EE373-Electrical Machines
Topic 2: Transformers

Topic 2: Transformer

LEARNING GOALS

Introduction

Construction and Principle of Operation

1. **Basic Component**
    1. **Two winding theory**
    2. **Ideal transformer**
    3. **Impedance Transfer**

Practical Transformer

1. **Equivalent Circuit**
2. **Referred & Approximate Equivalent Circuit**
3. **Analysis of Transformer**

Equivalent Circuit Parameters

1. **Open-Circuit Test**
2. **Short-Circuit Test**

Multi-secondary windings

Autotransformer

Voltage Regulation

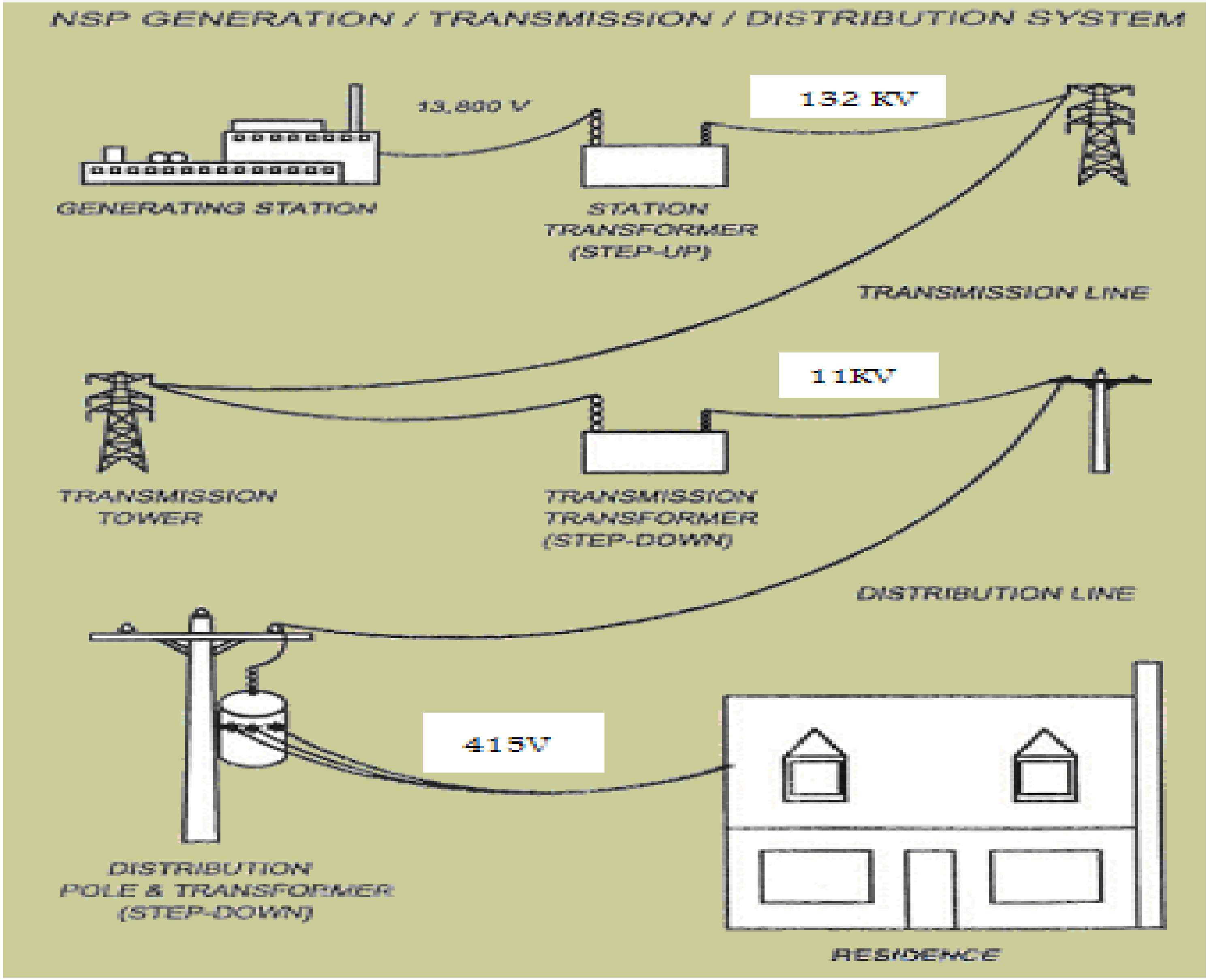
Efficiency

Introduction

A transformer is an electrical device that transfers energy from one electrical circuit to another by magnetic coupling but without any moving parts.

- **Its action is based on the laws of electromagnetic induction.**
- **There is no electrical connection between primary and secondary.**
- **There is no change in frequency.**
- **The ac power is transferred from primary to secondary through magnetic flux.**
- **Transformer has no moving parts.**
- **Rugged and durable in construction.**
- **High efficiency as well as 99%.**
- **Transformers alone cannot do the following:**
  1. **Convert DC to AC or vice versa**
  2. **Change the voltage or current of DC**
  3. **Change the frequency (the "cycles") of AC.**

Introduction



Transmission Transformer

220 KV – 1MV

161 kV Primary Delta-13.8 kV Secondary WYE, (47MVA), Transformer at the SNS site, Oak Ridge, Tennessee, USA.

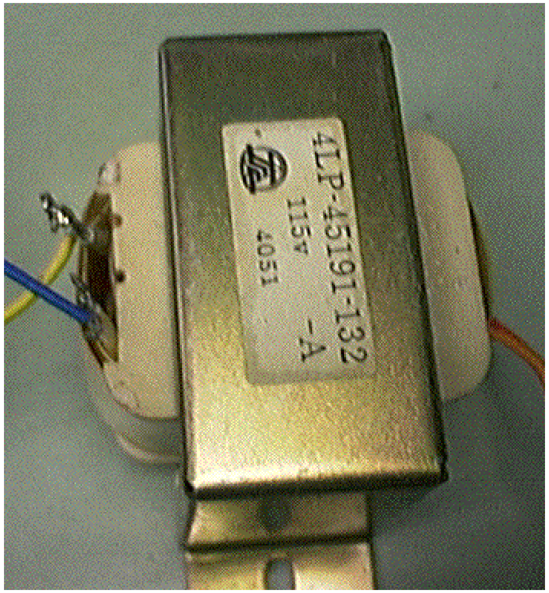
Distribution Transformer

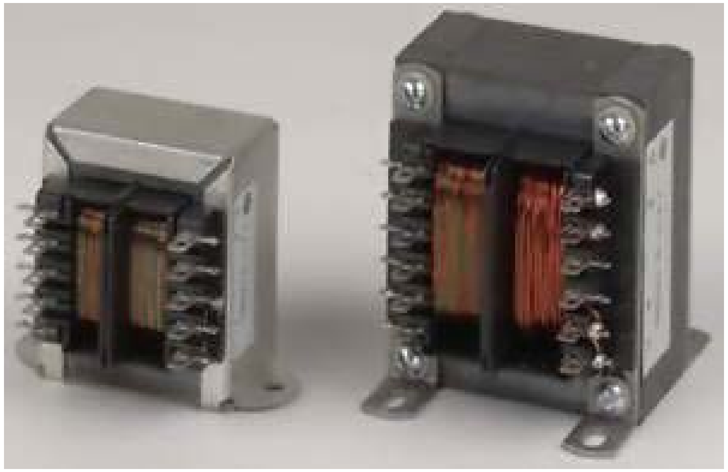
5 KV – 220 KV

Service Transformer

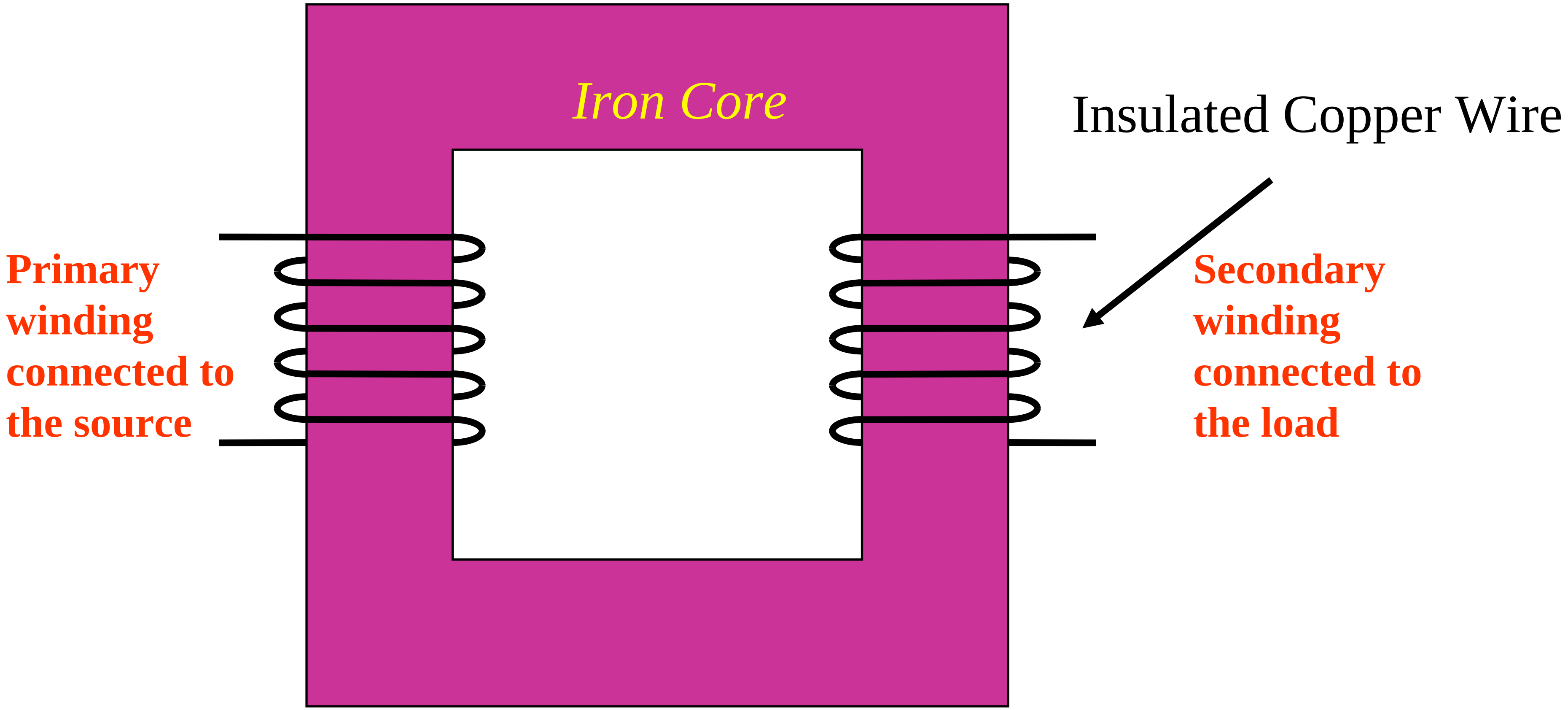
11 KV – 415V

Circuit Transformer



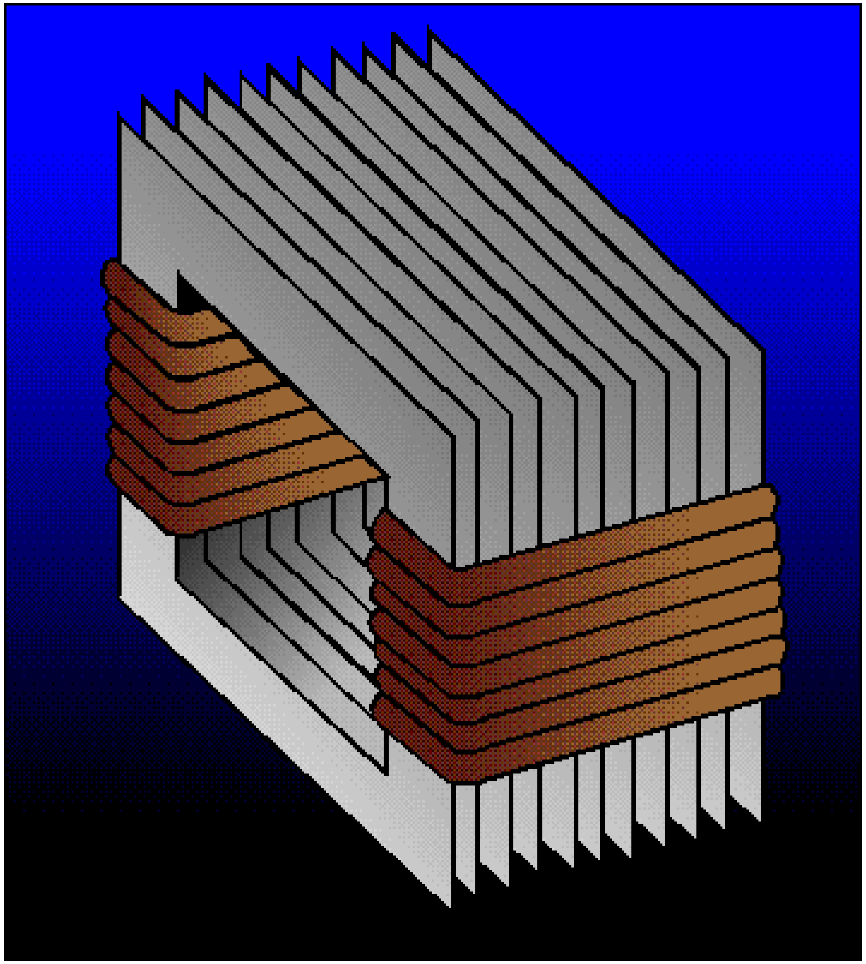


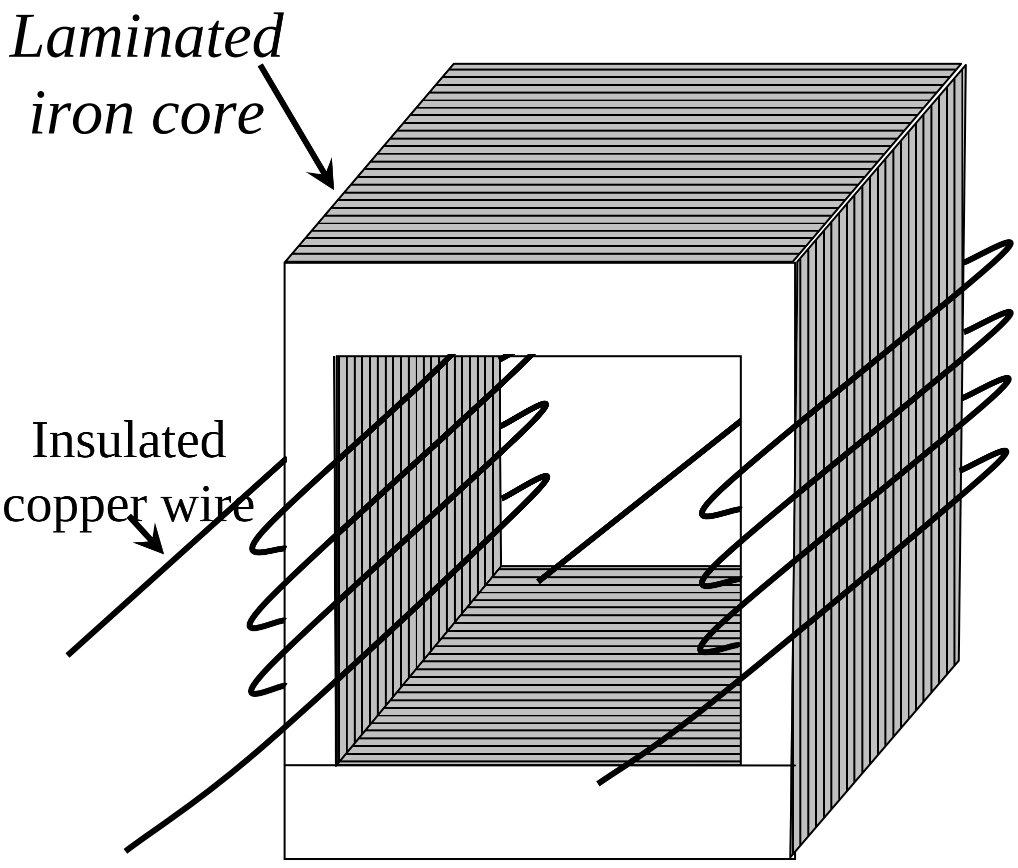
Basic Components



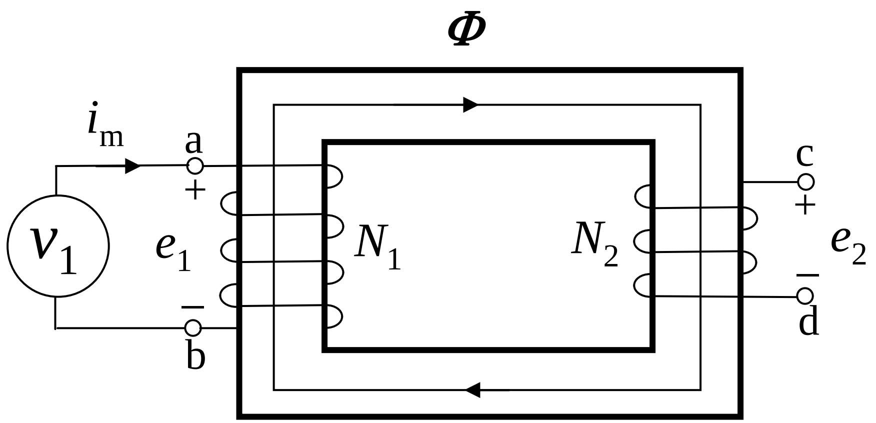
Both coils are electrically separated but magnetically linked through a low reluctance path (Iron Core)

Basic Components





The Two-Winding Theory



Primary

Secondary

$$e_1 = N_1 \frac{d\phi}{dt}$$

$$e_2 = N_2 \frac{d\phi}{dt}$$

If the flux varies sinusoidally, $\phi = \Phi_m \sin \omega t$ then,

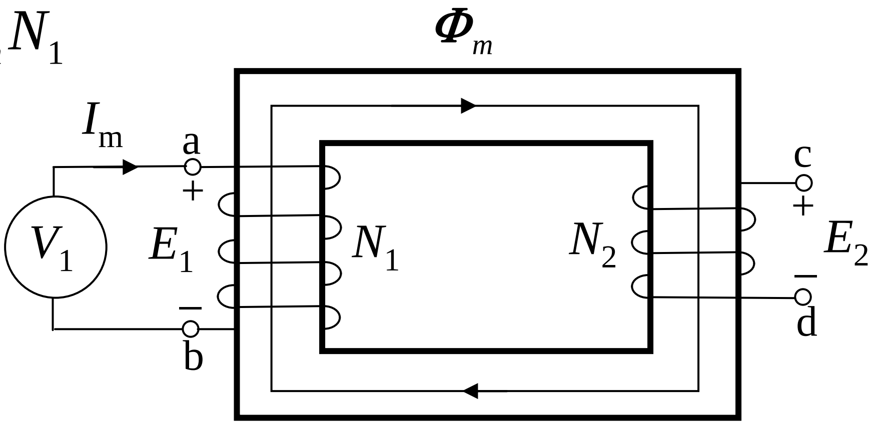
$$e_1 = \omega N_1 \Phi_m \cos \omega t = \sqrt{2} E_1 \cos \omega t$$

E_1 is the root-mean-square value

The Two-Winding Theory (cont.)

$$E_1 = \frac{N_1 \Phi_m \omega}{\sqrt{2}} = \frac{2\pi f}{\sqrt{2}} \Phi_m N_1 = 4.44\, f \Phi_m N_1$$

$$E_2 = 4.44\, f \boldsymbol{\Phi}_m N_2$$

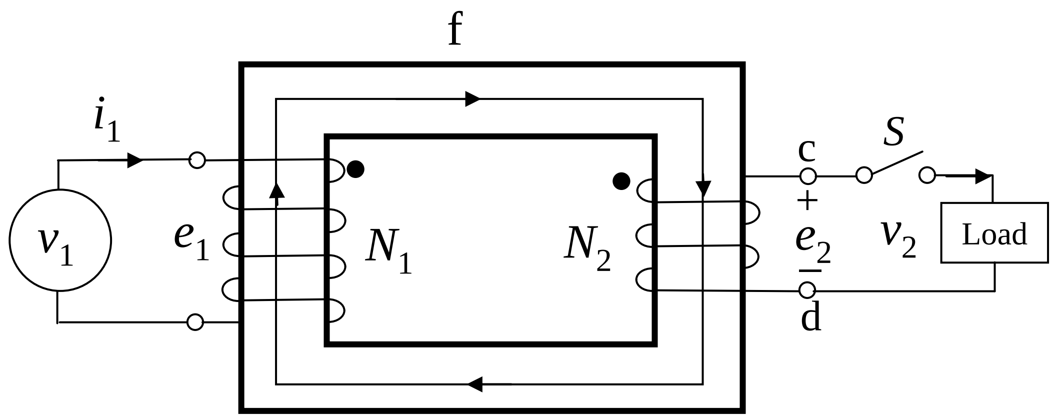


E_1 and E_2 are root-mean-square values

$$\frac{E_1}{E_2} = \frac{N_1}{N_2} = a = turns\ \ ratio$$

- ***Voltages are in phase (no phase shift)***
- ***Voltage magnitudes vary with turns ratio.***

Ideal Transformer at No-Load



<u>Ideal Transformer</u>

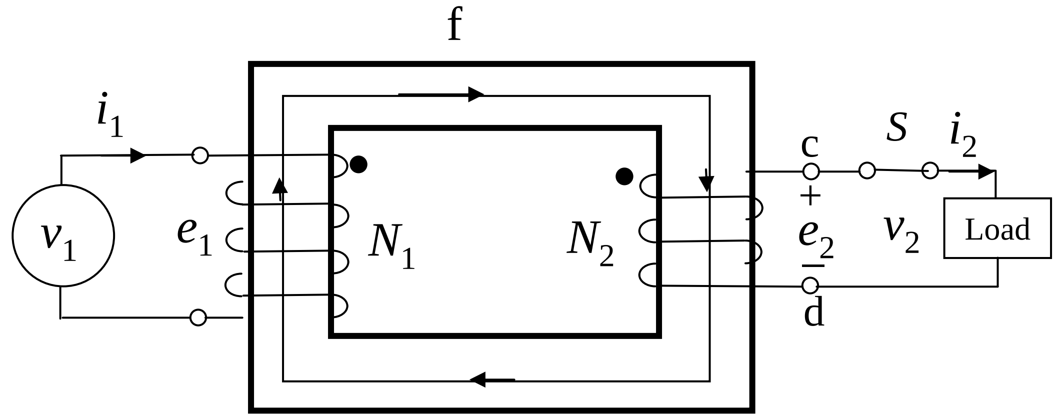
- $r_1 \approx r_2 \approx 0$
- No leakage flux => core losses are negligible
- m ≈ ∞ (high permeability)

⇒ exciting current = 0

$$v_1 = e_1 = N_1 \frac{d\phi}{dt} \qquad v_2 = e_2 = N_2 \frac{d\phi}{dt}$$

$$\frac{v_1}{v_2} = \frac{e_1}{e_2} = \frac{N_1}{N_2} = a \; (\text{turns ratio or transformer ratio})$$

Ideal Transformer Under Load



$$S_1 = S_2$$

$$\bar{E}_1 \bar{I}_1^* = \bar{E}_2 \bar{I}_2^*$$

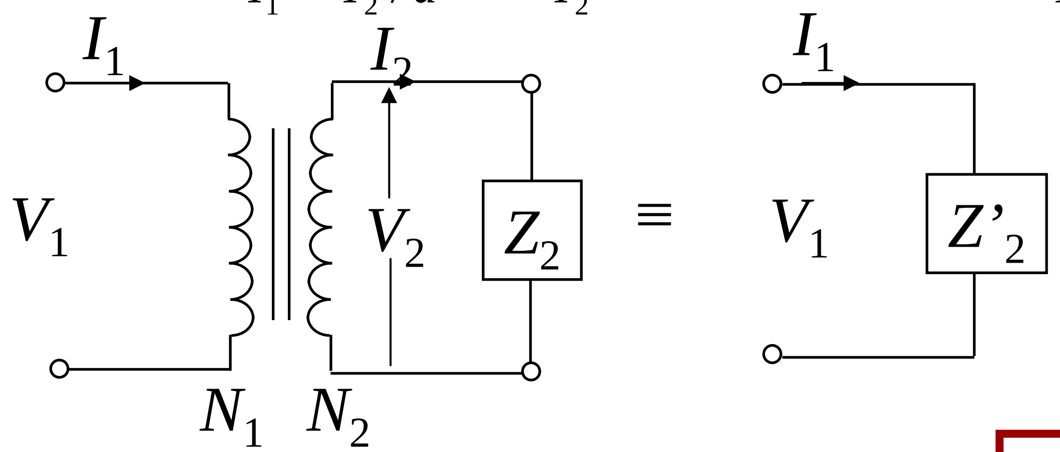
$$\frac{\bar{I}_1^*}{\bar{I}_2^*} = \frac{\bar{E}_2}{\bar{E}_1} \Rightarrow \frac{I_1}{I_2} = \frac{E_2}{E_1} = \frac{N_2}{N_1} \Rightarrow N_1 I_1 = N_2 I_2$$

- ***Currents are in phase.***
- ***Current ratio is opposite to the voltage ratio***

Impedance Transfer

$$\text{Secondary impedance} = Z_2 = \frac{V_2}{I_2}$$

$$\text{Primary impedance} = Z_1 = \frac{V_1}{I_1} = \frac{aV_2}{I_2 / a} = a^2 \frac{V_2}{I_2} = a^2 Z_2 \qquad where\ a = \frac{N_1}{N_2}$$

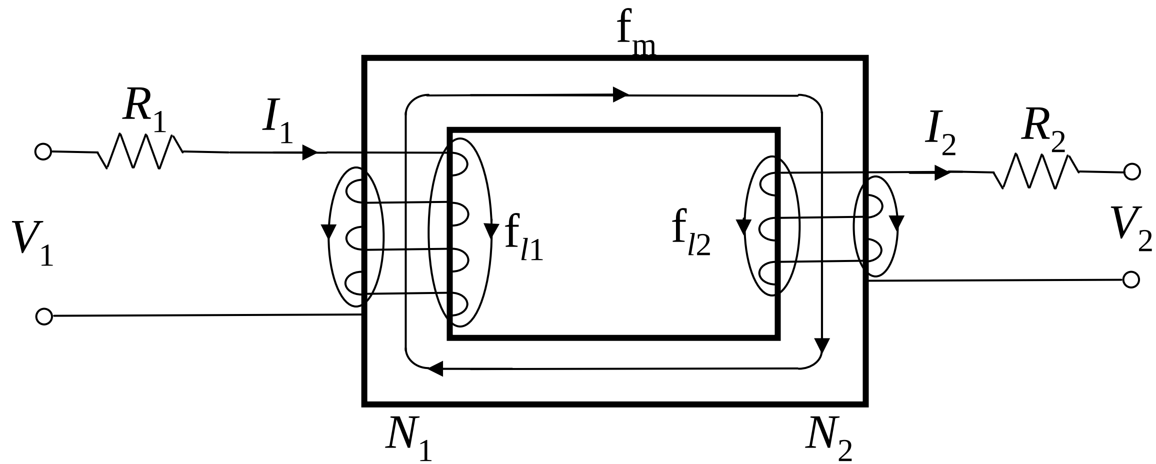


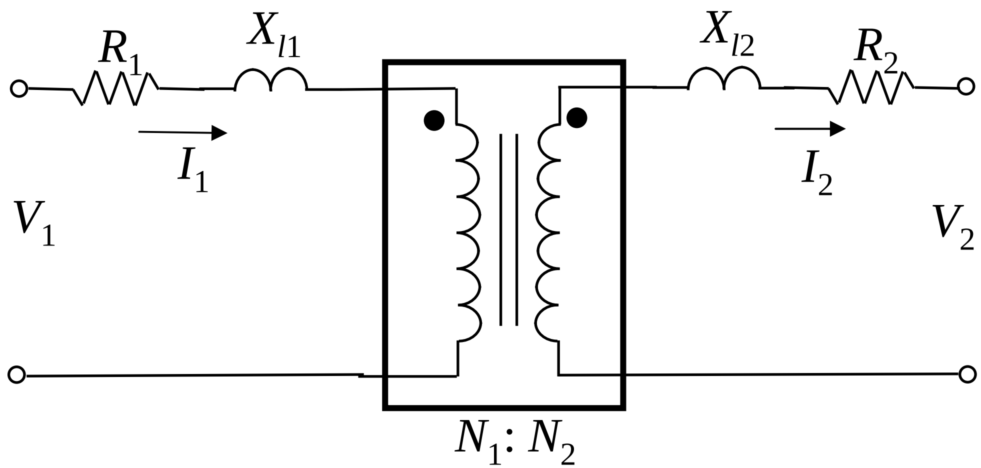
Secondary impedance is transferred to the primary side $\Rightarrow$ $Z_2' = Z_1 = a^2 Z_2$

Primary impedance is transferred to the secondary side $\Rightarrow$ $Z_1' = Z_2 = \frac{1}{a^2} Z_1$

This impedance transfer is very useful because it eliminates a coupled circuit in an electrical circuit and thereby simplifies the circuit.

Equivalent Circuit: Practical Transformer





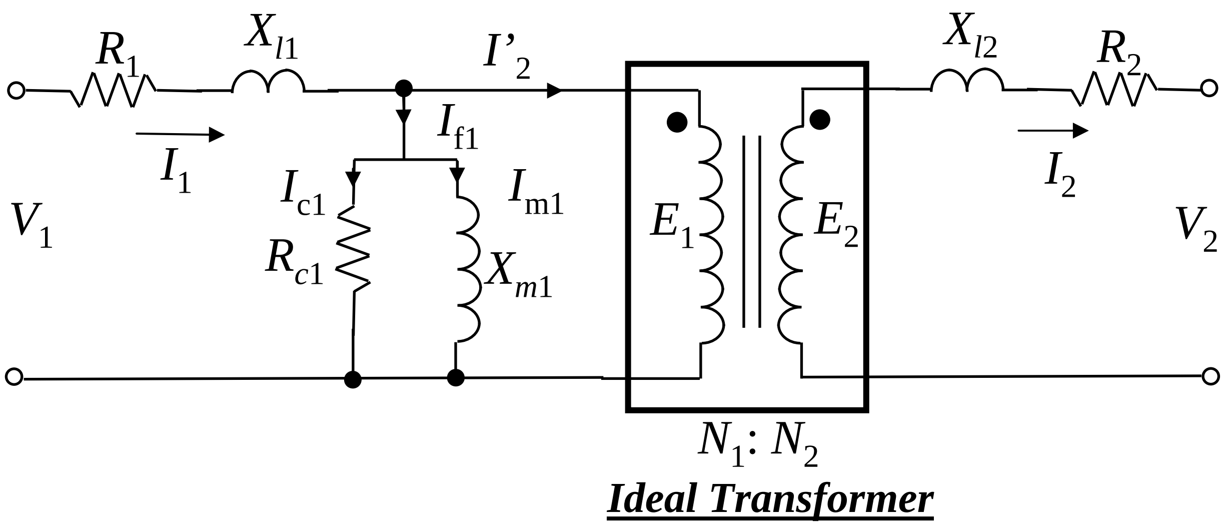
R_1 & R_2: the resistance of the primary and secondary winding

$$X_{l1} = 2\pi f L_{l1} = \text{leakage reactance of winding } 1 \Rightarrow L_{l1} = \frac{N_1 \Phi_{l1}}{I_1} = \text{leakage inductance of winding } 1$$

$$X_{l2} = 2\pi f L_{l2} = \text{leakage reactance of winding } 2 \Rightarrow L_{l2} = \frac{N_2 \Phi_{l2}}{I_2} = \text{leakage inductance of winding } 2$$

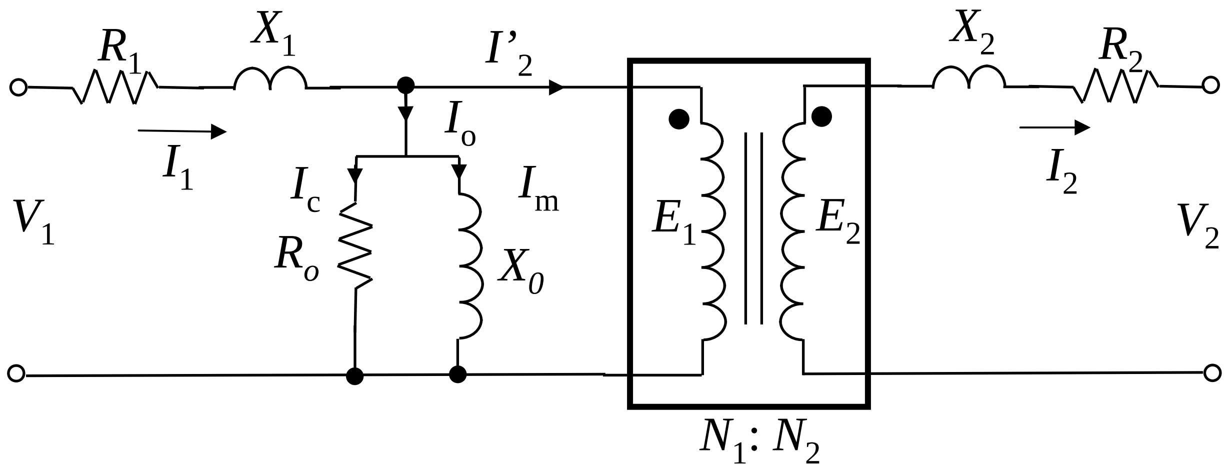
Equivalent Circuit: Practical Transformer

- In practice I_m is required to establish flux ϕ_m in the core.
  => This effect can be represented by a magnetizing inductance L_m.
- The core loss can be represented by a resistance R_c.



A practical transformer is equivalent to an ideal transformer + external impedances that represent imperfections of an actual transformer.

Equivalent Circuit: Practical Transformer



$$\bar{V_1} = \bar{E_1} + \bar{I_1}\left(R_1 + jX_1\right) \qquad \bar{E_2} = \left[\bar{V_2} + \bar{I_2}(R_2 + jX_2)\right]$$

$$\bar{V_1} = \bar{E_2}\frac{N_1}{N_2} + \bar{I_1}\left(R_1 + jX_1\right)$$

$$\bar{V_1} = \left[\bar{V_2} + \bar{I_2}(R_2 + jX_2)\right]\frac{N_1}{N_2} + \bar{I_1}\left(R_1 + jX_1\right)$$

$$but \quad I_2 = I_2'\left(\frac{N_1}{N_2}\right)$$

$$\bar{V_1} = \left[\bar{V_2}\frac{N_1}{N_2} + I_2'\left(\frac{N_1}{N_2}\right)^2 (R_2 + jX_2)\right] + \bar{I_1}\left(R_1 + jX_1\right)$$

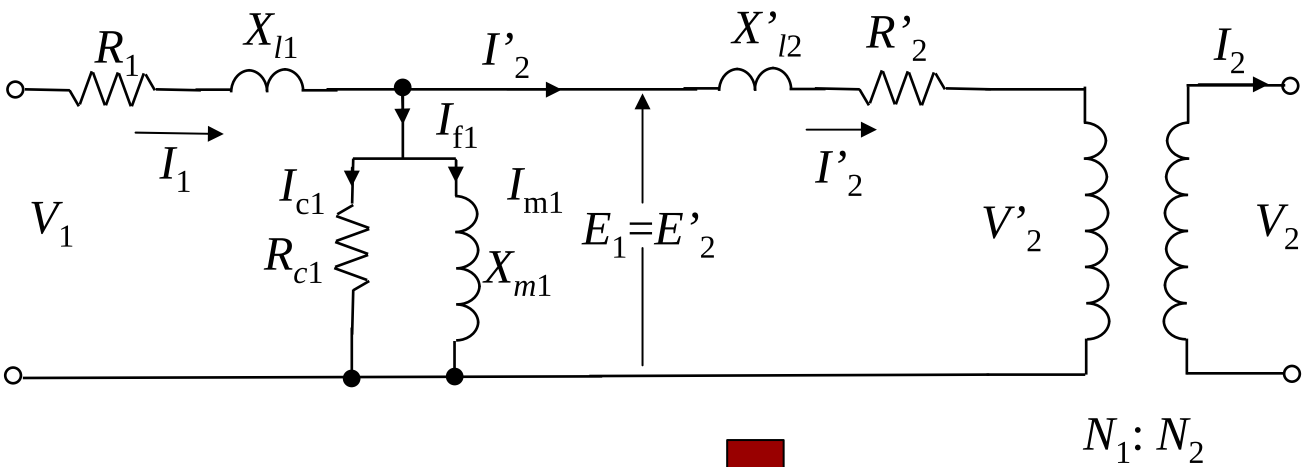
$$\bar{V_1} = \left[\bar{V_2}' + I_2'(R_2' + jX_2')\right] + \bar{I_1}\left(R_1 + jX_1\right)$$

$$R_2' = R_2\left(\frac{N_1}{N_2}\right)^2$$

$$X_2' = X_2\left(\frac{N_1}{N_2}\right)^2$$

$$V_2' = V_2\left(\frac{N_1}{N_2}\right)$$

Referred Equivalent Circuit



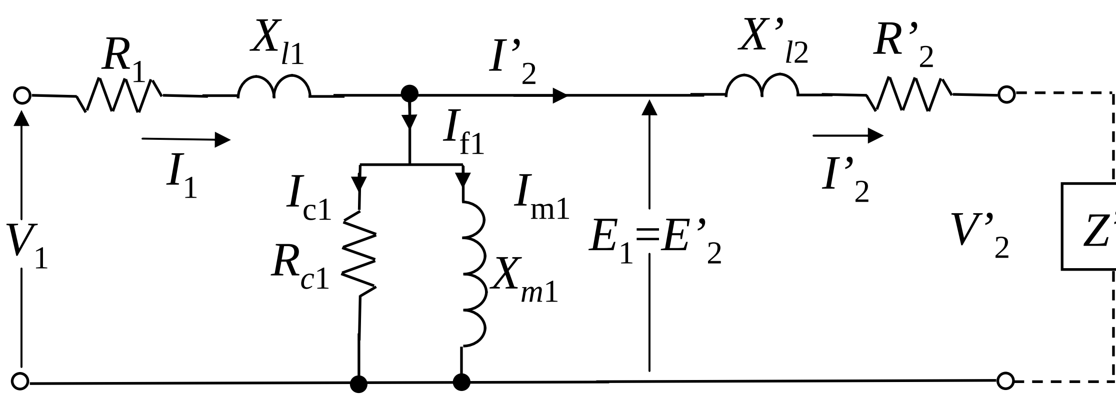
$$E_1 = E_2^{'} = aE_2$$

$$V_2^{'} = aV_2$$

$$I_2^{'} = I_2 / a$$

$$X_{l2}^{'} = a^2 X_{l2}$$

$$R_2^{'} = a^2 R_2$$



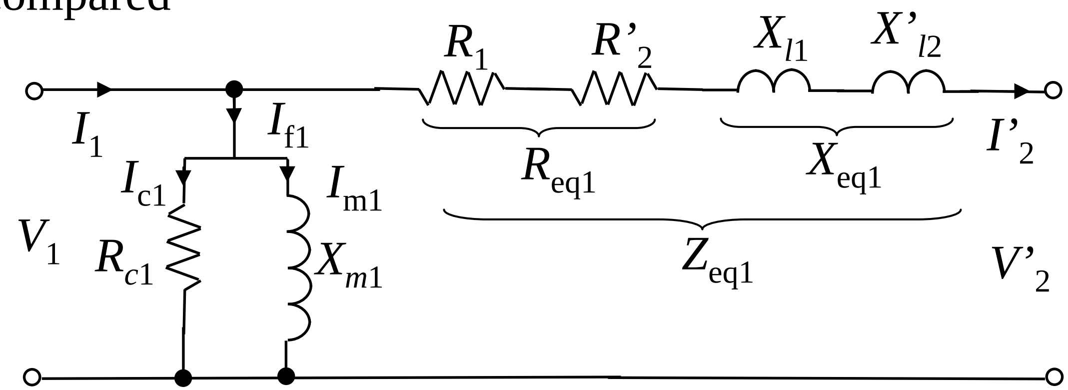
Load impedance transferred to the primary

Transformer Equivalent Circuit

Approximate Equivalent Circuit

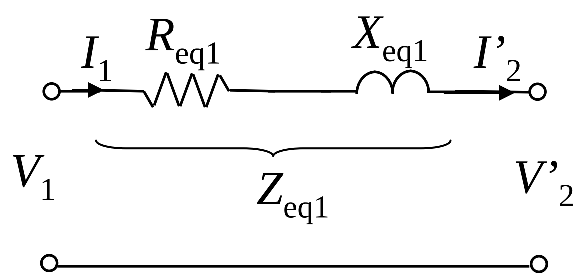
I_1R_1 and I_1X_{l1} are very small compared to $V_1 \Rightarrow |E_1| \approx |V_1|$

Shunt branch can be moved to the supply terminal



$I_{\phi1}$ is also very small compared to I_1

$I_{\phi1} \le 5\% \times I_1 \Rightarrow$ it's possible to remove the shunt branch.

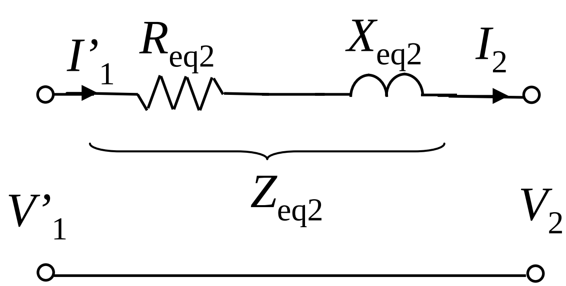


Referred to Primary

$$R_{eq2} = \frac{R_{eq1}}{a^2} = R_2 + R_1^{'}$$

$$X_{eq2} = \frac{X_{eq1}}{a^2} = X_{l2} + X_{l1}^{'}$$

$$V_1^{'} = \frac{V_1}{a} \quad , \quad I_1^{'} = I_2 = aI_1$$

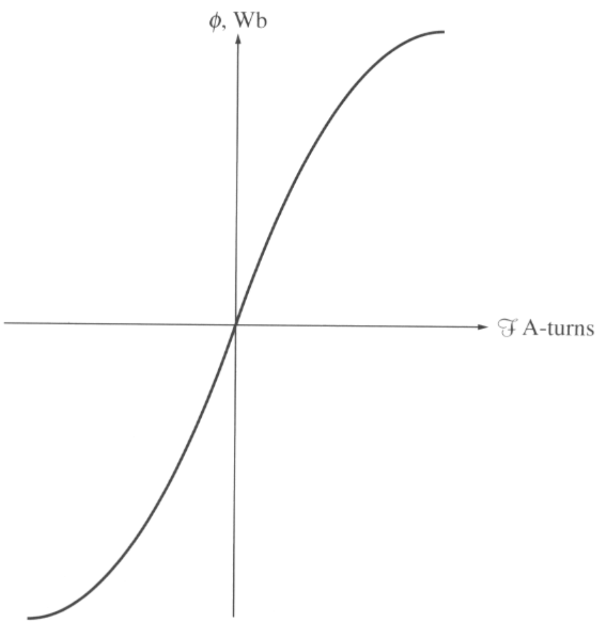


Referred to Secondary

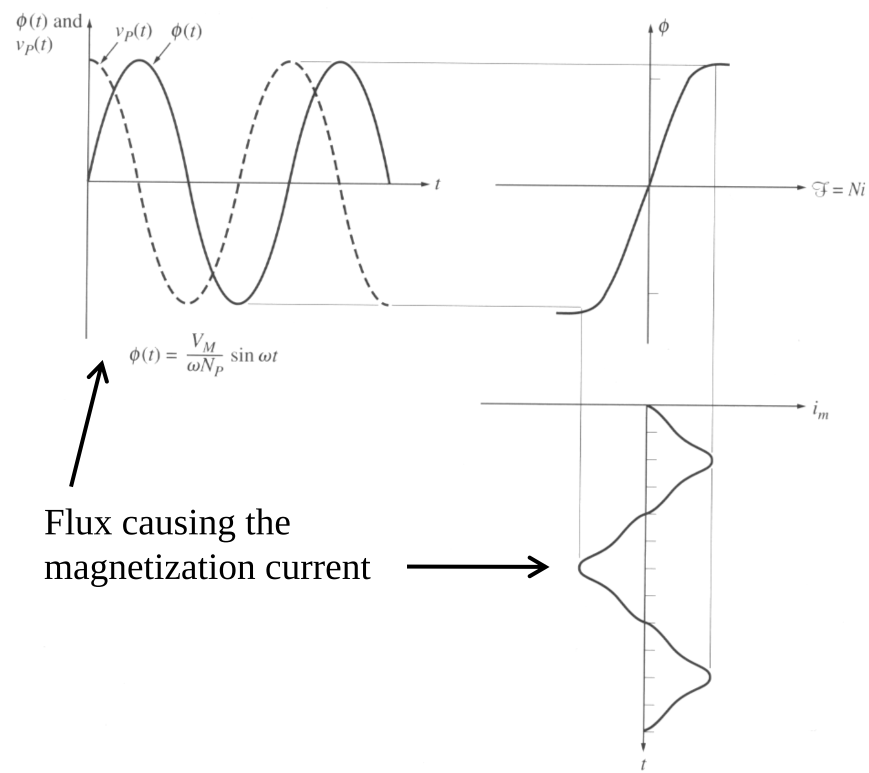
The magnetization current in a real transformer

Even when no load is connected to the secondary coil of the transformer, a current will flow in the primary coil. This current consists of:

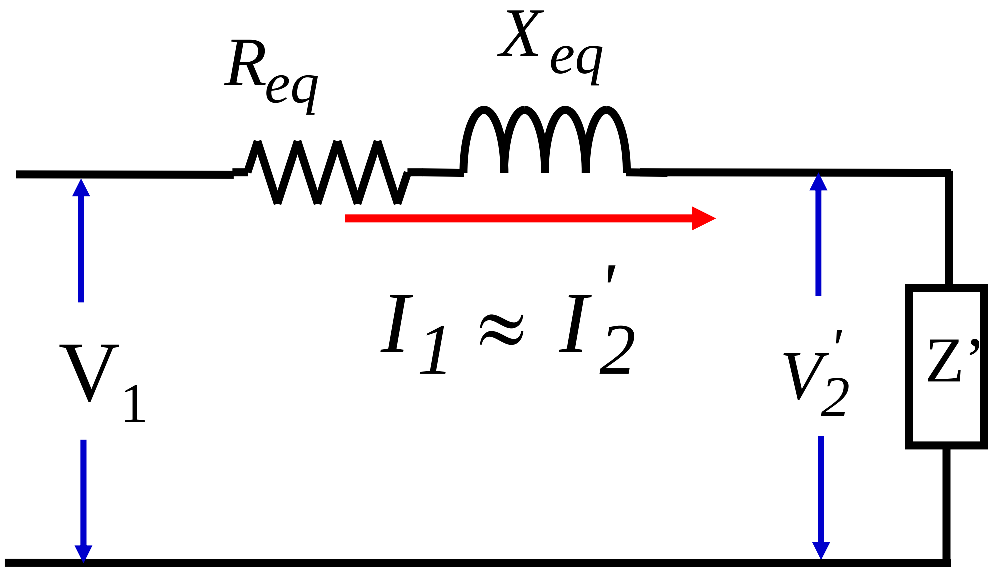
1. The magnetization current i_m needed to produce the flux in the core;
2. The core-loss current i_{h+e} hysteresis and eddy current losses.



Typical magnetization curve

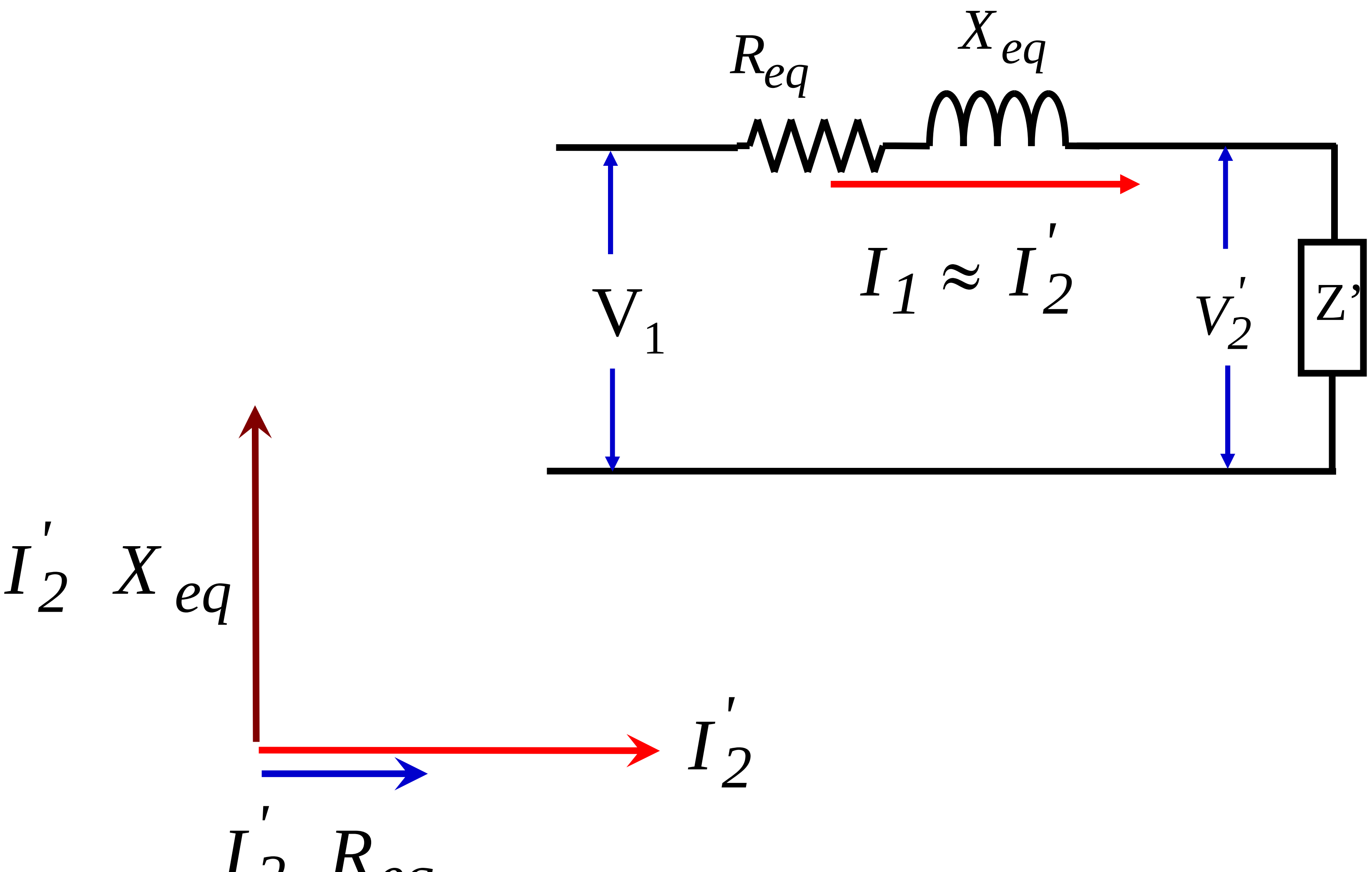


Analysis of Transformer

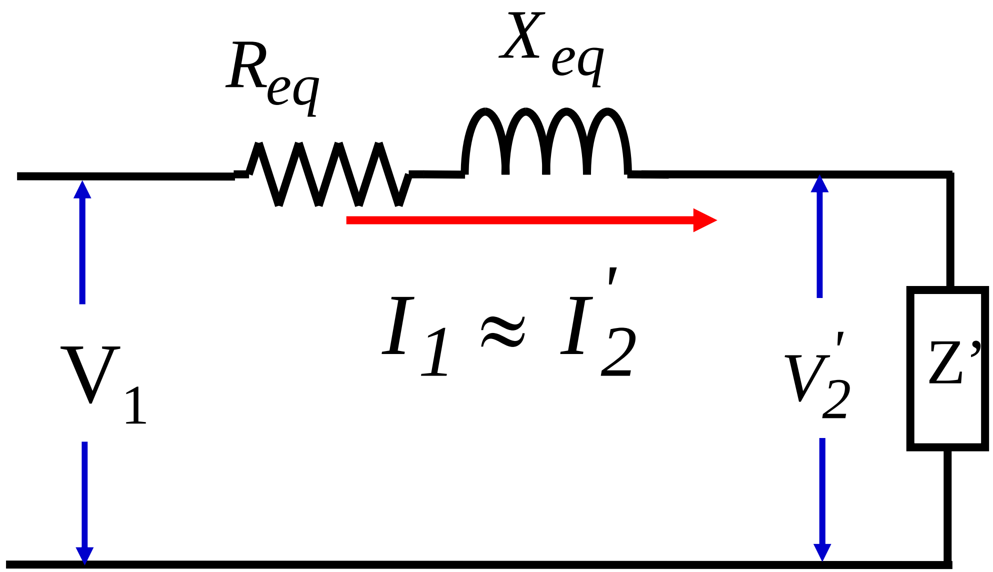


$$\bar{V}_1 = \bar{V}_2' + \bar{I}_2'\left(R_{eq} + jX_{eq}\right)$$

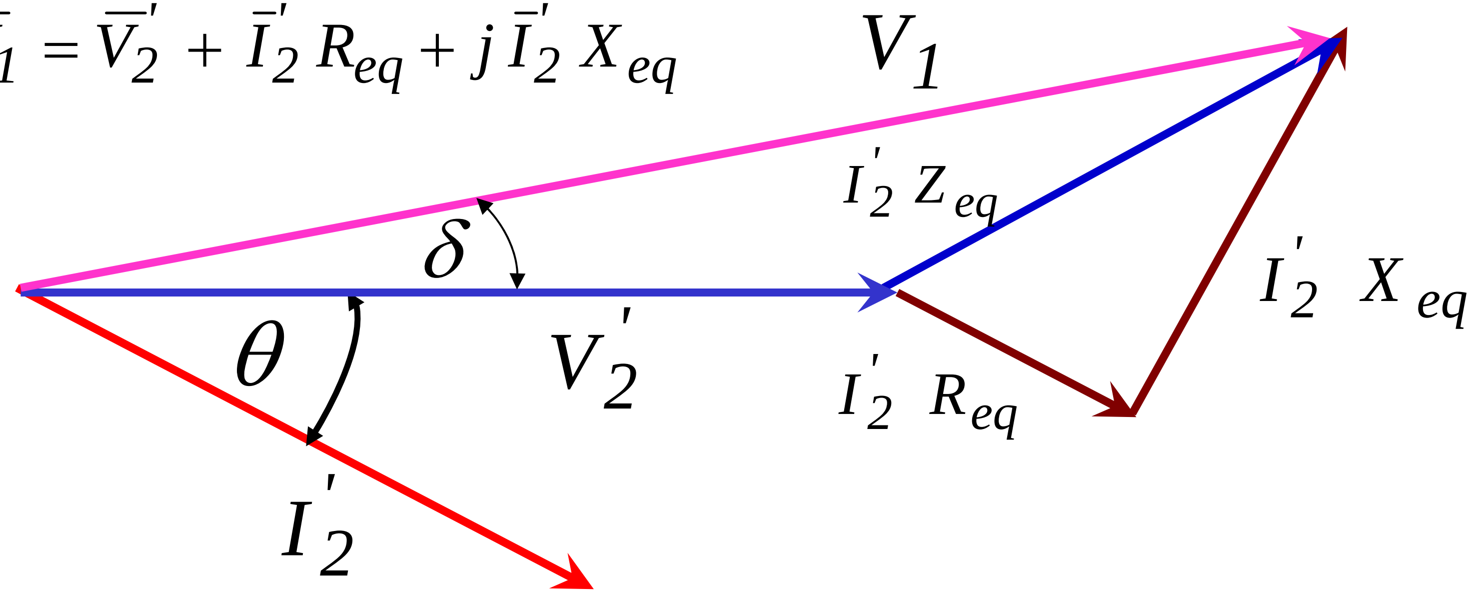
Analysis of Transformer



Analysis of Transformer



$$\bar{V}_1 = \bar{V}_2' + \bar{I}_2' R_{eq} + j\,\bar{I}_2' X_{eq}$$



Rated Values

- ***Rated voltage:*** The device can continuously operate at the rated voltage without being damaged due to insulation failure

- ***Rated current:*** The device can continuously operate at the rated current without being damaged due to thermal destruction

Transformer Rating and Name Plate

10kVA
1100/110 Volts

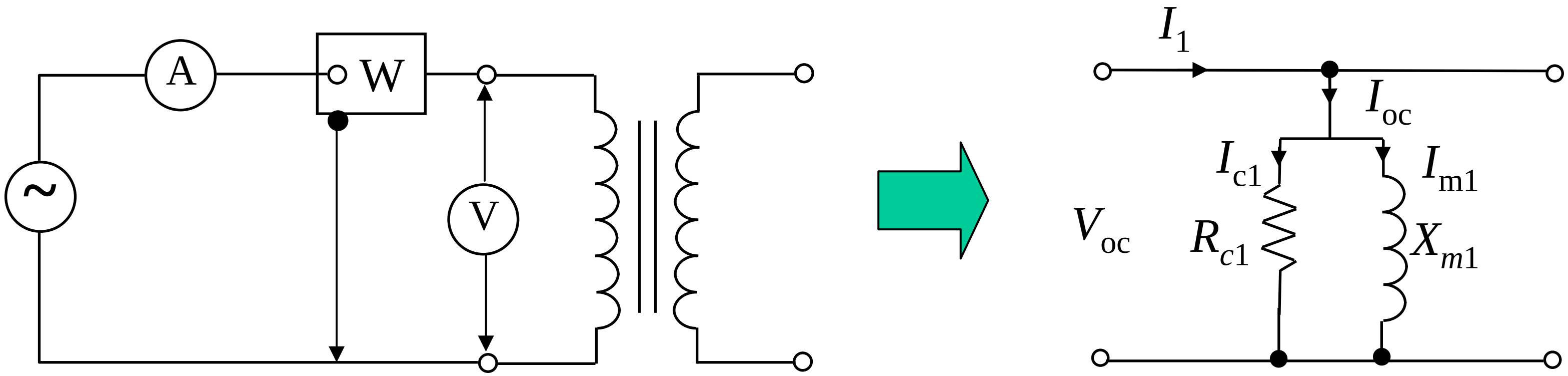
- The transformer has two windings one rated for 1100V an the other one for 110V
  a = 1100/110 = 10 = turns ratio

- Each winding is designed for 10 kVA.

- The current rating for high-voltage winding is 10000/1100 = 9.09 A
- The current rating for lower-voltage winding is 10000/110 = 90.9 A

Equivalent Circuit Parameters

No-Load test (Open-Circuit Test)



$$R_{c1} = \frac{V_{oc}^2}{P_{oc}}$$

$$I_{c1} = \frac{V_{oc}}{R_{c1}}, \quad I_{m1} = \sqrt{I_{oc}^2 - I_{c1}^2}$$

$$X_{m1} = \frac{V_{oc}}{I_{m1}}$$

$$P_{oc} = I_{oc} V_{oc} \cos(\Phi_o)$$

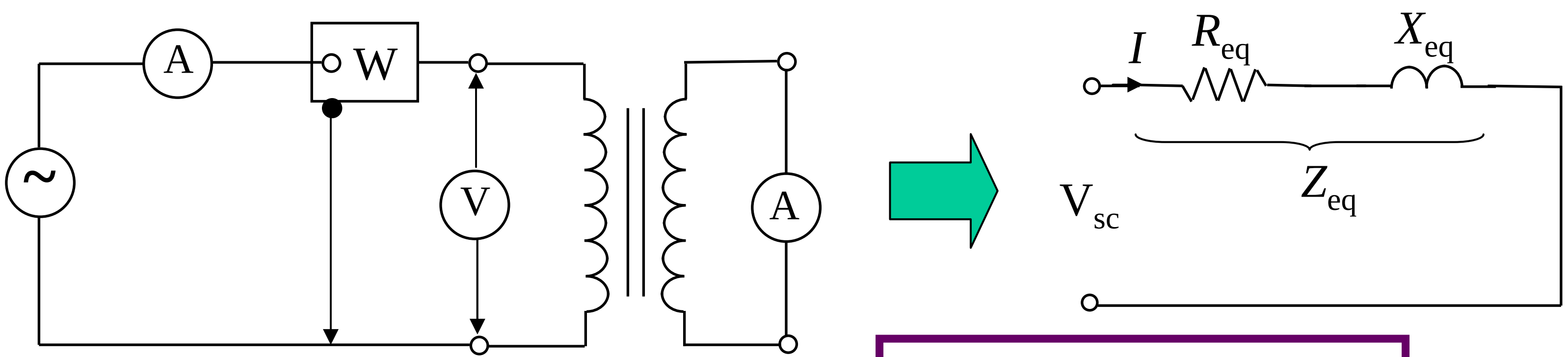
$$\cos(\Phi_o) = \frac{P_{oc}}{I_{oc} V_{oc}}$$

$$I_{c1} = I_{oc} \cos(\Phi_o) \ \& \ I_{m1} = I_{oc} \sin(\Phi_o)$$

$$R_{c1} = \frac{V_{oc}}{I_{C1}}, \quad X_{m1} = \frac{V_{oc}}{I_{m1}}$$

Equivalent Circuit Parameters

Short-Circuit Test



$$R_{eq} = \frac{P_{sc}}{I_{sc}^2}$$

$$Z_{eq} = \frac{V_{sc}}{I_{sc}}$$

$$X_{eq} = \sqrt{Z_{eq}^2 - R_{eq}^2}$$

$$\cos(\Phi_{sc}) = \frac{P_{sc}}{I_{sc} V_{sc}}$$

$$Z_{sc} = \frac{V_{sc}}{I_{sc}}$$

$$R_{eq} = Z_{sc} \cos(\Phi_{sc})$$

$$X_{eq} = Z_{sc} \sin(\Phi_{sc})$$

$$R_1 + a^2 R_2 = R_{eq1} \quad \& \quad X_1 + a^2 X_2 = X_{eq}$$

The primary resistance R_1 can be measured directly.

The leakage reactance is assumed to be divided equally, $X_1 = a^2 X_2 = 0.5\, X_{eq}$

Determining the values of components

Example:

Example 2: We need to determine the equivalent circuit impedances of a 20 kVA, 8000/240 V, 60 Hz transformer. The open-circuit and short-circuit tests led to the following data:

$V_{OC} = 8000\ V$	$V_{SC} = 489\ V$
$I_{OC} = 0.214\ A$	$I_{SC} = 2.5\ A$
$P_{OC} = 400\ W$	$P_{SC} = 240\ W$

The power factor during the open-circuit test is

$$PF = \cos\theta = \frac{P_{OC}}{V_{OC} I_{OC}} = \frac{400}{8000 \cdot 0.214} = 0.234\ \ lagging$$

The excitation admittance is

$$Y_E = \frac{I_{OC}}{V_{OC}} \angle -\cos^{-1} PF = \frac{0.214}{8000} \angle -\cos^{-1} 0.234 = 0.0000063 - j0.0000261 = \frac{1}{R_C} - j\frac{1}{X_M}$$

Determining the values of components

Example:

Therefore:

$$R_C = \frac{1}{0.0000063} = 159\,k\Omega; \quad X_M = \frac{1}{0.0000261} = 38.3\,k\Omega$$

The power factor during the short-circuit test is

$$PF = \cos\theta = \frac{P_{SC}}{V_{SC} I_{SC}} = \frac{240}{489 \cdot 2.5} = 0.196 \;\; lagging$$

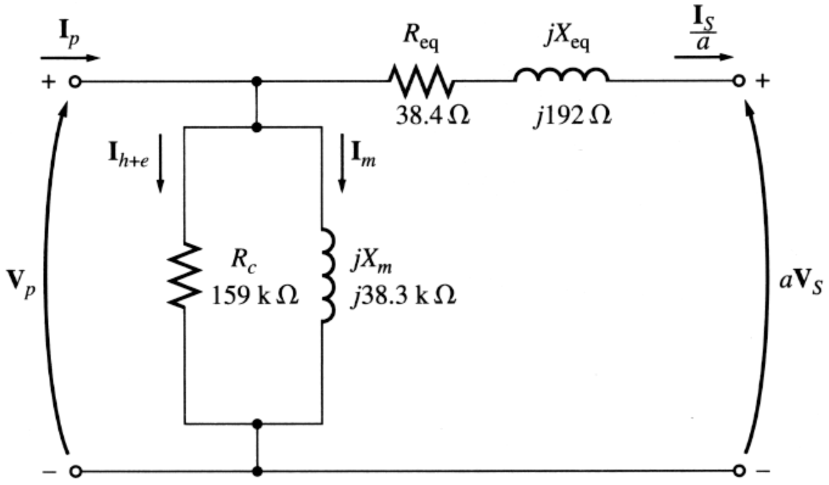
The series impedance is given by

$$Z_{SE} = \frac{V_{SC}}{I_{SC}} \angle \cos^{-1} PF = \frac{489}{2.5} \angle 78.7^{\circ}$$
$$= 38.4 + j192\,\Omega$$

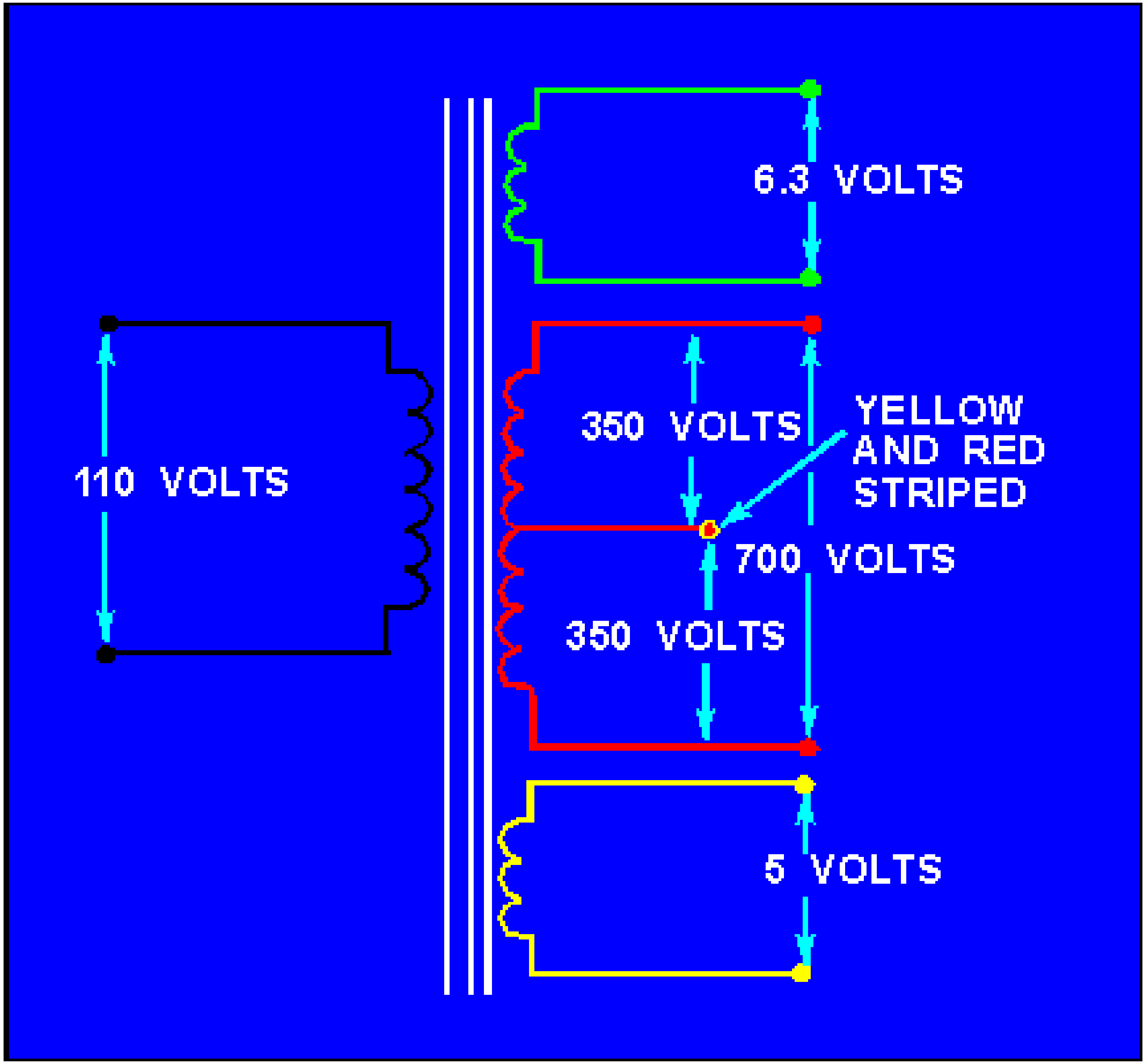
Therefore:

$$R_{eq} = 38.3\,\Omega; \quad X_{eq} = 192\,\Omega$$

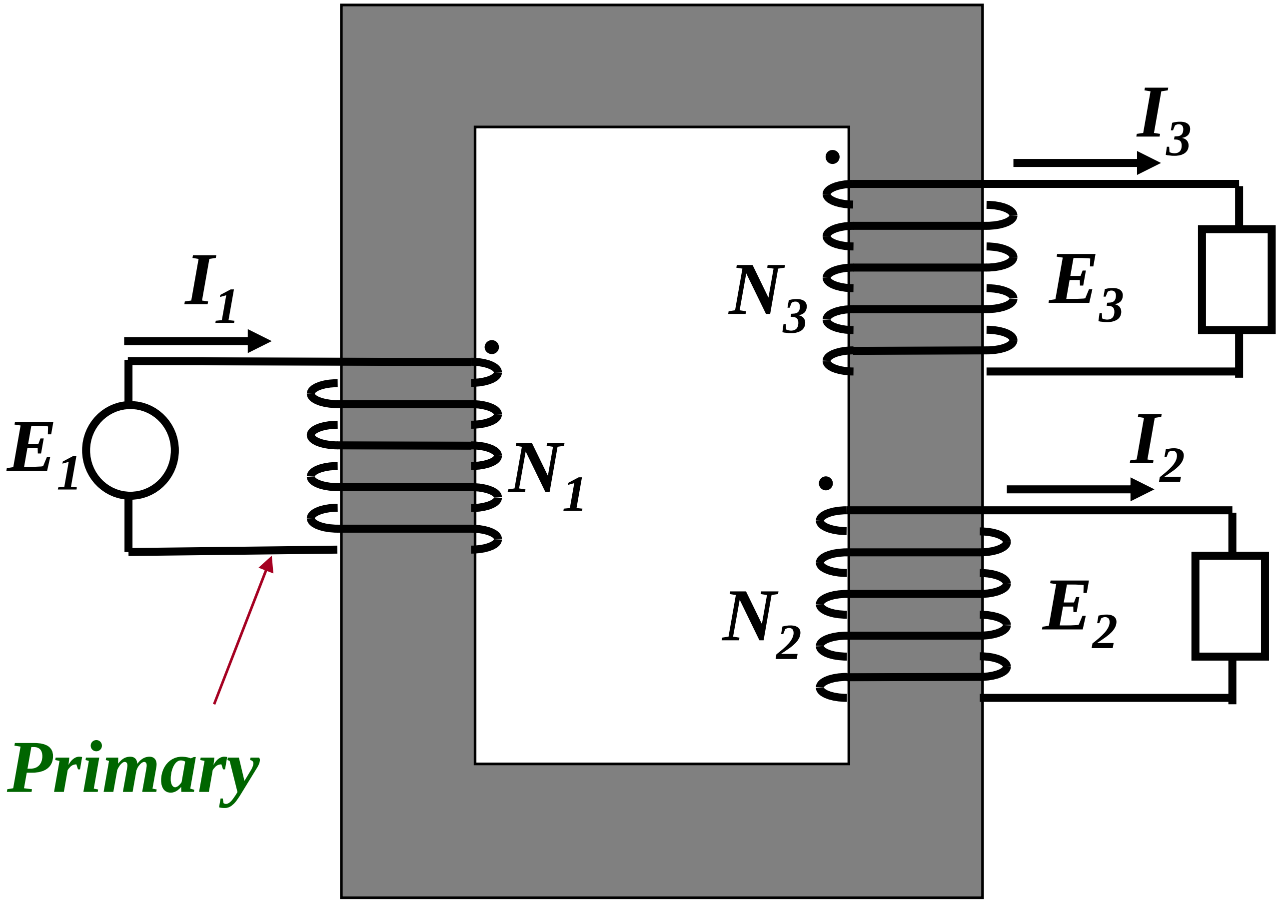
The equivalent circuit



Multi-secondary windings



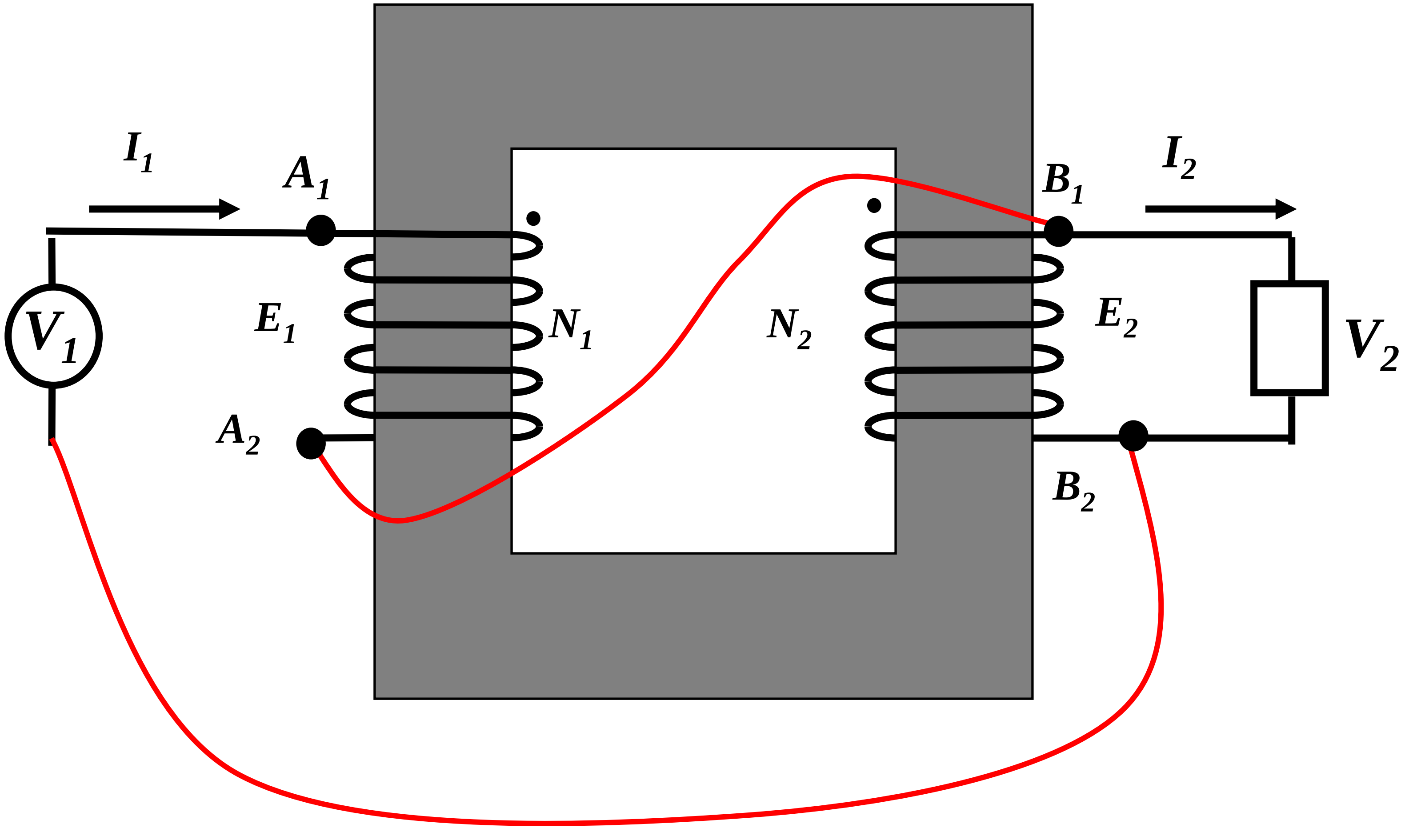
Multi-secondary windings



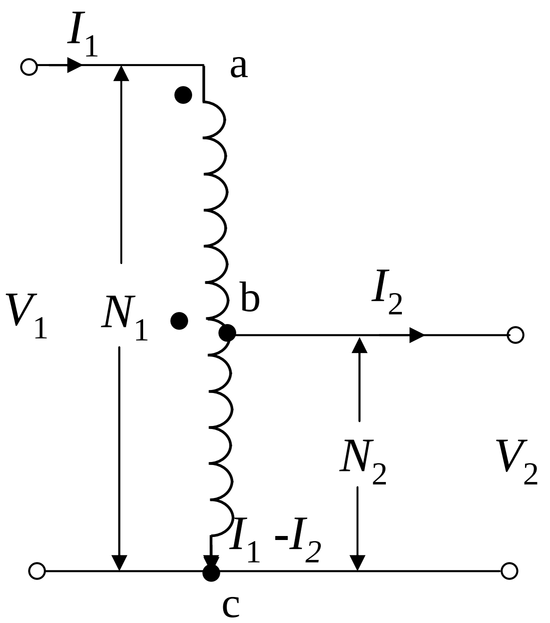
$$\frac{E_1}{E_2} = \frac{N_1}{N_2}$$

$$\frac{E_1}{E_3} = \frac{N_1}{N_3}$$

Autotransformer



Autotransformer



$$\frac{V_1}{V_2} = \frac{N_1}{N_2} = a$$

Advantages:

- Lower leakage reactances
- Lower losses
- Lower exciting current
- Increased kVA rating
- Variable voltage output

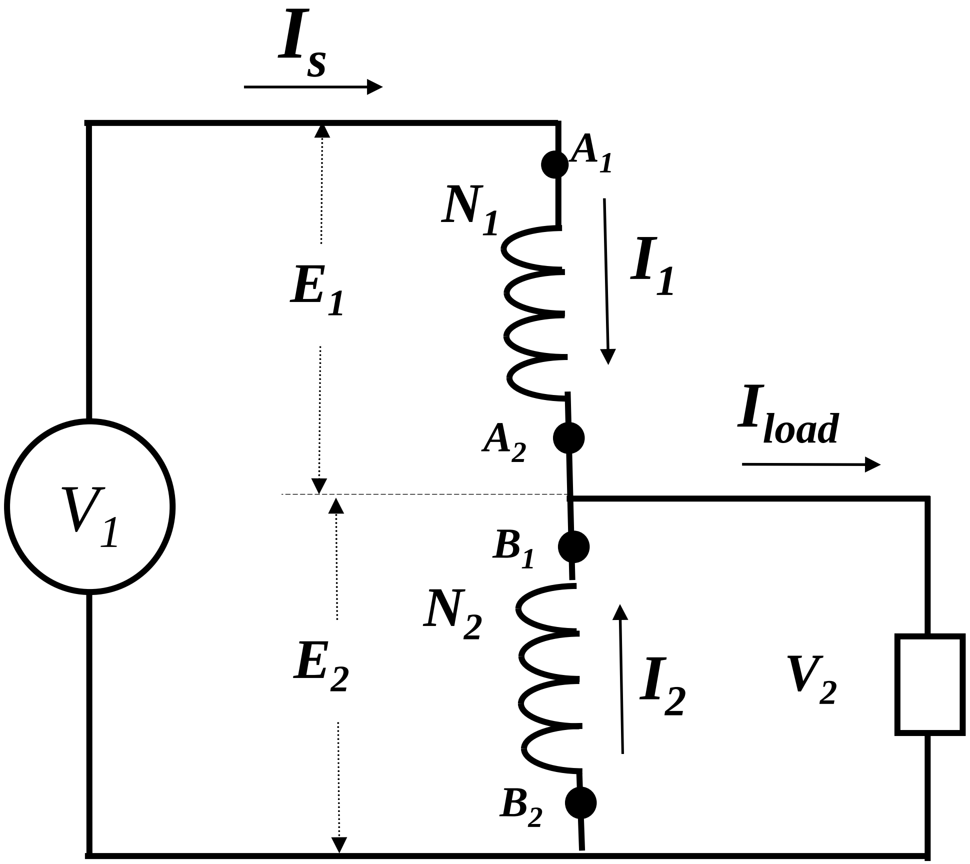
Disadvantage:

- The direct connection between the primary and secondary sides.

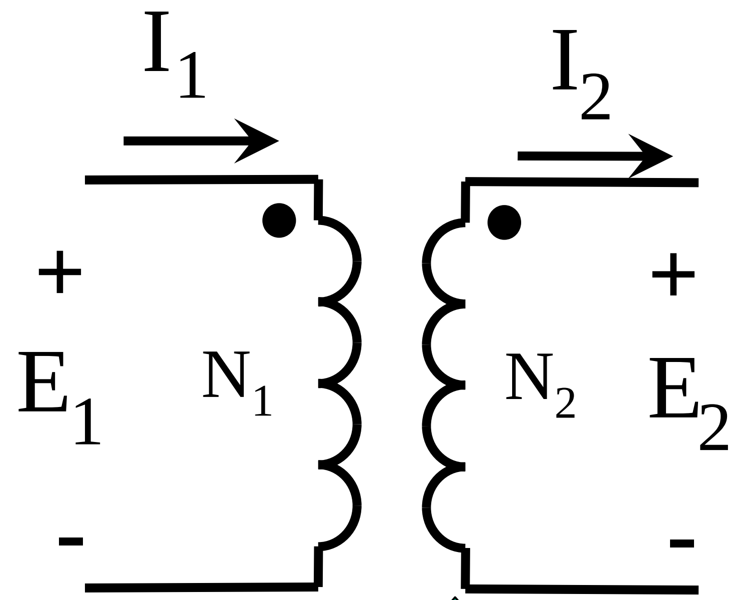
Autotransformer: Voltage and current

$$\bar{I}_{load} = \bar{I}_1 + \bar{I}_2$$

$$\bar{V}_1 = \bar{E}_1 + \bar{E}_2$$

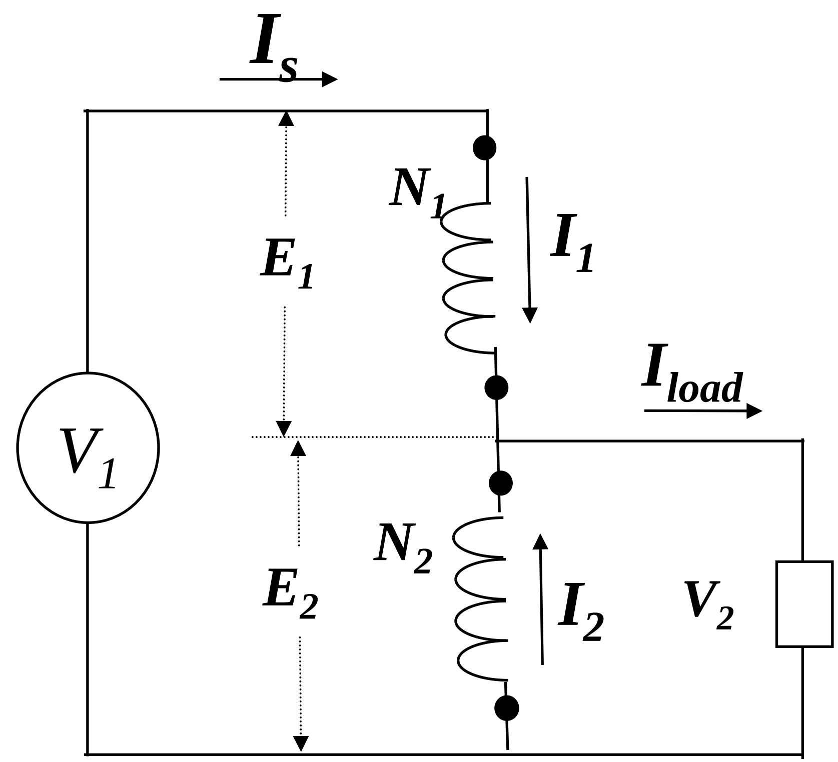


Autotransformer



$$|S_A| = E_1 I_1 = E_2 I_2$$

$$|S_B| = V_1 I_s = V_2\, I_{load}$$



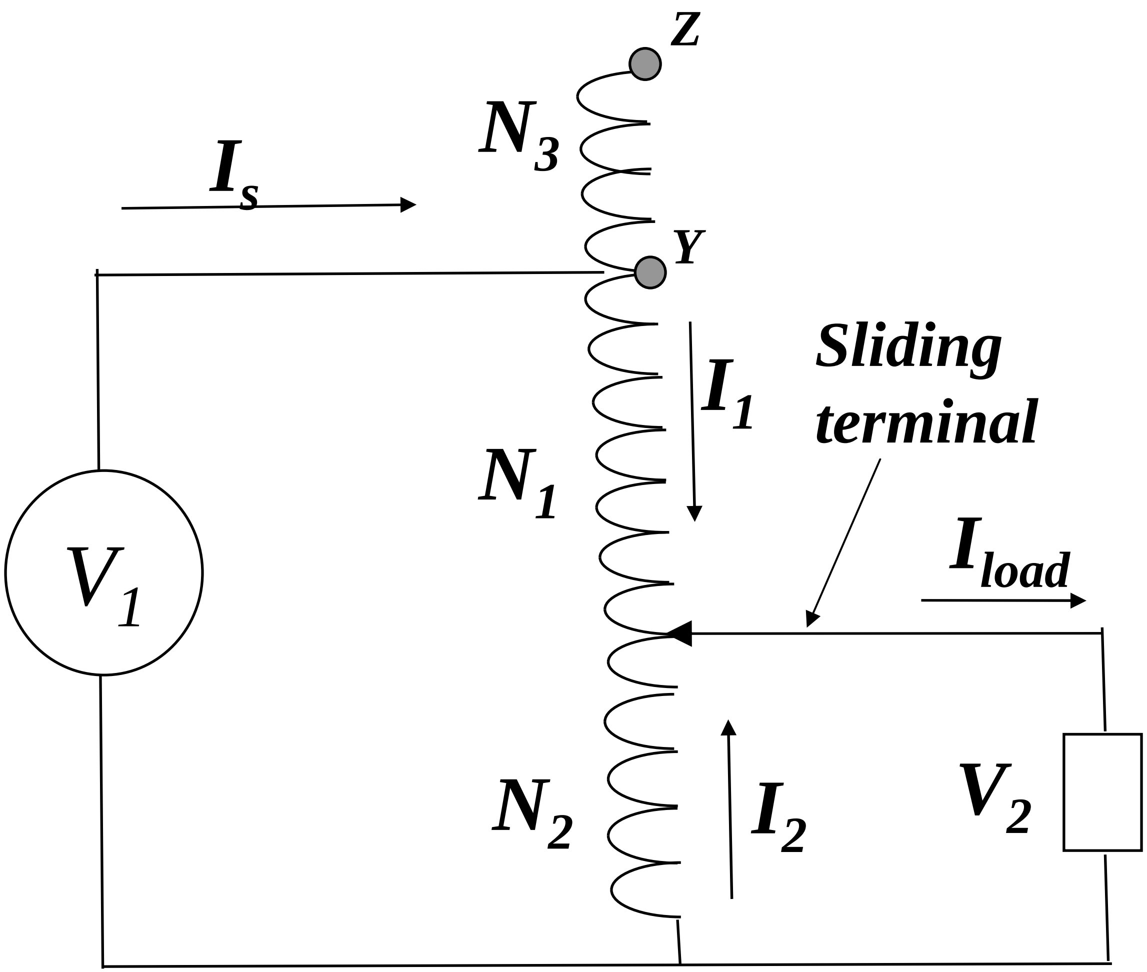
Autotransformer: Power

$$\left|S_B\right| = V_1 I_s = (E_1 + E_2) I_1 = E_1 I_1 + E_2 I_1$$

$$\left|S_B\right| = \left|S_A\right| + E_2 I_1$$

$$\left|S_B\right| > \left|S_A\right|$$

VARIC: Variable Auto-Transformer



VARIC: Output Voltage

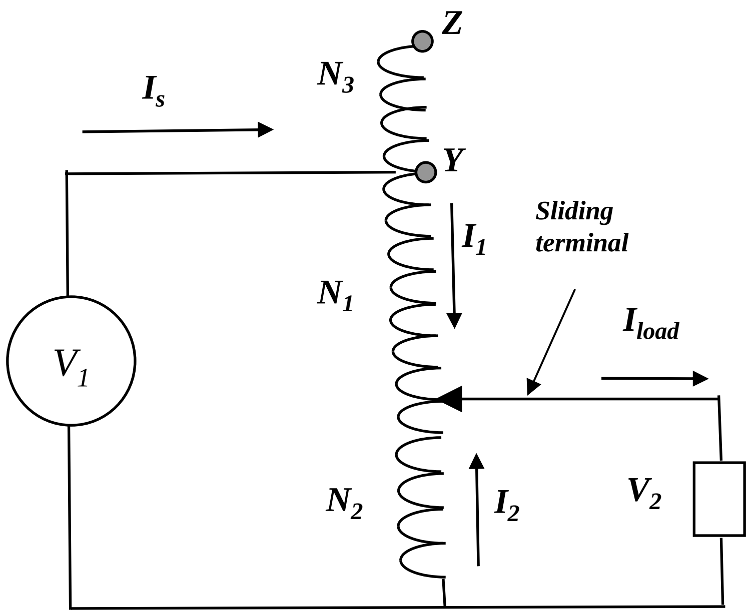
$$V_{load} = V_s \frac{N_2}{N_1 + N_2}$$

At Y

$$V_{load} = V_s \frac{N_1 + N_2}{N_1 + N_2} = V_s$$

At Z

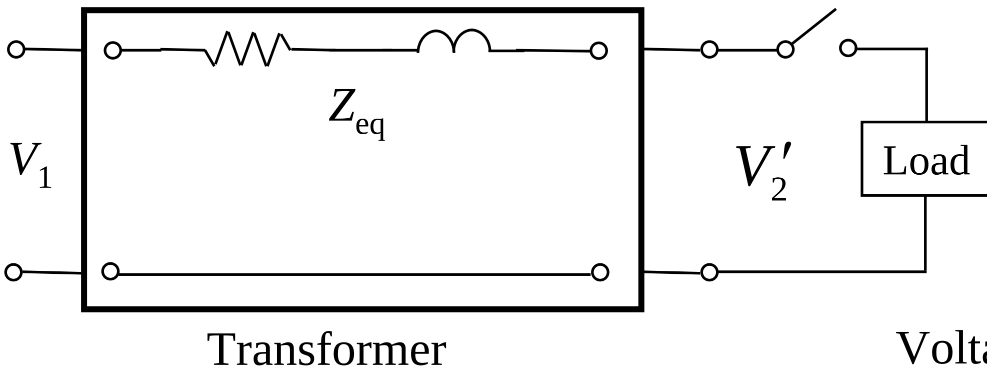
$$V_{load} = V_s \frac{N_1 + N_2 + N_3}{N_1 + N_2}$$



The Variac can adjust the load voltage from zero to greater than the supply voltage.

Voltage Regulation

voltage regulation is the ability of a system to provide near constant voltage over a wide range of load conditions.



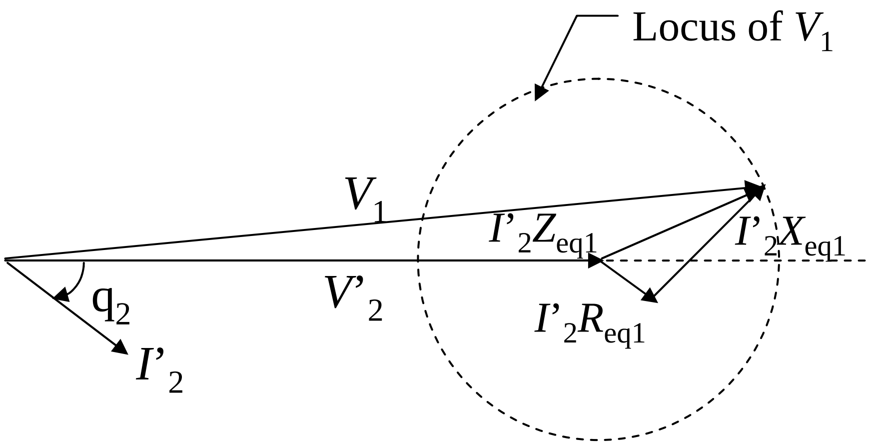
$$\text{Voltage regulation} = \frac{|V|_{NL} - |V|_L}{|V|_L}$$

Referred to Primary

$$\text{Voltage regulation} = \frac{|V_2'|_{NL} - |V_2'|_L}{|V_2'|_L}$$

$$|V_2'|_{NL} = |V_1|$$

$$\text{Voltage regulation} = \frac{|V_1| - |V_2'|_L}{|V_2'|_L}$$



θ_2 *is the angle of the load impedance*

Efficiency

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out} + P_{losses}} = \frac{P_{out}}{P_{out} + P_c + P_{cu}}$$

$$P_{out} = V_2 I_2 \cos\theta_2$$

$$P_{cu} = I_1^2 R_1 + I_2^2 R_2 = I_1^2 R_{eq1} = I_2^2 R_{eq2}$$

$$P_c = I_{c1}^2 R_c$$

⇩

$$\eta = \frac{V_2 I_2 \cos\theta_2}{V_2 I_2 \cos\theta_2 + I_{c1}^2 R_c + I_2^2 R_{eq2}} = F(I_2, \cos\theta_2)$$

The transformer efficiency:
Example

Example : A 15 kVA, 2300/230 V transformer was tested to by open-circuit and closed-circuit tests. The following data was obtained:

$V_{OC} = 2300\ V$	$V_{SC} = 47\ V$
$I_{OC} = 0.21\ A$	$I_{SC} = 6.0\ A$
$P_{OC} = 50\ W$	$P_{SC} = 160\ W$

a. Find the equivalent circuit of this transformer referred to the high-voltage side.

b. Find the equivalent circuit of this transformer referred to the low-voltage side.

c. Calculate the full-load voltage regulation at 0.8 lagging power factor, at 1.0 power factor, and at 0.8 leading power factor.

d. Plot the voltage regulation as load is increased from no load to full load at power factors of 0.8 lagging, 1.0, and 0.8 leading.

e. What is the efficiency of the transformer at full load with a power factor of 0.8 lagging?

The transformer efficiency:
Example

a. The excitation branch values of the equivalent circuit can be determined as:

$$\theta_{oc} = \cos^{-1}\frac{P_{oc}}{V_{oc}I_{oc}} = \cos^{-1}\frac{50}{2300\cdot 0.21} = 84°$$

The excitation admittance is:

$$Y_E = \frac{I_{oc}}{V_{oc}}\angle -84° = \frac{0.21}{2300}\angle -84° = 0.0000\,095 - j0.0000\,908\ S$$

The elements of the excitation branch referred to the primary side are:

$$R_c = \frac{1}{0.0000095} = 105\ k\Omega$$

$$X_M = \frac{1}{0.0000908} = 11\ k\Omega$$

The transformer efficiency:
Example

From the short-circuit test data, the short-circuit impedance angle is

$$\theta_{SC} = \cos^{-1}\frac{P_{SC}}{V_{SC} I_{SC}} = \cos^{-1}\frac{160}{47 \cdot 6} = 55.4°$$

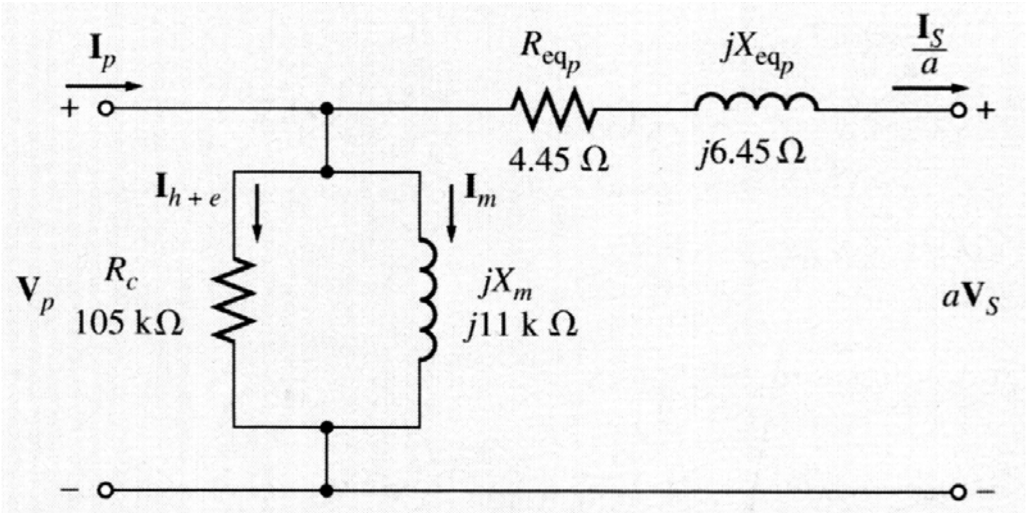
The equivalent series impedance is thus

$$Z_{SE} = \frac{V_{SC}}{I_{SC}} \angle \theta_{SC} = \frac{47}{6} \angle 55.4° = 4.45 + j6.45 \ \Omega$$

The series elements referred to the primary winding are:

$$R_{eq} = 4.45\,\Omega; \qquad X_{eq} = 6.45\,\Omega$$

The equivalent circuit

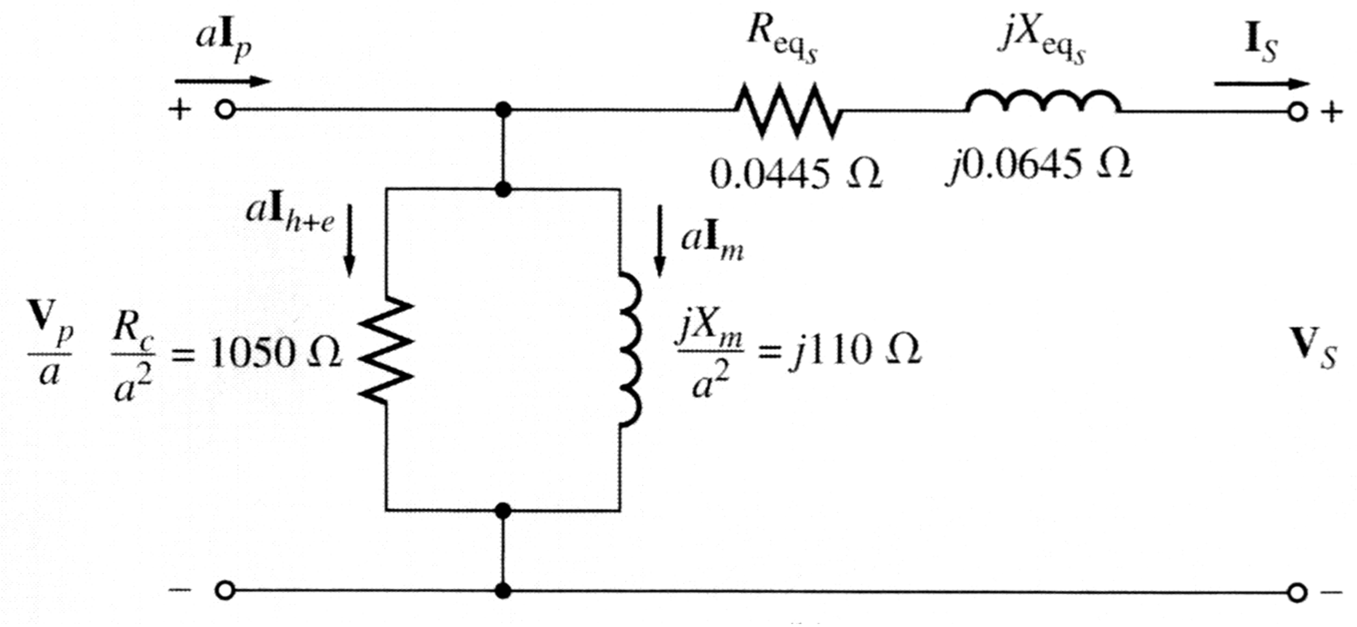


The transformer efficiency: Example

b. To find the equivalent circuit referred to the low-voltage side, we need to divide the impedance by a^2. Since a = 10, the values will be:

$$R_C = 1050\,\Omega \quad X_M = 110\,\Omega \quad R_{eq} = 0.0445\,\Omega \quad X_{eq} = 0.0645\,\Omega$$

The equivalent circuit will be



The transformer efficiency:
Example

c. The full-load current on the secondary side of the transformer is

$$I_{S,rated} = \frac{S_{rated}}{V_{S,rated}} = \frac{15\,000}{230} = 65.2\ A$$

Since:

$$\frac{V_p}{a} = V_S + R_{eq} I_S + jX_{eq} I_S$$

At PF = 0.8 lagging, current

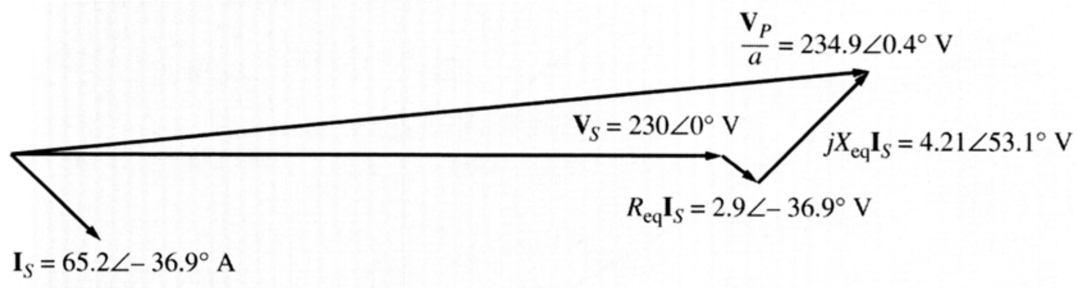
$$I_s = 65.2\angle -\cos^{-1}(0.8) = 65.2\angle -36.9°\ A$$

and

$$\frac{V_p}{a} = 230\angle 0° + 0.0445\cdot(65.2\angle -36.9°) + j0.0645\cdot(65.2\angle -36.9°) = 234.85\angle 0.40°\ V$$

The resulting voltage regulation is, therefore:

$$VR = \frac{|V_p/a| - V_{S,fl}}{V_{S,fl}}\cdot 100\% = \frac{234.85-230}{230}\cdot 100\% = 2.1\%$$



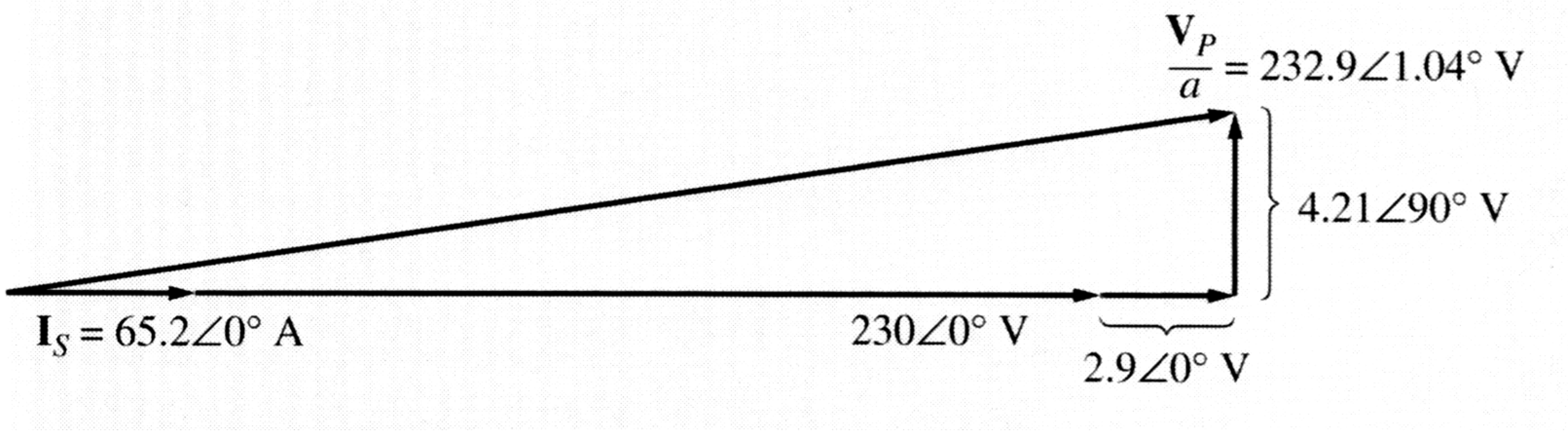
The transformer efficiency:
Example

At PF = 1.0, current $I_s = 65.2\angle\cos^{-1}(1.0) = 65.2\angle 0°\ A$

and $$\frac{V_p}{a} = 230\angle 0° + 0.0445\cdot(65.2\angle 0°) + j0.0645\cdot(65.2\angle 0°) = 232.94\angle 1.04°\ V$$

The resulting voltage regulation is, therefore:

$$VR = \frac{|V_p/a| - V_{S,fl}}{V_{S,fl}}\cdot 100\% = \frac{232.94 - 230}{230}\cdot 100\% = 1.28\%$$



The transformer efficiency:

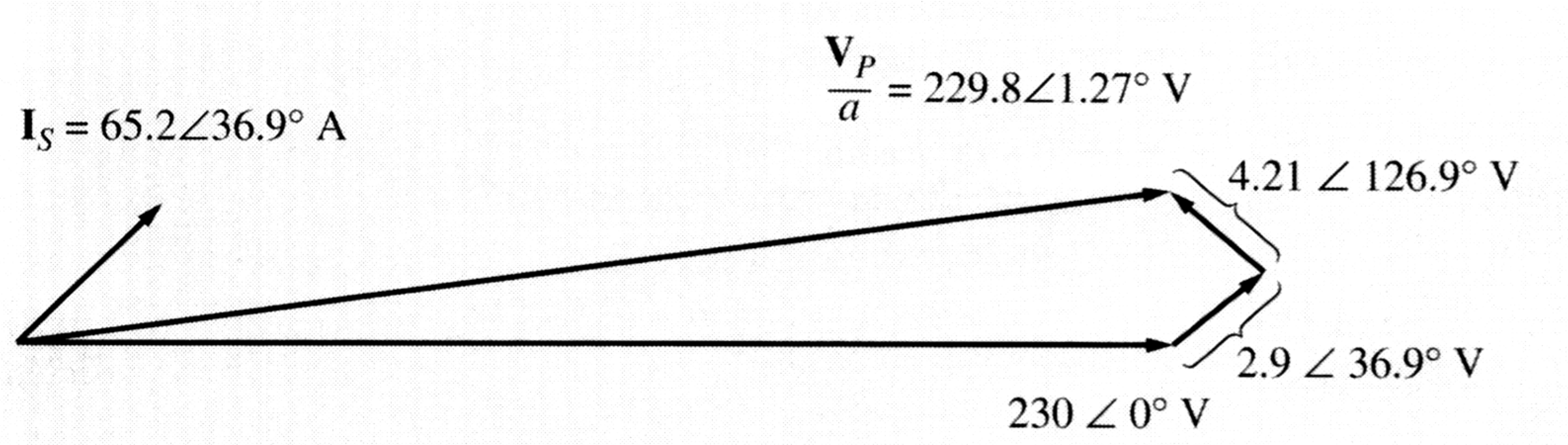
Example

At PF = 0.8 leading, current $$I_s = 65.2\angle\cos^{-1}(0.8) = 65.2\angle 36.9°\ A$$

and $$\frac{V_p}{a} = 230\angle 0° + 0.0445\cdot\left(65.2\angle 36.9°\right) + j0.0645\cdot\left(65.2\angle 36.9°\right) = 229.85\angle 1.27°\ V$$

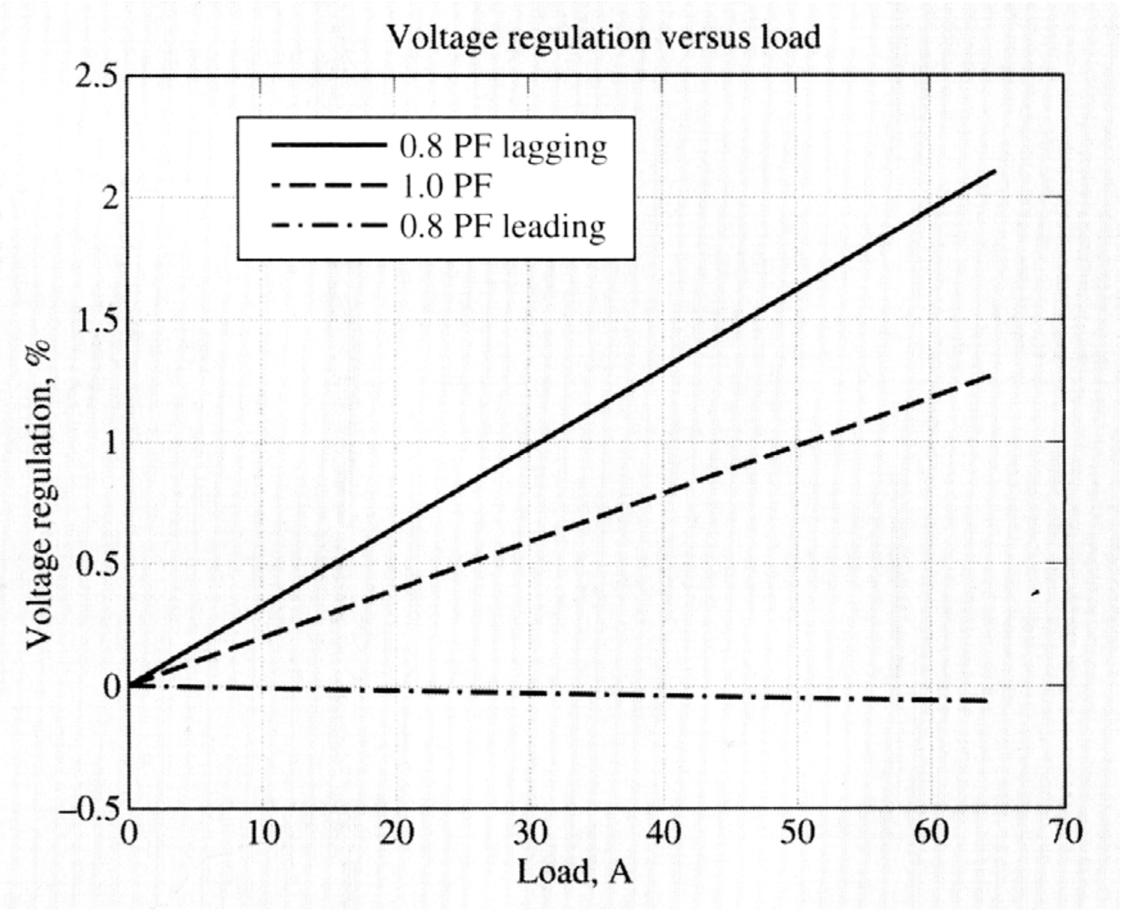
The resulting voltage regulation is, therefore:

$$VR = \frac{\left|V_p/a\right| - V_{S,fl}}{V_{S,fl}}\cdot 100\% = \frac{229.85-230}{230}\cdot 100\% = -0.062\%$$



The transformer efficiency: Example

Similar computations can be repeated for different values of load current. As a result, we can plot the voltage regulation as a function of load current for the three Power Factors.



The transformer efficiency:
Example

e. To find the efficiency of the transformer, first calculate its losses.

The copper losses are:

$$P_{Cu} = I_S^2 R_{eq} = 65.2^2 \cdot 0.0445 = 189\,W$$

The core losses are:

$$P_{core} = \frac{\left(V_p / a\right)^2}{R_C} = \frac{234.85^2}{1050} = 52.5\,W$$

The output power of the transformer at the given Power Factor is:

$$P_{out} = V_S I_S \cos\theta = 230 \cdot 65.2 \cdot \cos 36.9° = 12\,000\,W$$

Therefore, the efficiency of the transformer is

$$\eta = \frac{P_{out}}{P_{Cu} + P_{core} + P_{out}} \cdot 100\% = 98.03\%$$

Transformer taps and voltage regulation

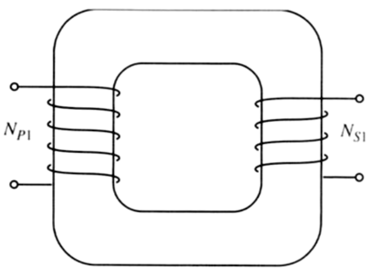
We assumed before that the transformer turns ratio is a fixed (constant) for the given transformer. Frequently, distribution transformers have a series of taps in the windings to permit small changes in their turns ratio. Typically, transformers may have 4 taps in addition to the nominal setting with spacing of 2.5 % of full-load voltage. Therefore, adjustments up to 5 % above or below the nominal voltage rating of the transformer are possible.

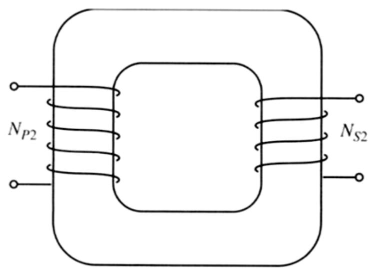
Example : A 500 kVA, 13 200/480 V transformer has four 2.5 % taps on its primary winding. What are the transformer's voltage ratios at each tap setting?

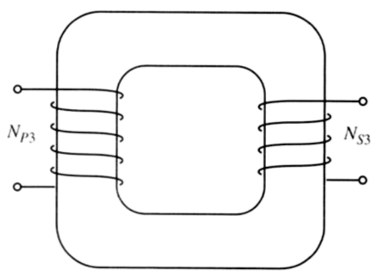
+ 5.0% tap	13 860/480 V
+ 2.5% tap	13 530/480 V
Nominal rating	13 200/480 V
- 2.5% tap	12 870/480 V
- 5.0% tap	12 540/480 V

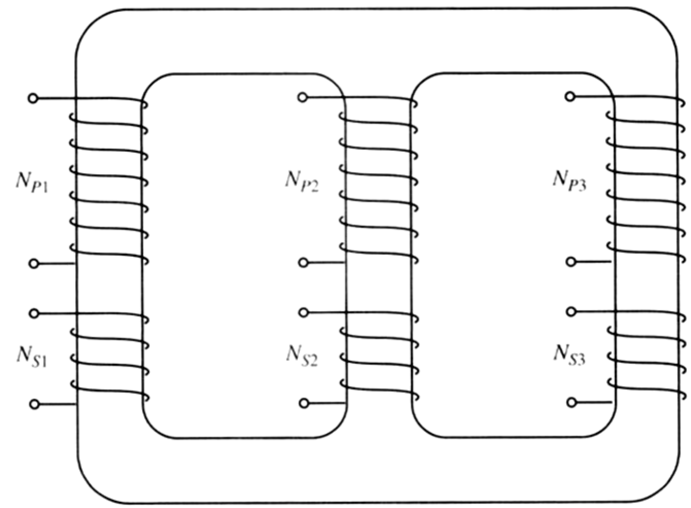
3-phase transformers

The majority of the power generation/distribution systems in the world are 3-phase systems. The transformers for such circuits can be constructed either as a 3-phase bank of independent identical transformers (can be replaced independently) or as a single transformer wound on a single 3-legged core (lighter, cheaper, more efficient).

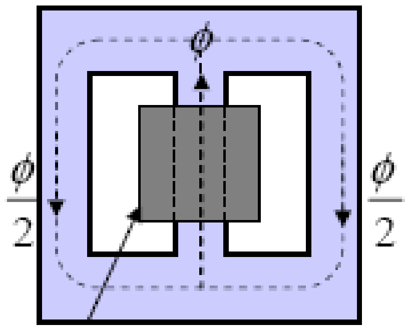


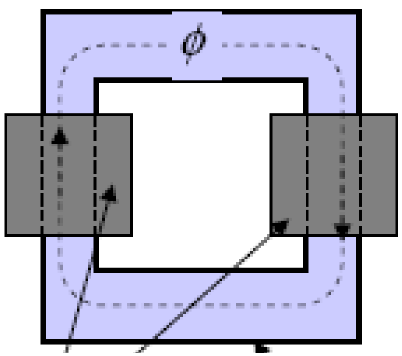






3-phase transformers





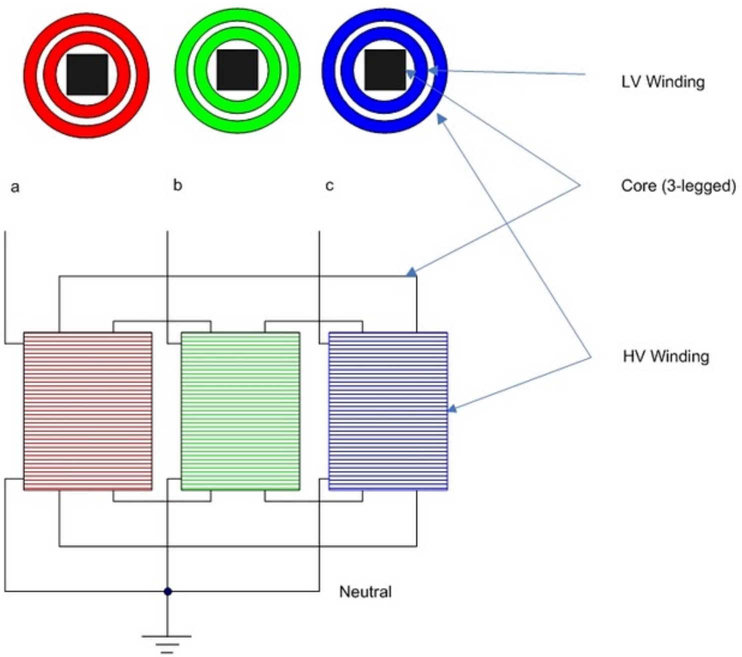
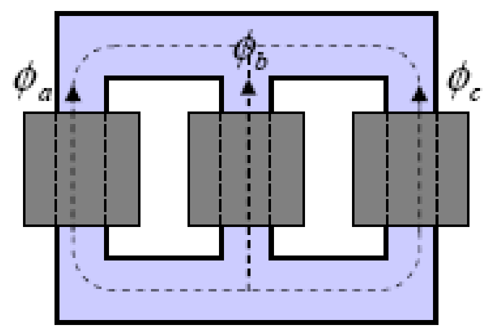


Fig – B: Three Phase Transformer with Top View



3-phase transformer Connection

We assume that any single transformer in a 3-phase transformer (bank) behaves exactly as a single-phase transformer. The impedance, voltage regulation, efficiency, and other calculations for 3-phase transformers are done on a per-phase basis, using the techniques studied previously for single-phase transformers.

Four possible connections for a 3-phase **transformer bank** are:

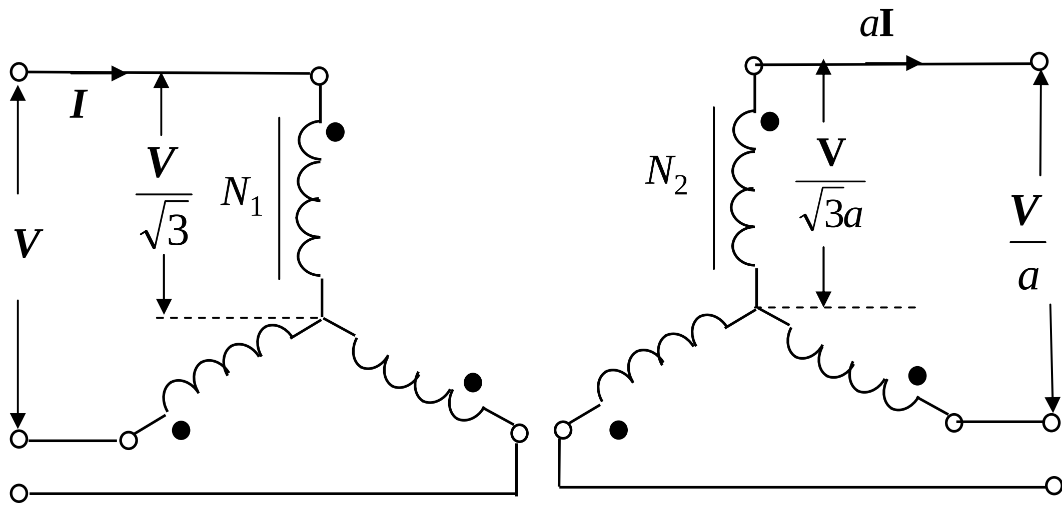
1. Y-Y
2. Y-Δ
3. Δ- Δ
4. Δ-Y

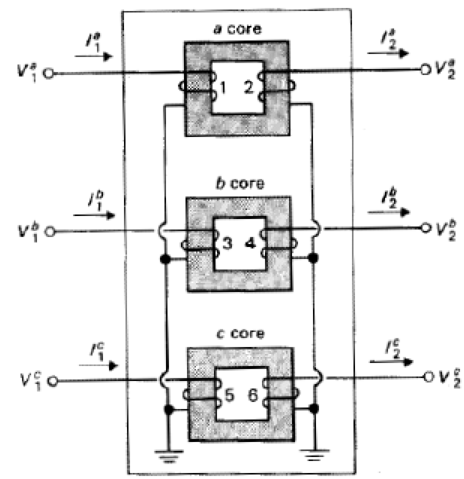
3-phase transformer Connection

1. Y-Y connection:

$$\frac{V_{ph1}}{V_{ph2}} = \frac{N_1}{N_2} = a$$

$$\frac{V_{L1}}{V_{L2}} = \frac{\sqrt{3}\,V_{ph1}}{\sqrt{3}\,V_{ph2}} = a$$



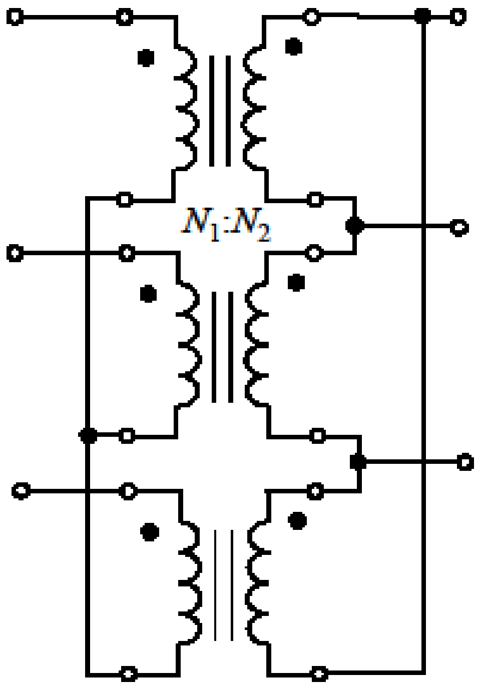


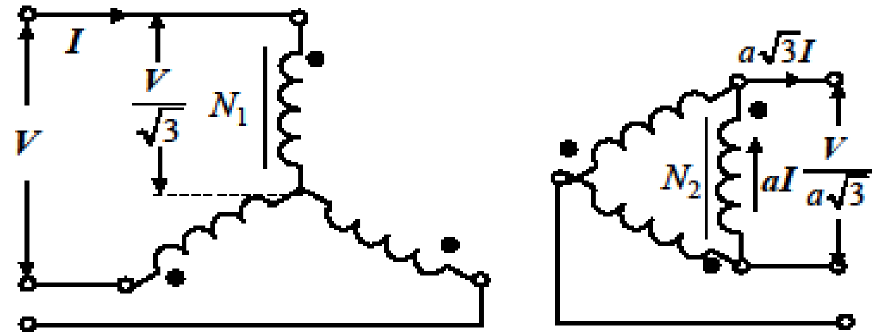
Y-Y

3-phase transformer Connection

2. Y-Δ connection:

- **Wye-Delta Connection Y-Δ**





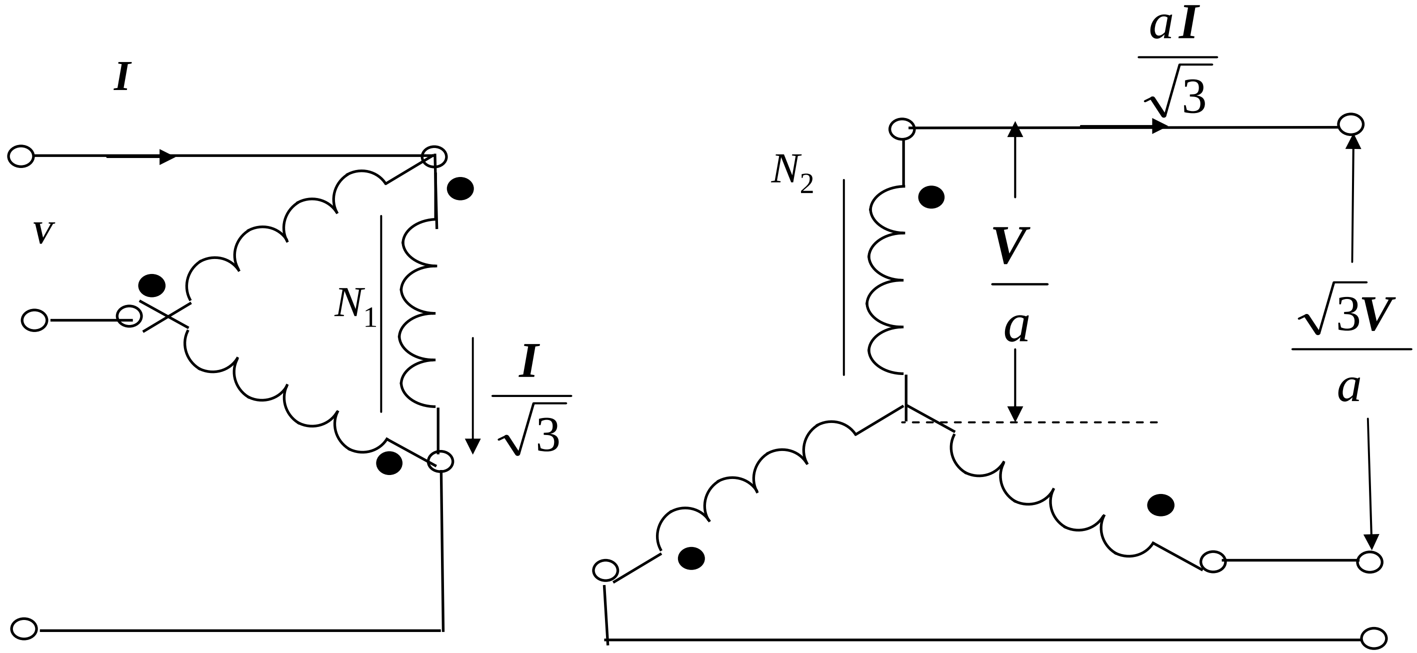
Y - Δ

$$a = \frac{N_1}{N_2} = turns\ ratio$$

3-phase transformer Connection

3. Δ -Y connection:

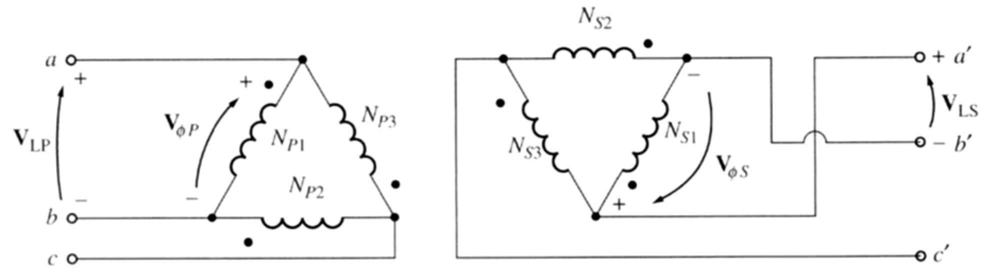
Delta – Way Connection Δ - Y



Δ - Y

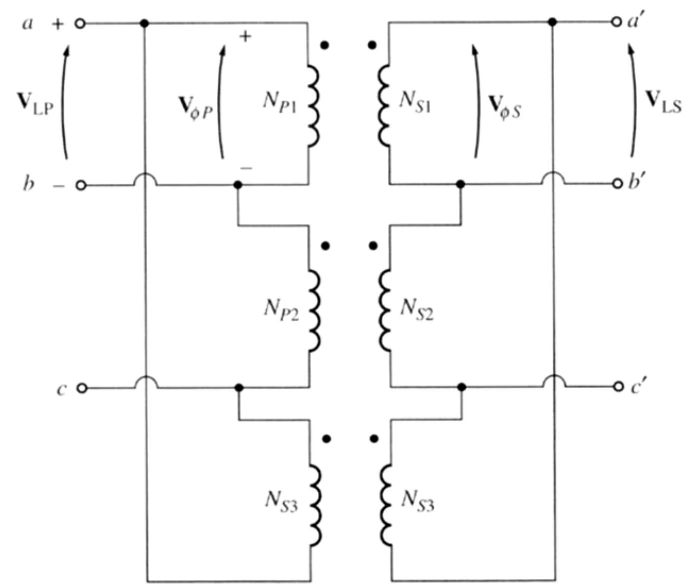
3-phase transformer Connection

4. Δ - Δ connection:



The primary voltage on each phase of the transformer is

$$V_{\phi P} = V_{LP}$$



The secondary phase voltage is

$$V_{LS} = V_{\phi S}$$

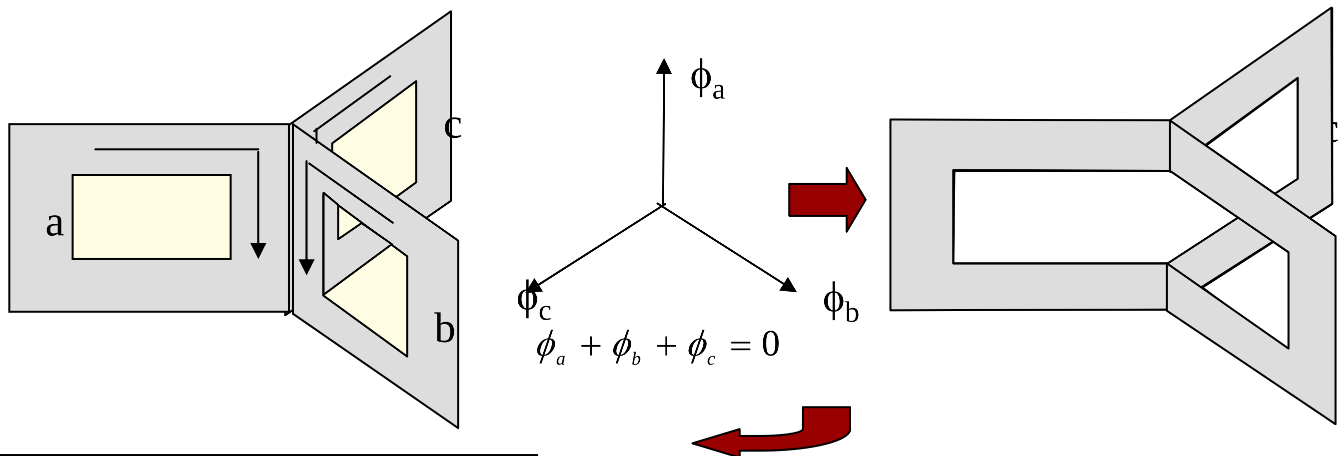
The overall voltage ratio is

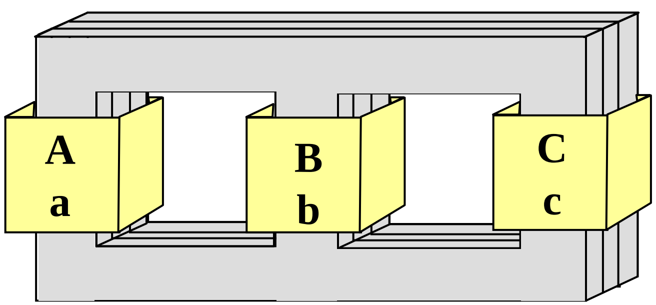
$$\frac{V_{LP}}{V_{LS}} = \frac{V_{\phi P}}{V_{\phi S}} = a$$

No phase shift, no problems with unbalanced loads or harmonics.

3-phase transformer

- A three phase transformer can be constructed by having three primary and three secondary windings on a common magnetic core as shown in the following Figure.





Advantages

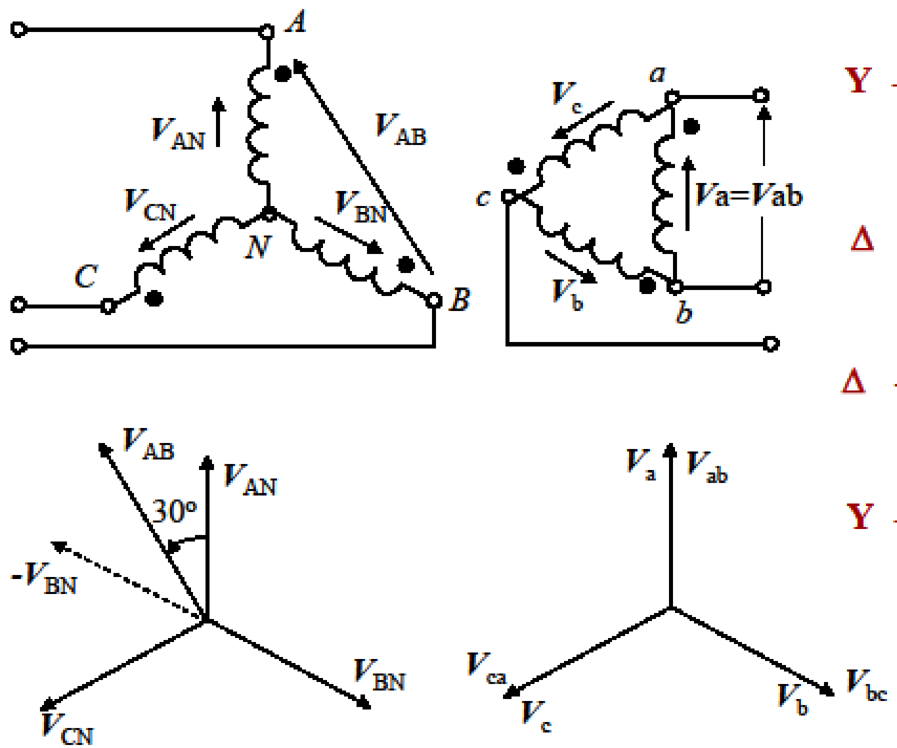
Weight less, Cost less, Required less space

Disadvantages

Magnetic current imbalance

3-phase transformer

- Phase Shift



- Y - Δ ⇒ V_{AB} leads V_{ab} by 30°
- Δ - Y ⇒ V_{AB} lags V_{ab} by 30°
- Δ - Δ ⇒ No phase shift
- Y - Y ⇒ No phase shift