ELECTRICAL MACHINES

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Reference

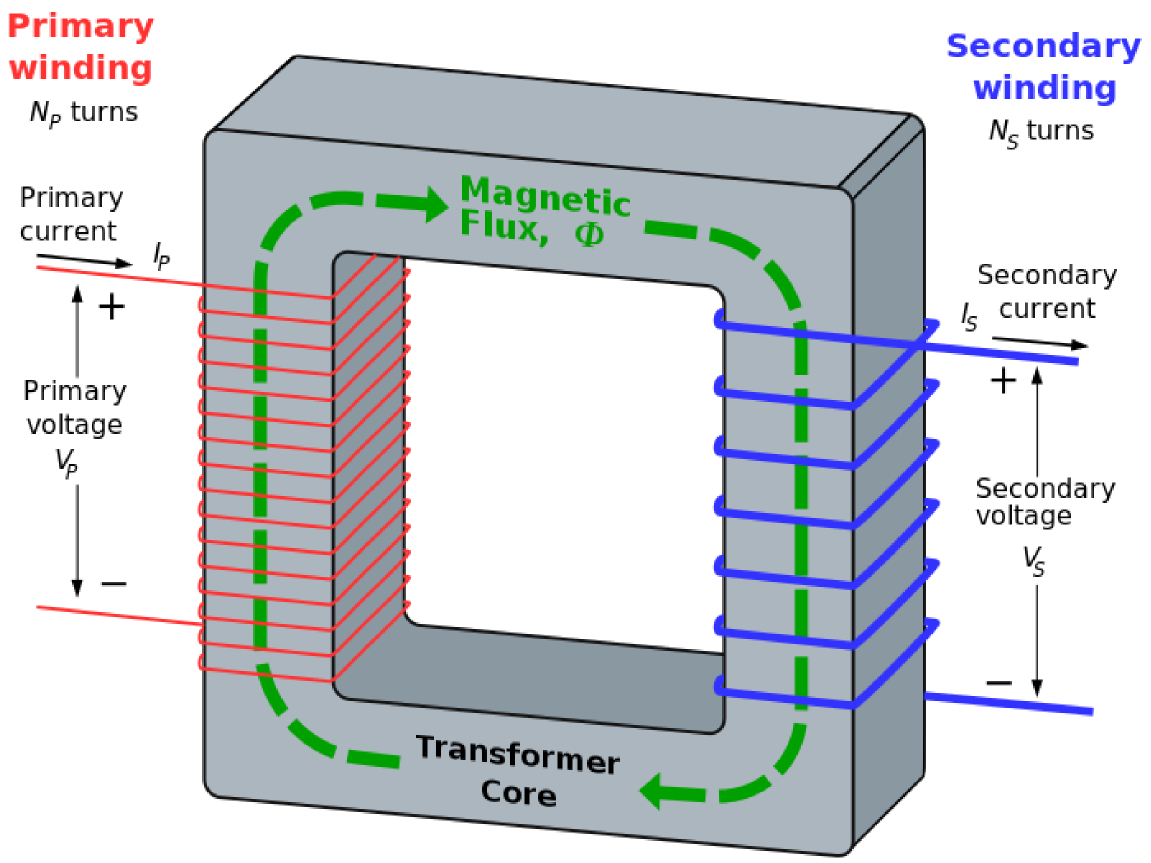
- Wildi T. Electrical Machines, Drives, and Power Systems / T. Wildi. — 3rd ed.. — New Jersey: Prentice Hall, 1997. — 814 p.
- Галкина А.А. Английский язык для бакалавров электротехнических специальностей = Electricity and everything connected with it : учебное пособие / А. А. Галкина. — Ростов-на-Дону: Феникс, 2013. — 235 с.
- Покушалова Л. В. Английский язык = English language : учебное пособие для вузов / Л. В. Покушалова, И. А. Матвеенко; Томский политехнический университет (ТПУ). — Томск: Изд-во ТПУ, 2009. — 211 с.
- Nagrath, I. J. Electric machines / I. J. Nagrath, D. P. Kothari. — 2-nd ed.. — New Delhi: Tata McGraw-Hill Publishing Company Limited, 2000. — 778 p.
- Glendinning, Eric H.Oxford English for Electrical and Mechanical Engineering : Answer book with teaching notes / E. H. Glendinning, N. Glendinning. — 5th ed.. — New York: Oxford University Press, 2010. — 39 p.

Reference

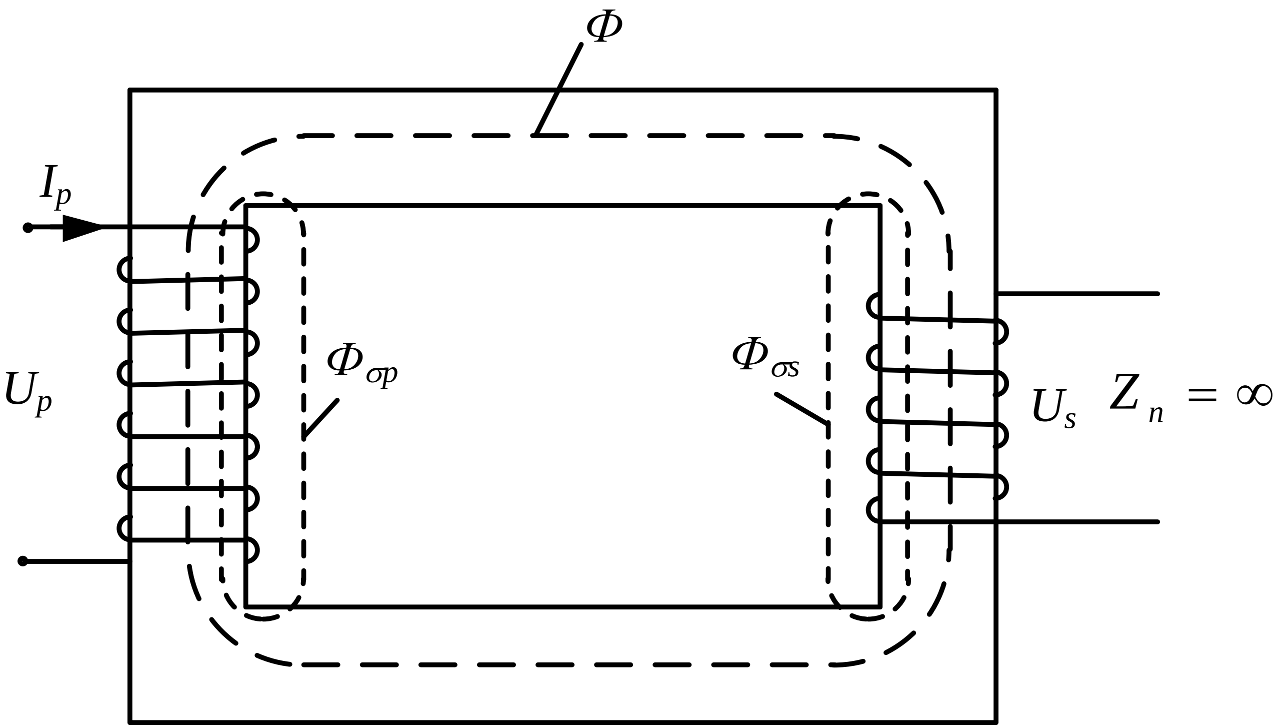
- gnatovich V. M. Electrical Machines : Textbook / V. M. Ignatovich, S. Sh. Roiz; TPU. Part 1. — Tomsk: TPU Press, 2001. — 84 p.
- Ройз Ш. С. Electrical machines [Электронный ресурс] : учебное пособие / Ш. С. Ройз, В. М. Игнатович, Н. Г. Новикова; Томский политехнический университет (ТПУ). — 1 компьютерный файл (pdf; 3322 KB). — Томск: Изд-во ТПУ, 2006. Схема доступа: http://www.lib.tpu.ru/fulltext3/m/2009/m4.pdf
- Евсеева А.М. Английский язык : учебное пособие по профессиональному иностранному языку, модуль "Электротехническое материаловедение" / А. М. Евсеева, В. С. Ким, С. В. Жаркова; Национальный исследовательский Томский политехнический университет (ТПУ). — Томск: Изд-во ТПУ, 2010. — 128 с.
- Sen, P. C.Principles of Electric Machines and Power Electronics / P. C. Sen. — 2nd ed.. — New York: John Wiley & Sons, 1996. — 613 p.
- Electric Power Transformer Engineering / edited by J. H. Harlow. — Second Edition. — New York: CRC Press, 2007. — 570 p.
- The Electrical Engineering Handbook / под ред. R. C. Dorfa. — 3rd ed.. — New York: Taylor & Francis, 2006 Systems, Controls, Embedded Systems, Energy, and Machines. — 2006. — 654 p.

TRANSFORMERS 1

The simplest transformer

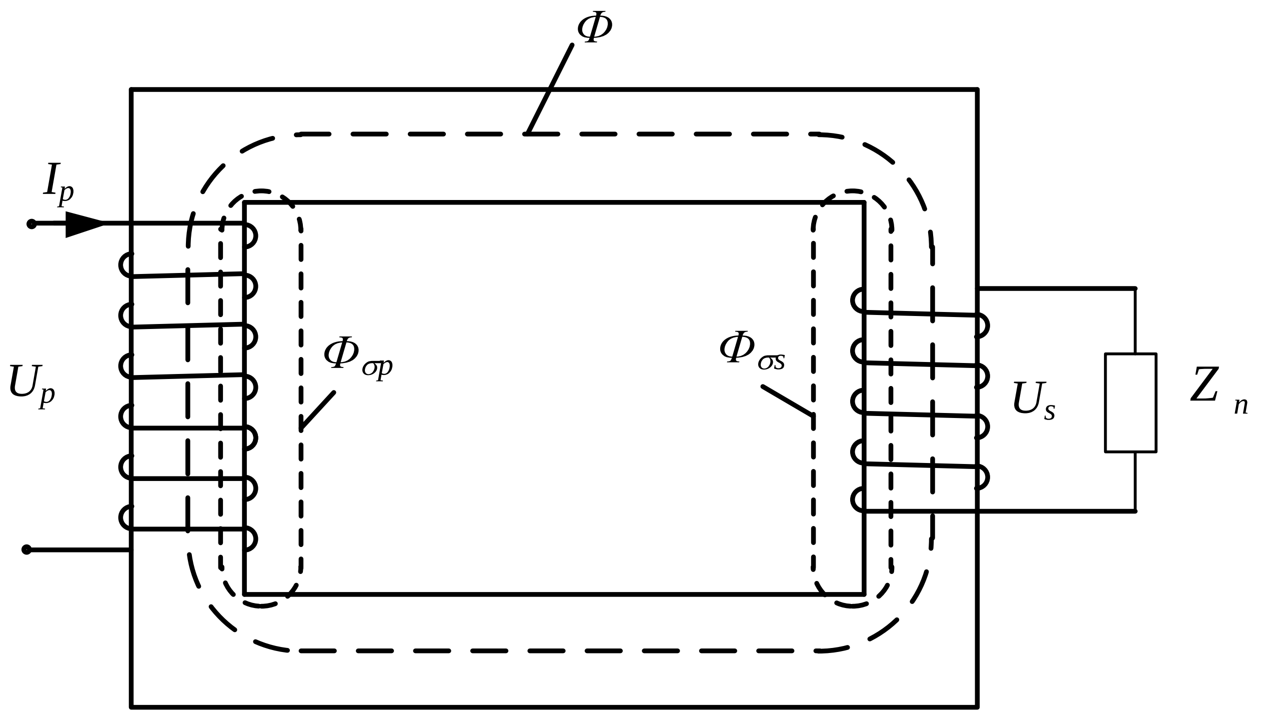


Operation principle of transformer under open circuit mode



- $U_p \rightarrow I_{p0} \rightarrow (I_{p0} \cdot N_p) \rightarrow \Phi_{p0} = \Phi \rightarrow$ $e_s = -N_s \cdot \frac{d\Phi}{dt}$, $e_p = -N_p \cdot \frac{d\Phi}{dt}$

Operation principle of transformer under load mode



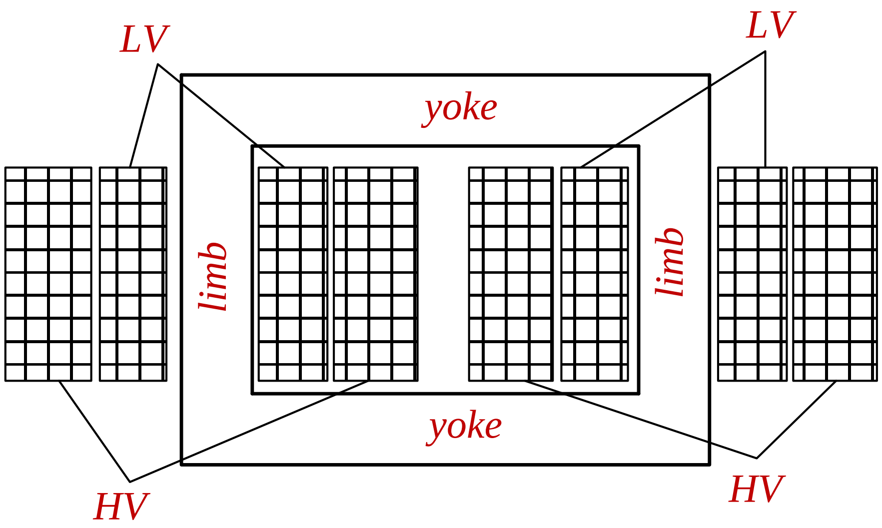
- $$U_p \to I_p \to (I_p \cdot N_{sp}) \to \Phi_p \searrow$$
  $$U_s \to I_{ps} \to (I_s \cdot N_s) \to \Phi_p \nearrow \Phi \to \begin{matrix} e_s = -N_s \cdot \frac{d\Phi}{dt} \\ e_p = -N_p \cdot \frac{d\Phi}{dt} \end{matrix}$$

Construction of the transformer

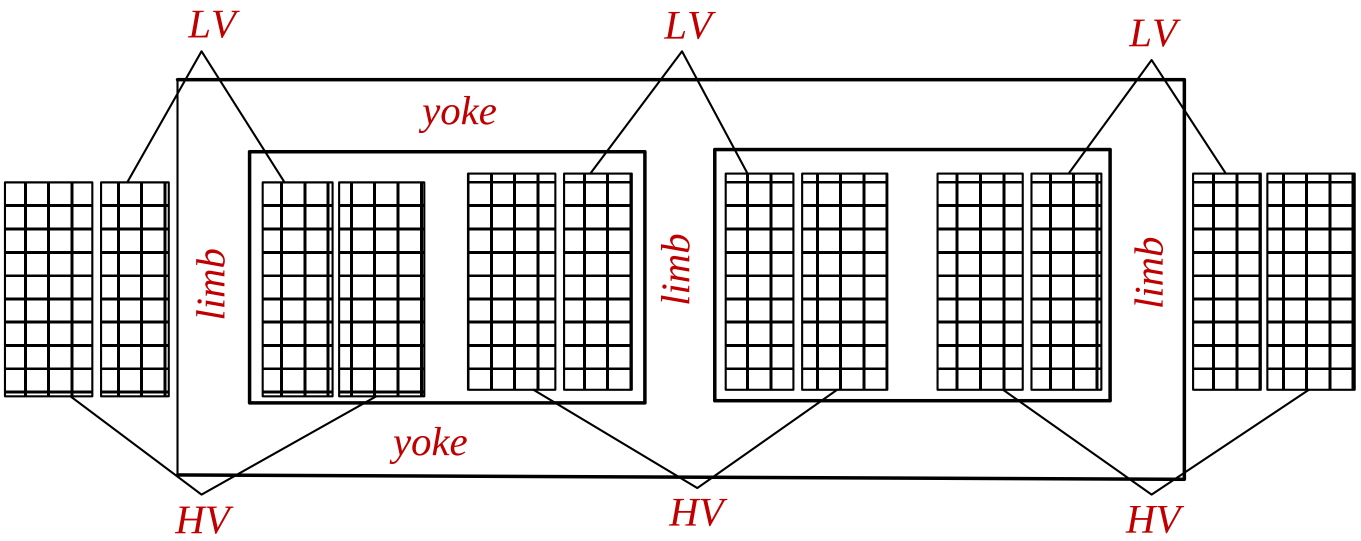
According to the design, transformers can be classified into two:

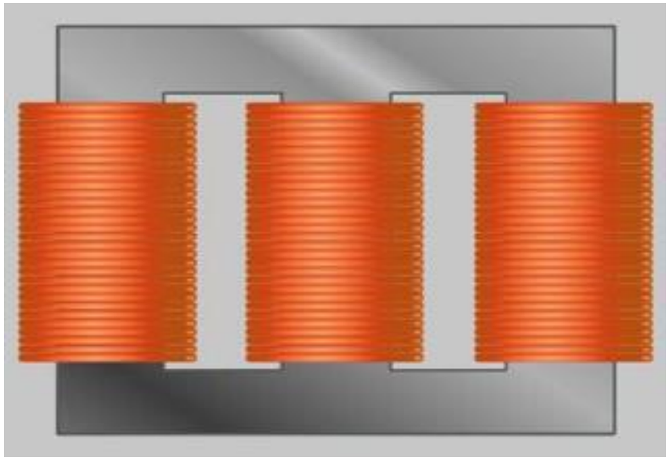
- **1. Core- Type Transformer**
- **2. Shell - Type Transformer**

Single phase Core - Type Transformer

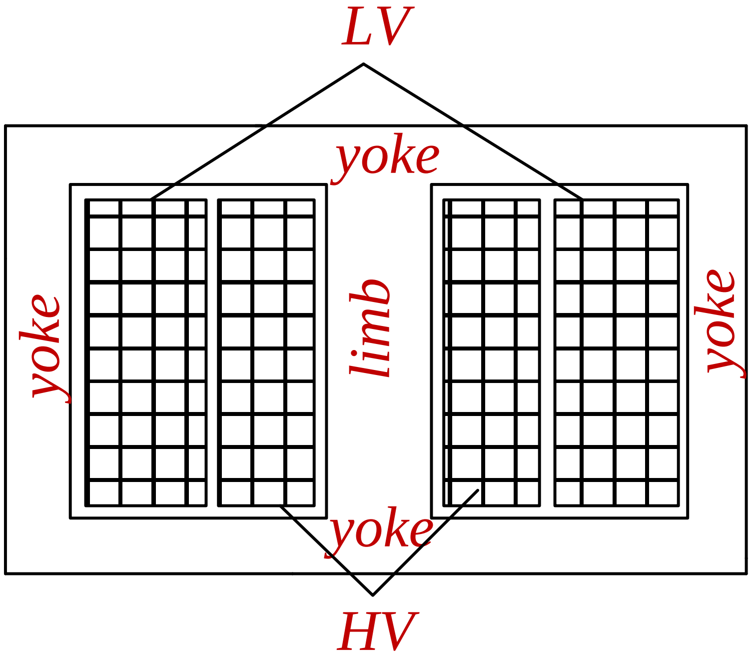


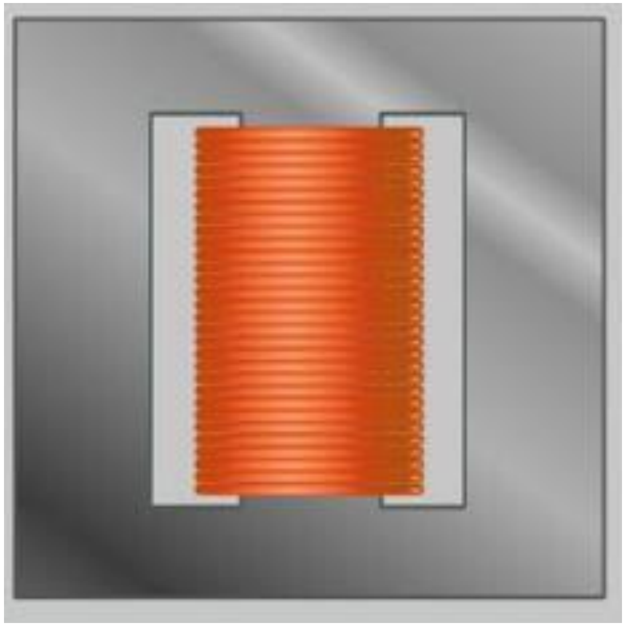
Three phase Core- Type Transformer





Single phase Shell - Type Transformer





Construction of the transformer

Transformers can also be classified according to the type of cooling employed. The different types according to these classifications are:

- **1. Oil Filled Self-Cooled Type**
- **2. Oil Filled Water Cooled Type**
- **3. Air Blast Type**

TRANSFORMERS 2

EMF Equation of the Transformer

It can be supposed that resultant alternating magnetic flux Φ in the transformer pole core is sinusoidal time function. Whereas instantaneous EMF value induced in the primary winding equals:

$$e_p = -N_p \cdot \frac{d\Phi}{dt} = -\omega \cdot N_p \cdot \Phi_{max} \cdot cos\,\omega t =$$

$$= -\omega \cdot N_p \cdot \Phi_{max} \cdot sin\left(\omega t - \frac{\pi}{2}\right),$$

where $\omega = 2\pi \cdot f$.

For the secondary winding this leads to the following:

$$e_s = -\omega \cdot N_s \cdot \Phi_{max} \cdot sin\left(\omega t - \frac{\pi}{2}\right).$$

EMF Equation of the Transformer

RMS value of EMF of the primary winding could be written:

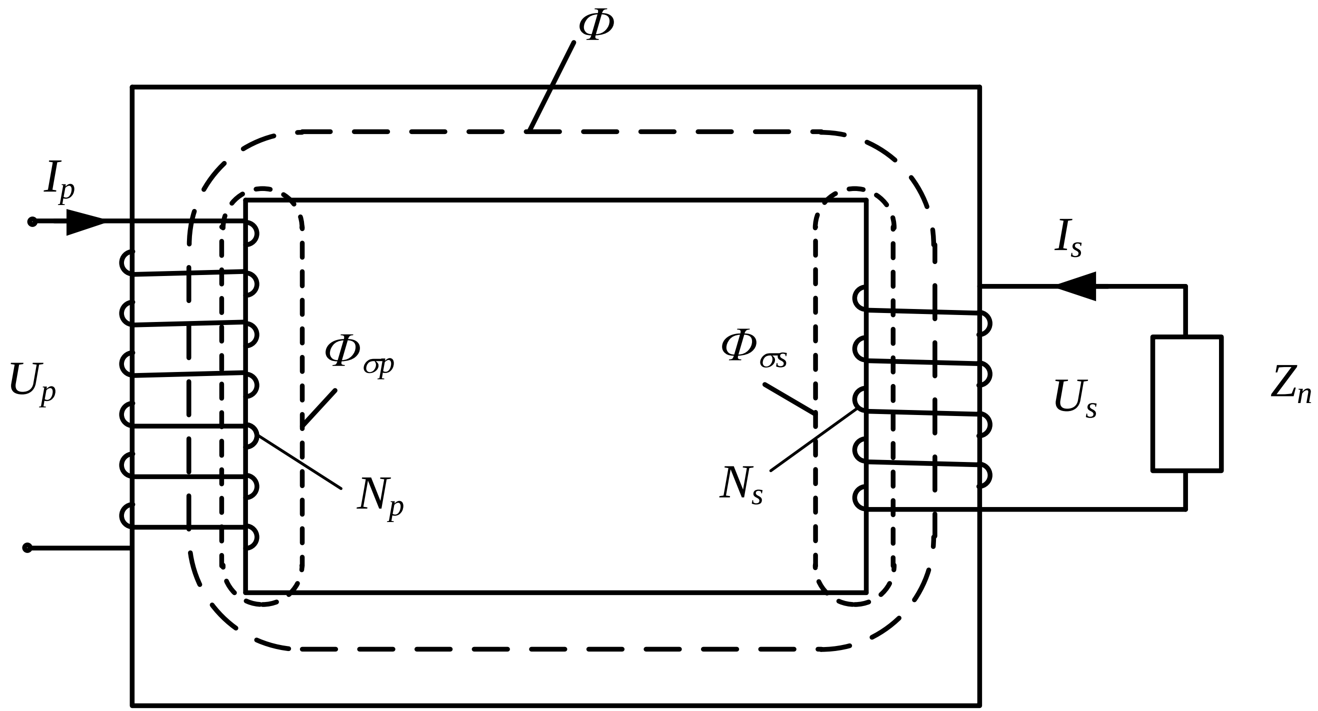
$$E_p = \frac{E_{p.max}}{\sqrt{2}} = \frac{\omega \cdot N_p \cdot \Phi_{max}}{\sqrt{2}} = \frac{2\pi \cdot f \cdot N_p \cdot \Phi_{max}}{\sqrt{2}}, \text{thus}$$

$$E_p = 4{,}44 \cdot f \cdot N_p \cdot \Phi_{max},$$

and for the secondary winding:

$$E_s = 4{,}44 \cdot f \cdot N_s \cdot \Phi_{max}.$$

EMF Equation of the Transformer



The transformer winding voltage ratio is thus shown to be directly proportion to the winding turns ratio according to:

$$k = \frac{N_p}{N_s} = \frac{E_p}{E_s} \approx \frac{U_p}{U_s}.$$

EMF Equation of the Transformer

RMS values of EMF leakage are proportional to the values of currents in winding:

$$\dot{E}_{\sigma p} = -j\dot{I}_p \cdot x_{\sigma p}, \ \dot{E}_{\sigma s} = -j\dot{I}_s \cdot x_{\sigma s},$$

where $x_{\sigma p}$ and $x_{\sigma s}$ – leakage inductance reactance of primary and secondary windings, $\dot{I}_p$ and $\dot{I}_s$ – currents in primary and secondary windings.

EMF Equation of the Transformer

Equations of primary and secondary windings could be written as:

$$\dot{U}_p = (-\dot{E}_p) + j\dot{I}_p \cdot x_{\sigma p} + \dot{I}_p \cdot r_p,$$

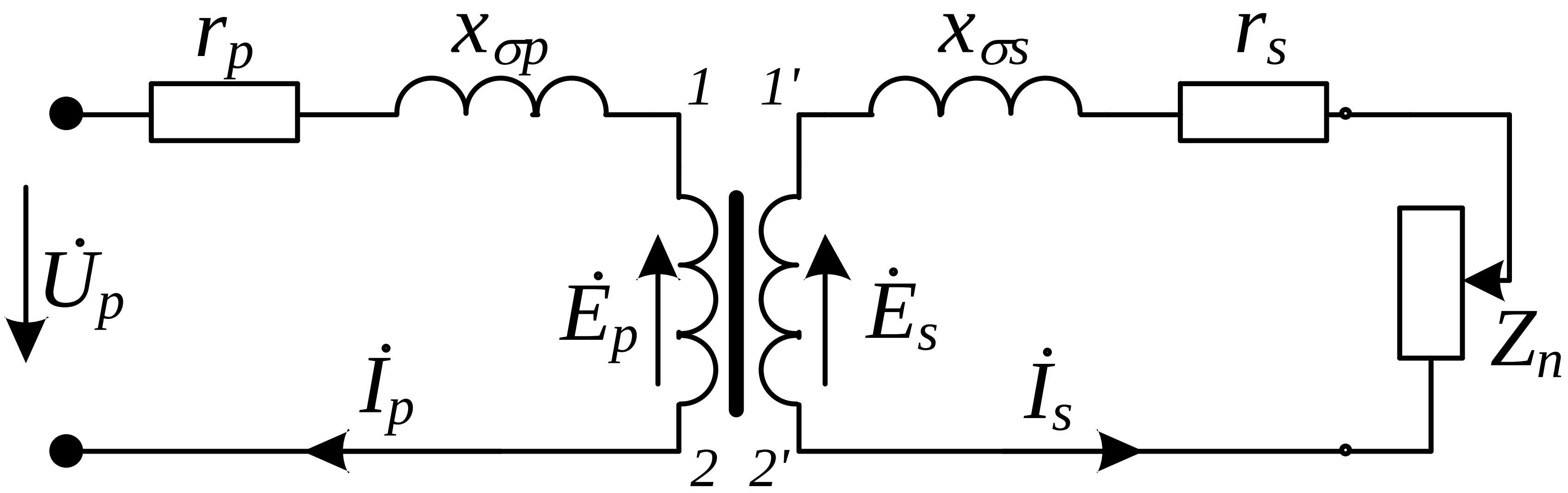
$$\dot{U}_s = \dot{E}_s - j\dot{I}_s \cdot x_{\sigma s} - \dot{I}_s \cdot r_s = \dot{I}_s \cdot Z_n,$$

where r_p and r_s – resistance of primary and secondary windings, Z_n – load impedance.

As resistance voltage drop in primary winding is rather small one can say that:

$$\dot{U}_p = (-\dot{E}_p).$$

Equivalent Circuit of the Transformer referred to the Primary



Equivalent circuit of transformer

Equivalent Circuit of Transformer referred to Primary

Referring secondary winding parameters the load to the primary is caused by referring number of turns in secondary winding to number of turns in primary winding. As a result, instead of a transformer with turns ratio:

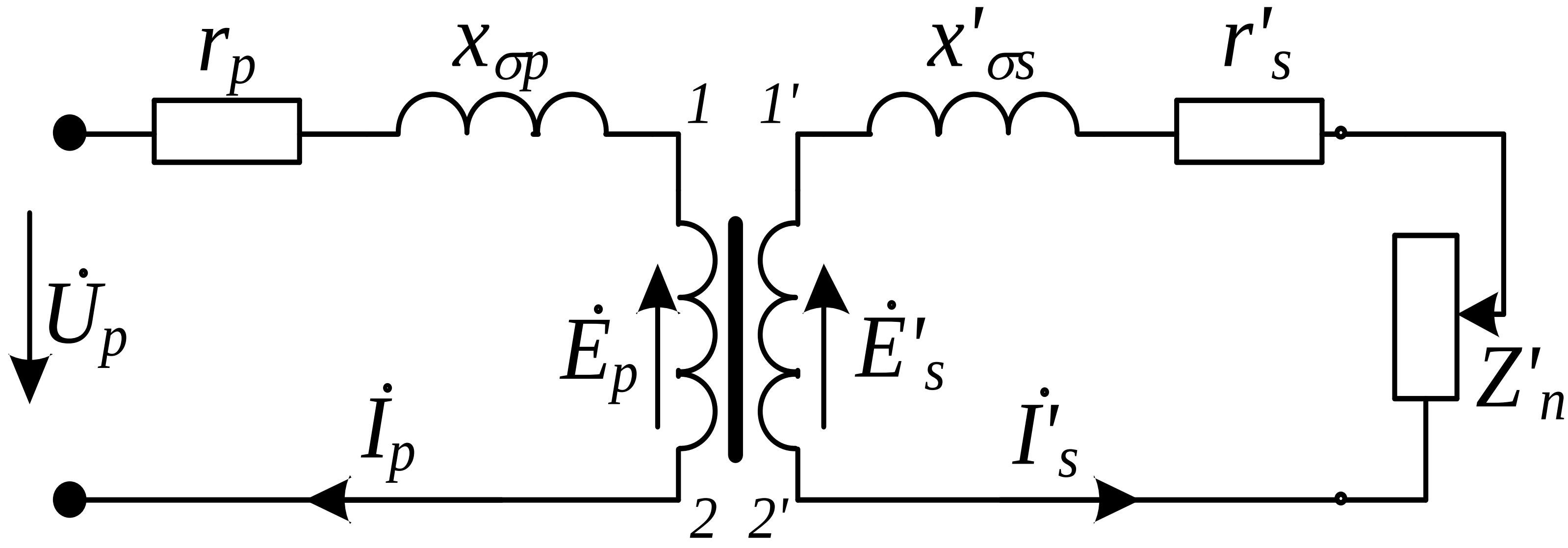
$$k = \frac{N_p}{N_s},$$

it will be equivalent transformer with turns ratio:

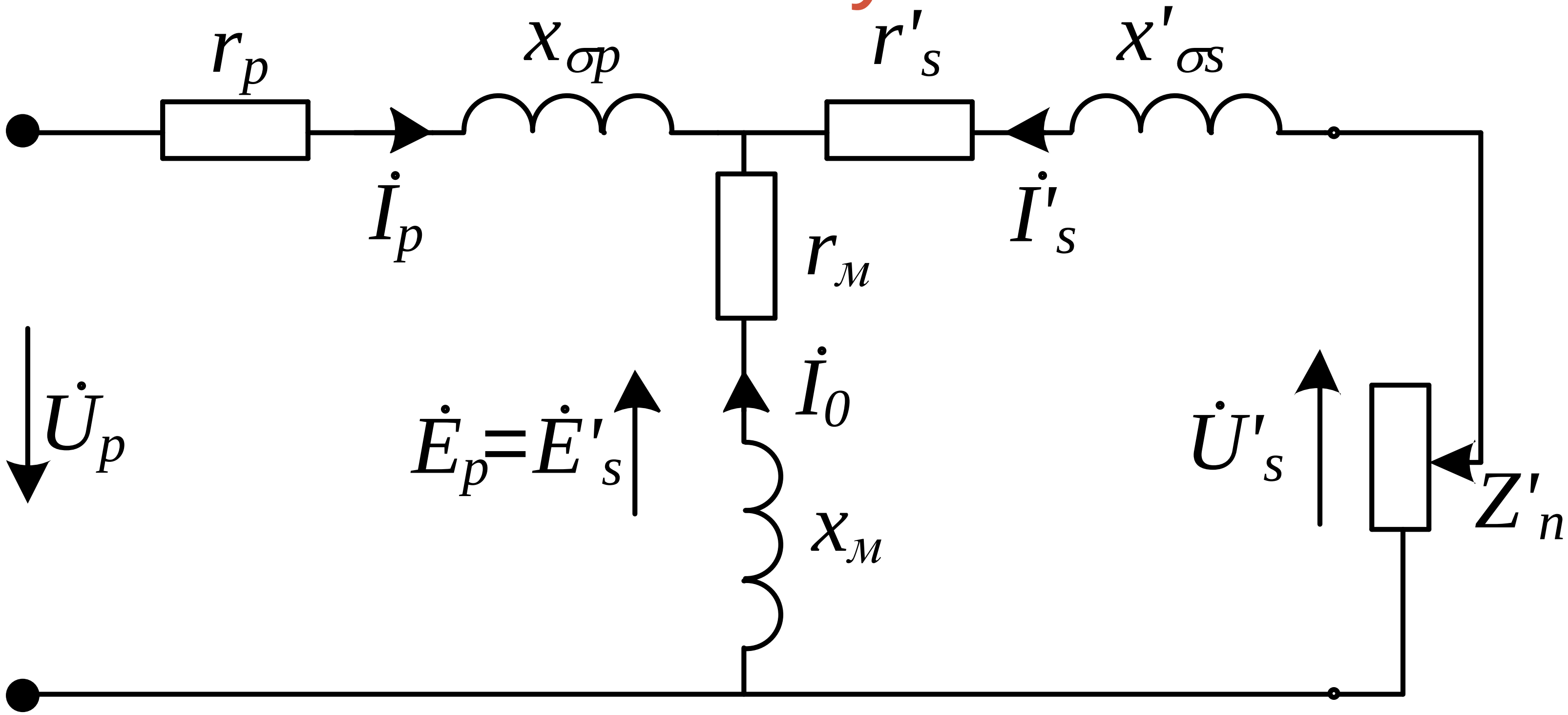
$$k = \frac{N_p}{N'_s} = 1, \quad N_p = N'_s.$$

where N'_s.- number of turns in secondary winding referred to the primary side.

Equivalent Circuit of the Transformer referred to the Primary



Equivalent Circuit of the Transformer referred to the Primary



According to the fact that $k = 1$, and $\dot{E}'_s = \dot{E}_p$. Where r_m and x_m - resistance and inductance reactance of the excitation circuit, $\dot{I}_0$ – current passed through the excitation circuit.

Equivalent Circuit of the Transformer referred to the Primary

Secondary winding parameters of referred transformer should not influence on transformer voltage, current and resistance values. As number of turns in the secondary winding changes into *k* times:

$$\dot{E}'_s = k \cdot \dot{E}_s, \dot{U}'_s = k \cdot \dot{U}_s \ ,$$

where $\dot{E}'_s$ and $\dot{U}'_s$ –EMF and voltage on of the secondary winding to the primary side.

Current in the secondary winding referred to the primary side:

$$\dot{E}_s \cdot \dot{I}_s = \dot{E}'_s \cdot \dot{I}'_s = k \cdot \dot{E}_s \cdot \dot{I}'_s, \qquad \dot{I}'_s = \frac{\dot{I}_s}{k}.$$

Equivalent Circuit of Transformer referred to Primary

Resistance of secondary winding referred to the primary side:

$$(\dot{I}_s)^2 \cdot r_s = (\dot{I}'_s)^2 \cdot r'_s = \left(\frac{\dot{I}_s}{k}\right)^2 \cdot r'_s, \qquad r'_s = k^2 \cdot r_s.$$

Leakage inductance reactance of secondary winding referred to the primary side:

$$(\dot{I}_s)^2 \cdot x_{\sigma s} = (\dot{I}'_s)^2 \cdot x'_{\sigma s} = \left(\frac{\dot{I}_s}{k}\right)^2 \cdot x'_{\sigma s}, \qquad x'_{\sigma s} = k^2 \cdot x_{\sigma s}.$$

Equivalent Circuit of the Transformer referred to the Primary

Equations of primary winding and secondary winding referred to the primary side could be written as:

$$\dot{U}_p = \left(-\dot{E}_p\right) + j\dot{I}_p \cdot x_{\sigma p} + \dot{I}_p \cdot r_p,$$

$$\dot{U}'_s = \dot{E}'_s - j\dot{I}'_s \cdot x'_{\sigma s} - \dot{I}'_s \cdot r'_s = \dot{I}'_s \cdot Z'_n,$$

Equation of the currents is the following:

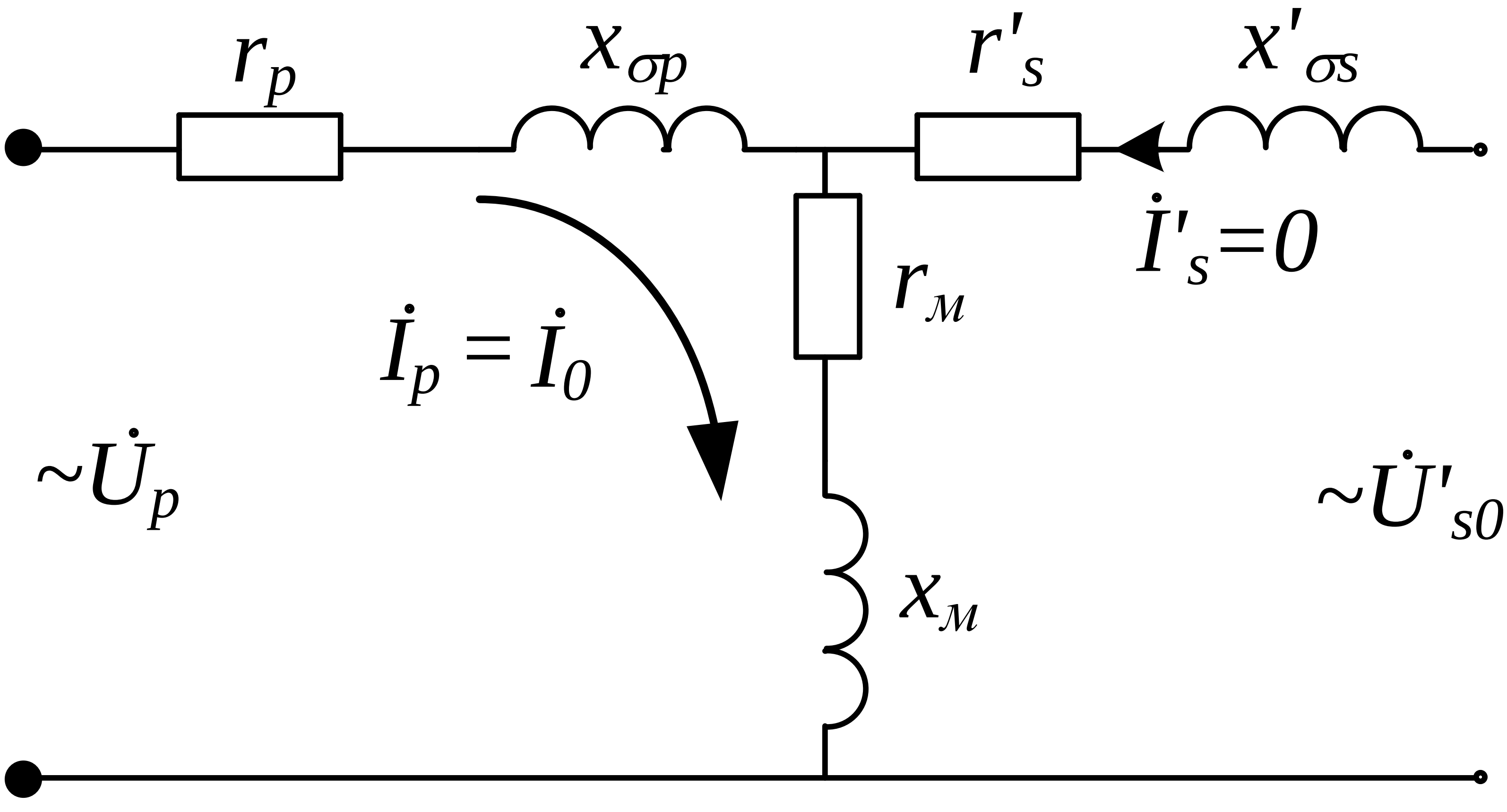
$$\dot{I}_p = \dot{I}_0 + \left(-\dot{I}'_s\right).$$

TRANSFORMERS 3

Determination of equivalent circuit parameters

These parameters can be directly and more easily determined by performing tests that involve little power consumption. Two tests, a no-load test (or open-circuit test) and a short-circuit test, will provide information for determining the parameters of the equivalent circuit of a transformer.

Open circuit test



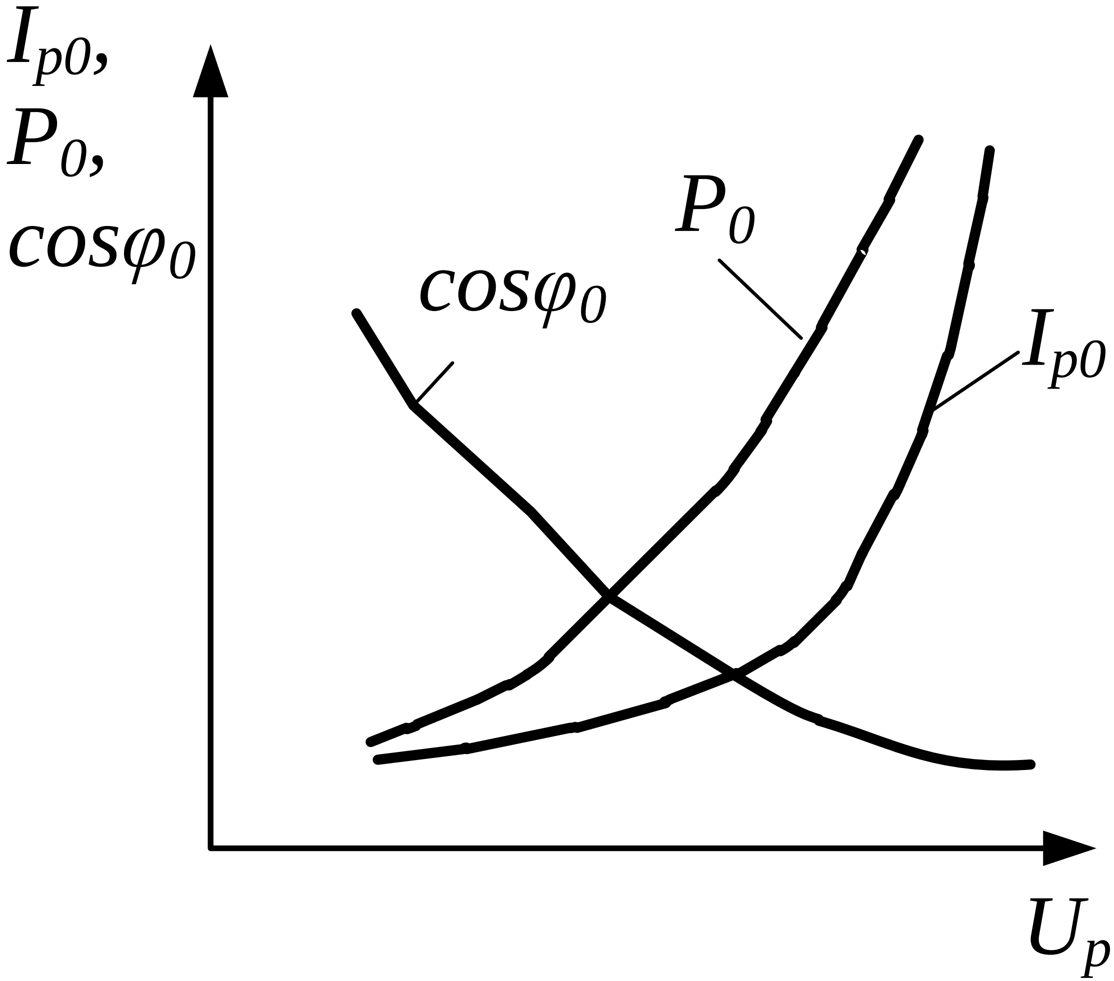
Open circuit test

As $\dot{I}'_s = 0$ and $Z'_n = \infty$ the current and voltage equations reduce to:

$$\dot{U}_p = \left(-\dot{E}_p\right) + \ j\dot{I}_0 \cdot x_{\sigma p} + \dot{I}_0 \cdot r_p,$$

$$\dot{U}'_{s0} = \dot{E}'_s, \qquad \dot{I}_p = \dot{I}_0.$$

Open circuit test



Short circuit test

As the name suggests, in this test primary applied voltage, the current and power input are measured keeping the secondary terminals short circuited and

$$\dot{U}'_s = 0 \text{ and } Z'_n = 0.$$

The supply voltage required to circulate rated current through the transformer is usually very small and is of the order of a few percent of the rated voltage $U_{p.rated}$. This voltage is called rated short circuit voltage:

$$u_{sc} = (U_{sc} / U_{p.rated}) 100\ \% = (5 \ldots 10)\ \%.$$

Short circuit test

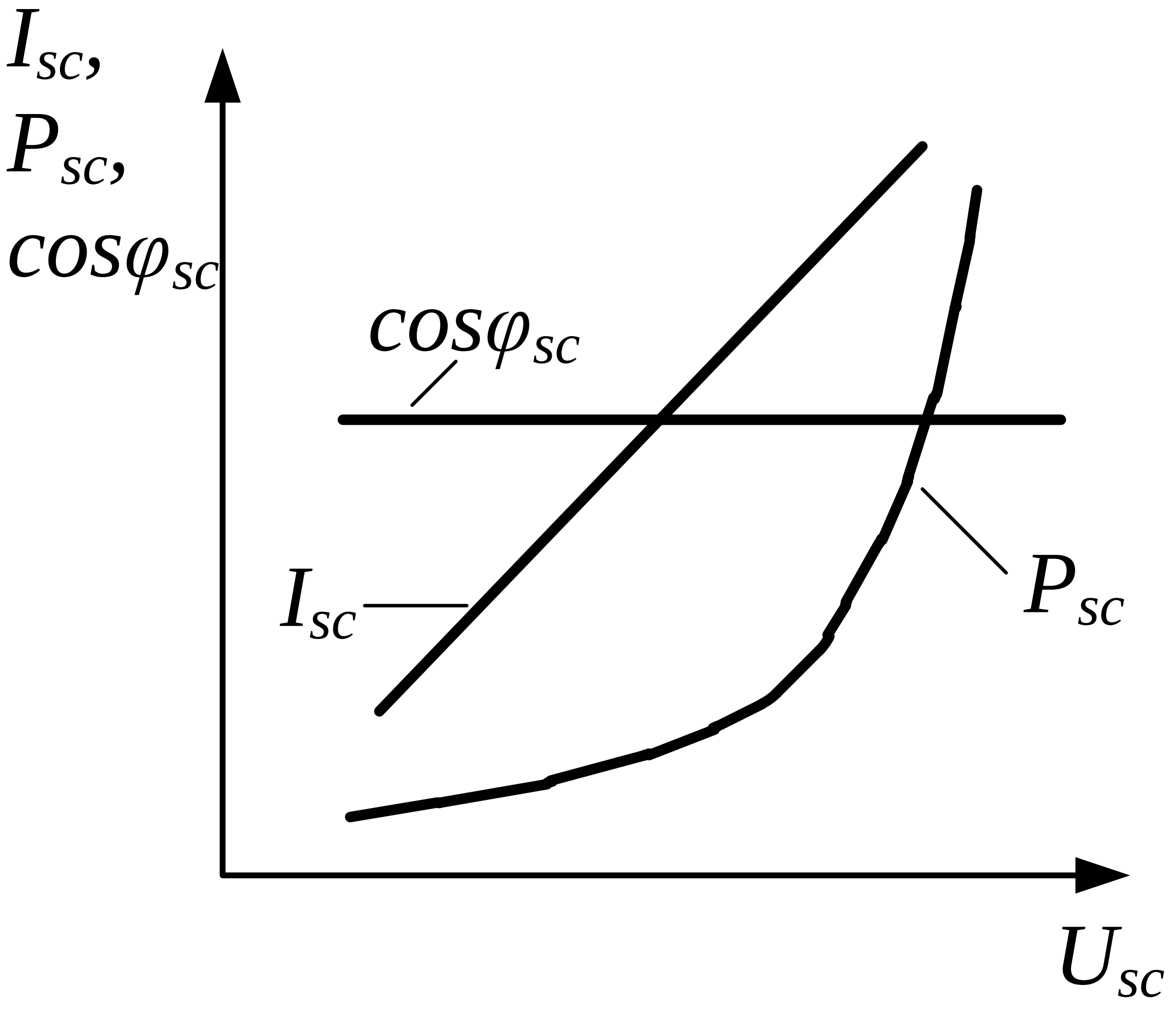
The current and voltage equations reduce to:

$$\dot{U}_{sc} = \dot{I}_{p.sc} \cdot \left(r_p + r'_s\right) + j\dot{I}_{p.sc} \cdot \left(x_{\sigma p} + x'_{\sigma s}\right) =$$

$$= \dot{I}_{p.sc} \cdot r_{sc} + j\dot{I}_{p.sc} \cdot x_{sc} = \dot{I}_{p.sc} \cdot z_{sc},$$

$$\dot{I}_{p.sc} = -\dot{I}'_{s.sc}.$$

Short circuit test



Voltage regulation

$$\Delta\dot{U} = \frac{\dot{U}_{s0} - \dot{U}_s}{\dot{U}_{s0}} \cdot 100\% = \frac{\dot{U}'_{s0} - \dot{U}'_s}{\dot{U}'_{s0}} \cdot 100\%,$$

where $\dot{U}_{s0}$ – voltage of secondary winding under open circuit mode $\dot{U}_p = \dot{U}_{p.rated}$ and

$\dot{U}'_{s0}$ – voltage of secondary winding referred to primary side under open circuit mode $\dot{U}_p = \dot{U}_{p.rated}$,

$\dot{U}_s$ – voltage of secondary winding and

$\dot{U}'_s$ – voltage of secondary winding referred to primary side.

Voltage regulation

For an ideal transformer, $\Delta\dot{\mathrm{U}} = 0$.

The voltage regulation is defined by the equation:

$$\Delta\dot{\mathrm{U}} = \beta \cdot (\dot{u}_{sc.a} \cdot \cos\varphi_2 + \dot{u}_{sc.r} \cdot \sin\varphi_2) + \\ +\beta^2 \cdot (\dot{u}_{sc.r} \cdot \cos\varphi_2 - \dot{u}_{sc.a} \cdot \sin\varphi_2)^2.$$

where β – load ratio:

$$\beta = \frac{\dot{I}_s}{\dot{I}_{s.rated}} = \frac{\dot{I}'_s}{\dot{I}'_{s.rated}},$$

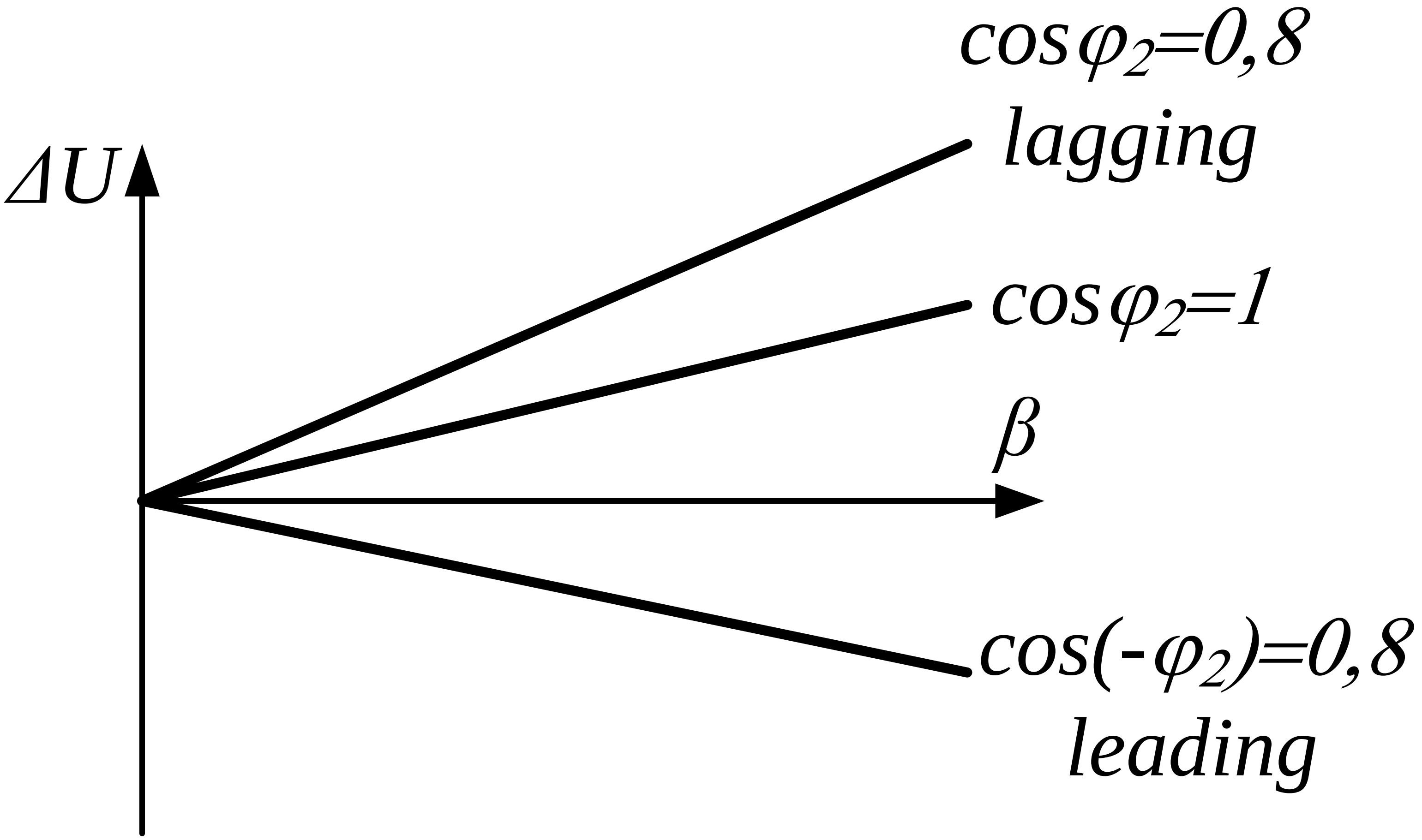
$\dot{u}_{sc.a}$ and $\dot{u}_{sc.r}$ – active and reactive component of rated short circuit voltage, $cos\varphi_2$ – power factor of the load.

Voltage regulation

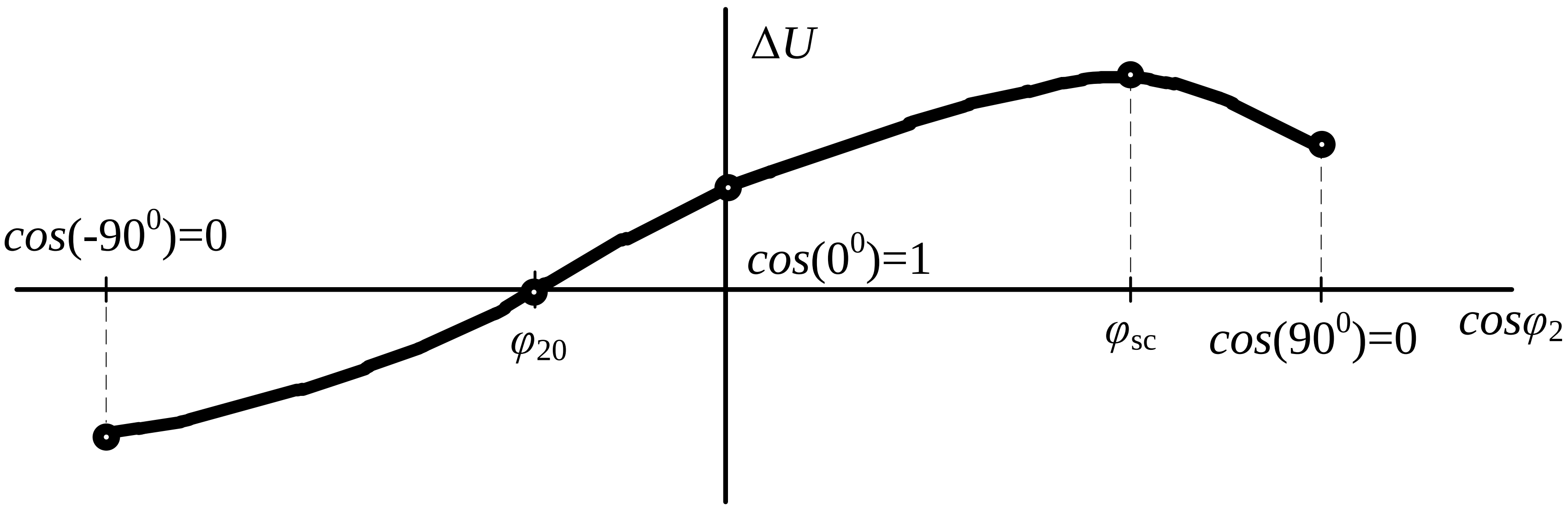
As the addend is small it could be neglected and equation transformed to:

$$\Delta \dot{\mathrm{U}} = \beta \cdot (\dot{u}_{sc.a} \cdot \cos\varphi_2 + \dot{u}_{sc.r} \cdot \sin\varphi_2)$$

Voltage regulation

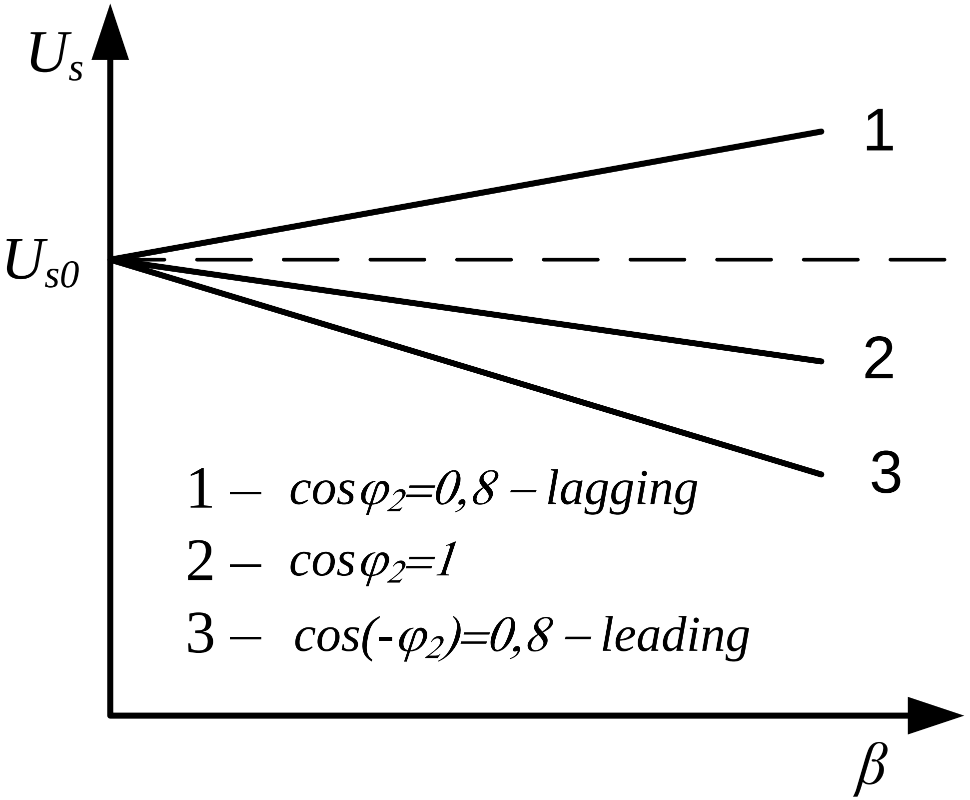


Voltage regulation



External transformer characteristic

$$U_s = U_{s0} \cdot \frac{1 - \Delta\dot{U}}{100}.$$



TRANSFORMERS 4

How it's work? Pole transformers

Listen to the information provided in video fragment and fill the gaps.

How it’s work? Pole transformers

- Without them ___________________________ would be virtually useless to the average person.

- An aluminum bus bar called the ___________________________ sends low voltage current out from the transformer.

How it's work? Pole transformers

- The insulating paper has epoxy glue on both sides this glue later __________and bound several ______________ in place.

- Now he solders a ______________________wire to the copper wire. Then roles yet another layer of copper wire.

How it's work? Pole transformers

- The component they just built is called _______________, now using electrical steel they build the transformers other main component called _______________________.

- The heat removes any traces of ____________________ to improve the insulation. The epoxy glue has fused the _______________, the _______________________and the _____________________________.

How it’s work? <u>Pole transformers</u>

- The oil is used for its _________________________ properties.

- Before transformers go into service they have to undergo some ______________________________ tests.

- To test the transformer for _________________________this equipment simulates a 145,000 volt _____________________.

How it's work? Pole transformers

Questions for discussion

- What are the main steps in transformer manufacturing?
- What tests should transformer to undergo after its manufacturing?
- What materials are used for main parts of transformer?

How it’s work? Pole transformers

- Electric transformers. We see them everywhere often take for granted the big part they play in our everyday lives. Without them raw electrical power would be virtually useless to the average person. Their job is to transform the high voltage from electrical power lines to the lower voltage that's suitable for home use.
- Transformers lower power line voltage levels to ensure that your appliances don't receive too much electricity. To make a transformer they start with two materials paper that's coated with epoxy glue, they tape it to a wooden block, and three millimeters thick aluminum strip, metal that withstands the heat a high voltage current produces. They secure both materials to the block and rotated wrapping the insulating paper and aluminum together. An aluminum bus bar called the low voltage lead sends low voltage current out from the transformer.
- They fold the lead and move the unit to another rotating block for more wrapping. The insulating paper has epoxy glue on both sides this glue later melt and bound several components in place. On the next block a worker tapes on more epoxy paper. Then epoxy coated by copper wire.
- He rows on a layer of wire covering the paper. Then repeats the same process forming a second layer of copper wire. Now he solders a high-voltage lead wire to the copper wire. Then roles yet another layer of copper wire. He attach is what's called the lead wire out. The wire that'll protrude from the transformer cylinder and vinyl coated wires that will connect two different voltages out the transformer.
- The component they just built is called the coil, now using electrical steel they build the transformers other main component called the core. a worker secures the coiling course tightly together with metal strapping which will help to fix the assembly in the tank, then sends them to an oven. Where they are baked for 8 hours at 135 degree Celsius. The heat removes any traces of humidity to improve the insulation. The epoxy glue has fused the paper, the aluminum strip and the copper wires. The assembly goes into a steel tank. They hammer on a rubber gasket around the perimeter and bolt-on a grounding wire then the insert three thermal plastic bushings. They connect the low voltage leads to the thermal plastic bushings then both the bushings to the tank. They adhere oil filling guide to the side of the tank, then position an automated filling machine. A machine fills the tank with mineral oil. Drawing a vacuum to make sure the oil disperses throughout the coil in course. The oil is used for its thermal and insulating properties. An internal fault detector will alarm maintenance crews if there's a short circuit
- He runs lead wires through the thermal plastic bushing and secures it is in place well. next comes the high voltage connector. Then he boasts the tank cover shot. The transformation so to speak is finished. Before transformers go into service they have to undergo some truly electrifying tests. To test the transformer for field use this equipment simulates a 145,000 volt lightning strike. Then it's into a water tank to test the transformer for leaks if it passes it will appear soon on a pole near you.

How it's work? Pole transformers

- Without them raw electrical power would be virtually useless to the average person.

- An aluminum bus bar called the low voltage lead sends low voltage current out from the transformer.
- The insulating paper has epoxy glue on both sides this glue later melt and bound several components in place.
- Now he solders a high-voltage lead wire to the copper wire. Then roles yet another layer of copper wire.
- The component they just built is called coil, now using electrical steel they build the transformers other main component called core.
- The heat removes any traces of humidity to improve the insulation. The epoxy glue has fused the paper, the aluminum strip and the copper wires.
- The oil is used for its thermal and insulating properties.
- Before transformers go into service they have to undergo some truly electrifying tests.
- To test the transformer for field use this equipment simulates a 145,000 volt lightning strike.

TRANSFORMERS 5

Losses and efficiency of transformer

The efficiency is defined as follows:

$$\eta = \frac{P_{out}}{P_{in}} \cdot 100\% = \frac{P_{out}}{P_{out} + \sum P} \cdot 100\%,$$

where P_{out} – output power of transformer, P_{in} – input power of transformer, $\sum P$ – losses in transformer.

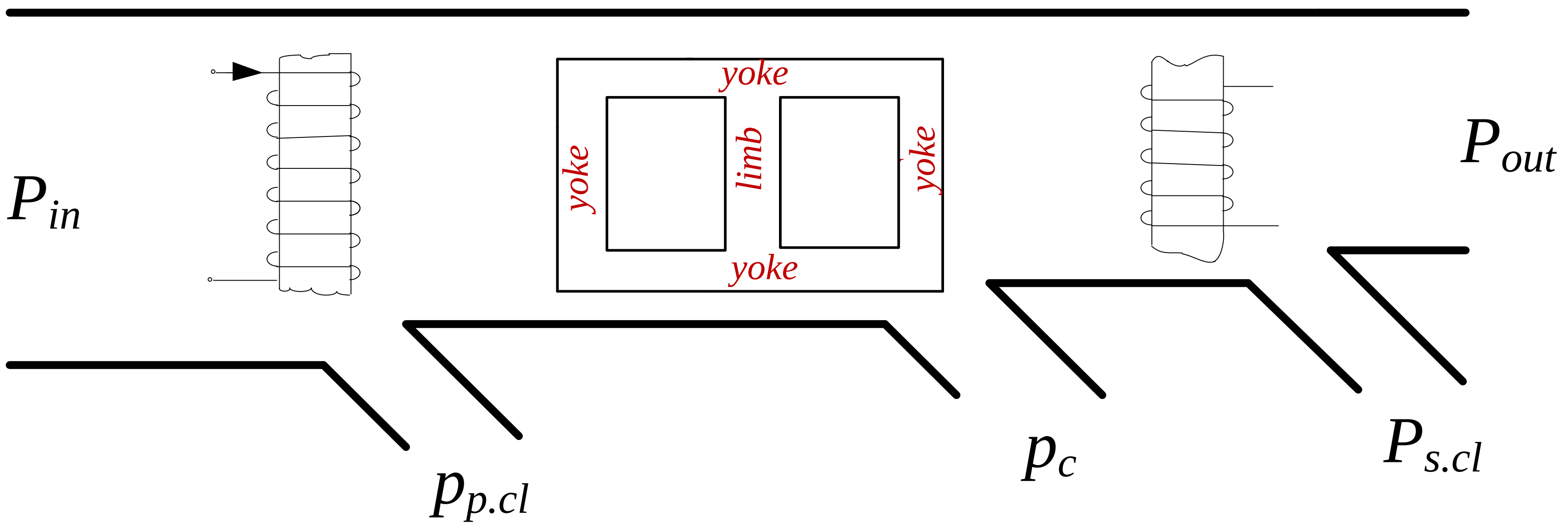
The losses in the transformer are the

- core loss p_c and
- copper losses in primary and secondary windings p_{cl}, and
- dielectric losses and
- stray losses.

Dielectric and stray losses are rather small in comparison with copper and core losses, therefore:

$$\eta = \frac{P_{out}}{P_{in}} \cdot 100\% = \frac{P_{out}}{P_{out} + p_c + p_{cl}} \cdot 100\%.$$

Losses and efficiency of transformer



Losses and efficiency of transformer

Copper losses also are known as variable losses as they depend on load current. The copper loss is a function of the load current. The copper loss can be determined if the winding currents and their resistances are known:

$$\mathrm{p_{cl}} = \mathrm{p_{p.cl}} + \mathrm{p_{s.cl}} = m \cdot \left(\dot{\mathrm{I}}_{\mathrm{p}}\right)^2 \cdot \mathrm{r_p} + m \cdot \left(\dot{\mathrm{I}}'_{\mathrm{s}}\right)^2 \cdot \mathrm{r'_s},$$

where m – number of transformer phases.

The copper losses could be defined from short circuit test:

$$\mathrm{p_{cl}} = \beta^2 \cdot \mathrm{p_{cl.sc}},$$

where $\mathrm{p_{cl.sc}}$ – short circuit power at rated currents in winding, β – load ratio.

Losses and efficiency of transformer

Therefore, if the parameters of the equivalent circuit of a transformer are known, the efficiency of the transformer under any operating condition may be determined. Now,

$$P_{out} = U_s \cdot I_s \cdot cos\varphi_s = U_p \cdot I_p \cdot \left(\frac{\dot{I}'_s}{\dot{I}'_{s.rated}}\right) cos\varphi_s$$

$$= S_r \cdot \beta \cdot cos\varphi_s.$$

where S_r –rated power of transformer.

Therefore,

$$\eta = \frac{S_r \cdot \beta \cdot cos\varphi_s}{S_r \cdot \beta \cdot cos\varphi_s + \mathrm{p_c} + \beta^2 \cdot \mathrm{p_{cl.sc}}},$$

$$\eta = \frac{S_r \cdot \beta \cdot cos\varphi_s}{S_r \cdot \beta \cdot cos\varphi_s + \mathrm{p_{const}} + \beta^2 \cdot \mathrm{p_{var}}},$$

Losses and efficiency of transformer

By differentiating η with respect to β and equating the same to zero, the condition for maximum efficiency is obtained. In the present case that condition comes out to be:

$$p_{const} = \beta^2 \cdot p_{var},$$

or

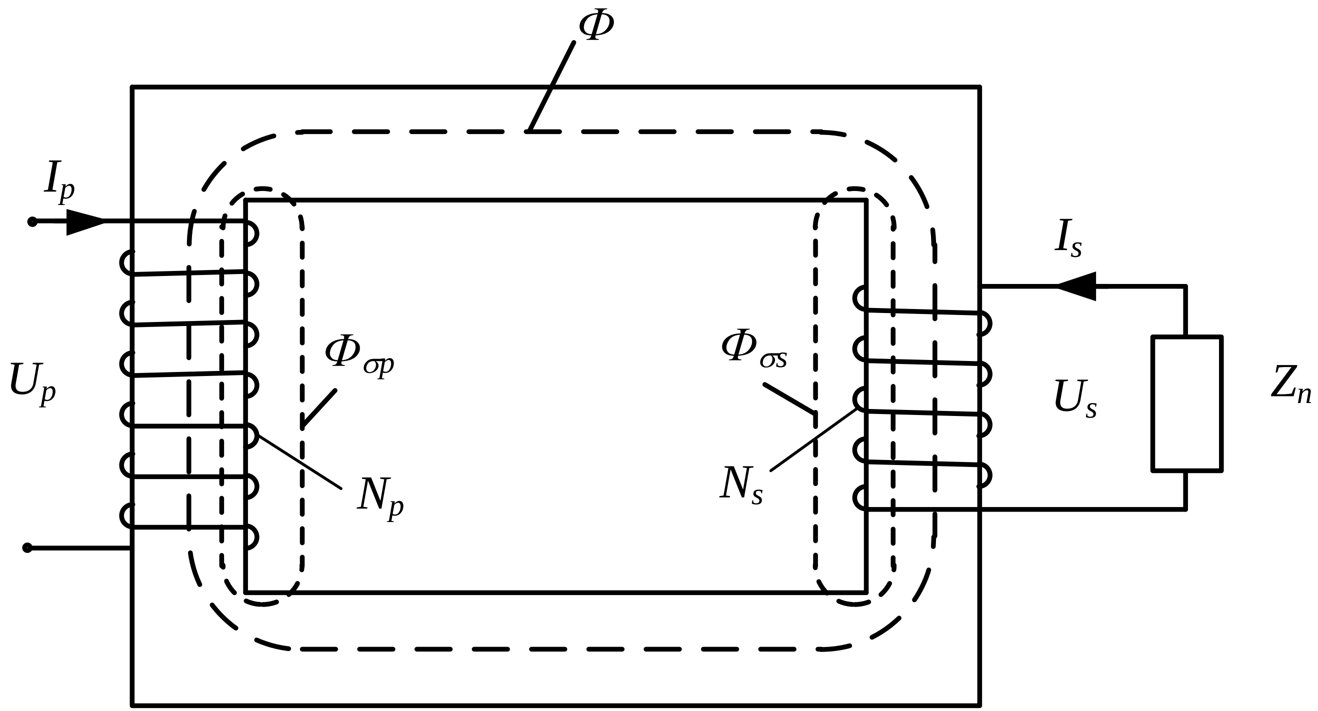
$$\beta = \sqrt{\frac{p_{const}}{p_{var}}}.$$

That is, when constant losses equal the variable losses at any fractional load β the efficiency reaches a maximum value. The maximum value of that efficiency at any given power factor is given by:

$$\eta_{max} = \frac{S_r \cdot \beta \cdot \cos\varphi_s}{S_r \cdot \beta \cdot \cos\varphi_s + 2 \cdot p_{const}} = \frac{S_r \cdot \beta \cdot \cos\varphi_s}{S_r \cdot \beta \cdot \cos\varphi_s + 2 \cdot \beta^2 \cdot p_{var}}.$$

TRANSFORMERS 6

EMF Equation of the Transformer



The transformer winding voltage ratio is thus shown to be directly proportion to the winding turns ratio according to:

$$k = \frac{N_p}{N_s} = \frac{E_p}{E_s} \approx \frac{U_p}{U_s}.$$

Turns ratio

A not quite ideal transformer having 90 turns on the primary and 2250 turns on the secondary is connected to a 120 V, 60 Hz source. The coupling between the primary and secondary is perfect, but the magnetizing current is 4 A.

Calculate:

- *a. The effective voltage across the secondary terminals*
- *b. The peak voltage across the secondary terminals*
- *c. The instantaneous voltage across the secondary when the instantaneous voltage across the primary is 37 V.*

Turns ratio

Solution:

a

- The turns ratio is: $N_1/N_2=90/2250=1/25$.
- The secondary voltage is therefore 25 times greater than the primary voltage because the secondary has 25 times more turns.
- Consequently: $E_2=25 * E_1 = 25 * 120=3000$ V

Turns ratio

b

- The voltage varies sinusoidal; consequently, the peak secondary voltage is: $E_{2peak}=\sqrt{2} * E_2 = \sqrt{2} * 3000=4242$ V

- *c*
- The secondary voltage is 25 times greater than E_1 at every instant. Consequently, when e_1= 37 V
- $e_2=25 * e_1 = 25 * 37=925$ V

Losses and efficiency of transformer

By differentiating η with respect to β and equating the same to zero, the condition for maximum efficiency is obtained. In the present case that condition comes out to be:

$$p_{const} = \beta^2 \cdot p_{var},$$

or

$$\beta = \sqrt{\frac{p_{const}}{p_{var}}}.$$

That is, when constant losses equal the variable losses at any fractional load β the efficiency reaches a maximum value. The maximum value of that efficiency at any given power factor is given by:

$$\eta_{max} = \frac{S_r \cdot \beta \cdot \cos\varphi_s}{S_r \cdot \beta \cdot \cos\varphi_s + 2 \cdot p_{const}} = \frac{S_r \cdot \beta \cdot \cos\varphi_s}{S_r \cdot \beta \cdot \cos\varphi_s + 2 \cdot \beta^2 \cdot p_{var}}.$$

Losses and efficiency of transformer

- *A 1ϕ, 10 kVA, 2400/240 V, 60 Hz distribution transformer has the following characteristics: Core loss at full voltage =100 W and Copper loss at half load =60 W*
- *(a) Determine the efficiency of the transformer when it delivers full load at 0.8 power factor lagging.*
- *(b) Determine the rating at which the transformer efficiency is a maximum. Determine the efficiency if the load power factor is 0.9.*
- *(c) The transformer has the following load cycle: No load for 6 hours, 70% full load for 10 hours at 0.8 PF and 90% full load for 8 hours at 0.9 PF*

Losses and efficiency of transformer

- ***(a)***

$$P_{out} = 10 * 0.8 = 8\ kW$$

$$P_{core} = 100\ W,\ \ P_{cu,FL} == 60 * 2^2 = 240W$$

$$\eta = \frac{8000}{8000 + 100 + 240} * 100 = 95.92$$

Losses and efficiency of transformer

- ***(b)***

$$x=\sqrt{\frac{100}{240}}=0.6455``$$

$$\eta_{\max}=\frac{10*10^{3}*0.6455*0.9}{\left(10^{4}*0.6455*0.9\right)+100+100}=96.67\%$$

Losses and efficiency of transformer

- ***(C)***
- Output energy in 24 hours is:

$$E_{24hrs} = 0 + 10 * 0.7 * 0.8 * 10 + 10 * 0.9 * 0.9 * 8 = 120.8kWh$$

- Energy losses in the core in 24 hours is

$$E_{core} = 100 * 24 * 10^{-3} = 2.4\,kWh$$

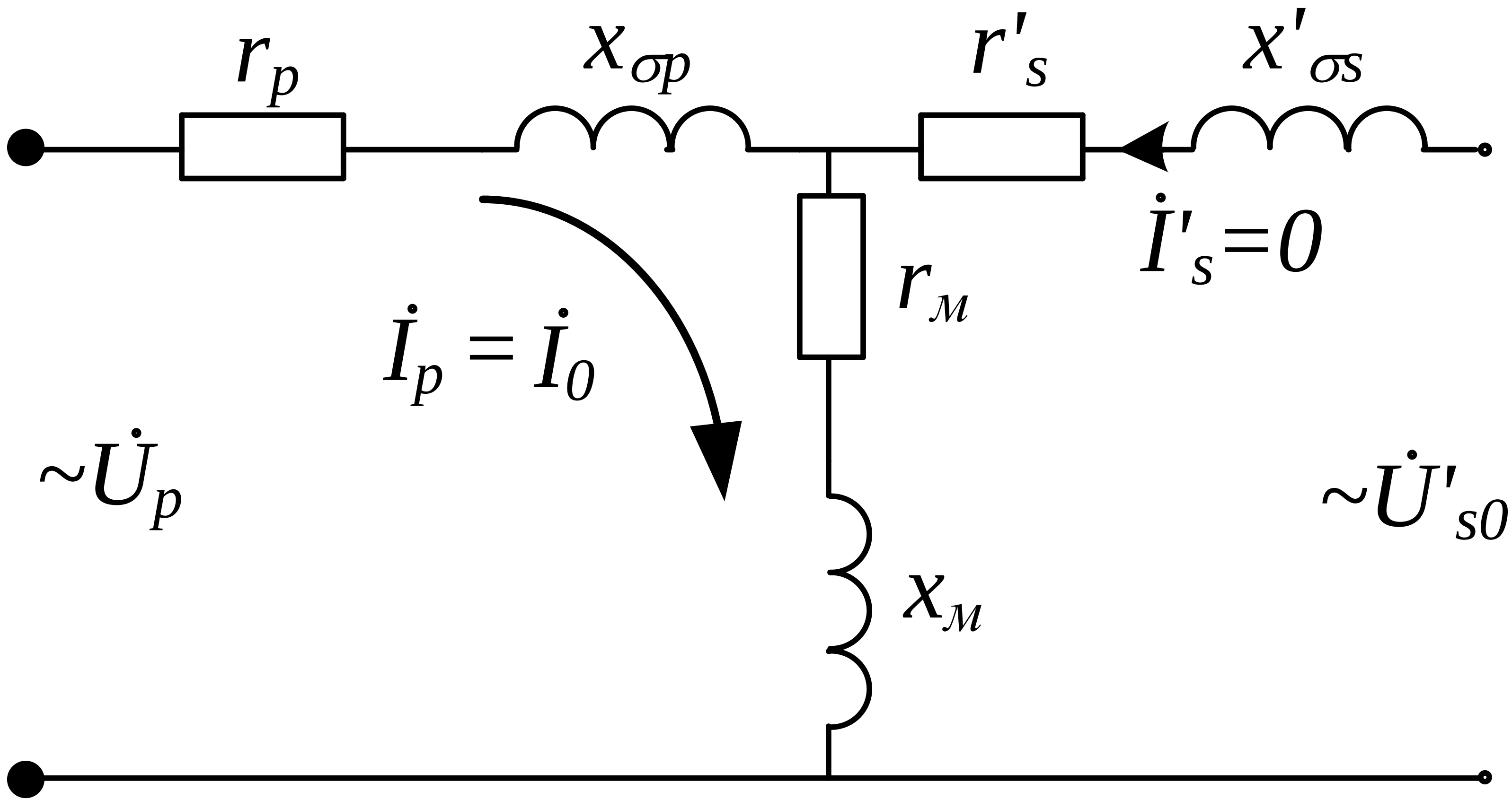
- Energy losses in the cupper in 24 hours is

$$E_{cu} = \left(240 * 0.7^2 * 10 + 240 * 0.9^2 * 8\right) * 10^{-3} = 2.7312kWh$$

$$\eta_{all\,day} = \frac{120.8}{120.8 + 2.4 + 2.7312} * 100 = 95.93\%$$

TRANSFORMERS 7

Open circuit test



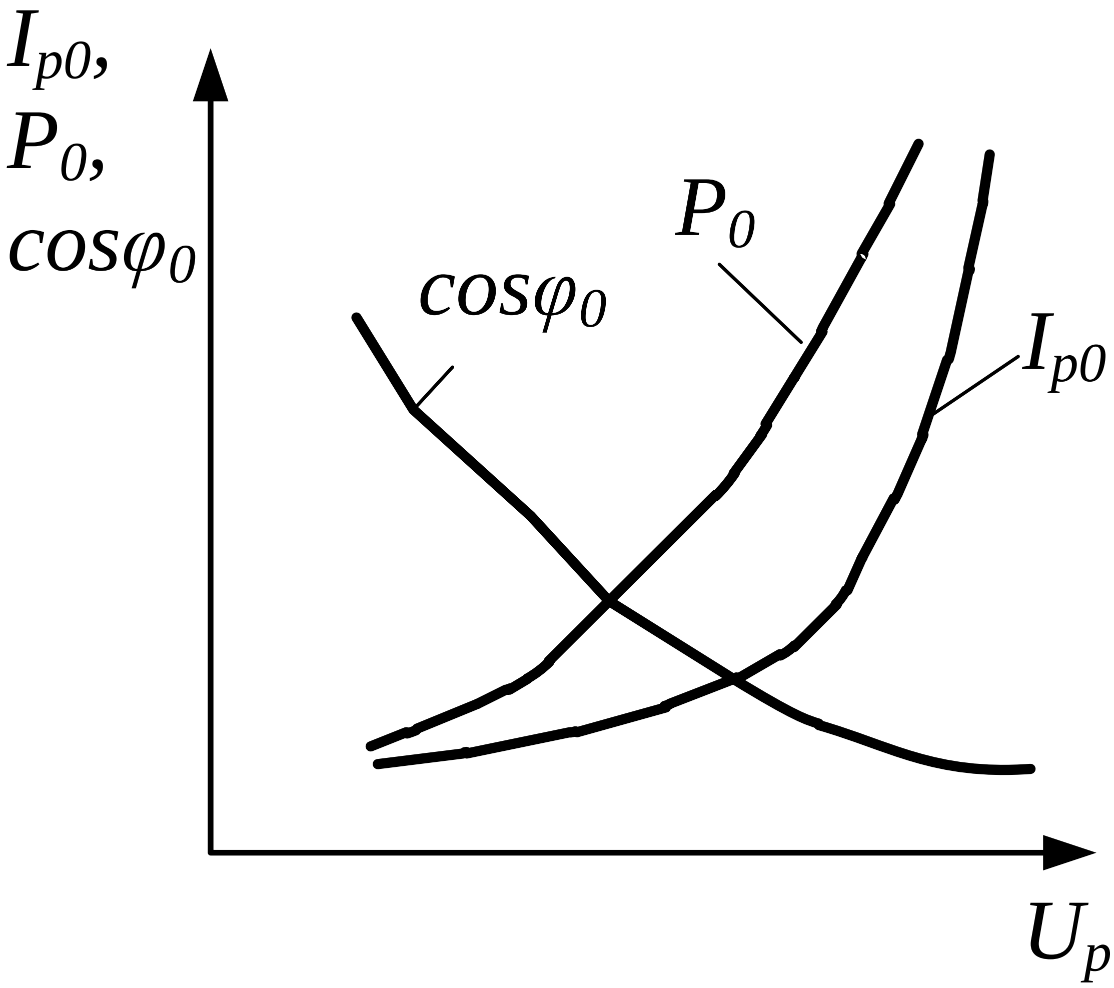
Open circuit test

As $\dot{I}'_s = 0$ and $Z'_n = \infty$ the current and voltage equations reduce to:

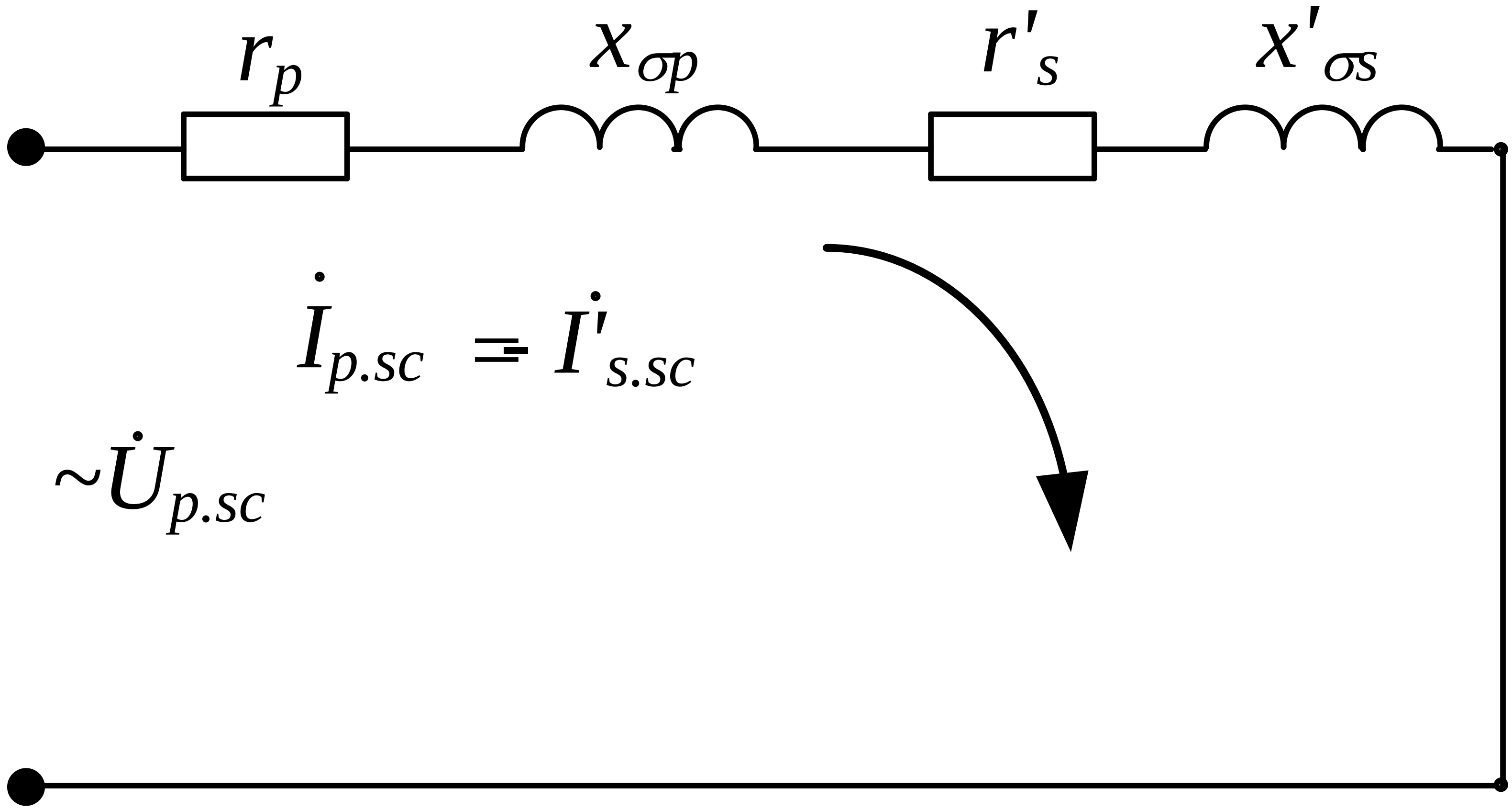
$$\dot{U}_p = \left(-\dot{E}_p\right) + \ j\dot{I}_0 \cdot x_{\sigma p} + \dot{I}_0 \cdot r_p,$$

$$\dot{U}'_{s0} = \dot{E}'_s, \qquad \dot{I}_p = \dot{I}_0.$$

Open circuit test



Short circuit test



Short circuit test

As the name suggests, in this test primary applied voltage, the current and power input are measured keeping the secondary terminals short circuited and

$$\dot{U}'_s = 0 \text{ and } Z'_n = 0.$$

The supply voltage required to circulate rated current through the transformer is usually very small and is of the order of a few percent of the rated voltage $U_{p.rated}$. This voltage is called rated short circuit voltage:

$$u_{sc} = (U_{sc} / U_{p.rated})100\,\% = (5 \ldots 10)\,\%.$$

Short circuit test

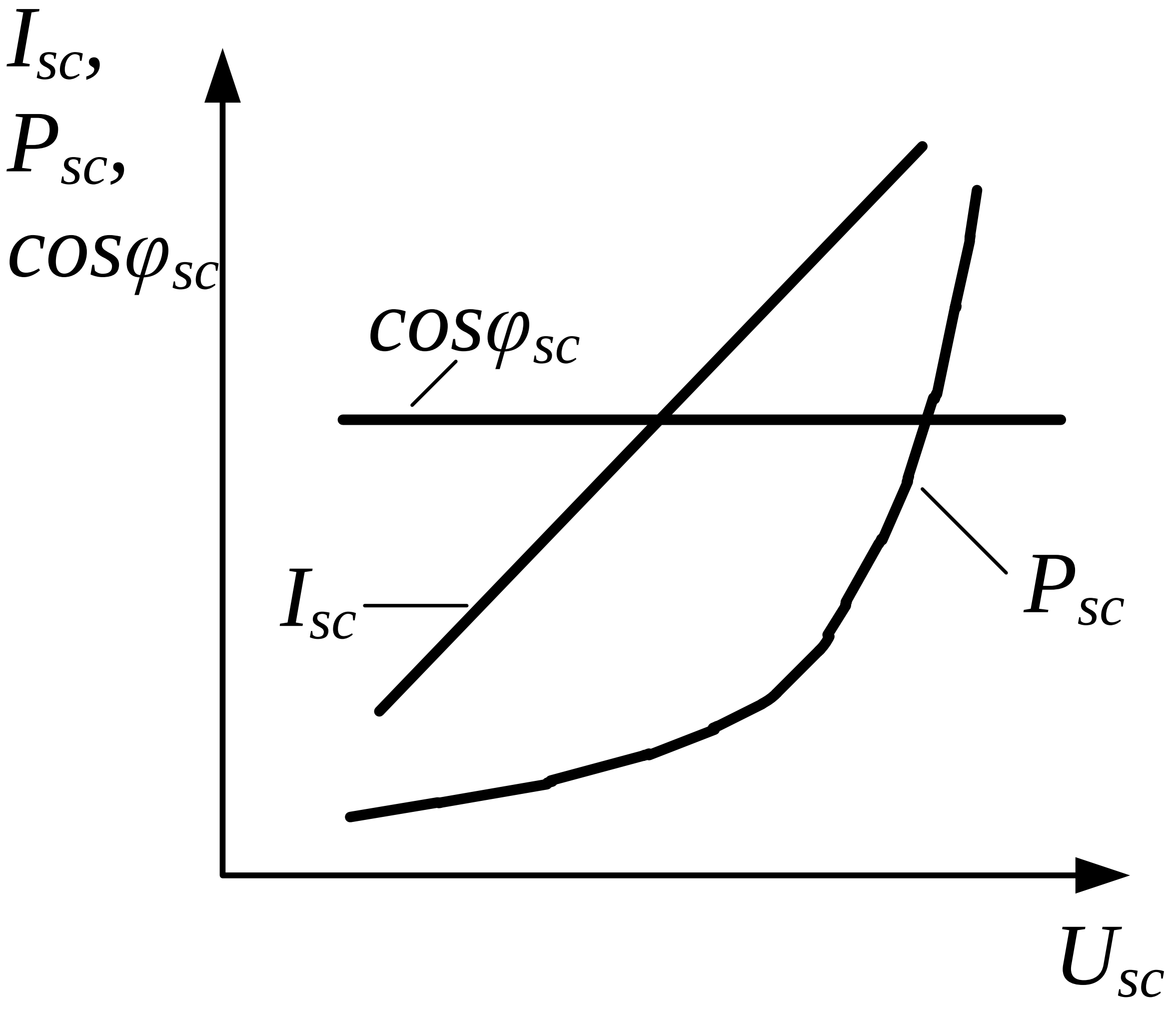
The current and voltage equations reduce to:

$$\dot{U}_{sc} = \dot{I}_{p.sc} \cdot \left(r_p + r'_s\right) + j\dot{I}_{p.sc} \cdot \left(x_{\sigma p} + x'_{\sigma s}\right) =$$

$$= \dot{I}_{p.sc} \cdot r_{sc} + j\dot{I}_{p.sc} \cdot x_{sc} = \dot{I}_{p.sc} \cdot z_{sc},$$

$$\dot{I}_{p.sc} = -\dot{I}'_{s.sc}.$$

Short circuit test



TESTING OF THREE PHASE TRANSFORMER UNDER SYMMETRICAL LOAD

Purpose of laboratory session

- The purpose of the given work is to carry out tests under open circuit and short circuit modes of the transformer and obtain parameters of equivalent circuits under different modes.

Operating program

- To examine the working principle of the transformer and to classify the types of transformers.
- To define the laboratory unit.
- To make an experiment of open circuit mode of the transformer and to build open circuit mode characteristics.
- To calculate parameters of the transformer equivalent circuit under open circuit mode.
- To provide test of short circuit mode of the transformer and to build short circuit mode characteristics.
- To calculate parameters of the transformer equivalent circuit under short circuit mode.
- To analyze the transformer characteristics under open circuit and short circuit modes and make conclusions.

Self-instruction

- Power transformer – *(give the definition)*____
- The transformer consists of following main components:
- 1.____
- 2.____
- 3.____

Self-instruction

- The working principle of the transformer is based on ____
- The equivalent circuit of the transformer is the combination three circuits:
- 1.____
- 2.____
- 3.____

Self-instruction

- The three windings on either side of a three-phase transformer can be connected either in:
- 1.____
- 2.____
- 3.____
- The three phase transformer windings can be connected in _____________________ vector groups and the most common used are_________________________________.

Self-instruction

- The voltage equations of primary and secondary windings:
- ______=____,
- ______=____,
- where ______ - ______________________________,
- ______ - ____,
- ______ - ____,
- ______ - ____,
- ______ - ____,
- ______ - ____,
- ______ - ____,
- ______ - ______________________________

Self-instruction

- The referring of the secondary winding values to the primary side:
- $\dot{E}'_s =$ ____,
- $\dot{I}'_s =$ ____,
- $r'_s =$ ____,
- $x'_{\sigma s} =$ ____,
- The purpose of referring of the secondary winding to the primary side is ________________________________
____
____
____

Self-instruction

- Draw the equivalent circuit of the transformer referred to the primary and make all necessary notes.

Self-instruction

- The ways for equivalent circuit parameters determination could be divided:
- 1.____
- 2.____
- The equivalent circuit of the transformer allows studying of ____

Self-instruction

- The open circuit test of the transformer is performed when ____
- The turns ratio of the transformer___________________
- To open circuit losses could be included following ___
  ____

Self-instruction

- Open circuit characteristics are following ____________ __________________________
- The short circuit mode of the transformer is _________ ____
- The difference between short circuit test and real short circuit mode____ ____________

Self-instruction

- The rated short circuit voltage is ___________________
  ____
- To short circuit losses could be included following ___
  ____
- Short circuit characteristics are following ___________
  ____

Self-instruction

- Draw the energy flow diagram of the transformer and make all necessary notes.

Self-instruction

- The efficiency of the transformer is ____________________

____

____

____

____