FACULTY OF ELECTRICAL
ENGINEERING
UNIVERSITY OF WEST BOHEMIA

EVROPSKÁ UNIE
Evropské strukturální a investiční fondy
Operační program Výzkum, vývoj a vzdělávání

MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY

ESF II – project of the University of West Bohemia
reg. no. CZ.02.2.69/0.0/0.0/18_056/0013239

Theory of Electric Machines 2

KEV/TS2

Karel Hruska / r20201116

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Triple Winding Transformer

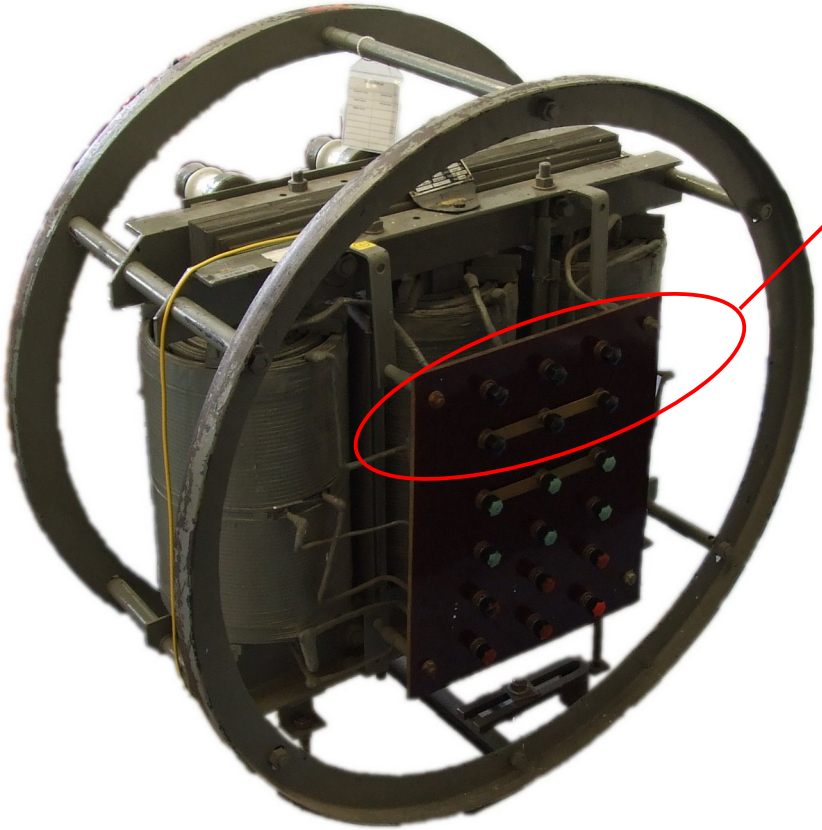
Triple Winding Transformer

- A transformer equipped with two secondary windings
- Used in case when power source for multiple galvanically divided places needed
- Used in
  - power plants (internal power consumption)
  - electric traction (division of input power)
  - electronics

Triple Winding Transformer

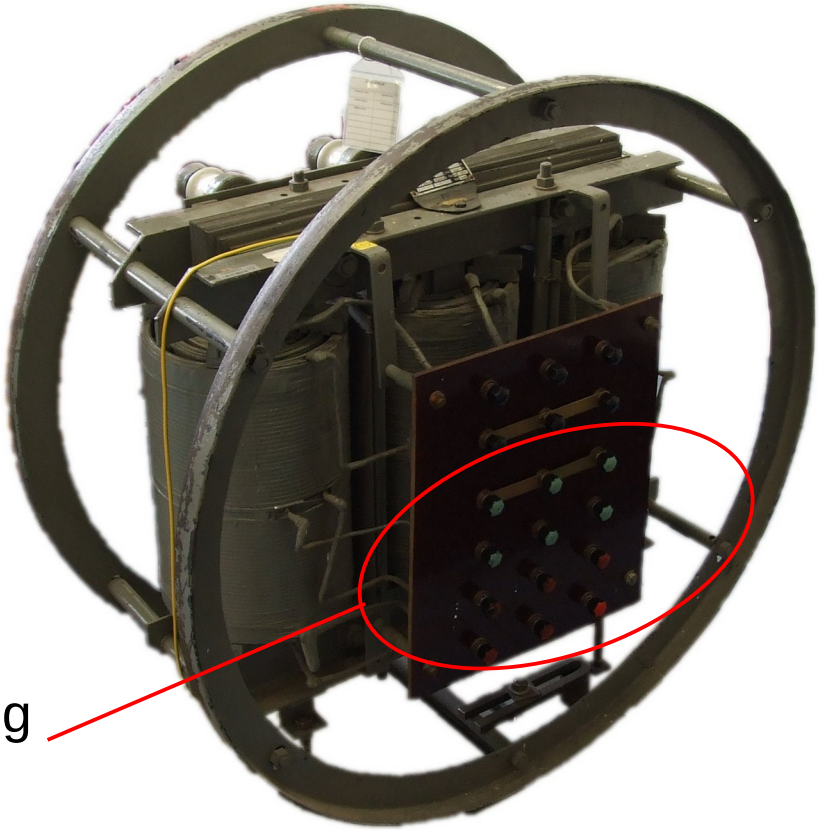


Triple Winding Transformer



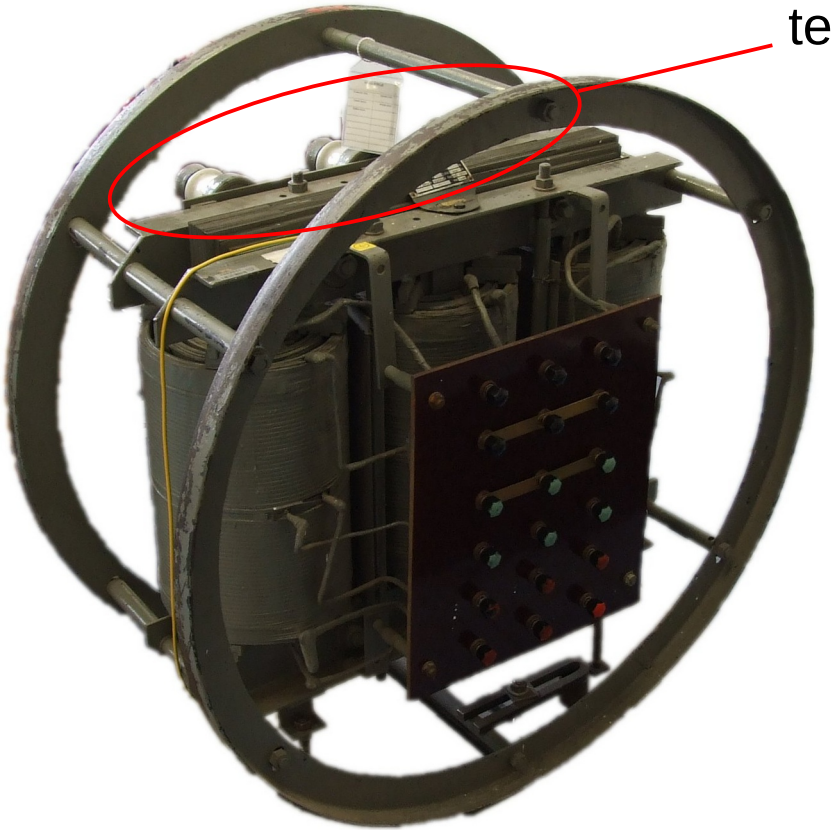
primary winding
3 x 380 V, D

Triple Winding Transformer

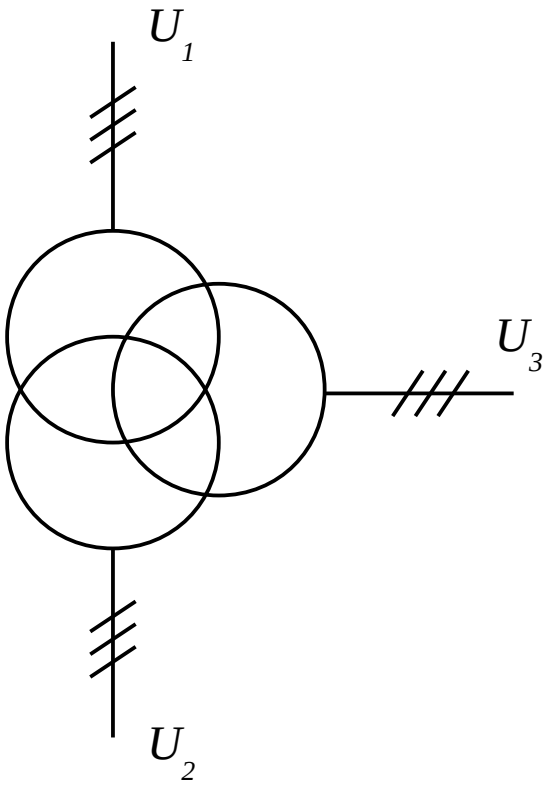


secondary winding
3 x 500 V, Z

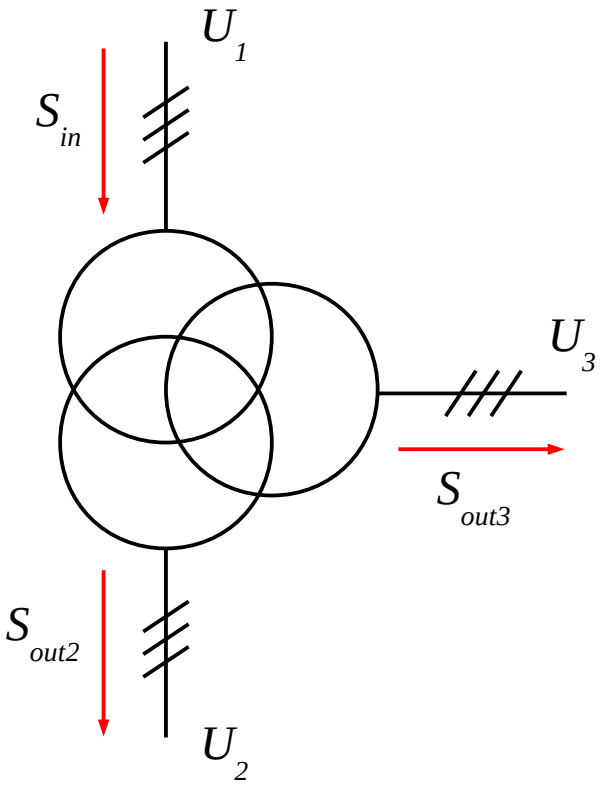
Triple Winding Transformer



Triple Winding Transformer



Triple Winding Transformer

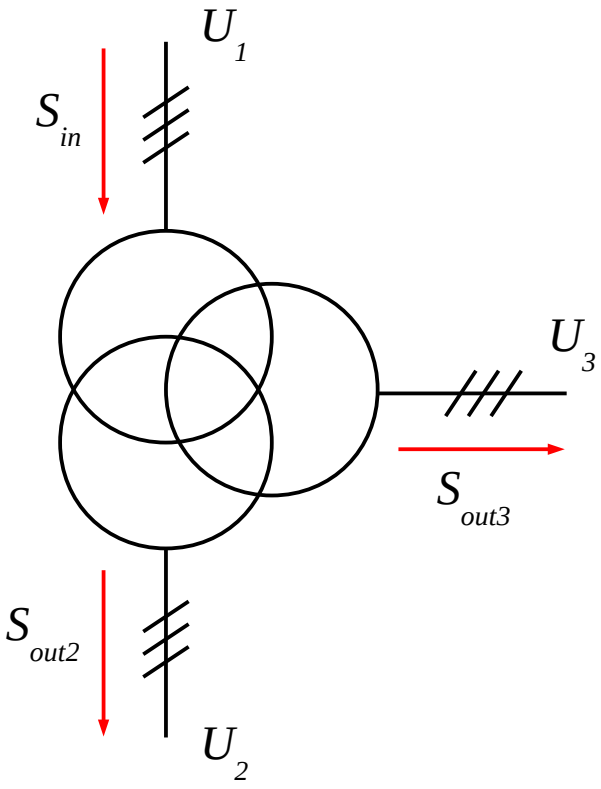


- The power invariance must be valid:

$$\sum_n S_i = 0$$

$$S_{\text{in}} = S_{out\,2} + S_{out\,3}$$

Triple Winding Transformer



- The power invariance must be valid:

$$\sum_n S_i = 0$$

$$S_{\text{in}} = S_{out\,2} + S_{out\,3}$$

- For the purpose of simplification let's use the system of per units:

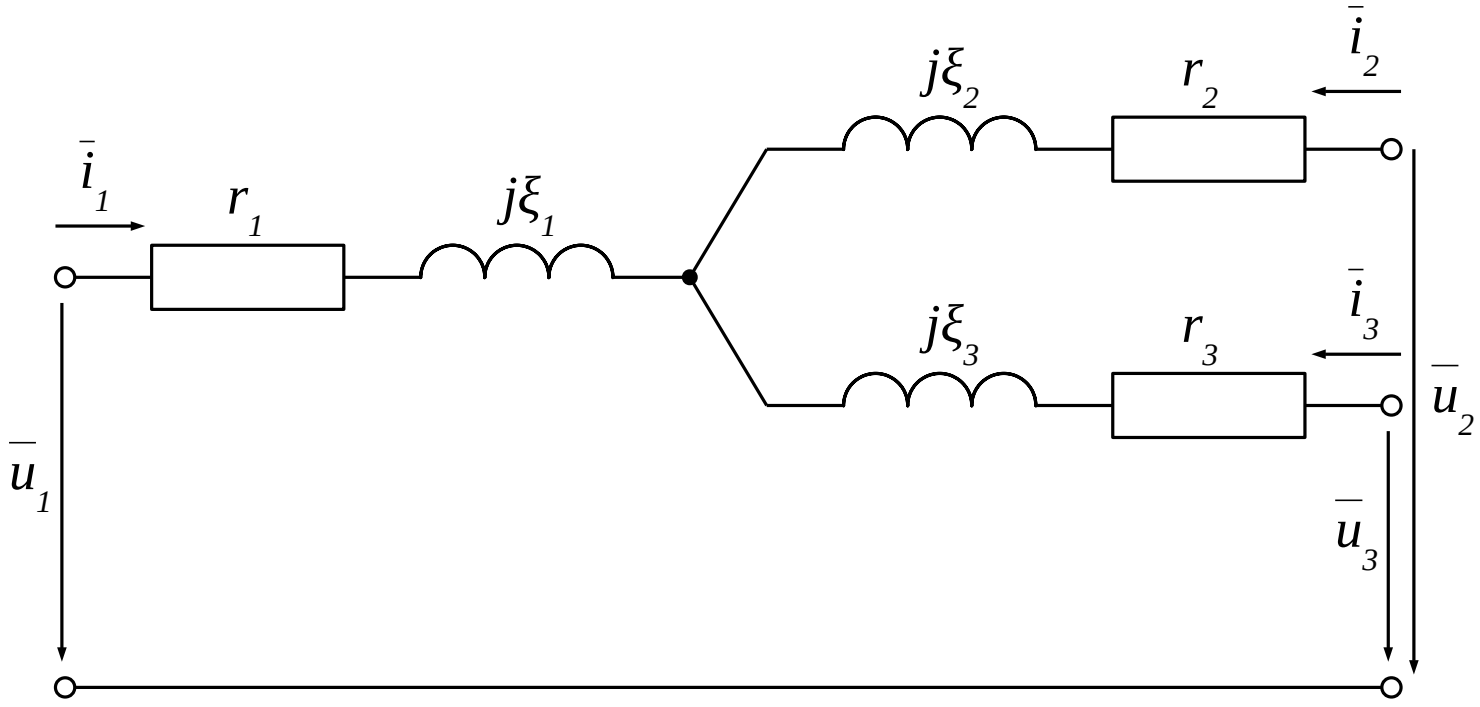
$$\bar{i}_{\mu} = 0$$

- Then the sum of currents from all inputs (outputs) is equal to zero:

$$0 = \bar{i}_1 + \bar{i}_2 + \bar{i}_3$$

Triple Winding Transformer

=> equivalent circuit of a triple winding transformer

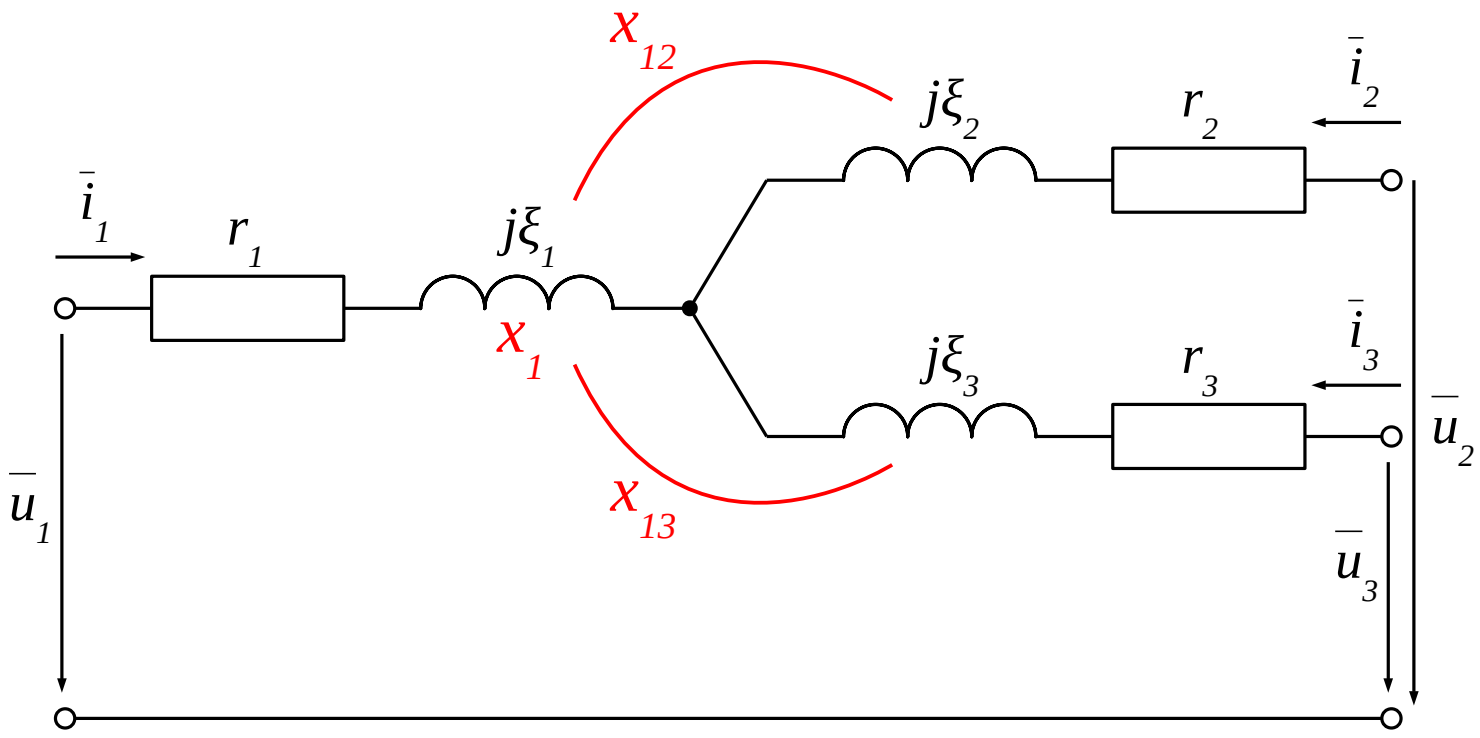


Triple Winding Transformer

- Standard leakage reactances are substituted by reactances ξ_1, ξ_2 and ξ_3
- The reason are mutual inductances between all windings
- The resulting reactance of each phase is then given by own leakage inductance with added value of mutual inductances to other windings

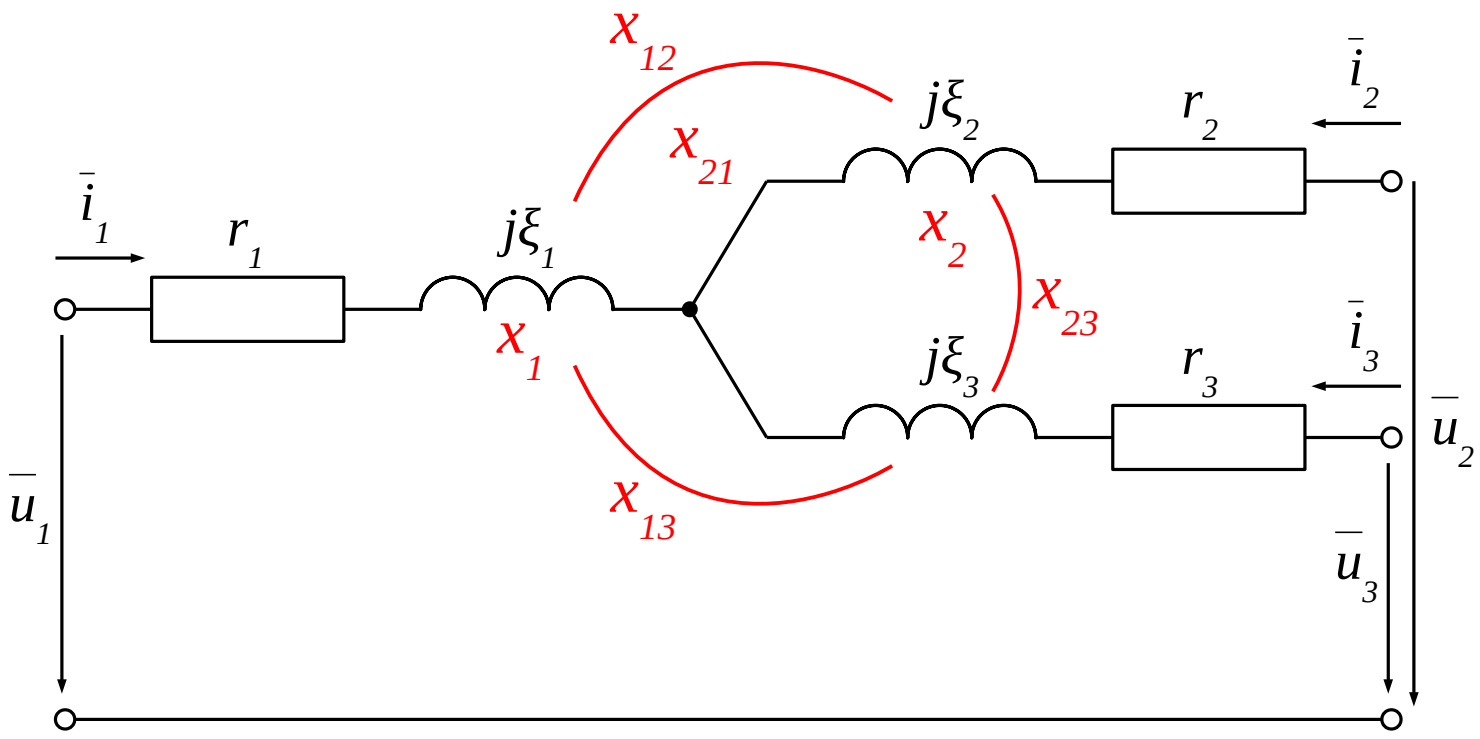
Triple Winding Transformer

=> equivalent circuit of a triple winding transformer



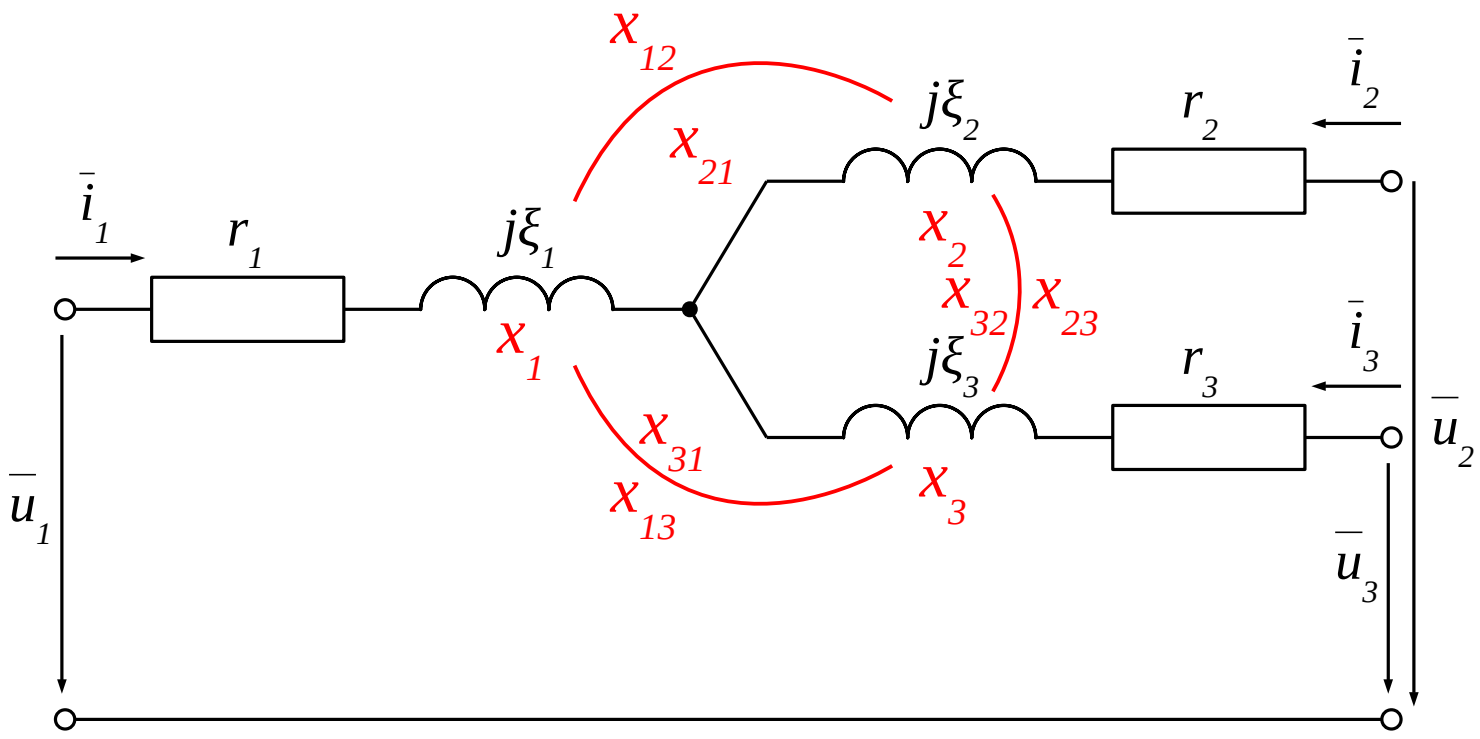
Triple Winding Transformer

=> equivalent circuit of a triple winding transformer



Triple Winding Transformer

=> equivalent circuit of a triple winding transformer



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Reactances of Triple Winding Transformer

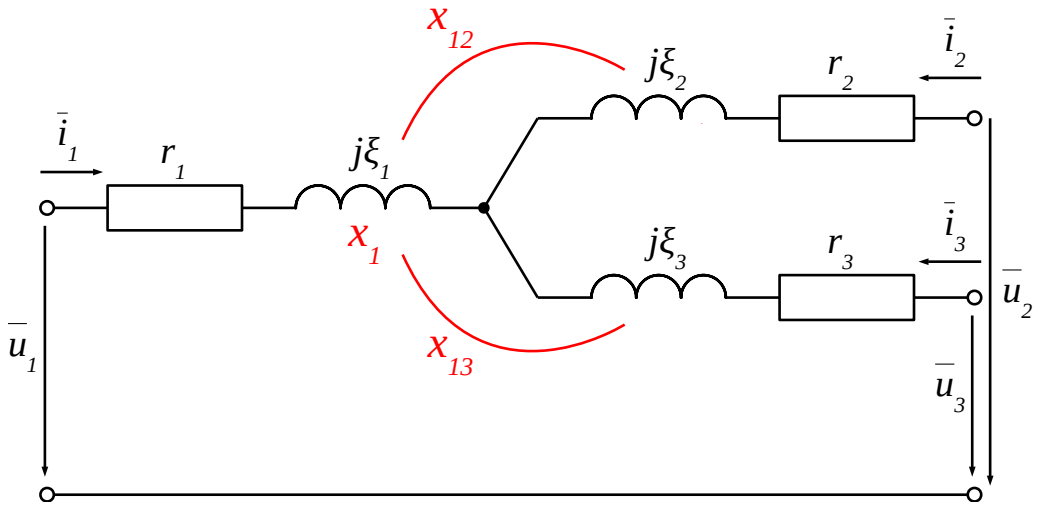
Reactances of Triple Winding Transformer

- Considering complicated induction coupling between windings it is not possible to describe the reactances (inductances) of each winding by leakage and magnetization reactance (inductance) only
- The calculation of reactances considering induction couplings is possible using the equivalent circuit

Reactances of Triple Winding Transformer

- Primary winding:

$$\bar{u}_1 = \left(r_1 + j\,x_1\right)\bar{i}_1 + j\,x_{12}\,\bar{i}_2 + j\,x_{13}\,\bar{i}_3$$

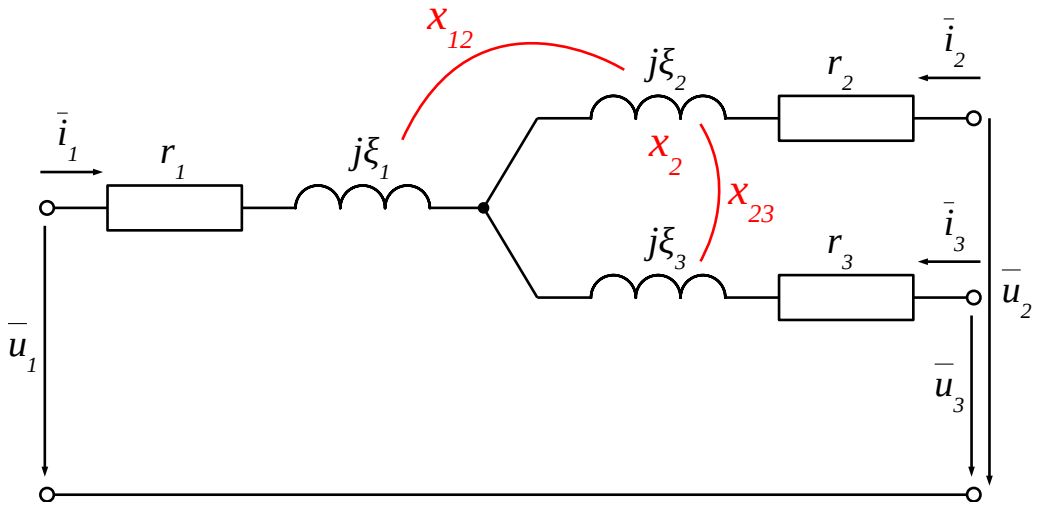


Reactances of Triple Winding Transformer

- Secondary winding:

$$\bar{u}_1 = \left(r_1 + j\,x_1\right)\bar{i}_1 + j\,x_{12}\,\bar{i}_2 + j\,x_{13}\,\bar{i}_3$$

$$\bar{u}_2 = j\,x_{12}\,\bar{i}_1 + \left(r_2 + j\,x_2\right)\bar{i}_2 + j\,x_{23}\,\bar{i}_3$$



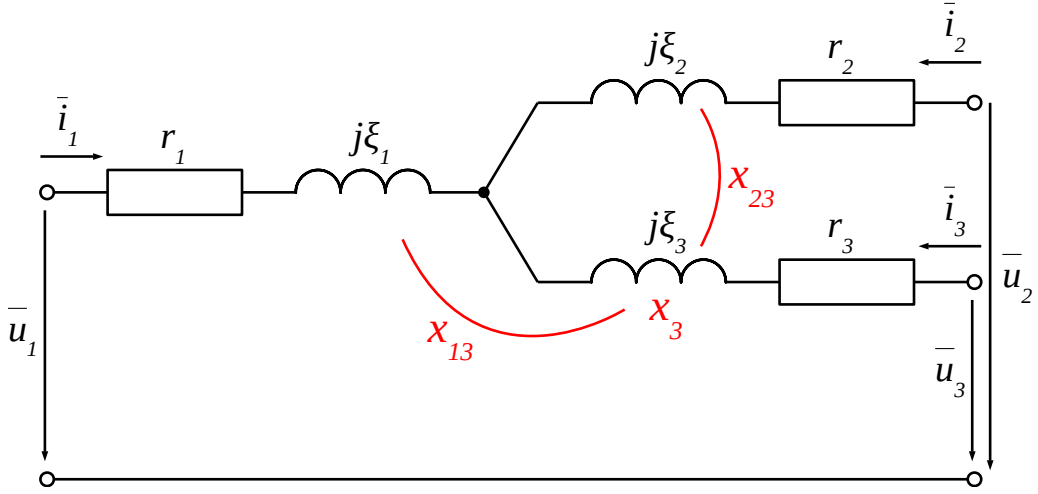
Reactances of Triple Winding Transformer

- Tertiary winding:

$$\bar{u}_1 = \left(r_1 + j\,x_1\right)\bar{i}_1 + j\,x_{12}\,\bar{i}_2 + j\,x_{13}\,\bar{i}_3$$

$$\bar{u}_2 = j\,x_{12}\,\bar{i}_1 + \left(r_2 + j\,x_2\right)\bar{i}_2 + j\,x_{23}\,\bar{i}_3$$

$$\bar{u}_3 = j\,x_{13}\,\bar{i}_1 + j\,x_{23}\,\bar{i}_2 + \left(r_3 + j\,x_3\right)\bar{i}_3$$



Reactances of Triple Winding Transformer

- From voltage relations:

$$\bar{u}_1 = \left(r_1 + j\,x_1\right)\bar{i}_1 + j\,x_{12}\,\bar{i}_2 + j\,x_{13}\,\bar{i}_3$$

$$\bar{u}_2 = j\,x_{12}\,\bar{i}_1 + \left(r_2 + j\,x_2\right)\bar{i}_2 + j\,x_{23}\,\bar{i}_3$$

$$\bar{u}_3 = j\,x_{13}\,\bar{i}_1 + j\,x_{23}\,\bar{i}_2 + \left(r_3 + j\,x_3\right)\bar{i}_3$$

Reactances of Triple Winding Transformer

- From voltage relations:

$$\bar{u}_1 = (r_1 + j x_1)\,\bar{i}_1 + j x_{12}\,\bar{i}_2 + j x_{13}\,\bar{i}_3$$
$$\bar{u}_2 = j x_{12}\,\bar{i}_1 + (r_2 + j x_2)\,\bar{i}_2 + j x_{23}\,\bar{i}_3$$
$$\bar{u}_3 = j x_{13}\,\bar{i}_1 + j x_{23}\,\bar{i}_2 + (r_3 + j x_3)\,\bar{i}_3$$

- It is possible to determine the cyclic voltage drops:

$$\bar{u}_1 - \bar{u}_2 = \left[r_1 + j\left(x_1 - x_{12}\right)\right]\bar{i}_1 - \left[r_2 + j\left(x_2 - x_{12}\right)\right]\bar{i}_2 + j\left(x_{13} - x_{23}\right)\bar{i}_3$$
$$\bar{u}_2 - \bar{u}_3 = j\left(x_{12} - x_{13}\right)\bar{i}_1 + \left[r_2 + j\left(x_2 - x_{23}\right)\right]\bar{i}_2 - \left[r_3 + j\left(x_3 - x_{23}\right)\right]\bar{i}_3$$
$$\bar{u}_3 - \bar{u}_1 = -\left[r_1 + j\left(x_1 - x_{13}\right)\right]\bar{i}_1 + j\left(x_{23} - x_{12}\right)\bar{i}_2 + \left[r_3 + j\left(x_3 - x_{13}\right)\right]\bar{i}_3$$

Reactances of Triple Winding Transformer

- It is possible to substitute from

$$\bar{i}_1 + \bar{i}_2 + \bar{i}_3 = 0$$

for each current (in relations one-by-one):

$$\bar{i}_3 = -\bar{i}_1 - \bar{i}_2$$
$$\bar{i}_1 = -\bar{i}_2 - \bar{i}_3$$
$$\bar{i}_2 = -\bar{i}_1 - \bar{i}_3$$

Reactances of Triple Winding Transformer

- It is possible to substitute from

$$\bar{i}_1+\bar{i}_2+\bar{i}_3=0$$

for each current (in relations one-by-one):

$$\bar{i}_3=-\bar{i}_1-\bar{i}_2$$
$$\bar{i}_1=-\bar{i}_2-\bar{i}_3$$
$$\bar{i}_2=-\bar{i}_1-\bar{i}_3$$

- Then we obtain:

$$\bar{u}_1-\bar{u}_2=\left[r_1+j\left(x_1-x_{12}\right)\right]\bar{i}_1-\left[r_2+j\left(x_2-x_{12}\right)\right]\bar{i}_2+j\left(x_{13}-x_{23}\right)\left(-\bar{i}_1-\bar{i}_2\right)$$
$$\bar{u}_2-\bar{u}_3=j\left(x_{12}-x_{13}\right)\left(-\bar{i}_2-\bar{i}_3\right)+\left[r_2+j\left(x_2-x_{23}\right)\right]\bar{i}_2-\left[r_3+j\left(x_3-x_{23}\right)\right]\bar{i}_3$$
$$\bar{u}_3-\bar{u}_1=-\left[r_1+j\left(x_1-x_{13}\right)\right]\bar{i}_1+j\left(x_{23}-x_{12}\right)\left(-\bar{i}_1-\bar{i}_3\right)+\left[r_3+j\left(x_3-x_{13}\right)\right]\bar{i}_3$$

Reactances of Triple Winding Transformer

- The resulting relations are:

$$\bar{u}_1 - \bar{u}_2 = \left[r_1 + j\left(x_1 + x_{23} - x_{12} - x_{13} \right) \right] \bar{i}_1 - \left[r_2 + j\left(x_2 + x_{13} - x_{12} - x_{23} \right) \right] \bar{i}_2$$
$$\bar{u}_2 - \bar{u}_3 = \left[r_2 + j\left(x_2 + x_{13} - x_{12} - x_{23} \right) \right] \bar{i}_2 - \left[r_3 + j\left(x_3 + x_{12} - x_{13} - x_{23} \right) \right] \bar{i}_3$$
$$\bar{u}_3 - \bar{u}_1 = -\left[r_1 + j\left(x_1 + x_{23} - x_{12} - x_{13} \right) \right] \bar{i}_1 + \left[r_3 + j\left(x_3 + x_{12} - x_{13} - x_{23} \right) \right] \bar{i}_3$$

Reactances of Triple Winding Transformer

- The resulting relations are:

$$\bar{u}_1-\bar{u}_2=\left[r_1+j\overbrace{\left(x_1+x_{23}-x_{12}-x_{13}\right)}^{\bar{\xi}_1}\right]\bar{i}_1-\left[r_2+j\overbrace{\left(x_2+x_{13}-x_{12}-x_{23}\right)}^{\bar{\xi}_2}\right]\bar{i}_2$$

$$\bar{u}_2-\bar{u}_3=\left[r_2+j\left(x_2+x_{13}-x_{12}-x_{23}\right)\right]\bar{i}_2-\left[r_3+j\left(x_3+x_{12}-x_{13}-x_{23}\right)\right]\bar{i}_3$$

$$\bar{u}_3-\bar{u}_1=-\left[r_1+j\left(x_1+x_{23}-x_{12}-x_{13}\right)\right]\bar{i}_1+\left[r_3+j\underbrace{\left(x_3+x_{12}-x_{13}-x_{23}\right)}_{\bar{\xi}_3}\right]\bar{i}_3$$

Reactances of Triple Winding Transformer

- Using simplified transcription

$$\bar{u}_1-\bar{u}_2=\left(r_1+j\,\xi_1\right)\bar{i}_1-\left(r_2+j\,\xi_2\right)\bar{i}_2$$
$$\bar{u}_2-\bar{u}_3=\left(r_2+j\,\xi_2\right)\bar{i}_2-\left(r_3+j\,\xi_3\right)\bar{i}_3$$
$$\bar{u}_3-\bar{u}_1=-\left(r_1+j\,\xi_1\right)\bar{i}_1+\left(r_3+j\,\xi_3\right)\bar{i}_3$$

where reactances ξ_1, ξ_2 and ξ_3 are

$$\xi_1=x_1+x_{23}-x_{12}-x_{13}$$
$$\xi_2=x_2+x_{13}-x_{12}-x_{23}$$
$$\xi_3=x_3+x_{12}-x_{13}-x_{23}$$

where ξ_2 has a negative value...

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The Proof of Negative Value of ξ_2

The Proof of Negative Value of ξ_2

- For better overview it is possible to transcribe reactances from a form of

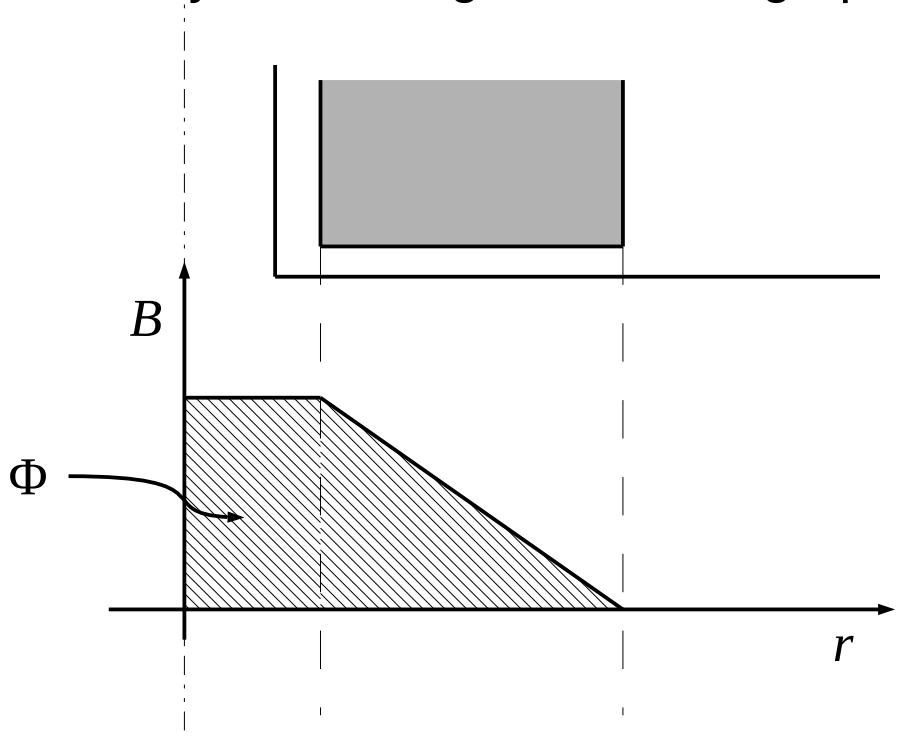
$$\xi_1 = x_1 + x_{23} - x_{12} - x_{13}$$
$$\xi_2 = x_2 + x_{13} - x_{12} - x_{23}$$
$$\xi_3 = x_3 + x_{12} - x_{13} - x_{23}$$

to

$$\xi_1 = \left(x_{23} - x_{13}\right) - \left(x_{12} - x_1\right)$$
$$\xi_2 = \left(x_2 - x_{23}\right) - \left(x_{12} - x_{13}\right)$$
$$\xi_3 = \left(x_3 - x_{23}\right) - \left(x_{13} - x_{12}\right)$$

The Proof of Negative Value of ξ_2

- Let us analyze the magnetic fluxes graphically:

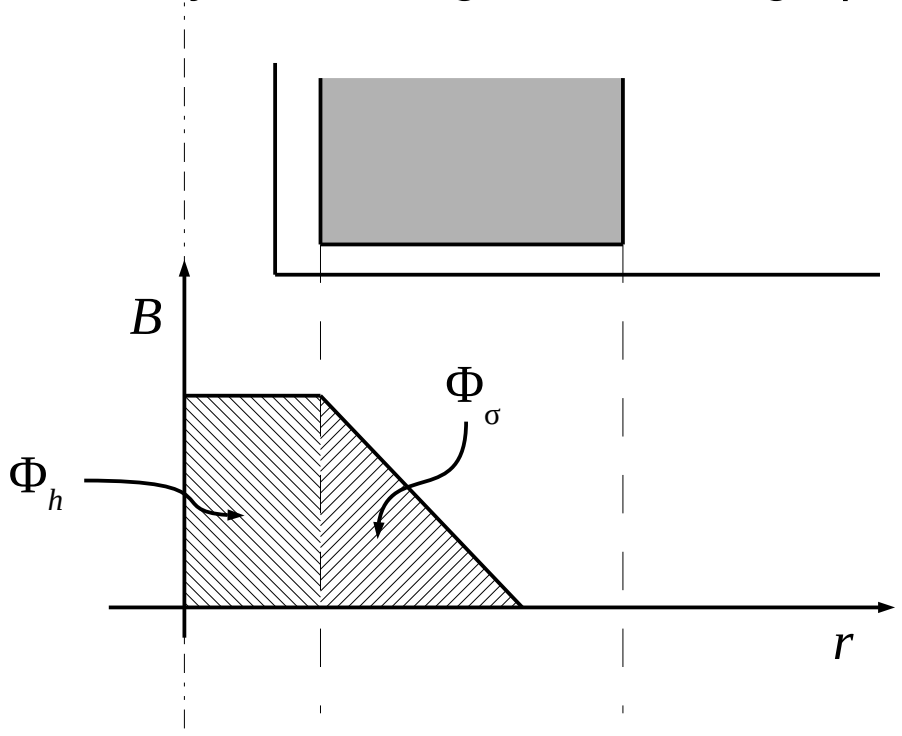


- magnetic flux excited by the winding = mutual flux for calculation for calculation of mutual reactances

$$X_{12} = \omega L_{12} = \omega \frac{\Phi_1}{I_2}$$

The Proof of Negative Value of ξ_2

- Let us analyze the magnetic fluxes graphically:

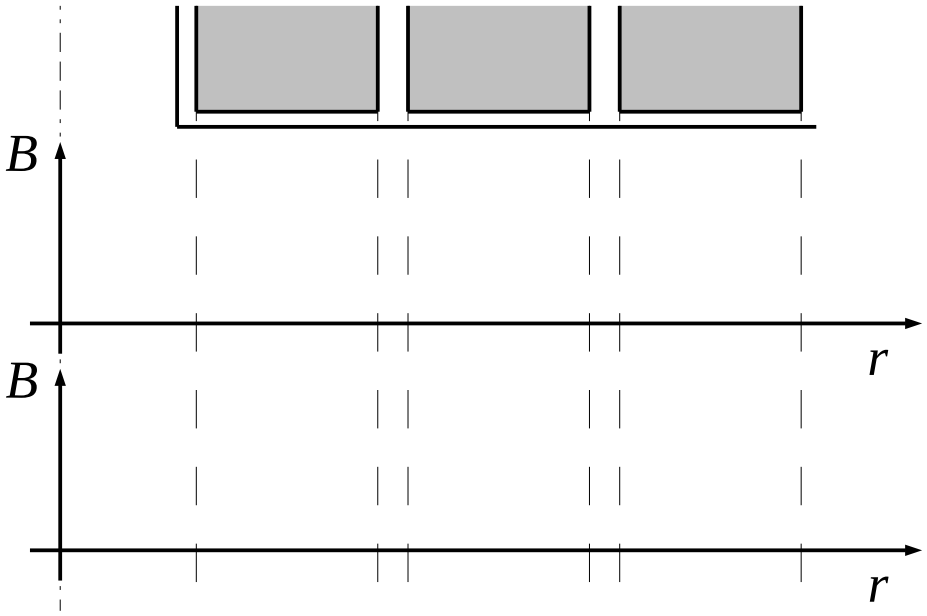


- magnetic flux interacting with the winding
= for calculation of magnetizing and leakage reactance

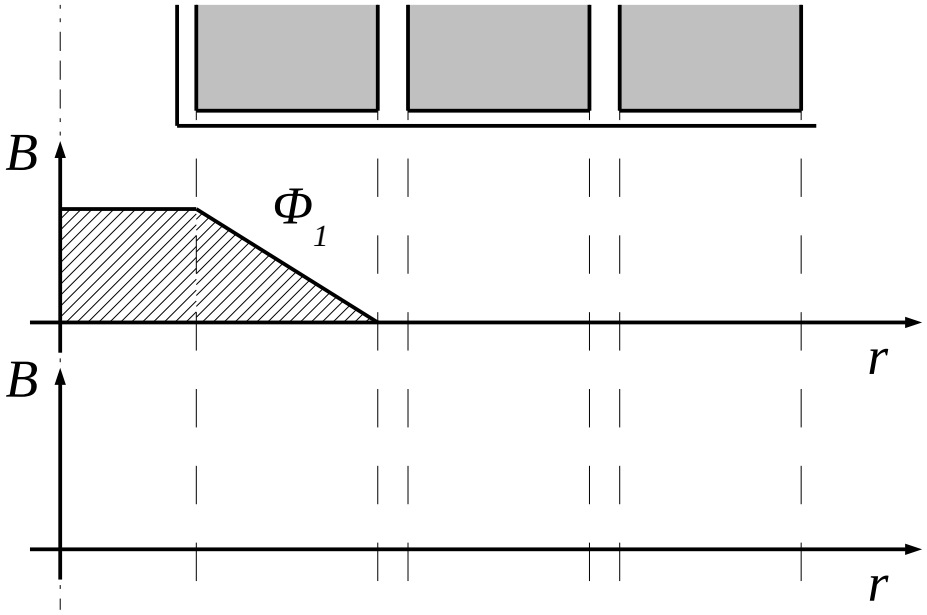
$$X_1 = X_\mu + X_{1\sigma} = X_\mu + \omega L_{1\sigma}$$

$$X_1 = X_\mu + \omega \frac{k \Phi_1}{I_1}$$

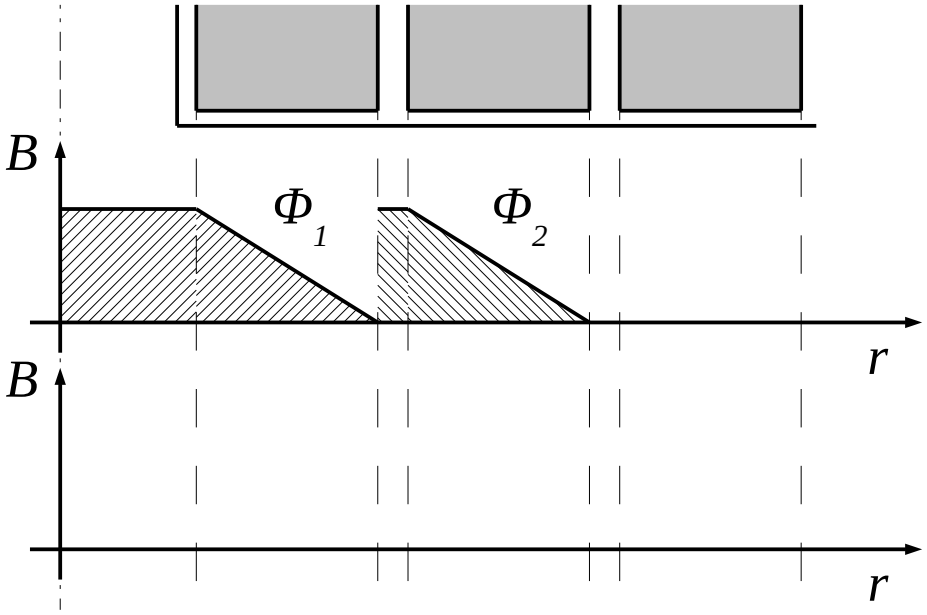
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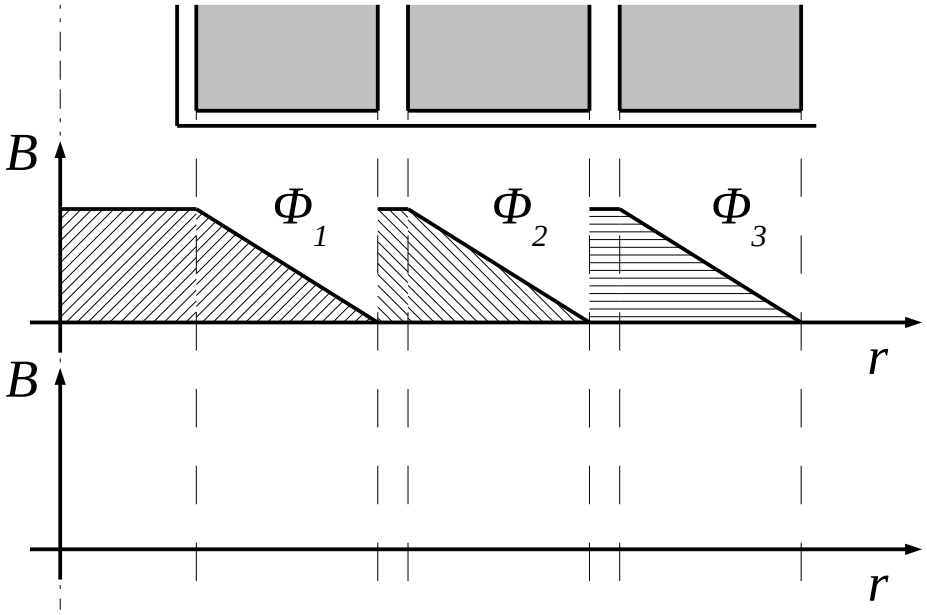
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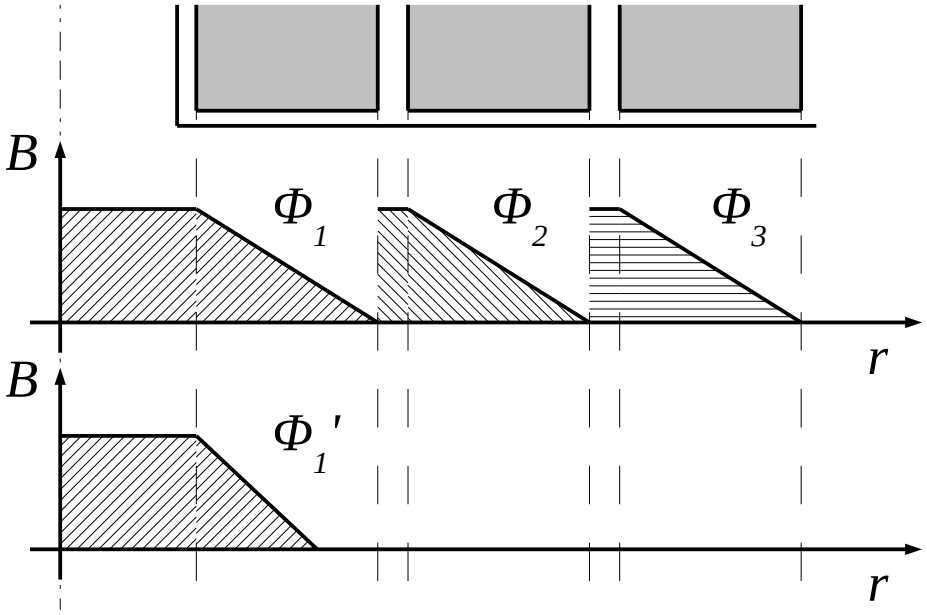
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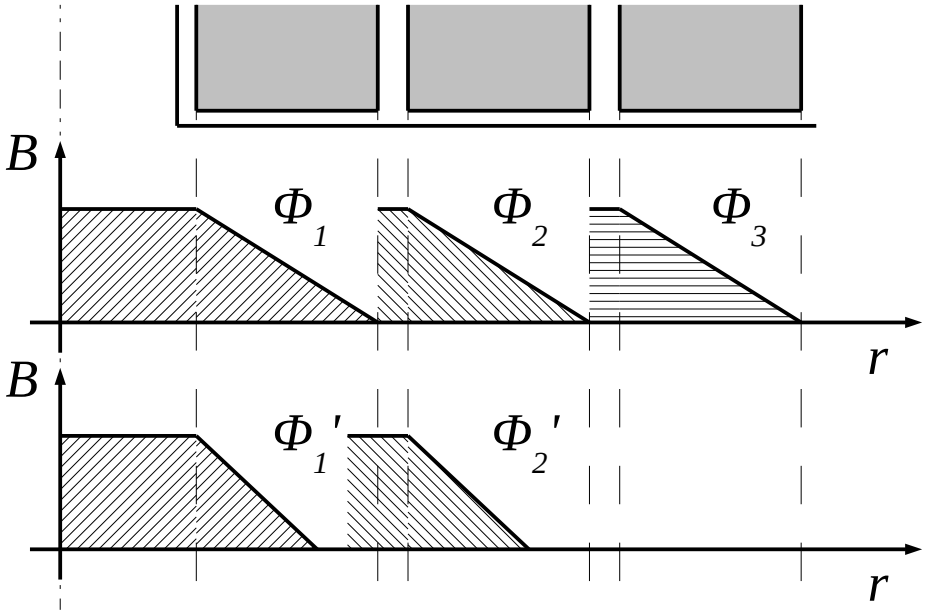
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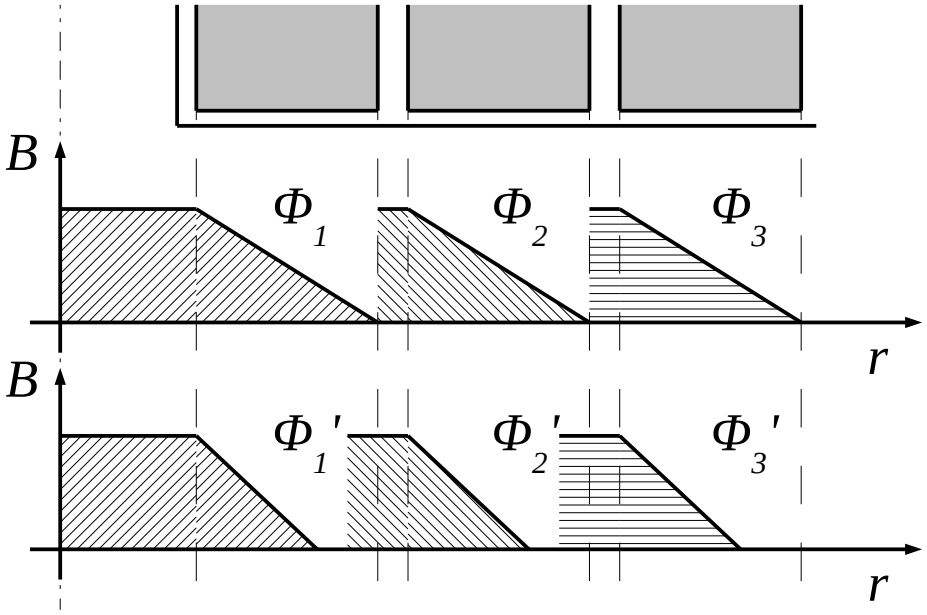
The Proof of Negative Value of ξ_2



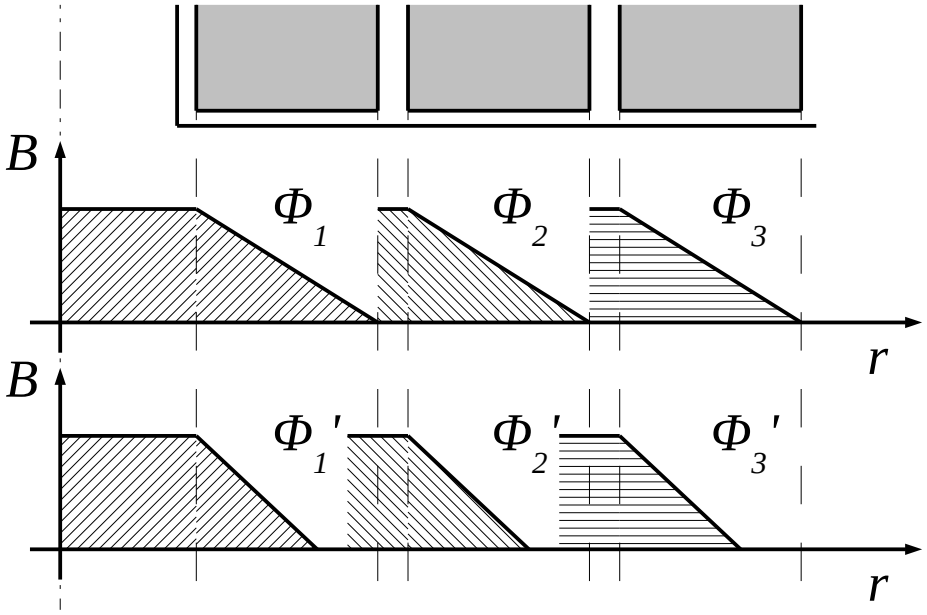
The Proof of Negative Value of ξ_2



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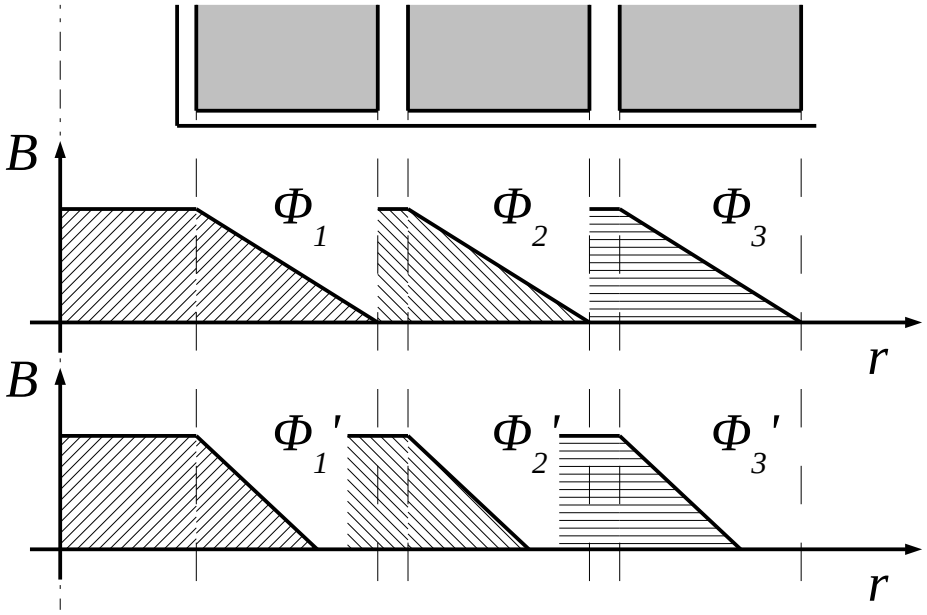
The Proof of Negative Value of ξ_2



→ magnetic fluxes excited by windings

→ mag. fluxes interacting with windings

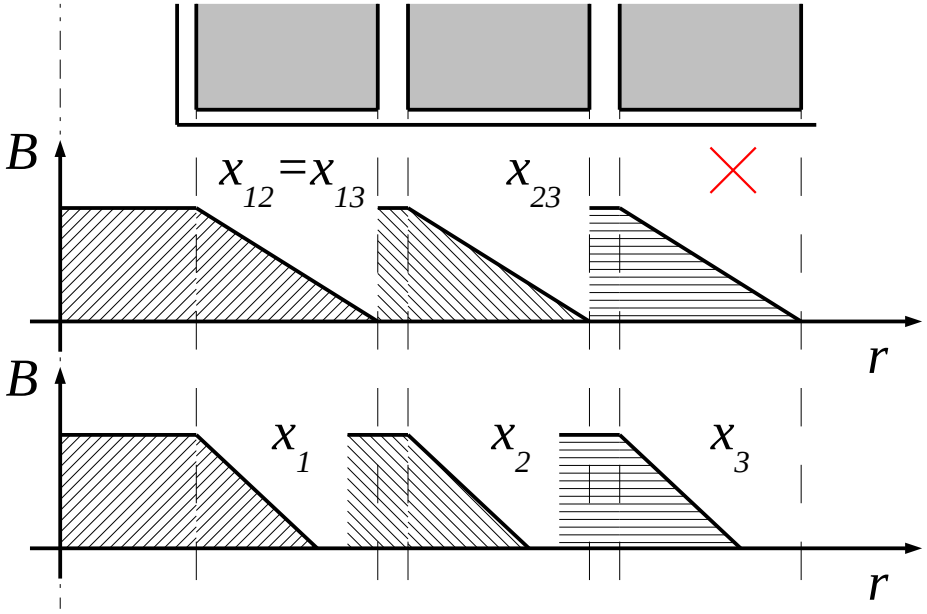
The Proof of Negative Value of ξ_2



→ magnetic fluxes excited by windings
=> mutual reactances

→ mag. fluxes interacting with windings
=> magnetizing and leakage reactances

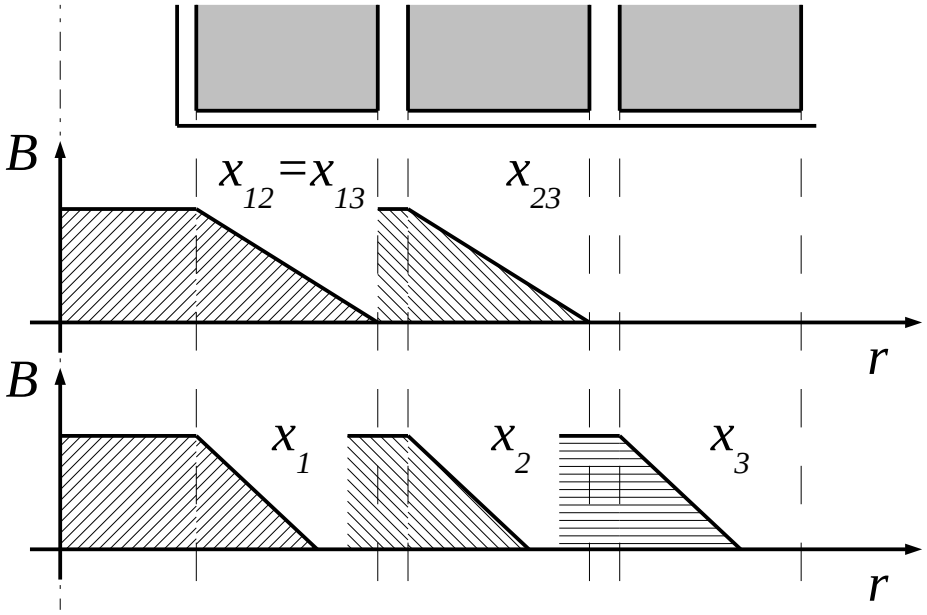
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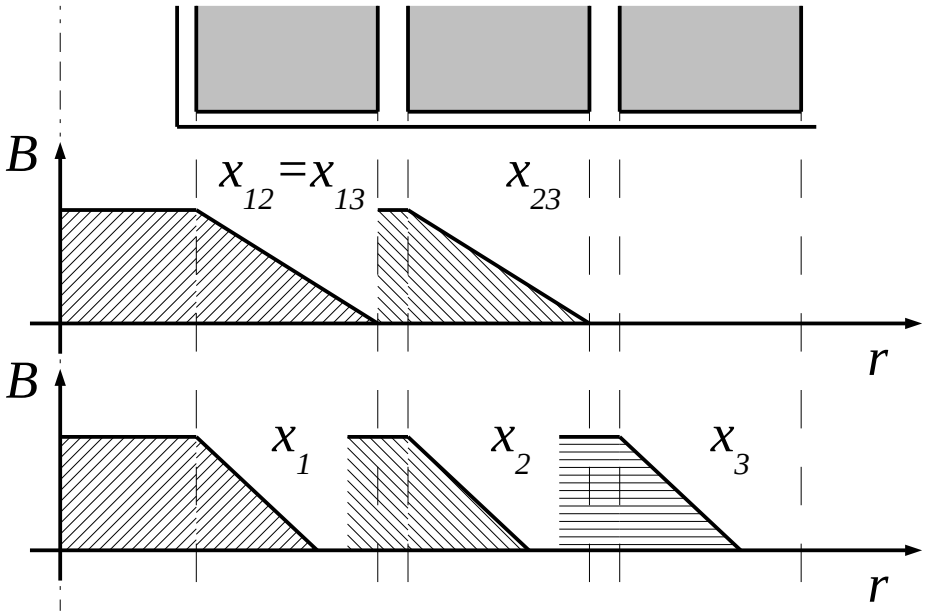
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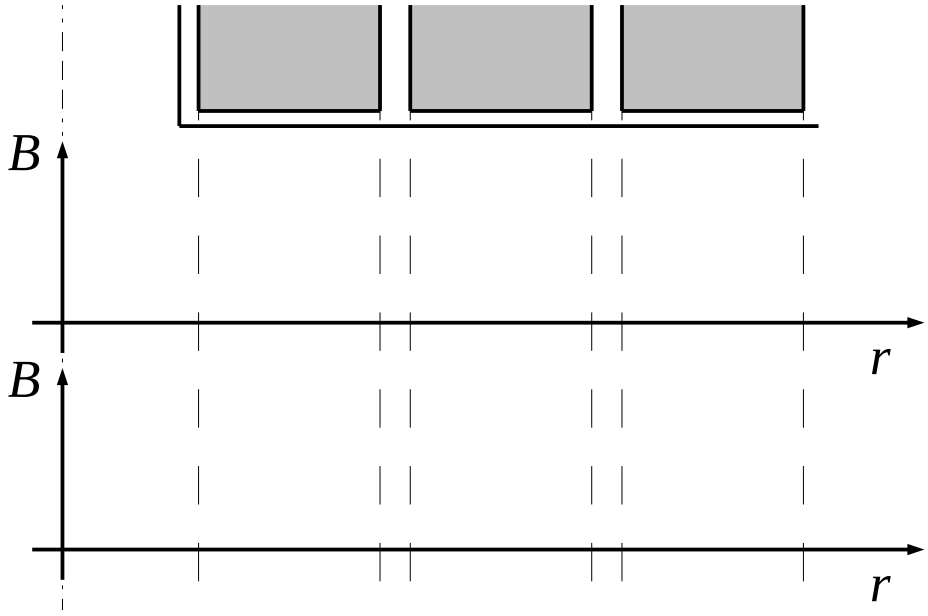


...not let us try to determine the values of each reactance according to

$$\xi_1 = \left(x_{23} - x_{13}\right) - \left(x_{12} - x_1\right)$$
$$\xi_2 = \left(x_2 - x_{23}\right) - \left(x_{12} - x_{13}\right)$$
$$\xi_3 = \left(x_3 - x_{23}\right) - \left(x_{13} - x_{12}\right)$$

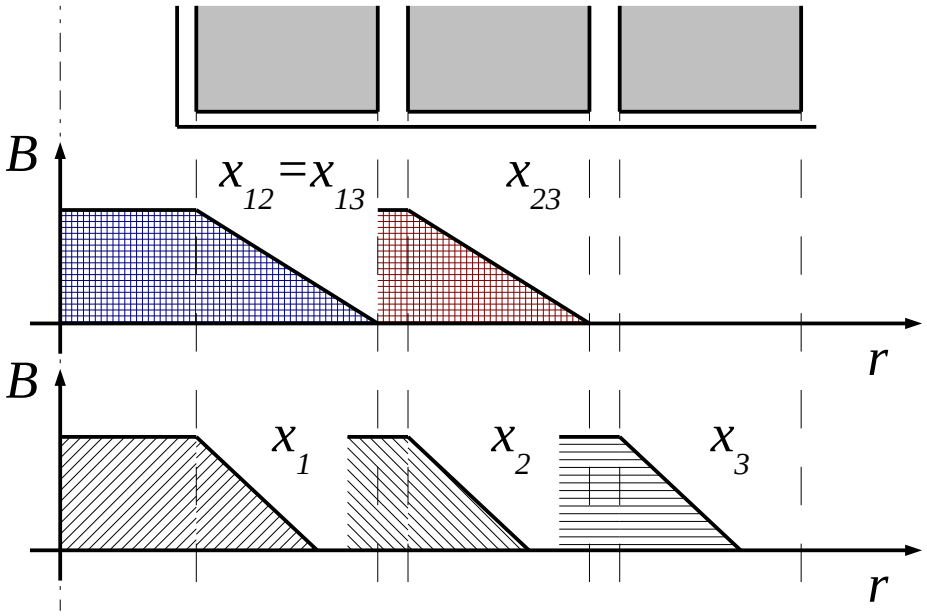
The Proof of Negative Value of ξ_2

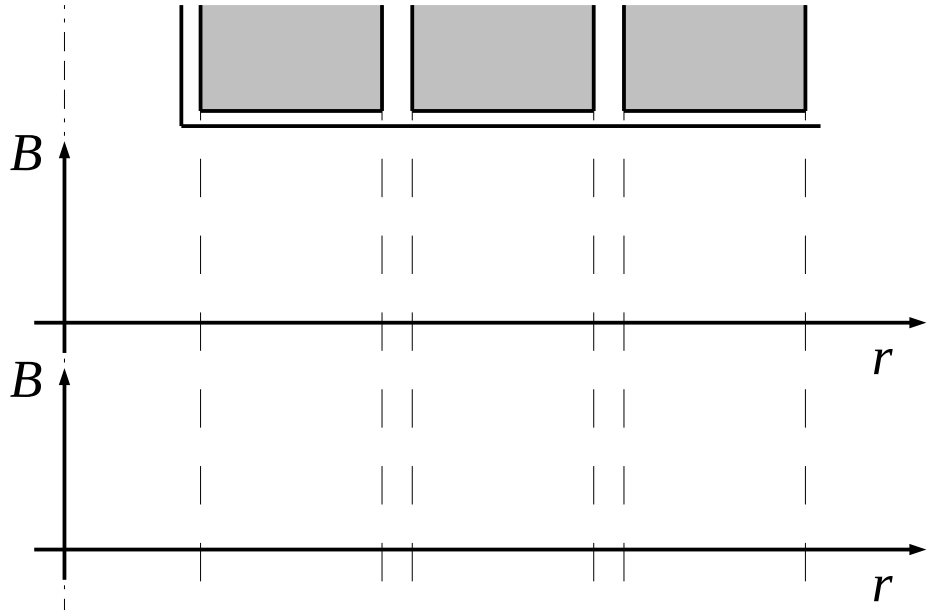




$$\xi_1=\left(x_{23}-x_{13}\right)-\left(x_{12}-x_1\right)$$

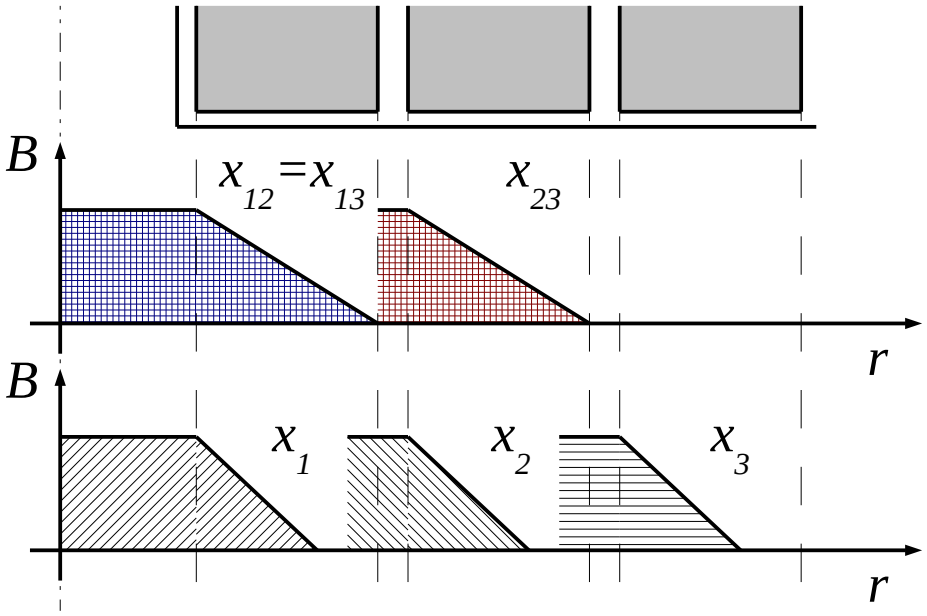
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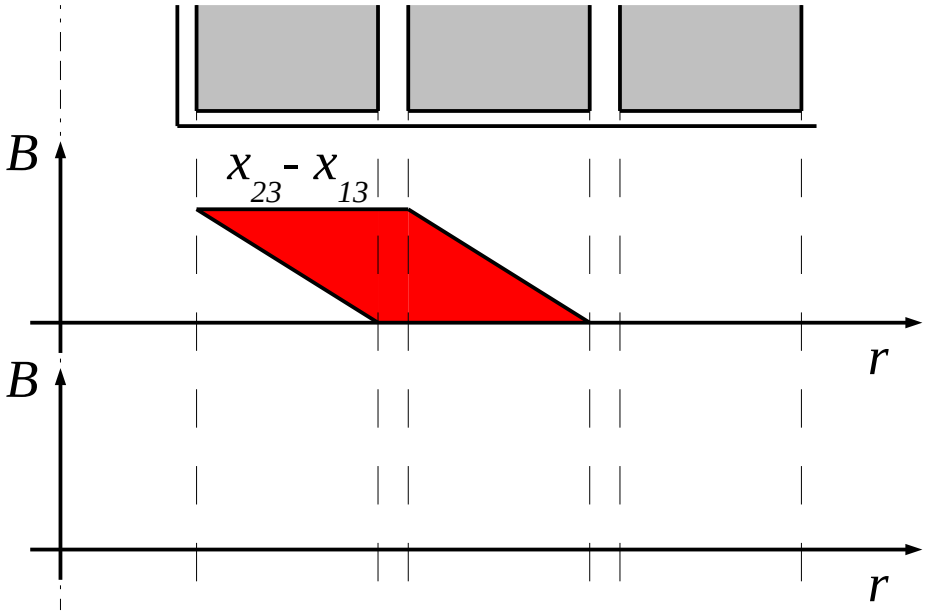




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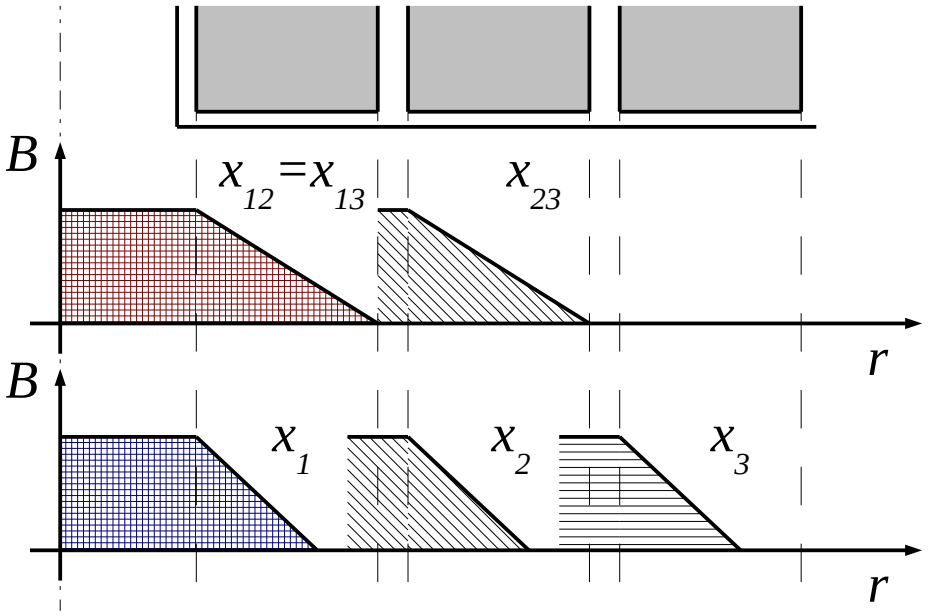
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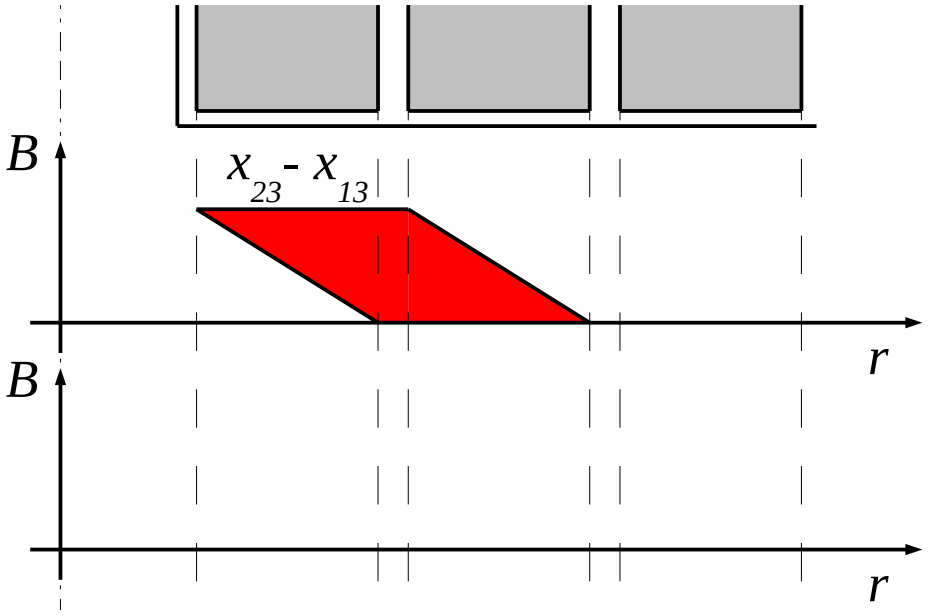




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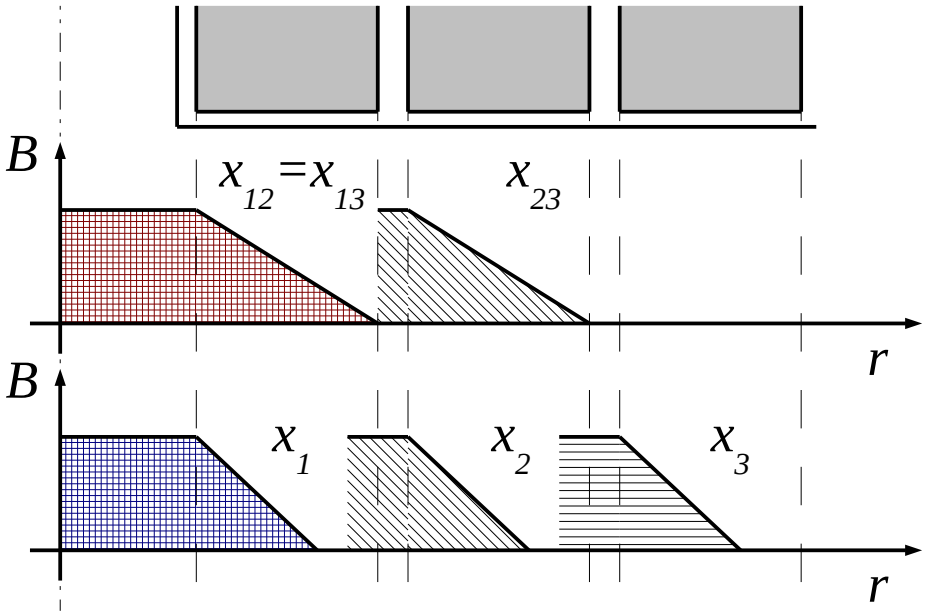
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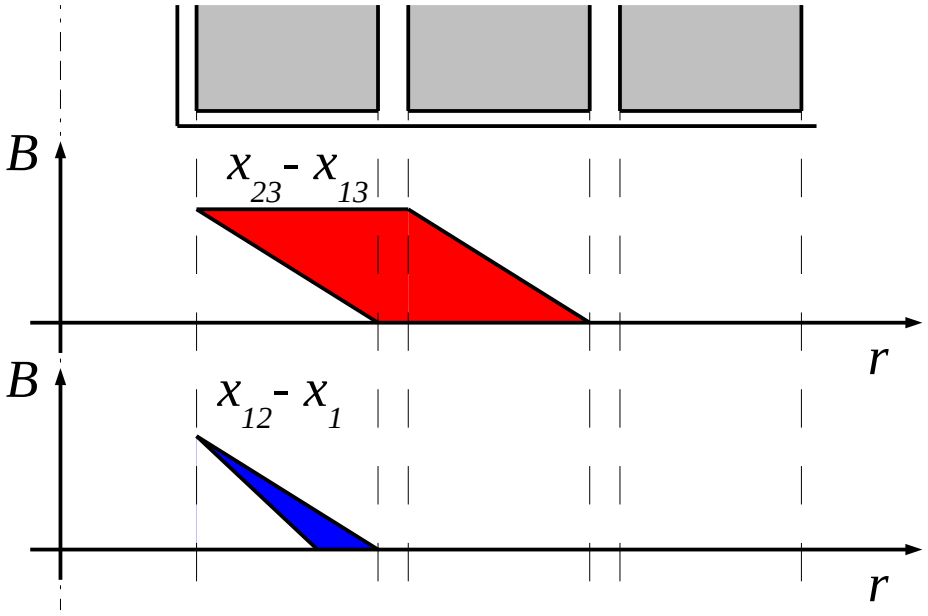




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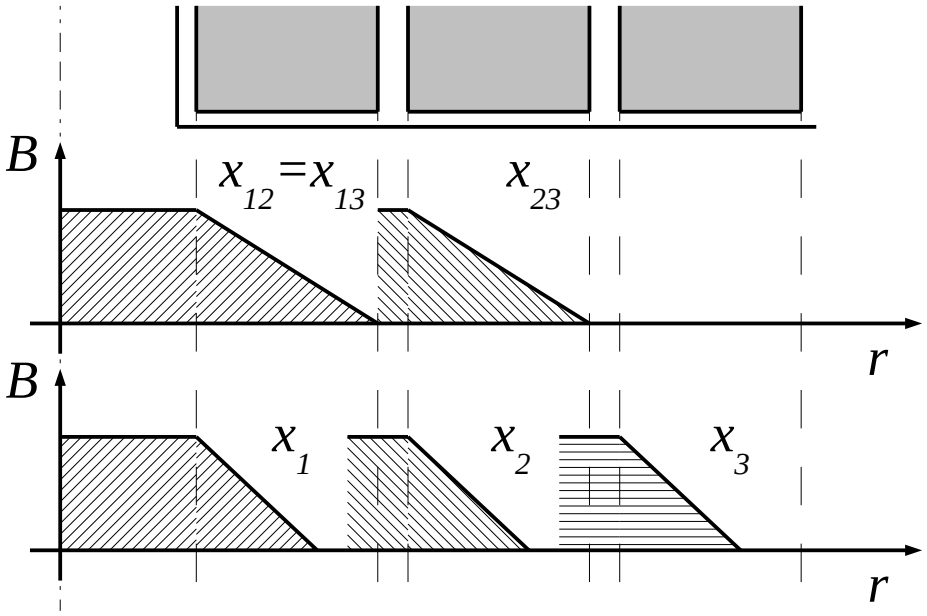
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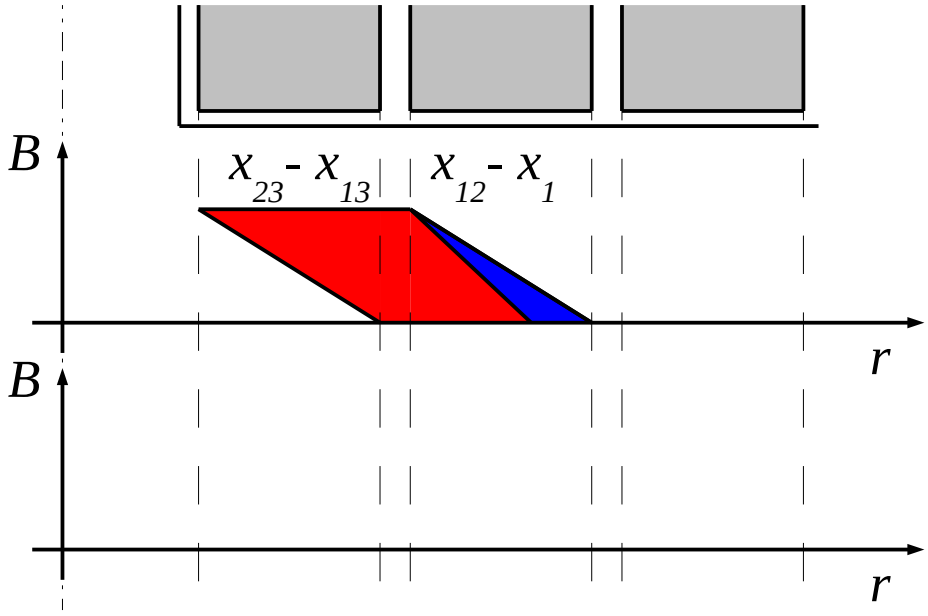




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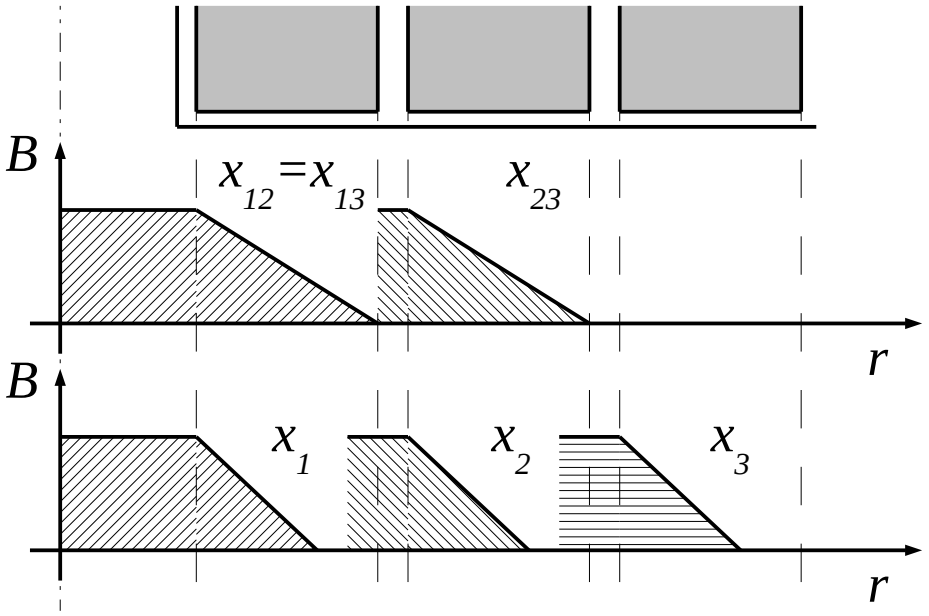
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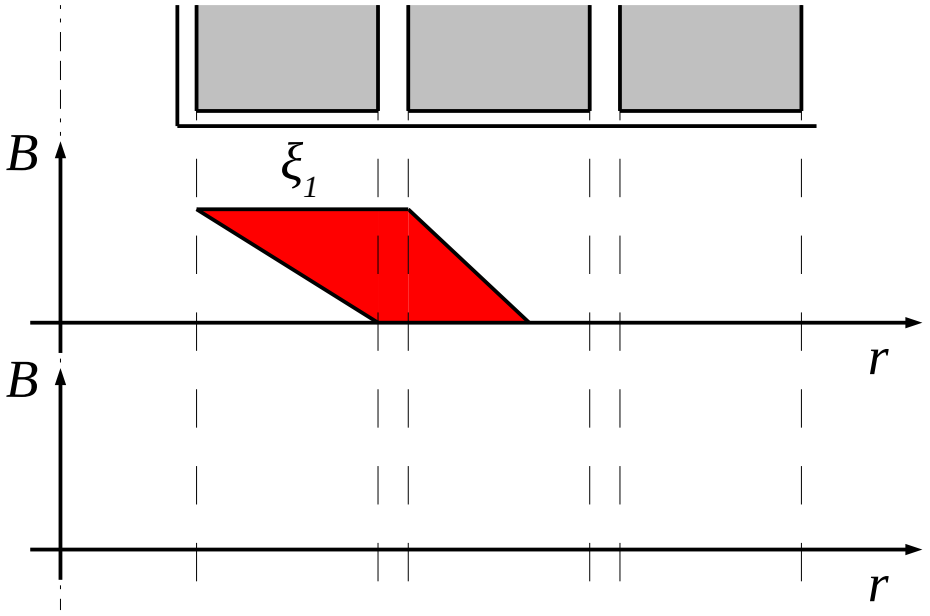




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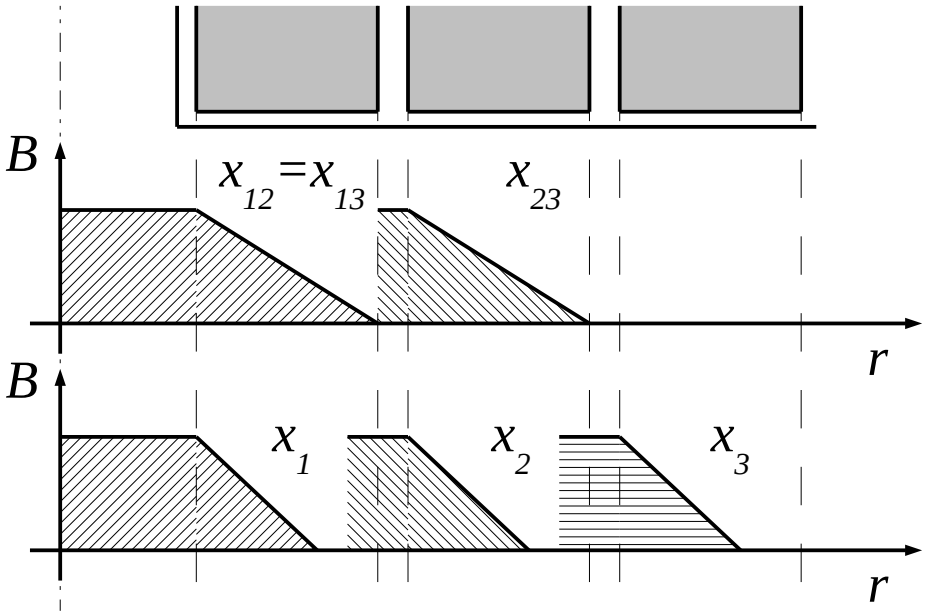
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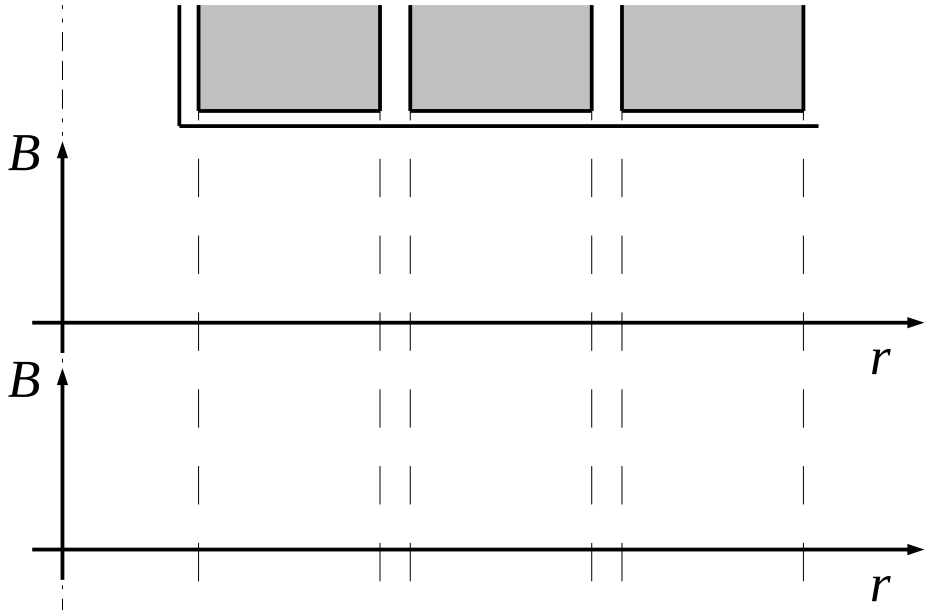




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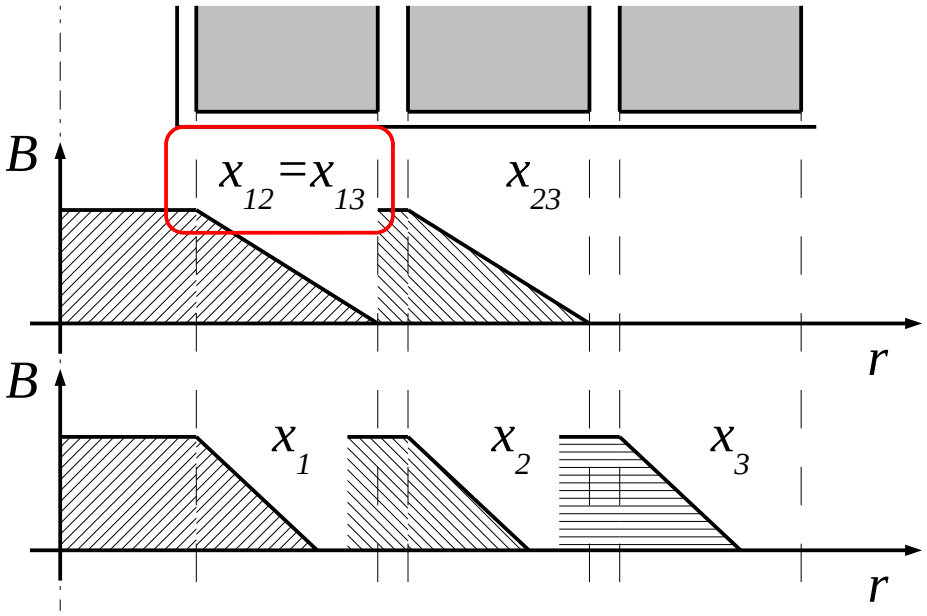
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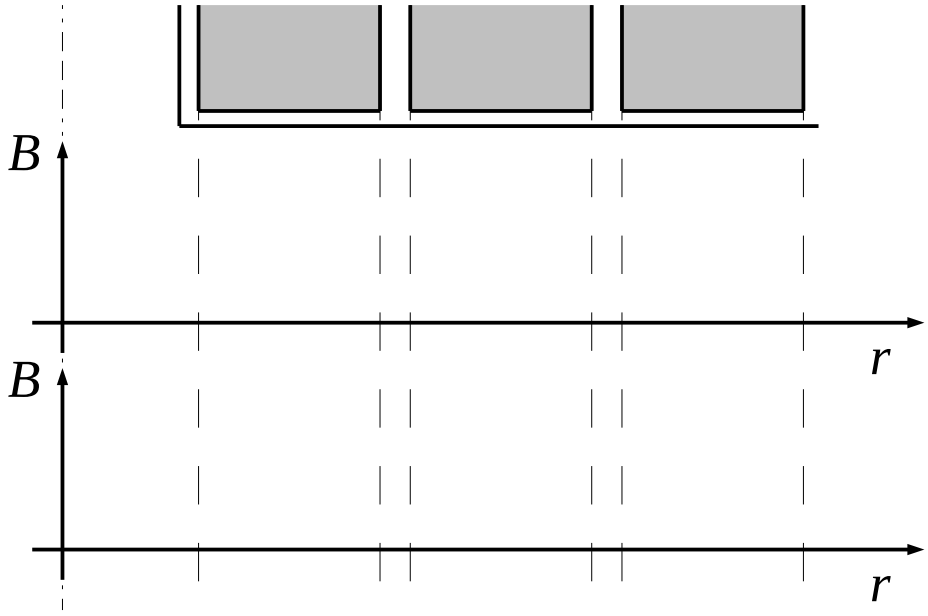




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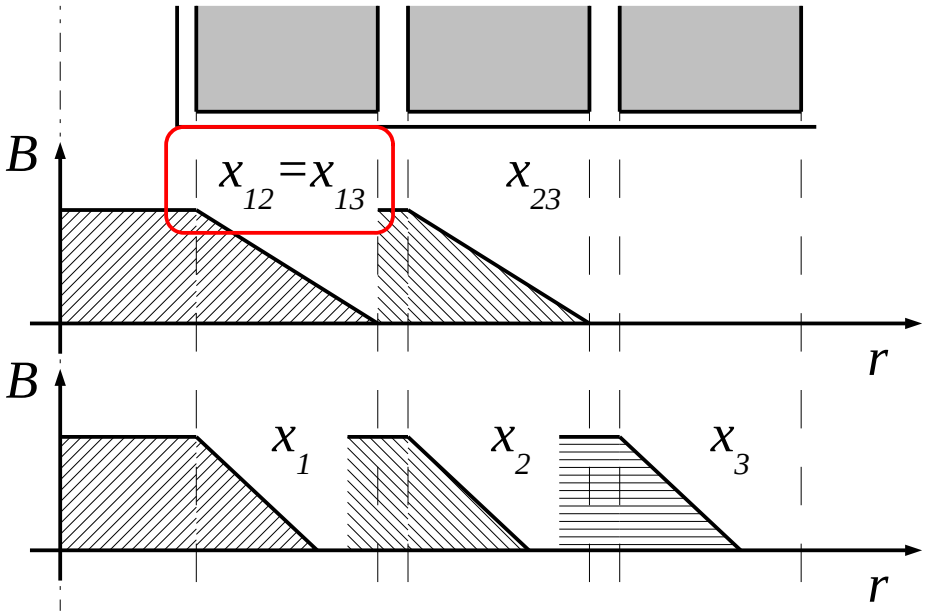
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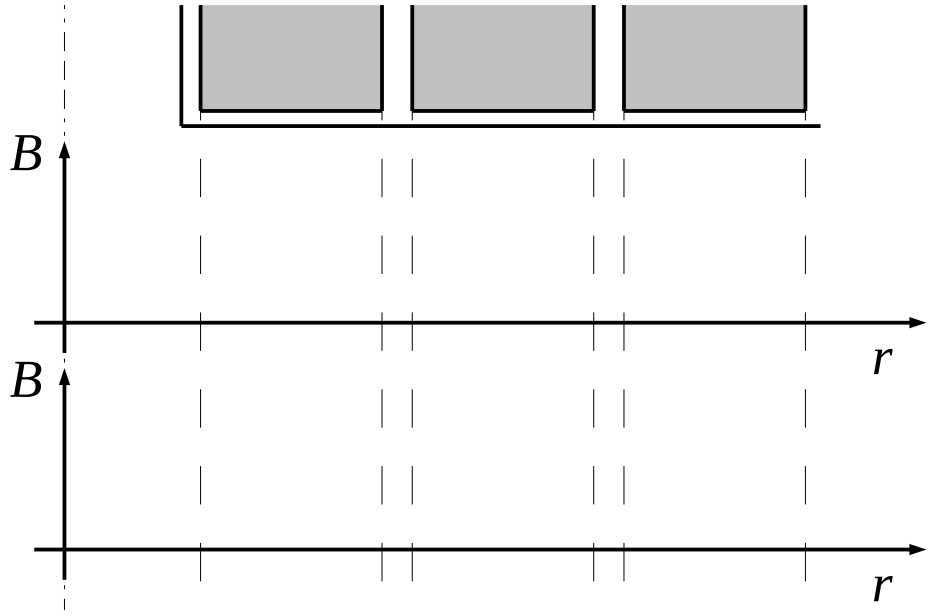




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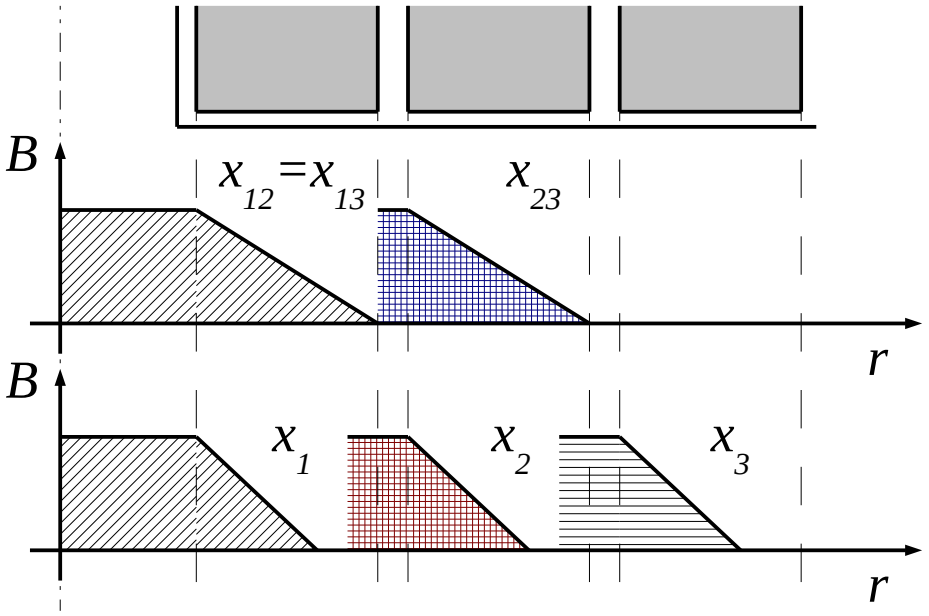
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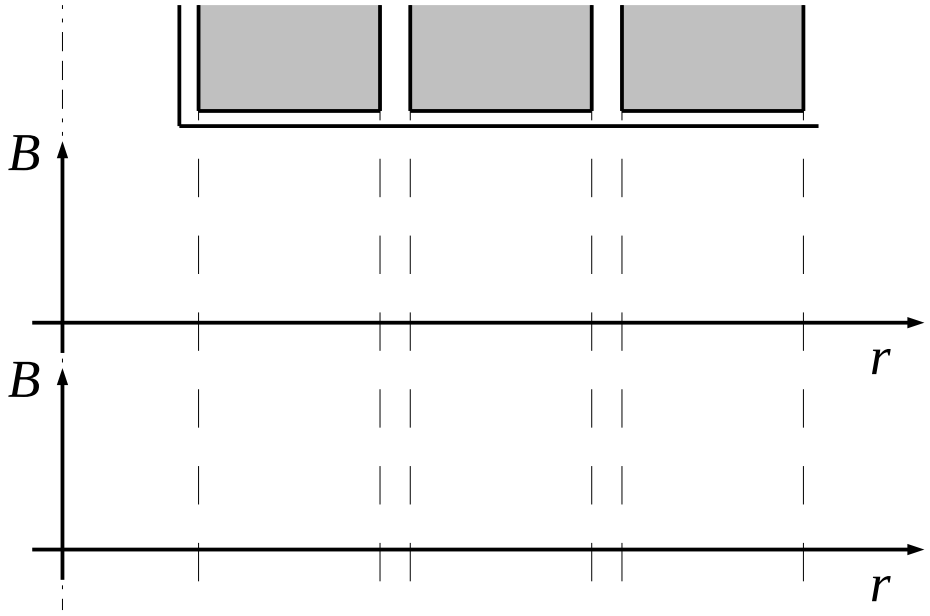




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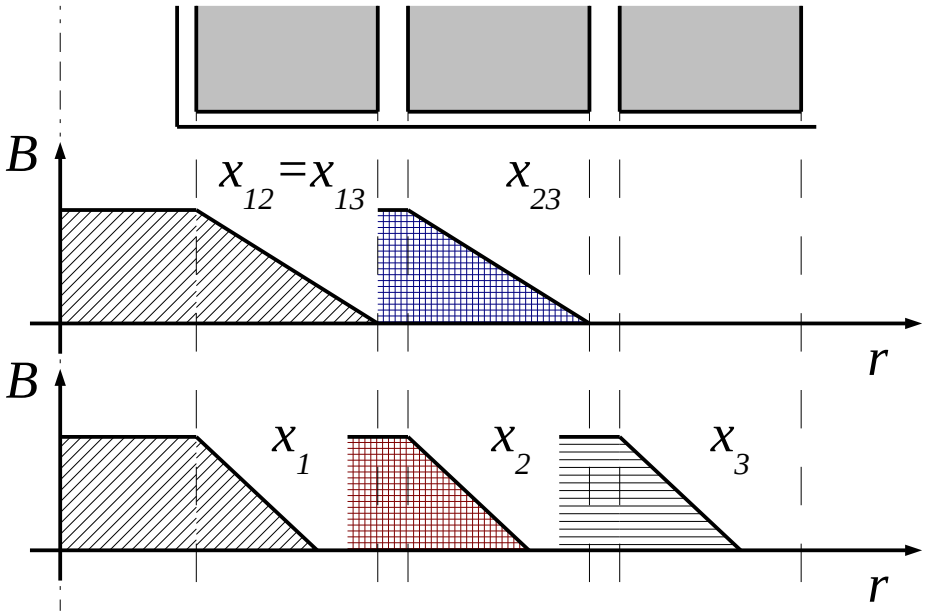
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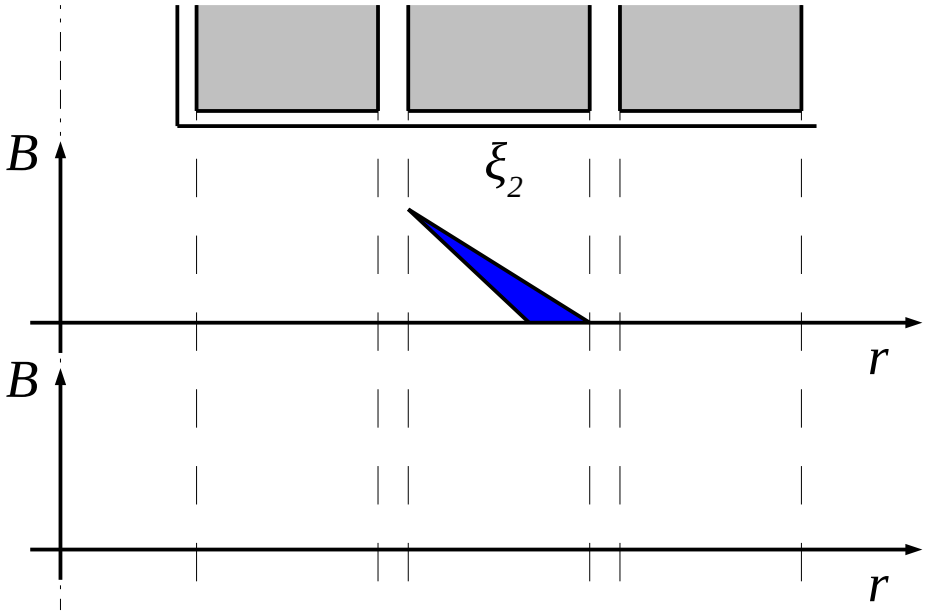




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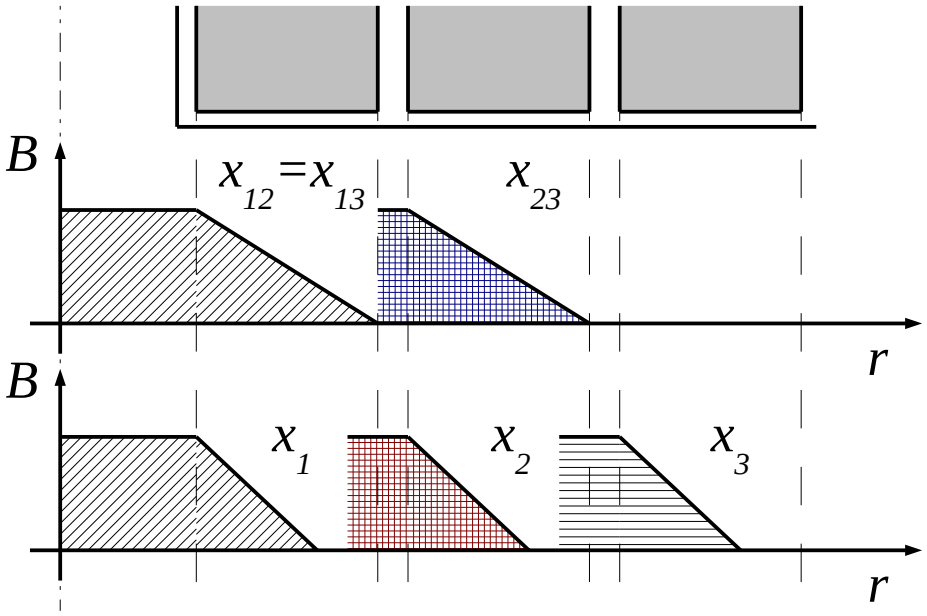
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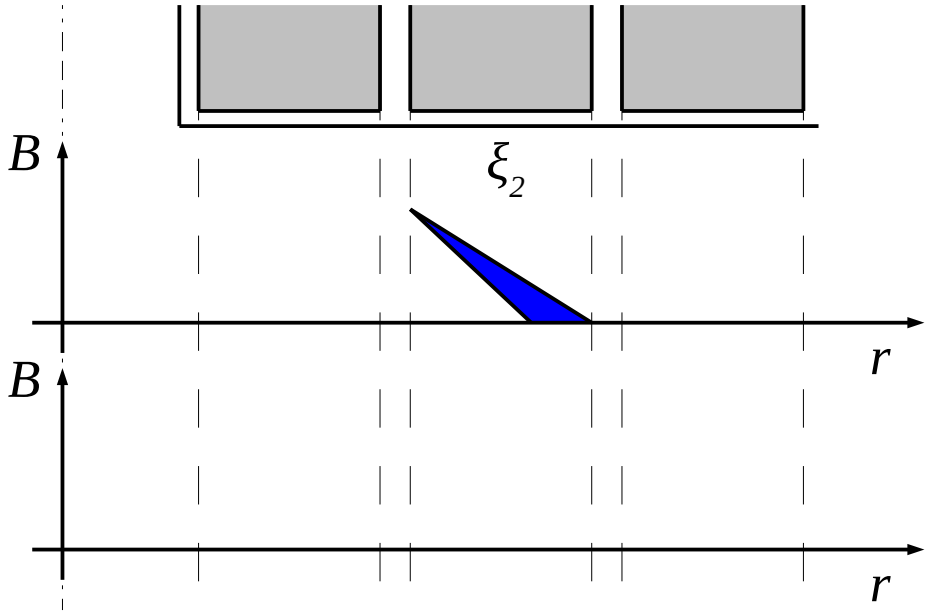




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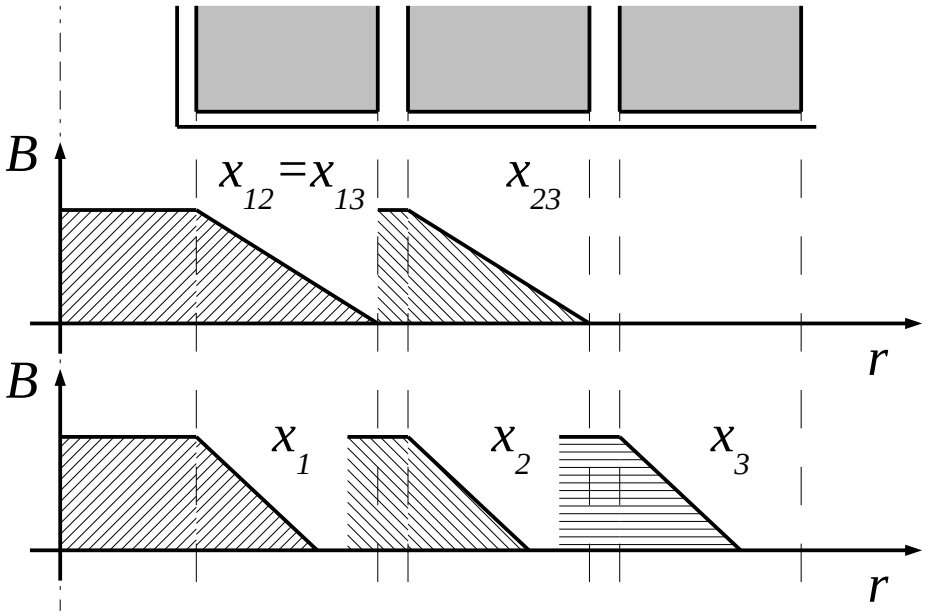


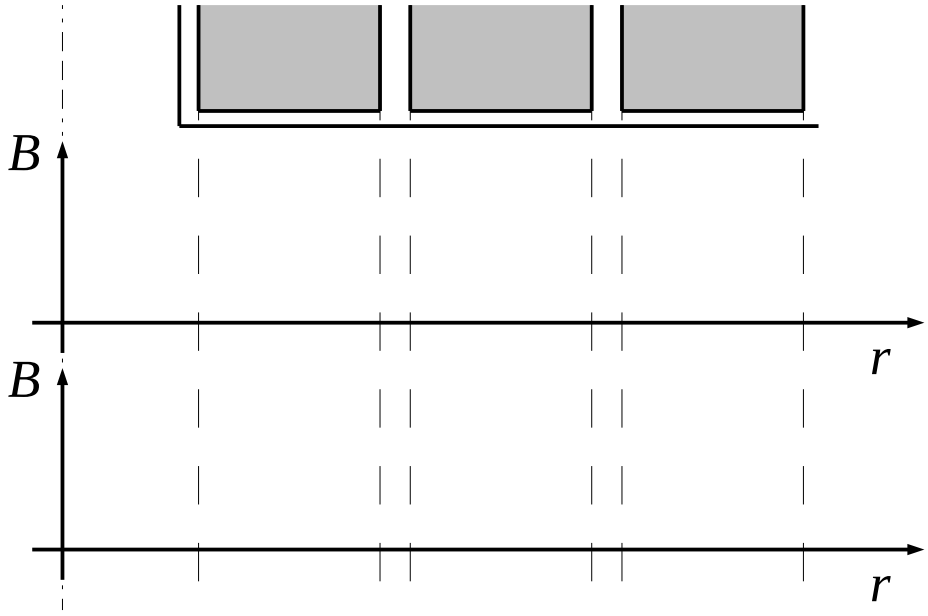


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!!! ξ_2 results negative !!!

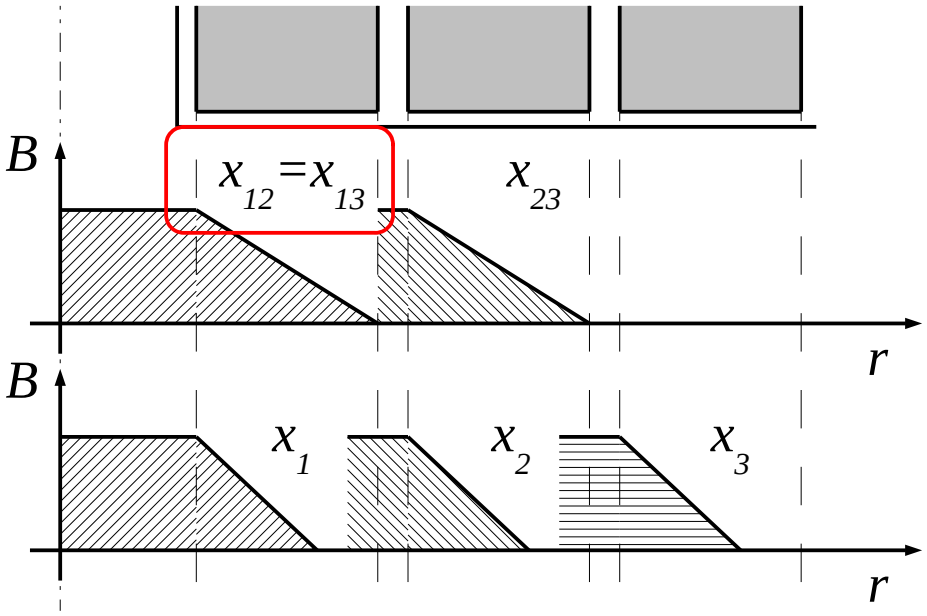
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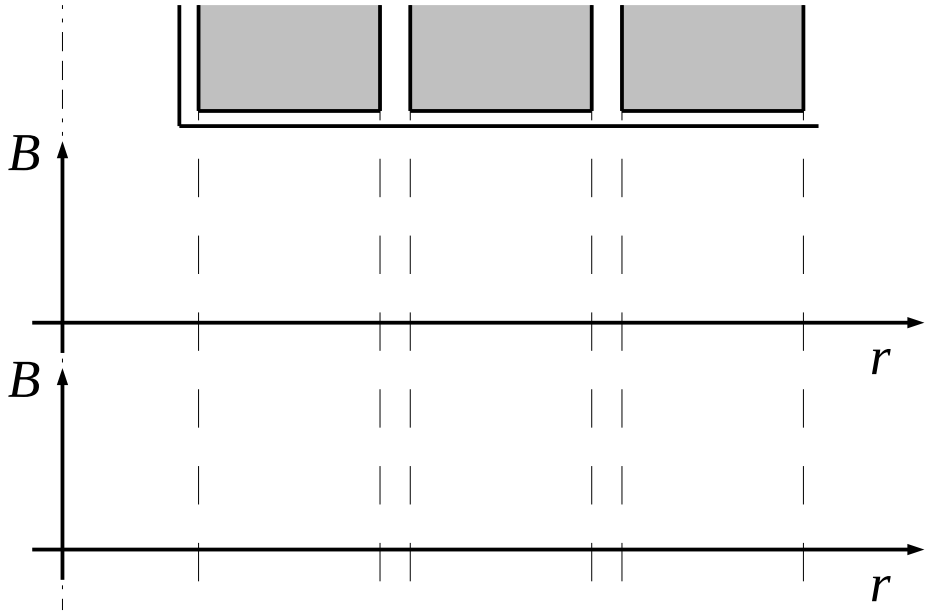




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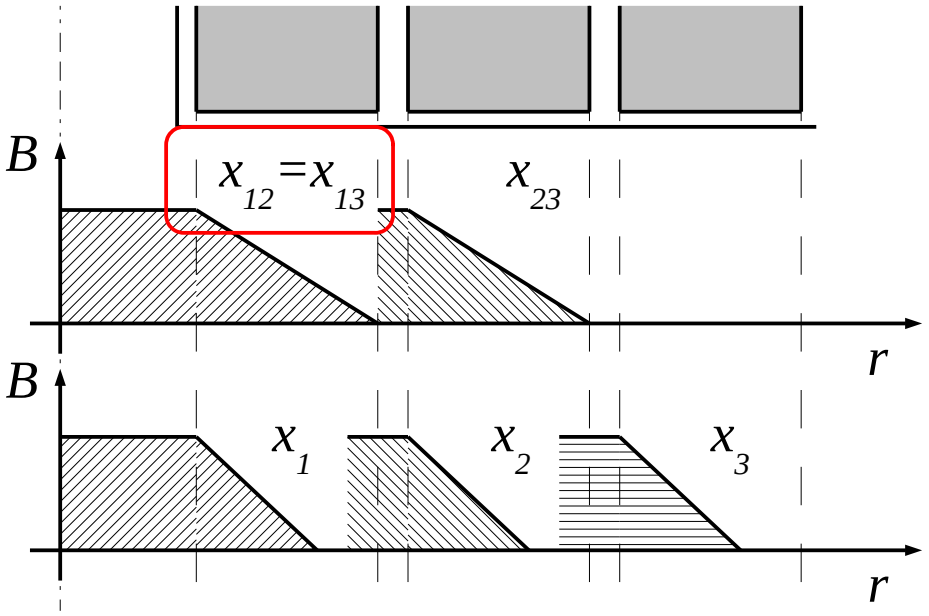
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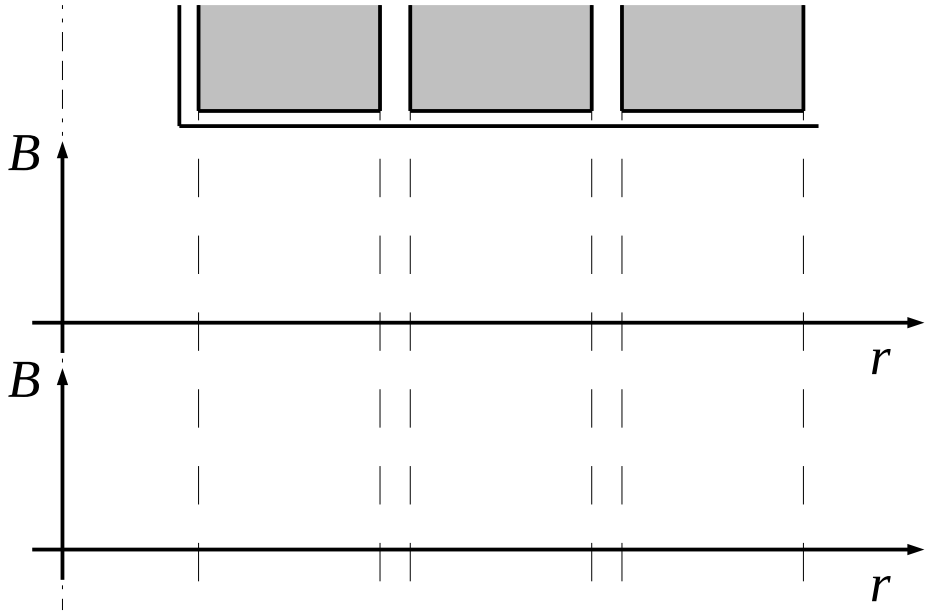




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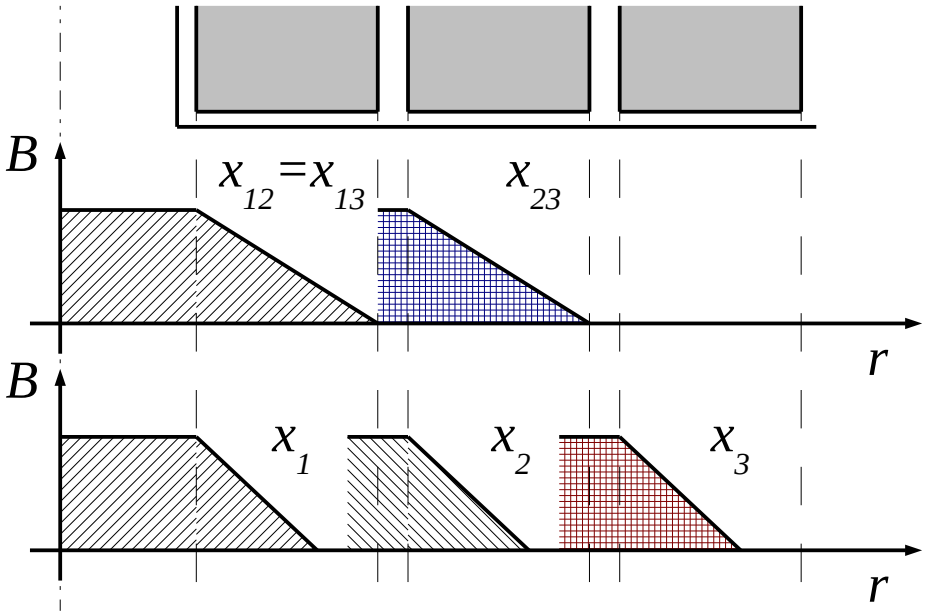
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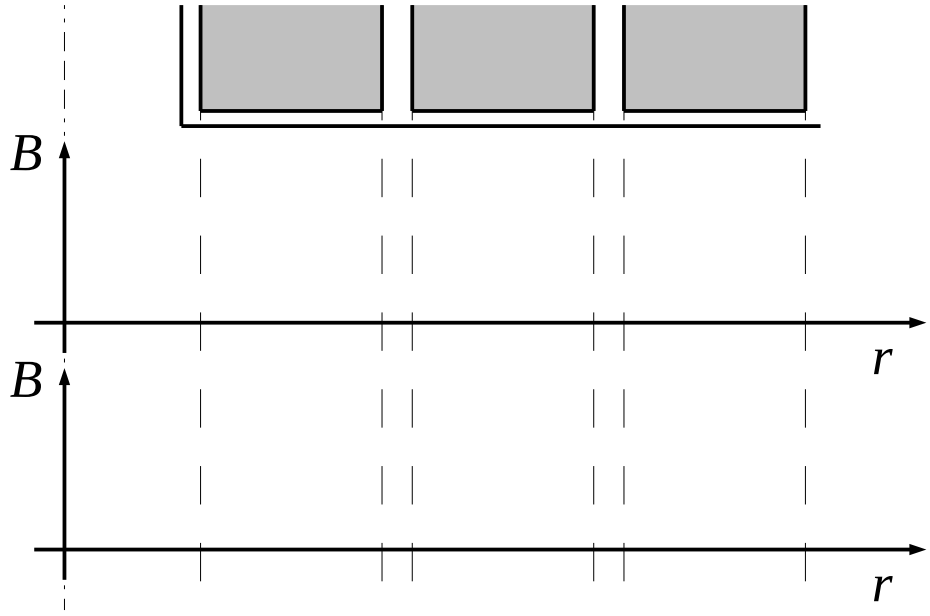




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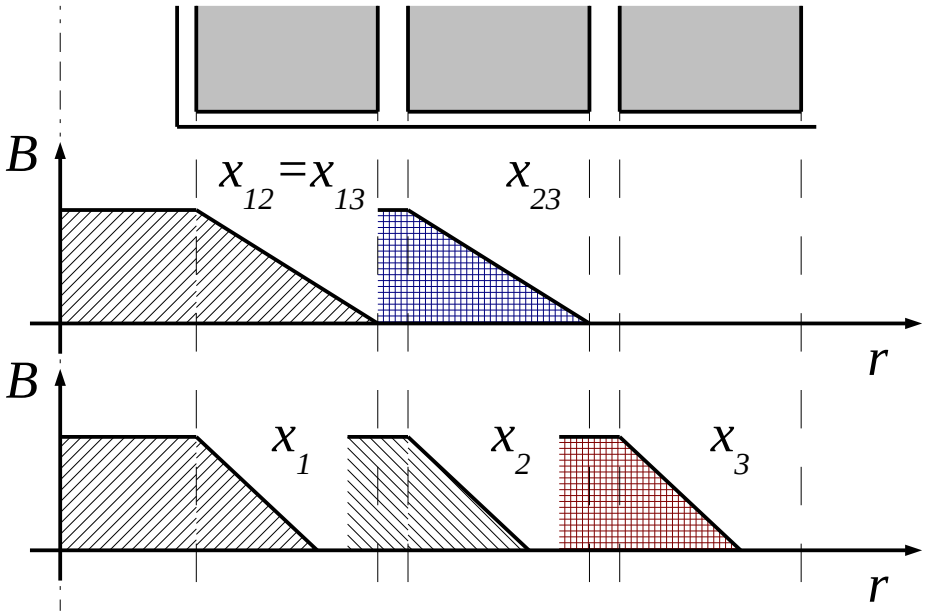
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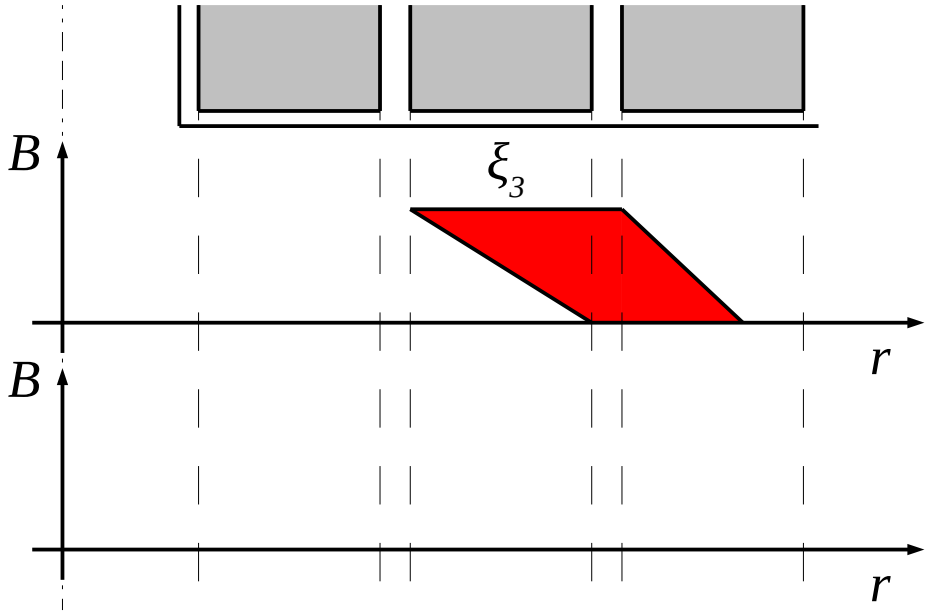




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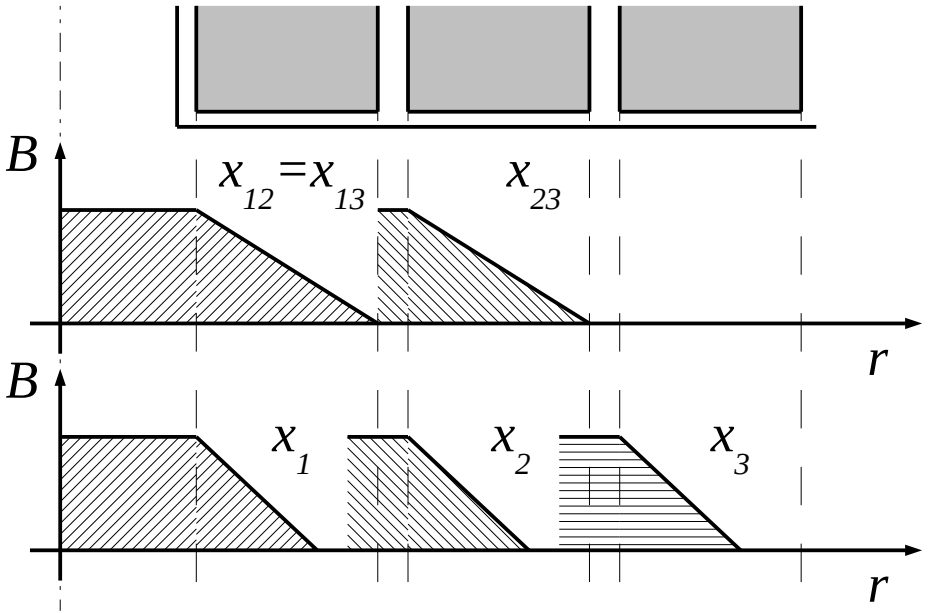
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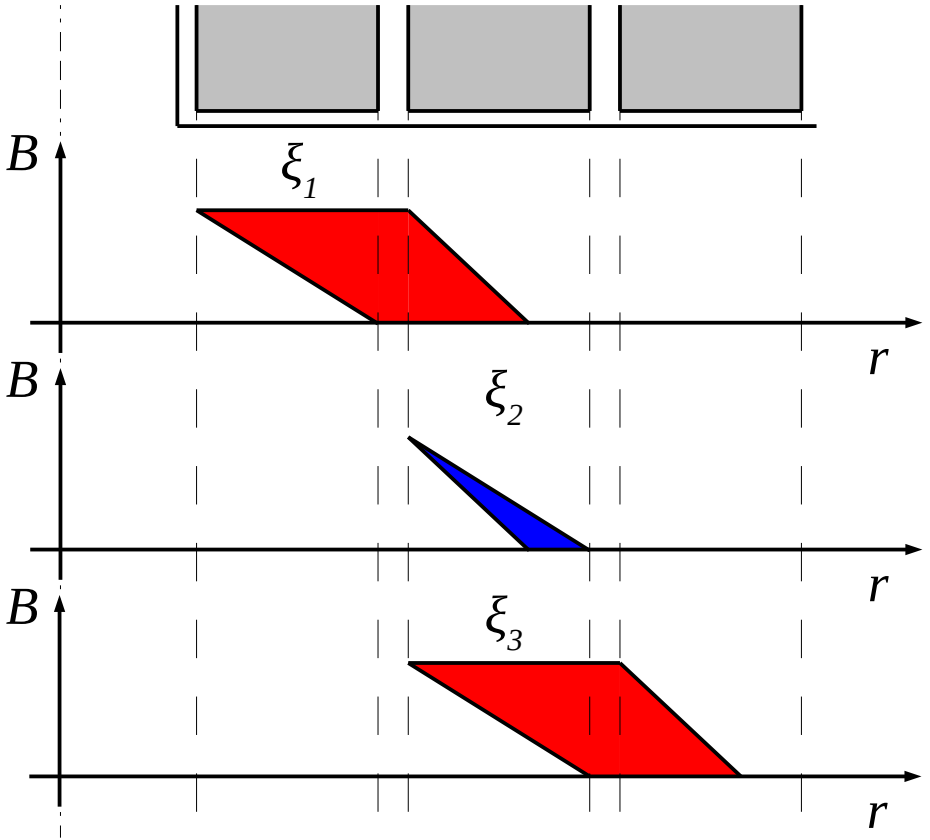


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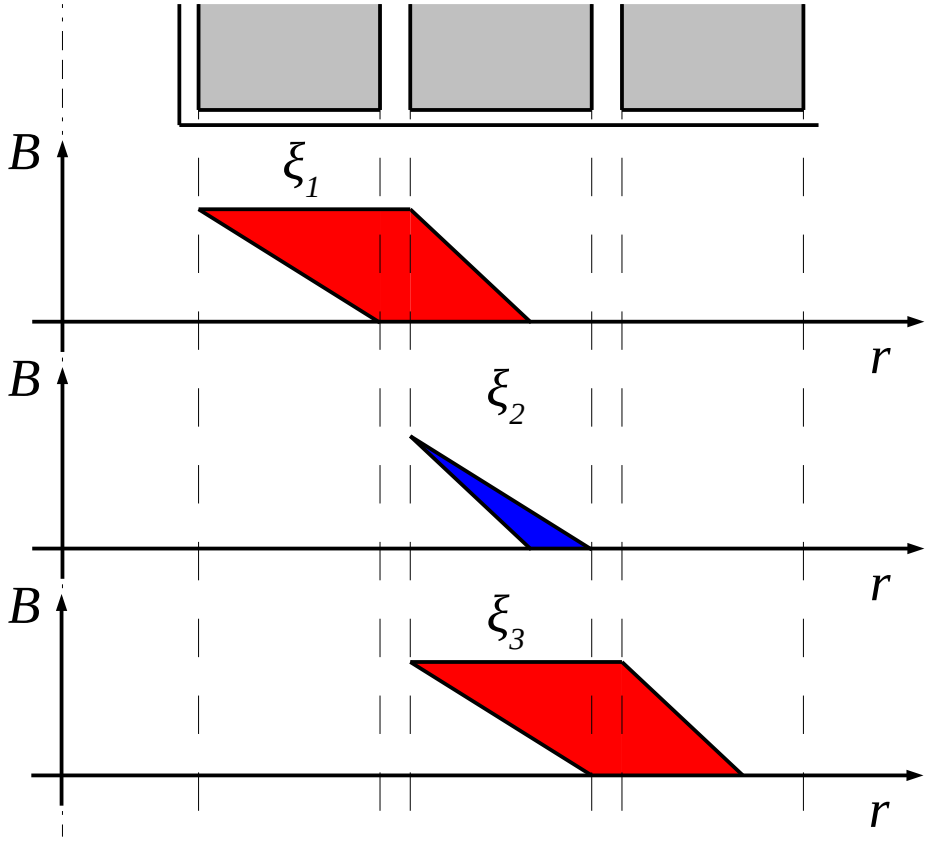
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The Proof of Negative Value of ξ_2

- Conclusion:
  - For a triple winding with concentrically wound coils is valid:

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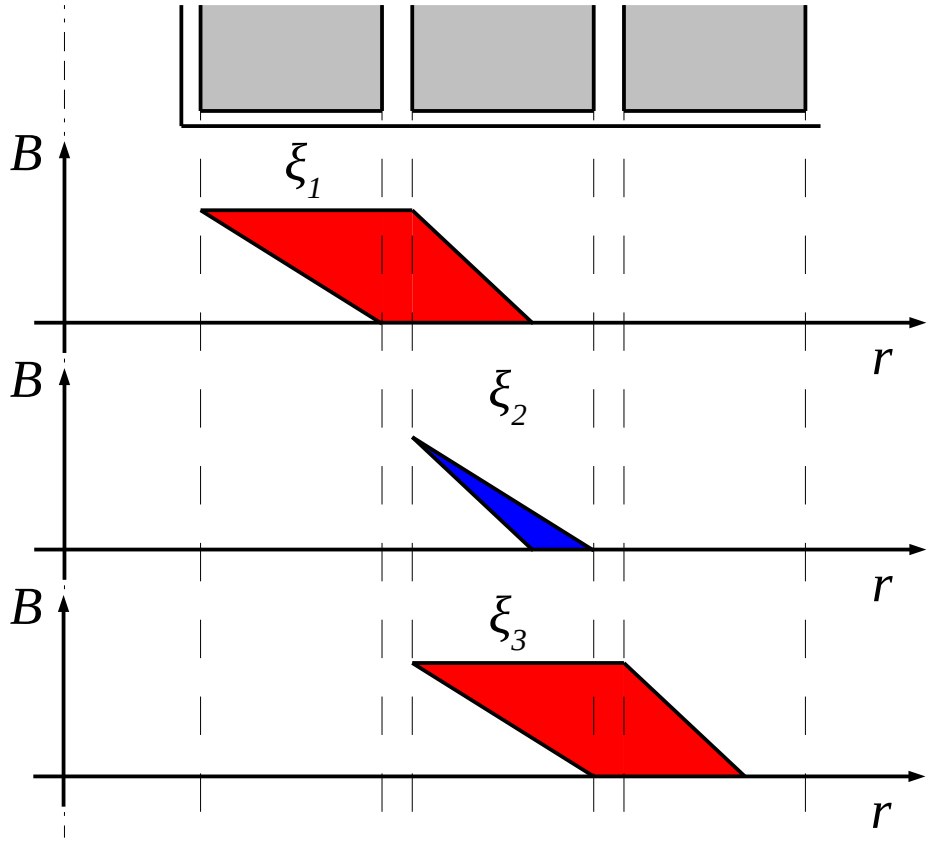


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  where ξ_1 and ξ_3 have approximately the same value, ξ_2 is significantly lower and negative in value

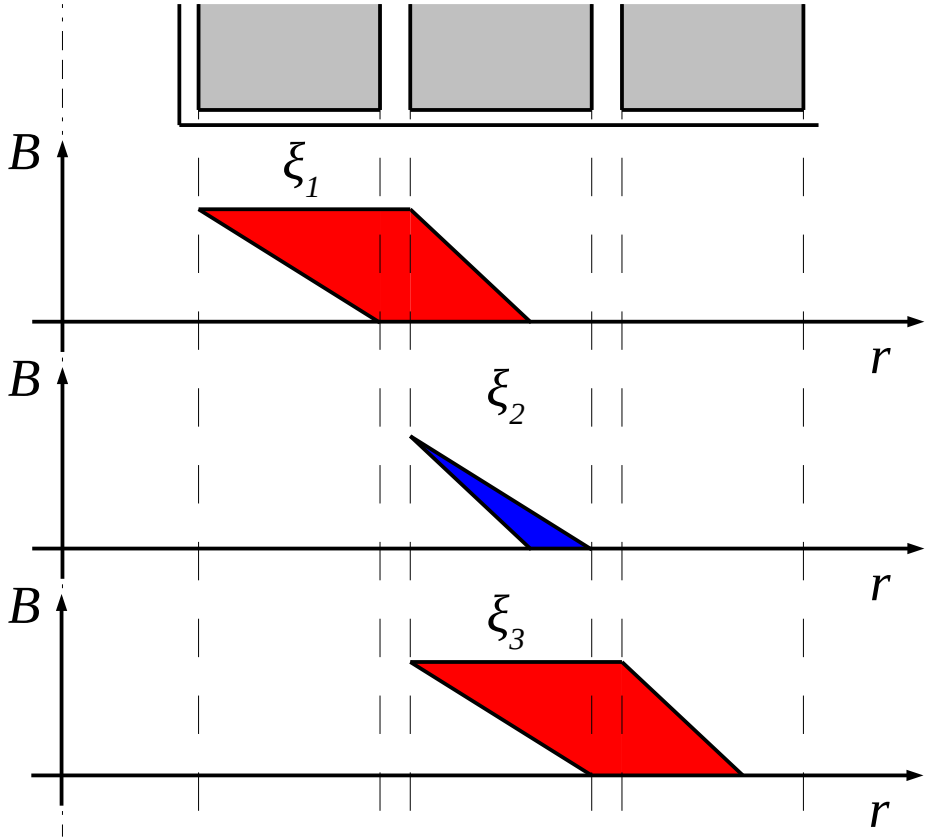


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    where ξ_1 and ξ_3 have approximately the same value, ξ_2 is significantly lower and negative in value
  - Physical proof see measurement :-)



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EVROPSKÁ UNIE
Evropské strukturální a investiční fondy
Operační program Výzkum, vývoj a vzdělávání

MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY

ESF II – project of the University of West Bohemia
reg. no. CZ.02.2.69/0.0/0.0/18_056/0013239

Non-Symmetric Transformer Load

Non-Symmetric Transformer Load

- Non-symmetric transformer load
  = load of a transformer with different composition in each phase
- Non-symmetrical current flowing from the transformer will project in non-symmetry of current flowing into the transformer and in its magnetic field
- All these components lead to additional losses
- The analysis may be performed:
  - Quantitatively: analysis of transformer connection and its field
  - Qualitatively: method of symmetric components
- The first method is able to describe the effects in non-symmetrical transformer load, the second one then speficies the value of after-effects

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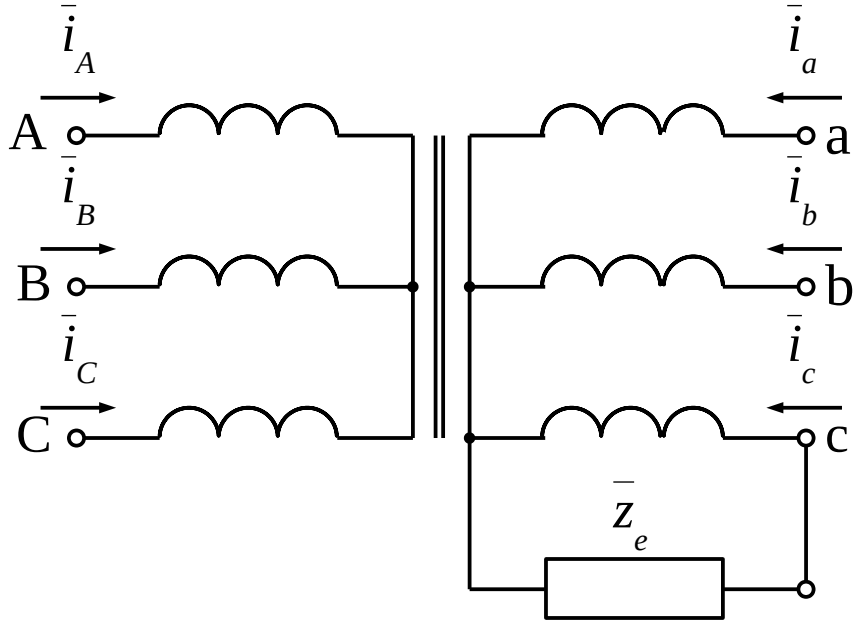
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Three Phase Transformer with a Single Phase Load (Yyn)

Three Phase Transformer with a Single Phase Load (Yyn)

- Qualitative analysis:
  - mathematical description of the transformer connection
  - description of transformer magnetic field
- Presumptions:
  - ideal transformer with $i_{\mu} = 0$
  - usage of per units

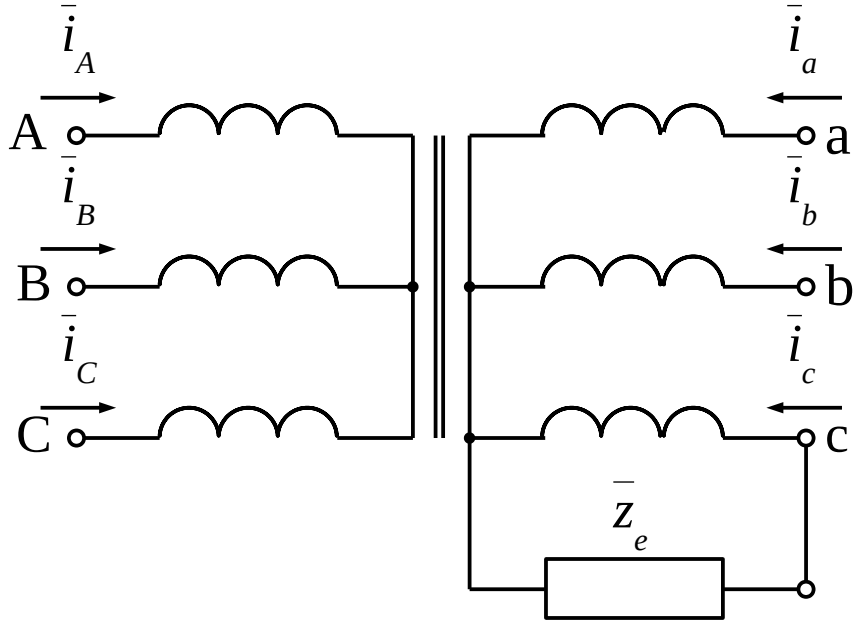
Three Phase Transformer with a Single Phase Load (Yyn)



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- For the primary winding node we have:

$$\bar{i}_A + \bar{i}_B = \bar{i}_C$$



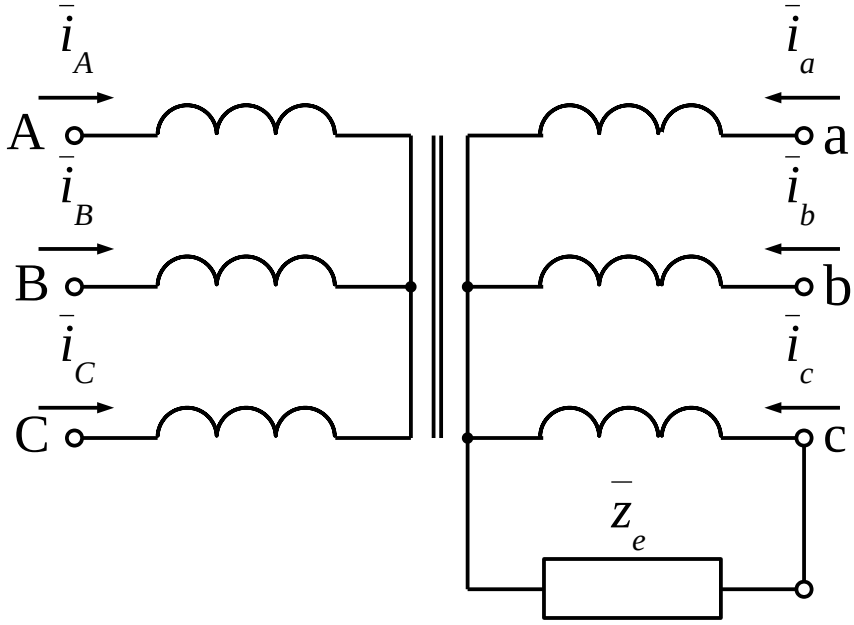
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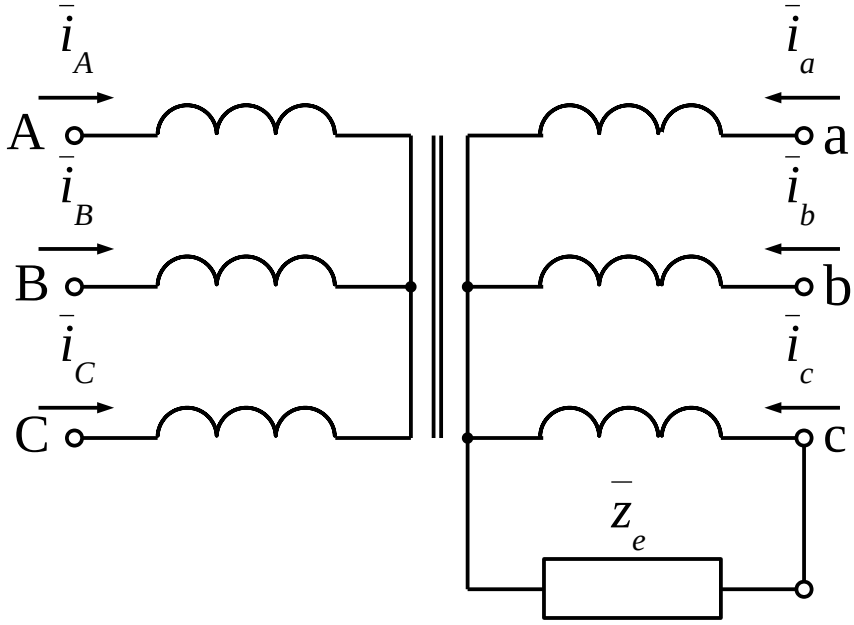
$$\bar{i}_A + \bar{i}_B = \bar{i}_C$$

- Currents in phases A and B are equal:

$$\bar{i}_A = \bar{i}_B$$

- Current through phase C is then:

$$\bar{i}_C = 2\,\bar{i}_A = 2\,\bar{i}_B$$



Three Phase Transformer with a Single Phase Load (Yyn)

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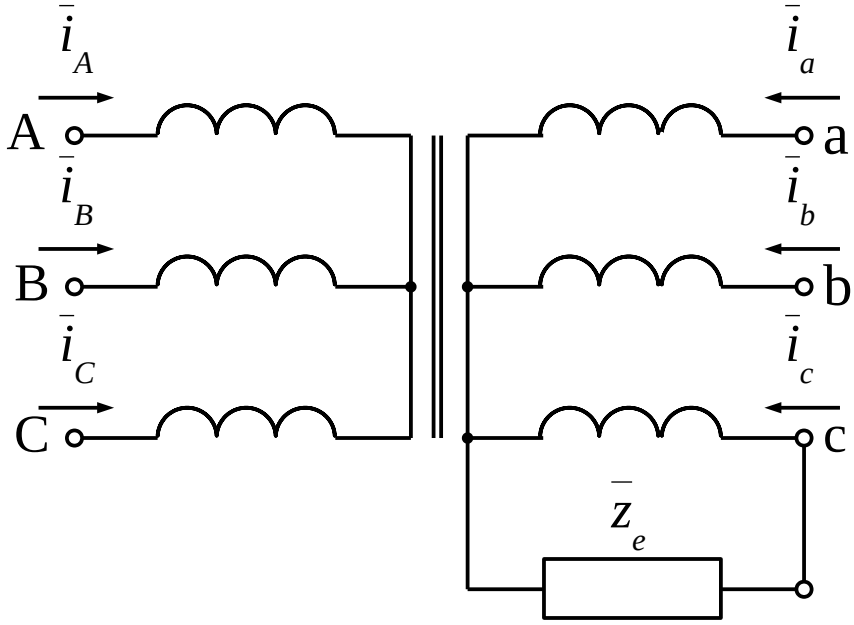
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- Currents in phases A and B are equal:

$$\bar{i}_A = \bar{i}_B$$

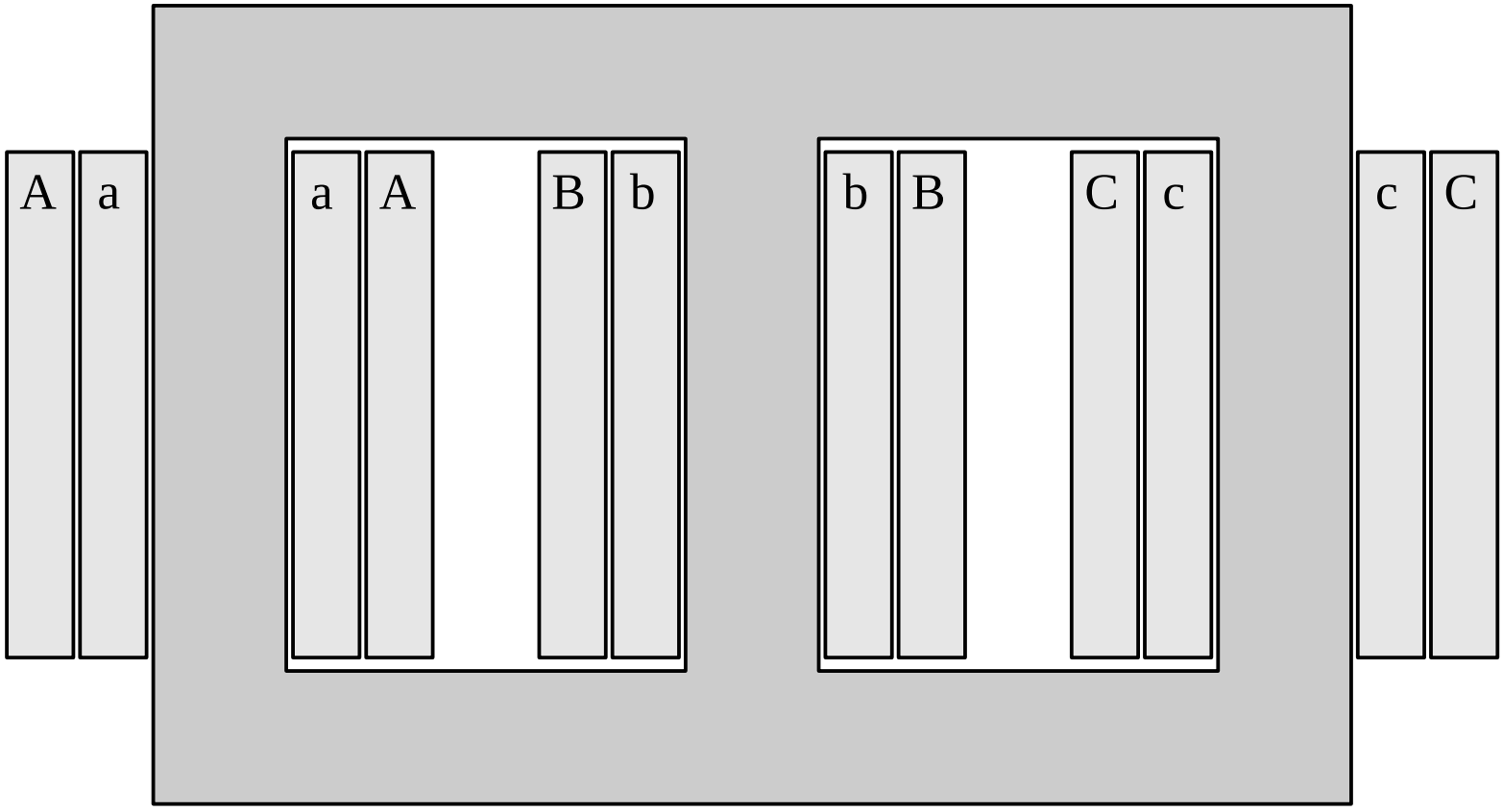
- Current through phase C is then:

$$\bar{i}_C = 2\,\bar{i}_A = 2\,\bar{i}_B$$

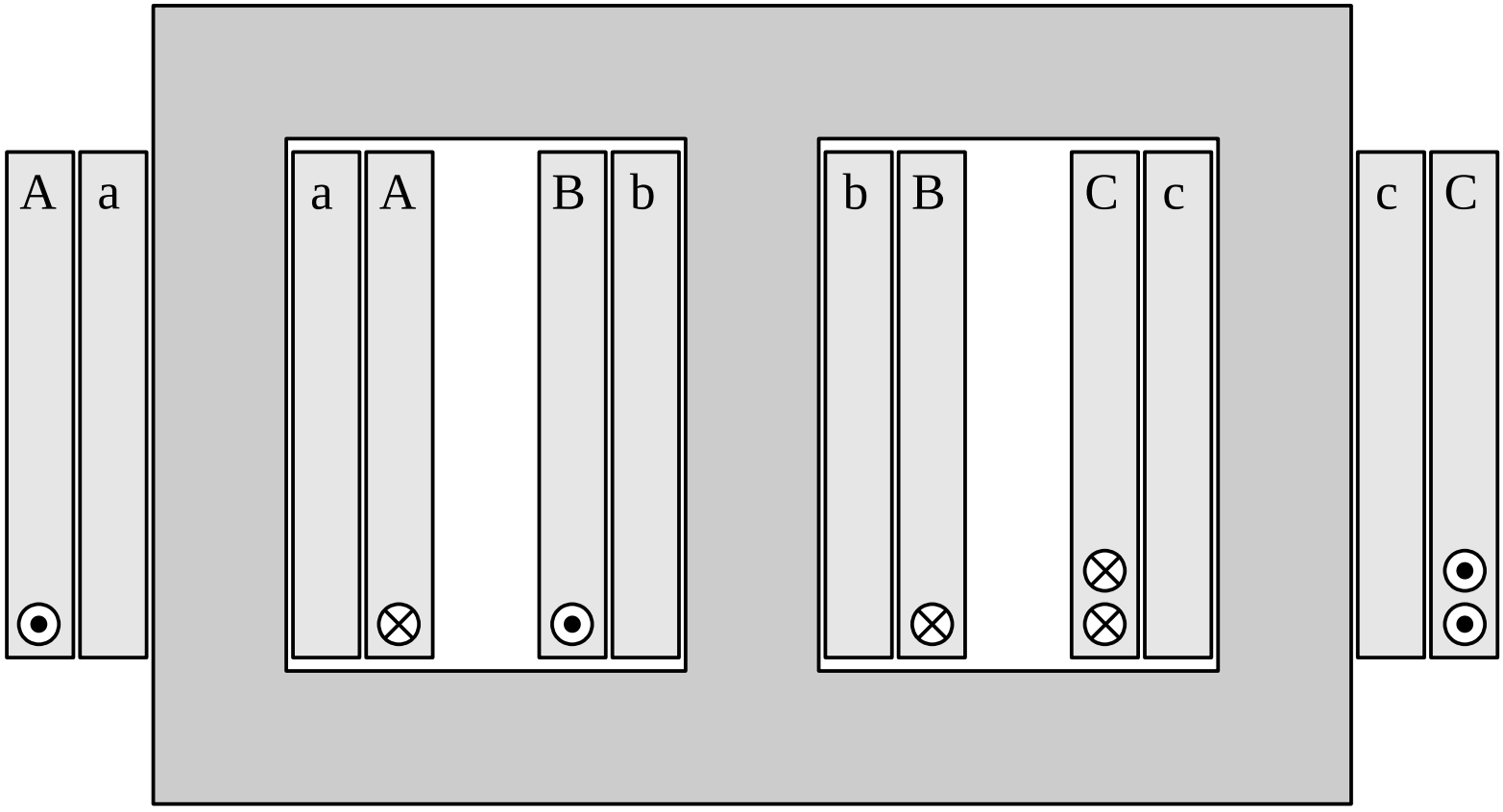


- On the secondary side, the current flows through phase c only
- Its magnitude may be obtained through magnetic field analysis

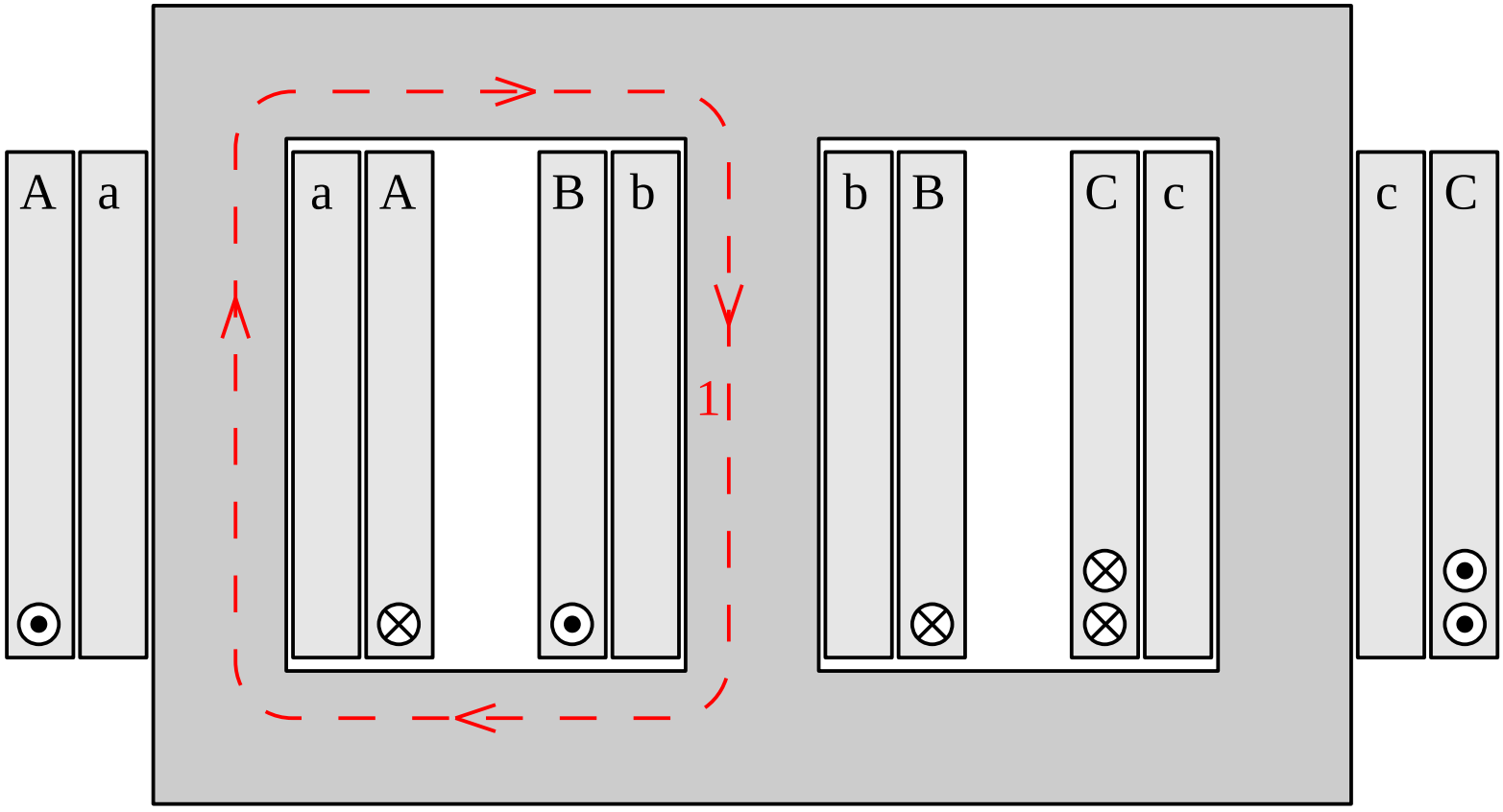
Three Phase Transformer with a Single Phase Load (Yyn)



Three Phase Transformer with a Single Phase Load (Yyn)

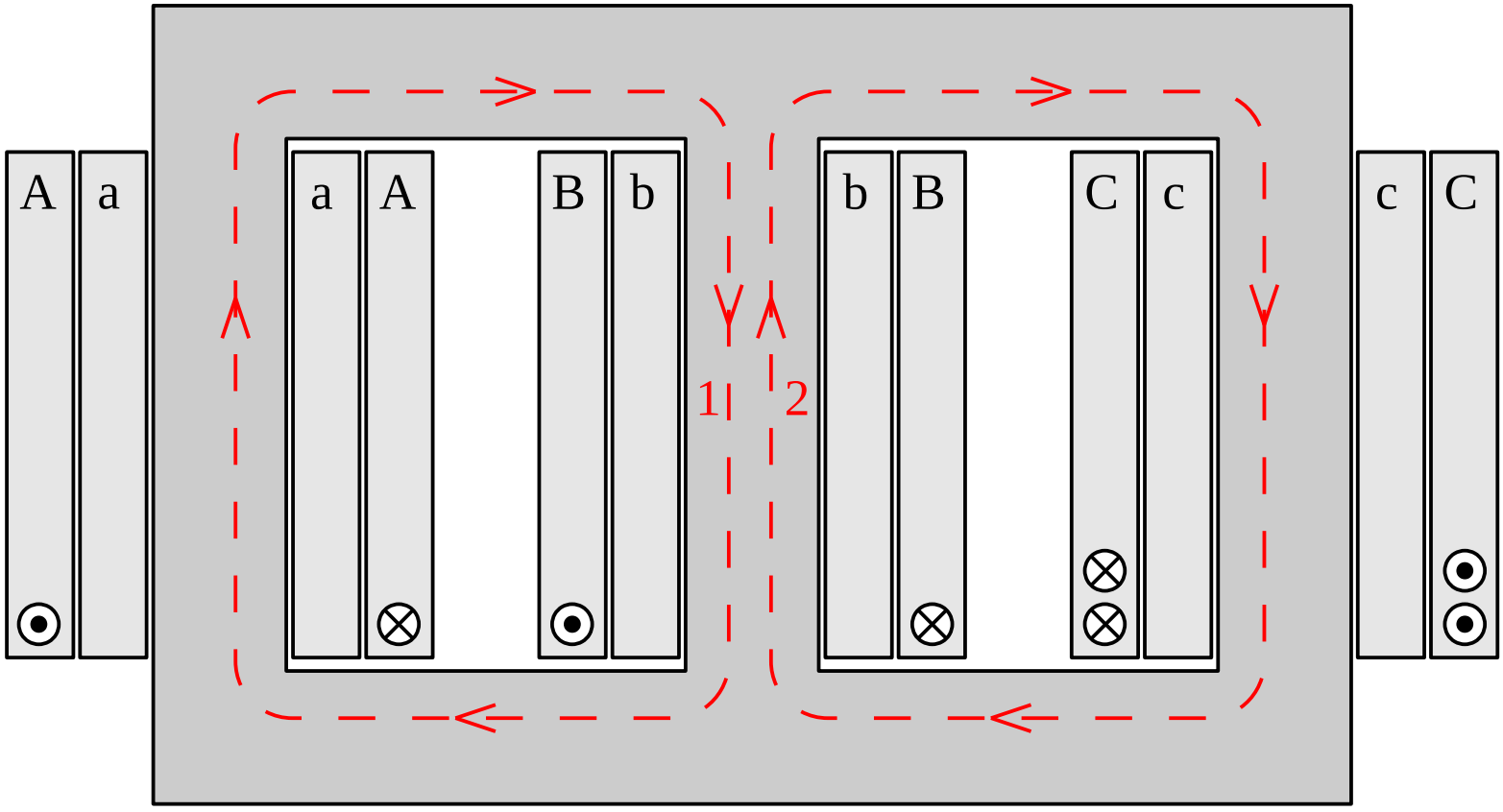


Three Phase Transformer with a Single Phase Load (Yyn)

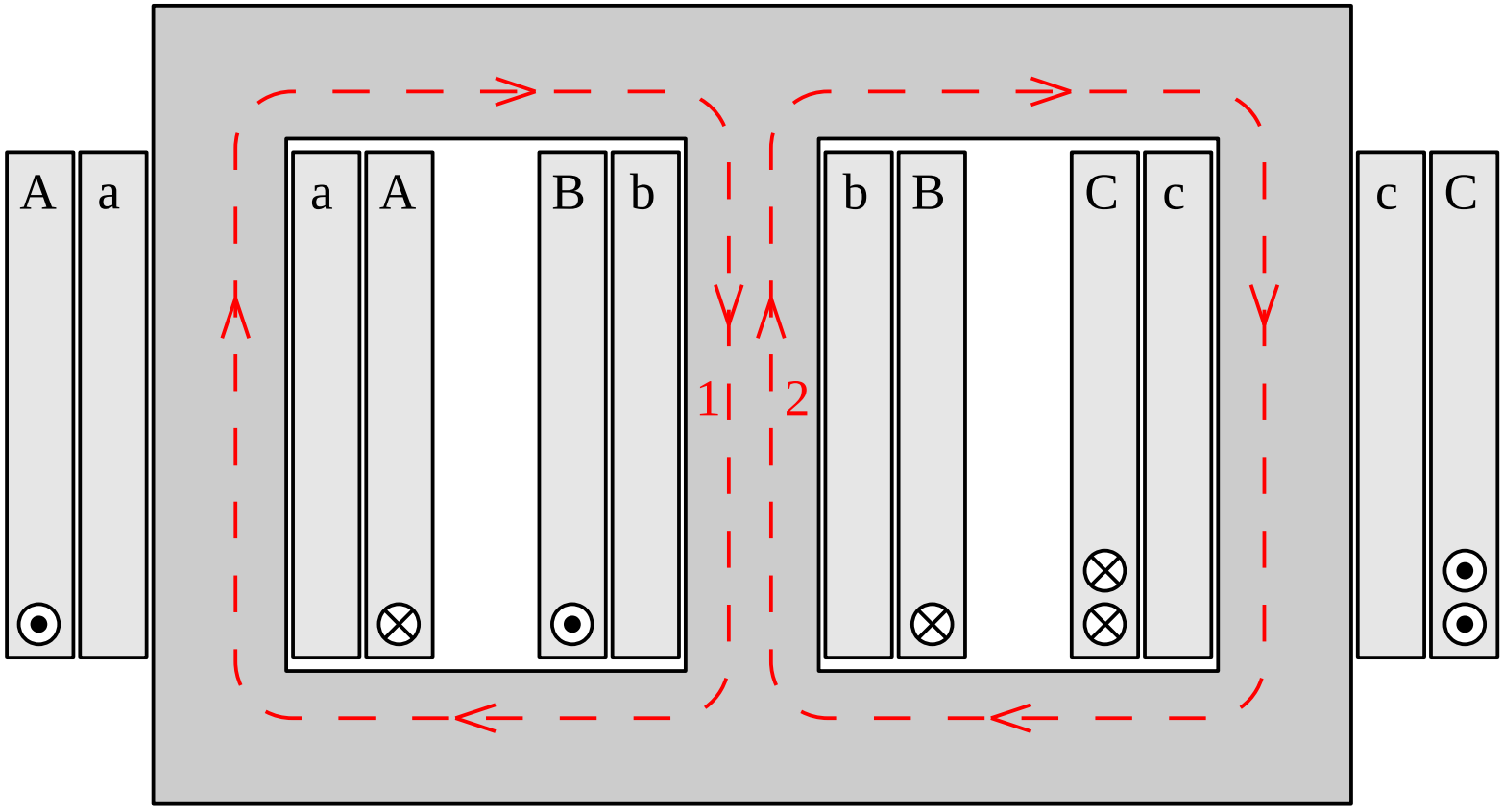


$$\bar{i}_A = \bar{i}_B$$

Three Phase Transformer with a Single Phase Load (Yyn)

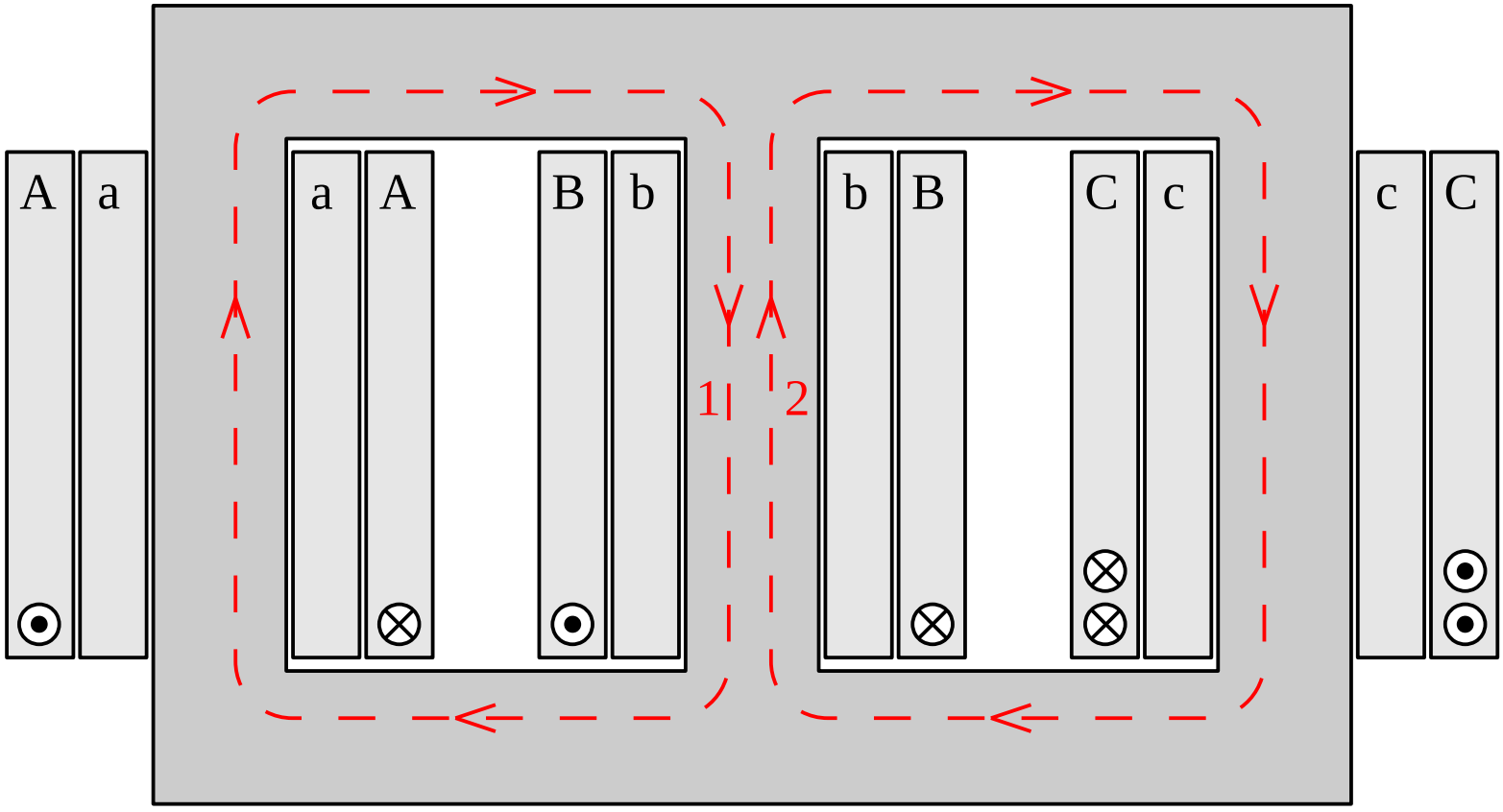


Three Phase Transformer with a Single Phase Load (Yyn)



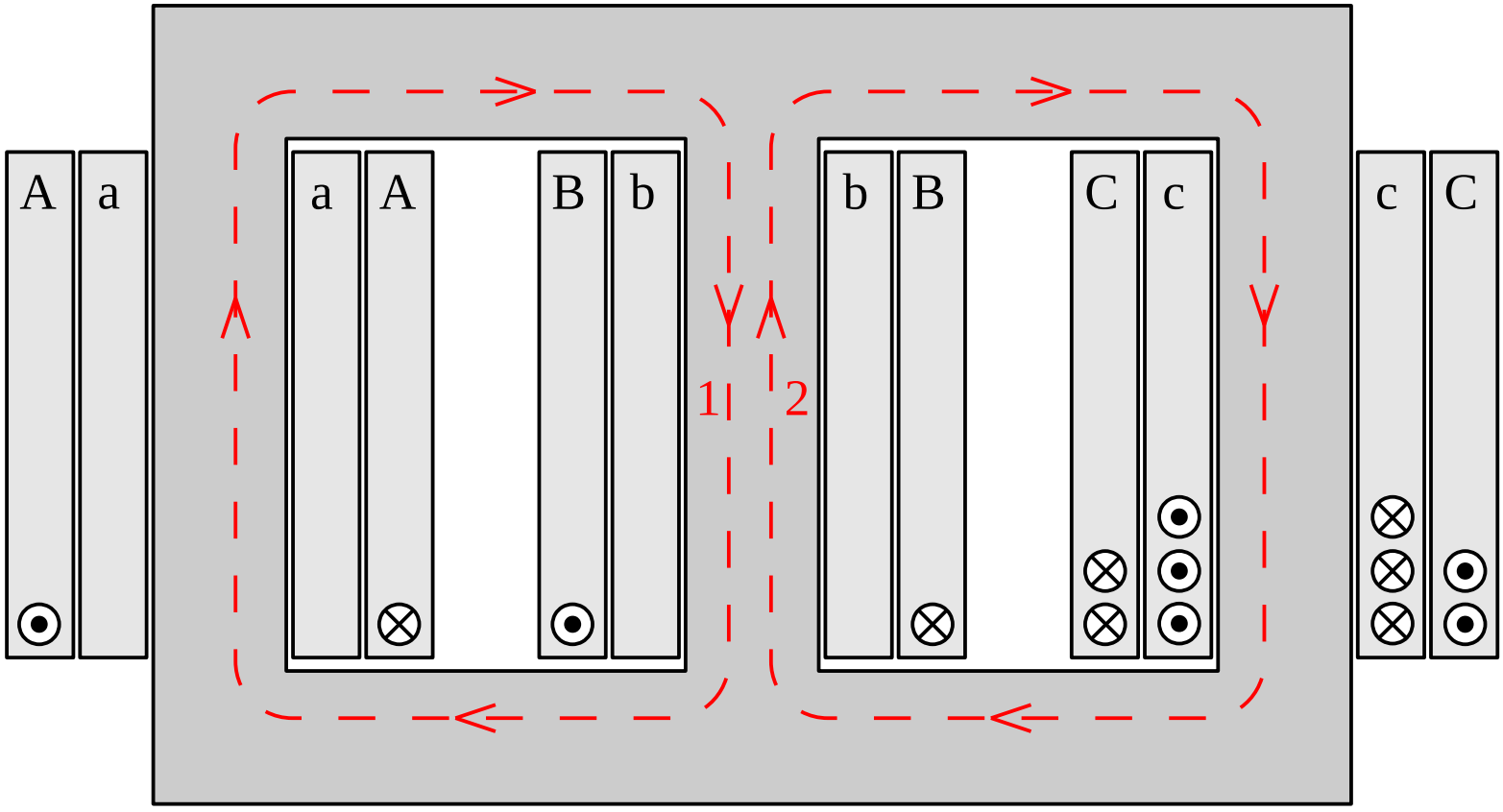
$$\bar{i}_c = \bar{i}_B + \bar{i}_C$$

Three Phase Transformer with a Single Phase Load (Yyn)



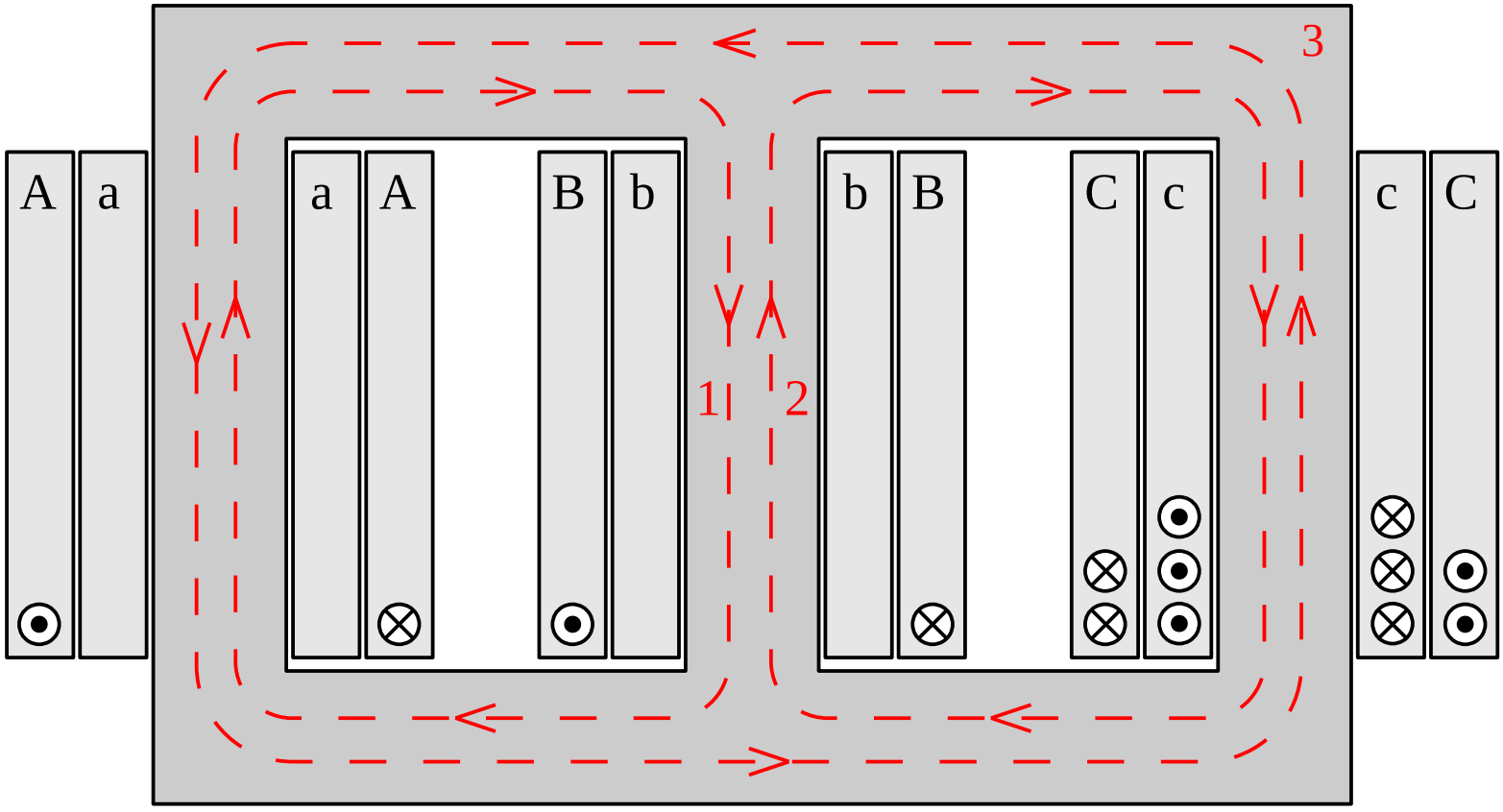
$$\bar{i}_c = \bar{i}_B + 2\,\bar{i}_B = 3\,\bar{i}_B$$

Three Phase Transformer with a Single Phase Load (Yyn)

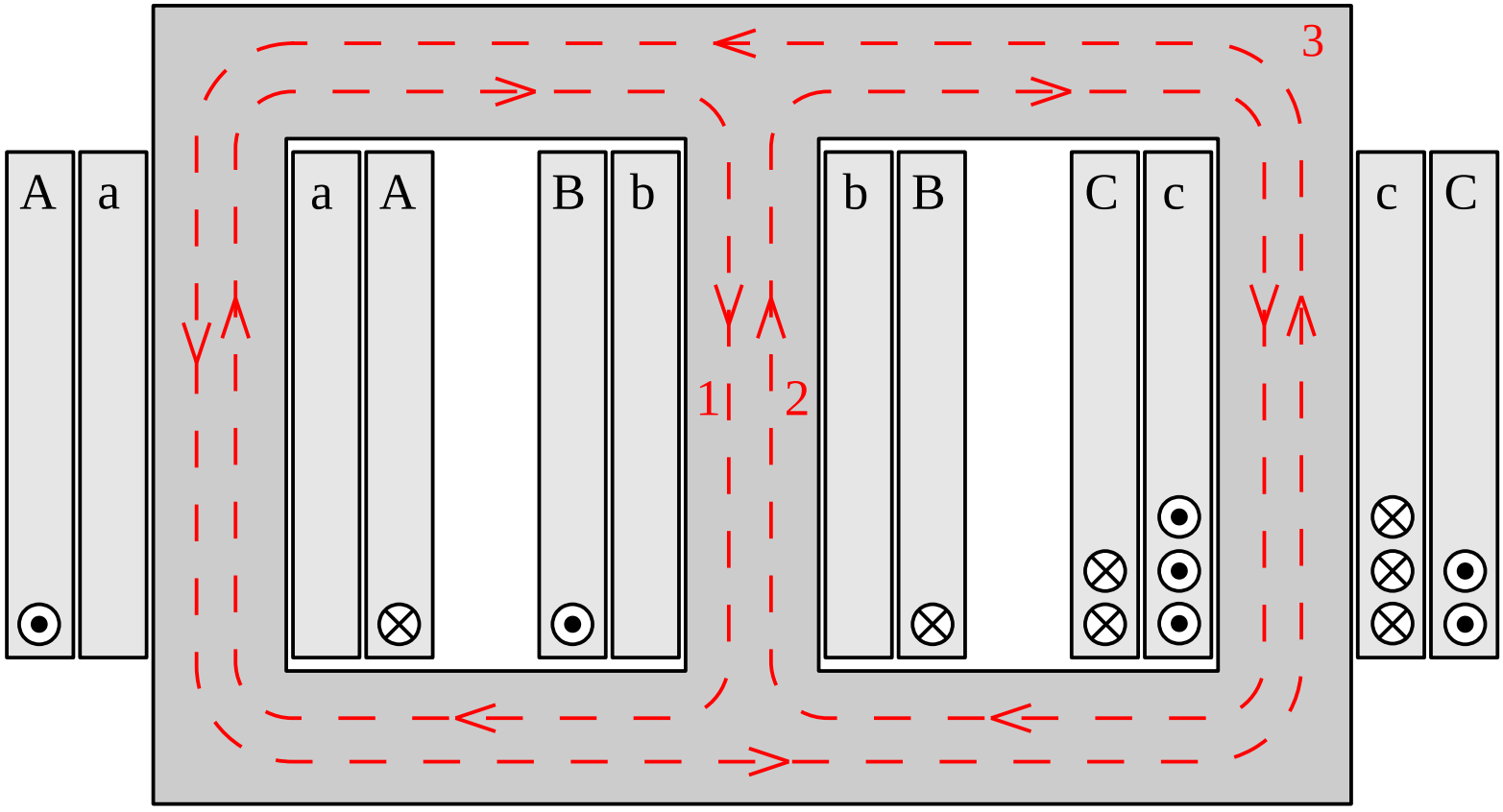


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Three Phase Transformer with a Single Phase Load (Yyn)

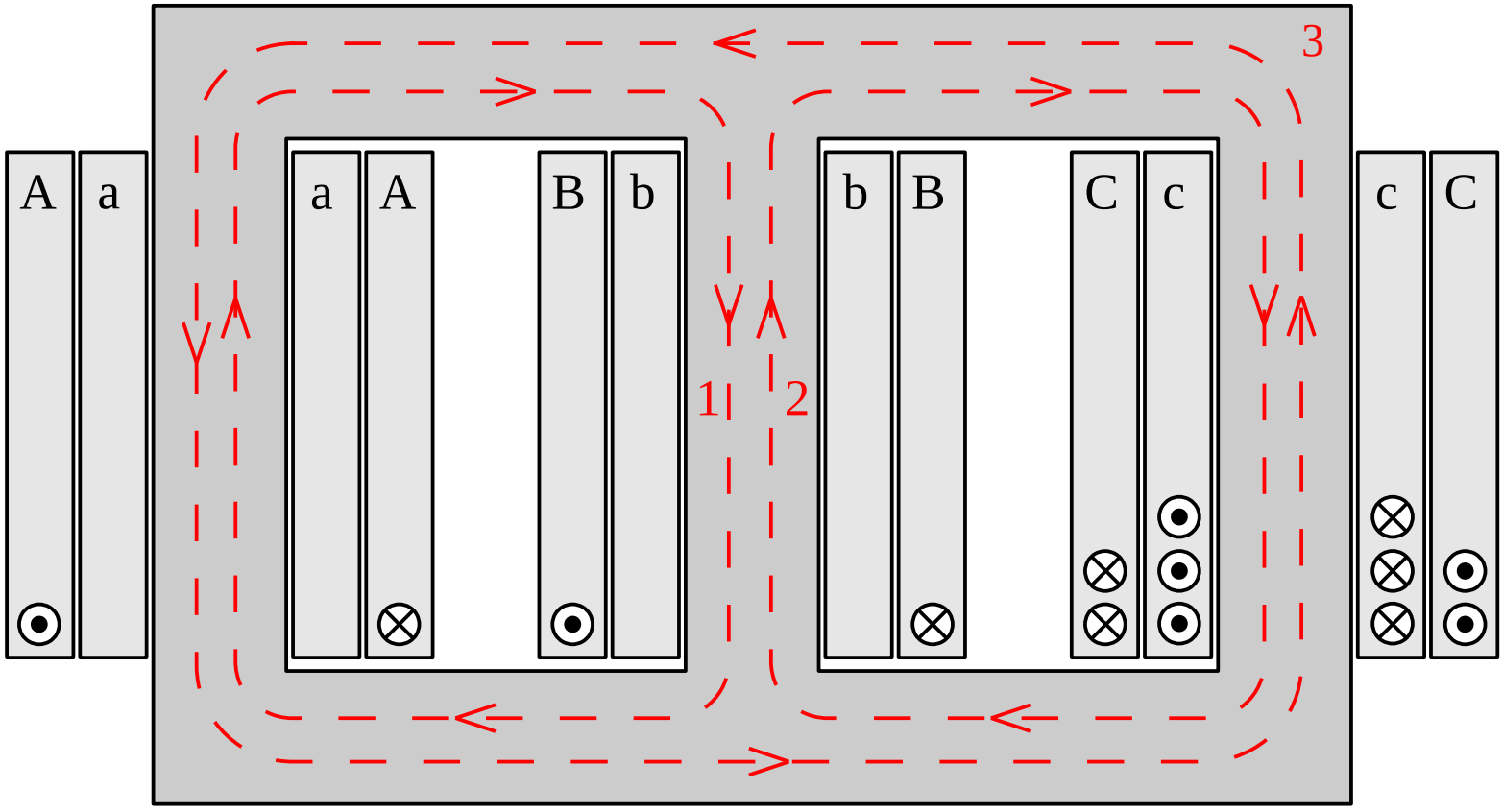


Three Phase Transformer with a Single Phase Load (Yyn)



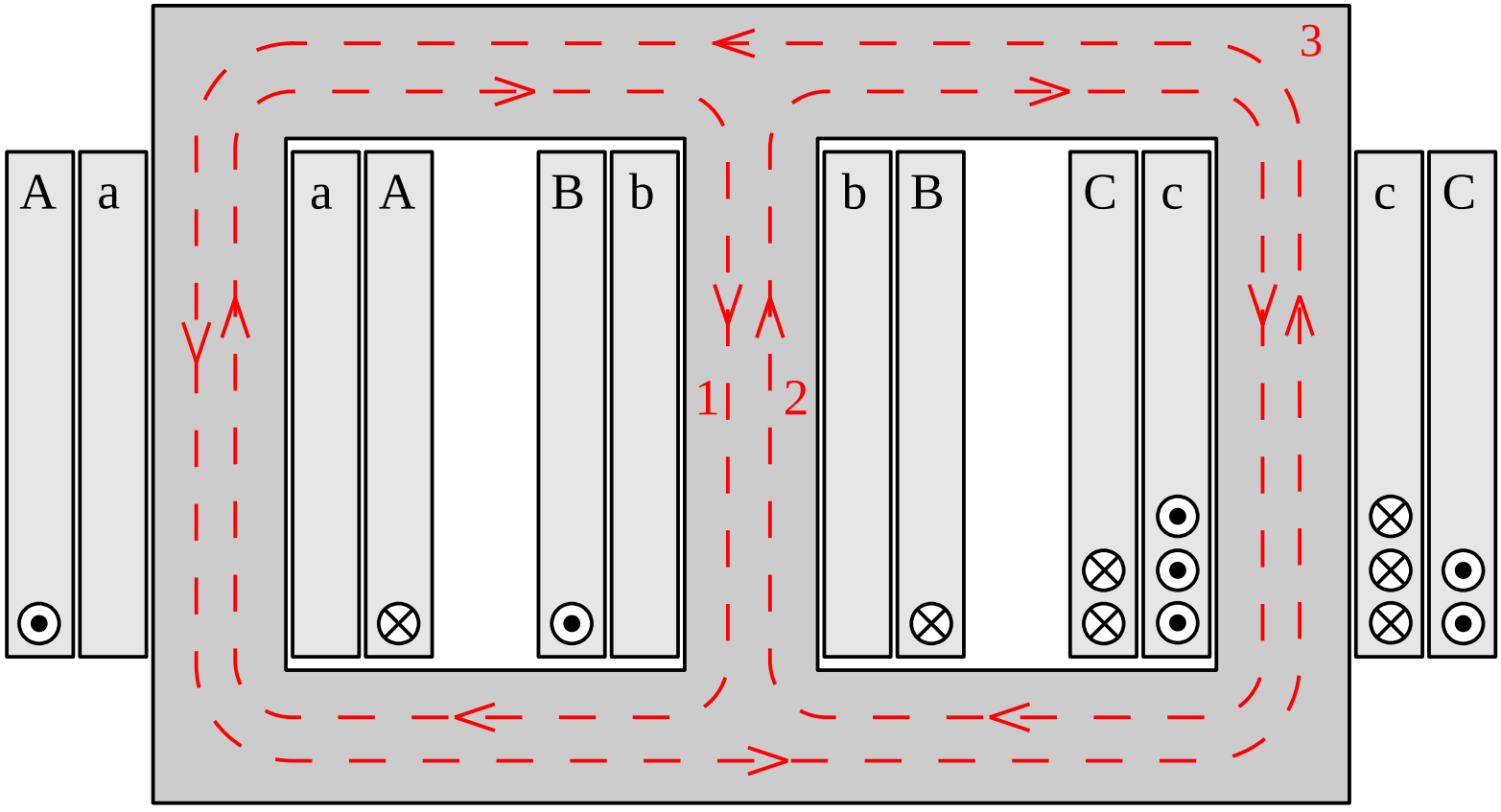
$$\bar{i}_c - \bar{i}_C - \bar{i}_A = 0$$

Three Phase Transformer with a Single Phase Load (Yyn)



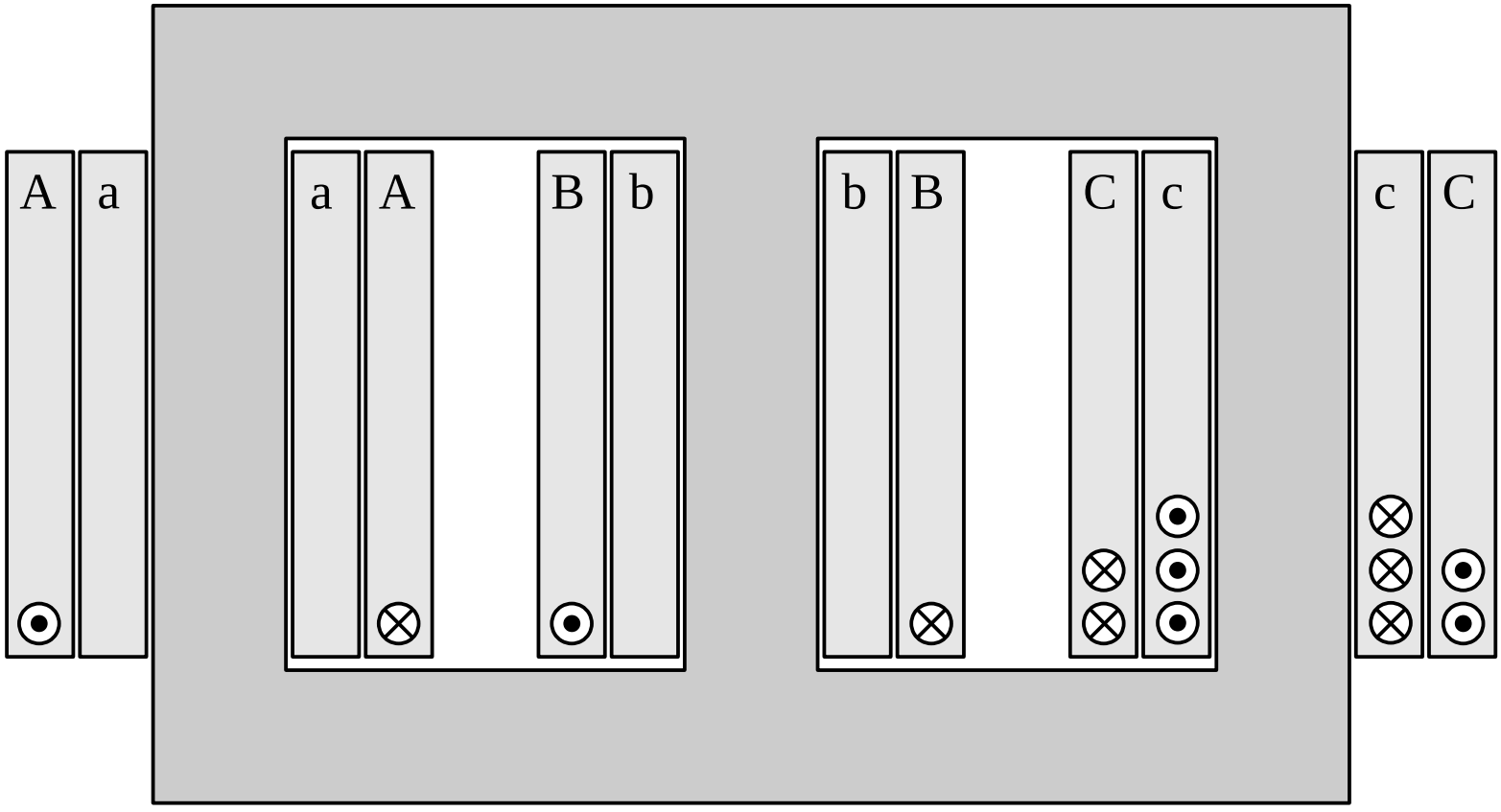
$$3\bar{i}_A - 2\bar{i}_A - \bar{i}_A = 0$$

Three Phase Transformer with a Single Phase Load (Yyn)

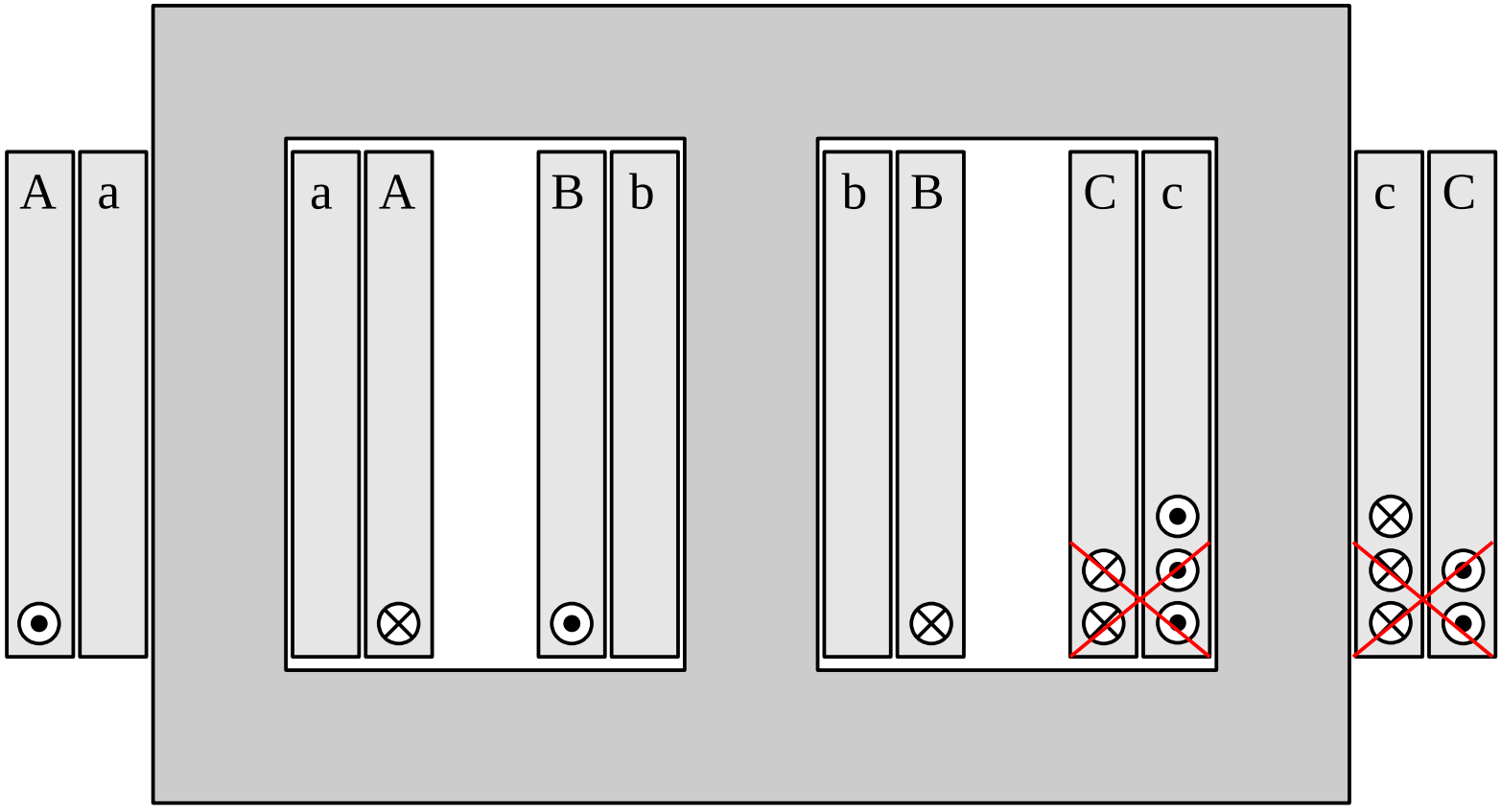


$0 = 0$

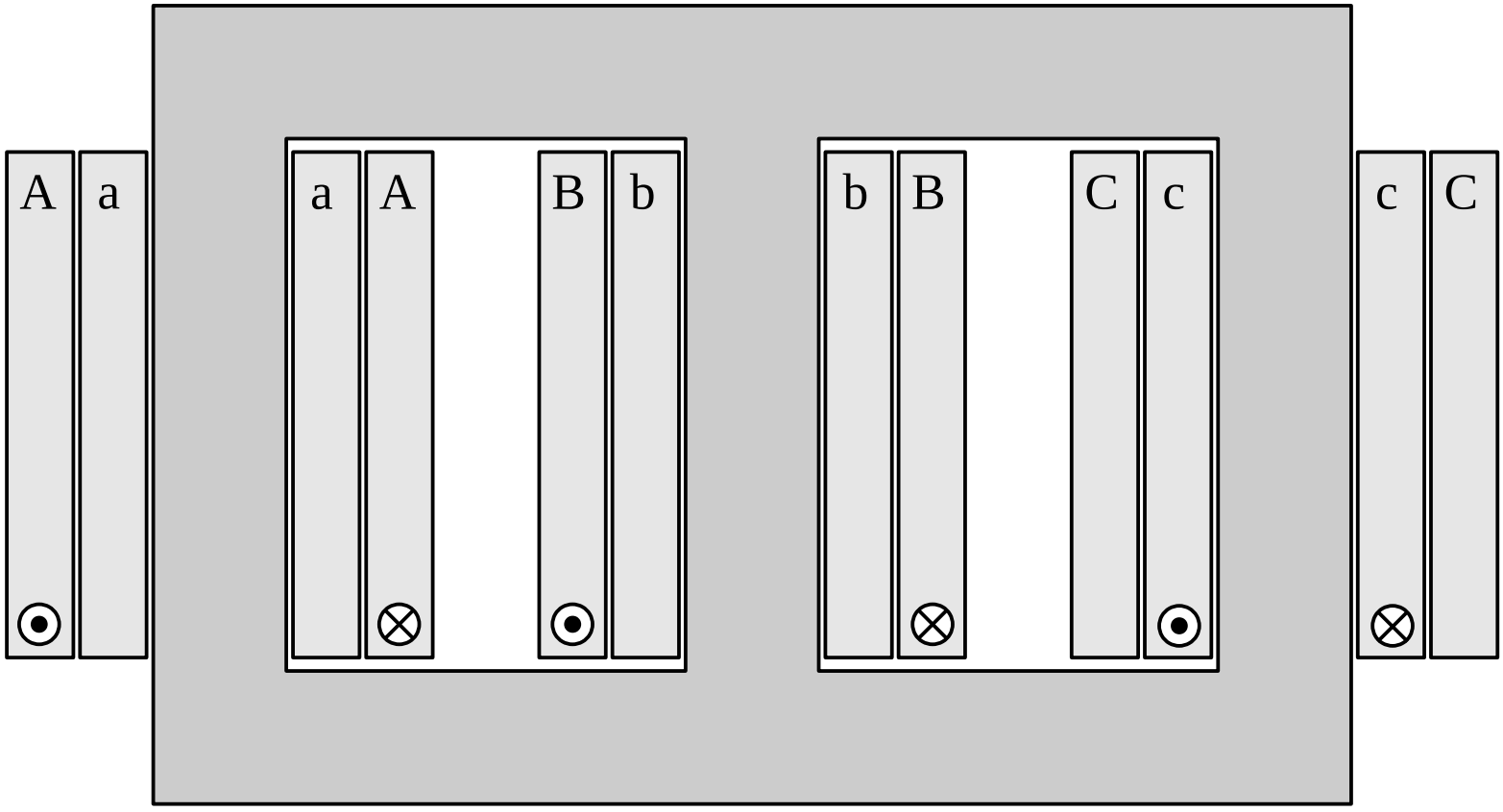
Three Phase Transformer with a Single Phase Load (Yyn)



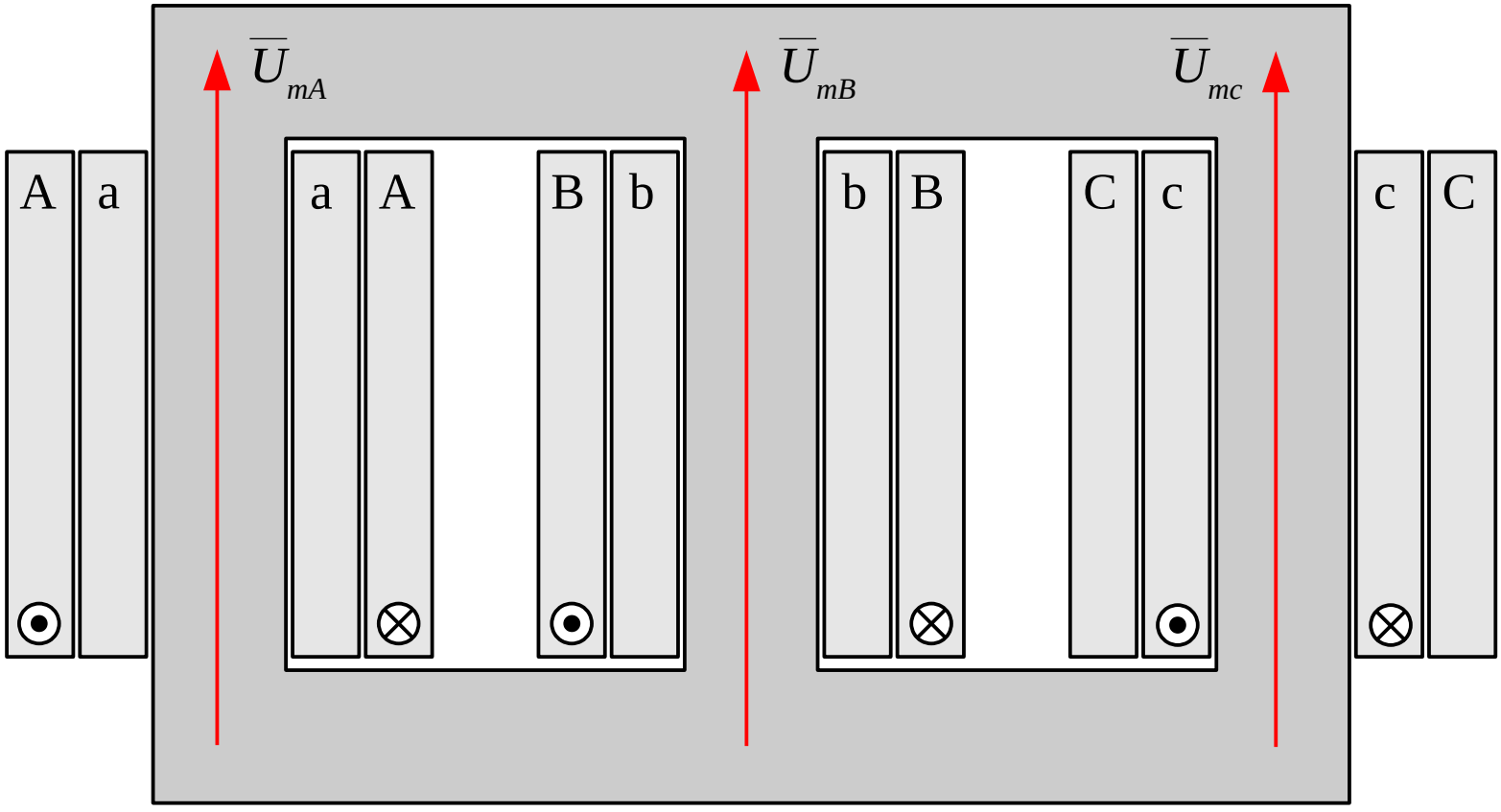
Three Phase Transformer with a Single Phase Load (Yyn)



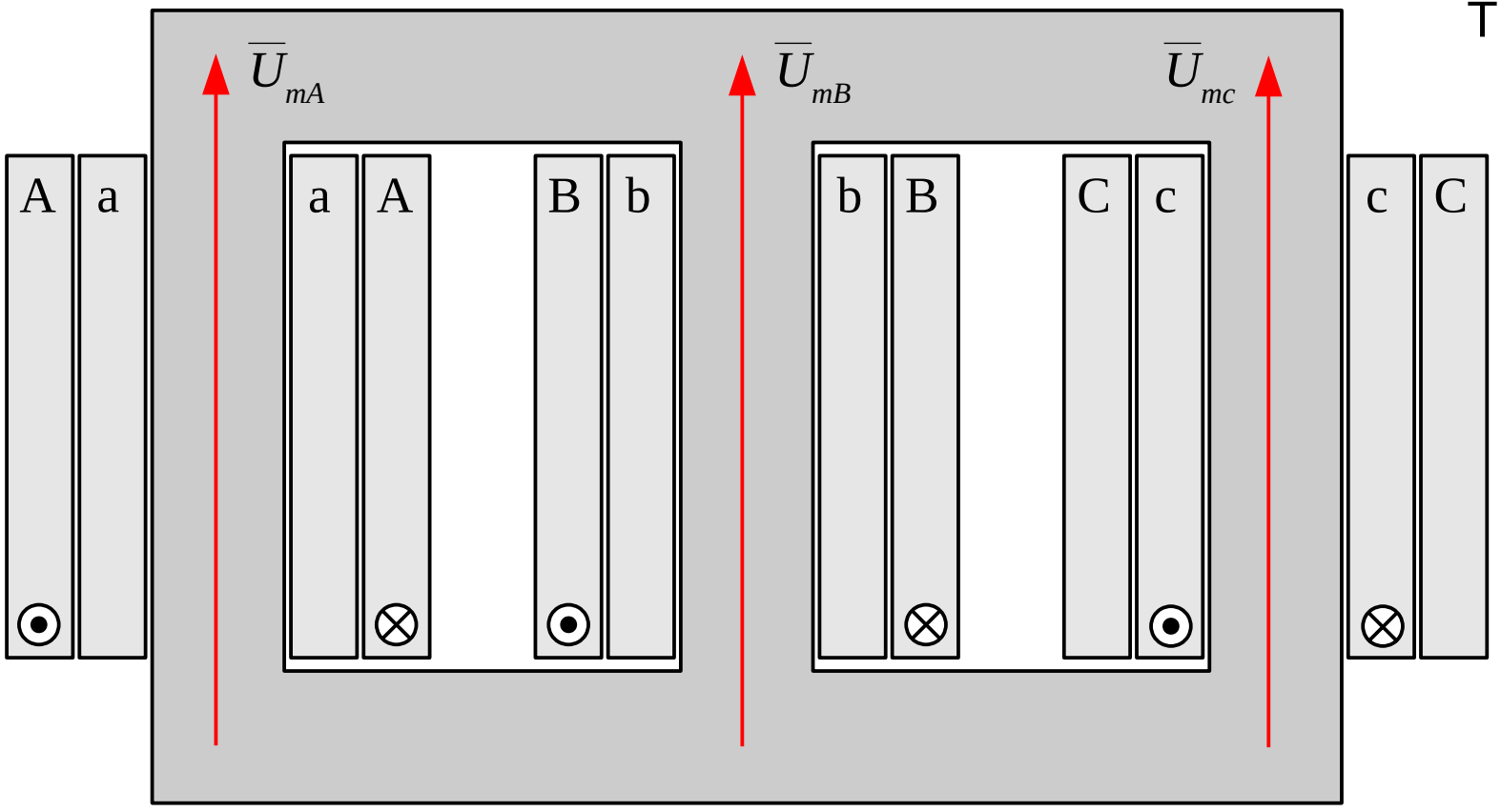
Three Phase Transformer with a Single Phase Load (Yyn)



Three Phase Transformer with a Single Phase Load (Yyn)



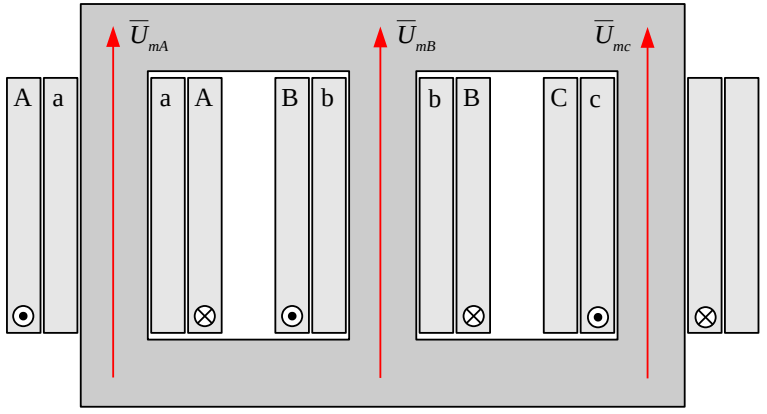
Three Phase Transformer with a Single Phase Load (Yyn)



The result is then single-direction magnetization.

Three Phase Transformer with a Single Phase Load (Yyn)

- Conclusions of quantitative analysis:
  - The current through phase C will be twice as high in comparison to other currents of the primary winding
  - The current through phase c will be 3/2 of phase C current (in per units)
  - A single-direction magnetization will appear in the transformer, which will project as a non-rotary component of the magnetic field
  - The magnetic field of the transformer will flow through leakage paths



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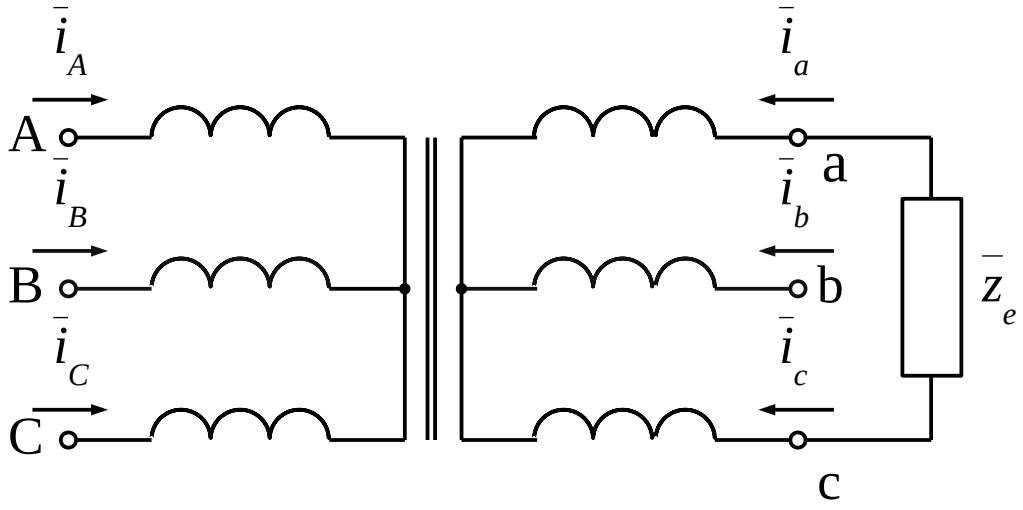
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Three Phase Transformer with a Double Phase Load (Yy)

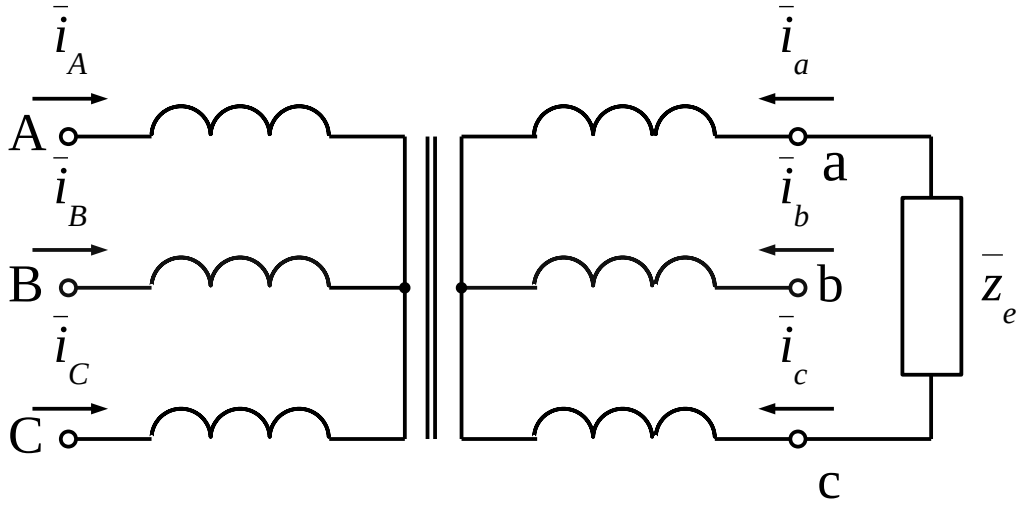
Three Phase Transformer with a Double Phase Load (Yy)



Three Phase Transformer with a Double Phase Load (Yy)

- For the node of primary winding:

$$\bar{i}_A + \bar{i}_B + \bar{i}_C = 0$$



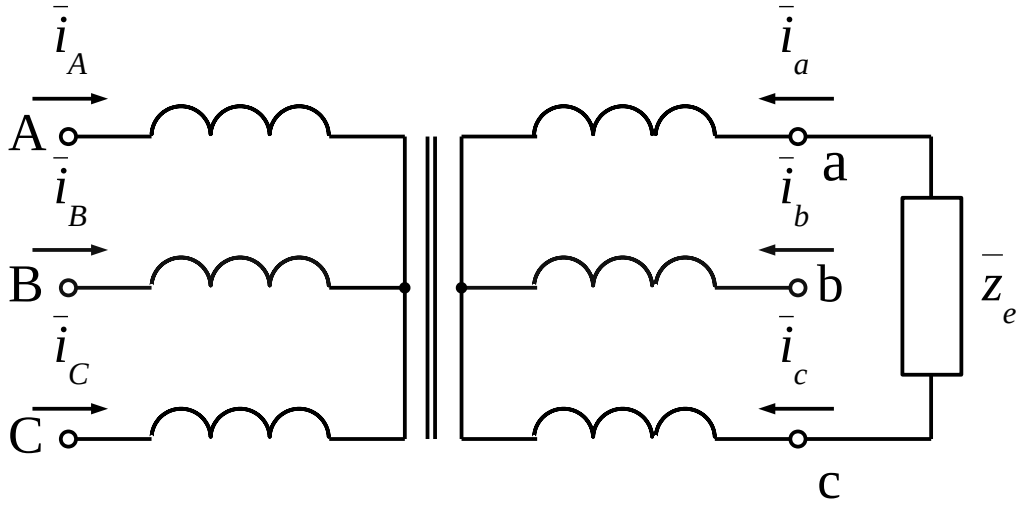
Three Phase Transformer with a Double Phase Load (Yy)

- For the node of primary winding:

$$\bar{i}_A + \bar{i}_B + \bar{i}_C = 0$$

- The current in secondary winding are (neglecting direction) equal:

$$\bar{i}_a = -\bar{i}_c$$



Three Phase Transformer with a Double Phase Load (Yy)

- For the node of primary winding:

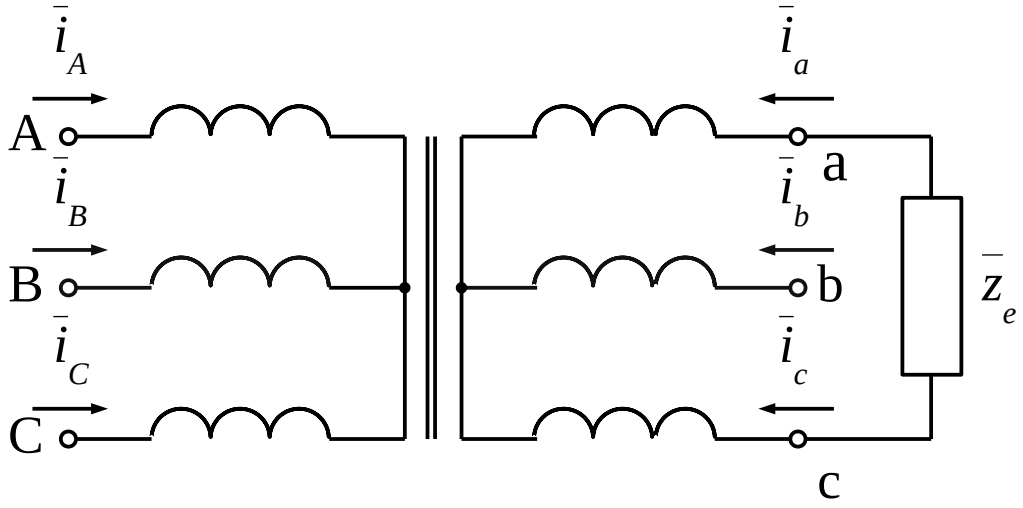
$$\bar{i}_A + \bar{i}_B + \bar{i}_C = 0$$

- The current in secondary winding are (neglecting direction) equal:

$$\bar{i}_a = -\bar{i}_c$$

- Then we become:

$$\bar{i}_A = -\bar{i}_C$$



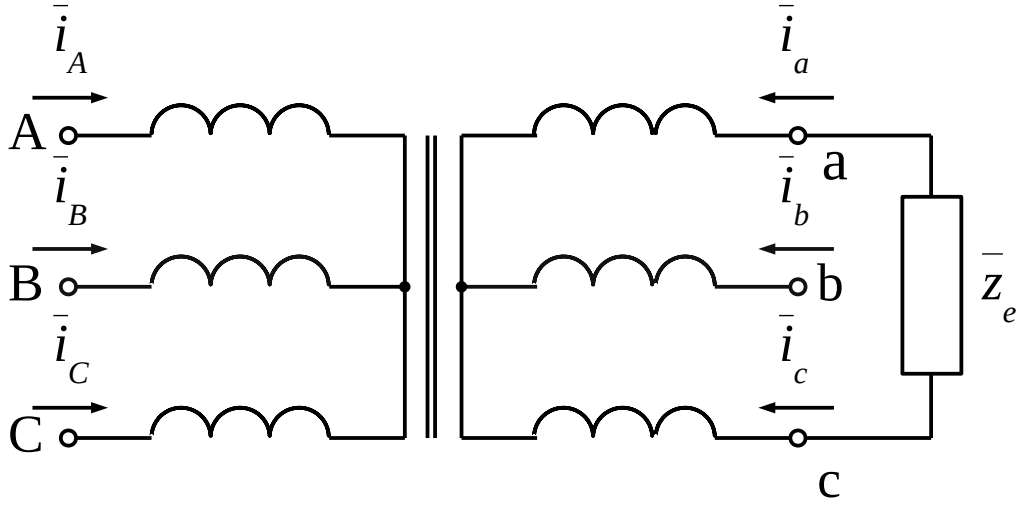
Three Phase Transformer with a Double Phase Load (Yy)

- For the node of primary winding:

$$\bar{i}_A + \bar{i}_B + \bar{i}_C = 0$$

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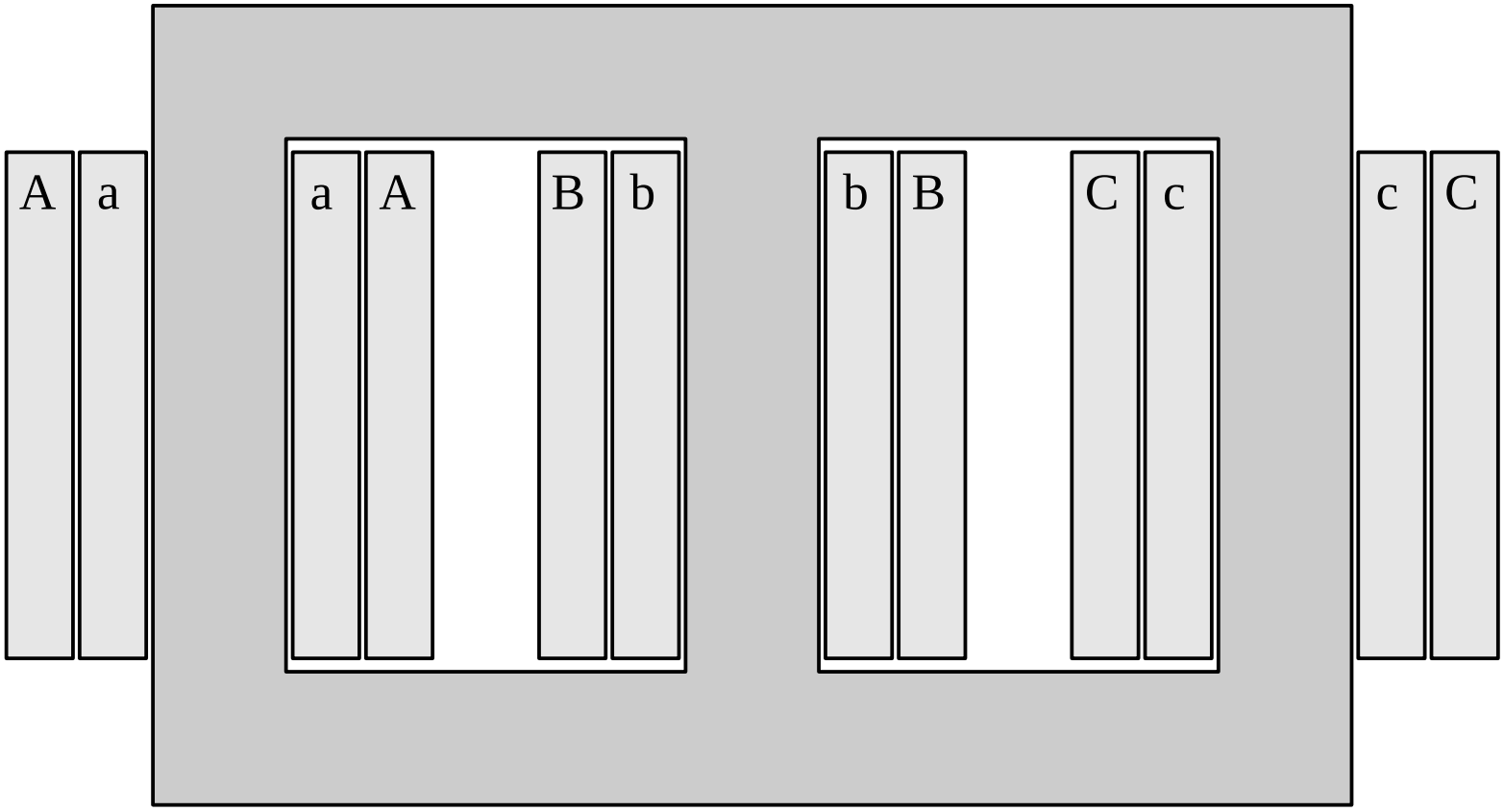


- Then we become:

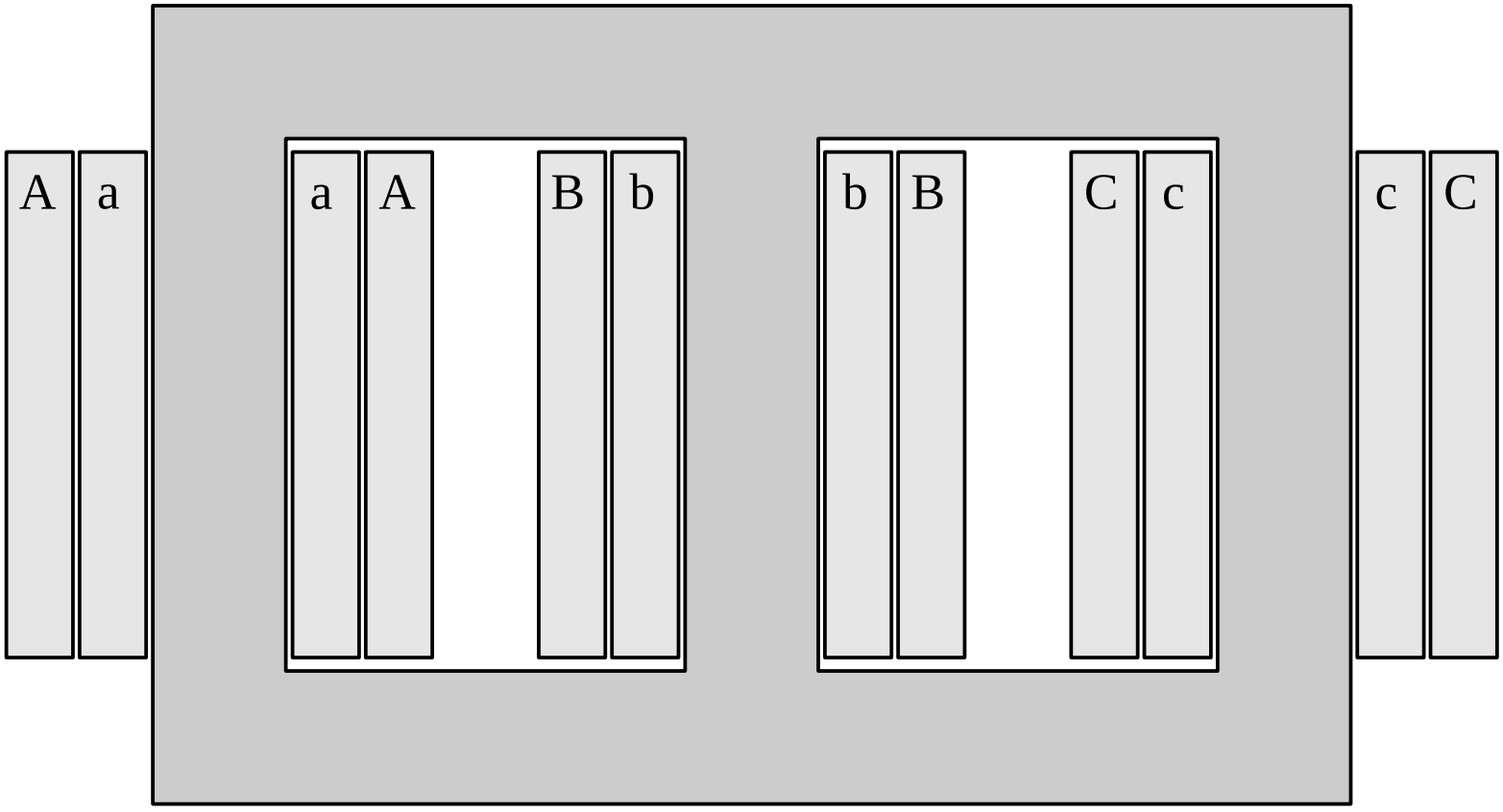
$$\bar{i}_A = -\bar{i}_C$$

- The current through phase B will be on both primary and secondary side zero...

Three Phase Transformer with a Double Phase Load (Yy)



Three Phase Transformer with a Double Phase Load (Yy)



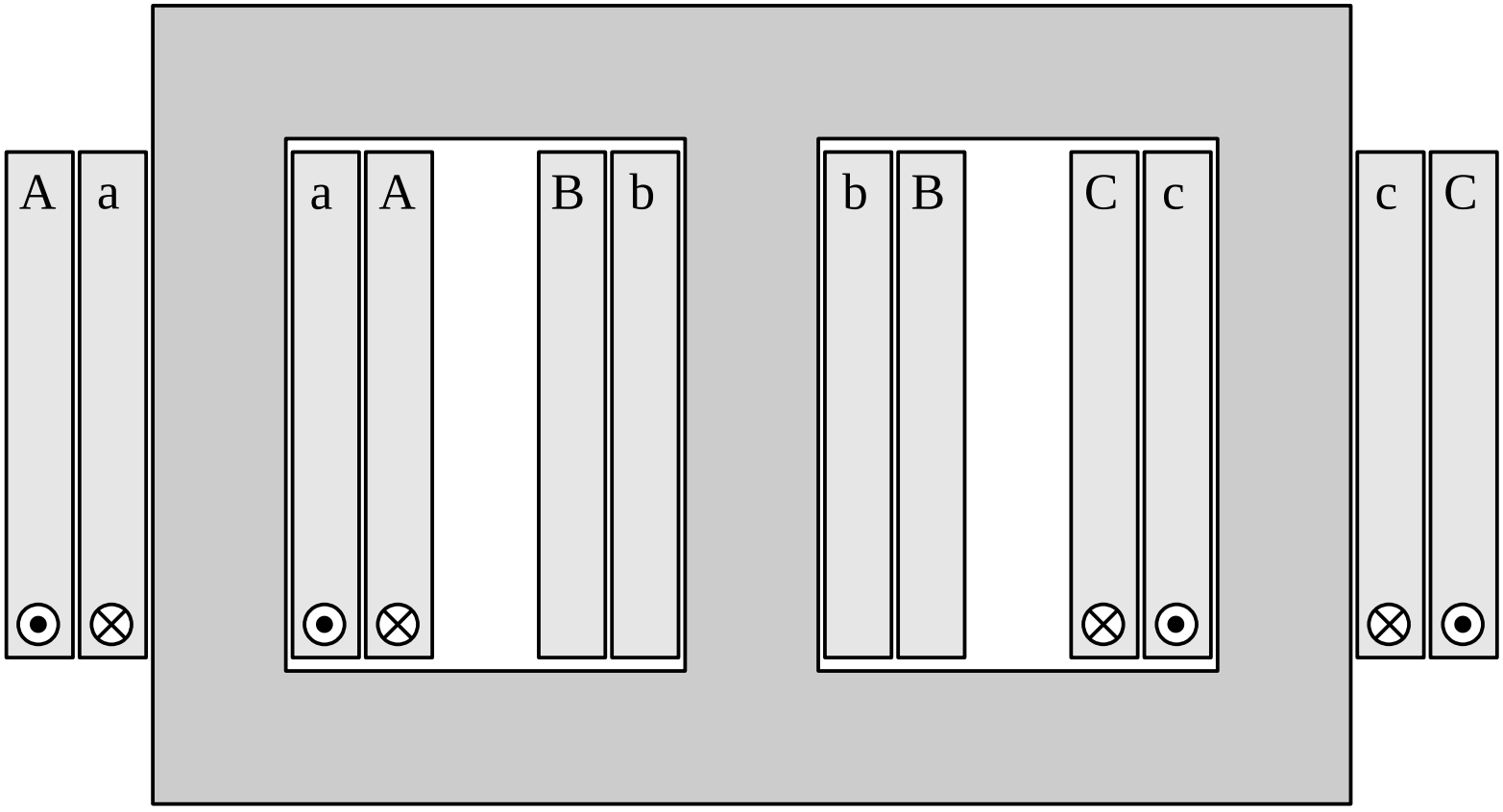
$$\bar{i}_a = -\bar{i}_c$$

$$\bar{i}_A = -\bar{i}_C$$

$$\bar{i}_B = 0$$

$$\bar{i}_b = 0$$

Three Phase Transformer with a Double Phase Load (Yy)



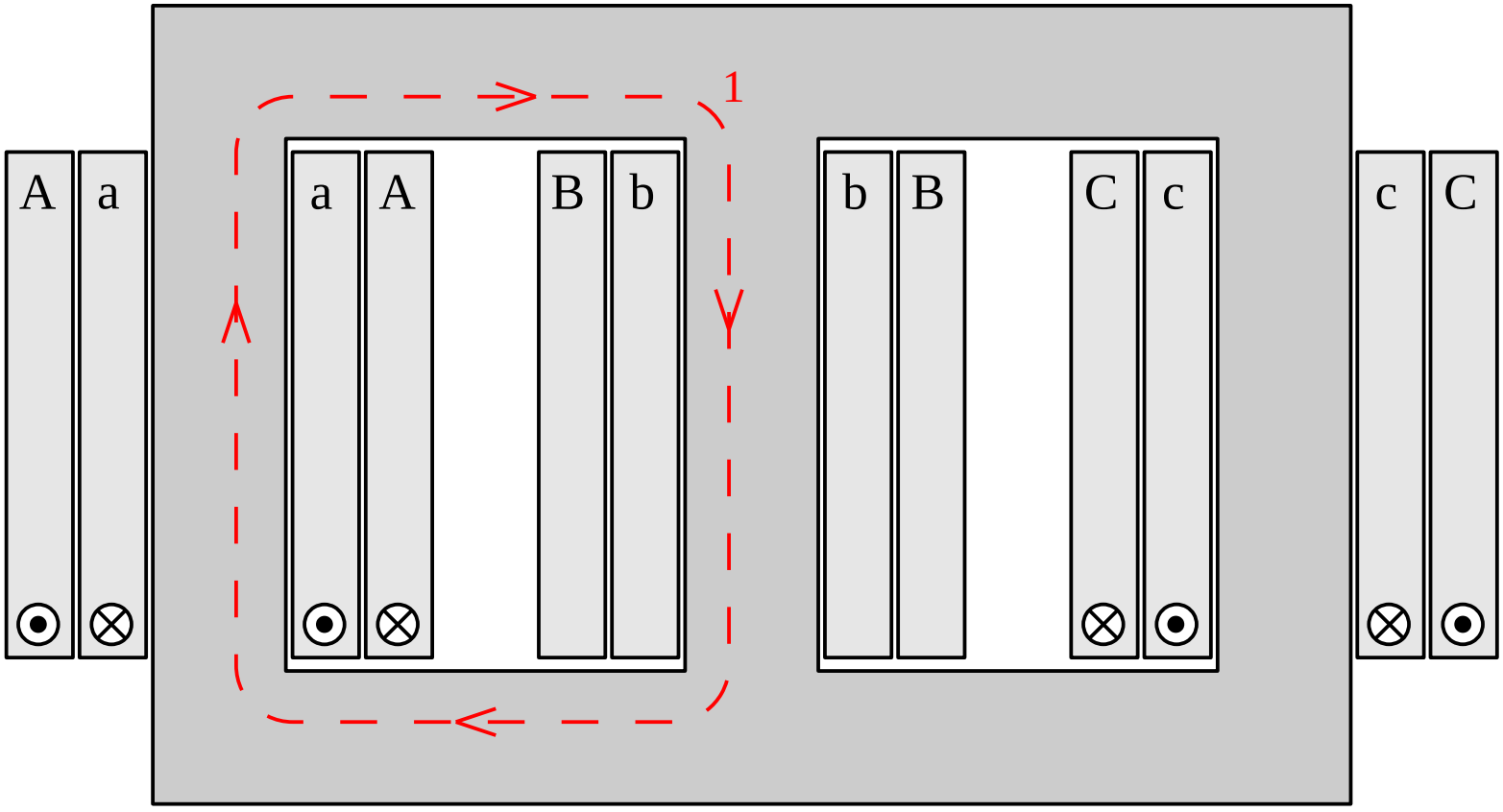
$$\bar{i}_a = -\bar{i}_c$$

$$\bar{i}_A = -\bar{i}_C$$

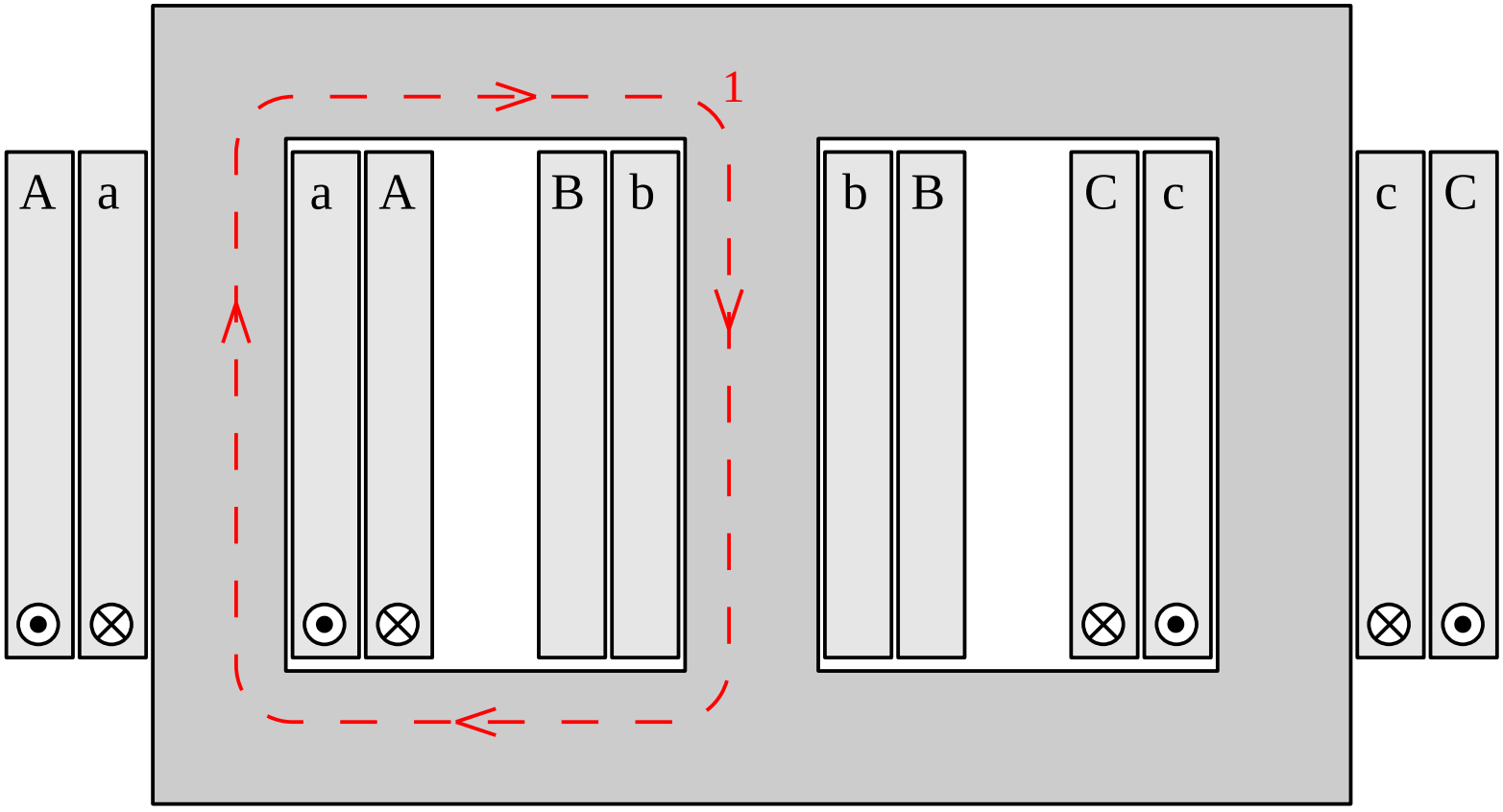
$$\bar{i}_B = 0$$

$$\bar{i}_b = 0$$

Three Phase Transformer with a Double Phase Load (Yy)

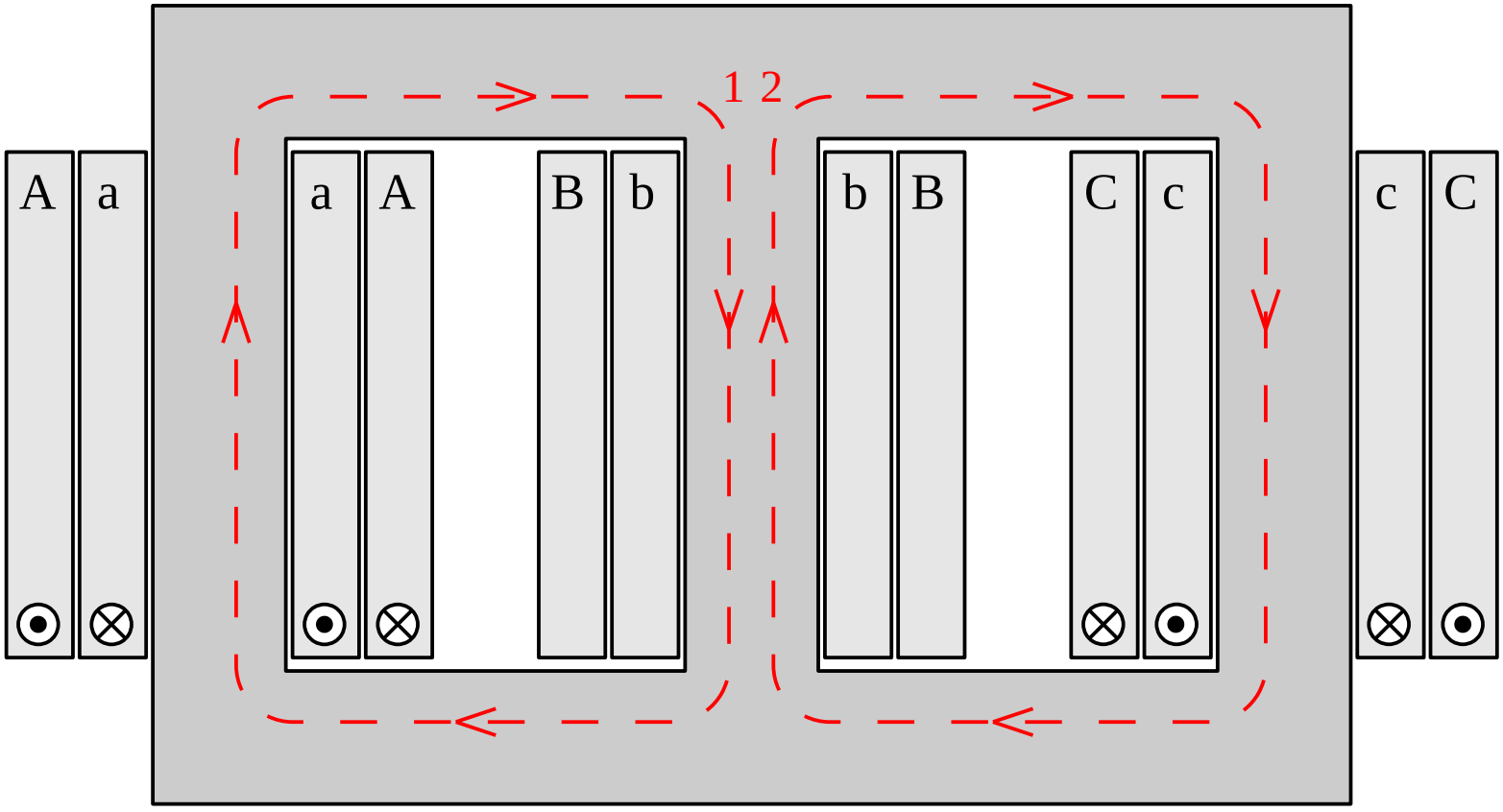


Three Phase Transformer with a Double Phase Load (Yy)

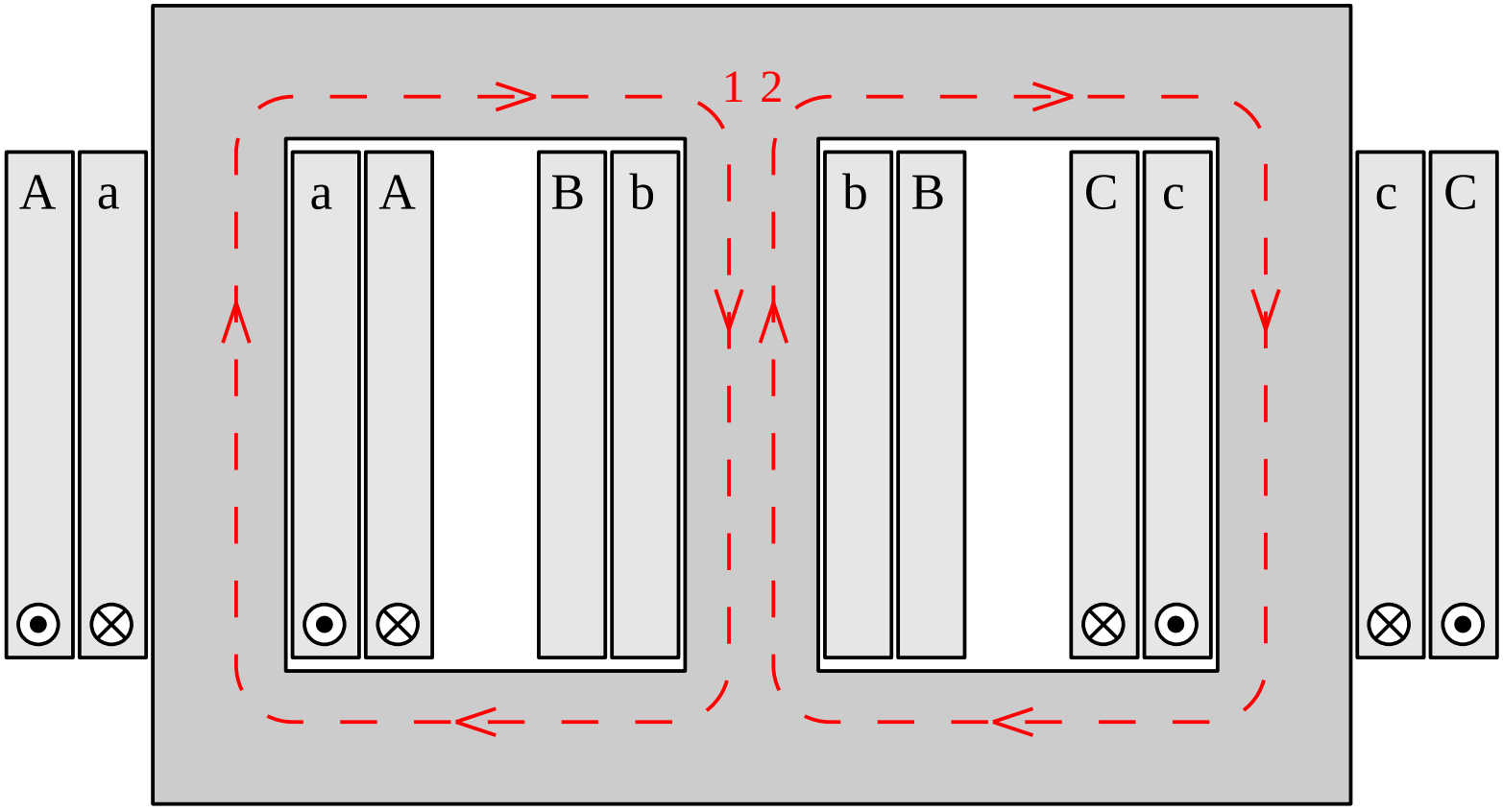


$$\bar{i}_A - \bar{i}_a = 0$$

Three Phase Transformer with a Double Phase Load (Yy)

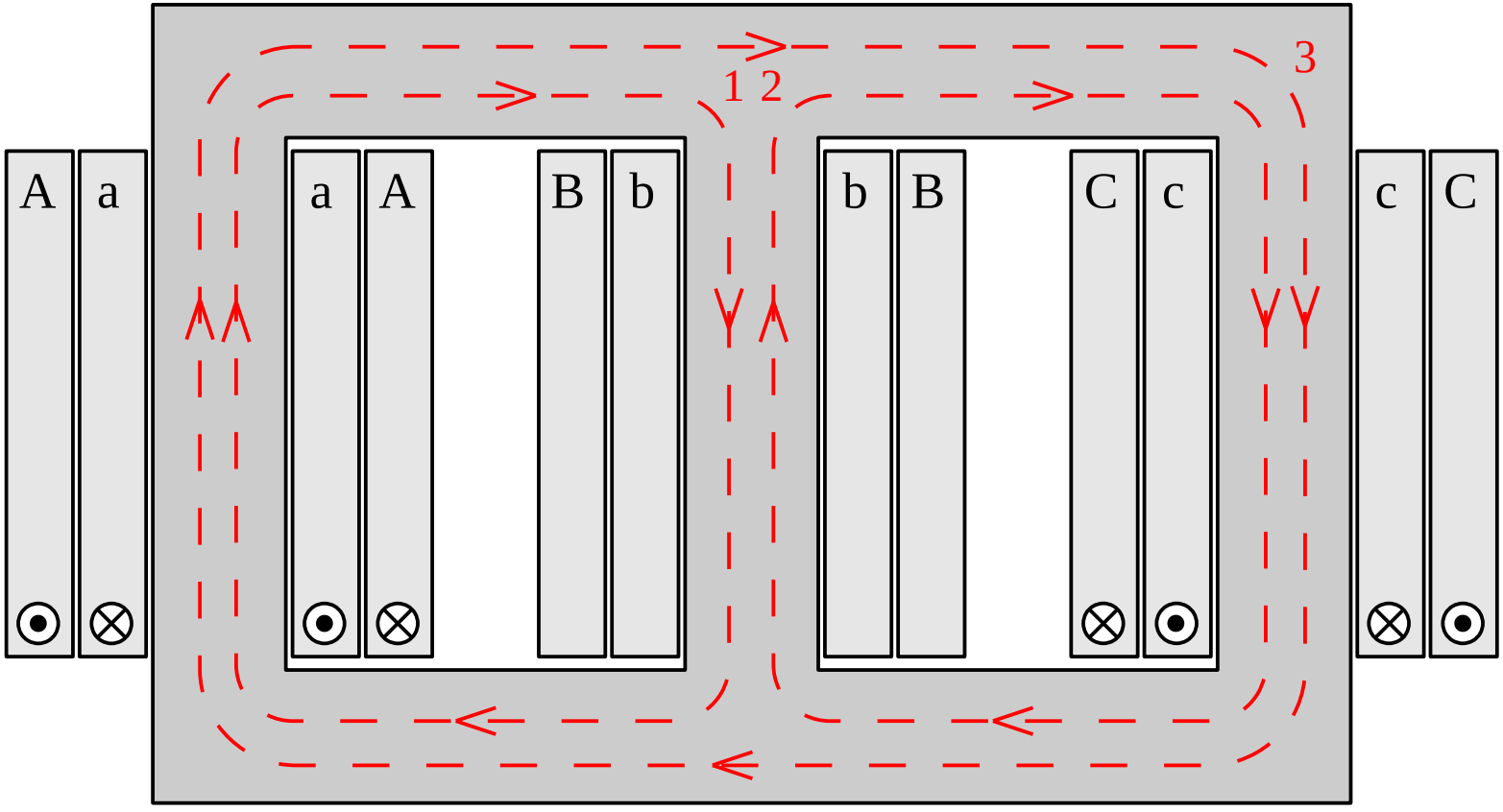


Three Phase Transformer with a Double Phase Load (Yy)



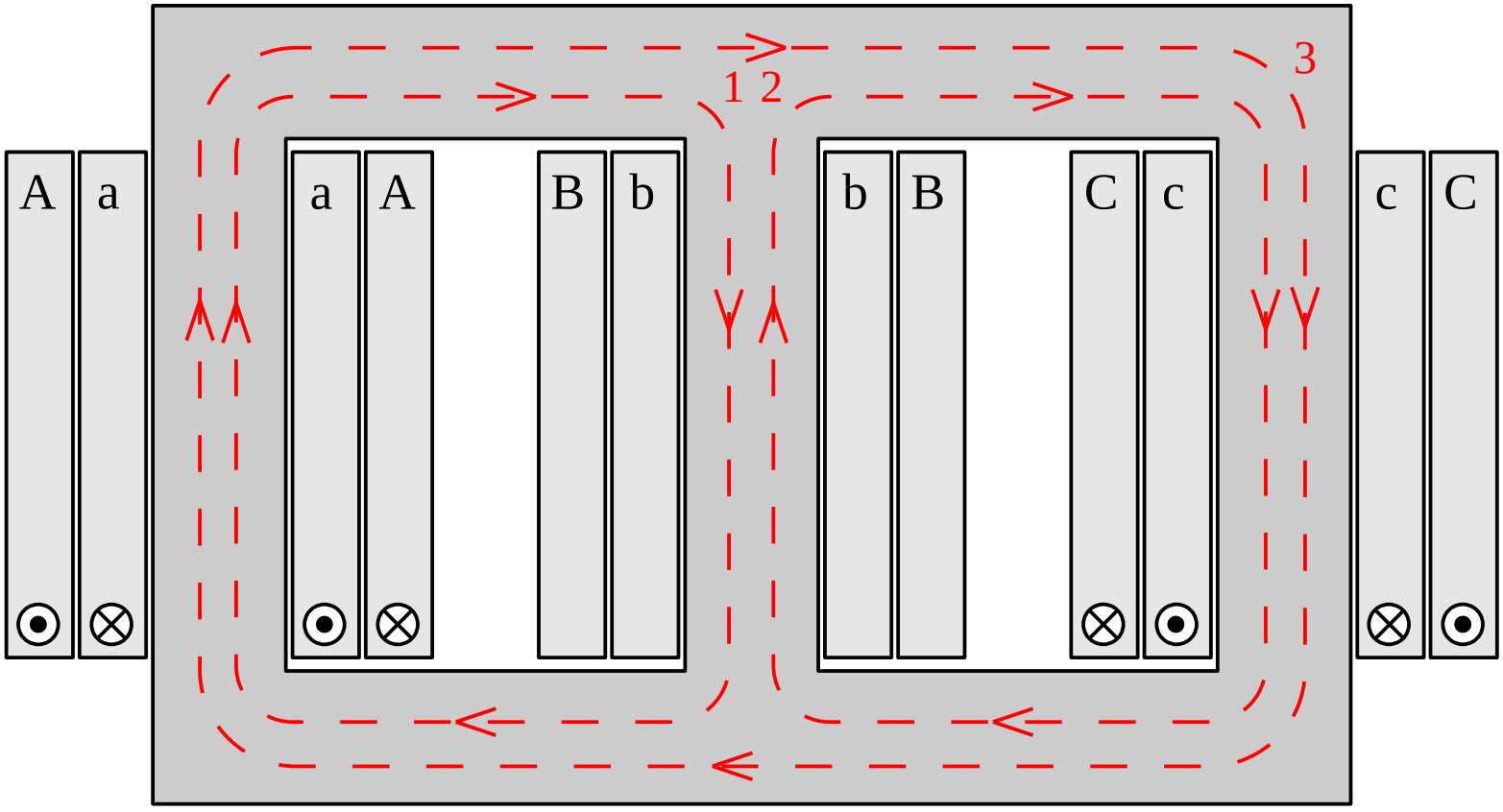
$$\bar{i}_C - \bar{i}_c = 0$$

Three Phase Transformer with a Double Phase Load (Yy)



$$\bar{i}_A - \bar{i}_a + \bar{i}_C - \bar{i}_c = 0$$

Three Phase Transformer with a Double Phase Load (Yy)



$$\bar{i}_A - \bar{i}_a + \bar{i}_C - \bar{i}_c = 0$$

There is no single-direction magnetization.

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Zero-Sequence Transformer Reactance

Zero-Sequence Transformer Reactance

- While performing quantitative analysis of non-symmetrically loaded transformer the method of symmetric components is used (dále v KEV/EST2)
- The transformed is described by three reactances:
  - positive sequence $\bar{z}_1$
  - negative sequence $\bar{z}_2$
  - zero sequence $\bar{z}_0$
- $\bar{z}_1$ and $\bar{z}_2$ independently on the type of the transformer correspond with the short circuit transformer impedance $\bar{z}_k$

Zero-Sequence Transformer Reactance

- The zero-sequence reactance $\underline{z}_0$ depends on type of the transformer and its connection
- E.g. in star connection the zero-sequence reactance is
  - $\underline{z}_0 \rightarrow \underline{z}_\mu$ for shell type
  - $\underline{z}_0 \rightarrow \underline{z}_k$ for core type
- It may be calculated with certain accuracy, practically it is more often measured … see measurements

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Thank You for Your Attention!

Karel Hruska / +420 377 63 4429 / khruska@fel.zcu.cz