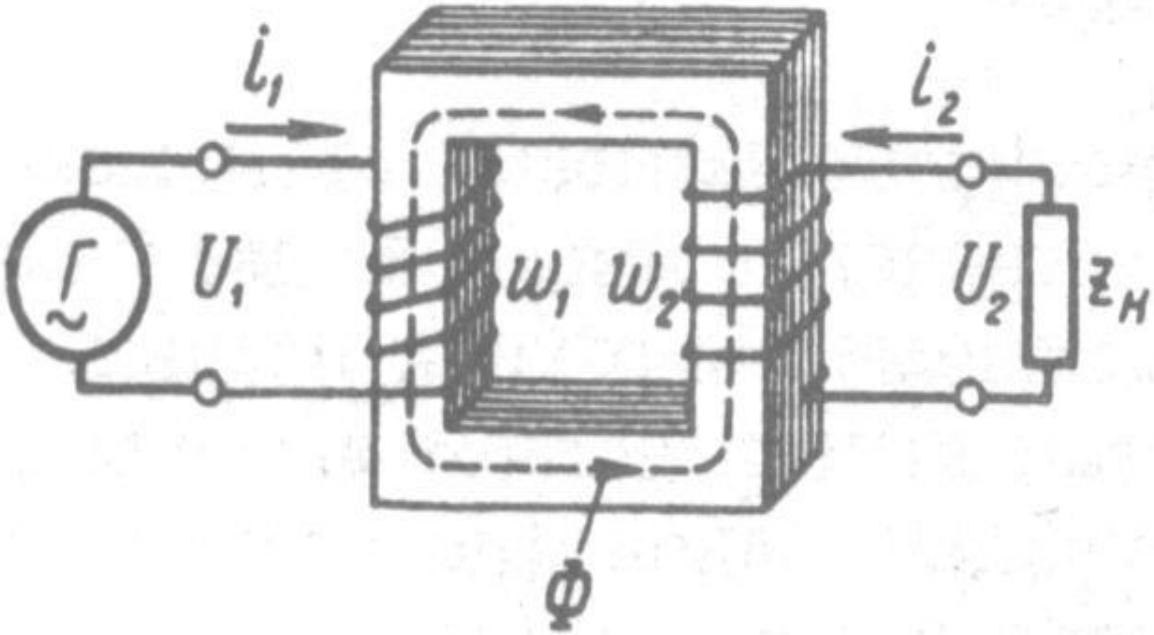
Трансформаторы

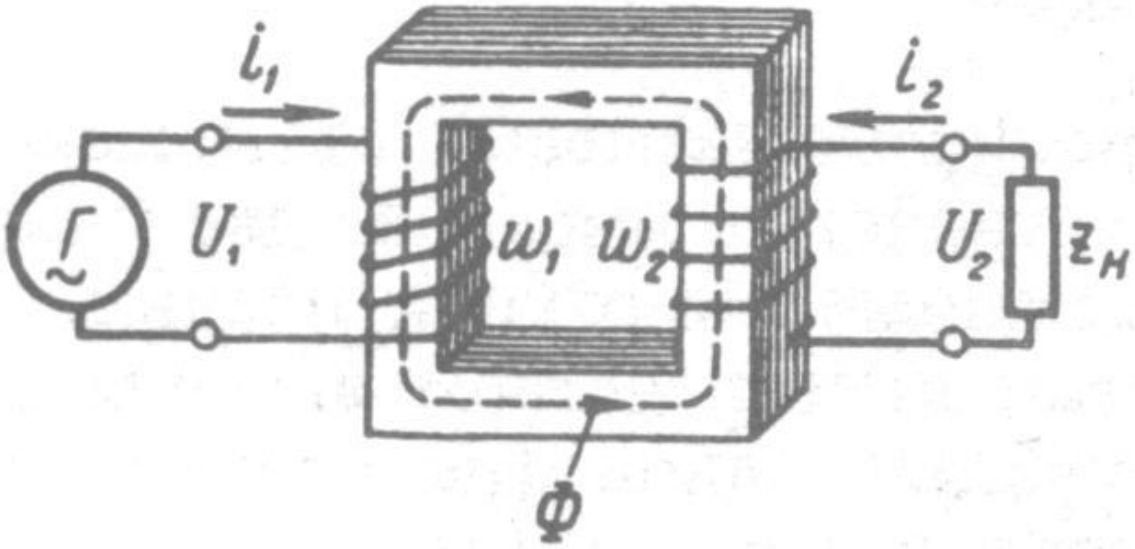
Трансформатор – статическое электромагнитное устройство, имеющее две (или более) индуктивно связанные обмотки, и предназначенное для преобразования посредством явления электромагнитной индукции одной (первичной) системы переменного тока в другую (вторичную) систему переменного тока.



$$e_1 = -w_1 \frac{d\Phi}{dt}$$

$$e_2 = -w_2 \frac{d\Phi}{dt}$$

Идеализированный трансформатор



Режим холостого хода

$$e_1 = -w_1 \frac{d\Phi}{dt}$$

$$e_2 = -w_2 \frac{d\Phi}{dt}$$

$U_1 = i_1 r_1 + w_1 \frac{d\Phi}{dt}$

$\Phi = \Phi_M Sin\omega t$

$\omega = 2\pi f$

$U_1 = i_1 r_1 - e_1$

$U_1 + e_1 = 0$

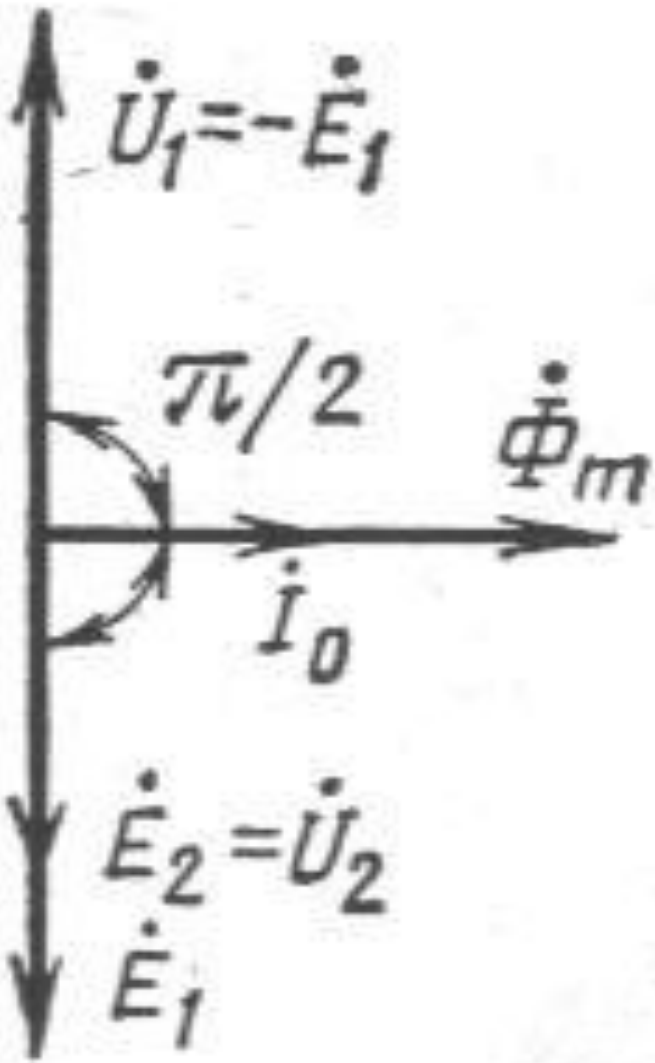
$$e_1 = -\omega \cdot w_1 \Phi_M \cdot Cos\omega t = 2\pi f w_1 \Phi_M \, Sin\left(\omega t - \frac{\pi}{2}\right)$$

$$e_2 = -\omega \cdot w_2 \Phi_M \cdot Cos\omega t = 2\pi f w_2 \Phi_M \, Sin\left(\omega t - \frac{\pi}{2}\right)$$

$$\left[\begin{array}{l} E_1 = \dfrac{2\pi}{\sqrt{2}} f w_1 \Phi_M = 4{,}44 \mathrm{f w}_1 \Phi_M \\ E_2 = \dfrac{2\pi}{\sqrt{2}} f w_2 \Phi_M = 4{,}44 \mathrm{f w}_2 \Phi_M \end{array}\right]$$

$$\frac{E_1}{E_2} = \frac{\mathrm{w}_1}{\mathrm{w}_2} \qquad \frac{U_1}{U_{20}} \approx \frac{E_1}{E_2} = \frac{\mathrm{w}_1}{\mathrm{w}_2} = k$$

$$\dot{U} + \dot{E} = 0$$



Режим нагрузки

$$U_1 = w_1 \frac{d\Phi_1}{\mathrm{dt}} + w_1 \frac{d\Phi_2}{\mathrm{dt}} = w_1 \frac{d}{\mathrm{dt}}(\Phi_1 + \Phi_2)$$

$$e_1 = -w_1 \frac{d}{\mathrm{dt}}(\Phi_1 + \Phi_2)$$

$$U_1 + e_1 = 0$$

$$\Phi_1 + \Phi_2 = \Phi_0$$

$$\dot{\Phi}_{M1} + \dot{\Phi}_{M2} = \dot{\Phi}_{M0}$$

Магнитодвижущая сила (МДС) – намагничивающая сила – характеристика способности источников магнитного поля (эл. токов) создавать магнитные потоки.

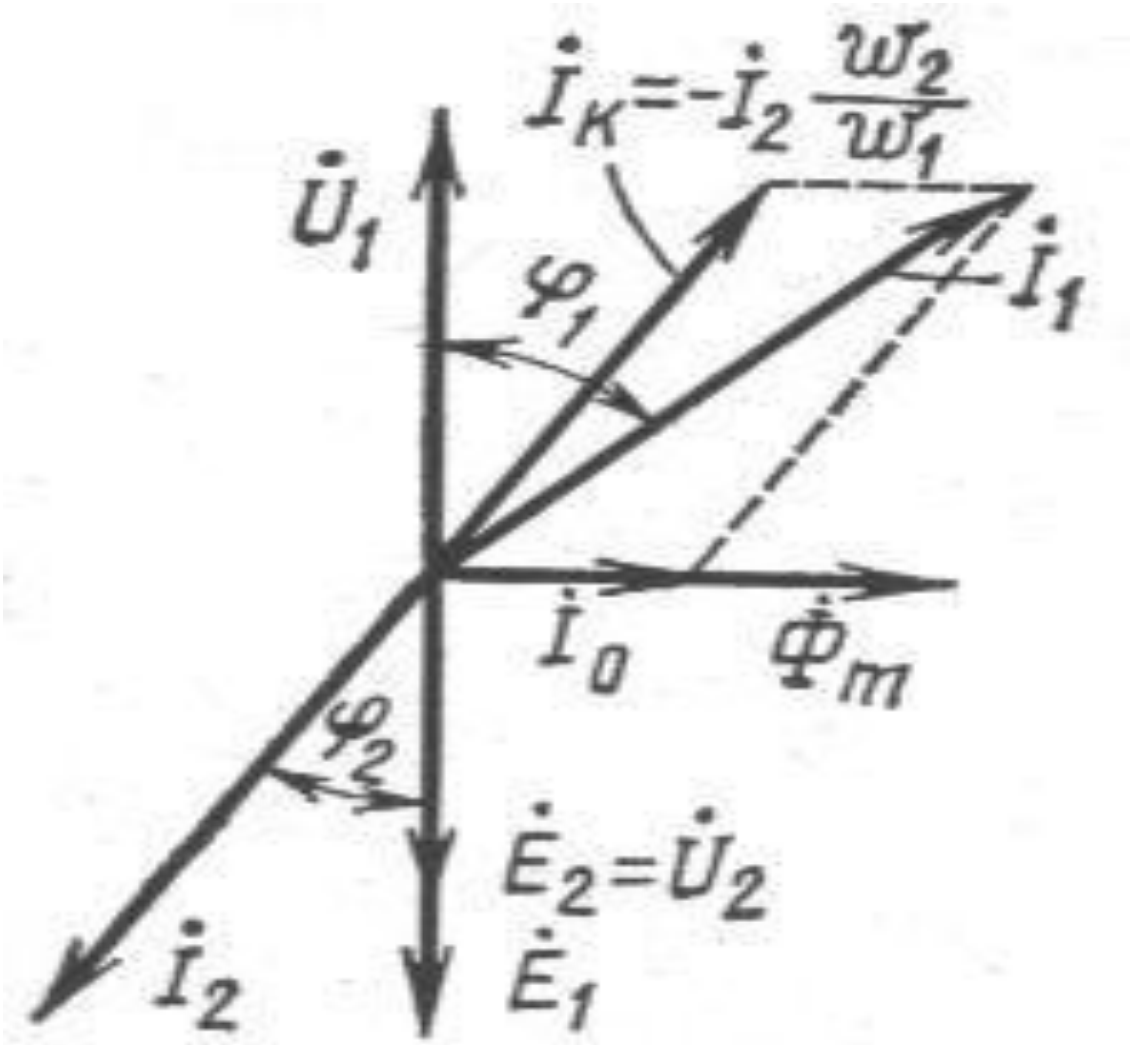
$$\dot{F}_1 + \dot{F}_2 = \dot{F}_0$$

$$\sqrt{2}\,\dot{I}_1 w_1 + \sqrt{2}\,\dot{I}_2 w_2 = \sqrt{2}\,\dot{I}_0 w_1 \,|\, \sqrt{2} w_1$$

$$\dot{I}_1 = \dot{I}_0 + \left[-\dot{I}_2 \left(\frac{w_2}{w_1} \right) \right] \qquad \dot{I}_K = -\dot{I}_2 \left(\frac{w_2}{w_1} \right)$$

$$\dot{I}_1 = \dot{I}_0 + \dot{I}_K$$

$$I_K E_1 Cos\varphi_2 = I_2 (\frac{w_2}{w_1}) E_2 (\frac{w_1}{w_2}) Cos\varphi_2 = I_2 E_2 Cos\varphi_2$$



$$\Phi = \Phi_M \mathrm{Sin}\omega t$$

$$\Phi_M = \frac{E_1}{4{,}44 f w_1}$$

Намагничивающий ток и ток холостого хода

Магнитная характеристика трансформатора, как и других машин переменного тока, дает связь между амплитудными или мгновенными значениями потока и МДС.

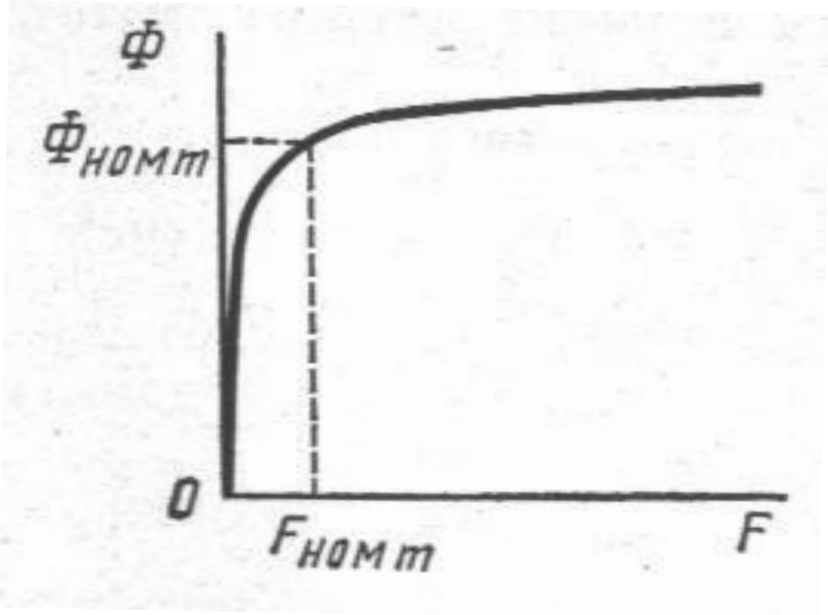
$$F=F_{СТ}+F_{Я}+F_{З}$$

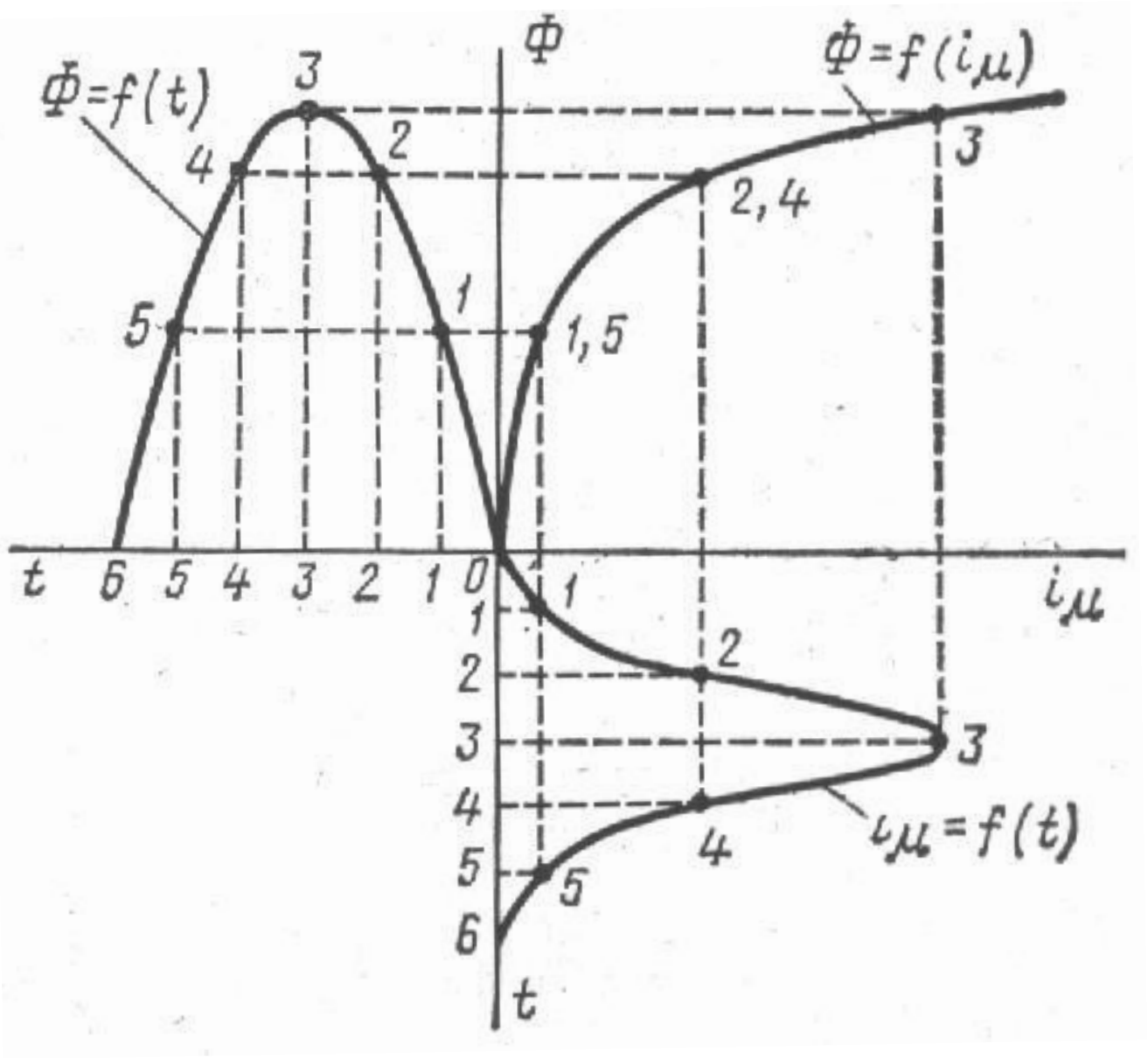
$$\Phi=f(F)$$

$$F_{СТ}=H_{СТ}l_{СТ}$$

$$F_{Я}=H_{Я}l_{Я}$$

$$F_{З}=H_{З}l_{З}$$





$$i_\mu = \frac{F}{w_1}$$

$$I_\mu = \sqrt{I_{\mu 1}^2 + I_{\mu 3}^2 + I_{\mu 5}^2 + I_{\mu 7}^2 + ..}$$

$$I_\mu = I_{\mu 1}\sqrt{1 + \alpha^2 + \beta^2 + \gamma^2 + ..} = k_Д I_{\mu 1}$$

$I_\mu \approx I_{\mu 1}$

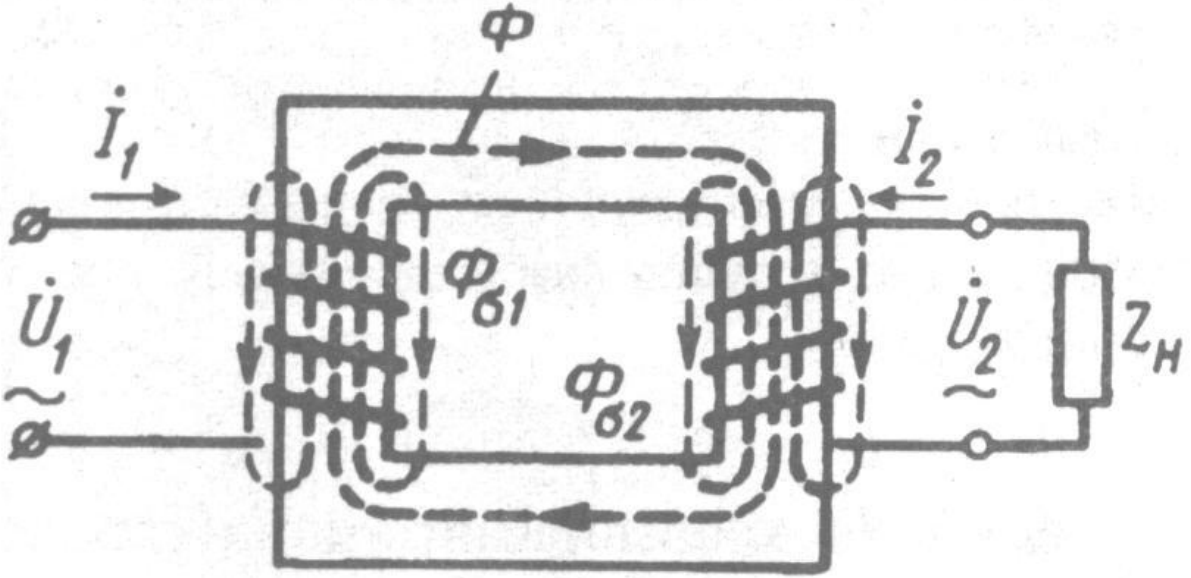
$$I_\mu = I_{OP}$$

$$I_{oa} = \frac{\Delta P_M}{U_1}$$

$$\dot{I}_o = I_\mu + \dot{I}_{ao}$$

$$\mathrm{I_o} = \sqrt{I_\mu^2 + I_{ao}^2}$$

Комплексные уравнения и векторные диаграммы трансформатора



$$E_{\sigma 1} = 4.44 f w_1 \Phi_{\sigma 1м}; E_{\sigma 2} = 4.44 f w_2 \Phi_{\sigma 2м}$$

$$\left.\begin{aligned}
&\dot{U}_1 + \dot{E}_1 = \dot{I}_1 r_1 + j\dot{I}_1 x_1 \\
&\dot{U}_2' = \dot{E}_2' - \dot{I}_2 r_2 - j\dot{I}_2 x_2 \\
&\dot{I}_1 = \dot{I}_0 + (-\dot{I}_2)
\end{aligned}\right\}$$

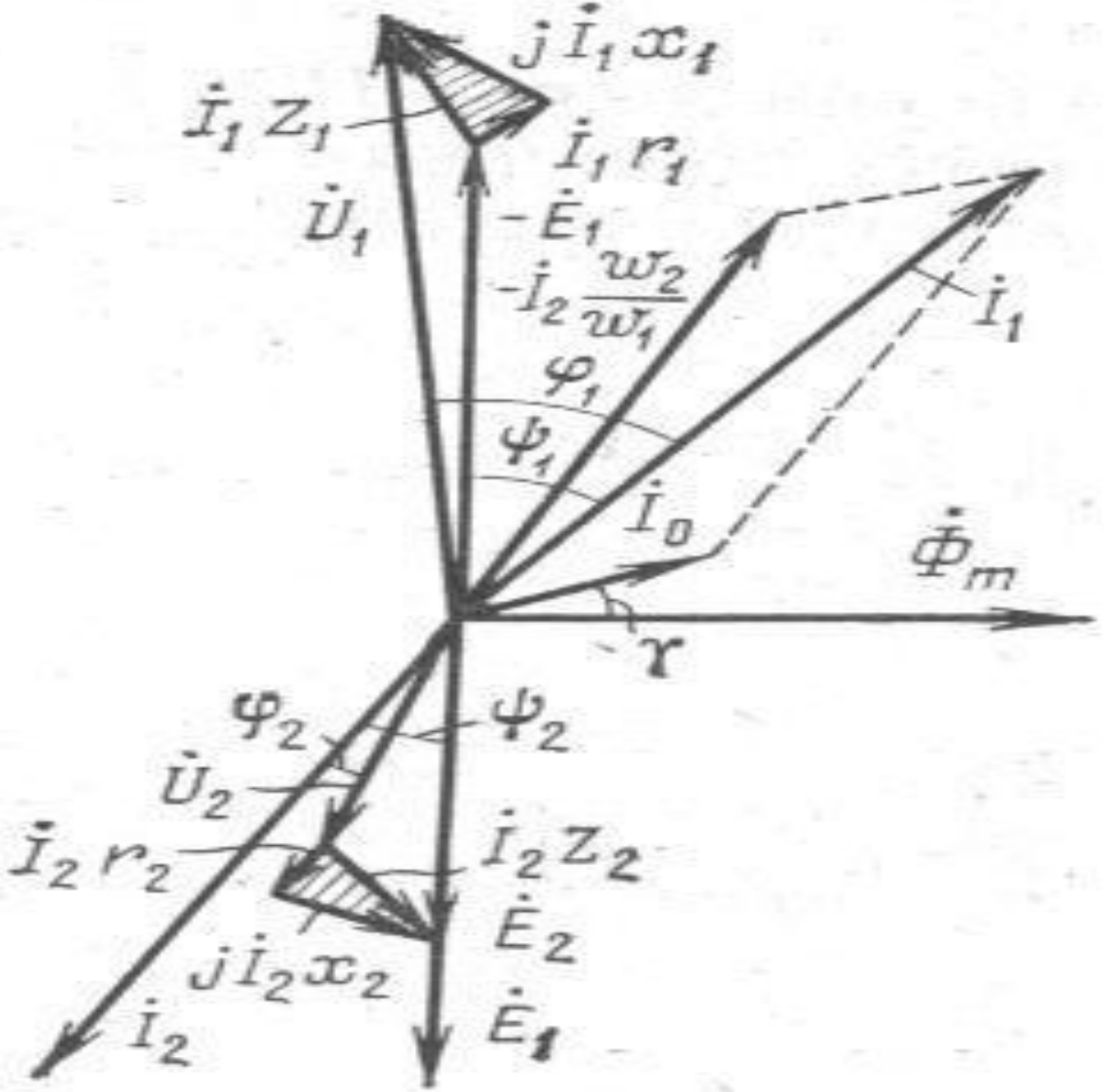
$$E_{\sigma 1} = I_1 x_1 ; E_{\sigma 2} = I_2 x_2$$

$$\dot{E}_{\sigma 1} = -j\dot{I}_1 x_1 ; \dot{E}_{\sigma 2} = -j\dot{I}_2 x_2$$

$$\left.\begin{aligned}
&\dot{U}_1 + \dot{E}_1 = \dot{I}_1 R_1 + j\dot{I}_1 x_1 = \dot{I}_1 Z_{-1} && (1)\\
&\dot{E}_2 = \dot{I}_2 R_2 + j\dot{I}_2 x_2 + \dot{I}_2 Z_{-H} = \dot{I}_2 Z_2 + \dot{I}_2 Z_H && (2)\\
&\dot{I}_1 + \left(-\dot{I}_2 \frac{w_2}{w_1}\right) = \dot{I}_0 && (3)
\end{aligned}\right\}$$

$$\dot{U}_2 = \dot{I}_2 Z_{-H}$$

$$\dot{U}_2 = \dot{E}_2 - \dot{I}_2 R_2 - j\dot{I}_2 x_2$$

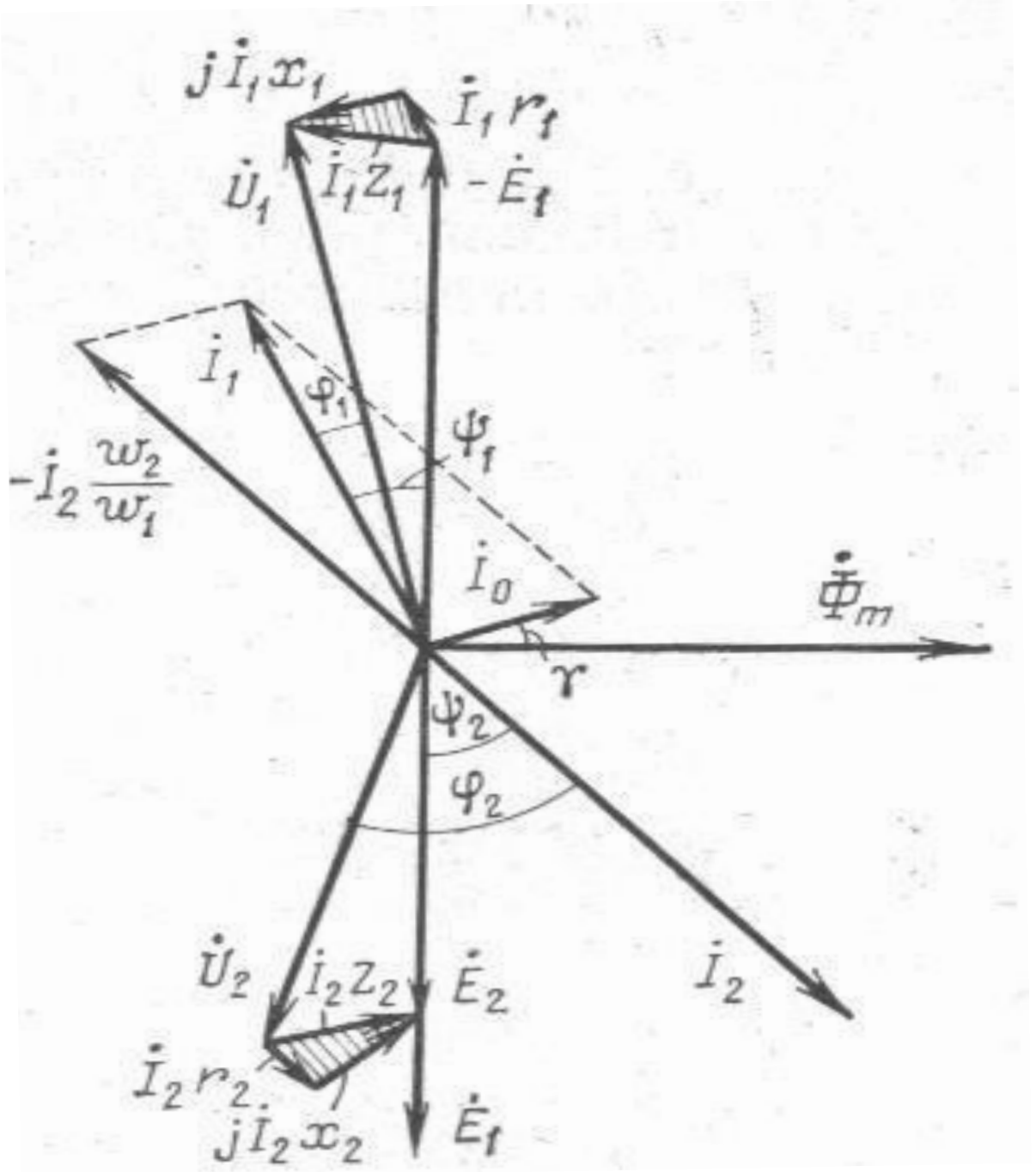

$j\dot{I}_1 x_1$
$\dot{I}_1 Z_1$
$\dot{I}_1 r_1$
$\dot{U}_1$
$-\dot{E}_1$
$-\dot{I}_2 \frac{w_2}{w_1}$
$\dot{I}_1$
φ_1
ψ_1
$\dot{I}_0$
$\dot{\Phi}_m$
γ
φ_2
ψ_2
$\dot{U}_2$
$\dot{I}_2 r_2$
$\dot{I}_2 Z_2$
$\dot{E}_2$
$j\dot{I}_2 x_2$
$\dot{I}_2$
$\dot{E}_1$

$$\dot{I}_{2p}\, w_2 = \dot{I}_2\, w_2 Sin\varphi_2, \text{ где } \dot{I}_2 = \mathrm{I}_2 Sin\psi_2$$

$$\dot{\Phi}_м = \frac{E_1}{4{,}44 f w_1}$$

γ=5..10^0

$$\psi = arctg\frac{x_2 + x_H}{r_2 + r_H}$$


$j\dot{I}_1 x_1$
$\dot{I}_1 r_1$
$\dot{U}_1$
$\dot{I}_1 Z_1$
$-\dot{E}_1$
$\dot{I}_1$
φ_1
ψ_1
$-\dot{I}_2 \frac{w_2}{w_1}$
$\dot{I}_0$
$\dot{\Phi}_m$
γ
ψ_2
φ_2
$\dot{U}_2$
$\dot{I}_2 Z_2$
$\dot{E}_2$
$\dot{I}_2$
$\dot{I}_2 r_2$
$j\dot{I}_2 x_2$
$\dot{E}_1$

Составление схемы замещения

$E_1 =$

$кE_2$

$$\dot{E}_1 = \dot{I}_0 Z_m = \dot{I}_0 (R_m + jx_m)$$

$$E_1 \approx U_1$$

$$\dot{I}_0 = \frac{\dot{E}_1}{R_m + x_m} = \frac{\dot{E}_1}{Z_{-m}}$$

$$I_0 E_1 Cos\varphi_0 = I_0 R_m^2$$

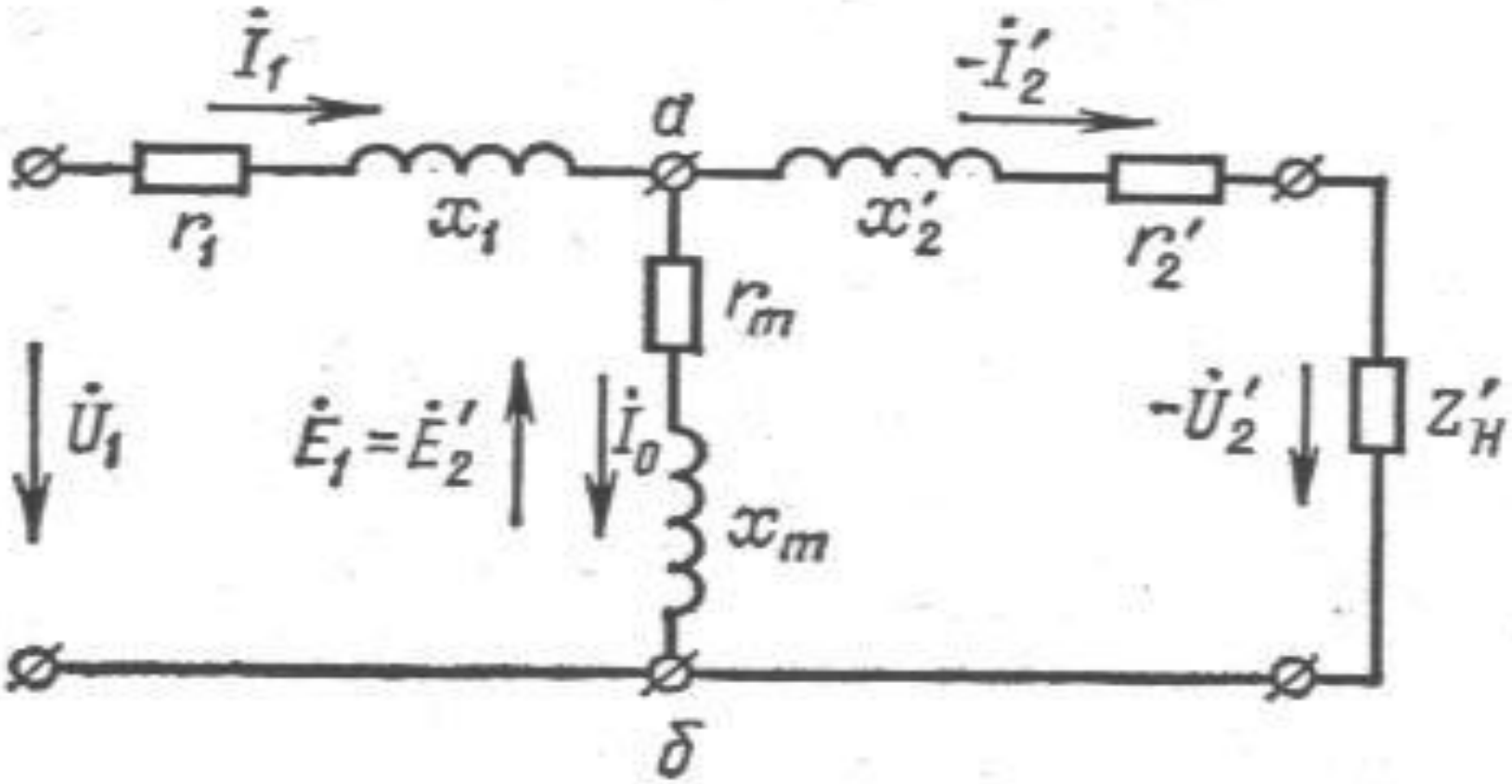
$$\dot{I}_1 = \frac{\dot{U}_1}{Z_1 + \left[Z_m\left(k^2 Z_H + k^2 Z_2\right)\right] / \left[Z_{\mathrm{m}} + \left(k^2 Z_H + k^2 Z_2\right)\right]} = \frac{\dot{U}_1}{Z_{экв}}$$

$$Z_{экв} = Z_1 + \frac{Z_m (Z_H^{'} + Z_2^{'})}{Z_m + Z_H^{'} + Z_2^{'}}$$

$$Z_1 = R_1 + jx_1 \ , Z_m = R_m + jx_m \ , Z_H^{'} = k^2 Z_{\mathrm{H}}$$

$$Z_2^{'} = k^2 Z_2 = k^2 (R2 \ + jx_2)$$

$$R_2^{'} = R_2 k^2 , x_2^{'} = x_2 k^2$$


$\dot{I}_1$
$-\dot{I}'_2$
a
r_1
x_1
x'_2
r'_2
r_m
$\dot{U}_1$
$\dot{E}_1=\dot{E}'_2$
$\dot{I}_0$
$-\dot{U}'_2$
Z'_H
x_m
б

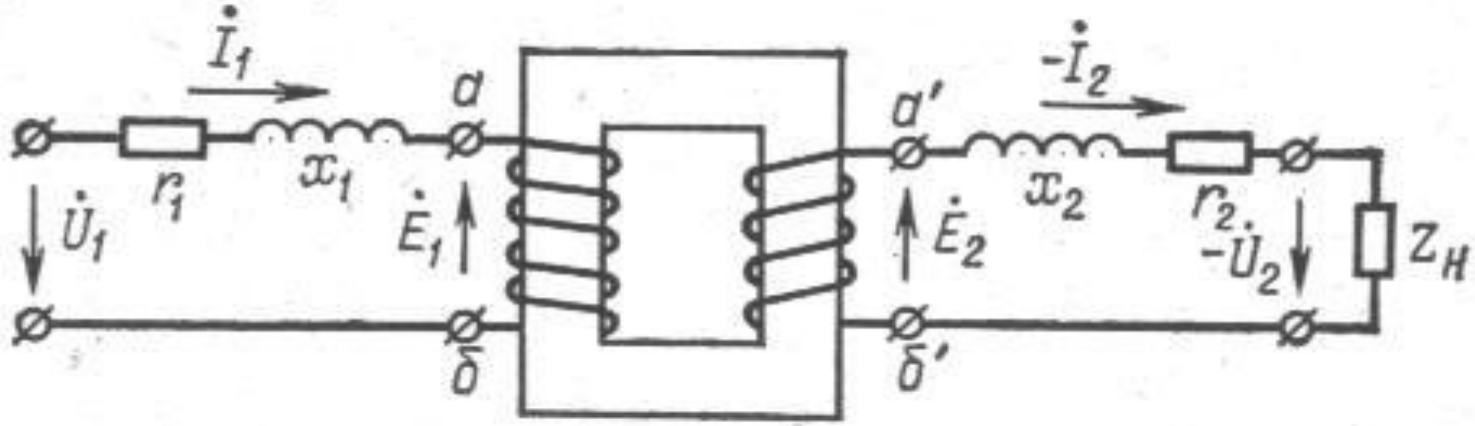
$$E_2^{'} = kE_2 = E_1, I_2^{'} = \frac{I_2}{k}$$

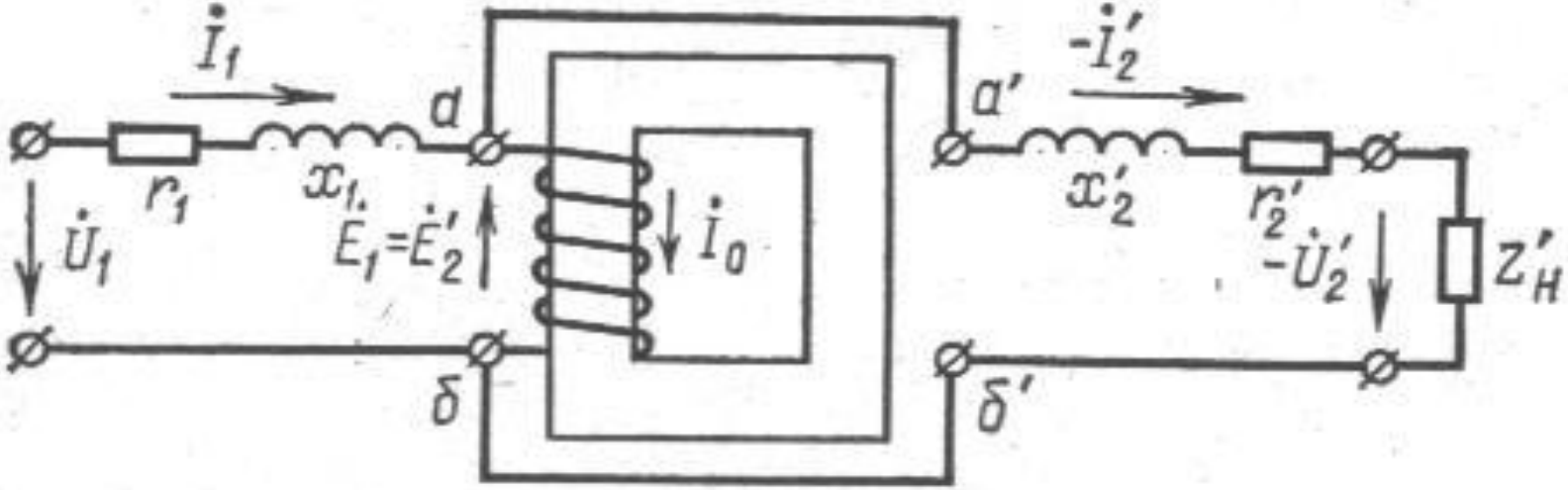
$$I_2^{'} E_2^{'} = \frac{I_2}{k} kE_2 = I_2 E_2$$

$$I_2^{'2} R_2^{'} = \left(\frac{I_2}{k}\right)^2 R_2 k^2 = I_2^2 R_2$$

$$\frac{I_2^{'} R_2^{'}}{E_2^{'}} = \frac{\left(\frac{I_2}{k}\right) k^2 R_2}{kE_2} = \frac{I_2 R_2}{E_2}$$

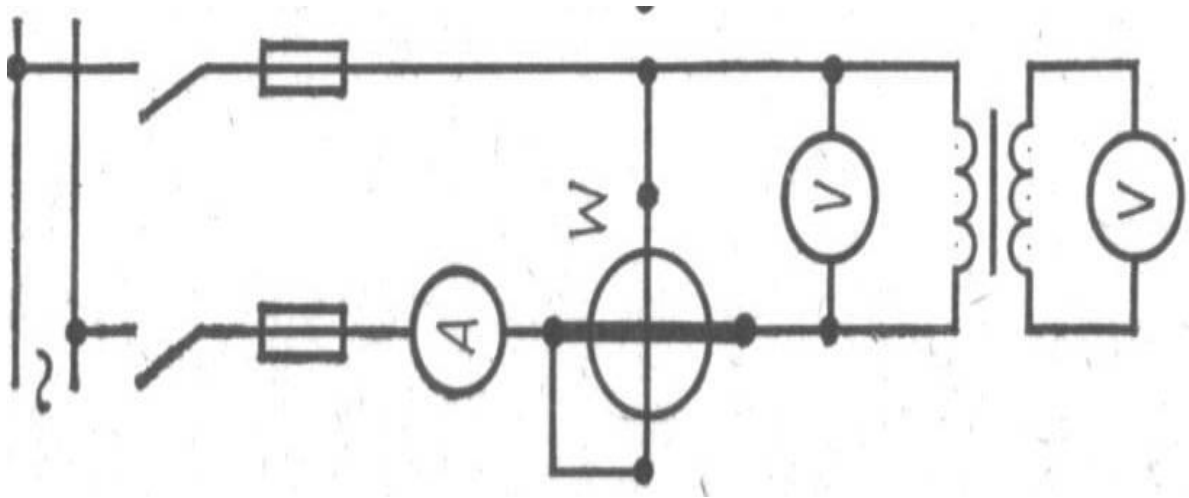
$$\frac{I_2^{'} x_2^{'}}{E_2^{'}} = \frac{\left(\frac{I_2}{k}\right) k^2 x_2}{kE_2} = \frac{I_2 x_2}{E_2}$$


$\dot{I}_1$
a
a'
$-\dot{I}_2$
r_1
x_1
$\dot{U}_1$
$\dot{E}_1$
$\dot{E}_2$
x_2
r_2
$-\dot{U}_2$
Z_H
б
б'


$\dot{I}_1$
a
a'
$-\dot{I}'_2$
r_1
x_1
$\dot{U}_1$
$\dot{E}_1=\dot{E}'_2$
$\dot{I}_0$
x'_2
r'_2
$-\dot{U}'_2$
Z'_H
б
б'

Определение параметров схемы замещения по опытам холостого хода и короткого замыкания

Опыт холостого хода



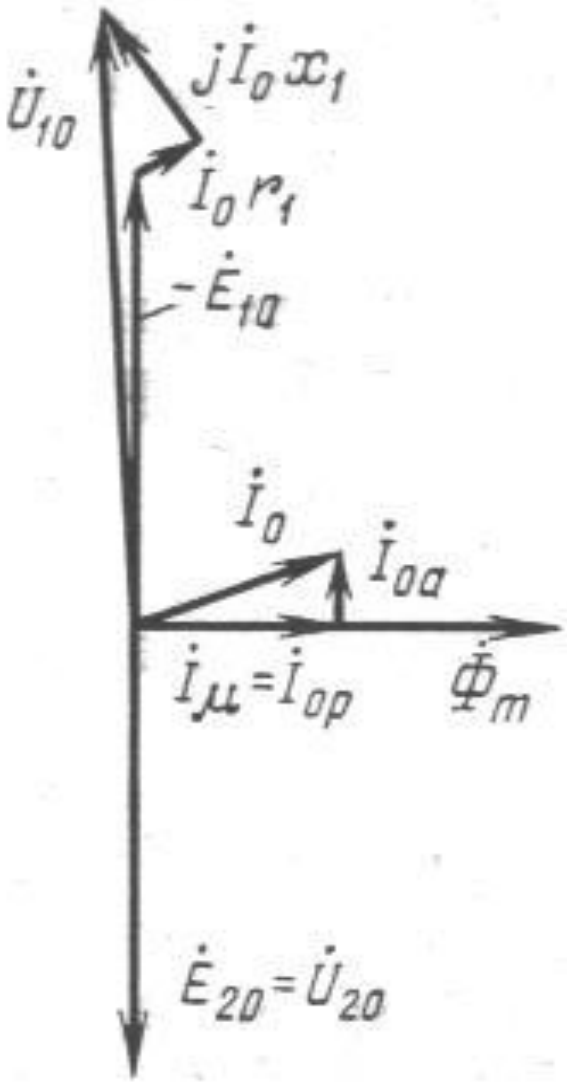
$$\left.\begin{aligned} Z_1 + Z_m &= \frac{U_0}{I_0};\; R_1 + R_m = \frac{P_0}{I_0^2} \\ x_1 + x_m &= \sqrt{(Z_1 + Z_m)^2 - (R_1 + R_m)^2} \end{aligned}\right\}$$

$$P_0 = I_0^2(R_1 + R_m) \approx I_0^2 R_m \Rightarrow R_m = \frac{P_0}{I_0^2}$$

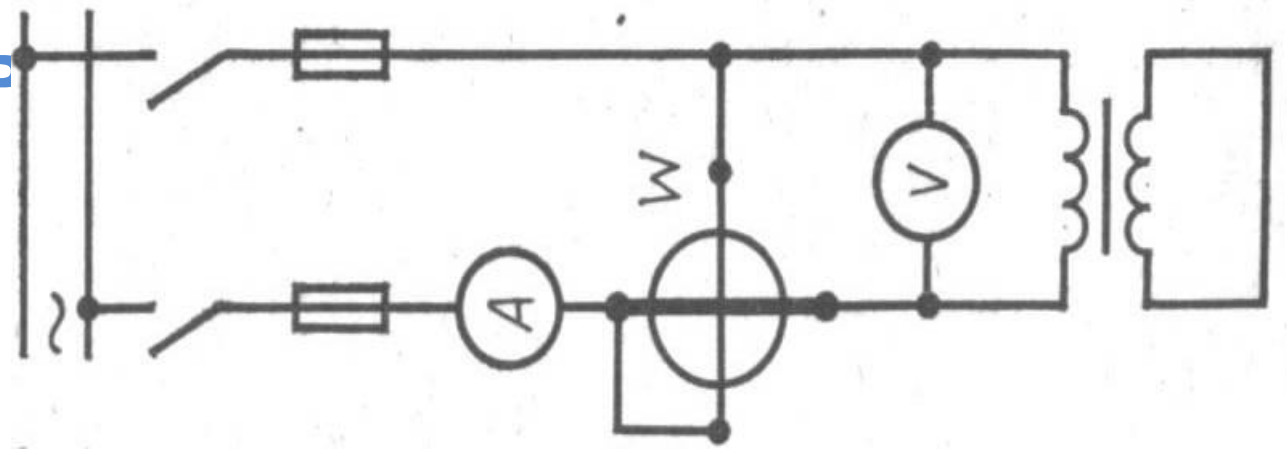
$$Z_{\mathrm{m}} = \frac{U_0}{I_0} \qquad x_m = \sqrt{Z_m^2 - R_m^2}$$

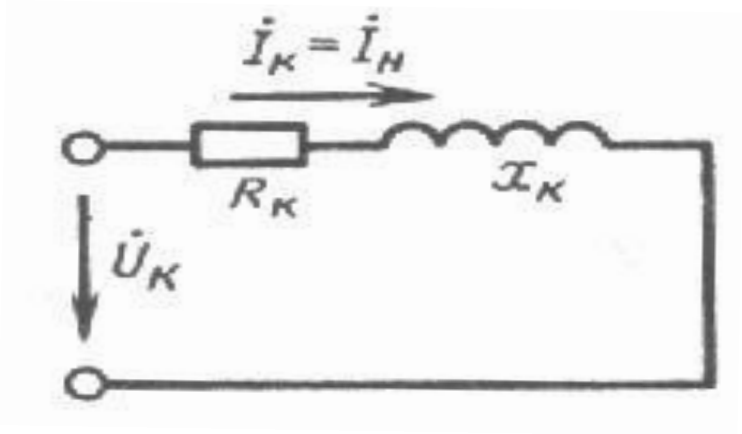
$$k = \frac{U_0}{U_{20}}$$

$$\dot{U}_0 = -\dot{E}_{10} + \dot{I}_0 R_1 + j\,\dot{I}_0 x_1$$



Опыт короткого замы

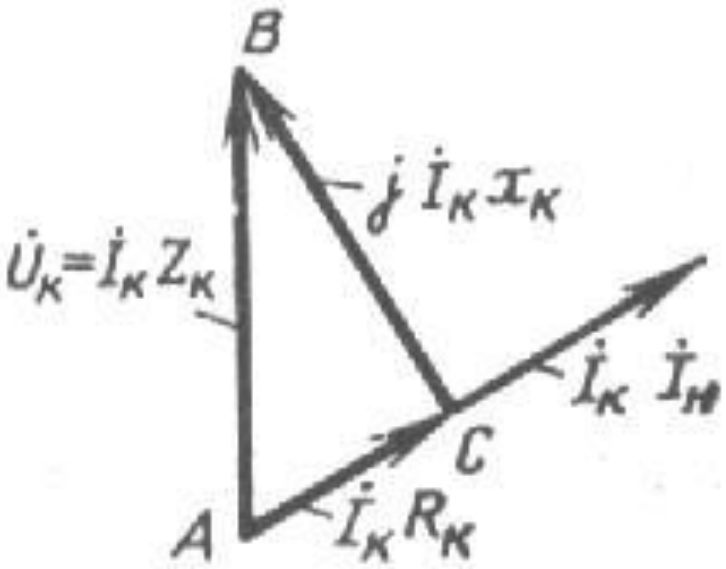




$$Zk = Z_1 + Z_2' = \frac{U_k}{I_{HOM}};$$

$$R_k = R_1 + R_2' = \frac{P_k}{I_{HOM}^2};$$

$$x_k = x_1 + x_2' = \sqrt{Z_k^2 - R_k^2};$$



$$U_k = \left(\frac{I_{HOM} Z_k}{U_{HOM}} \right) \cdot 100\%$$

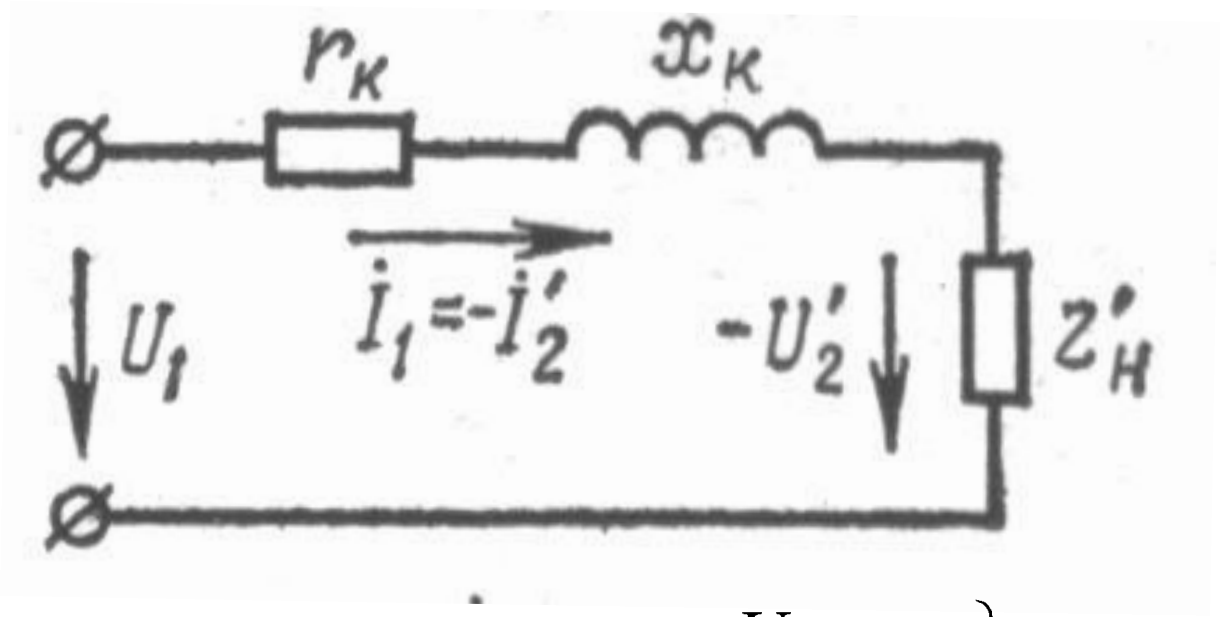
$$U_{ka}\% = \left(\frac{I_{HOM} R_k}{U_{HOM}} \right) \cdot 100\%$$

$$U_{kp}\% = \left(\frac{I_{HOM} x_k}{U_{HOM}} \right) \cdot 100\%$$

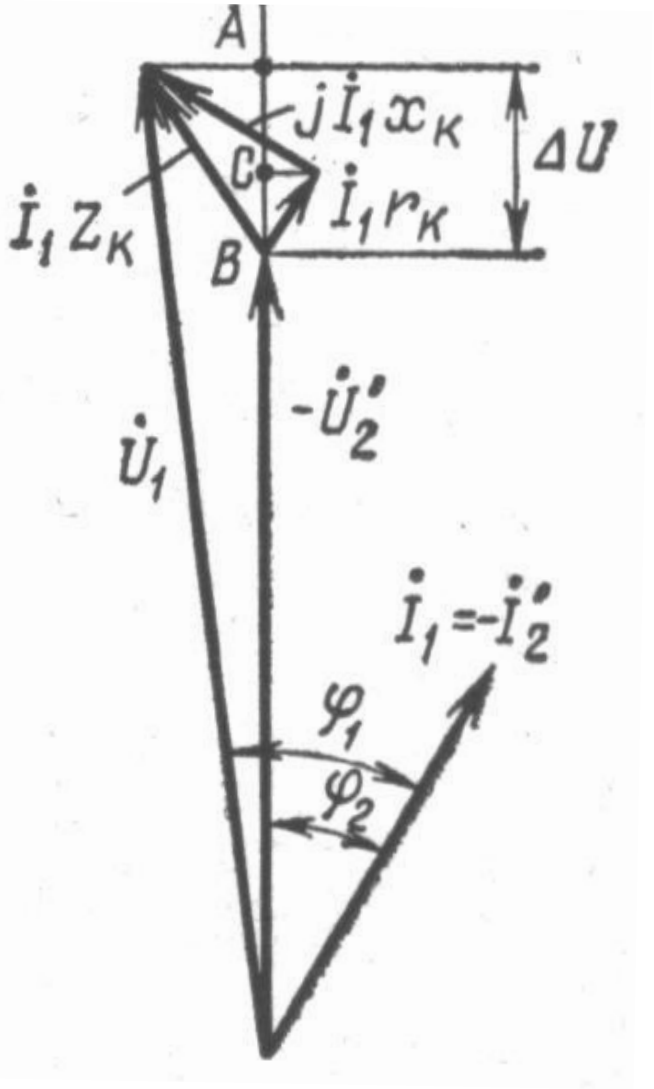
$$U_{ka} = U_k Cos\varphi_k \qquad U_{kp} = U_k Sin\varphi_k$$

$$U_k = \sqrt{U_{ka}^2 + U_{kp}^2}$$

Упрощенная схема замещения трансформатора



$$\left.\begin{aligned} Zk = Z_1 + Z_2^{'} &= \frac{U_k}{I_{НОМ}}; \\ R_k = R_1 + R_2^{'} &= \frac{P_k}{I_{НОМ}^2}; \\ x_k = x_1 + x_2^{'} &= \sqrt{Z_k^2 - R_k^2}; \end{aligned}\right\}$$



$$\dot{I}_1 Z_k = \dot{I}_1 R_k + j \dot{I}_1 x_k$$

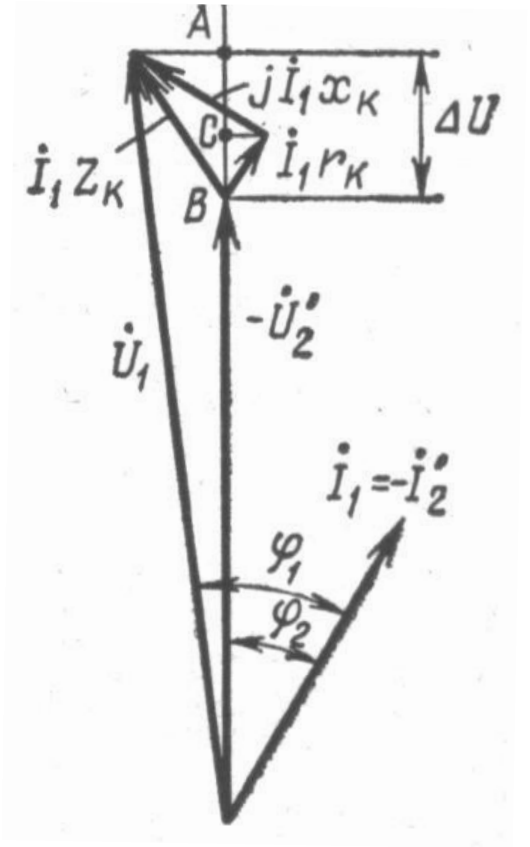
$$I_1 Z_k = \frac{\beta U_k \% U_{HOM}}{100}$$

$$I_1 R_k = \frac{\beta U_{ka} \% U_{HOM}}{100}$$

$$I_1 x_k = \frac{\beta U_{kp} \% U_{HOM}}{100}$$

$$\beta = \frac{I_2}{I_1} \approx \frac{I_1}{I_{1HOM}}$$

$$\Delta U\% = \frac{U_{20} - U_2}{U_{20}} 100\% = \frac{U_{1H} - U_2'}{U_{1H}'} 100\%$$



$$\Delta U = U_1 - U_2^{'} = \overline{OA} - \overline{OB} = \overline{BA}$$

$$\Delta U = \overline{BC} + \overline{CA} = I_1 R_k Cos\varphi_2 + I_1 x_k Sin\varphi_2$$

$$\Delta U\% = \left[\frac{\left(I_1 R_k Cos\varphi_2 + I_1 x_k Sin\varphi_2\right)}{U_{HOM}}\right]100 \Rightarrow$$

$$\Delta U_{HOM}\% = \left[\frac{\left(I_{HOM} R_к Cos\varphi_2 + I_{HOM} x_k Sin\varphi_2\right)}{U_{HOM}}\right]100$$

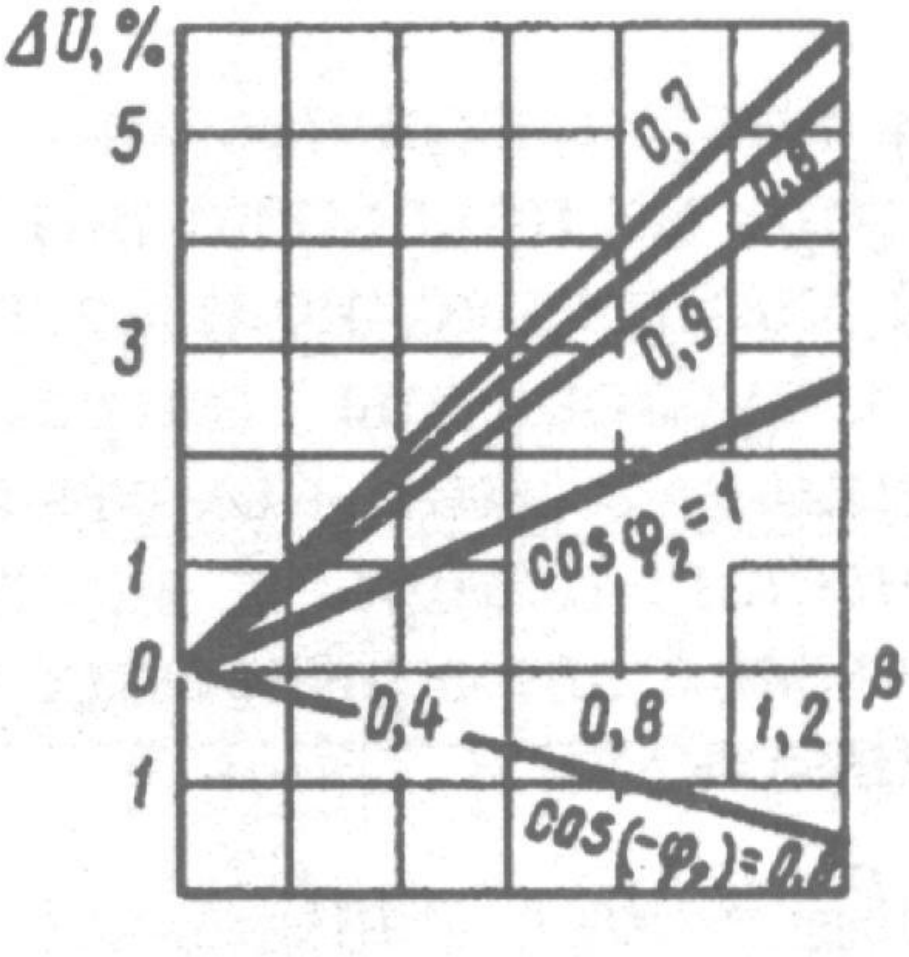
$$\Delta U_{HOM}\% = U_{k.a} Cos\varphi_2 + U_{k.p} Sin\varphi_2$$

$$\Delta U\% = \beta \Delta U_{HOM} = \beta\left(U_{k.a} Cos\varphi_2 + U_{k.p} Sin\varphi_2\right)$$

$$\Delta U\% = \beta\left(U_{k.a} Cos\varphi_2 + U_{k.p} Sin\varphi_2\right) + \frac{\beta^2\left(U_{k.p} Cos\varphi_2 - U_{k.a} Sin\varphi_2\right)^2}{200}$$

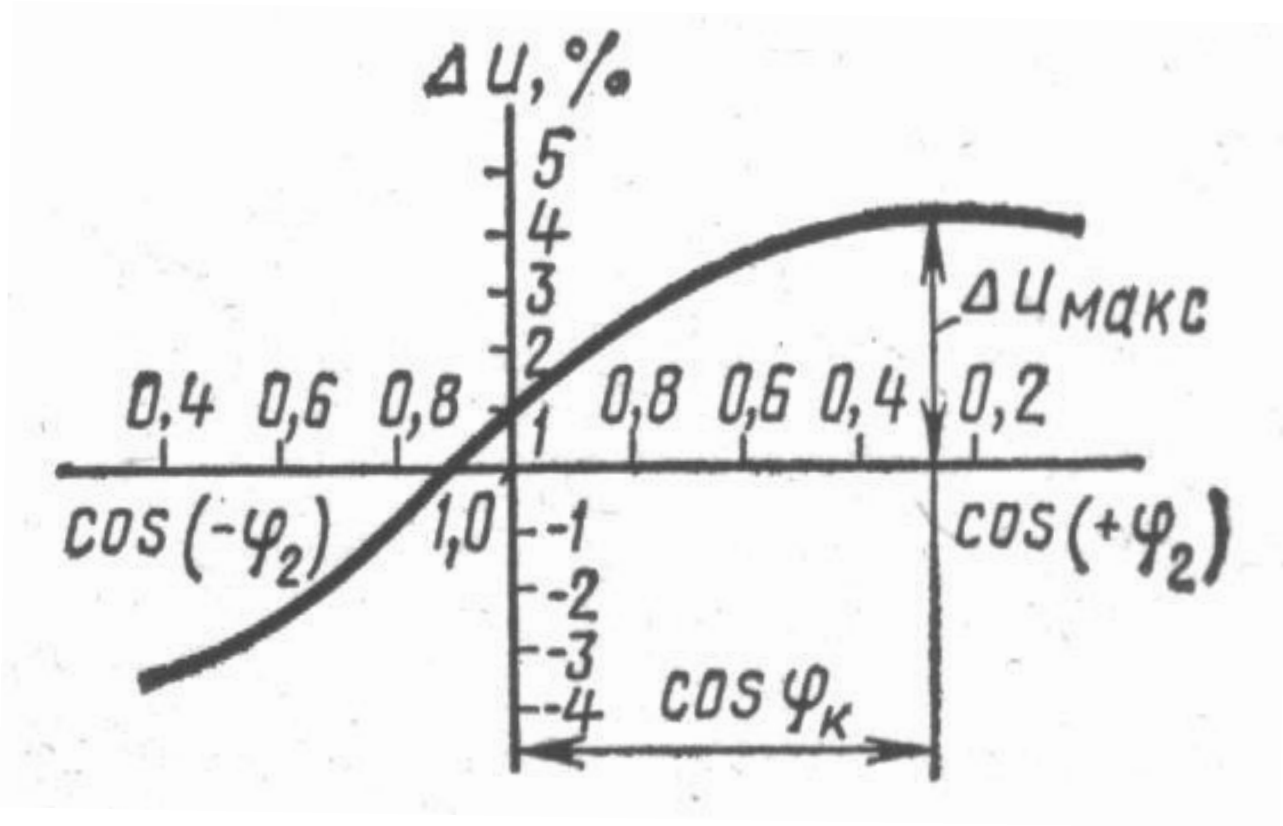
Внешние характеристики

$U_2 = f(I_2)$ или $U_2 = f(\beta)$ при $U_1 = U_{НОМ} = const$ и $f = f_{НОМ} = const$ и $Cos\varphi_2 - const$



$\Delta U = f(\beta)\ при\ Cos\varphi_2 = const$

$$\Delta U = f(Cos\varphi_2) при \beta = const$$

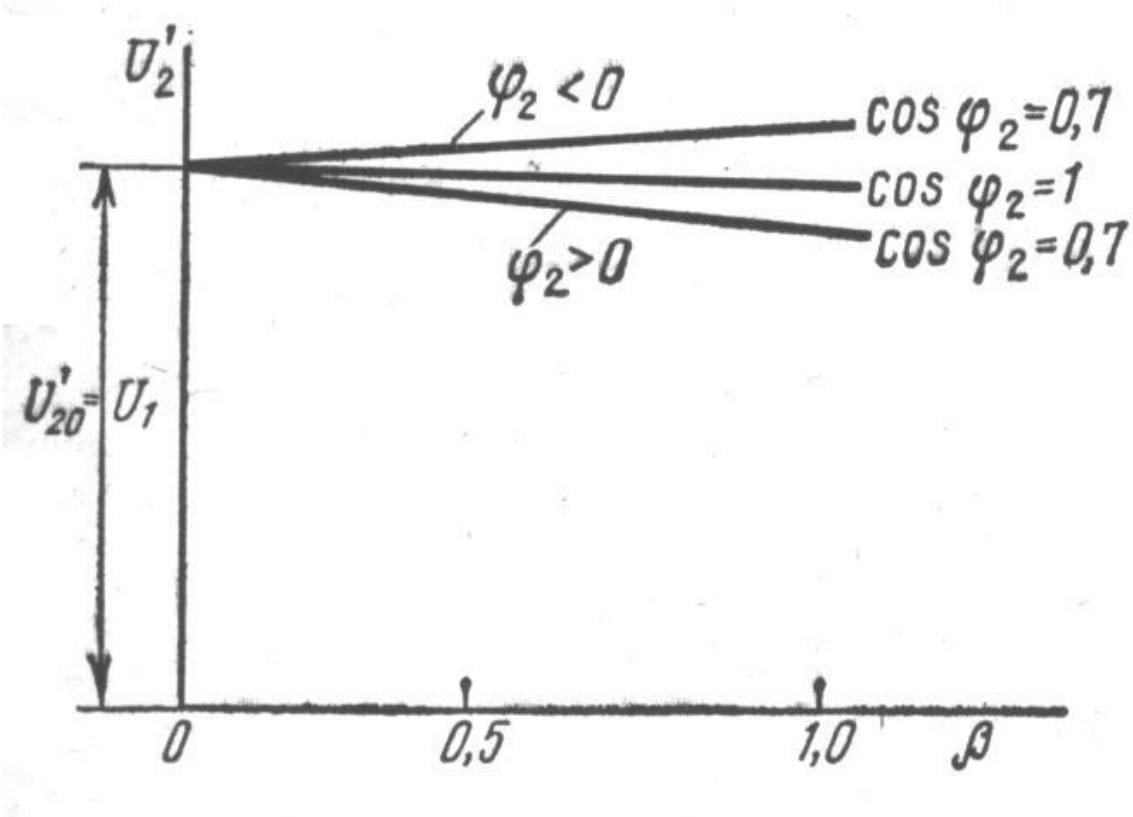


$$U_2 = f(\beta)$$

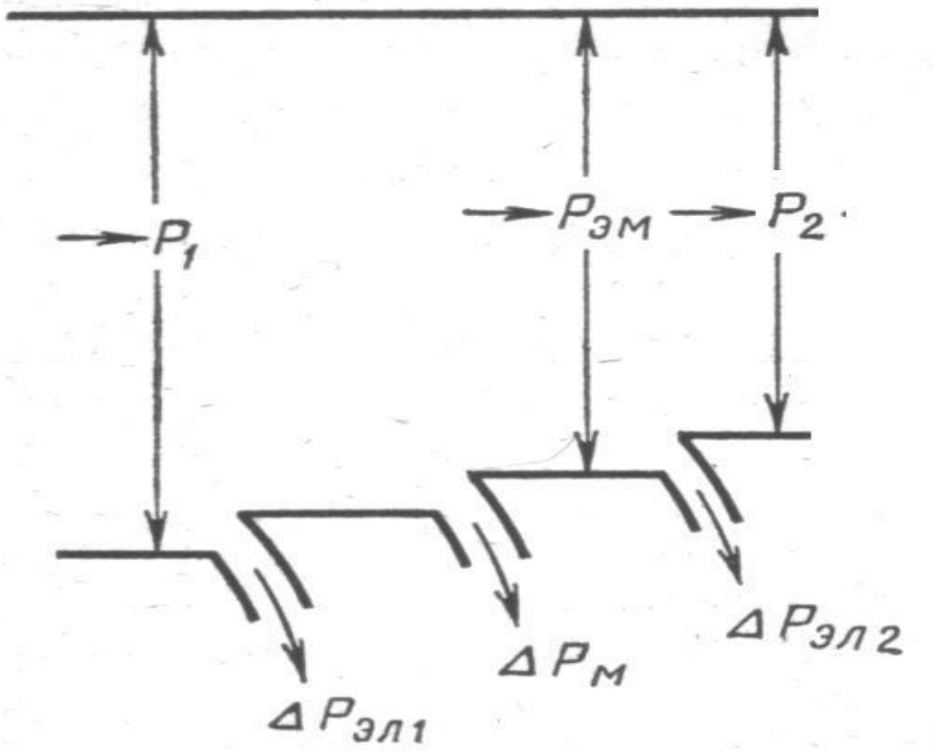
$$U_{ka} = U_k Cos\varphi_k;$$

$$U_{kp} = U_k Sin\varphi_k$$

$$\Delta U = \beta U_k \left(Cos\varphi_k Cos\varphi_2 + Sin\varphi_k Sin\varphi_2\right) = \beta U_k Cos(\varphi_k - \varphi_2)$$



Энергетическая



$$\Delta P_2 = P_1 - \Delta P_{ЭЛ1} - \Delta P_{ЭЛ2} - \Delta P_м$$

$$P_{ЭМ} = P_1 - \Delta P_{ЭЛ1} - \Delta P_м$$

$$\eta = \frac{P_2}{P_1} = \frac{U_2 I_2 Cos\varphi_2}{U_1 I_1 Cos\varphi_1}$$

$$\eta = \frac{P_1 - \Delta P}{P_1} = 1 - \frac{\Delta P}{P_2 + \Delta P}$$

$$\eta = \frac{P_2}{P_2 + \Delta P_{ЭЛ1} + \Delta P_{ЭЛ2} + \Delta P_M} = 1 - \frac{\Delta P_{ЭЛ1} + \Delta P_{ЭЛ2} + \Delta P_M}{P_2 + \Delta P_{ЭЛ1} + \Delta P_{ЭЛ2} + \Delta P_M}$$

$$I_2^{'} = I_1 \Rightarrow \Delta P_{ЭЛ} = \Delta P_{ЭЛ1} + \Delta P_{ЭЛ2} = \mathrm{I}_1^2 R_1 + I_2^{'2} R_2 \approx I_2^{'2}(R_1 + R_2^{'}) \approx I_2^{'2} R_k$$

$$\Delta P_{ЭЛ} \approx \beta^2 \mathrm{I}_{2\mathrm{НОМ}}^{'2} \mathrm{R_k} \approx \beta^2 \Delta P_{ЭЛ.НОМ}$$

$$\Delta P_{ЭЛ.НОМ} \approx I'^{2}_{2НОМ} R_k \approx I'^{2}_{1НОМ} R_k$$

$$\Delta P_{ЭЛ} = \beta^2 P_K$$

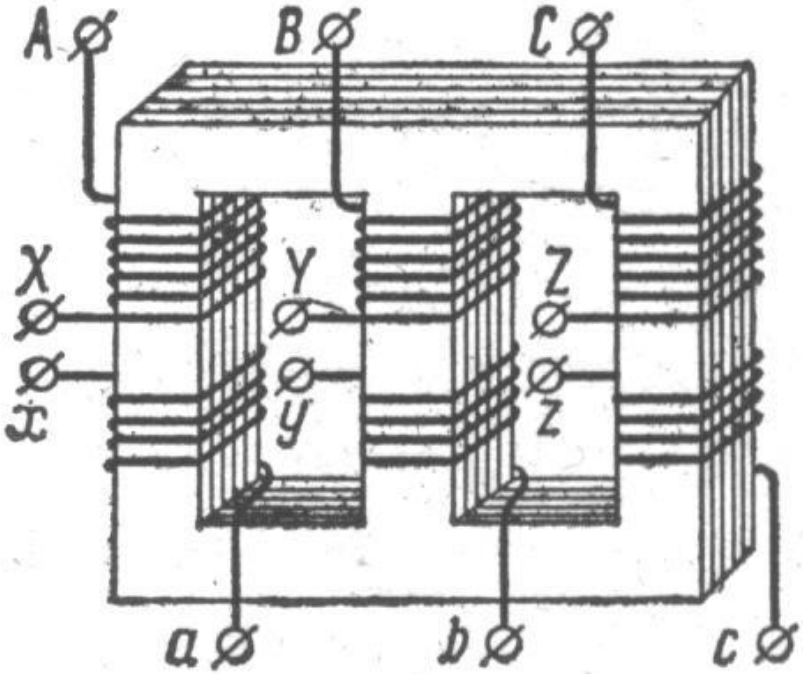
$$\Delta P = P_0 + \beta^2 P_K$$

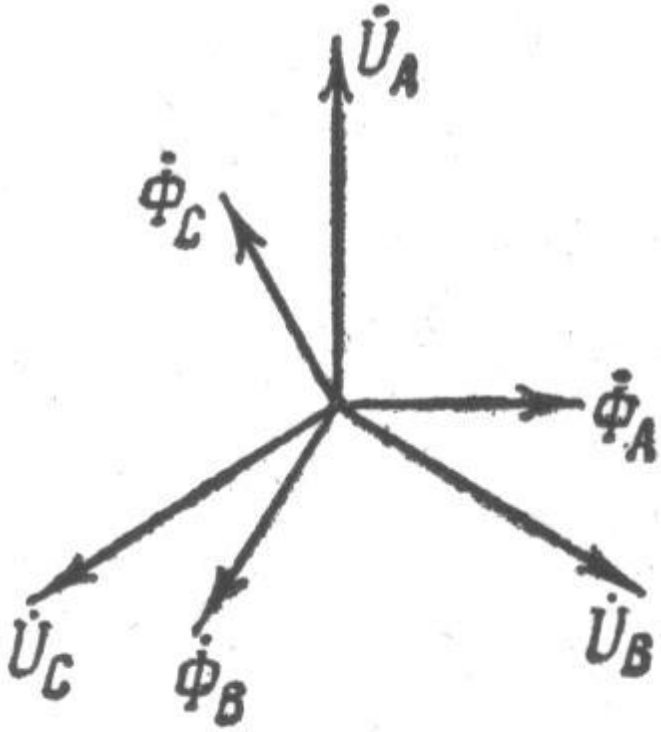
$$P_2 = I_2 U_2 Cos\varphi_2 \approx \beta S_{НОМ} Cos\varphi_2$$

$$\eta = 1 - \frac{\beta^2 P_K + P_0}{\beta S_{НОМ} Cos\varphi_2 + \beta^2 P_K + P_0}$$

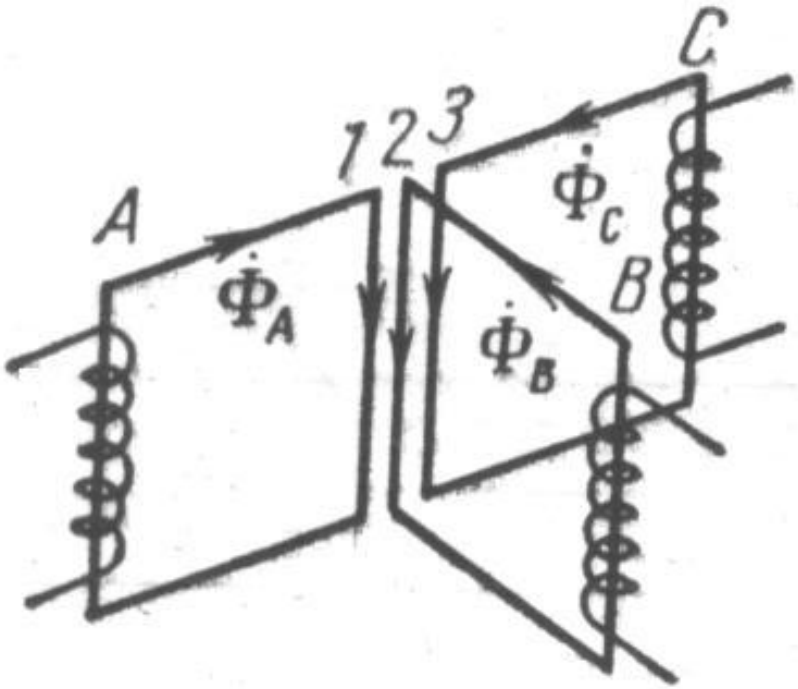
$$P_{0НОМ} = \beta'^2 P_{К.НОМ} \qquad \beta' = \sqrt{\frac{P_{0НОМ}}{P_{КНОМ}}} \qquad \eta = \frac{W_2}{W_1}$$

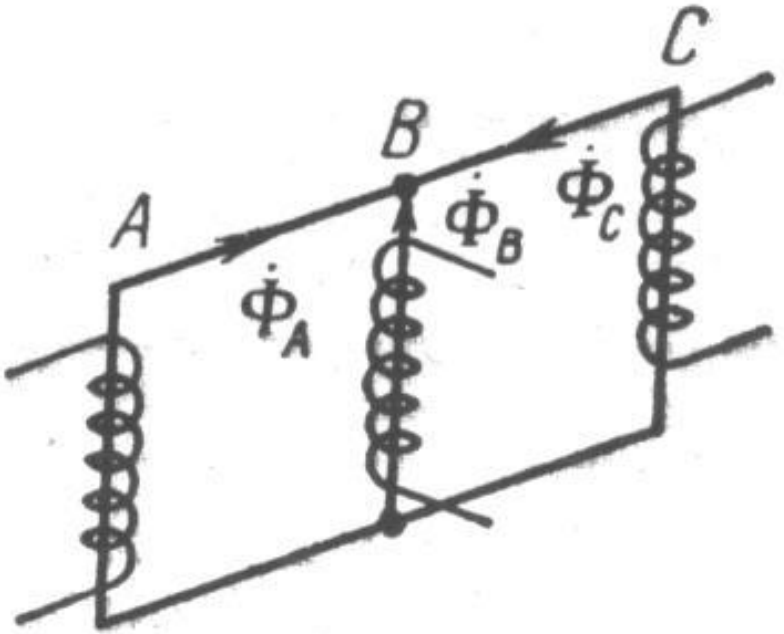
Трехфазные трансформаторы





Трехстержневой 3-фазный трансформатор





$$\dot{\Phi}_{PE3} = \dot{\Phi}_A + \dot{\Phi}_B + \dot{\Phi}_C$$

Схемы соединений

A, B, C; X, У, Z

a, b, c , x, y, z

O

$$K_{\Phi} = \frac{W_{ВН}}{W_{НН}} = \frac{U_{0\Phi\,ВН}}{U_{0\Phi\,НН}}$$

Y/Y, Δ /Δ

$K_{Л} = K_{Ф}$

$$K_{Л} = \frac{U_{0Л\,ВН}}{U_{0Л\,НН}}$$

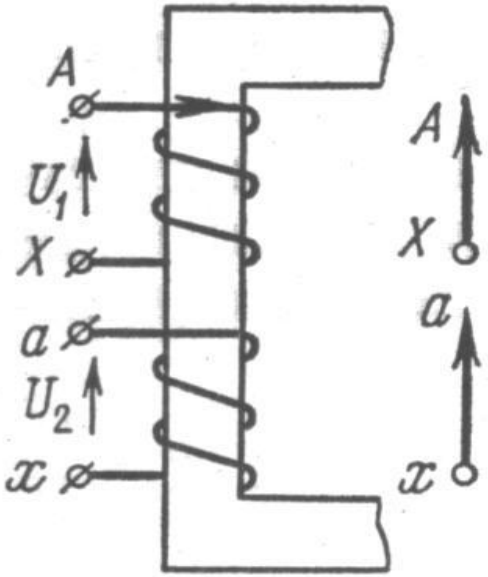
Y/
Δ

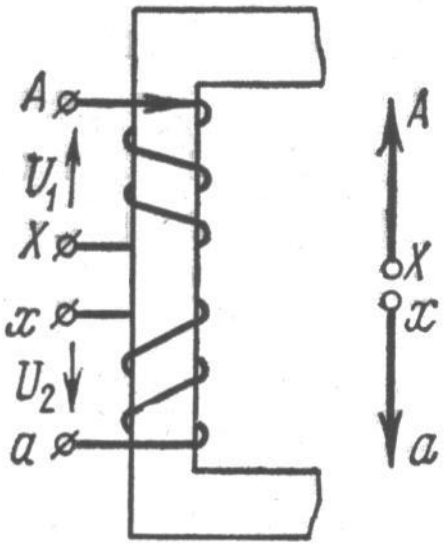
$$K_{Л} = \sqrt{3} K_{\Phi}$$

Δ/Y

$$K_{Л} = \frac{K_{\Phi}}{\sqrt{3}}$$

Группы соединений обмоток трансформаторов

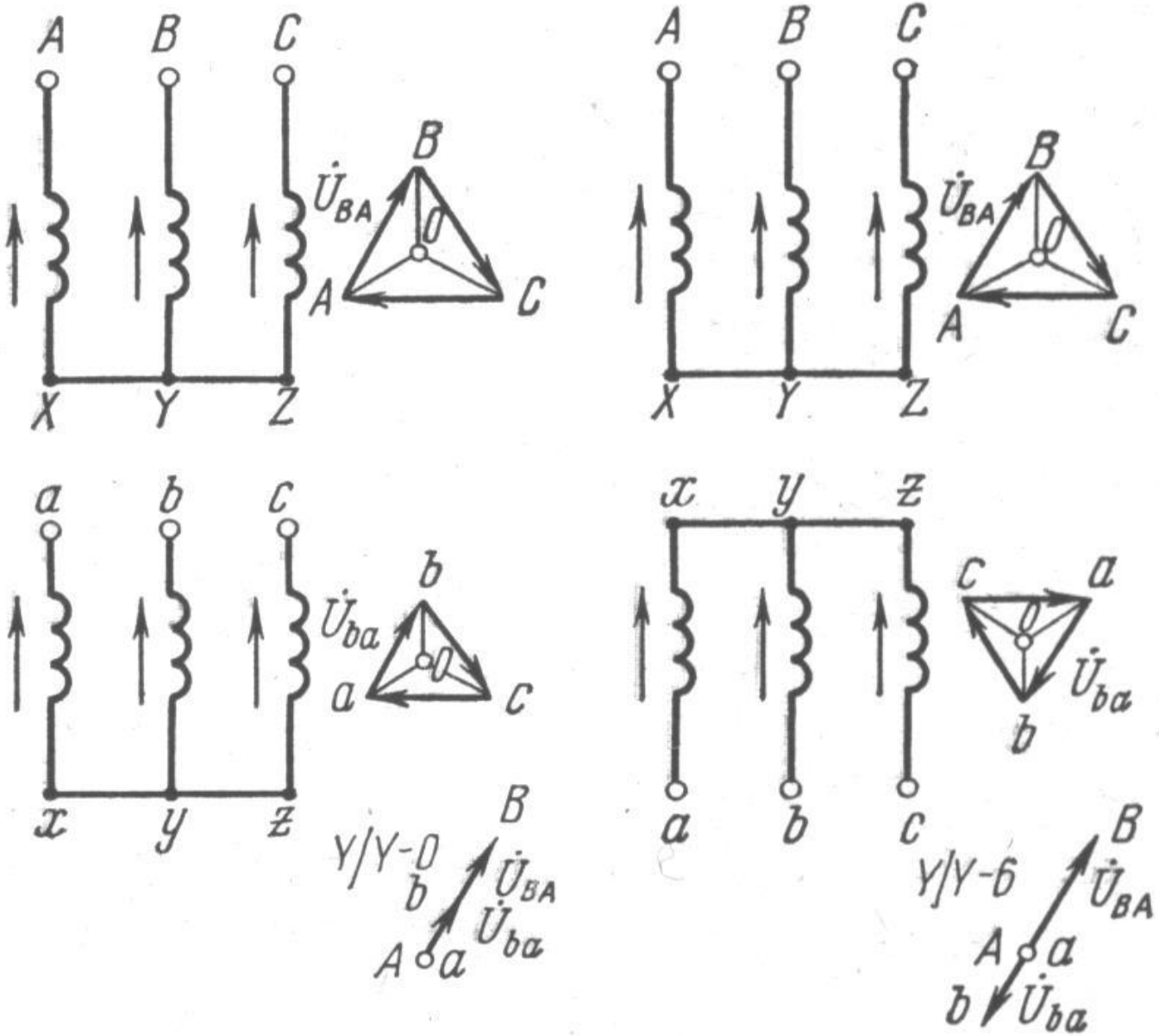


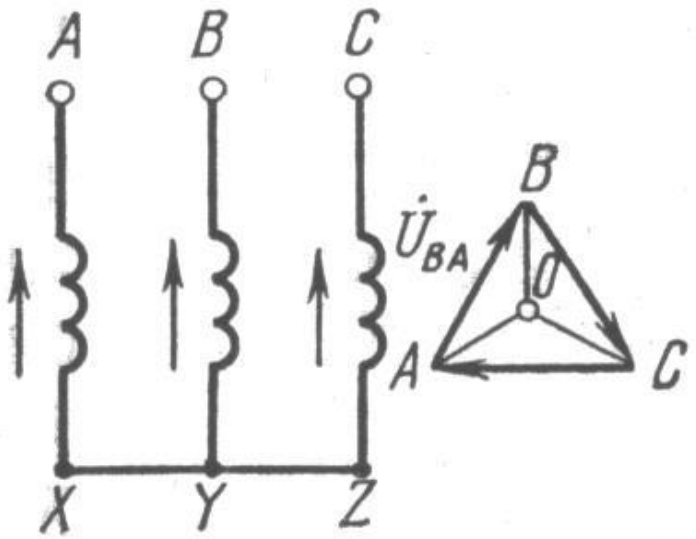


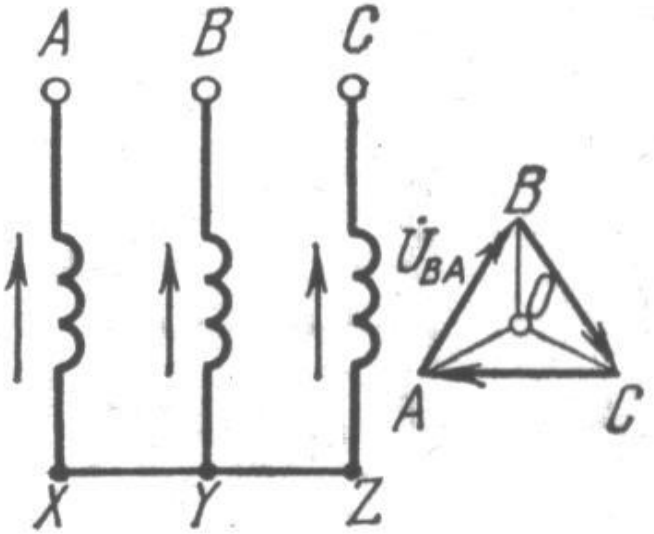
Номер группы определяют величиной угла, на который вектор линейного напряжения обмотки НН отстает от вектора линейного напряжения обмотки ВН.

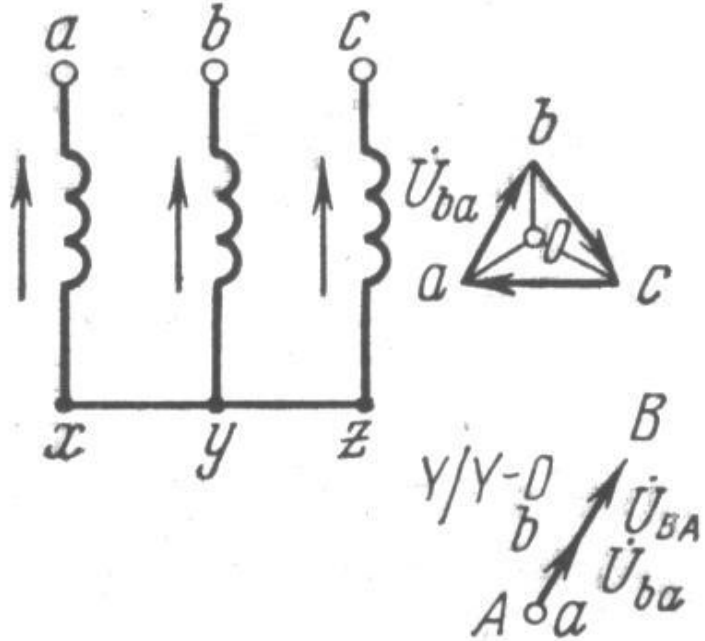
Для определения номера группы этот угол следует разделить на 30^0.

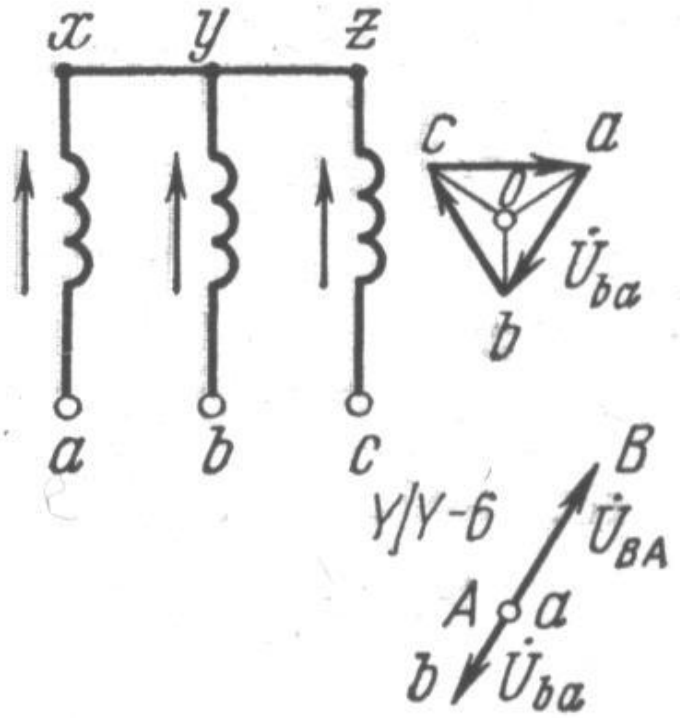
Трехфазные трансформаторы

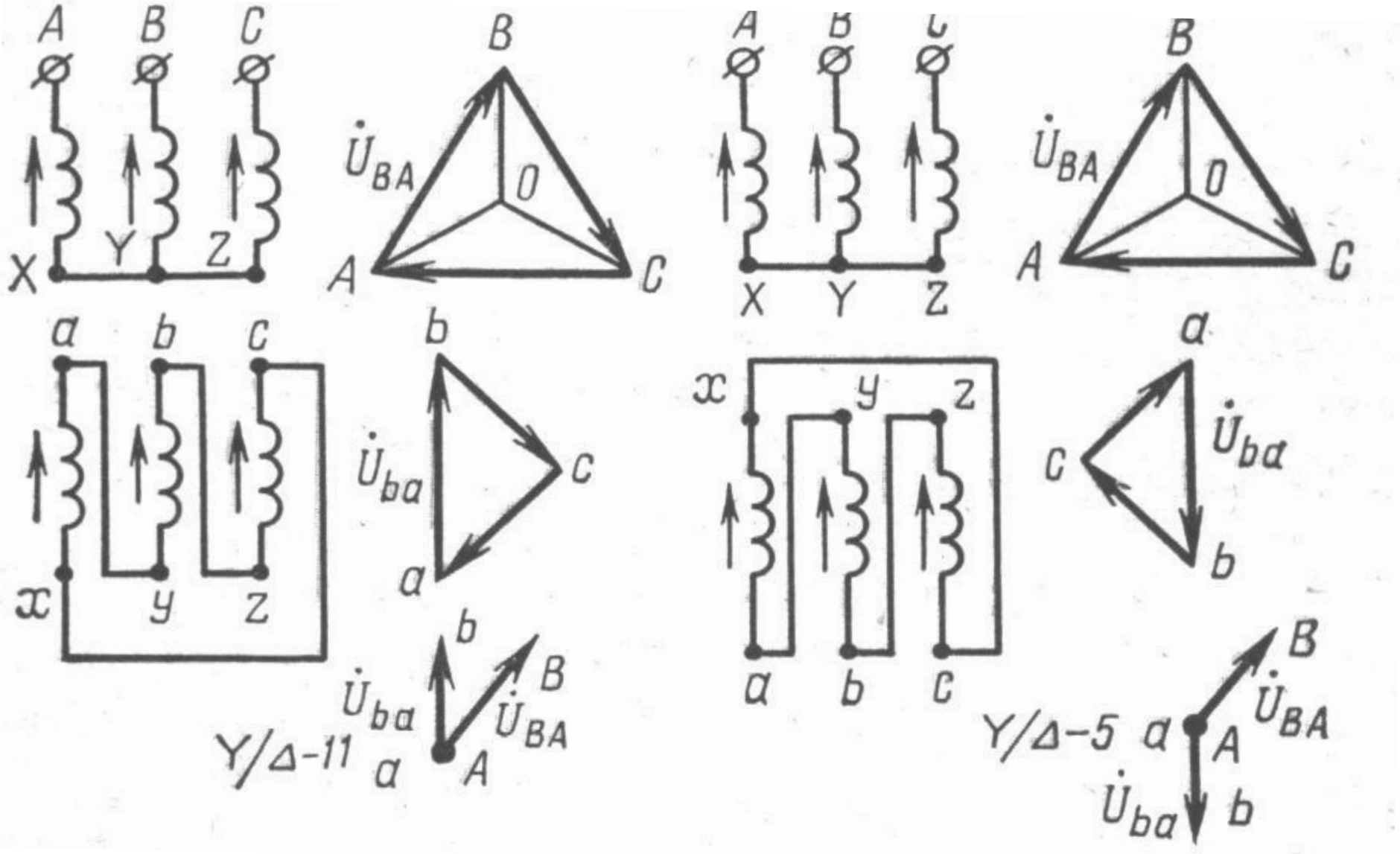


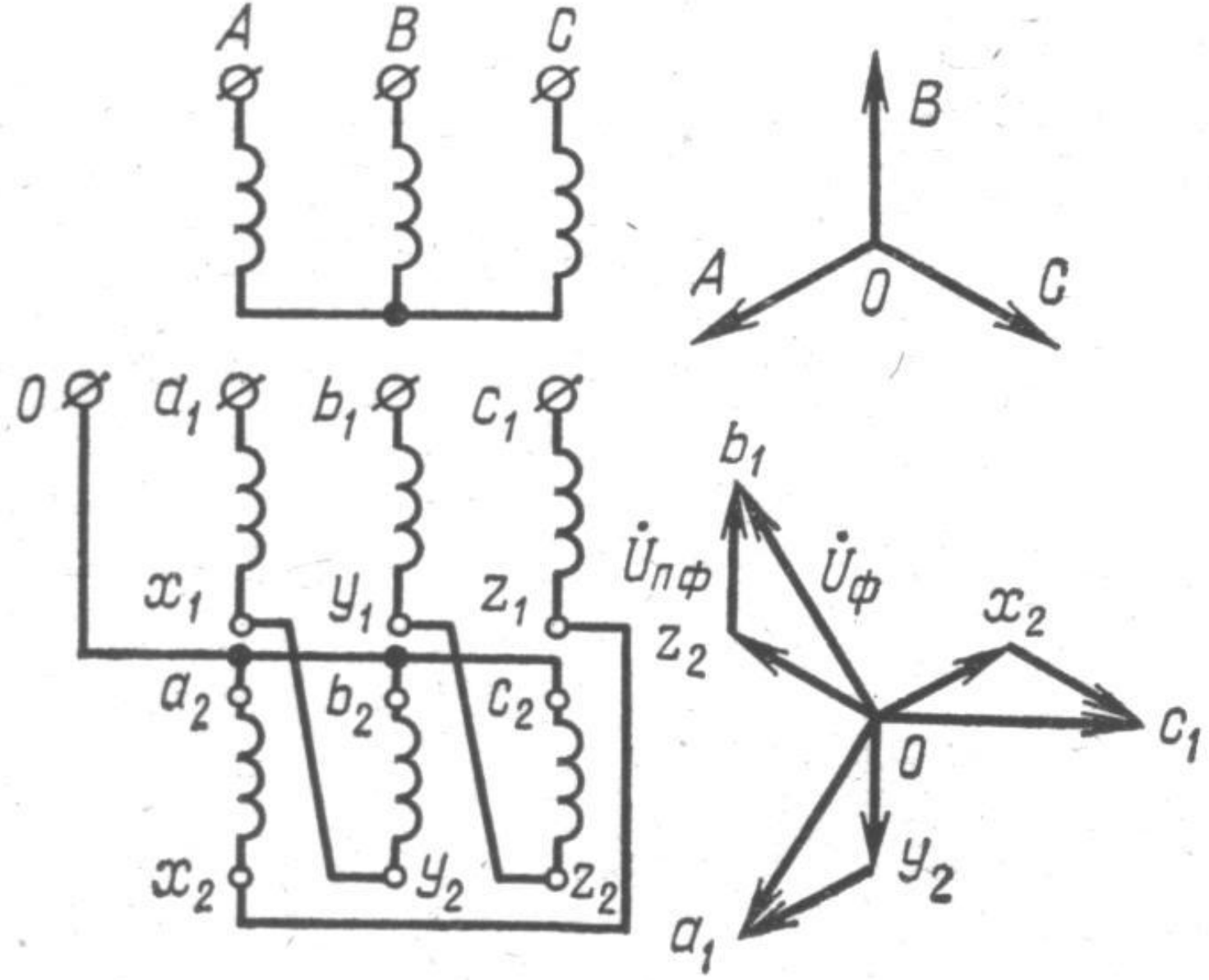

A
B
C
X
Y
Z
$\dot{U}_{BA}$
B
A
C
0


A
B
C
X
Y
Z
$\dot{U}_{BA}$
B
A
C
0

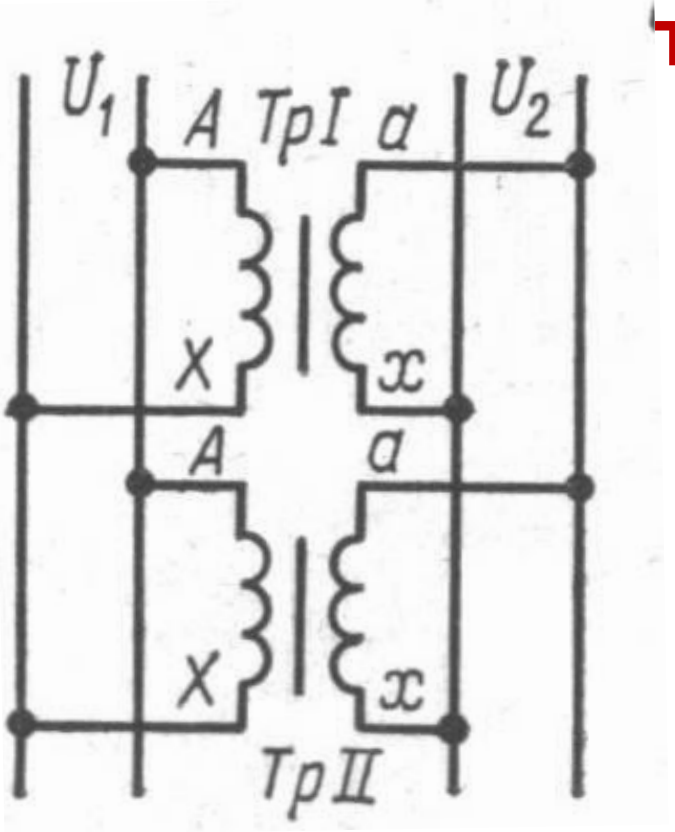

a
b
c
x
y
z
$\dot{U}_{ba}$
b
a
c
0
Y/Y-0
B
$\dot{U}_{BA}$
b
$\dot{U}_{ba}$
A
a

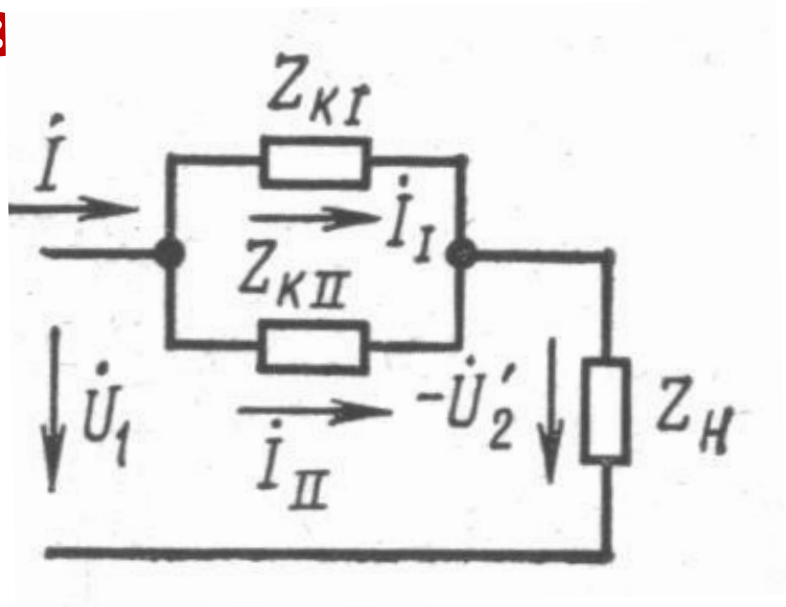

x
y
z
a
b
c
C
a
0
$\dot{U}_{ba}$
b
Y/Y-6
B
$\dot{U}_{BA}$
A
a
b
$\dot{U}_{ba}$


A
B
C
X
Y
Z
B
$\dot{U}_{BA}$
O
A
C
a
b
c
x
y
z
b
$\dot{U}_{ba}$
c
a
b
$\dot{U}_{ba}$
B
$\dot{U}_{BA}$
Y/Δ-11
a
A
A
B
C
X
Y
Z
B
$\dot{U}_{BA}$
O
A
C
x
y
z
a
b
c
a
C
$\dot{U}_{ba}$
b
B
$\dot{U}_{BA}$
Y/Δ-5
a
A
$\dot{U}_{ba}$
b


A
B
C
B
A
0
C
0
a_1
b_1
c_1
x_1
y_1
z_1
a_2
b_2
c_2
x_2
y_2
z_2
$\dot{U}_{л\phi}$
$\dot{U}_{\phi}$
b_1
z_2
x_2
c_1
0
y_2
a_1

Параллельная работа торов



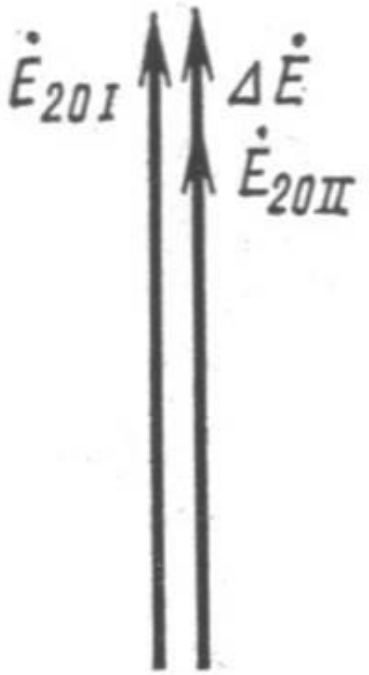


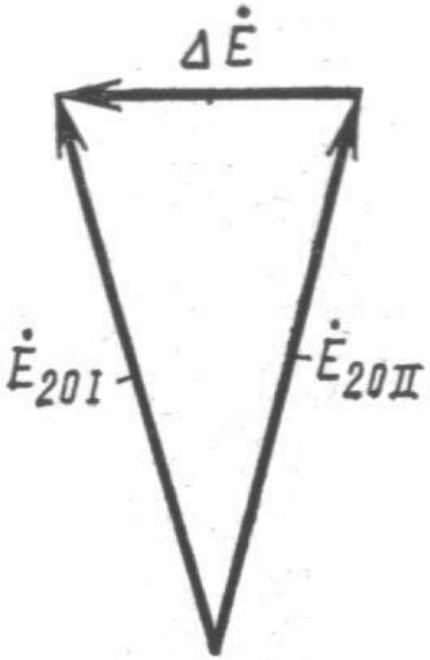
$$\dot{I}_{УР} = \frac{\dot{E}_{2OI} - \dot{E}_{2OII}}{Z_{-KI} + Z_{-KII}}$$

1. Равенство вторичных ЭДС

2. Совпадение по фазе ЭДС

$\dot{E}_{2OI}$ $\dot{E}_{2OII}$





3. Распределение нагрузок в соответствии с номинальной мощностью

$$\dot{I}_I Z_{-KI} = \dot{I}_{II} Z_{-KII} = \dot{I}_{III} Z_{-KIII} = .. = \dot{I}_n Z_{-Kn}$$

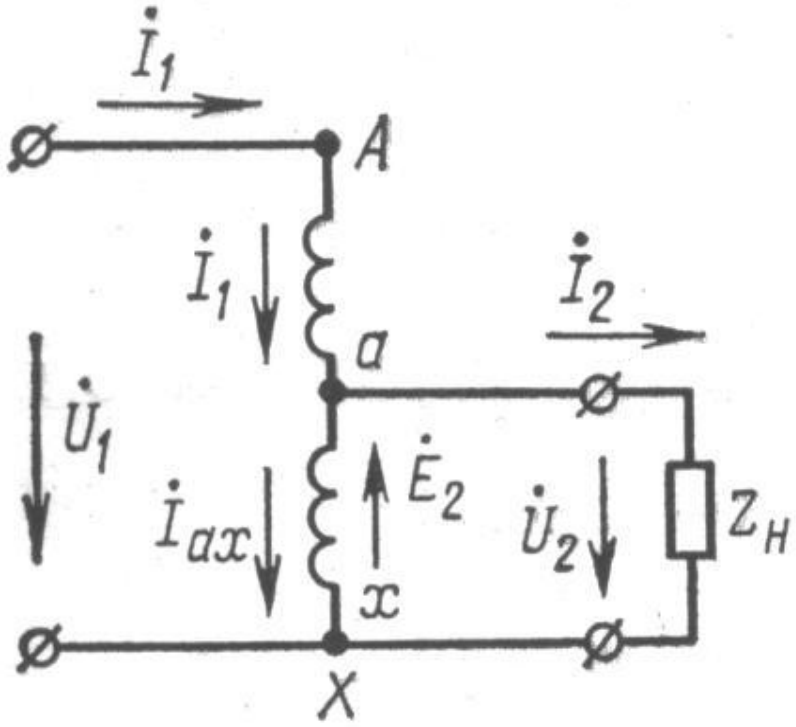
$$\frac{I_I}{I_{II}} = \frac{Z_{KII}}{Z_{KI}} \qquad I_I : I_{II} = \frac{1}{Z_{KI}} : \frac{1}{Z_{KII}}$$

$$I_I : I_{II} = \frac{I_{HOMI}}{I_{HOMI} Z_{KI}} : \frac{I_{HOMII}}{I_{HOMII} Z_{KII}} \qquad U_2 \mathrm{Cos}\varphi_2 \qquad \frac{U_{HOM}^2}{100}$$

$$P_1 : P_2 = \frac{S_{HOMI}}{U_{KI}} : \frac{S_{HOMII}}{U_{KII}}$$

$$\frac{P_1}{S_{HOMI}} : \frac{P_2}{S_{HOMII}} = \frac{1}{U_{KI}} : \frac{1}{U_{KII}}$$

Автотрансформатор



$$E = 4.44 f \Phi_м$$

$$U_2 = 4.44 f w_{ax} \Phi_м = U_1 \frac{w_{ax}}{w_{AX}} = \frac{U_1}{K}$$

$$S_н = U_{1н} I_{1н} = U_{2н} I_{2н}$$

$$\frac{U_1}{U_{20}} \approx \frac{E_1}{E_2} = \frac{w_1}{w_2} = k$$

$$\dot{I}\,ax = \dot{I}_2 + \dot{I}_1$$

$$I_1 w_1 + I_2 w_2 = 0$$

$$I_{ax} = I_1 \left(1 - \frac{w_1}{w_2}\right)$$

$$I_{ax} w_2 = I_1 \left(1 - \frac{w_1}{w_2}\right) w_2 = - I_1 (w_1 - w_2)$$

Sпр=$E_1 I_1 = E_2 I_2$ **Sрасч=$E_2 I_a$**

$$S_{ПР} = E_2 I_2 = E_2 (I_1 + I_{ax}) = E_2 Iax + E_2 I_1 = S_{ЭМ} + S_{ЭЛ}$$

$$S_{ЭМ} = E_2 Iax = S_{РАСЧ}$$

$$S_{ЭЛ} = E_2 I_1$$

$$I_1 = I_2^{'} = \frac{I_2}{K} \qquad I_{ax} = I_2 (1 - \frac{1}{K})$$

$$S_{РАСЧ} = E_2 I_{ax} = E_2 I_2 (1 - \frac{1}{K})$$

$$K_{ВЫГ} = \frac{S_{РАСЧ}}{S_{ПРОХОДНАЯ}} = (1 - \frac{1}{K})$$

$$K_{ВЫГ} = \frac{S_{РАСЧ}}{S_{ПРОХОДНАЯ}} = (1 - \frac{1}{K})$$

$$\frac{\textit{отношение эл.потерь АТР}}{2 - x\ \textit{обм. тр} - m} \qquad \frac{\Delta P_{ЭЛ\ АТР}}{\Delta P_{ЭЛ\ ТР}} \approx 1 - \frac{1}{K}$$

$$R_{К.АТР} = R_{К.ТР}(1 - \frac{1}{K});$$

$$X_{К.АТР} = X_{К.ТР}(1 - \frac{1}{K})$$

Многообмоточные трансформаторы

$K_{12} = w_{вн} / w_{сн}$ $K_{13} = w_{вн} / w_{нн}$

$$
\left.
\begin{aligned}
\dot{U}_1 &= -\dot{E}_1 + \dot{I}_1 R_1 + j \dot{I}_1 x_1 \\
\dot{U}_2 &= \dot{E}_2 - \dot{I}_2 R_2 - j \dot{I}_2 x_2 \\
\dot{U}_3 &= \dot{E}_3 - \dot{I}_3 R_3 - j \dot{I}_3 x_3 \\
\dot{I}_1 &= \dot{I}_0 + \left(-\dot{I}_2 \frac{w_2}{w_1} \right) + \left(-\dot{I}_3 \frac{w_3}{w_1} \right)
\end{aligned}
\right\}
$$

Регулирование напряжения в трансформаторах