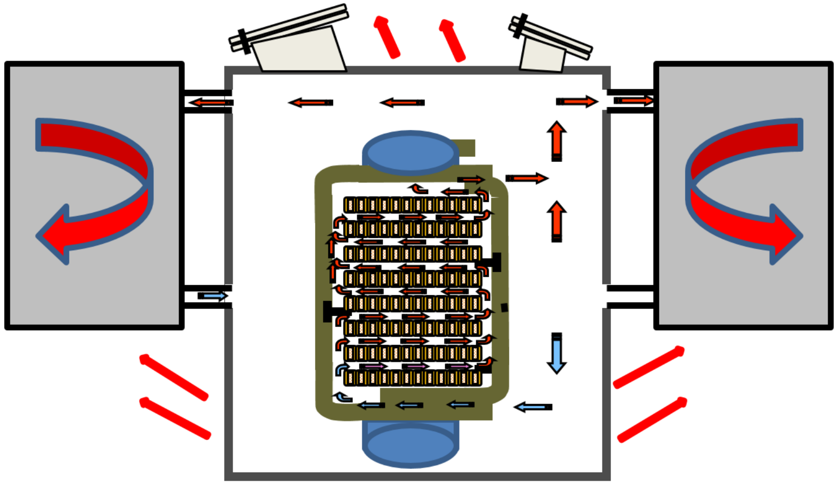
System with two cooling circuit

Primary cooling circuit:

Cooling medium (oil) being in contact with the active parts of the transformer circulates by free heat flow or forced in a closed system. Its heat amount is transferred to the secondary circuit through the wall of the transformer or through a heat exchanger.

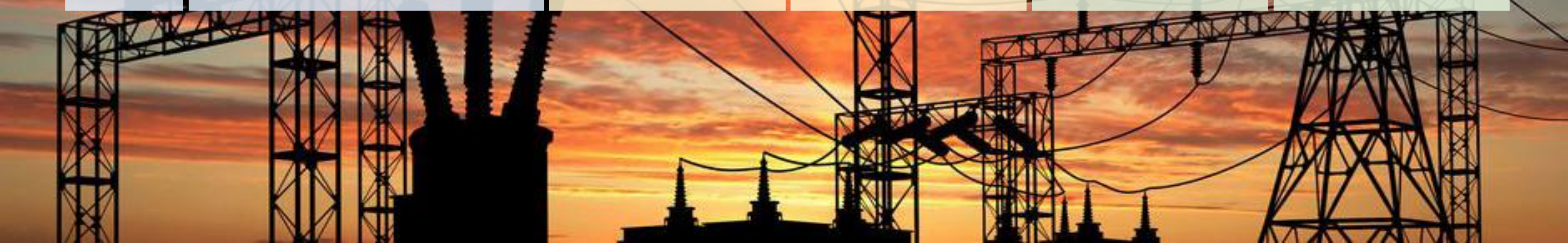
Secondary cooling circuit:

The cooling medium moves by free heat flow (air) or forced (air, water). Its role is to transport the heat amount adopted from the primary circuit to the ambient or remote medium.



COOLING OF TRANSFORMERS – COOLING SYSTEMS

Cooling systems		Cooling circuits			
		Primary		Secondary	
Marking	Description	Cooling medium	Art of transport of the cooling medium	Cooling medium	Art of transport of the cooling medium
AN	Air Natural	air	natural	-	-
AF	Air Forced (Air Blast)	air	artificial	-	-
ONAN	Oil Natural Air Natural	oil	natural	air	natural
ONAF	Oil Natural Air Forced	oil	natural	air	artificial
OFAF	Oil Forced Air Forced	oil	artificial	air	artificial
ODAF	Oil Directed Air Forced	oil	artificial directed	air	artificial
OFWF	Oil Forced Water Forced	oil	artificial	water	artificial



COOLING OF TRANSFORMERS – COOLING SYSTEMS

Cooling with natural air flow (AN=Air Natural)

- **Heat transport is realized by natural flow and by radiation from the covering.**
- **Application: In case of transformers with low power (5-10 kVA).**

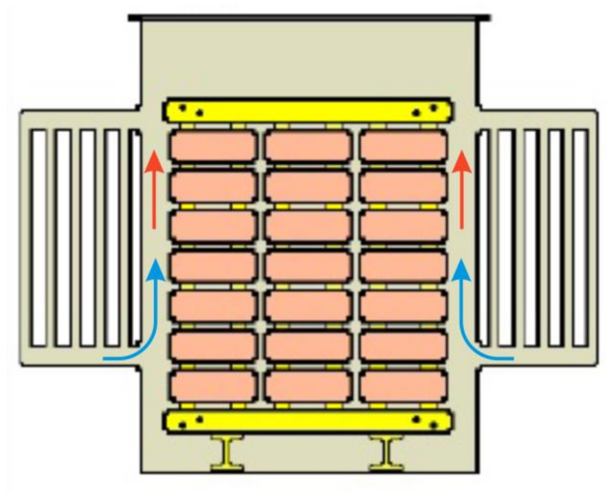
Cooling with forced air flow (AF=Air Forced)

- **Heat dissipation is ensured by air flowing through the iron core and windings by external fans.**
- **Application: In case of dry transformers, $V_r \leq 25$ kV.**

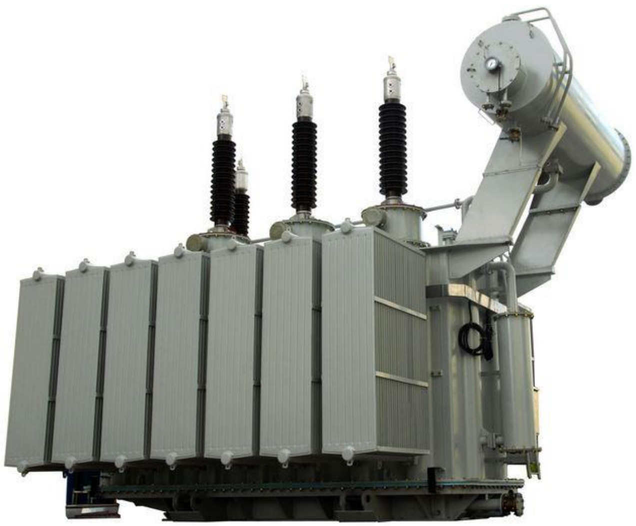
COOLING OF TRANSFORMERS – COOLING SYSTEMS

Cooling with natural oil and air flow (ONAN)

- **Core and windings are immersed into the insulating oil in the iron boiler.**
- **Oil in contact with heat producing parts (core, windings) takes over their heat power by thermal conduction and flows upward along the wall of the boiler by natural flow and cool oil comes to its place from the bottom of the boiler.**
- **The oil having been getting warm can transfer its heat to the air in the vicinity of the transformer:**
  - **through the wall of the boiler (plain or ribbed),**
  - **through the pipes,**
  - **through the radiators.**



- **Advantages:**
  - **No fans, pumps:**
    - **⇒ low maintenance need,**
    - **⇒ long expected life,**
    - **⇒ low noise level,**
    - **⇒ low price.**
  - **Cooling capacity can be increased (ONAN ⇒ ONAF)**
- **Application: In case of power transformers with low and medium power range.**

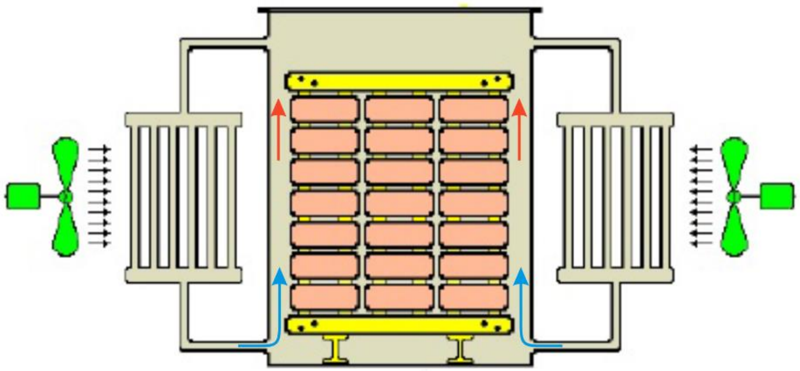


COOLING OF TRANSFORMERS – COOLING SYSTEMS

Cooling with natural oil and forced air flow (ONAF)

- Cooling mechanism of the primary circuit is identical with that of the cooling system ONAN.
- Air is forced to the outer surfaces by fans mounted on the outside of the transformer:
  - housing,
  - pipes,
  - radiators.

  The air flow increases heat dissipation.



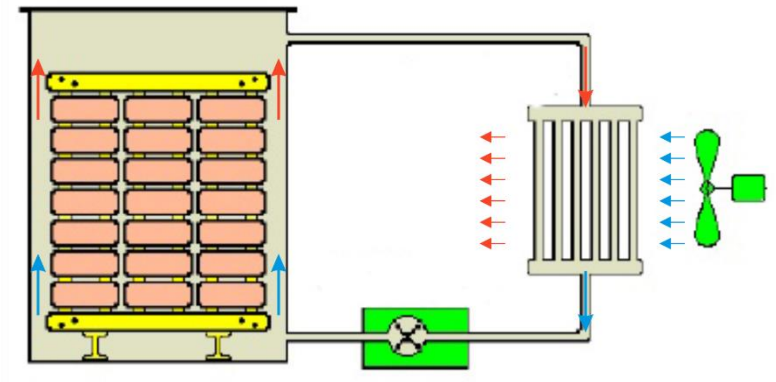
- Advantages:
  - No need for pump,
  - radiators with low maintenance need, fans can be replaced,
  - Long expected life.
- Enables a double rated value list:
  1) ONAN (fans switched off)
  2) ONAF (fans switched on)

- Application:
  - Most frequently application in the field,
  - In case of transformers with medium and high powers.

COOLING OF TRANSFORMERS – COOLING SYSTEMS

Cooling with forced oil and air flow (OFAF)

- Flow of cooling medium is forced:
  - oil → pumps
  - air → fans
- Oil cools down – with the help of the air circulated by the fans – through an outer heat exchanger.



Outer heat exchanger

Radiators

- The most flexible system:
  - ONAN at low temperatures,
  - at higher loads fans and pumps are switched on by temperature sensors → energy consumption can be optimized.
- Low maintenance and cleaning need.
- Long expected life.

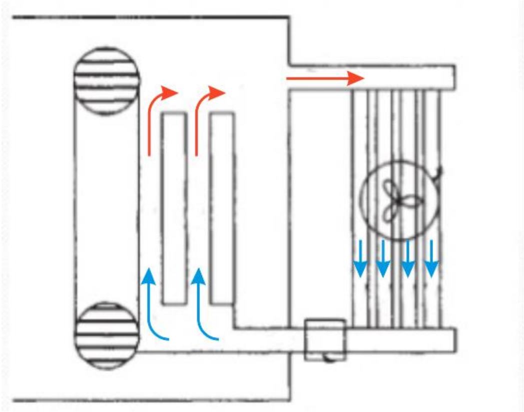
Coolers

- Several cooling surface and ribbing constructions.
- High cooling capacity, however the fans and pumps operate continuously ⇒ energy consumption ⇑ ⇒ noise level ⇑.
- Maximum oil temperature is lower.
- Higher maintenance and cleaning need.

- Application: For transformers with higher power,
  $S_r \geq 30$ MVA.

COOLING OF TRANSFORMERS – COOLING SYSTEMS

Cooling with directed oil and forced air flow (ODAF)



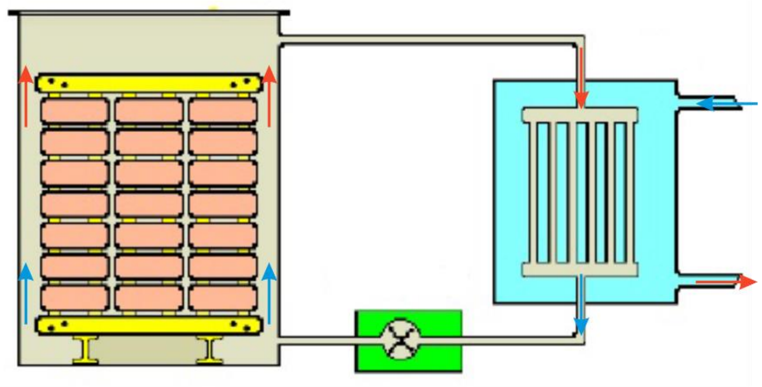
- **The oil flows forced on predetermined paths in the windings of the transformer.**
- **For increasing the intensity of the heat transfer gaps or predetermined flow paths are available between the insulated wires of the windings of the transformer for the oil.**
- **A variant of the OFAF system with increased cooling capacity.**
- **Application: In case of transformers with powers of several hundreds of MVAs.**

Notice: In systems with directed oil flow a secondary circuit with forced water flow can be used for cooling the oil ⇒ ODWF.

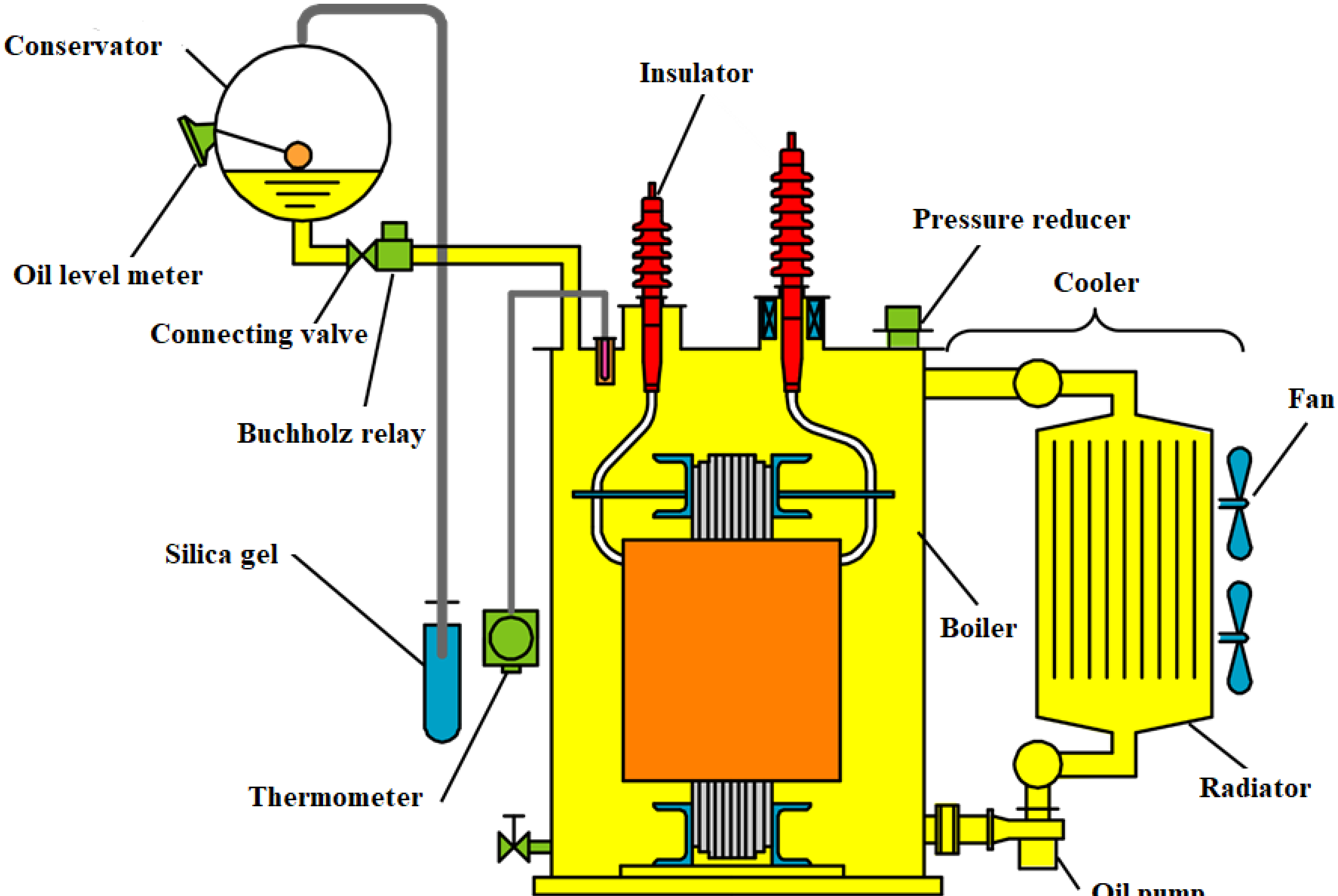
COOLING OF TRANSFORMERS – COOLING SYSTEMS

Cooling with forced oil and water flow (OFWF)

- Oil is cooled by a unit with forced water flow (radiator, heat exchanger) ⇒ highest cooling capacity.
- Pressure of the primary system is higher than that of the secondary system ⇒ leakage can occur only from the oil to the water.
- Advantages:
  - It is small and compact, however with higher maintenance need.
  - Low noise level.
- Disadvantages:
  - Higher risk of malfunctions (pumps).
  - In case of failures the cooling media can be deteoriated.
  - If the water cooling is not of closed system:
    ⇒ water supply must be available,
    ⇒ risk of bacteria.
- Application: In case of transformers with high powers.



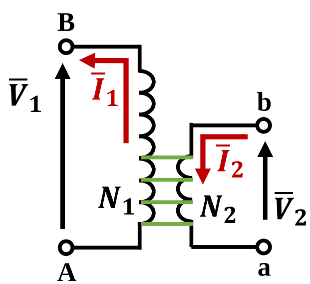
OUTER FITTINGS OF OIL TRANSFORMERS



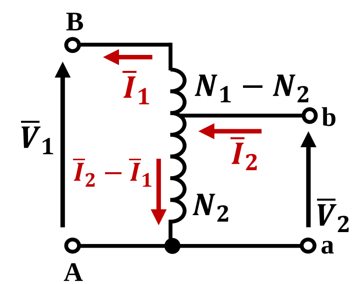
AUTOTRANSFORMERS

On the closed core of autotransformers there are no separate primary and secondary windings. On the single winding of a phase there can be taps of any number but at least one.

Derivation



A Main flux of the transformer induces turn voltages of the same magnitude in the primary and the secondary winding ⇒ points with the same potential can be connected to each-other ⇒ the two windings can be joined.



Advantages

- **Lower number of turns ⇒ decrease in wire lengths.**
- **The joint part of the winding has to be dimensioned for a current load of $I_{2r} - I_{1r}$ ⇒ lower wire cross-sections.**

Lower winding loss

- **Lower windings space cane be surrounded by shorter core length ⇒ smaller core.**

Lower core loss

LESS EXPENSIVE MANUFACTURE

MORE SIMPLE CONSTRUCTION

LOWER DIMENSIONS

SPECIAL TRANSFORMERS
AUTOTRANSFORMERS

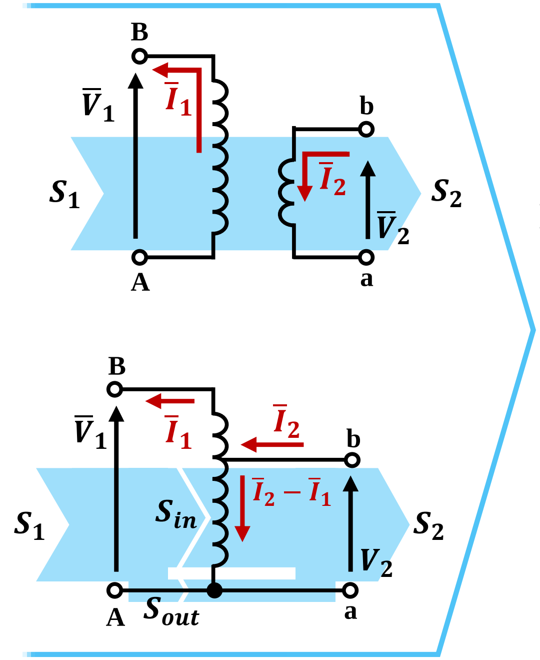
Calculation of the saving

- In case of transformers <u>with two windings </u>the whole throughput power is transformed by the transformer. If losses are neglected:

  $S_1 = S_2 = S = V_1 I_1 = V_2 I_2$

- <u>In case of autotransformers</u> the part I_1 of the I_2 secondary current flows in the circuit AabB and the power $S_{out} = V_2 I_1$ has not to be transformed by the transformer.
  The modified internal power (internal loadability) to which the transformer has to be dimensioned:

  $S_{in} = S - S_{out} = V_1 I_1 - V_2 I_1 = (V_1 - V_2) I_1$



Extent of type power decrease:

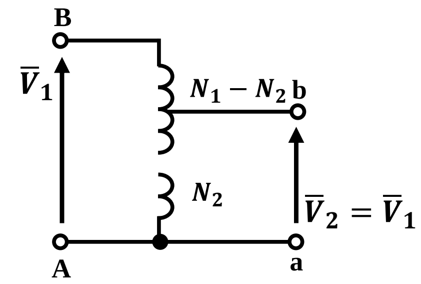
$$\frac{S_{in}}{S} = \frac{V_1 I_1 - V_2 I_1}{V_1 I_1} = 1 - \frac{1}{a}$$

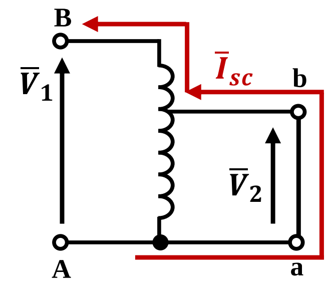
Notice:

- *The closer is the ratio to one (0.5 < a < 1,5) the higher is the saving (in dimensions, weight, cost).*
- *Losses of autotransformers have the extent according to the internal power.*

Disadvantages limiting application opportunities

- **There is no galvanic seperation between the primary and secondary winding. → Potential difference of both sides is the same related to the ground.**
- **In case of malfunction (e.g. break in the common part of the winding) the entire higher voltage can appear on the terminals with lower voltage of the transformer. In case of load the winding part with N_1 - N_2 turns behaves as a choke coil.**
- **In case of short-circuit the current is limited only by the winding part with N_1 - N_2 turns.**





Autotransformers can not be used for life support purposes. E.g. transformers for direct supply of consumers or transformers producing extra low voltage (for hand tools).

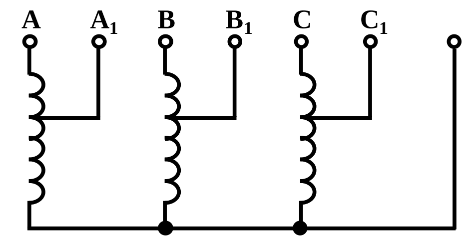
AUTOTRANSFORMERS

Autotransformers are made in single- and three-phase construction.

Single-phase construction

Three-phase construction

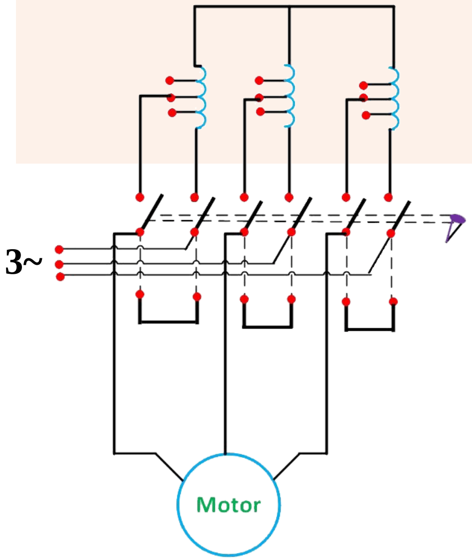
Connection: start connection with taps in every phase



AUTOTRANSFORMERS

Fields of application

Motor starter and speed varying transformers



Toroid transformers with variable ratio

- Windings are placed on ring shaped cores.

- Access to the voltage:
  - with carbon brush contacts

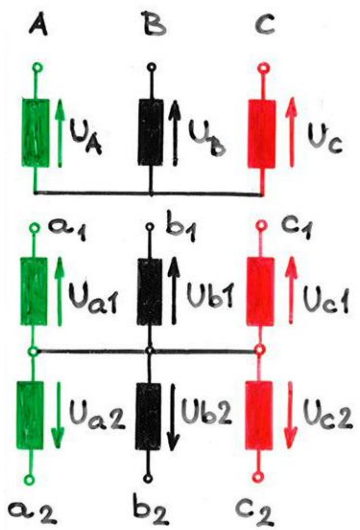
  - with sliding carbon brush contacts

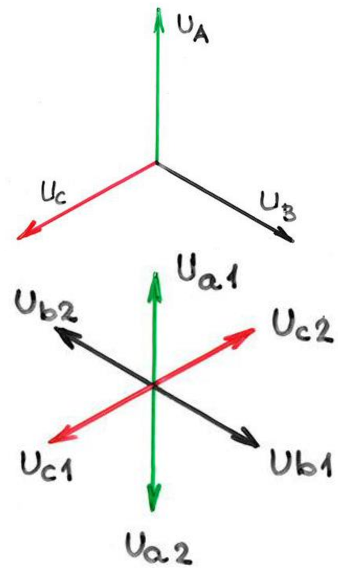
- Three phase toroid: Three single-phase ones built onto each-other.

Connection: start connection with led-out star point

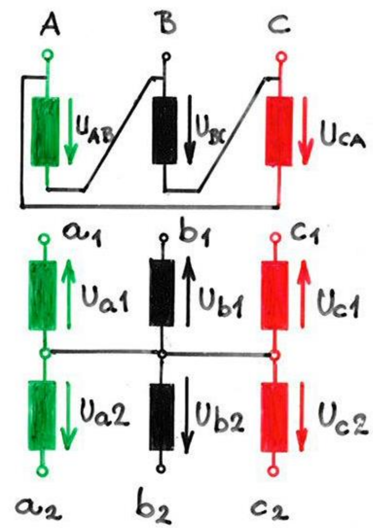
TRANSFORMERS WITH VARIABLE NUMBER OF PHASES

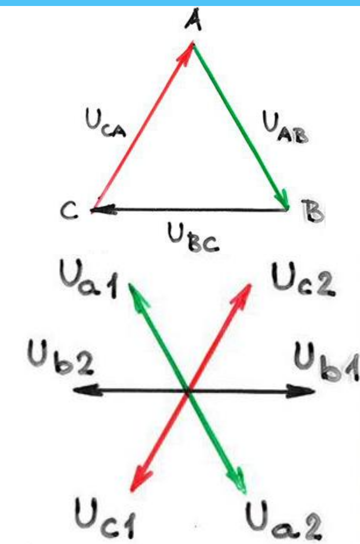
3/6 phase, Yy (Yy_0) connection





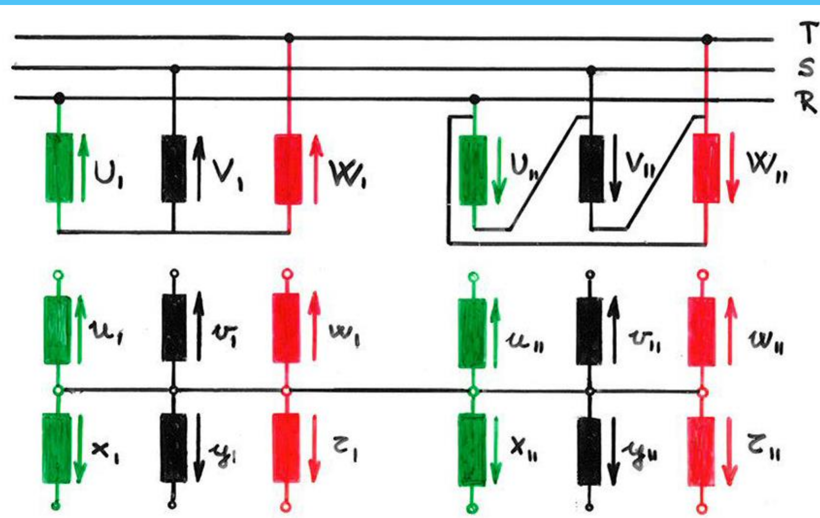
3/6 phase, Dy (Dy_0) connection

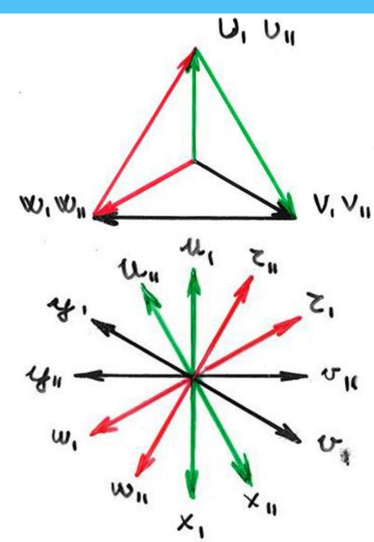




Notice: Can be used with uneven load.

3/12 phase, Yy connection



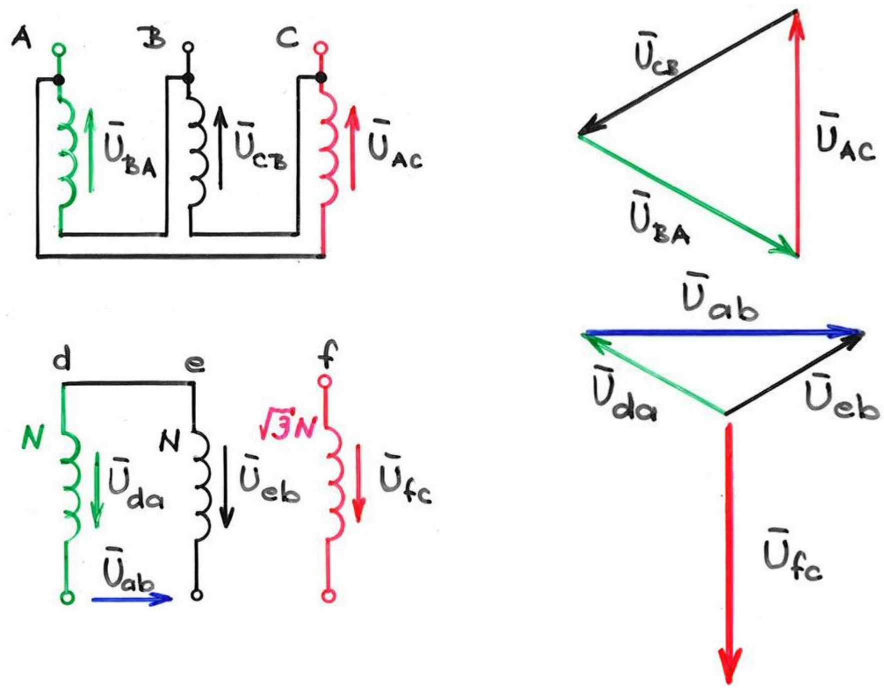


TRANSFORMERS WITH VARIABLE NUMBER OF PHASES

connection with 3/2 phases with three-phase core

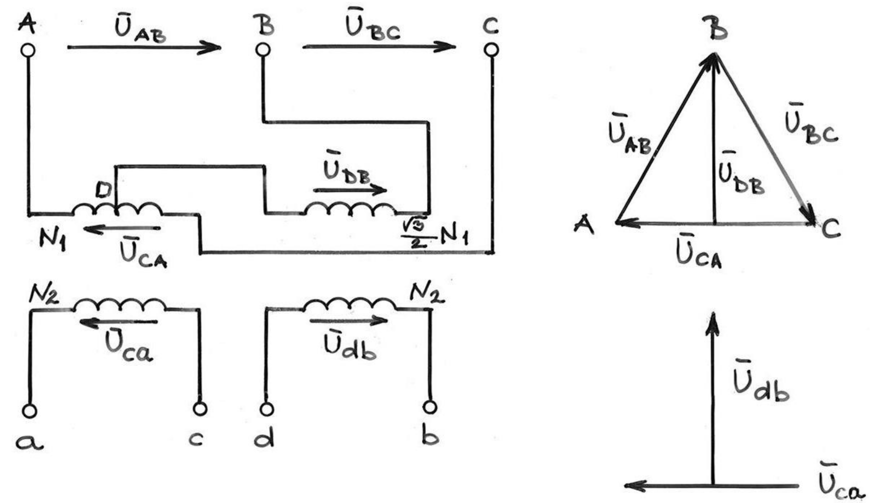
- **Properties of the two-phase system:**
  - **phase voltages have the same magnitude,**
  - **the two phase voltage vectors are apart from each-other by 90°.**

- **This connection is appropriate for taking uneven loads.**



Scott-connection

Connecting two single-phase transformers together.

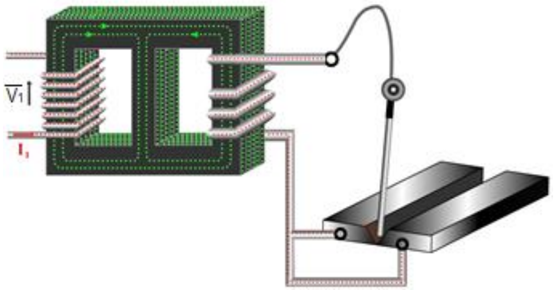


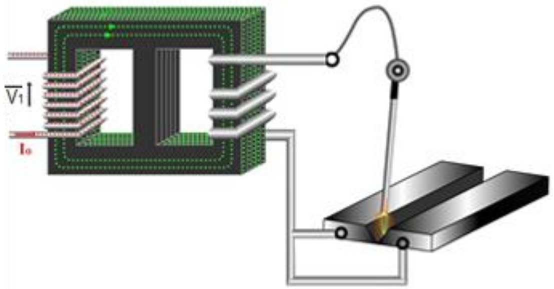
SPECIAL TRANSFORMERS

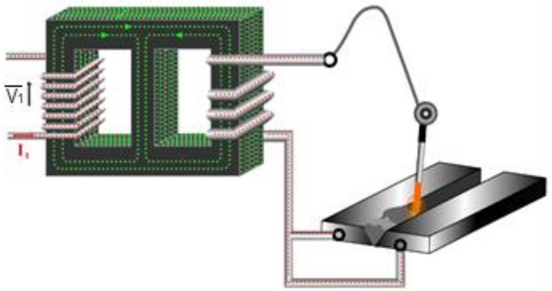
WELDING TRANSFORMERS

Procedure of welding

Phase of working	Effect Physical phenomenon	Transformer state of operation
Electrode and work piece are in contact with each-other.	The tip of the electrode glows as an effect of the high current.	Short-circuit (100-300A)
Removal of the electrode from the and work pieces.	Ignition of the arc.	No-load operation (60-100V)
Ensuring constant arc length.	Maintaining the arc its heat melts the electrode and the work piece.	Load (20-30V; 50-250A)
	Melt drops develop continuously at the tip of the electrode, they elongate (variation of the arc length), then separate.	Load → Short-circuit → No-load → (back to Load)



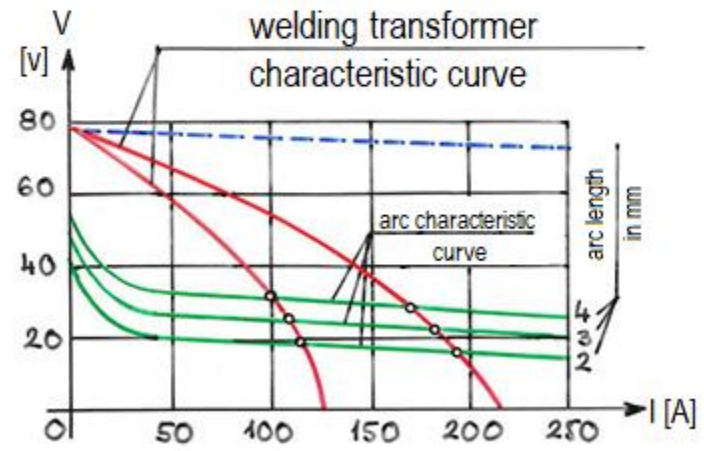




Transformers appropriate for arc welding

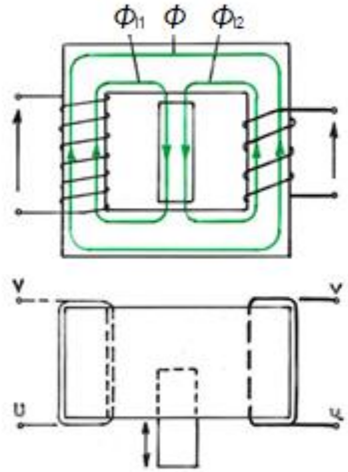
Requirements

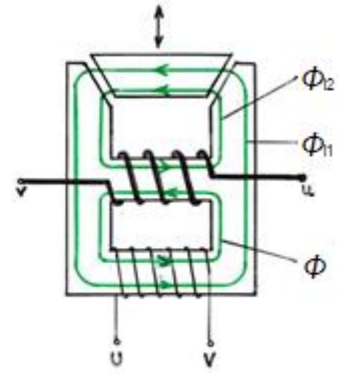
- This transformer has to ensure the no-load voltage necessary for arc ignition.
- Must be able to be short-circuited without getting damaged.
- No high dynamic current peaks are allowed to appear at the moment of getting short-circuited.



Application of magnetic a shunt

- A steep downward characteristic curve can be achieved with increasing the leakage flux:
  - primary and secondary windings are placed on separate core legs,
  - application of a movable magnetic shunt.
- Good efficiency, bad power factor ($cos\varphi_1 \approx 0,3$).





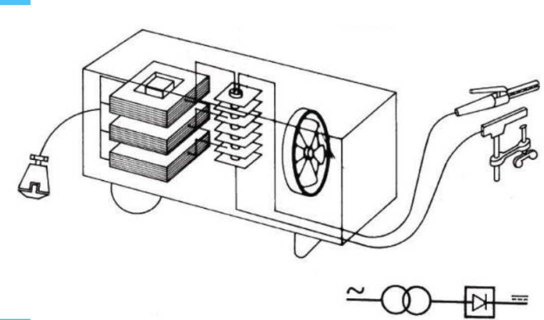
WELDING TRANSFORMERS

Up-to-date welding appliances

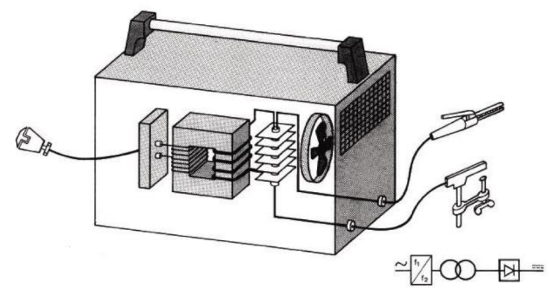
Application of arc welding rectifier and smoothing choke

In case of direct current maintaining the arc is more stable.

It makes the waviness of the direct current more.



Welding machine with inverter



The inverter ensures a closed loop controlled alternating voltage with increased frequency:

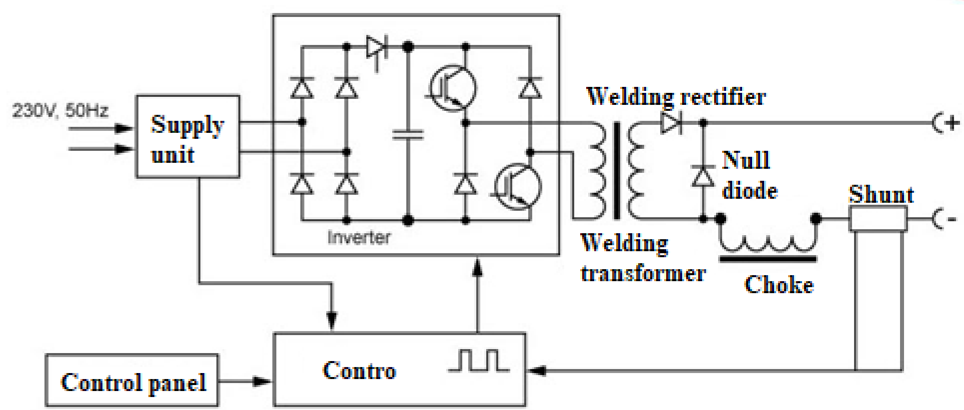
- **dimensions and weight of the transformer is reduced,**

$$N\,A_{core} = \frac{V_i}{4{,}44\;B\;f}$$

if ↑

then ↓

- **dimension of the choke coil decreases.**



INSTRUMENT TRANSFORMERS – VOLTAGE TRANSFORMERS

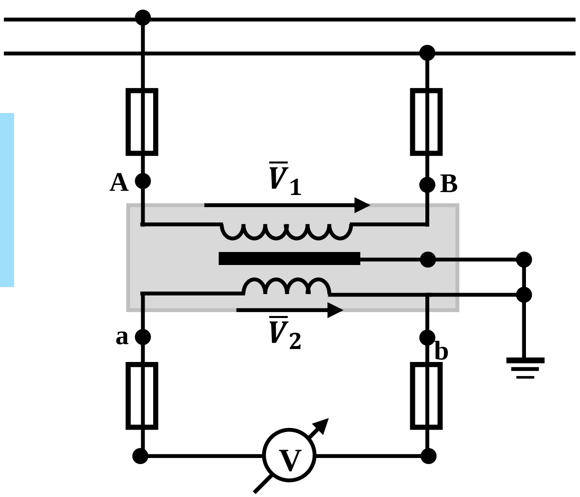
Their role

These transformers transform high alternating voltages to lower ones able to be directly utilized (e.g. can be measured), in general to 100 or 200 V.

Connection for measurement

- Primary winding: is connected to the high voltage network.
- Secondary winding: Is connected to a measuring device with high internal resistance.

No-load operating transformer



- Both windings have to be equipped with protection (e.g. with fuses).
- One terminal of the secondary side has to be grounded.

Calculated voltage

$$V_1 = a_r V_2$$

where: a_r – is the ratio of the instrument transformer: $a_r = \frac{V_{1r}}{V_{2r}}$,

V_2 – is the measured voltage.

SPECIAL TRANSFORMERS
INSTRUMENT TRANSFORMERS – VOLTAGE TRANSFORMERS

Relative errors of voltage transformers

- As an effect of varying load (e.g. replacement of the meter, connecting more meters) the internal voltage drops of the instrument transformer vary → V_2 varies in spite of the constant V_1.

ERROR OF THE RATIO

Calculated value

$$h_v = \frac{aV_2 - V_1}{V_1} \approx (0,1 \dots 3)\%$$

Actual value

- Difference between the phase displacements of the actual primary voltage and the measured secondary voltage causes measurement error in case of applying watt meters, cosφ meters or kilowatt-hour meters.

ERROR OF ANGLE $\delta \approx (4 - 40)'$

- Accuracy classes (standard, prescription).
  The highest allowable value of the error is given.
  E.g. if the accuracy class of a precision voltage transformer is 0.1M then the maximum allowed error values are:
  - Voltage error: 0,1%,
  - Angle error: 0,15 crad (centiradian).

INSTRUMENT TRANSFORMERS – VOLTAGE TRANSFORMERS

Arts of voltage transformers

According to the use

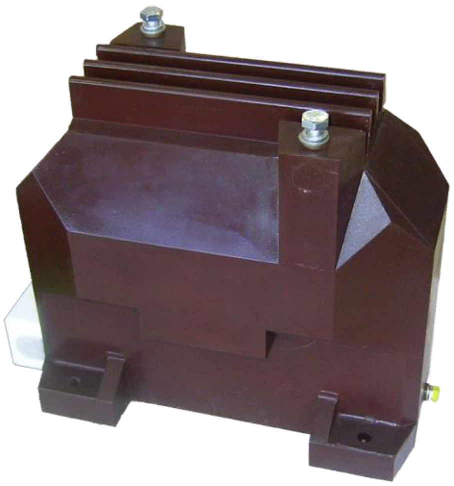
- **measurement voltage transformers,**
- **protection voltage transformers,**

Grounding fault voltage transformers (with the role of signaling grounding faults and protection).

According to the connection and number of phases

- **Single-phase voltage transformer**

  With primary terminals, both insulated



With primary terminals, one insulated

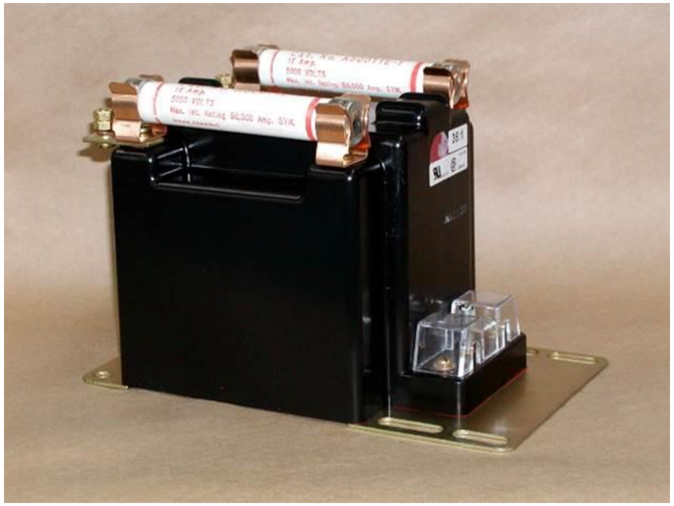
- **Three-phase voltage transformer** (Yy)
  - **without led-out star point,**
  - **with led-out star point (has to be grounded).**

Arts of voltage transformers

According to environmental conditions

Outdoor design

Indoor design



INSTRUMENT TRANSFORMERS – CURRENT TRANSFORMERS

Their role

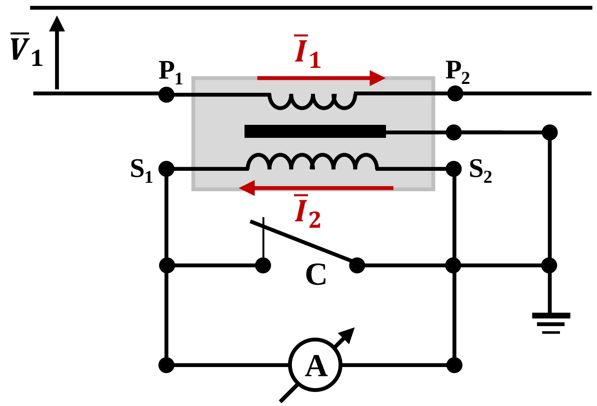
These transformers transform high alternating currents to lower ones able to be directly utilized, in general to 1 or 5 A. Secondary windings of current transformers supply the current coils of measuring devices or network protection devices.

Connection for measurement

- Primary winding: Is connected in series to the network high current.

  I_1=5; 20; 50; 200; 500; 2000A
- Secondary winding: Supplies the current coil of the measuring device.

  $I_2 = 5A(1A)$
- One terminal of the secondary coil has to be grounded.
- The secondary circuit of the current transformer must not be broken:
  - It forbidden to use fuses in the secondary circuit,
  - Application of “C” short-circuiting switch.



Calculated current

The excitation producing the flux in current transformers is negligible:

$$I_1 N_1 - I_2 N_2 \approx 0 \quad \Rightarrow \quad \frac{I_1}{I_2} \approx \frac{N_2}{N_1} = a_i \quad \Rightarrow \quad I_1 = a_{ir}\, I_2$$

I_2 – Measured current

$a_{ir} = \frac{I_{1r}}{I_{2r}}$ – current ration of the instrument transformer

Relative errors of current transformers

Causes of errors

- Negotigation of Θ_e,
- Impedance of the load of current transformers (current coils of instruments, relays) is low → practically short-circuit operation.

As an effect of variable load (connecting several instruments) loading impedance can be significant, thus – in spite of a constant I_1 – value of I_2 varies.

Error of ratio (h_i)

- Calculation: $$h_i = \frac{a_{ir} I_2 - I_1}{I_1} 100\%$$
- Its allowed values: Application objective is determined by accuracy prescriptions.

Measure purposes	Accuracy class	0,1M	0,2M	0,5M	1M	3M	5M
	Allowed error	0,1%	0,2%	0,5%	1%	3%	5%
Protection purposes	Accuracy class	2,5P	5P	10P			
	Allowed error	2,5%	5%	10%			

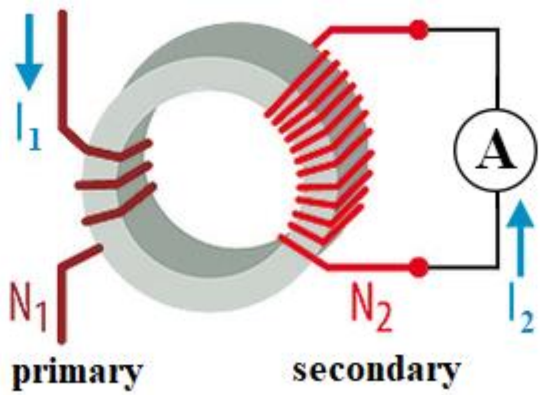
Angle error (δ)

- Its highest allowed values depending on the accuracy class: $\delta = (6 - 60)'$.

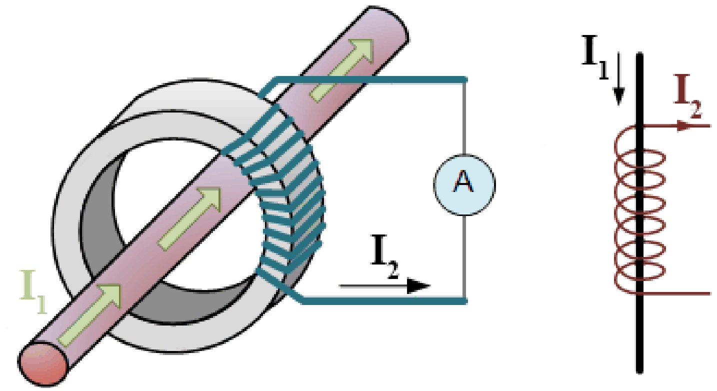
SPECIAL TRANSFORMERS
INSTRUMENT TRANSFORMERS – CURRENT TRANSFORMERS

Arts of current transformers

Current transformers with primary winding



Busbar current transformers



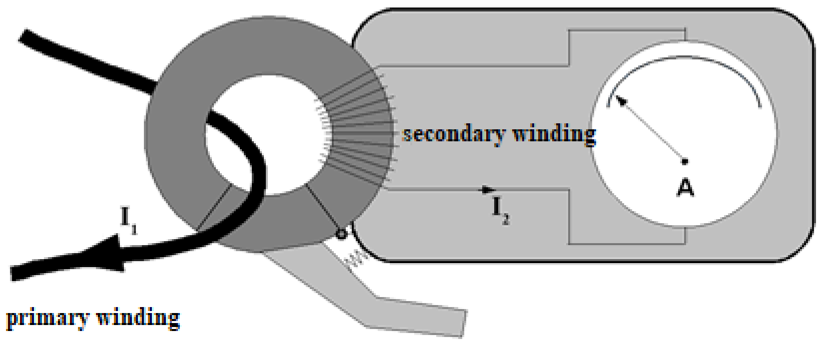
- The primary winding is composed by a conductor of the measured circuit (coil with a single turn).
- Application: In case of high currents.

Arts of current transformers

Busbar current transformers that can be opened

The busbar current transformer (the core) can be dismounted and can be mounted onto the bus without breaking the circuit to be measured.

Clamp-on measuring device

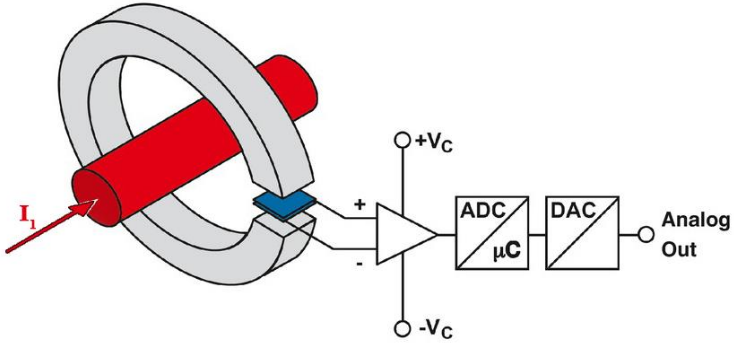


- **Handheld ampere meter the core of which can be opened as pliers.**
- **It can be used without breaking the measured conductor.**
- **Secondary terminals are short-circuited by a multi-range moving-coil instrument.**

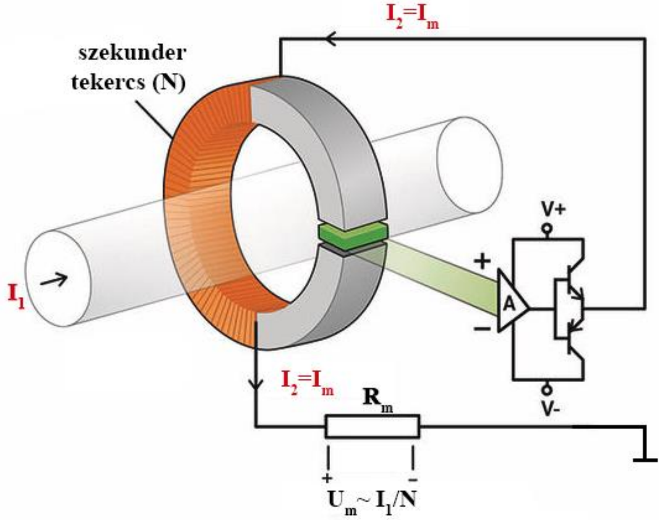
Arts of current transformers

Busbar current transformer with transmitter

Open-loop current transformer with a Hall sensor



Closed-loop current transformer with a Hall sensor



SPECIAL TRANSFORMERS

INSTRUMENT TRANSFORMERS – CURRENT TRANSFORMERS

Arts of current transformers

Busbar current transformer with transmitter and integrated switch

Sensitivity of the input of the transmitter can be varied by the integrated DIP switch → selection of the range.

Current transformer for protection purposes

It senses the current peaks of the network errors remaining within the limit factor of the protection.

Arts of current transformers

Summarizing current transformers

Application: At locations where the sum of currents flowing in different circuits or different sections of a circuit have to be determined.

Combined current transformers

Primary coil:

- is of split design,
- measurements ranges are designed related to terminal P_1.

Secondary coil:

- one or more coils with standard measurement ranges (1 A, 5 A).