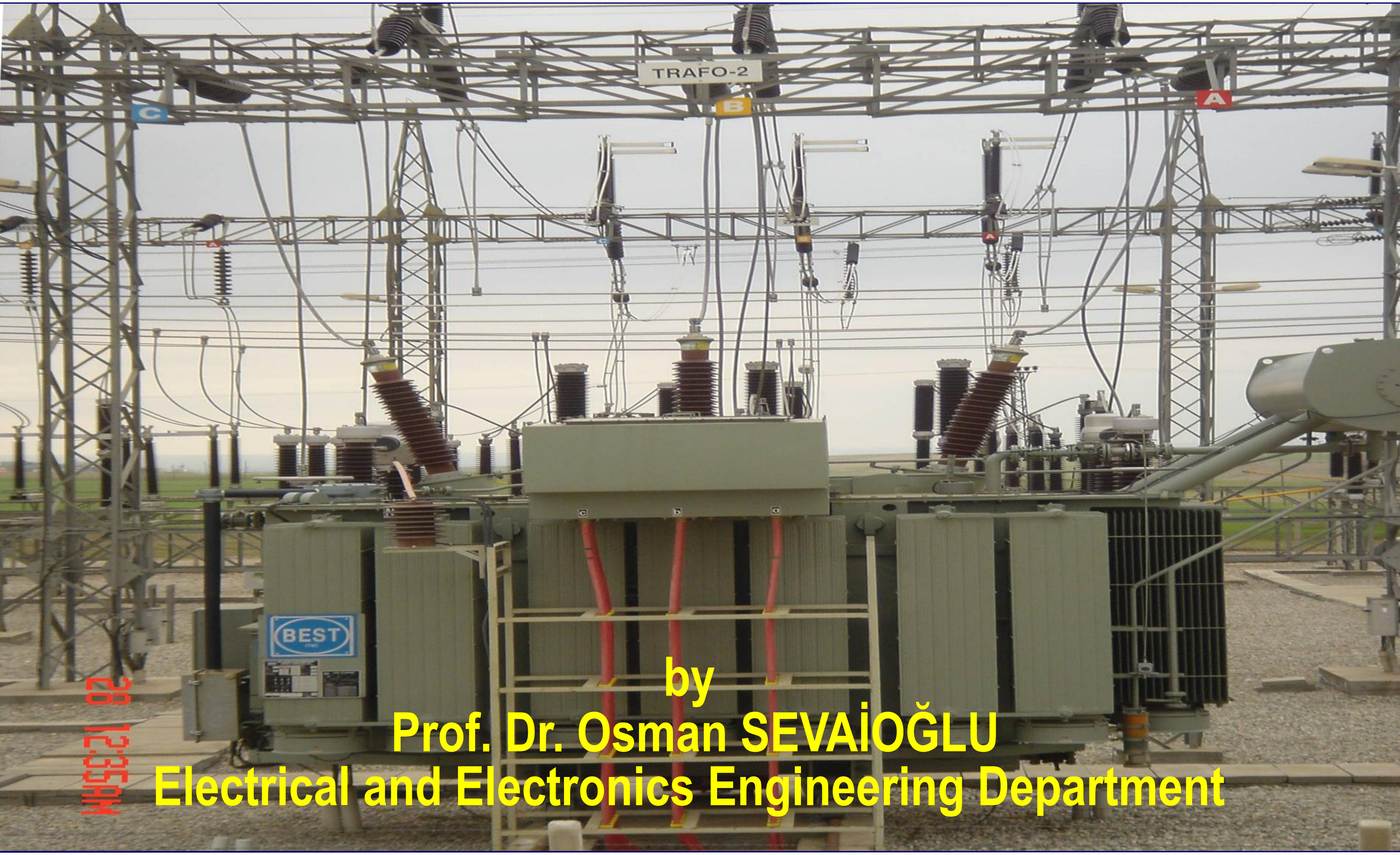
METU

Transformers



by
Prof. Dr. Osman SEVAİOĞLU
Electrical and Electronics Engineering Department

Transformers - Principle

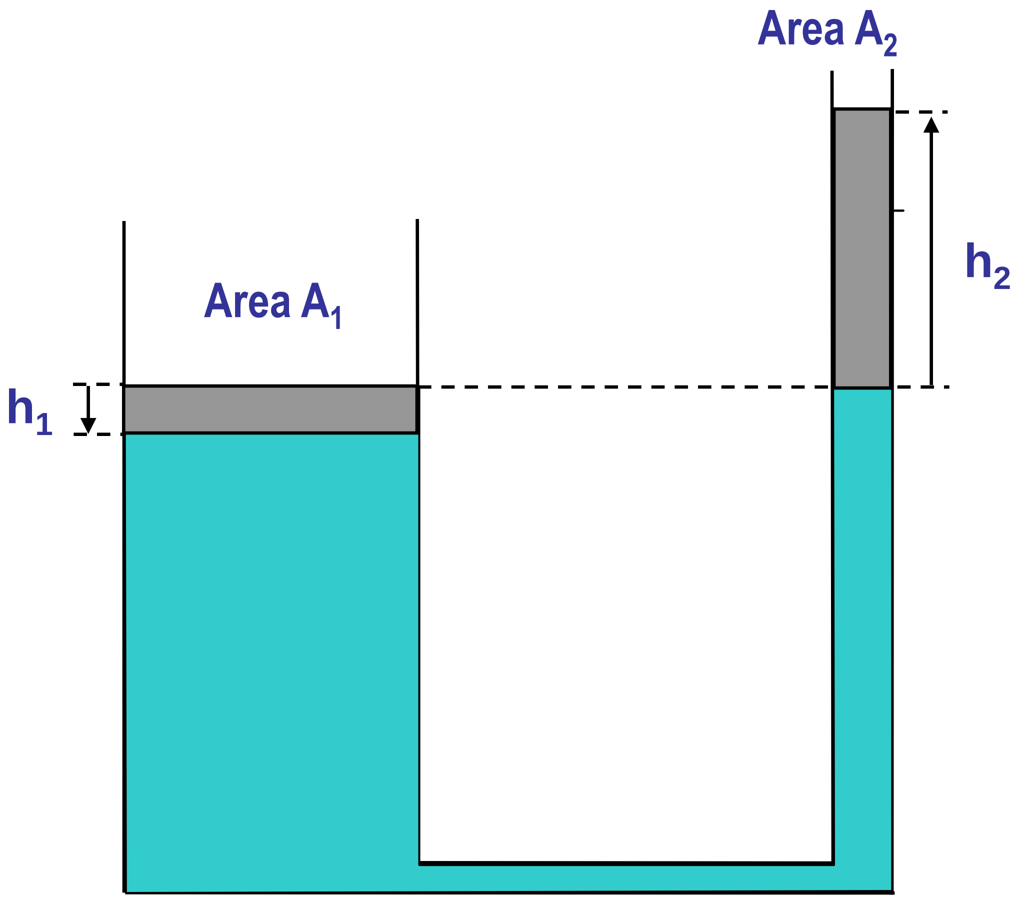
Principle

Operation of a transformer can be best explained in terms of a connected reservoir shown on the RHS

Let the cross-sectional areas of the reservoirs in the figure on the LHS and RHS be;

$Area_1 = A_1$

$Area_2 = A_2$



Transformers - Principle

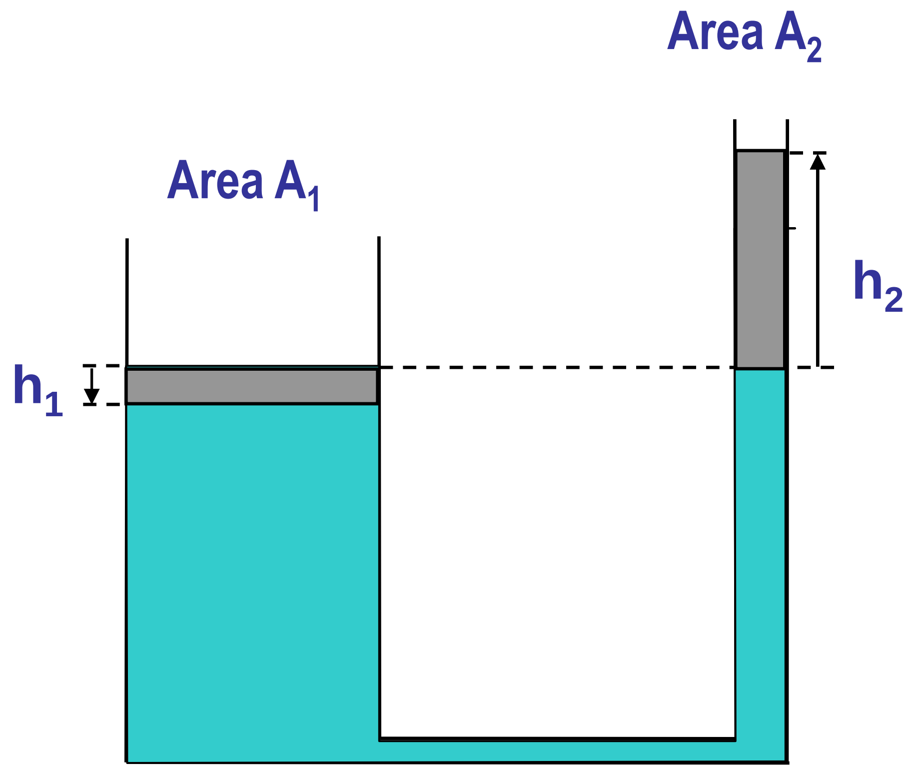
Basic Principle

Displacement of water on the LHS =
Displacement of water on the RHS

$Volume_1 = A_1 \times h_1$
$Volume_2 = A_2 \times h_2$

$Volume_1 = Volume_2$

$A_1 \times h_1 = A_2 \times h_2$
$A_1 / A_2 = h_2 / h_1$



Transformers - Principle

Basic Principle

Pressure of water on the LHS =
Pressure of water on the RHS

$Pressure_1 = Pressure_2$

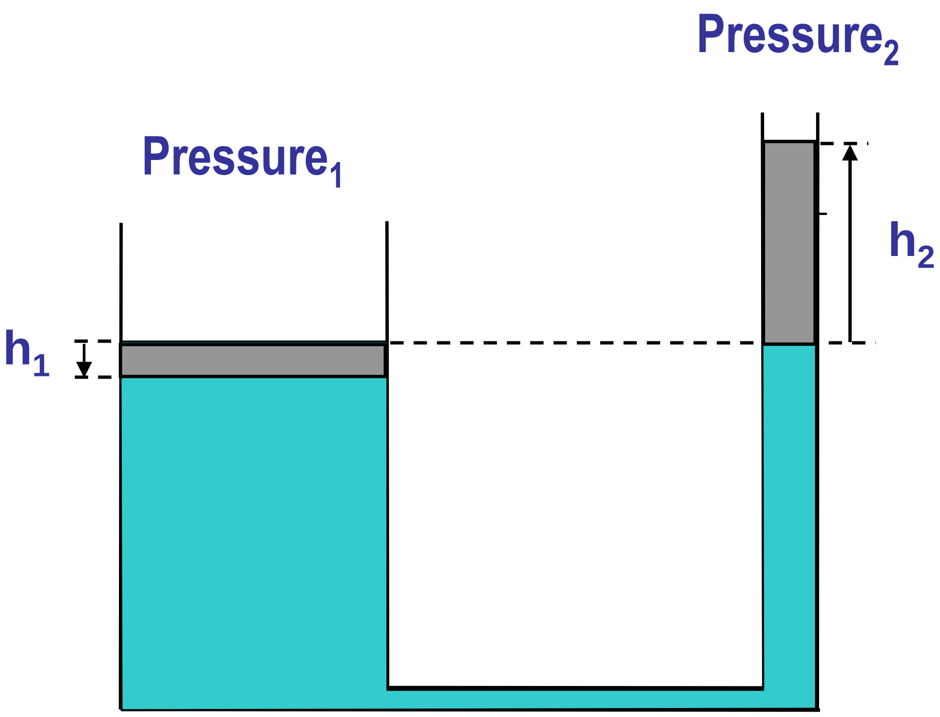
Definition:
$P = Pressure = Force / Area$

$P_1 = P_2$

$F_1 / A_1 = F_2 / A_2$

or

$F_1 / F_2 = A_1 / A_2$



Transformers - Principle

Basic Principle; Energy on the LHS = Energy on the RHS

$F_1 / F_2 = A_1 / A_2$
$A_1 / A_2 = h_2 / h_1$
or

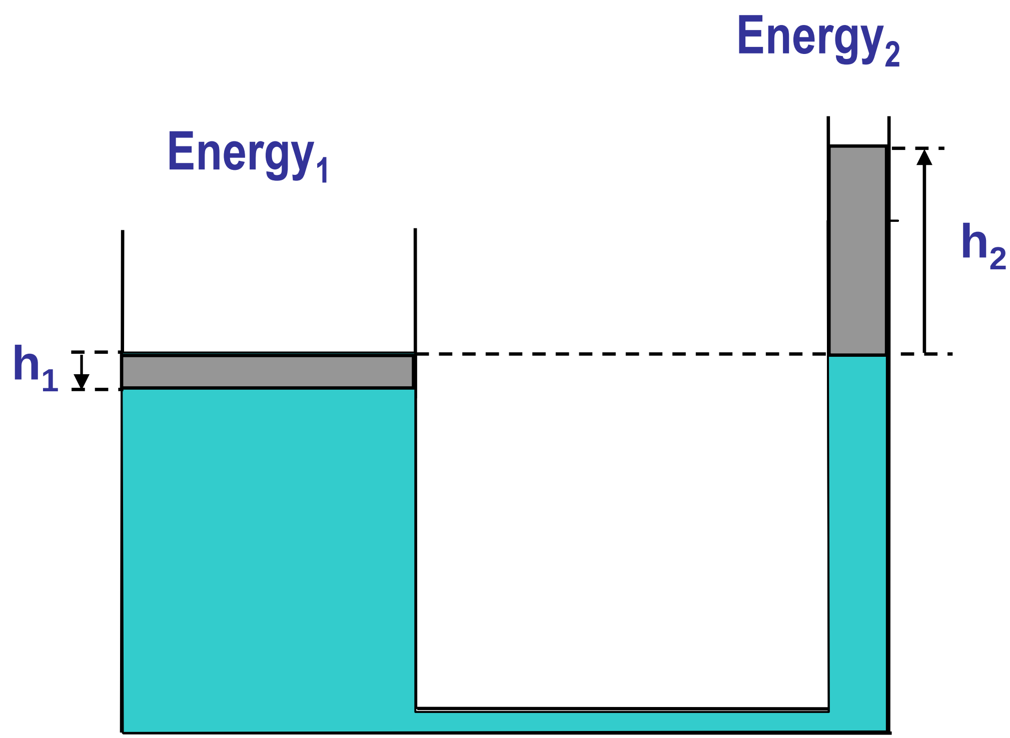
$F_1 / F_2 = h_2 / h_1$

or

$F_1 \times h_1 = F_2 \times h_2$

Definition:
$Energy_1 = Height_1 \times Force_1$
$Energy_2 = Height_2 \times Force_2$

$Energy_1 = Energy_2$



Transformers - Principle

Basic Principle; Power on the LHS = Power on the RHS

Let us now divide both sides by Δt

Definition:

Power = Energy / Time

$$F_1 \times h_1 / \Delta t = F_2 \times h_2 / \Delta t$$

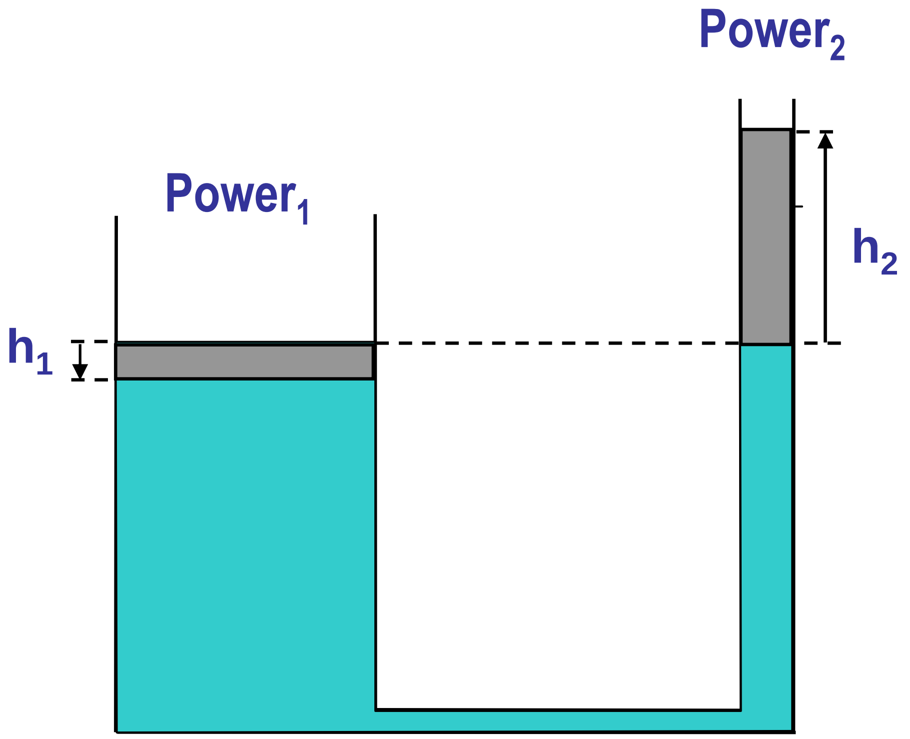
Definition:

Water flow rate $_1 = I_1$

$= h_1 / \Delta t$

Water flow rate $_2 = I_2$

$= h_2 / \Delta t$



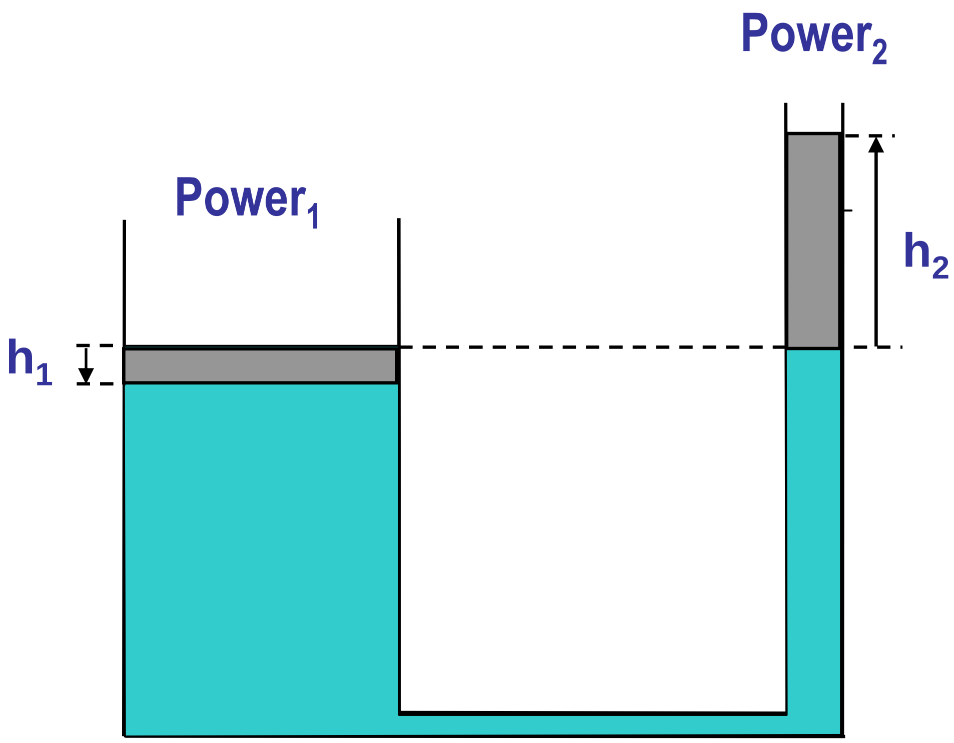
Transformers - Principle

Basic Principle; Power on the LHS = Power on the RHS

$F_1 \times l_1 = F_2 \times l_2$

Conservation of Power;

$Power_1 = Power_2$



Transformers - Electrical Case

Basic Principle; Power on the LHS = Power on the RHS

<u>Conservation of Power;</u>

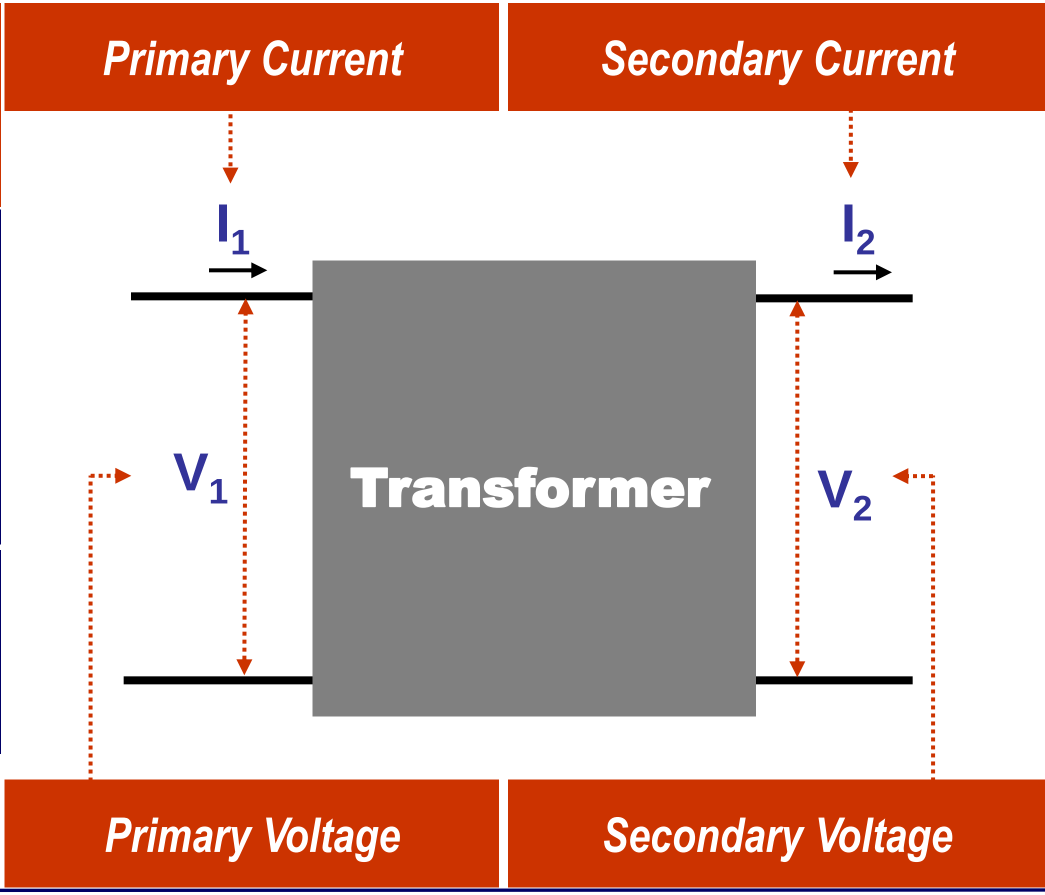
$Power_1 = Power_2$

Input Power = Output Power

$S_1 = V_1 \times I_1^*$
$S_2 = V_2 \times I_2^*$
$S_1 = S_2$

or

$V_1 / V_2 = I_2^* / I_1^*$



Transformers - Electrical Case

Basic Principle; Power on the Primary Side = Power on the Secondary Side

Conservation of Power

$P_1 = P_2$

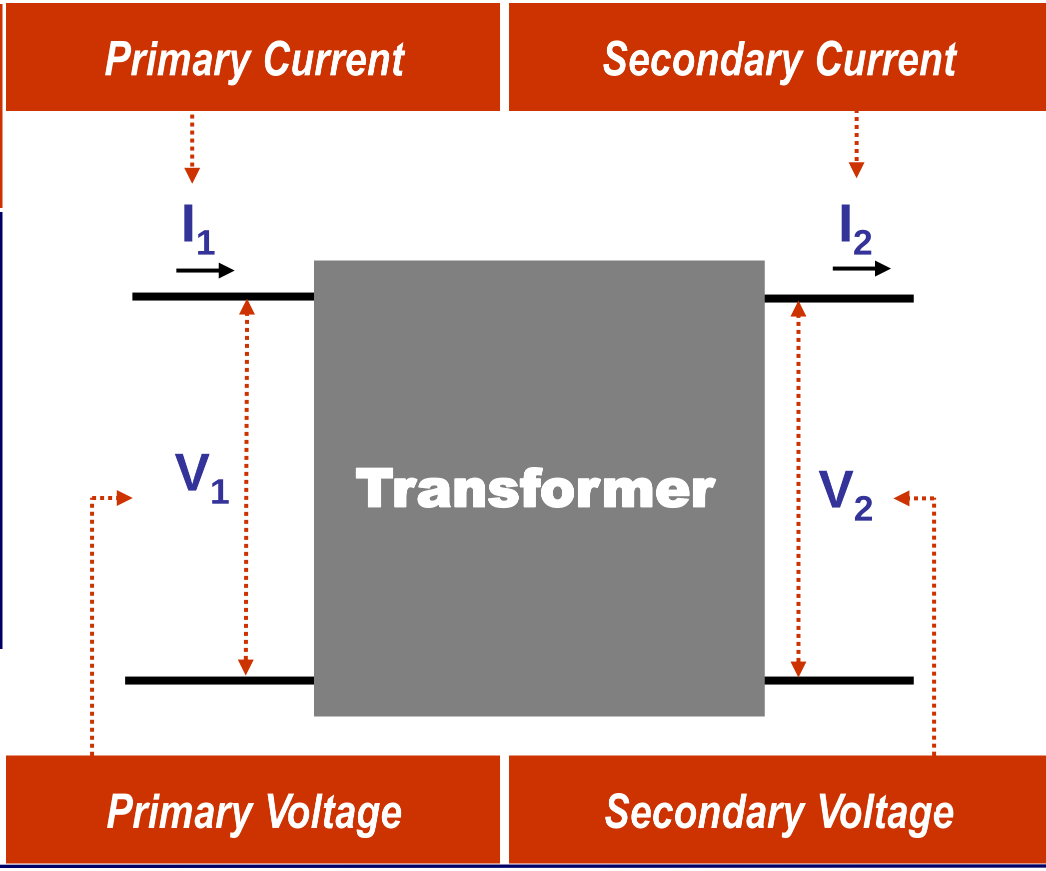
Primary Power = Secondary Power

$V_1 \times I_1^* \cos\theta = V_2 \times I_2^* \cos\theta$

$P_1 = S_1 \times \cos\theta$

$P_2 = S_2 \times \cos\theta$

$P_1 = P_2 = P$



Transformers

Transformers - Electrical Case

Basic Principle; Energy on the Primary Side = Energy on the Secondary Side

Conservation of Energy

$W_1 = W_2$

Primary Energy = Secondary Energy

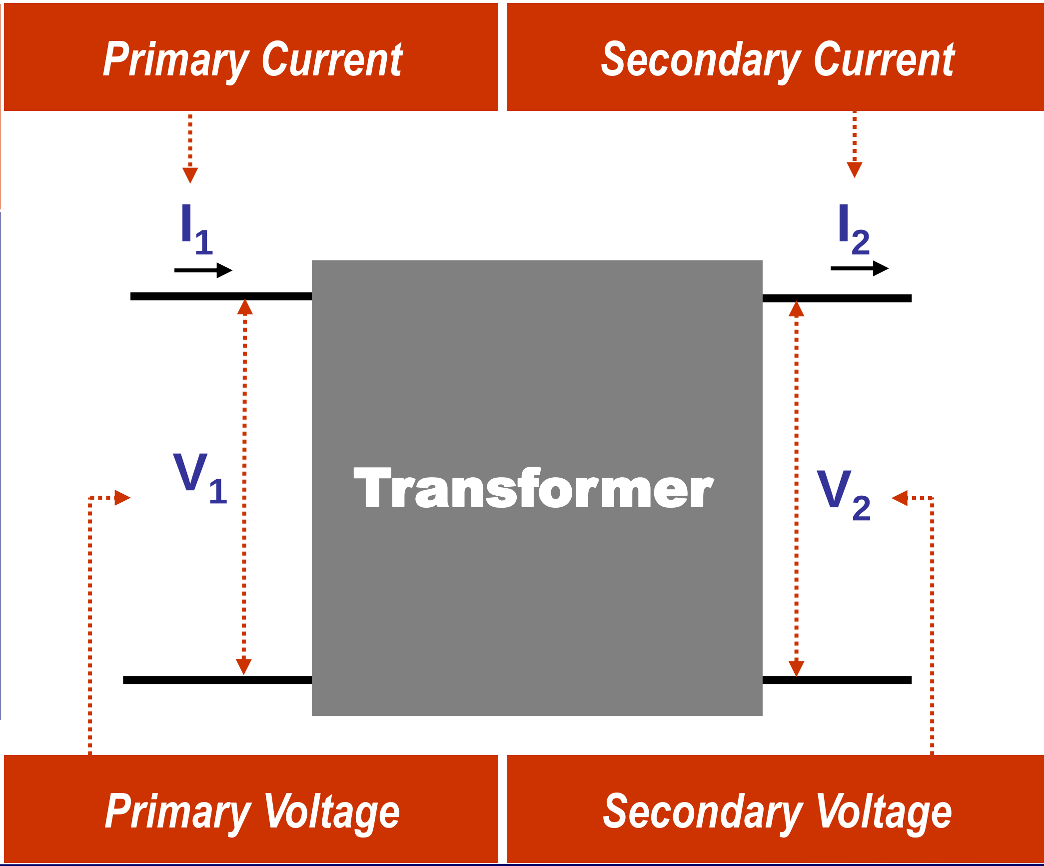
$V_1 \times I_1^* \cos\theta \times \Delta t = V_2 \times I_2^* \cos\theta \times \Delta t$

$P_1 \times \Delta t = P_2 \times \Delta t$

$= P \times \Delta t$

$W_1 = S_1 \times \cos\theta \times \Delta t$

$W_2 = S_2 \times \cos\theta \times \Delta t$



Transformers - Example

Basic Principle of Conservation of Power; Power on the LHS = Power on the RHS

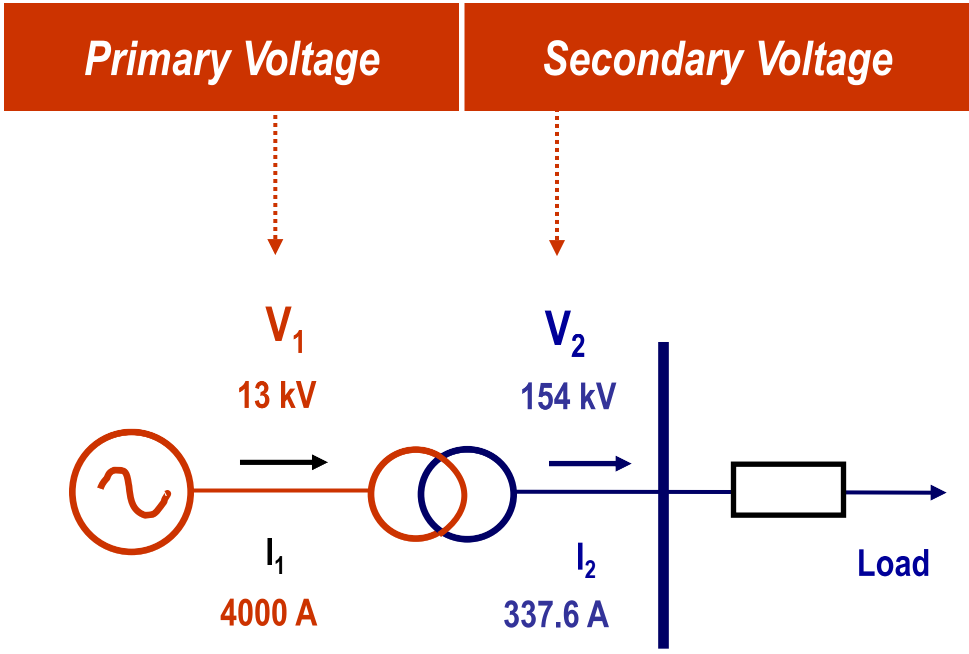
Conservation of Power;

Power Input = Power Output

$V_1 \times I_1 = V_2 \times I_2$

$13000\ V \times 4000\ A = 154000\ V \times 337.67\ A$

$52\ MVA = 52\ MVA$



Turn Ratio of a Transformer

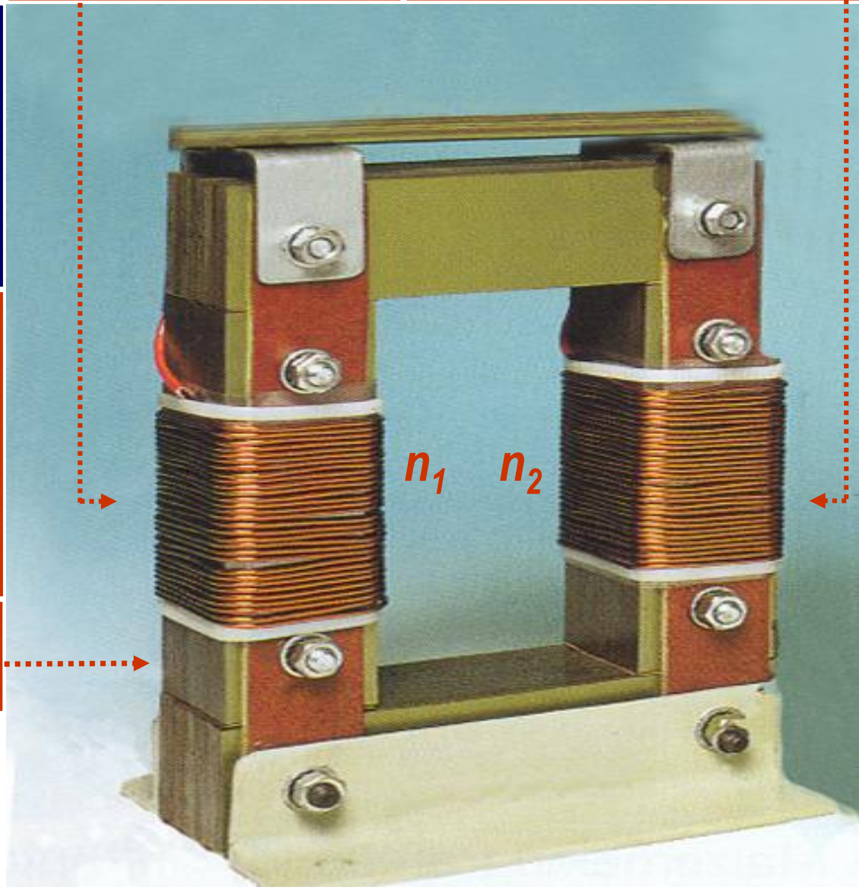
Definition

In principle, a transformer consists of two windings wound around a single closed magnetic core, one called the primary winding and the other, secondary winding

Turn Ratio of the transformer is defined as the ratio of the number of turns of the secondary winding to that of the primary, i.e;

$$n = n_2 / n_1$$

Primary Winding | *Secondary Winding*



Laminated Iron Core

Transformers

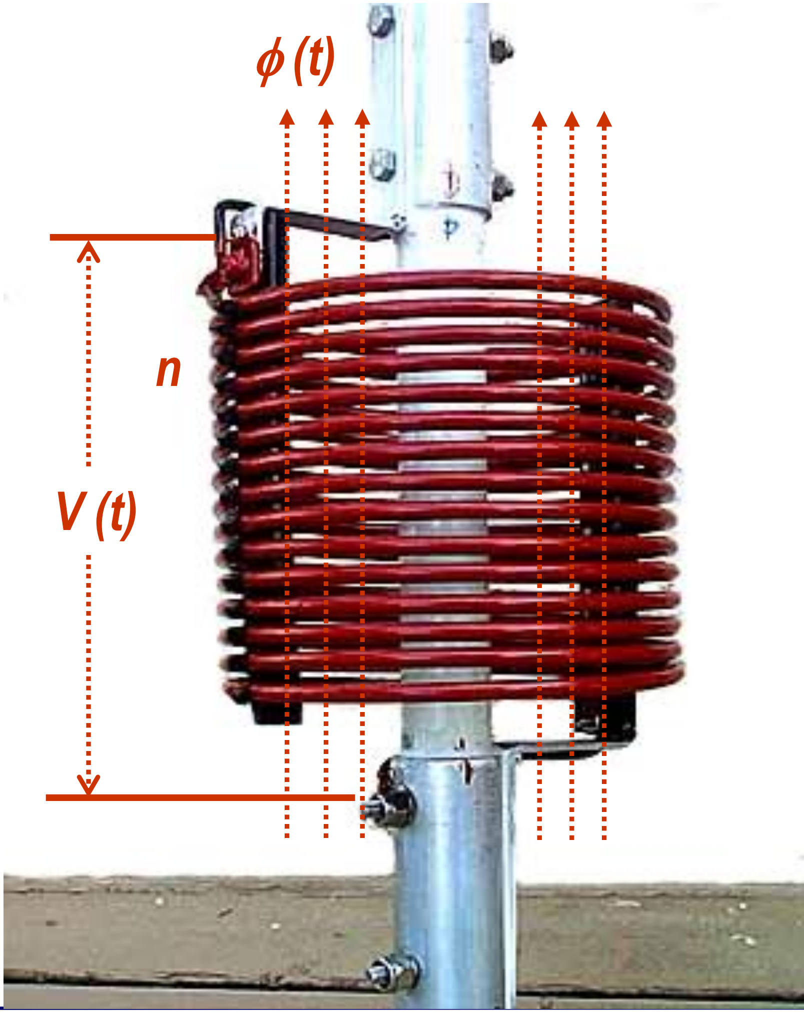
Lenz's Law

Statement

Voltage across and inductor can be written as;

$$V(t) = n \, d/dt \;\; \phi(t)$$

where V(t) is the voltage induced,
n is the number of turns,
ϕ (t) is the flux passing through the winding



Transformers

Lenz's Law

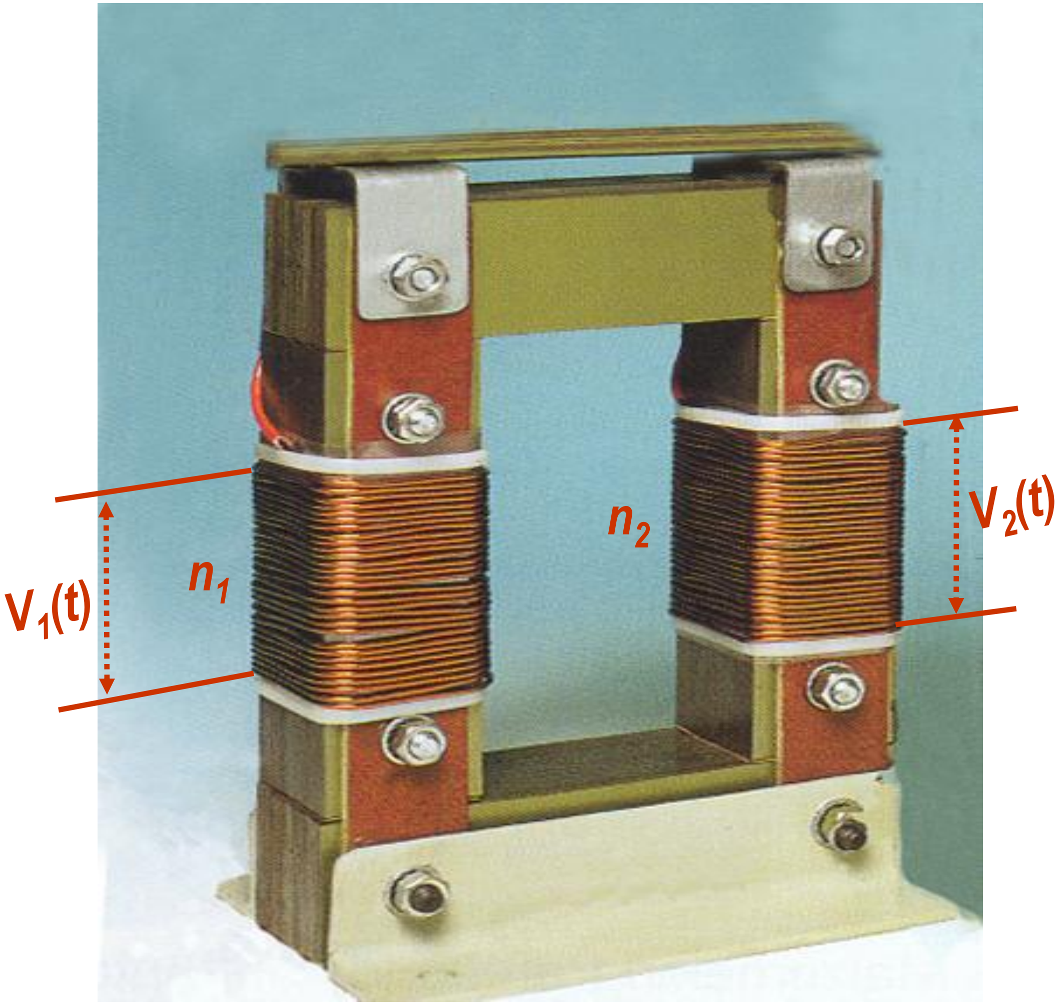
Definition

Now, if we have two windings wound around a single magnetic core

$$V_1(t) = n_1 \, d/dt \; \phi(t)$$

$$V_2(t) = n_2 \, d/dt \; \phi(t)$$

where $V_1(t)$, $V_2(t)$ *are the primary and secondary voltages,*
n_1, n_2 *are the number of turns in the primary and secondary windings,*
$\phi(t)$ *is the flux passing through the windings*



Transformers

Lenz's Law

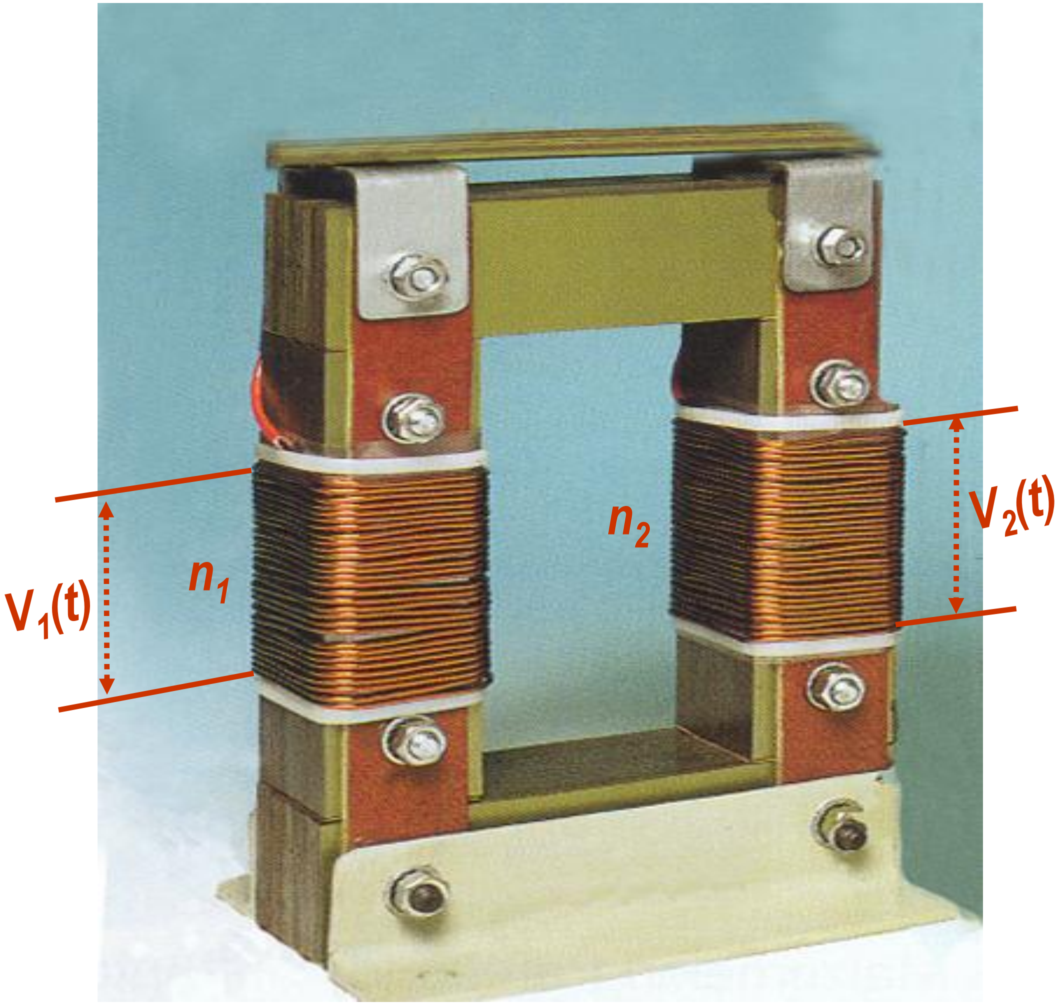
Definition

Now, Dividing the above equations side by side and cancelling;

$$\frac{V_2(t)}{V_1(t)} = \frac{n_2 \, d/dt \; \phi(t)}{n_1 \, d/dt \; \phi(t)}$$

or

$$V_2(t)/V_1(t) = n_2/n_1 = n$$



Voltage Changing in a Transformer

Definition

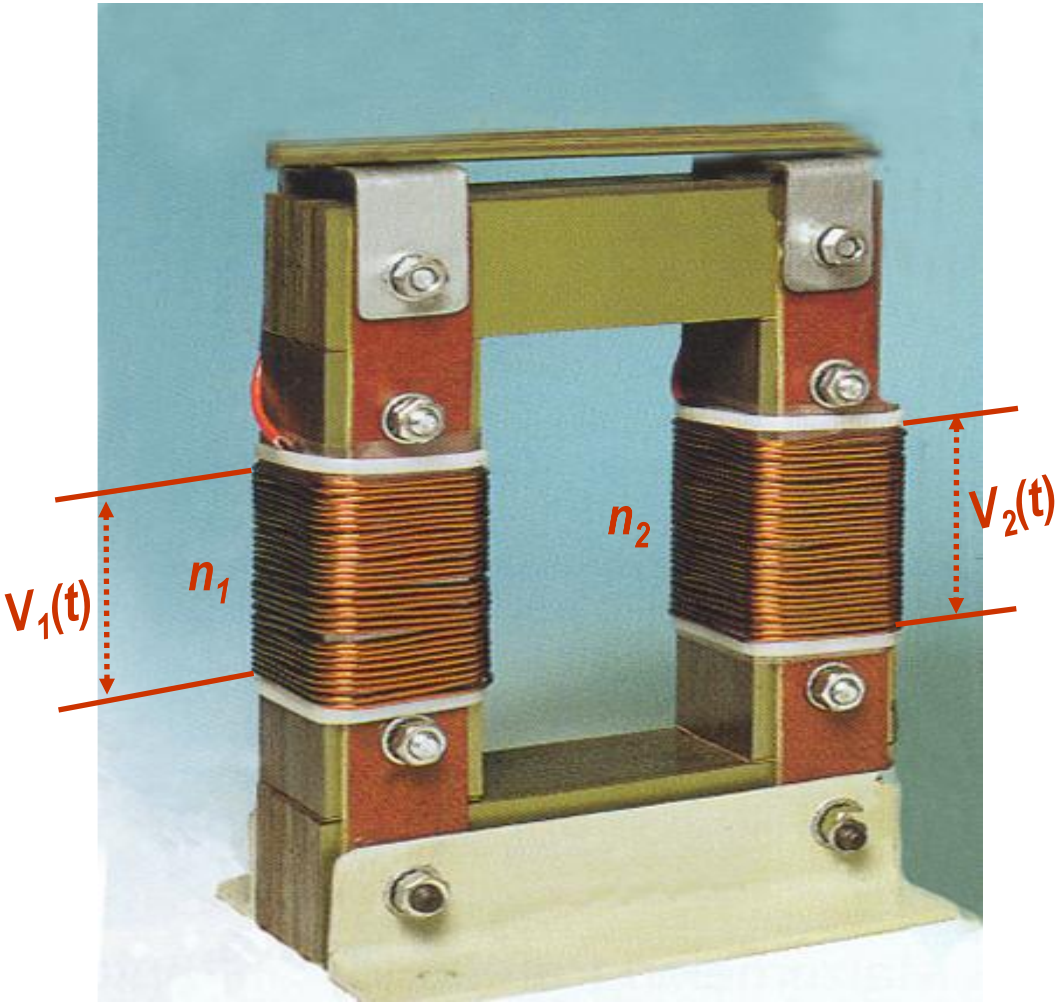
The relation between the primary and secondary side voltages can simply be stated as;

or

$$V_2(t) = V_1(t) \times n_2 / n_1$$
$$= V_1(t) \times n$$

similarly

$$V_{2(rms)} = V_{1(rms)} \times n_2 / n_1$$
$$= V_{1(rms)} \times n$$



Current Changing in a Transformer

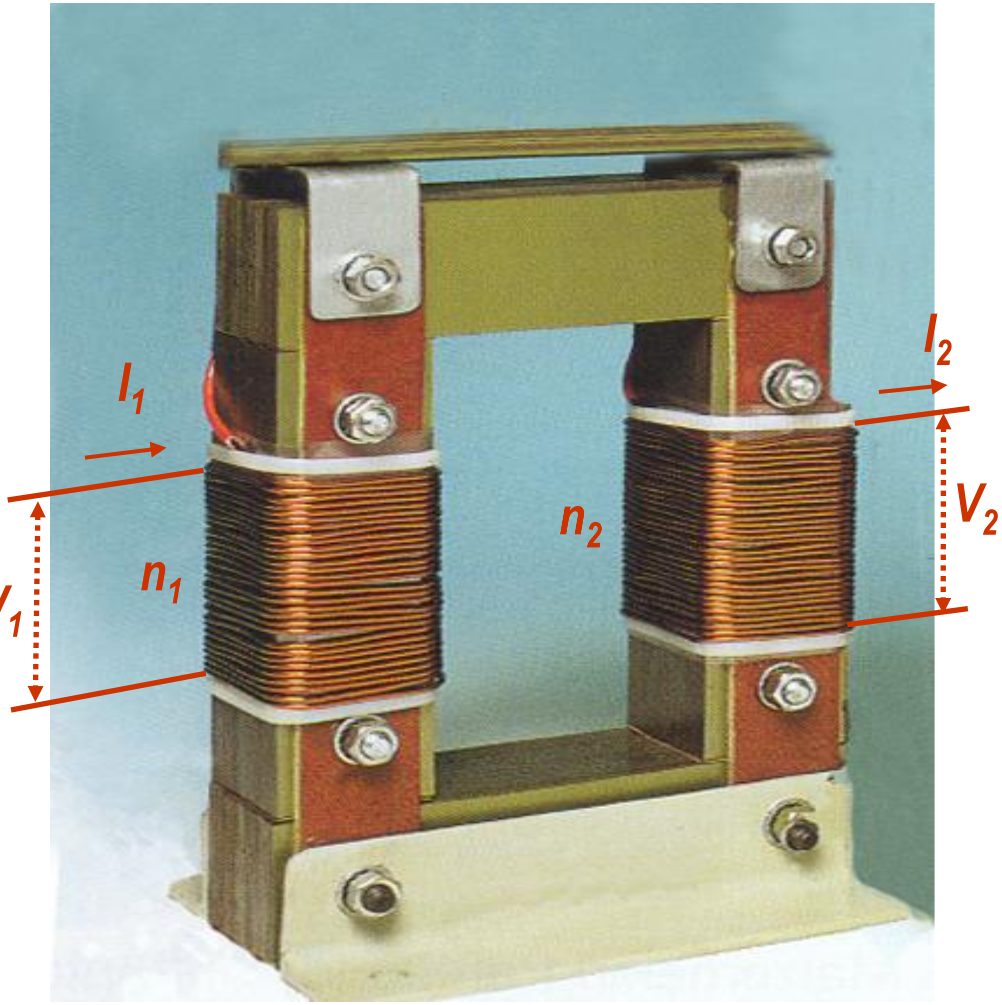
Definition

The relation between the primary and secondary side currents can simply be stated as;

$$I_2 / I_1 = n_1 / n_2$$

or

$$I_2 = I_1 \times n_1 / n_2 = I_1 / n$$



Transformers

Conservation of Power

Principle of Conservation of Power

Principle of Conservation of Power states that

$Power_1 = Power_2$

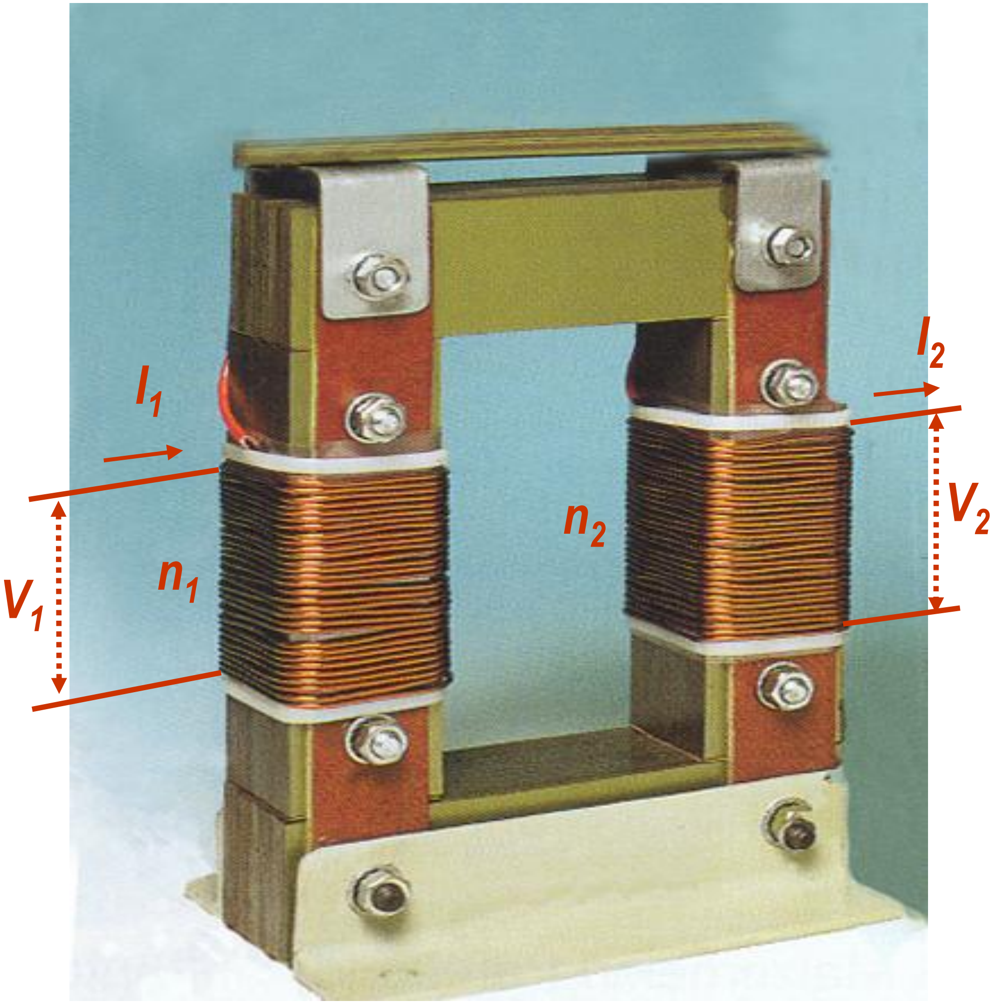
$Power_1 = V_{1(rms)} I_{1(rms)} = V_1 I_1$

$Power_2 = V_2 I_2$

Hence

$$V_2 I_2 = (n_2 / n_1) V_1 (n_1 / n_2) I_1 = V_1 I_1$$

Conclusion;
Transformer does not increase or decrease power, it just changes the voltage and current inversely

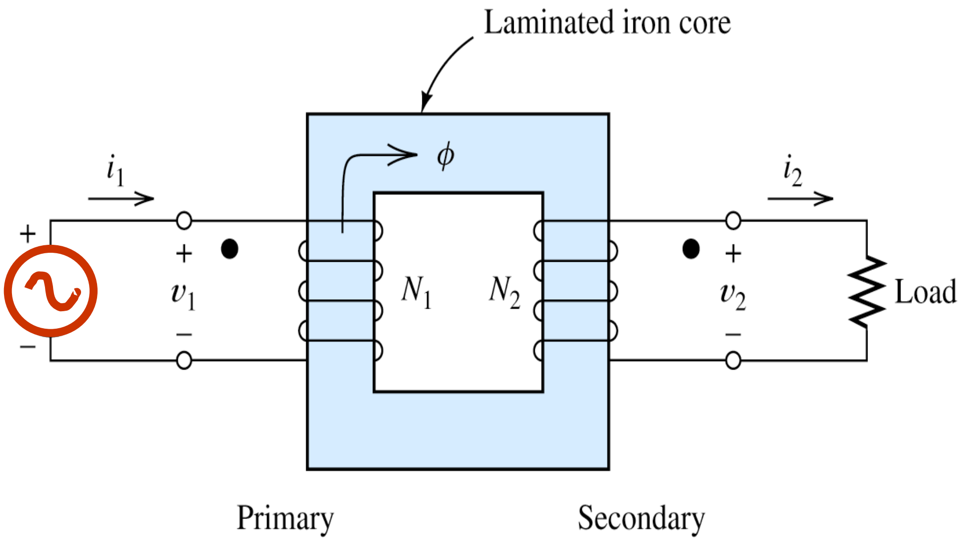


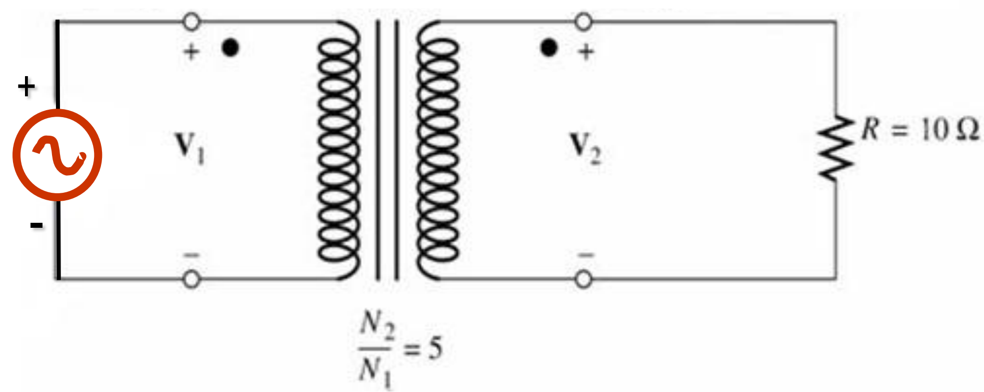
Schematic Representation

Schematic Representation

Laminated iron core may be represented as a frame passing through the primary and secondary windings

For simplicity, laminated iron core may be omitted from the drawing leaving only the two windings





Impedance Reflection in a Transformer

Principle

Impedance on the secondary side of the transformer shown on the RHS may be transferred (referred) to the primary side as follows;

$$V_2 = I_2 \, Z_L$$

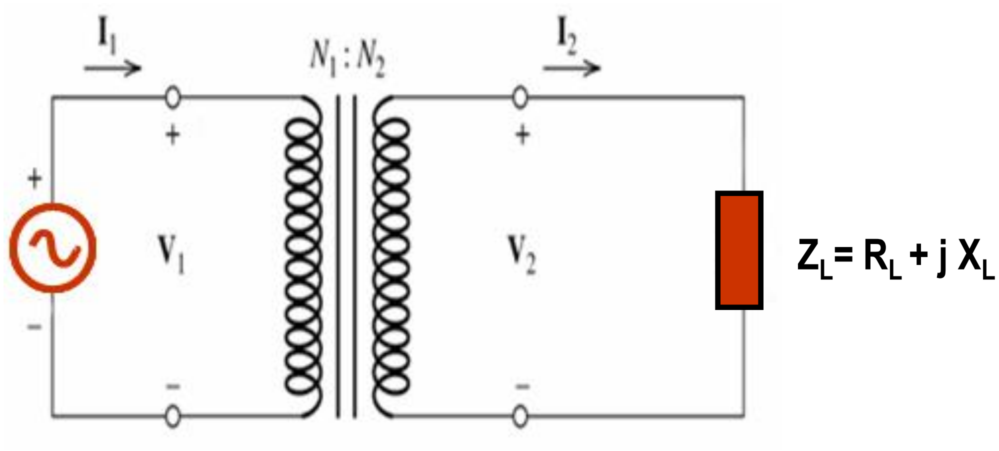
$$I_2 = I_1 \times n_1 / n_2$$

$$V_2 = V_1 \times n_2 / n_1$$

Hence;

$$V_1 \times n_2 / n_1 = I_1 \times n_1 / n_2 \, Z_L$$

$$V_1 / I_1 = Z_L \times (n_1 / n_2)^2$$

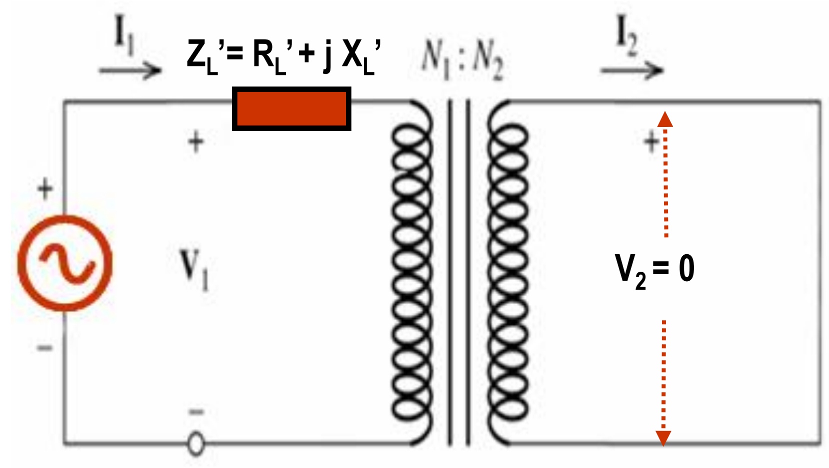


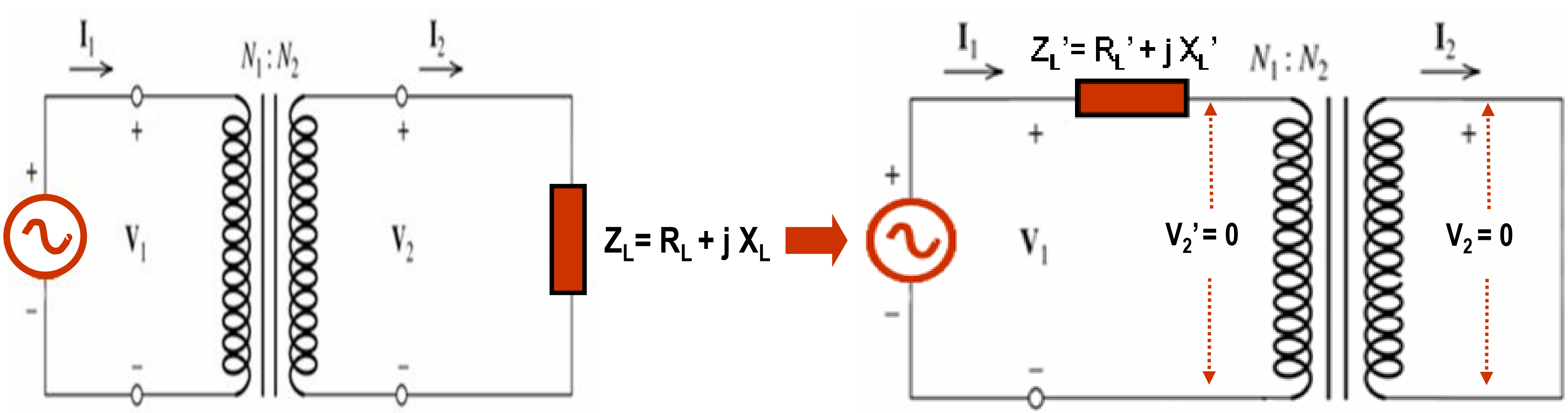
$$Z_L' = Z_L \times (n_1 / n_2)^2$$

Impedance Reflection in a Transformer

Principle

$$Z_L' = Z_L \times (n_1 / n_2)^2$$





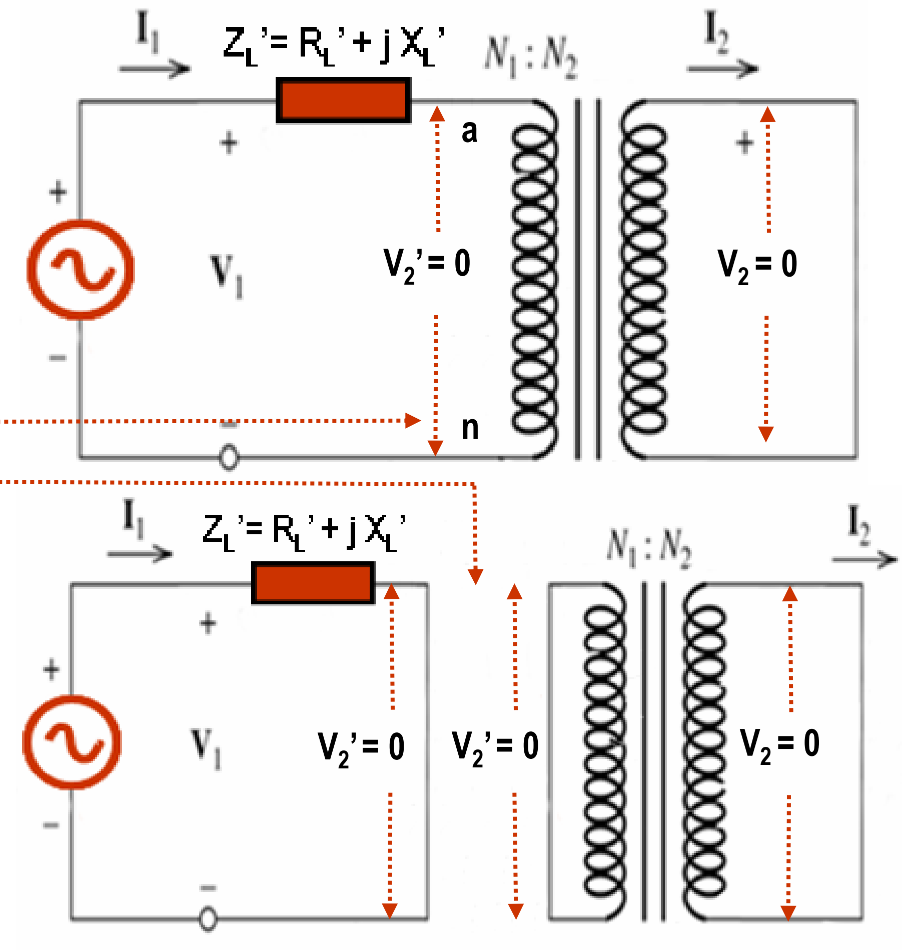
Impedance Reflection in a Transformer

Principle

$$Z_L' = Z_L \times (n_1 / n_2)^2$$

$$I_1 = V_1 / Z_L'$$

Please note that;
V = 0 means the points "a" and "n" are short circuited, which means that the circuit including the transformer becomes electrically unconnected

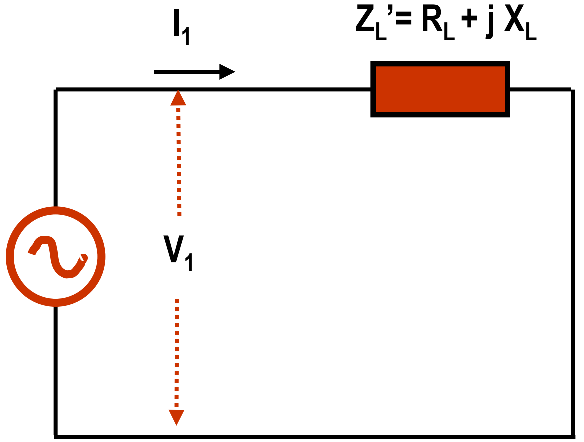


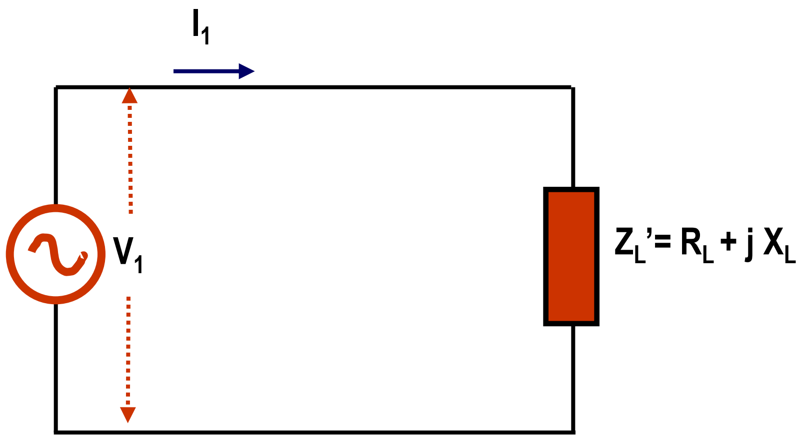
Impedance Reflection in a Transformer

Principle

The circuit then becomes of the form shown on the RHS, which can be solved by using the techniques given in the previous chapters as follows;

$$I_1 = V_1 / Z_L'$$





Example

Example

Solve the transformer circuit shown on the RHS for secondary current I_2

$Z_L' = Z_L \times (n_1 / n_2)^2$

$Z_L' = (0.1 + j0.2) \times (n_1 / n_2)^2$ ← $(n_1 / n_2)^2 = 25$

$= 2.5 + j\,5\ \Omega$

$I_1 = 220 \angle 0^o \;/\; (2.5 + j5)$

$= 220 \angle 0^o \;/\; 5.590 \angle 63.43^o$

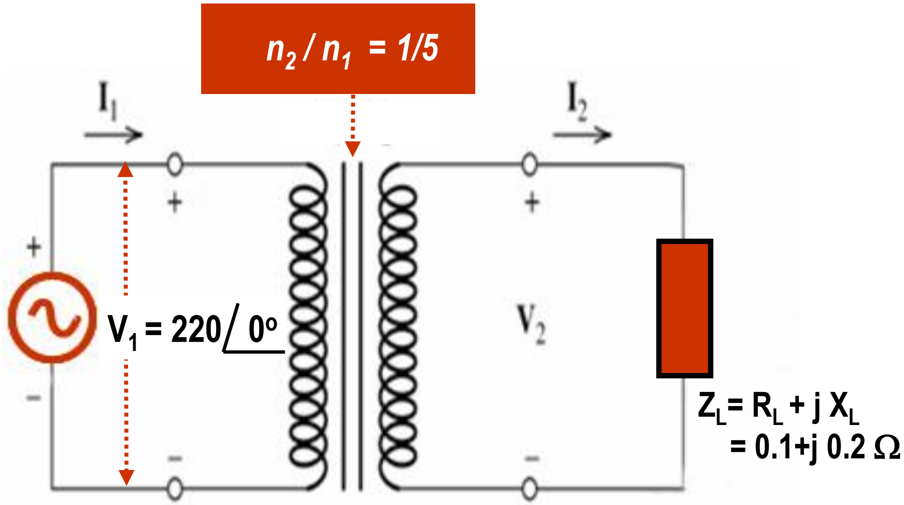
$= 39.35 \angle -63.43^o$ Amp

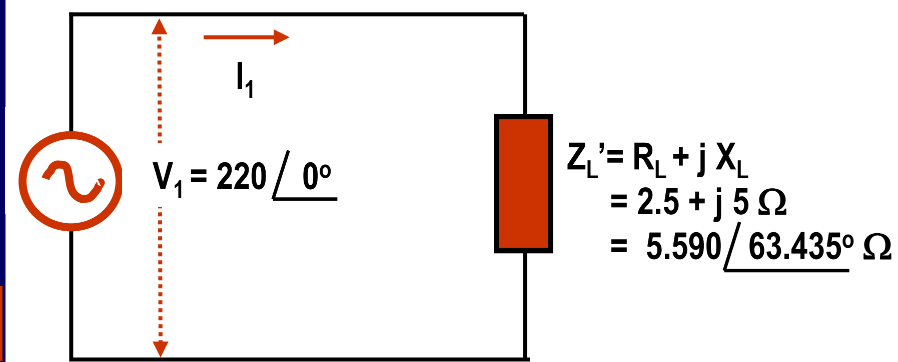
$I_2 = I_1\ n_1 / n_2$

$= 39.35 \angle -63.43^o \ (n_1 / n_2)$ ← $n_1 / n_2 = 5$

$= 39.35 \times 5 \angle -63.43^o$

$= 196.75 \angle -63.43^o$ Amp





Impedance Matching in Transformers

Problem

Determine the best value of the load impedance, i.e. the total impedances of the load and secondary side, such that the real (active) power transferred to the load ($Z_2 = R_2 + jX_2$) is maximum

Solution

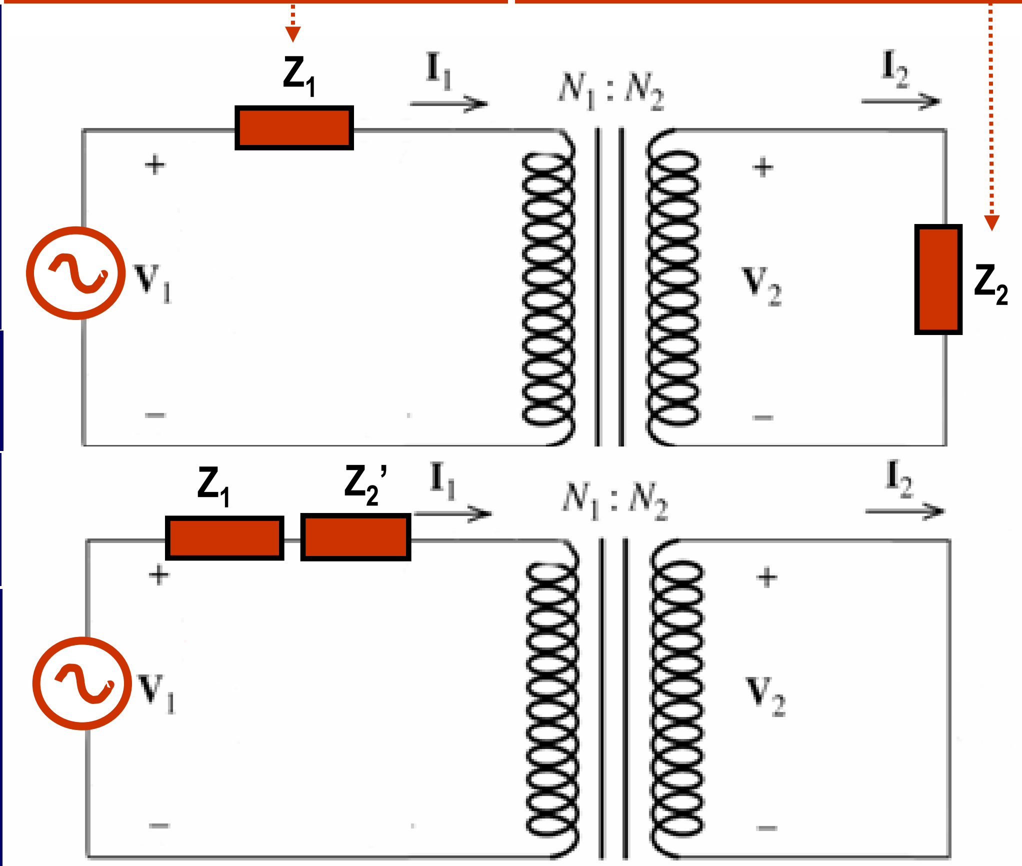
$$P_2 = V_2 I_2^* \cos\theta$$

The first thing to do is to reflect the load impedance to the primary side,

$$Z_2' = Z_2 \times (n_1 / n_2)^2$$

$$I_1 = V_1 / (Z_1 + Z_2')$$

$Z_1 = Z_{source} + Z_{primary}$ | $Z_2 = Z_{load} + Z_{secondary}$



Impedance Matching in Transformers

Solution (Cont'd)

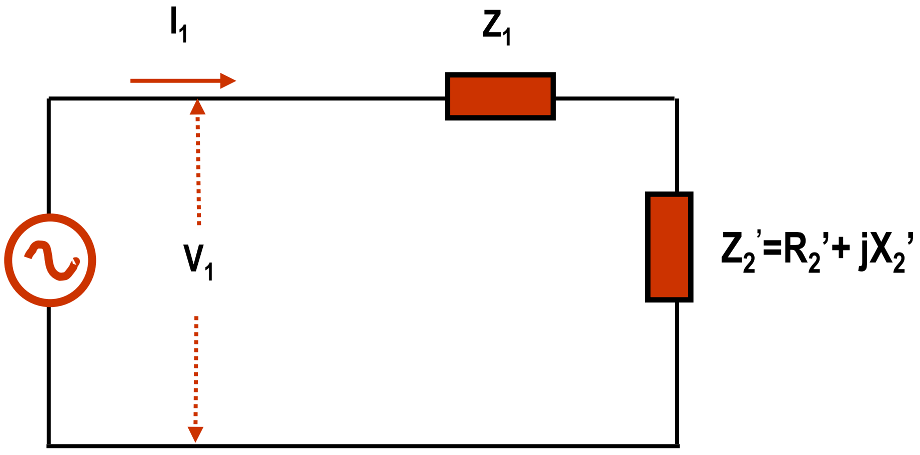
$$I_1 = V_1/(Z_1 + Z_2')$$

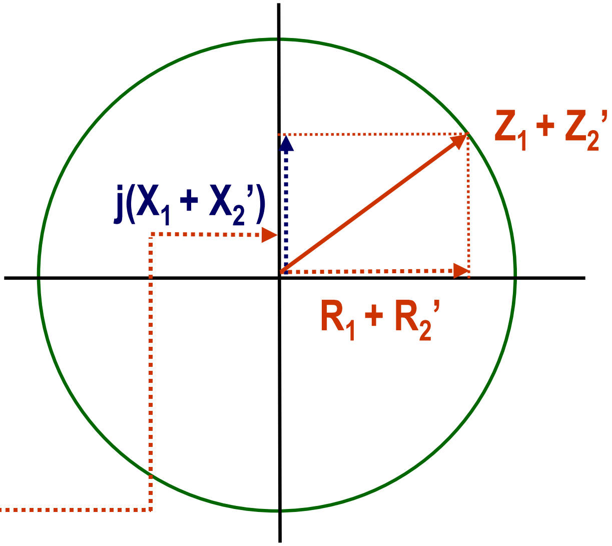
Hence power transferred to the load resistance is R_2' will be

$$P_{out} = R_2' I_1^2$$
$$= R_2' V_1^2 / | Z_1 + Z_2' |^2$$
$$= R_2' V_1^2 / | (R_1 + R_2') + j(X_1 + X_2') |^2$$

Please note that the vertical component can be made zero, by choosing;

$X_2' = - X_1$ (i.e. full compensation)





Transformers

Impedance Matching in Transformers

Solution (Cont'd)

Then;

$$P_{out} = R_2' V_1^2 / (R_1 + R_2')^2$$

which can then be maximized by differentiating P_{out} wrt R_2' as follows;

$d/dR_2' \; [\, V_1^2 R_2' / (R_1 + R_2')^2 \,] = 0$

$[\, V_1^2 (R_1 + R_2')^2 - 2\,(R_1 + R_2')\, R_2' \,] / denom^2 = 0$

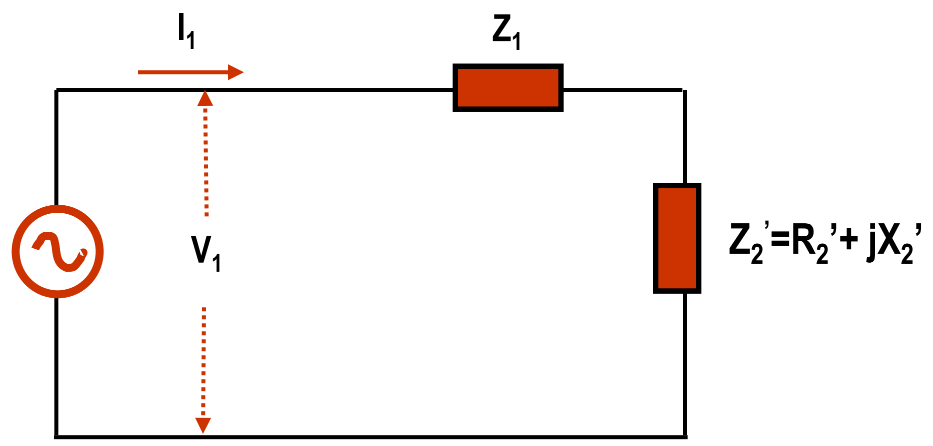
denom = denominator

$2\,(R_1 + R_2') = 0$

or

$(R_1 + R_2')^2 - 2\,(R_1 + R_2')\, R_2' = 0$

$R_1 + R_2' - 2\,R_2' = 0$



$R_1 = R_2' \qquad X_1 = -X_2'$

$Z_2' = Z_1^*$

Transformers

Impedance Matching in Transformers

Solution (Cont'd)

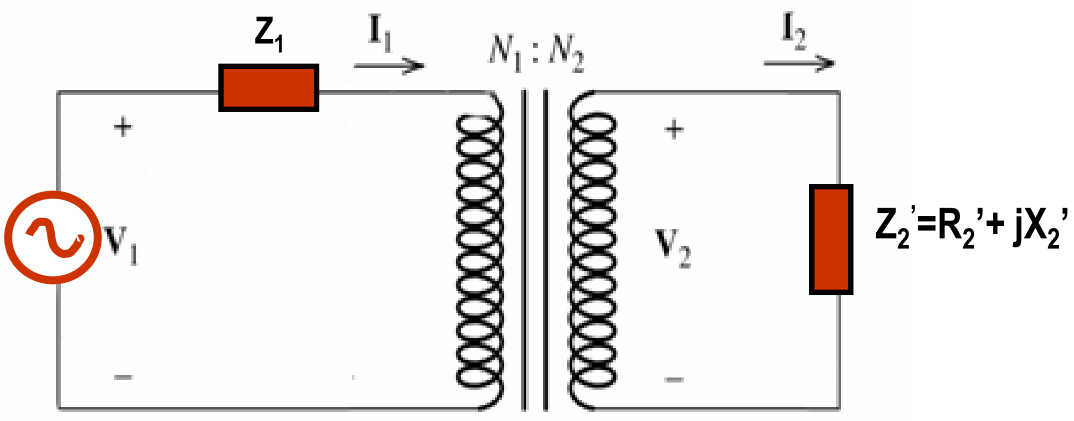
Turn ratio of the transformer may then be calculated as follows;

$$R_1 = R_2'$$
$$R_1 = R_2 (n_1 / n_2)^2$$

Hence

$$(n_1 / n_2)^2 = R_1 / R_2$$
$$n_1 / n_2 = \sqrt{(R_1 / R_2)}$$

Since, Z_1 and Z_2 are both fixed, they can not be varied. But the turn ratio n_1 / n_2 can be adjusted to match them



Calculation of no. of Turns of a Transformer

Cureent and Flux Waveforms

Now, assume that current $I_1(t)$ has a sinusoidal waveform;

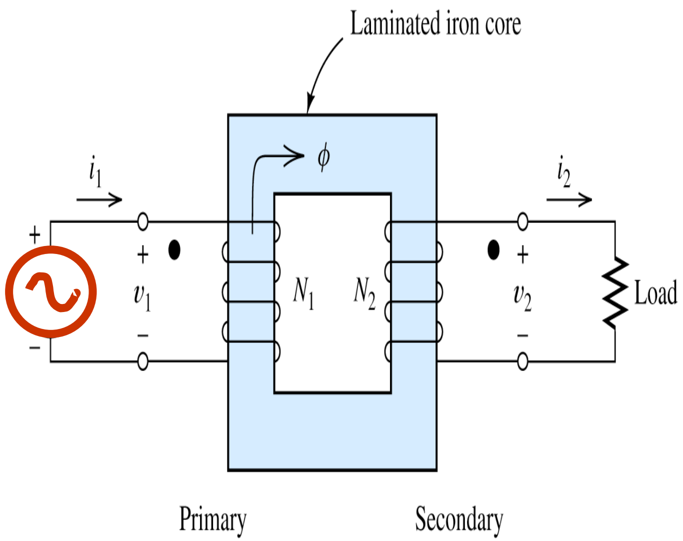
$$I_1(t) = I_{max} \sin wt$$

where I_{max} *is the peak value of the sinusoidal current waveform*

Thus the resulting flux $\phi(t)$ has a sinusoidal waveform;

$$\phi(t) = \phi_{max} \sin wt$$

where ϕ_{max} *is the peak value of the sinusoidal flux waveform*



Transformers

Calculation of no. of Turns of a Transformer

Voltage across the Primary Coil

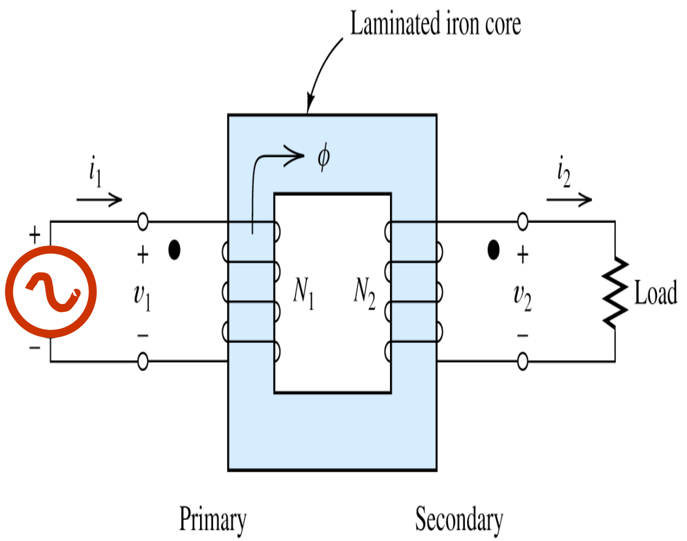
Voltage across the primary coil may then be written as;

$$V_1\,(t) = n_1\, d/dt\ \ \phi\,(t)$$

where $V_1(t)$ *is the primary side voltage,*
n_1 *is the number of turns on the primary side,*
$\phi\,(t)$ *is the flux passing through the core*

$$V_1\,(t) = n_1\, d/dt\ \phi_{max} \sin wt$$
$$= n_1\, \phi_{max}\, w \cos wt$$
$$= n_1\, \phi_{max}\ \ 2\,\pi\, f \cos wt$$
$$= V_{1,max} \cos wt$$

where $V_{1,max} = n_1\, \phi_{max}\ \ 2\,\pi\, f$ *is the peak value of the voltage waveform*



Transformers

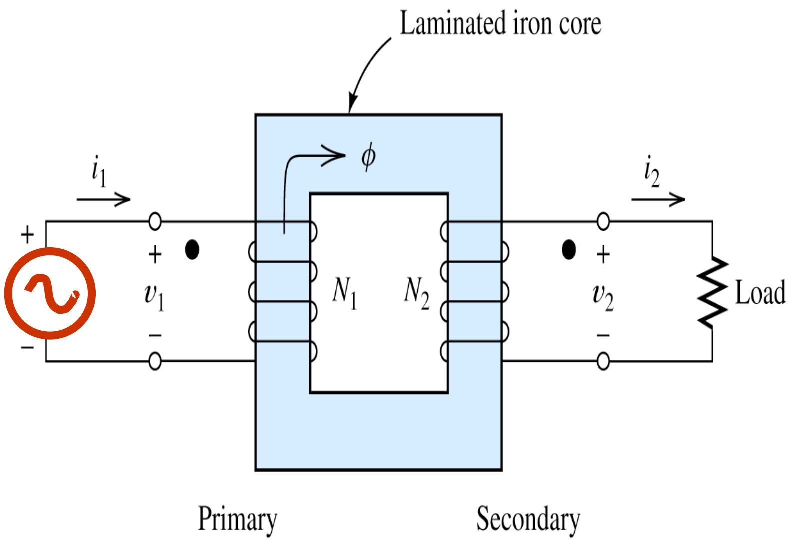
Calculation of no. of Turns of a Transformer

Voltage across the Primary Coil

RMS value of that waveform will then be;

$$V_{1,RMS} = V_{1,max} / \sqrt{2}$$
$$= 2\,\pi / \sqrt{2}\;\; f \times n_1 \times \phi_{max}$$
$$= 4.44 \times f \times n_1 \times \phi_{max}$$

Hence, voltage across the primary coil $V_{1,RMS}$ depends on frequency f, no. of turns of the primary side n_1 and ϕ_{max}



Calculation of no. of Turns of a Transformer

No. of Turns of the Primary Coil

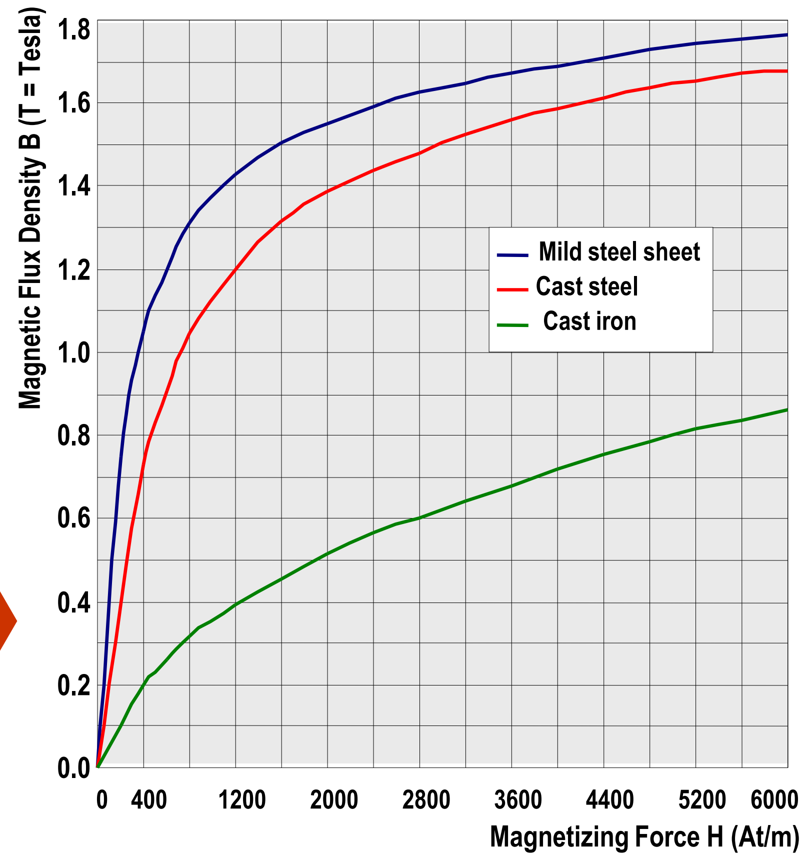
$$V_{1,RMS} = 4.44 \times f \times n_1 \times \phi_{max}$$

Please note that;

$V_{1,RMS}$ depends only on f, n_1 and ϕ_{max}. Hence, in order to have a certain desired voltage $V_{1,RMS}$ on the primary side, we must vary either f, n_1 and ϕ_{max}

- *f cannot be inreased arbitrarily, as hysteresis losses would be increased,*
- *ϕ_{max} cannot be increased arbitrarily, as core saturates,*
- *Thus, the only remaining parameter that can be varied for obtaining a desired voltage is n_1*

B-H Characteristics

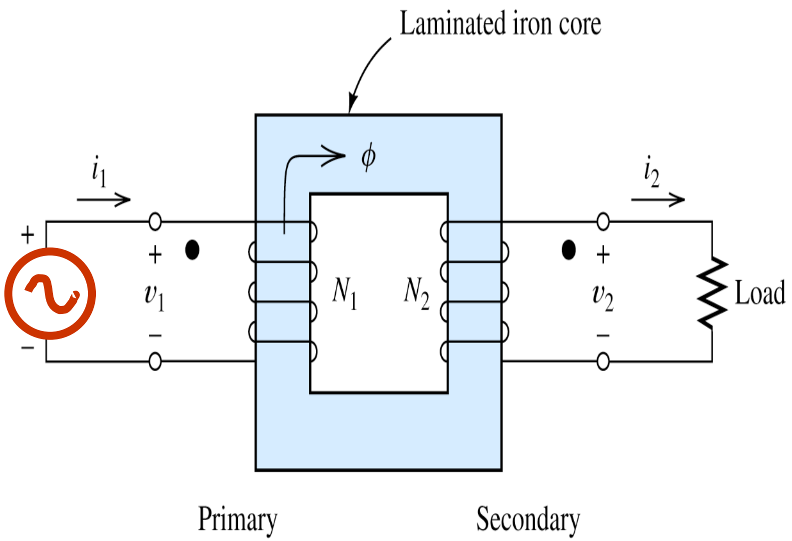


Calculation of no. of Turns of a Transformer

Voltage across the Secondary Coil

Similarly, voltage across the secondary side coil may be written as;

$$V_{2,RMS} = 4.44 \times f \times n_2 \times \phi_{max}$$



Transformers

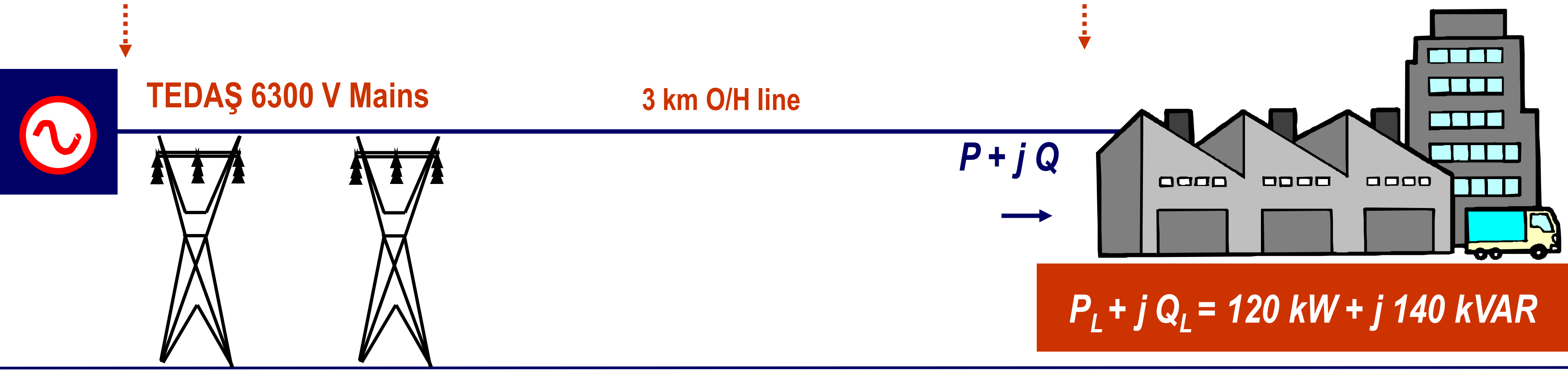
Why do we need Transformers ?

Basic Principle of Power Transmission

Basic principle of power transmission is to transfer power at the sending end, (i.e. at Node A) to the receiving end, (i.e. to Node B at the entry point of factory) with minimum power loss on the line

Node A

Node B



$P_L + j\,Q_L = 120\text{ kW} + j\,140\text{ kVAR}$

Transformers

Why do we need Transformers ?

Average Power (Review)

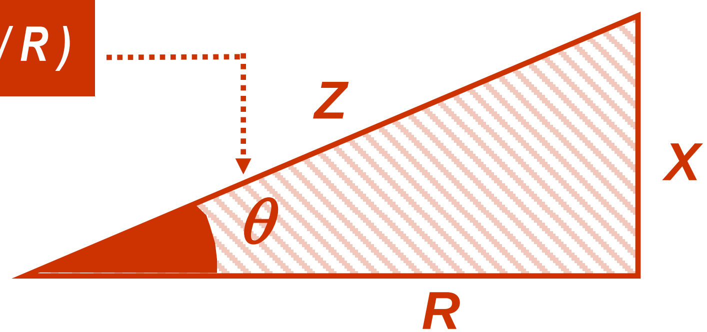
$$P_{avg} = V_{rms}\, I_{rms} \cos\theta$$

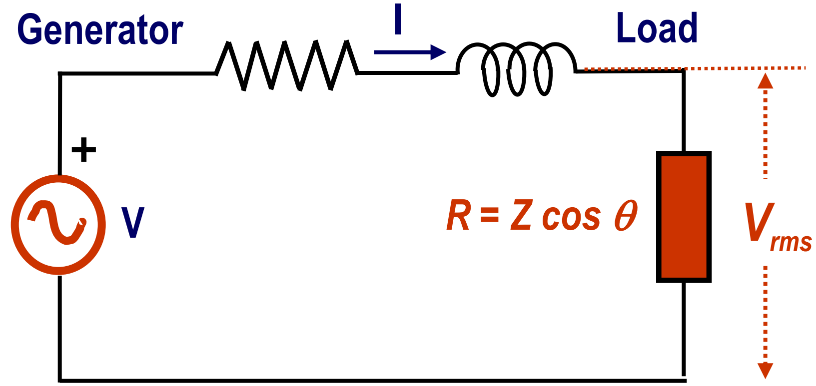
$$P_{avg} = Z \times I_{rms} \times I_{rms} \cos\theta$$
$$= I_{rms}^2\, Z \cos\theta$$
$$= I_{rms}^2\, R$$

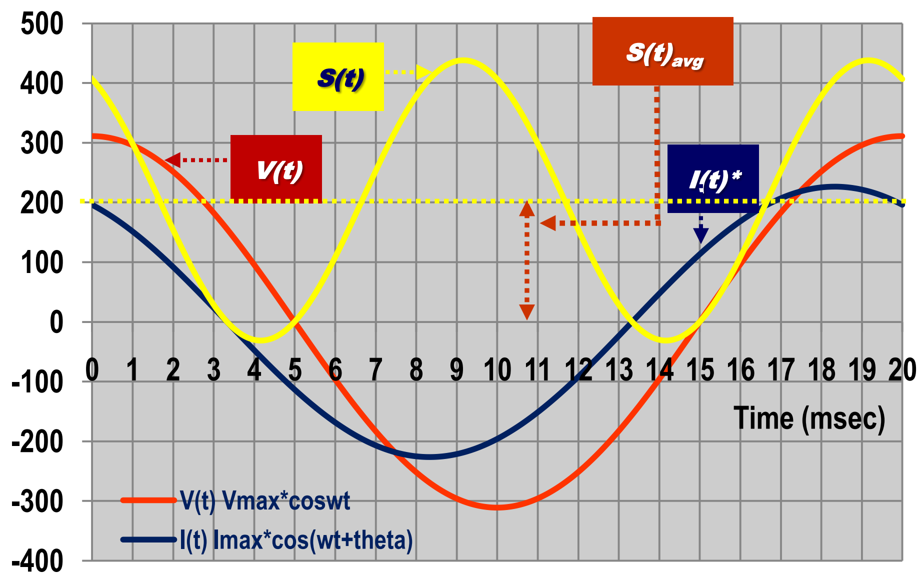
$R = Z \cos\theta$

$$P_{avg} = R\, I_{rms}^2$$

$\theta = Tan^{-1} (X / R)$







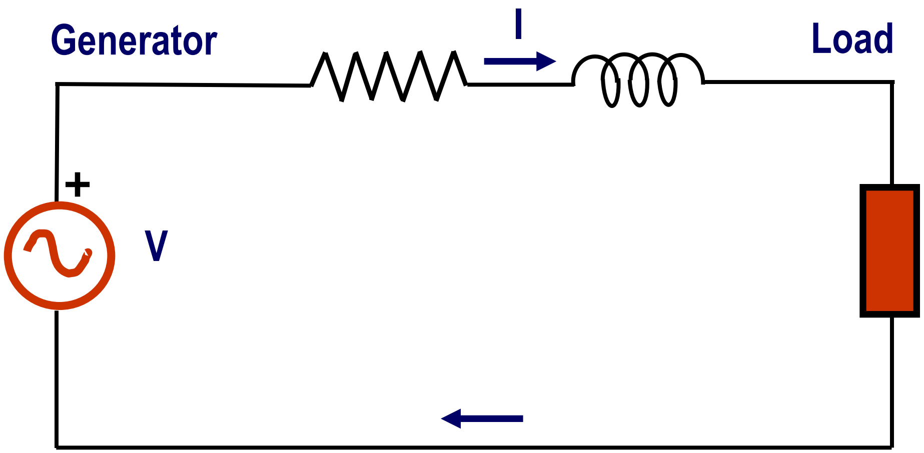
Transformers

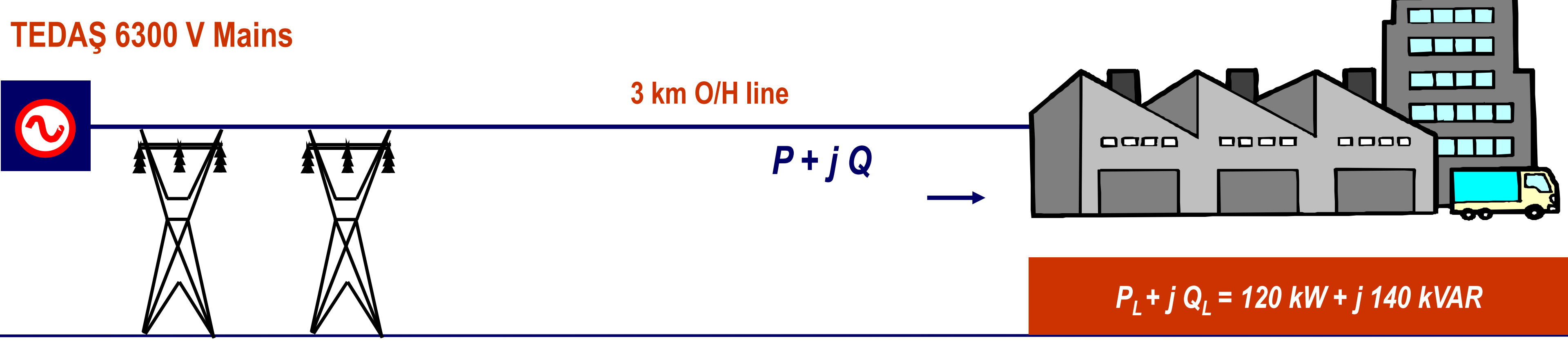
Why do we need Transformers ?

Average Power (Review)

$$P_{avg} = V_{rms}\, I_{rms} \cos\theta$$

$$P_{avg} = R\, I_{rms}^2$$





$P_L + j\,Q_L = 120$ kW $+ j$ 140 kVAR

Why do we need Transformers ?

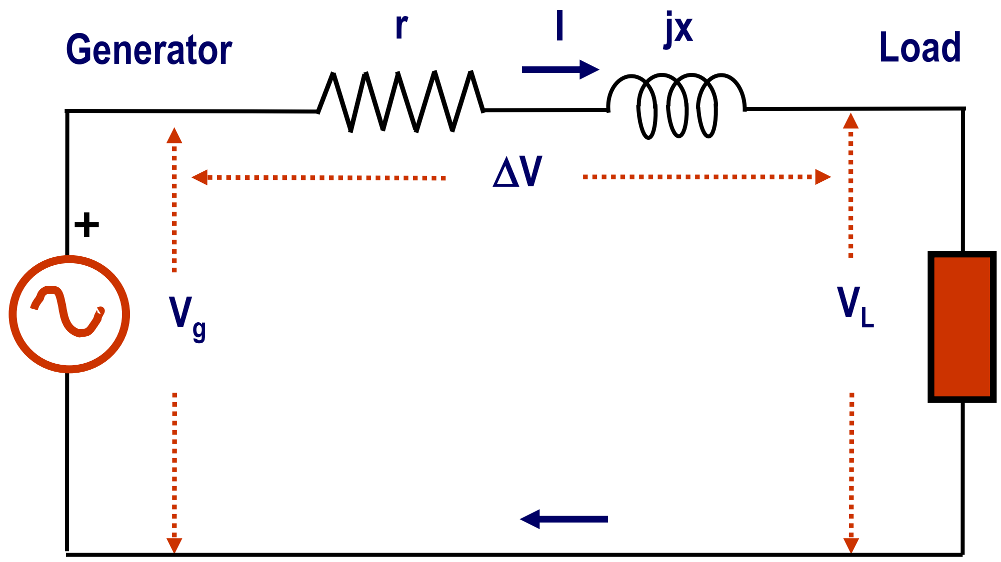
Kirchoff's Voltage Law

$$V_g = V_L + \Delta V$$
$$= V_L + (r + jx)\, I$$

Multiply both sides by I^*

$$V_g\, I^* = V_L(t)\, I^* + (r + jx)\, I^2$$

Power delivered by the generator (Variable)	Power received by the load (Constant)	Power losses in the line (Variable)



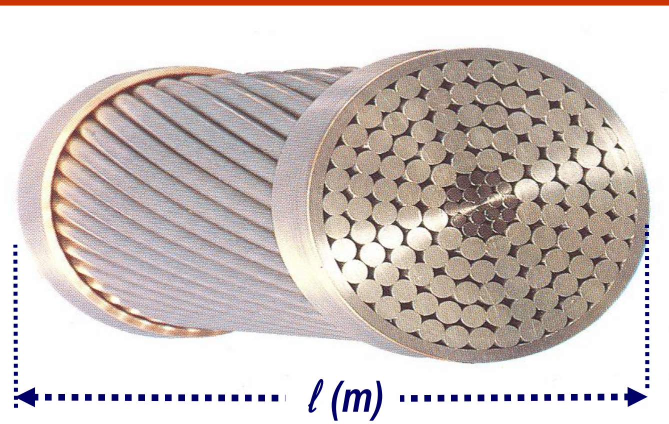
Why do we need Transformers ?

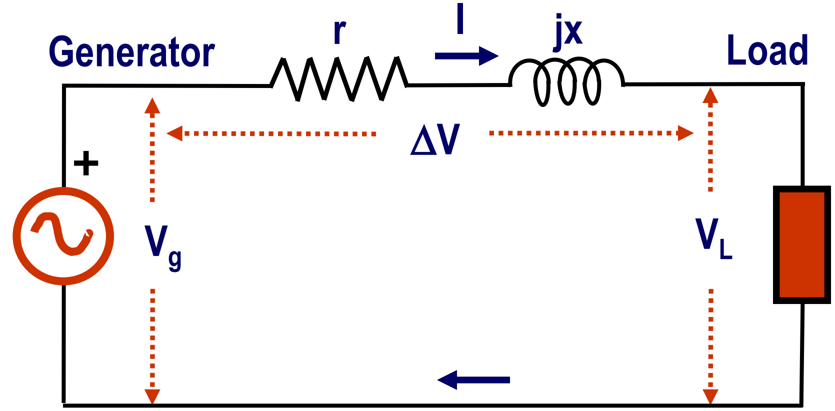
Reduction of Line Losses

$$Power_{loss} = (r + jx) \quad I^2$$

- Active and reactive power losses in the line
- Line resistance and reactance (Constant)
- Square of line or load current

ACSR Conductor
(Aluminum Conductor Steel Reinforced)





$$r = \rho \, \ell \, / \, A$$

where, r is the resistance of conductor,

ρ is the resistivity coefficient,

ρ = 1 / 56 Ohm-mm²/m (Copper)

1 / 32 Ohm-mm²/m (Aluminum)

ℓ (m) is the length of the conductor

A (mm²) is the cross sectional area of the conductor

Hence, line resistance can not be reduced
Similarly, line reactance cannot be reduced

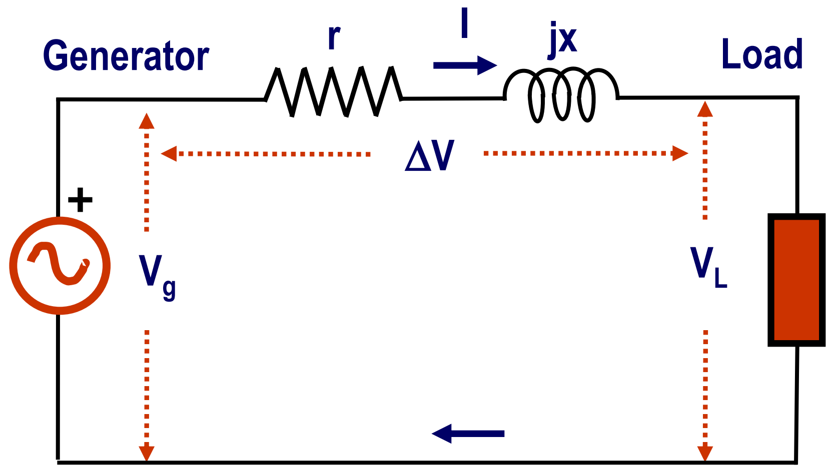
Why do we need Transformers ?

Reduction of Line Losses

$$Power_{loss} = (r + jx)\ \ I^2$$

- $Power_{loss}$: Active and reactive power losses in the line (must be reduced)
- $(r + jx)$: Line resistance and reactance (Constant)
- I^2: Square of line current (or square of the load current)

Hence, the only possibility for reducing the line losses is to reduce the load current



$$S_L = V_L\ I^*$$

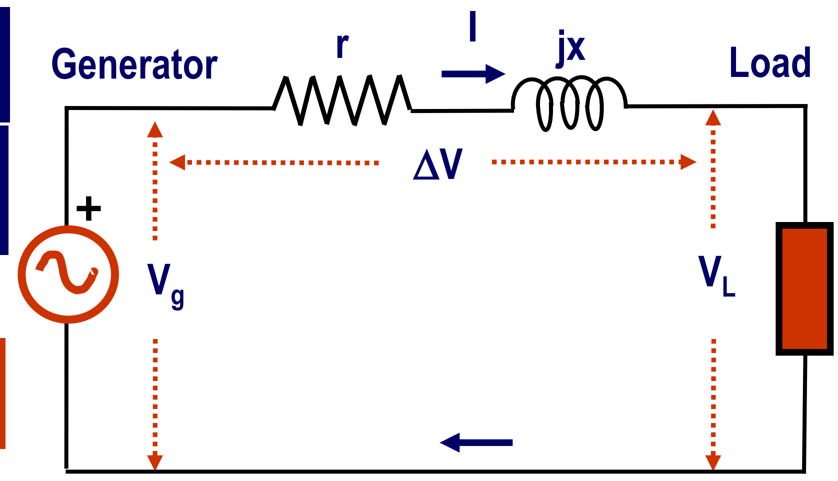
S_L: Power received by the load (Constant)

Why do we need Transformers ?

How can the load current be reduced ?

$S_L \quad = \quad V_L \quad I^*$

- S_L: Active and reactive power (Constant)
- V_L: Load Voltage (Can only be changed by +/- 10 %)
- I^*: Load or line current (Can be changed)



An obvious solution is to reduce the line current I^* by a constant factor n, while increasing the load voltage V_L by the same factor n

$S_L = V_L \, I^*$

Power received by the load (Constant)

$S_L \quad = \quad (V_L \, n)\ (I^* / n)$

This factor n is called the transformation turn ratio

Why do we need Transformers ?

Reduction in Line Losses

$$S_L = (V_L\, n)\ (I^* / n)$$

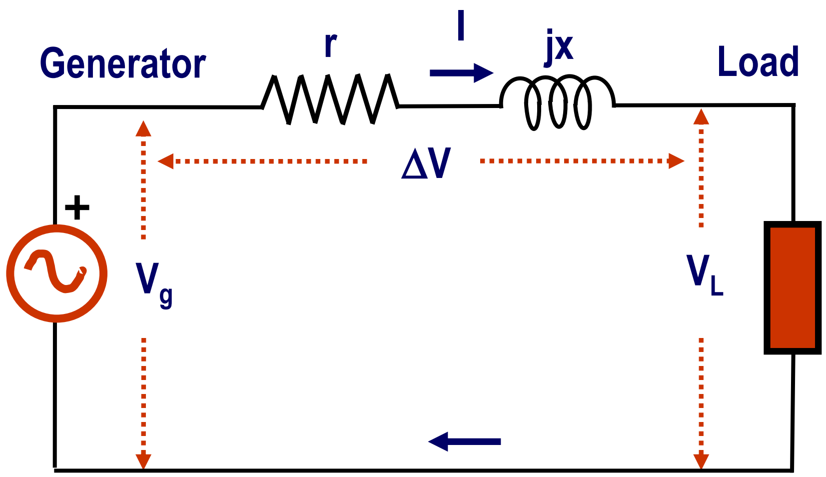
Please note that;

- Voltage is increased by a factor of n
- Current is reduced by the same factor n

Hence, the line loss now becomes;

$$Power_{loss} = (r + jx)\ (I / n)^2 = (r + jx)\ I^2 / n^2$$

Active and reactive power losses in the line	Line resistance and reactive (Constant)	Square of line / n^2 Hence, loss is reduced by n^2



Example;

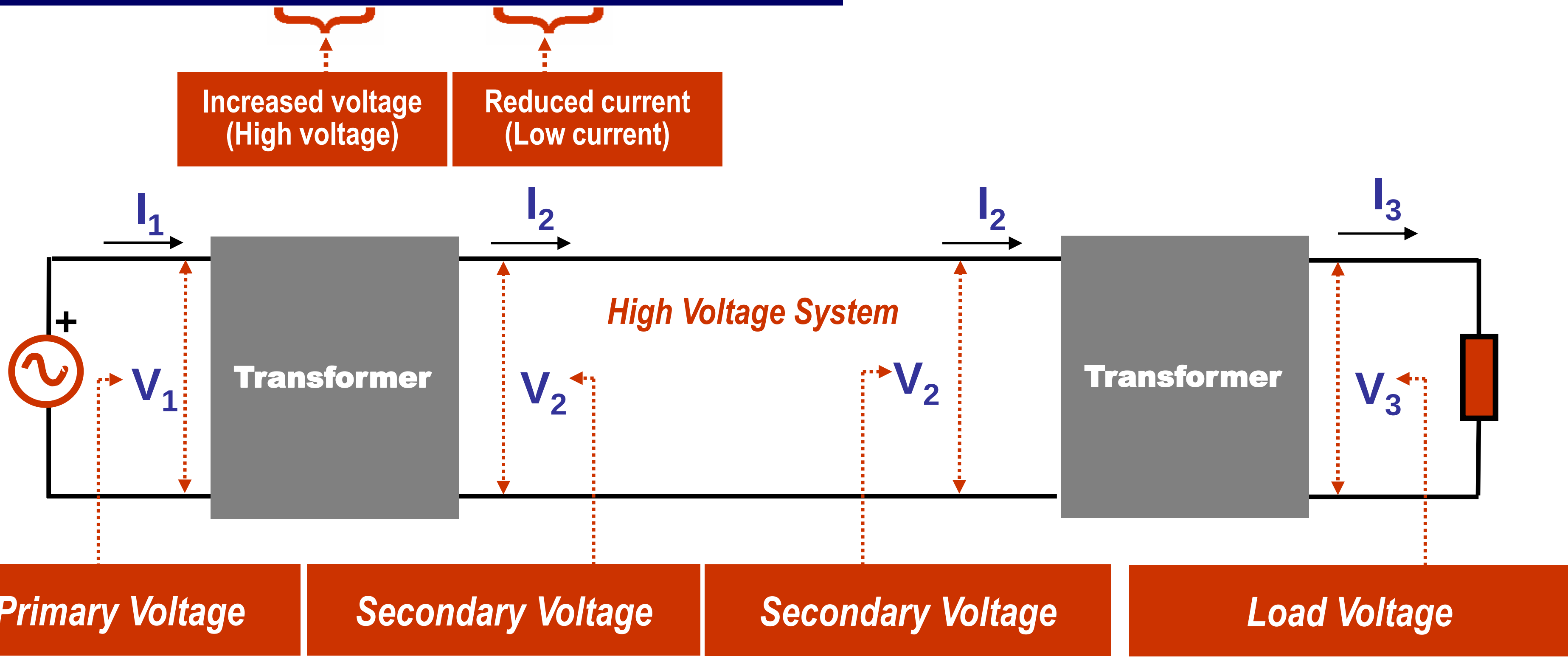
n = 380 000 Volt / 15 000 Volt = 25.333

n^2 = 641.77

Why do we need Transformers ?

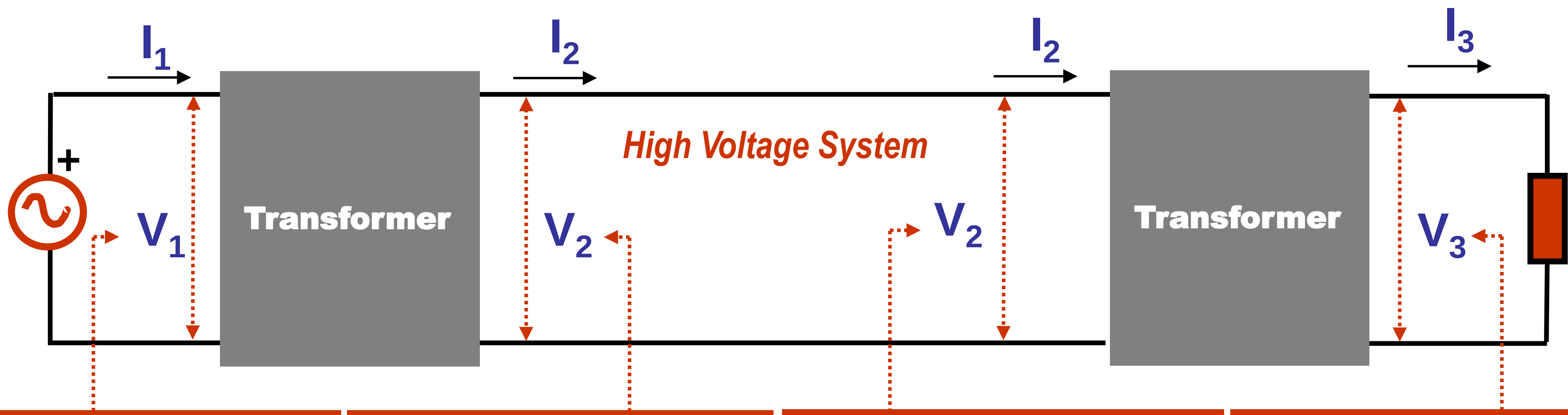
Transmission System Configuration

$$S_L \quad = \quad (V_L\, n) \quad x \quad (I^* / n)$$



Why do we need Transformers ?

Voltage Levels in a Power System



Generation Voltage	Transmission Voltage	Transmission Voltage	Load (Distribution) Voltage
13.0 kV	66 kV		31.5 kV
13.5 kV	154 kV		34.5 kV
15.0 kV	380 kV		6.3 kV
			0.4 kV (380 Volts)

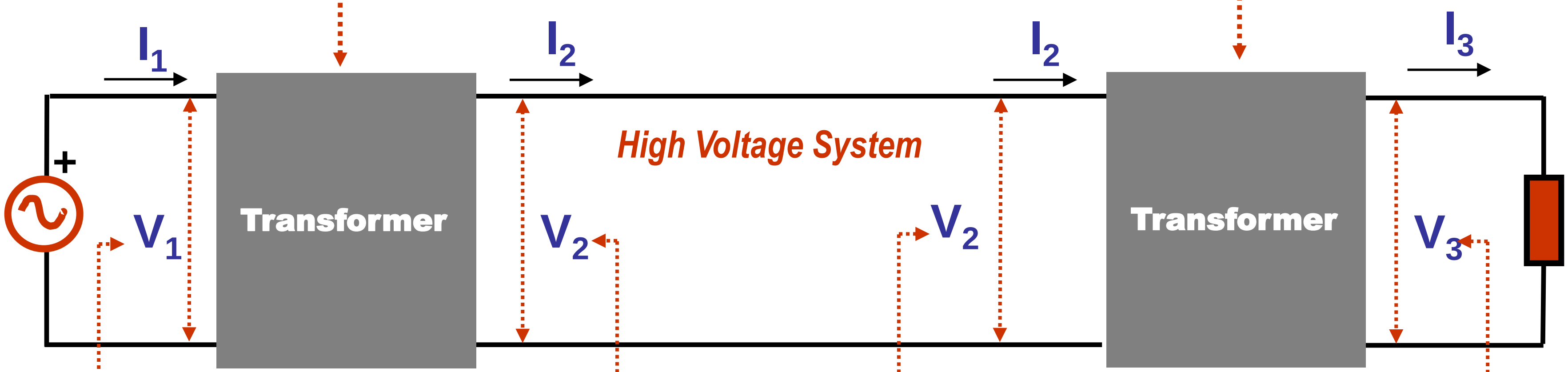
Why do we need Transformers ?

Step-up and Step-down Transformers

Transformers used to raise the voltage are called step-up and lower the voltage are called step down transformers

Step-up Transformer
(1/n =15 kV/154kV), $1/n = n_1 / n_2$

Step-down Transformer
(1/n = 154 kV/34.5), $1/n = n_2 / n_3$



Generation Voltage | *Transmission Voltage* | *Transmission Voltage* | *Load Voltage*

Transformers

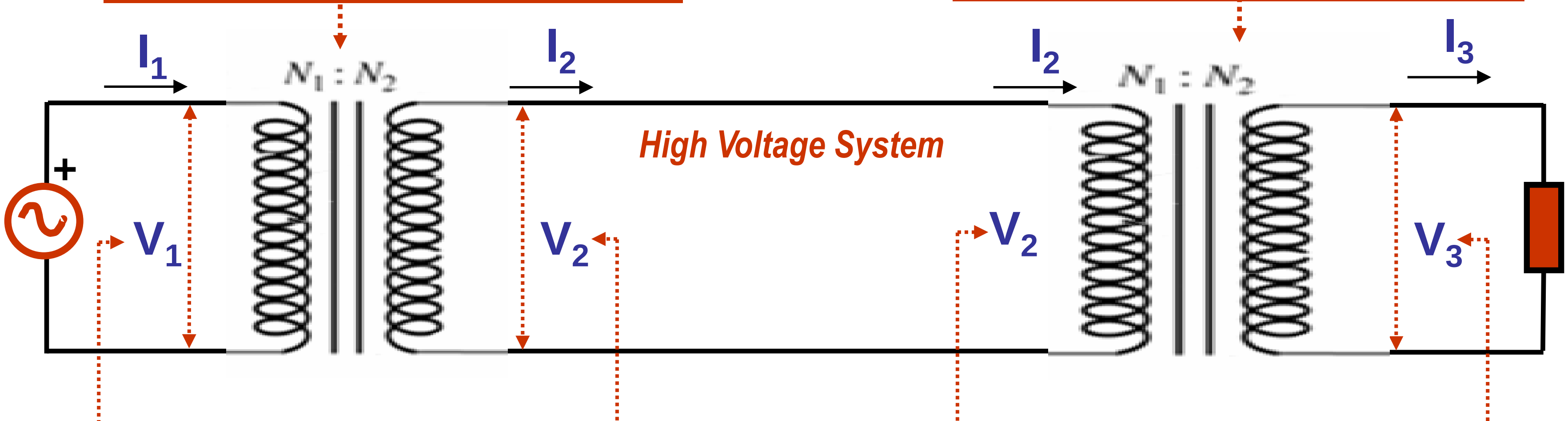
Why do we need Transformers ?

Step-up and Step-down Transformers

Transformers that raise and reduce the voltage are called step-up and step down transformers, respectively

Step-up Transformer
($1/n$ =15 kV/154kV), $1/n = n_1 / n_2$

Step-down Transformer
($1/n$ = 154 kV/34.5), $1/n = n_2 / n_3$



Generation Voltage | *Transmission Voltage* | *Transmission Voltage* | *Load Voltage*

METU

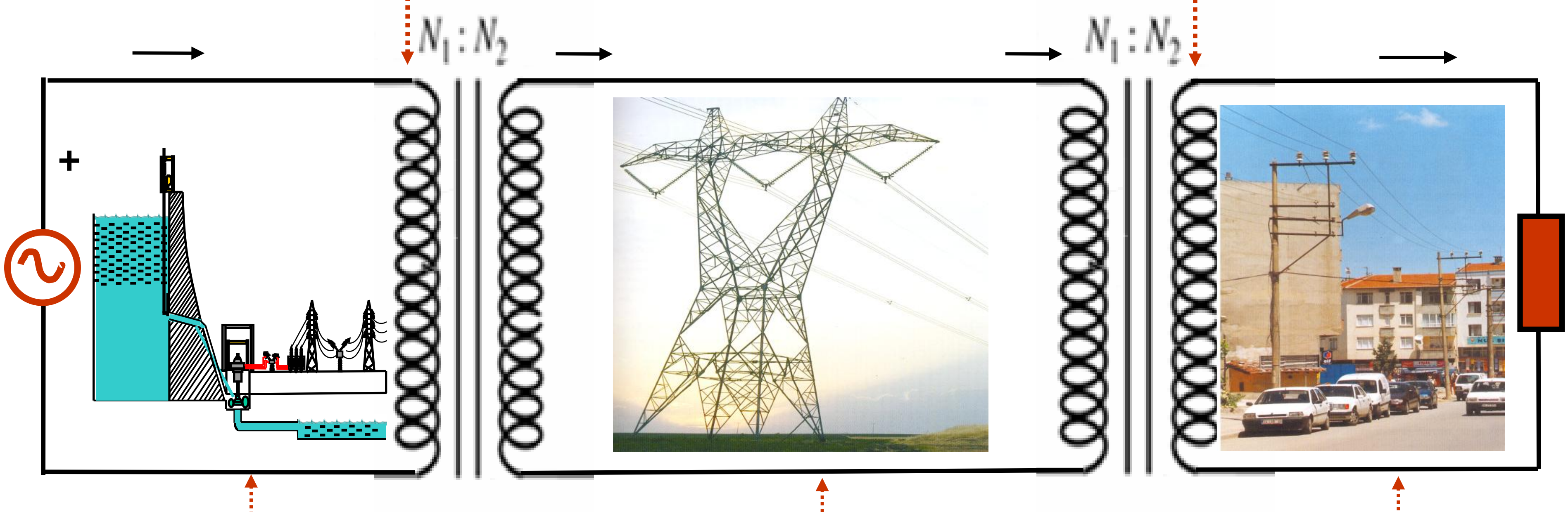
Transformers

Why do we need Transformers ?

Generation-Transmission-Distribution Systems

Step-up Transformer
(1/n =15 kV/154kV), 1/n = n_1 / n_2

Step-down Transformer
(1/n = 154 kV/34.5), 1/n = n_2 / n_3



Generation System

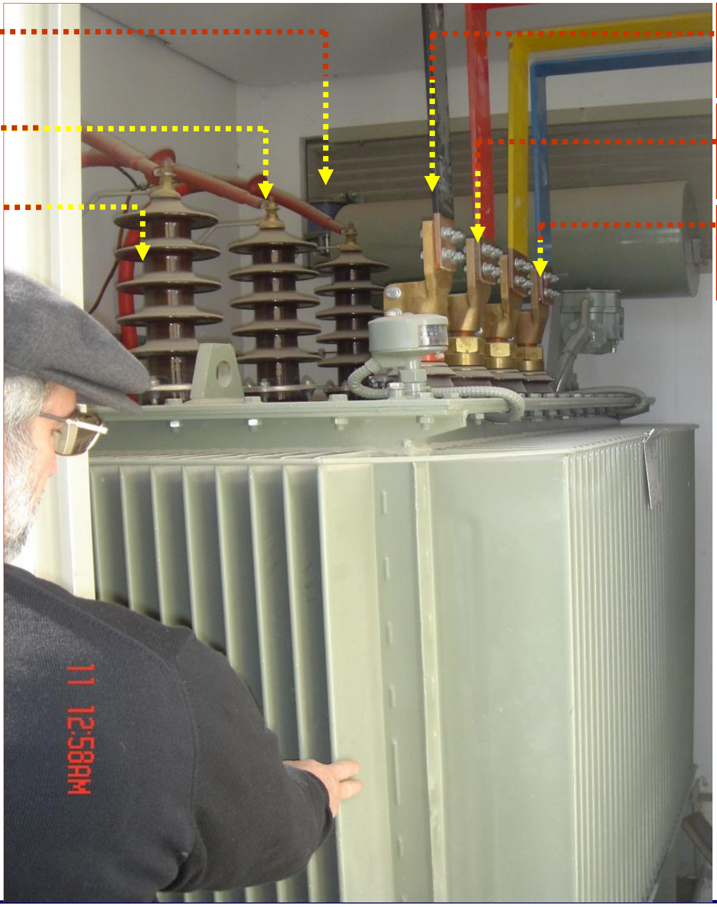
Transmission System

Distribution System

Transformers

Three Phase Transformer

Primary Side (Delta)	Secondary Side (Star)
Primary Side Phase - a	Secondary Side Phase - a
Primary Side Phase - b	Secondary Side Phase - b
Primary Side Phase - c	Secondary Side Phase - c



Voltages

Primary Side

V_{line} = 34500 Volts

$V_{phase} = V_{line}$ = 34500 Volt

Secondary Side

V_{line} = 380 Volts

$V_{phase} = 380 / \sqrt{3} = 220$ Volts

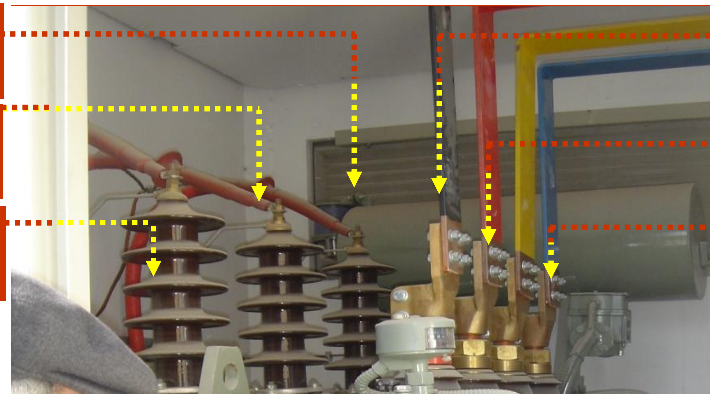
Three Phase Transformer

Primary Side (Delta)	Secondary Side (Star)

Primary Side Phase - a

Primary Side Phase - b

Primary Side Phase - c

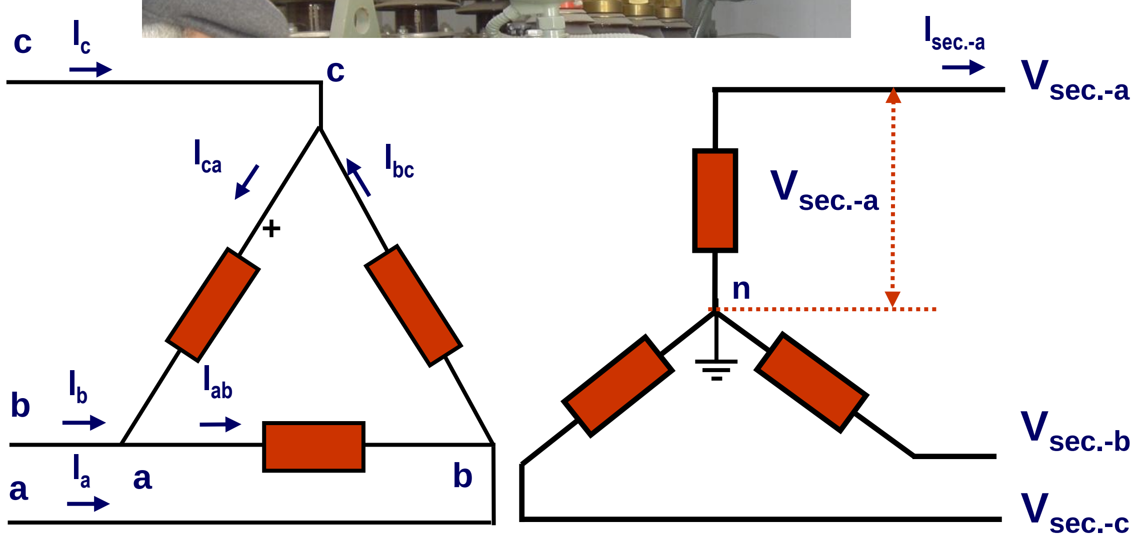


Secondary Side Phase - a

Secondary Side Phase - b

Secondary Side Phase - c

Please note that almost all distribution transformers are delta-star connected



Three Phase Transformer

Three-Phase Power (Overview)

$$P_{prim.-a} = V_a I_a \cos\theta$$

$$P_{prim.-b} = V_b I_b \cos\theta$$

$$P_{prim.-c} = V_c I_c \cos\theta$$

+

$$\begin{aligned} P_{prim.-Total} &= V_a I_a \cos\theta + V_b I_b \cos\theta + V_c I_c \cos\theta \\ &= 3\, V_{phase}\, I_{phase} \cos\theta \\ &= 3\, V_{line}\, I_{line} / \sqrt{3} \cos\theta \\ &= \sqrt{3}\, V_{line}\, I_{line} \cos\theta \end{aligned}$$

Three Phase Transformer

Three-Phase Power (Overview)

Power on the Primary Side

$$P_{Prim.\,-\,Total} = \sqrt{3}\; V_{Prim.\text{-}\,line}\; I_{Prim.\text{-}line}\; \cos\theta$$

$$Q_{Prim.\,-\,Total} = \sqrt{3}\; V_{Prim.\text{-}\,line}\; I_{Prim.\text{-}line}\; \sin\theta$$

$$S_{Prim.\,-\,Total} = \sqrt{3}\; V_{Prim.\text{-}\,line}\; I_{Prim.\text{-}line}$$

Power on the Secondary Side

$$P_{Sec.\,-\,Total} = \sqrt{3}\; V_{Sec.\text{-}\,line}\; I_{Sec.\text{-}line}\; \cos\theta$$

$$Q_{Sec.\,-\,Total} = \sqrt{3}\; V_{Sec.\text{-}\,line}\; I_{Sec.\text{-}line}\; \sin\theta$$

$$S_{Sec.\,-\,Total} = \sqrt{3}\; V_{Sec.\text{-}\,line}\; I_{sec.\text{-}line}$$

Example: Delta-Star Connected Dry Type Transformer

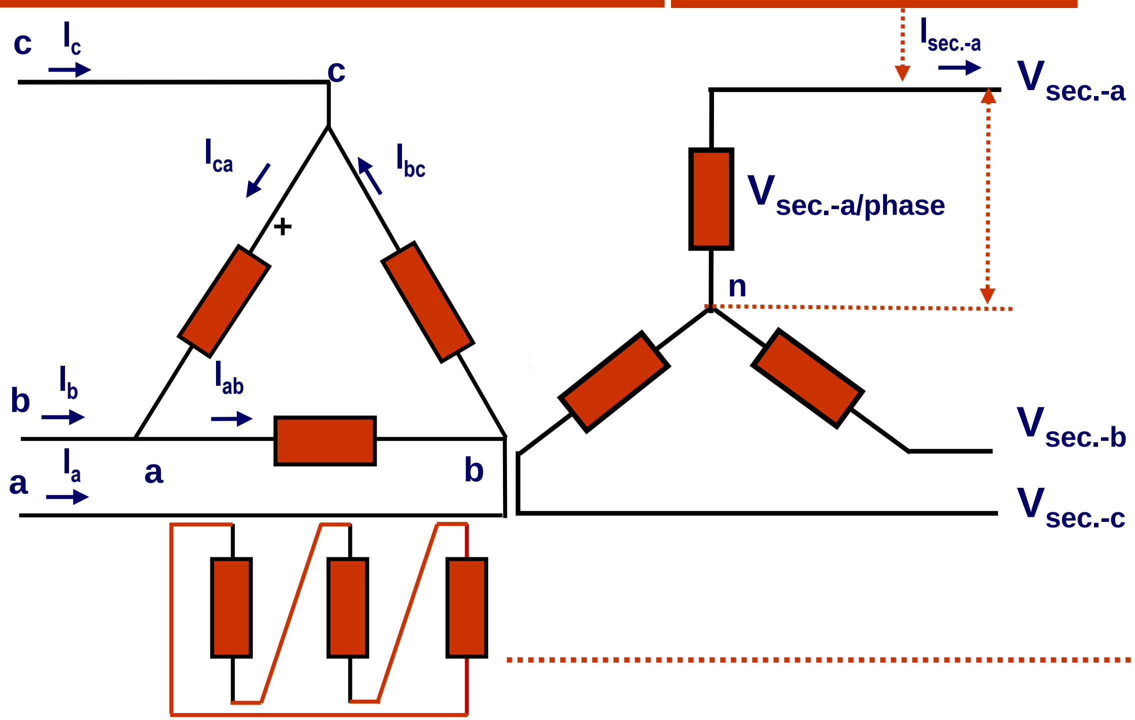
Delta – Star Connection

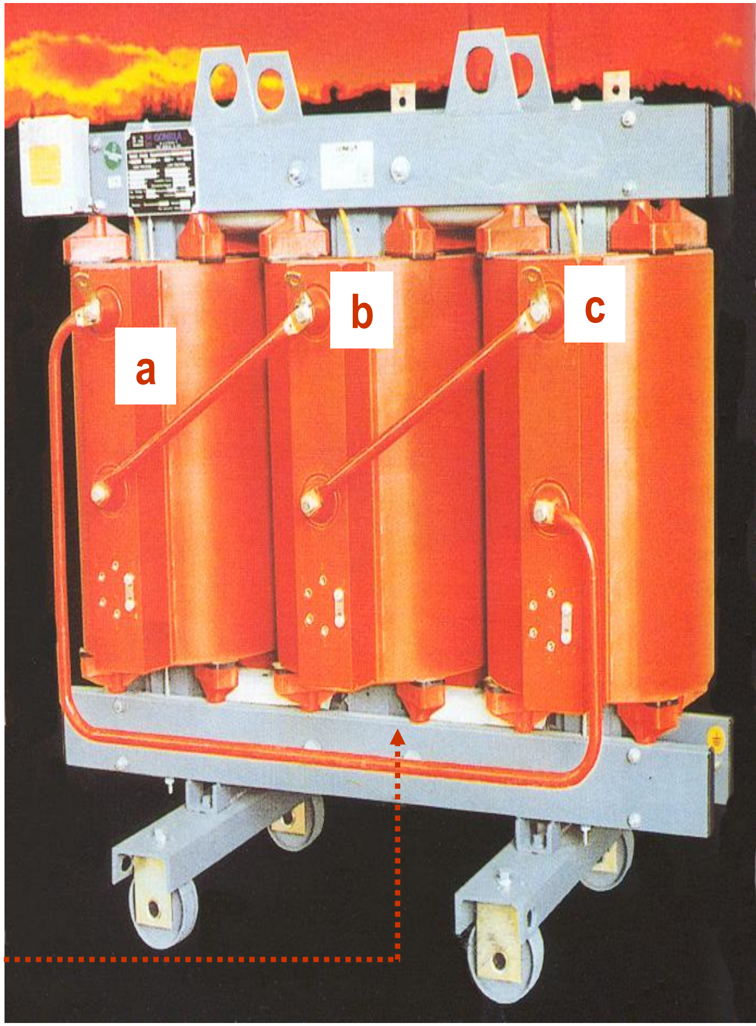
Line Voltage = Phase Voltage

|Line Current| = $\sqrt{3}$ x |Phase Current|

I_{ba} = *Phase Current*

$I_a = I_{ba}$ = *Line Current*





Example: Delta-Star Connected Dry Type Transformer

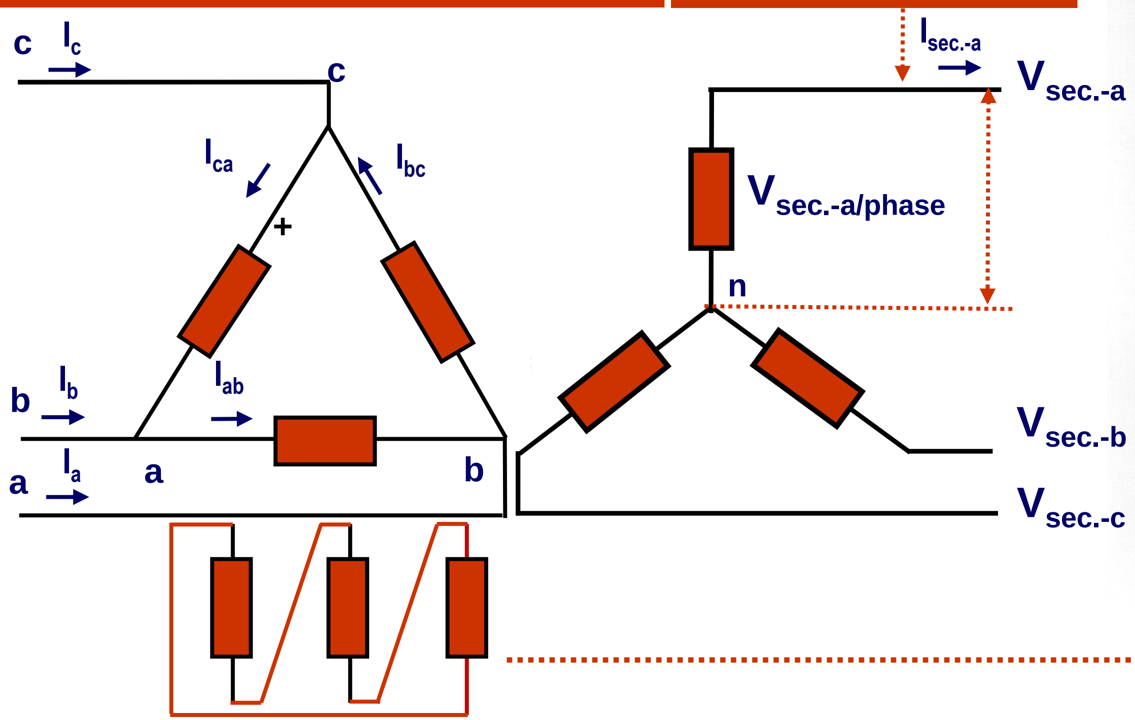
Delta – Star Connection

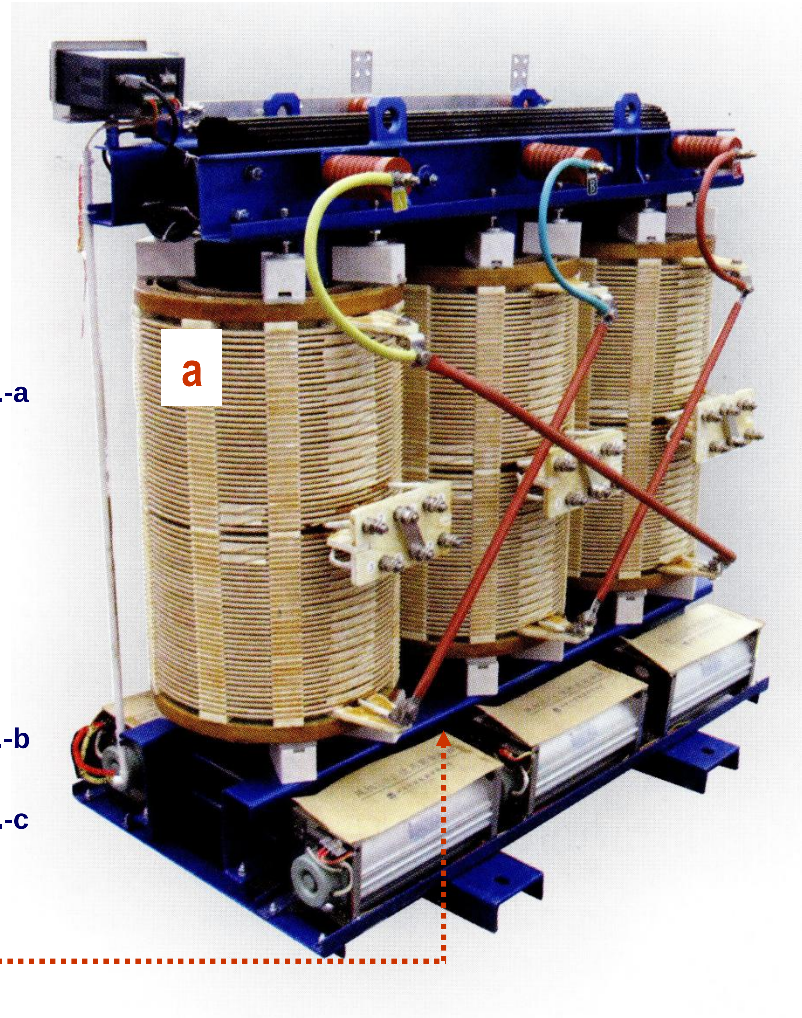
Line Voltage = Phase Voltage

$|\text{Line Current}| = \sqrt{3} \times |\text{Phase Current}|$

I_{ba} = Phase Current

$I_a = I_{ba}$ = Line Current





Example: Delta-Star Connected Dry Type Transformer

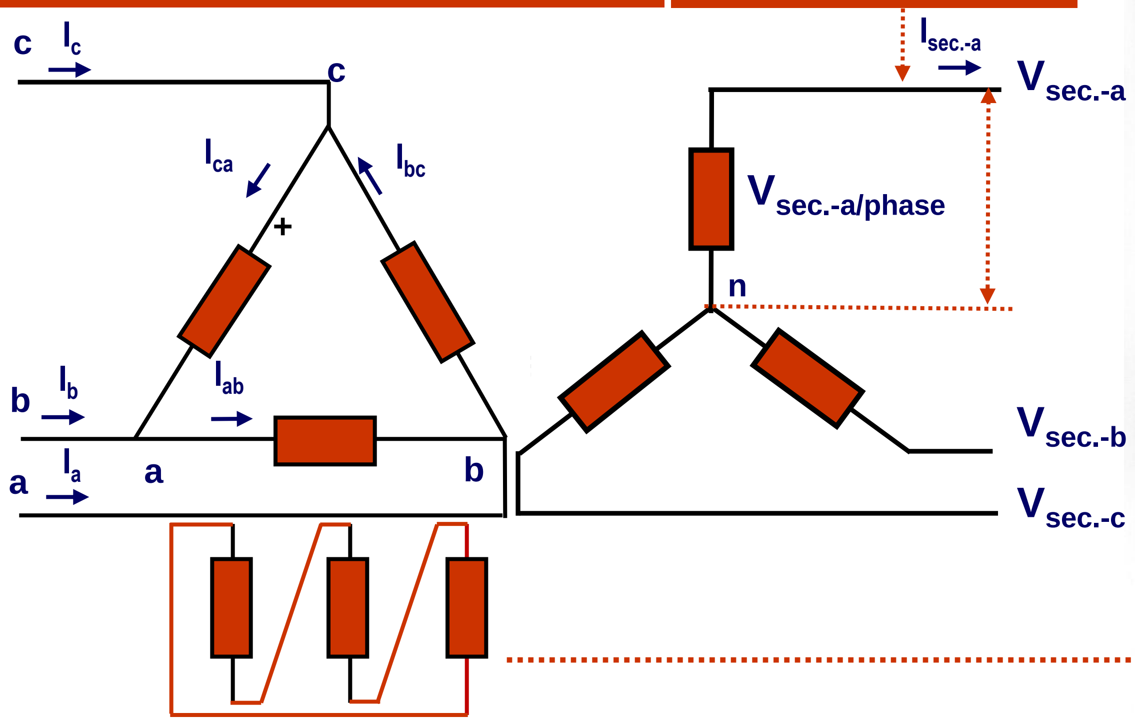
Delta – Star Connection

Line Voltage = Phase Voltage

$|\text{Line Current}| = \sqrt{3} \times |\text{Phase Current}|$

I_{ba} = Phase Current

$I_a = I_{ba}$ = Line Current



Transformers

Dry Type Transformers

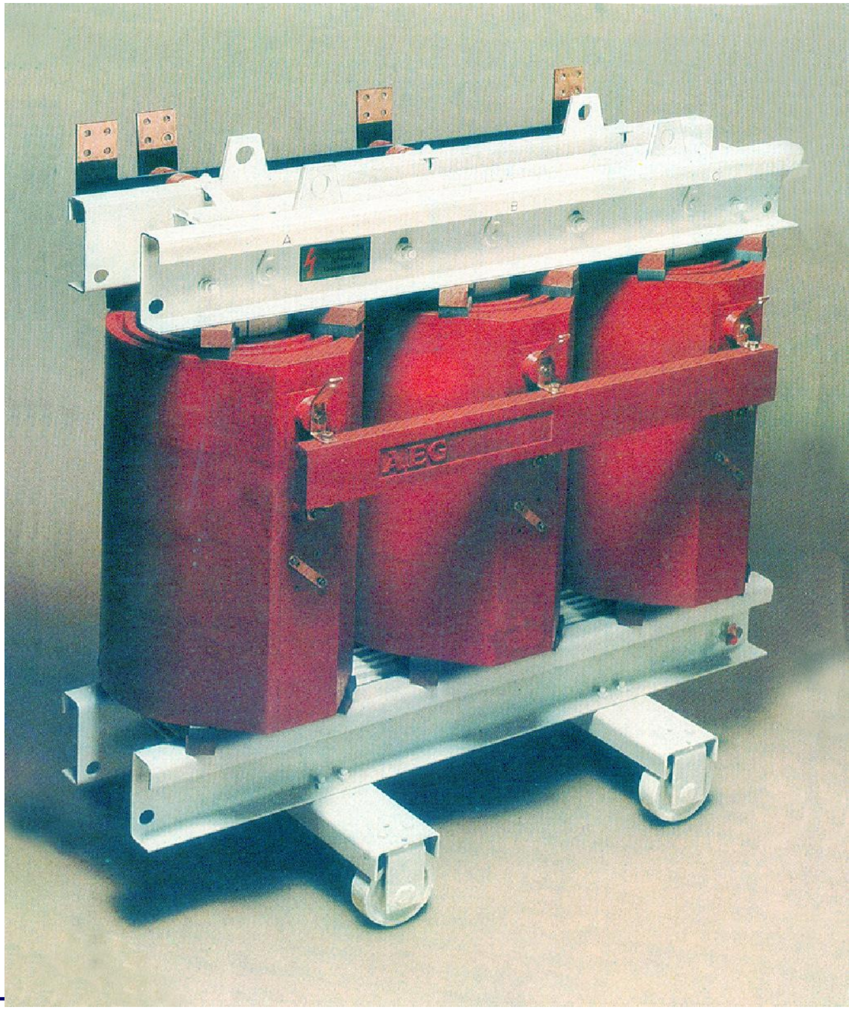
Configuration

- Since there is no oil, outside cover is not needed,
- No oil, hence no fire risk, and no need for oil maintenance,
- Open ventilation, hence, no need for forced cooling, fans etc.
- Relatively lighter and smaller

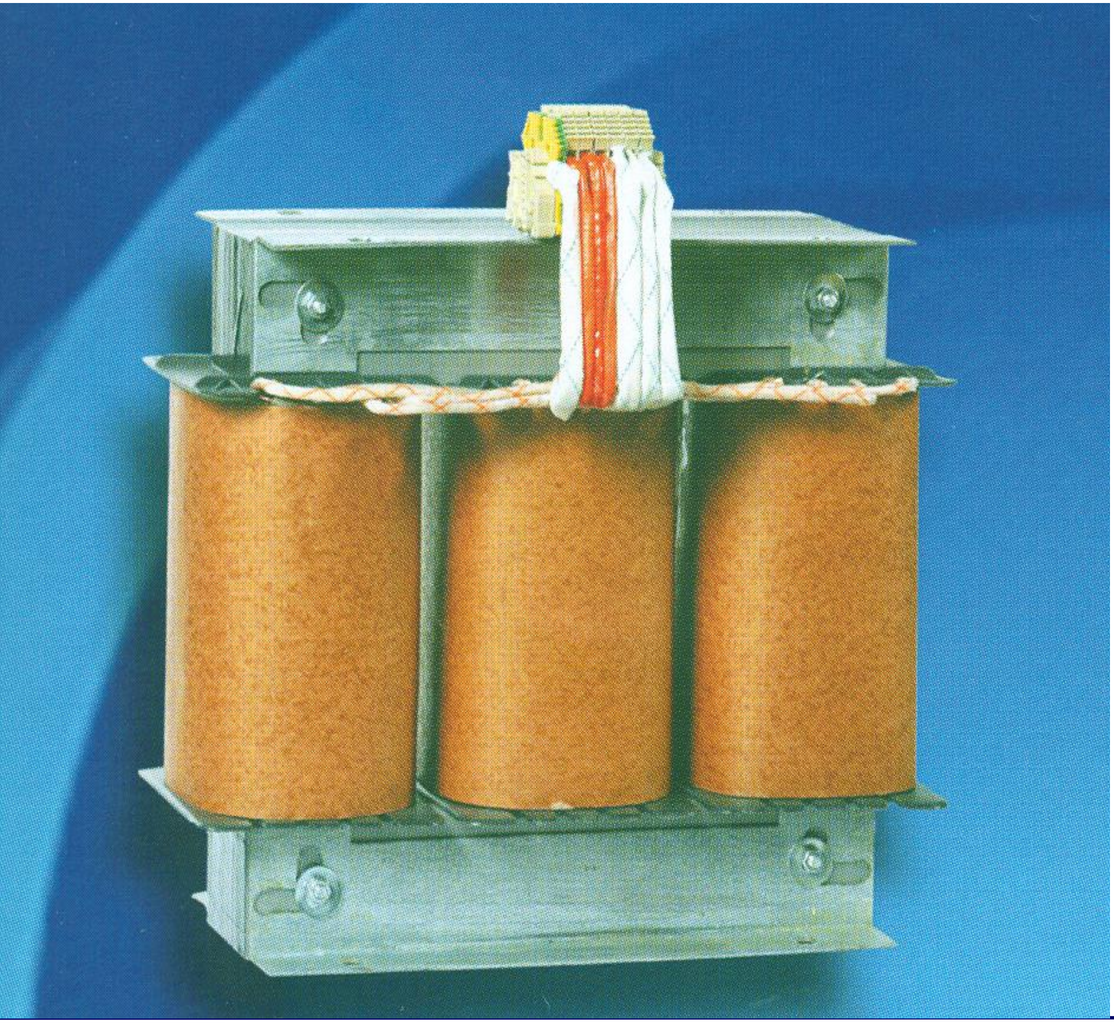
Application

- High buildings, where fire risk, oil maintenance and weight is a problem

Disadvantage: Expensive !

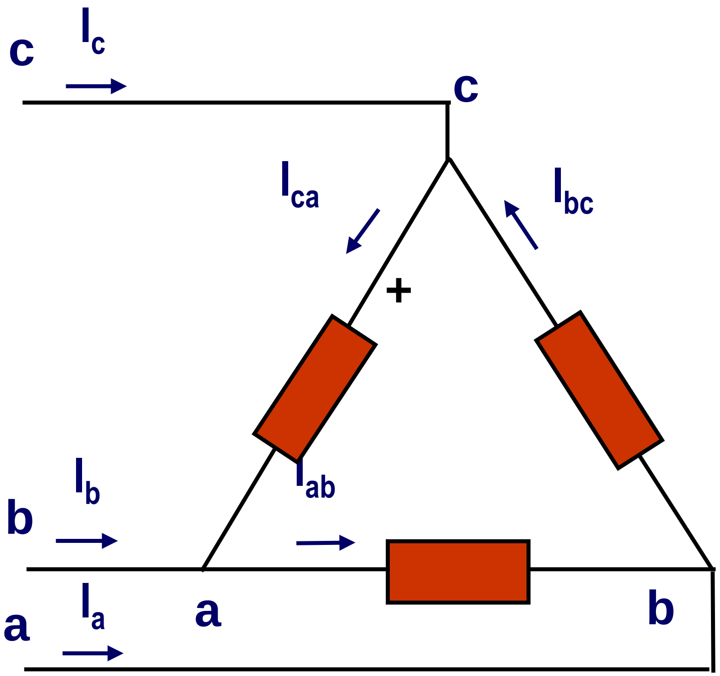


Transformer Windings

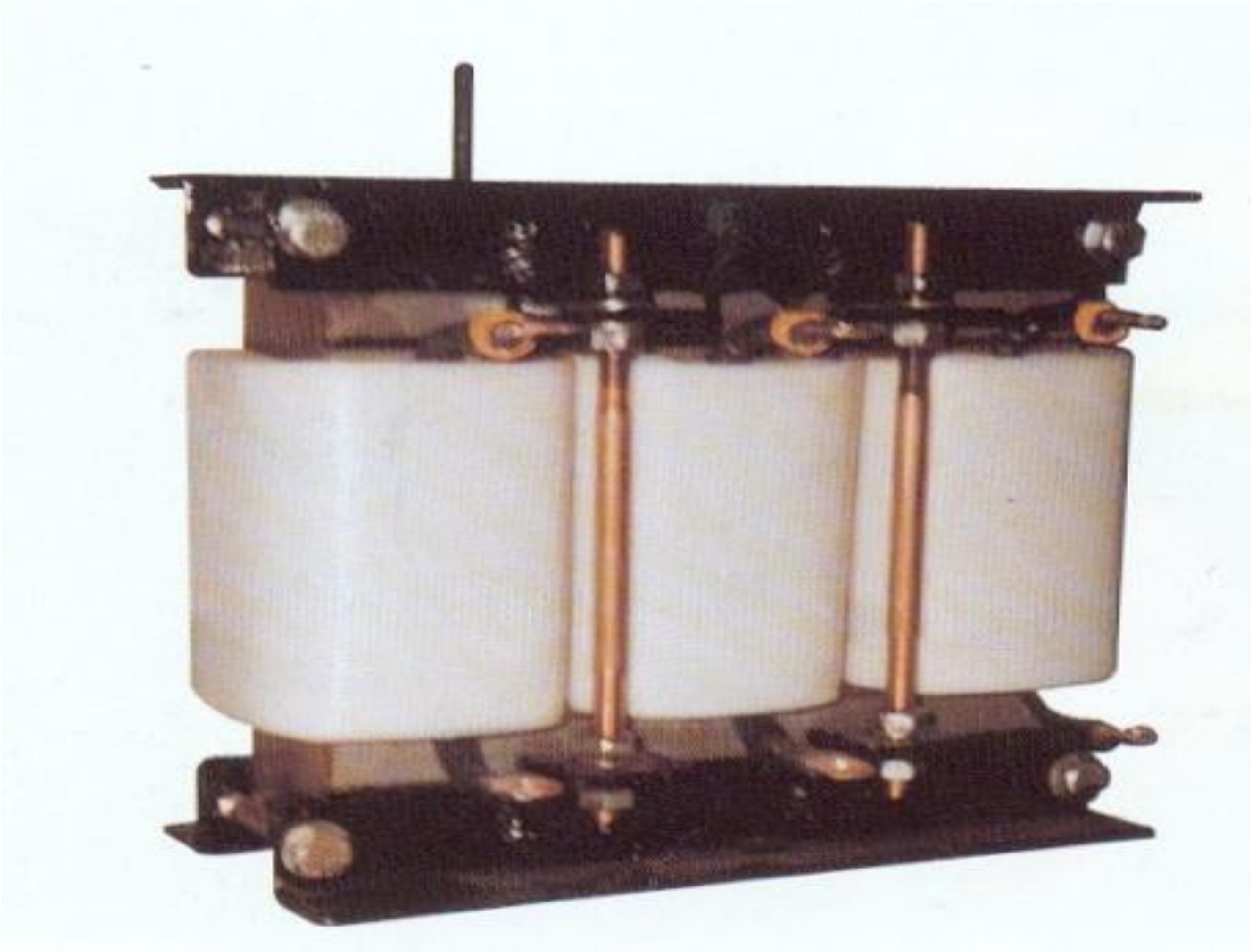


Line Voltage = Phase Voltage

$|\text{Line Current}| = \sqrt{3} \times |\text{Phase Current}|$



Transformer Windings



Measuring Devices – Clamp Ammeter

Sometimes the electrical service carried out by the circuit may be so vital, that it is not allowed to break it for a series connection of ammeter

Ammeter shown on the RHS is a particular design for such tasks for measuring the current flowing in the circuit as well as the resistance without breaking the circuit

Measuring Devices – Electronic Current Transformer

Sometimes the electrical service carried out by the circuit may be so vital, that it is not allowed to break it for a series connection of ammeter

Ammeter shown on the RHS is a particular design for such tasks for measuring the current flowing in the circuit as well as the resistance without breaking the circuit

Transformers

Manufacturing Process

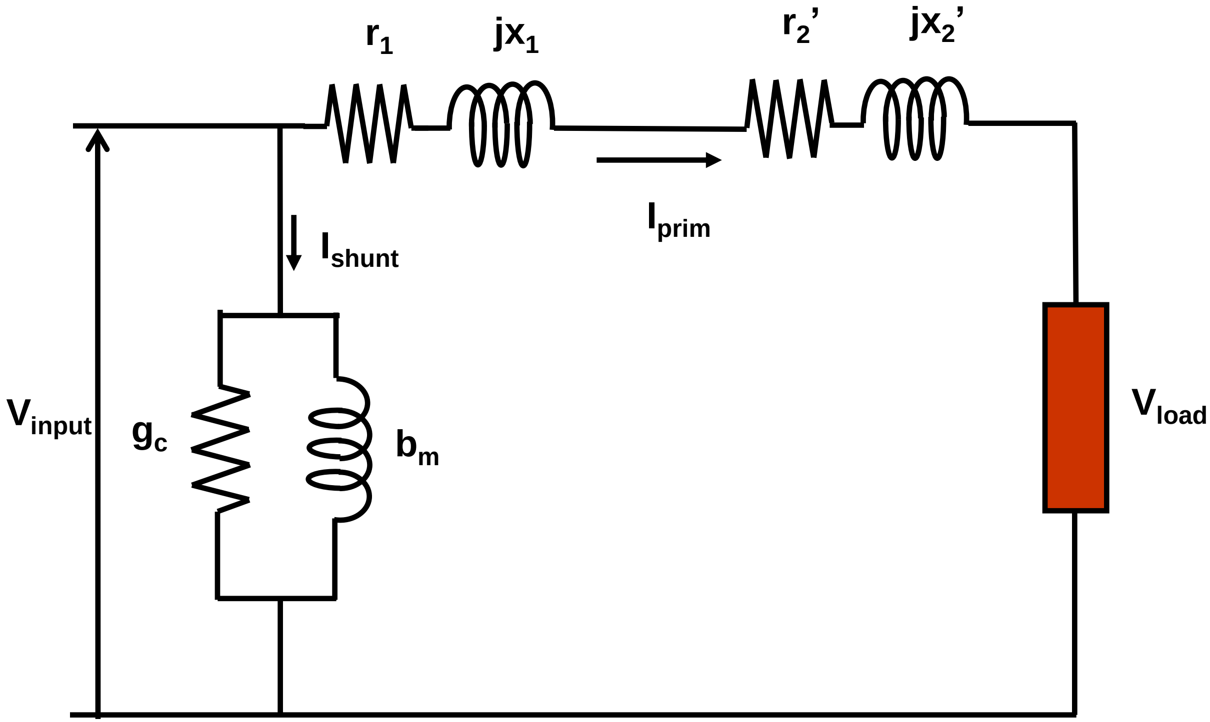
Manufacturing Process

Transformers

Manufacturing Process

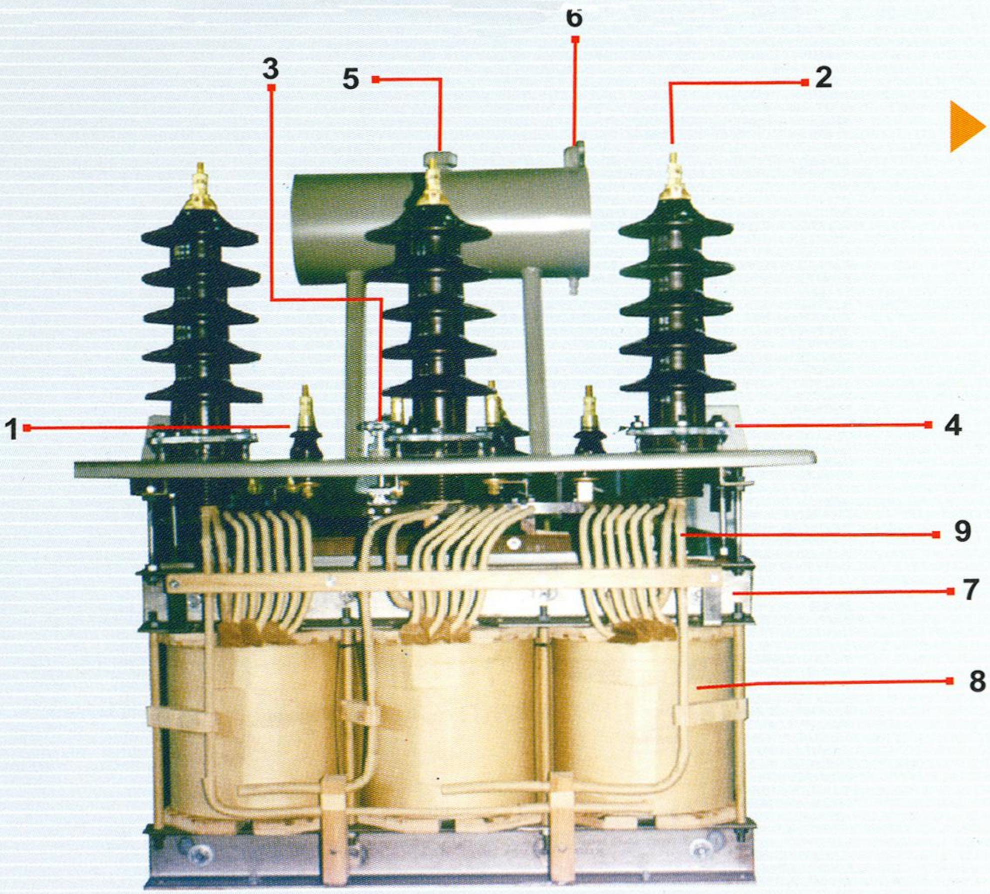
Transformers - Representation

Equivalent Circuit of a Transformer



380 kV Current Transformers

Transformers - Representation



AKTİF KISIM / ACTIVE PART

1) AG İzolatör / LV Insulator

2) YG İzolatör / HV Insulator

3) Komütatör / Tap Changer

4) Vinç Bağlantı kulağı / Lifting Lugs

5) Yağ Doldurma Kapağı / Oil Filling Plug

6) Silikajel Bağlantı Flanşı
The De Hydrating Breathers Connection

7) Boyunduruk / Yoke

8) Bobinler / Windings

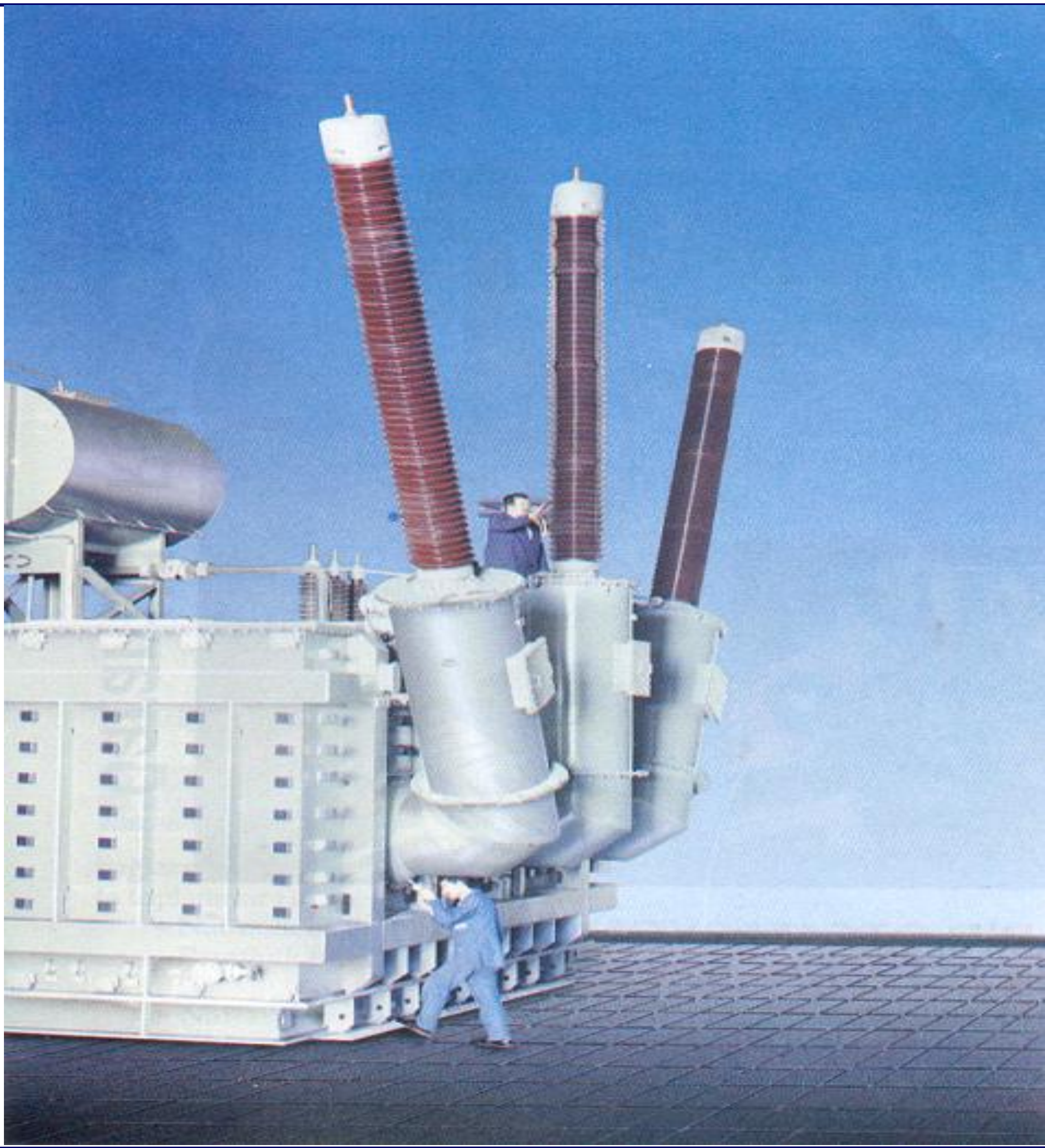
9) Komütatör Bağlantı Kabloları
Tap Changer Connection Cables

Transformers

Generator (Step-up) Transformers at Atatürk HPP

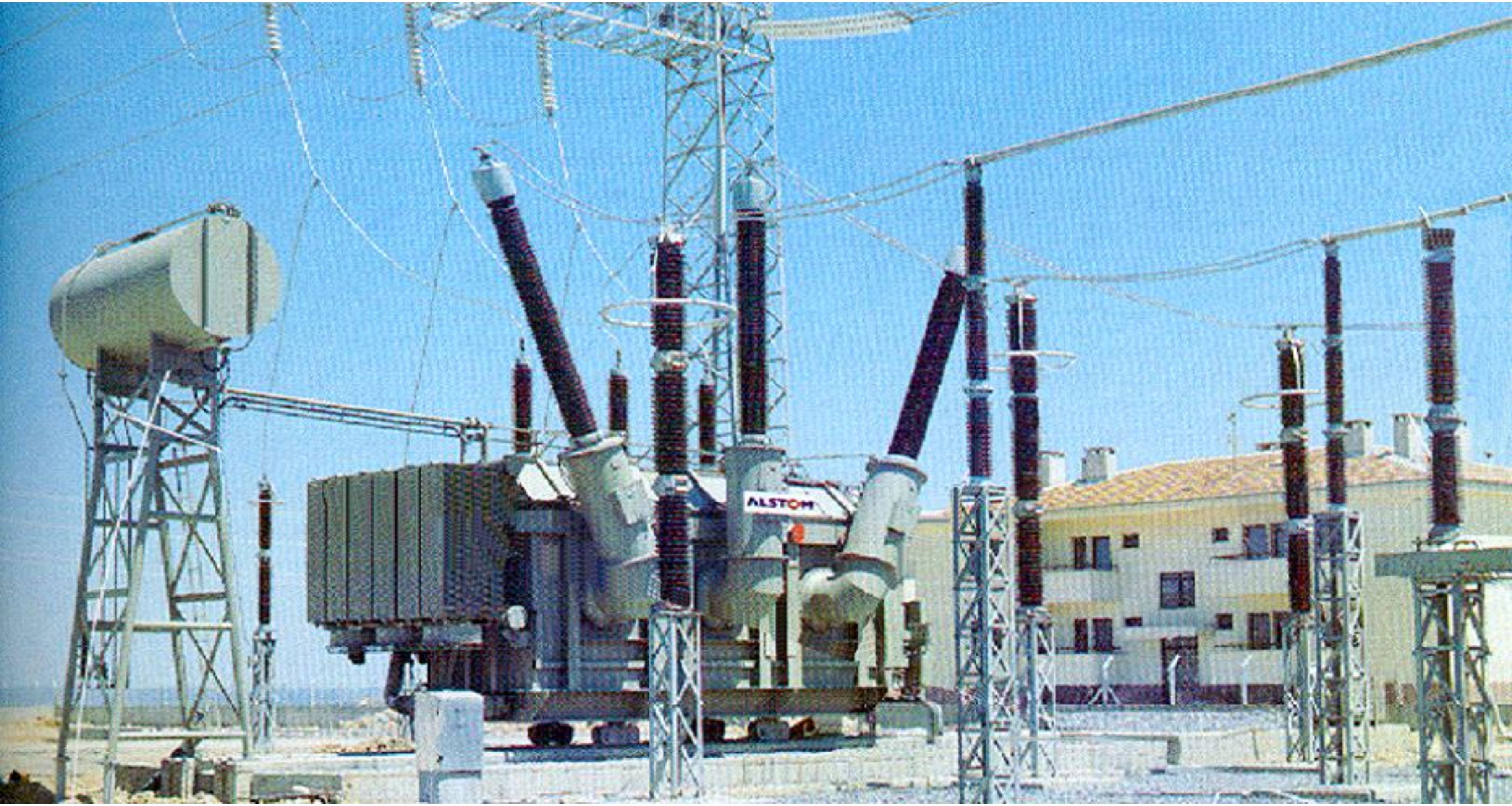
Transformers

Generator Transformers

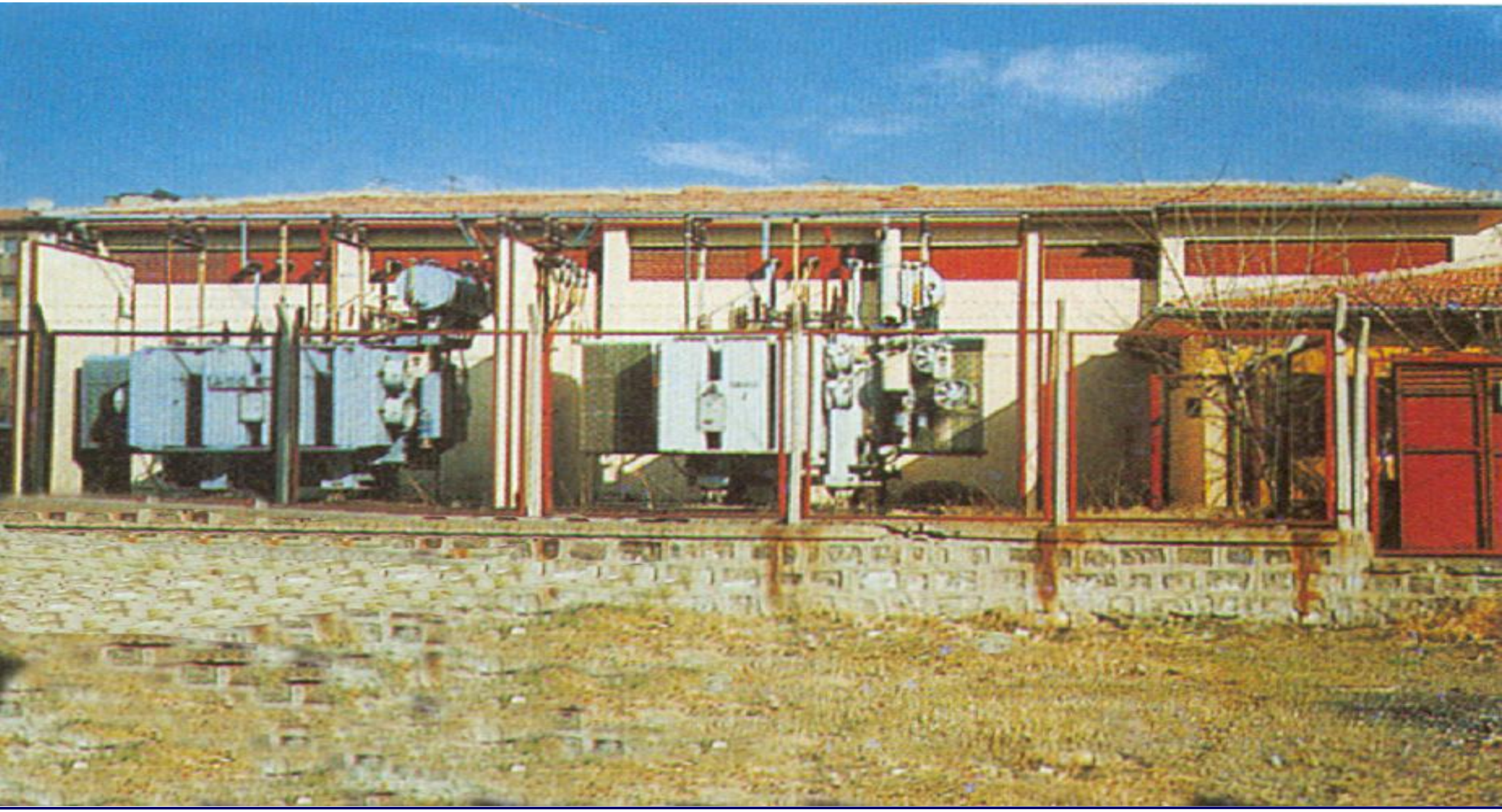


Distribution Transformer Factory

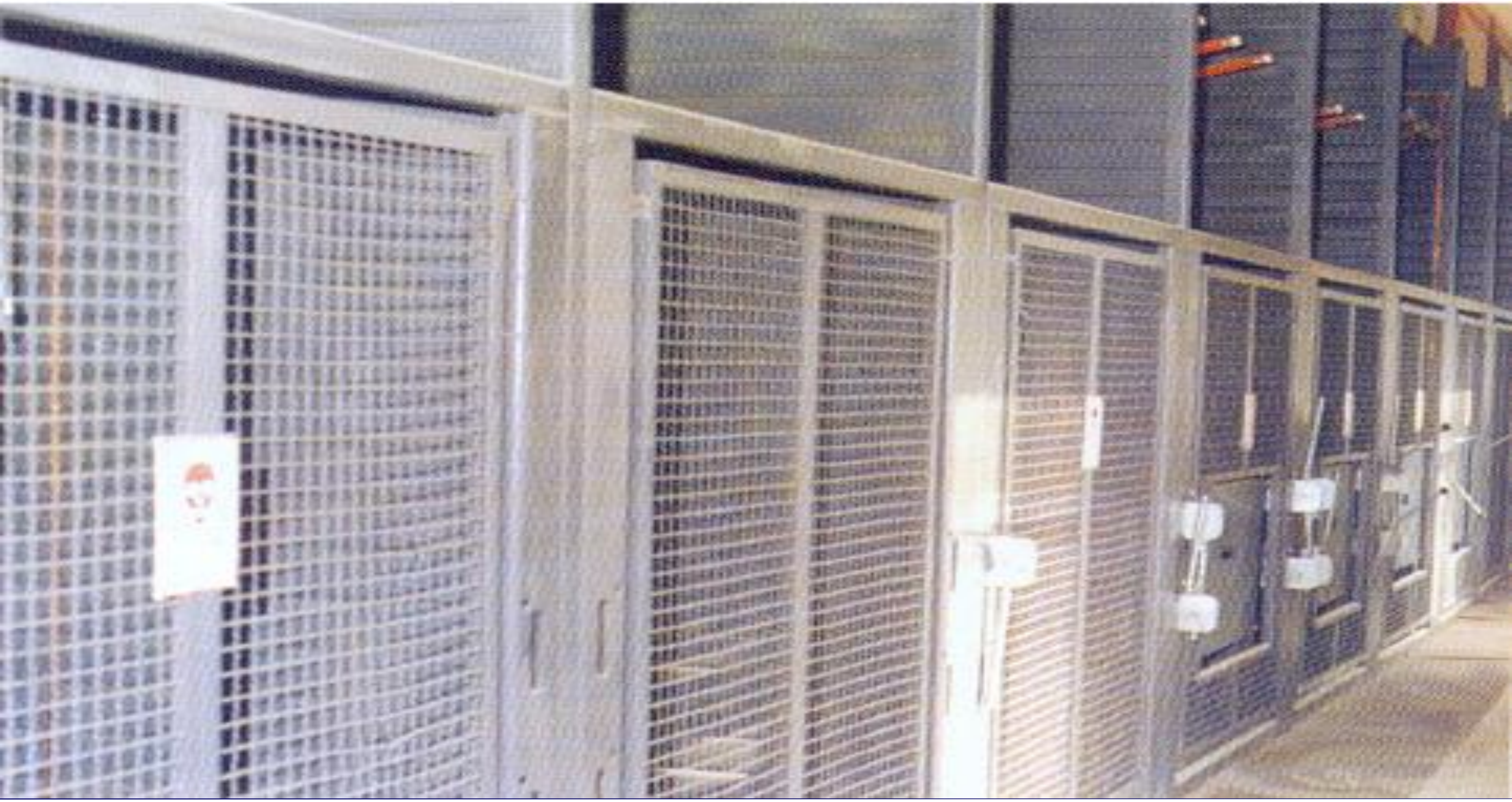
380/154 kV Power Transformers



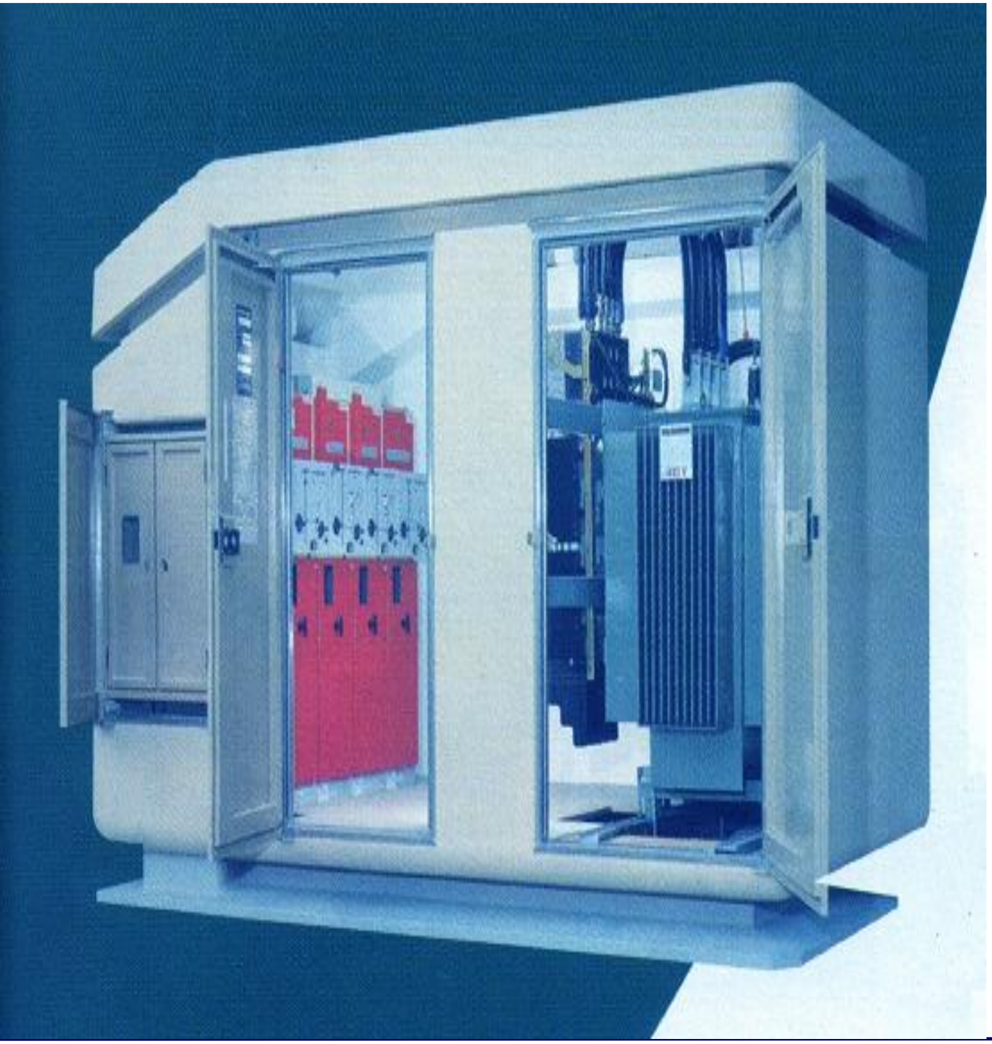
Step-down Transformers in a MV/LV Substation

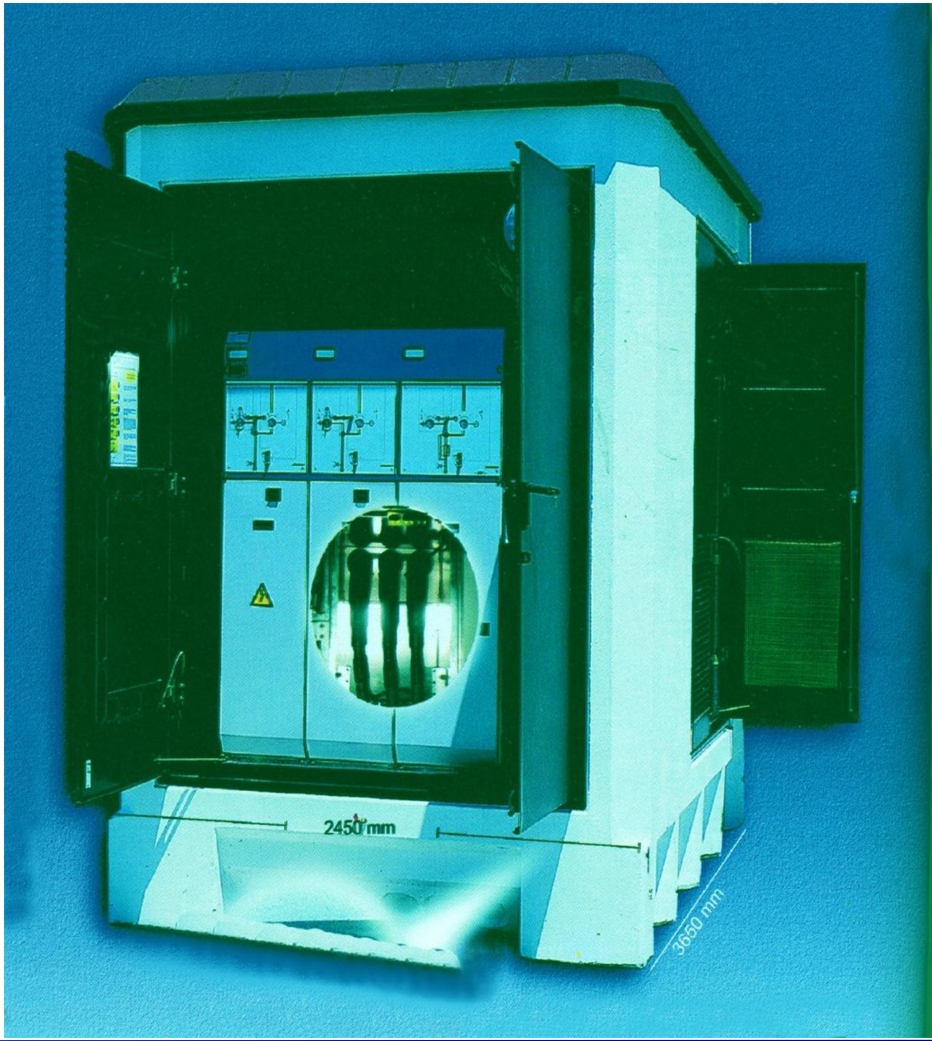


MV/LV Substation Inside



MV/LV RMU Kiosk





Transformers

MV/LV Metal Substation

Transformers

Transformers

Transformers

METU

METU

Transformers

METU

Transformers

Transformers

Transformers

METU

Transformers

Transformers

Transformers

Transformers

Transformers

Transformers

Transformers

MV/LV Transformer Stockyard (Bingöl)

Transformers

MV/LV Step-down Transformer - Installation

Transformers

Pole Type Step-down Transformers

European Design (6.3 kV)	USA Design (4 kV)
	

METU

Transformer R&M Activity

Transformers

Pole Mounted Transformer

Transformers

Transformer Factory (Malatya)

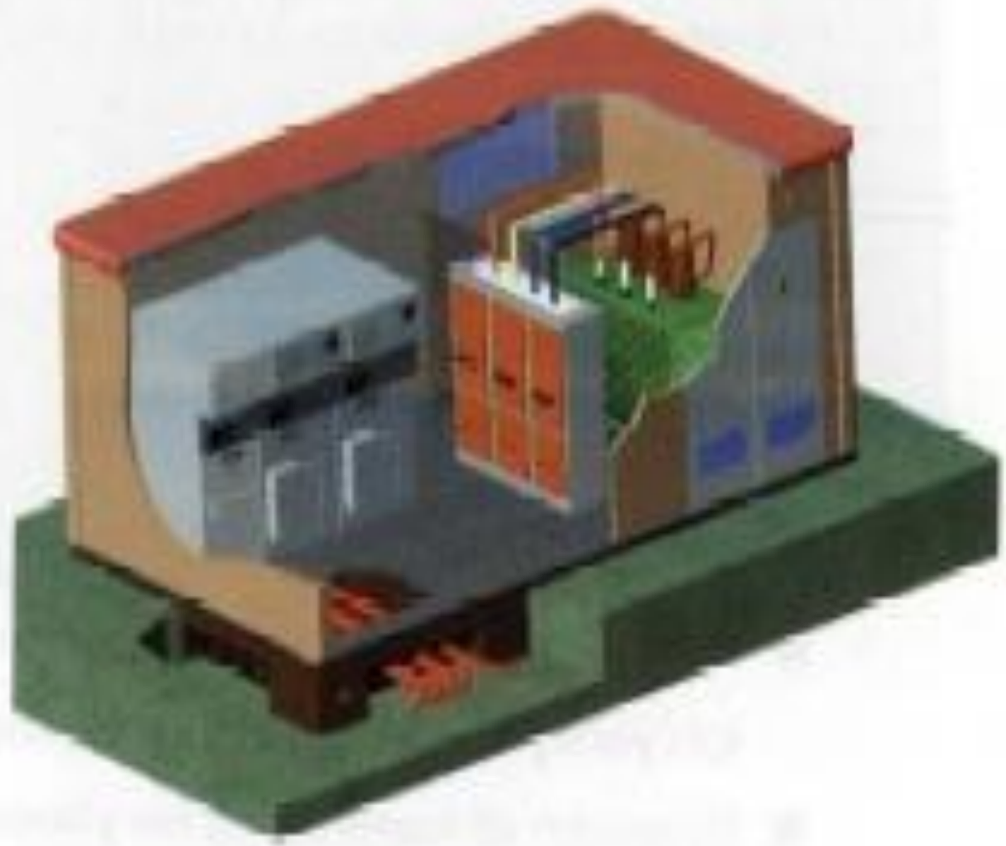
Transformer Factory (Kartal)

Transformer Factory (Ş. Urfa)

Transformers

Kiosk Sizes

KOD	Ölçüler		
	En	Boy	yükseklik
MOD 1		5430	
MOD 2 - 3		6950	
MOD 4		9475	
MOD 5		11975	
PBK 7260		7260	
PBK 7740		7740	
PBK 8260	3800	8260	3140
PBK 8760	4200	8760	3440
PBK 9260		9260	
PBK 10260		10260	
PBK 11280		11280	
PBK 12280		12280	
PBK 12780		12780	
PBK 14200		14200	



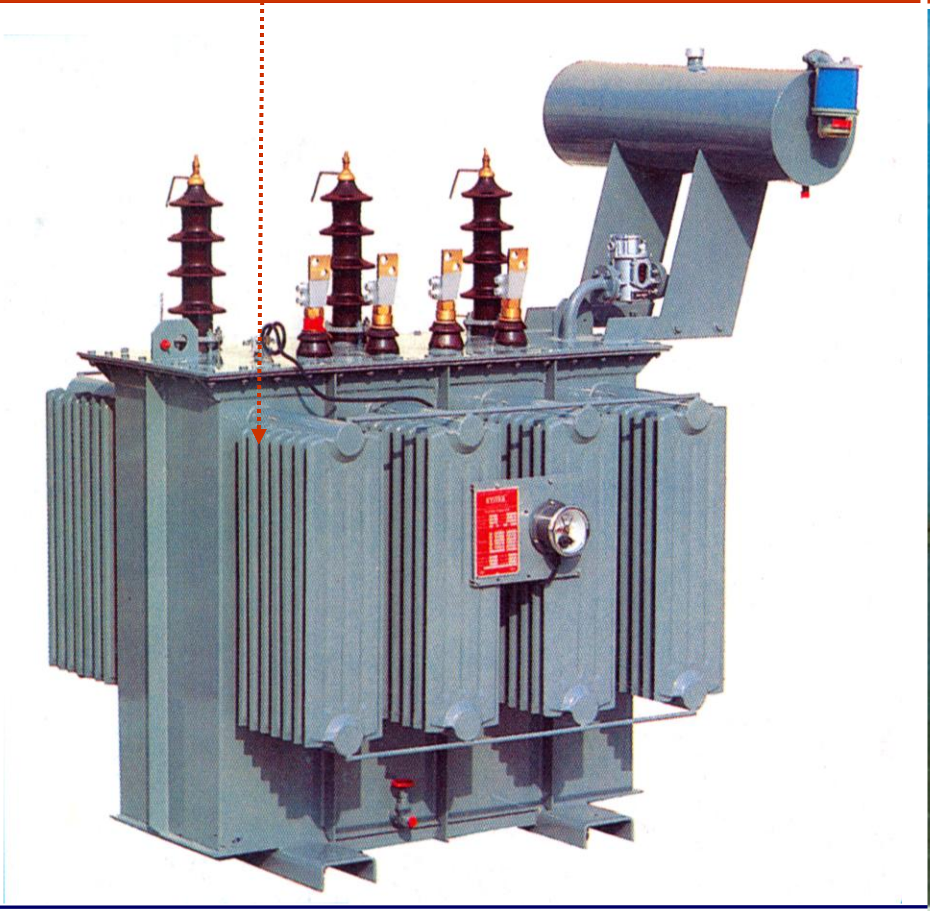
Transformers

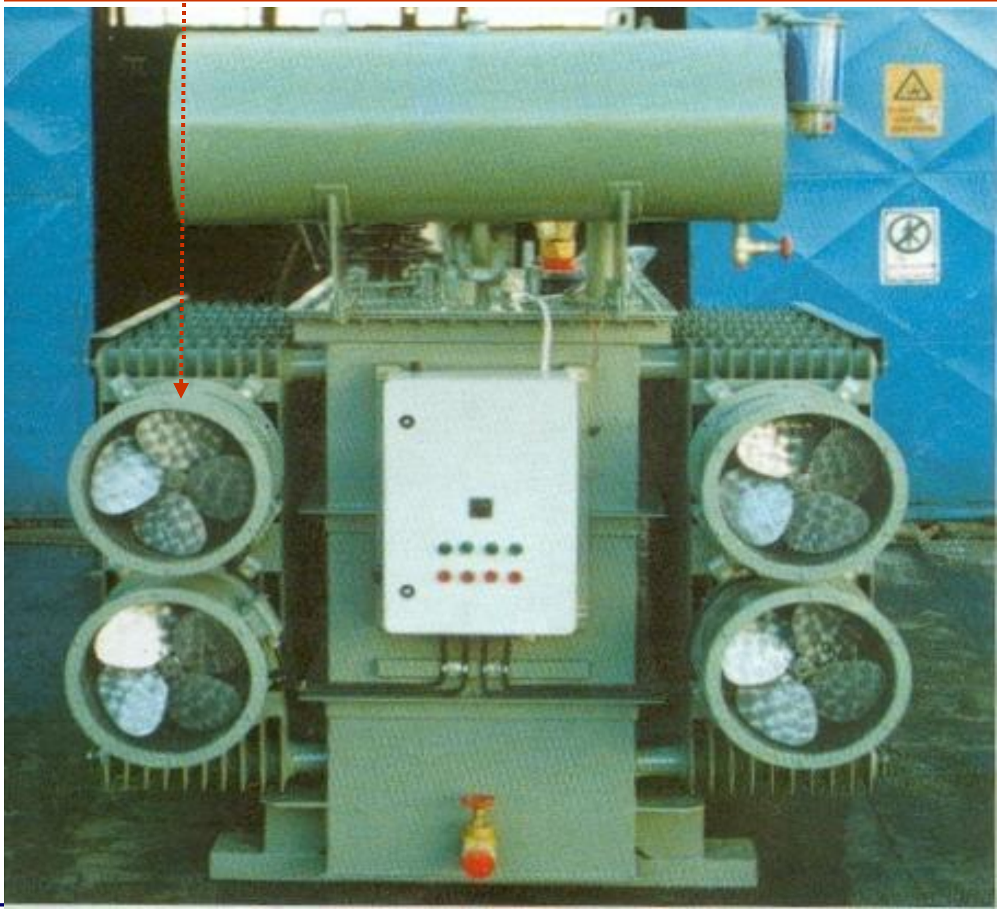
Voltage Levels in the Turkish Electrical System

Generation	Transmission	Distribution
13 kV	66 kV	0.4 kV
13.5 kV	154 kV	3.3 kV
15 kV	380 kV	6.3 kV
		15.8 kV
		31.5 kV
		33 kV
		34.5 kV

Cooling of MV Transformers

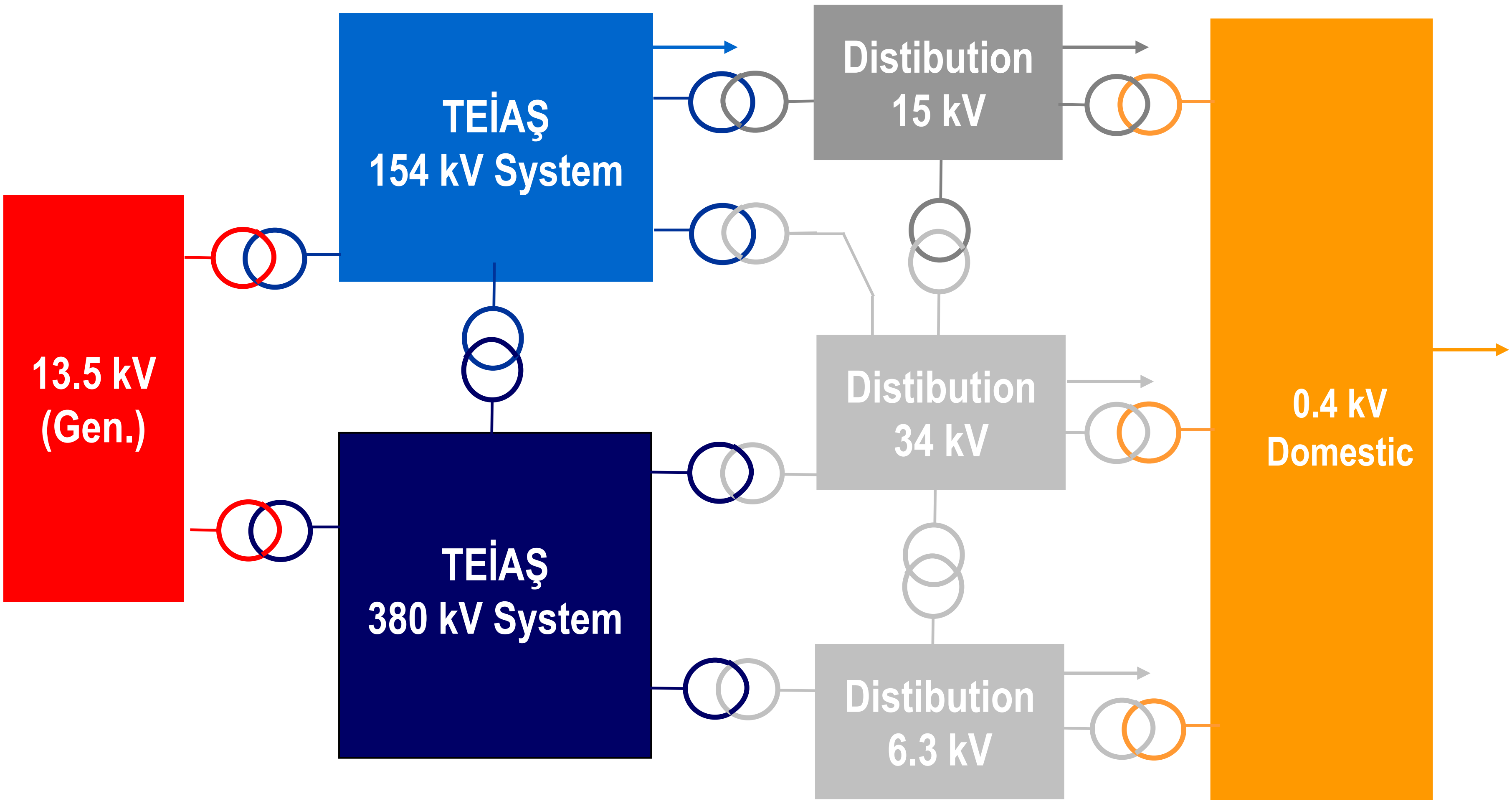
Oil Circulating Radiators	Fans





Transformers

System Voltage Regions



Transformers

Is there anyone who did not understand the principles transformers ?

Transformers

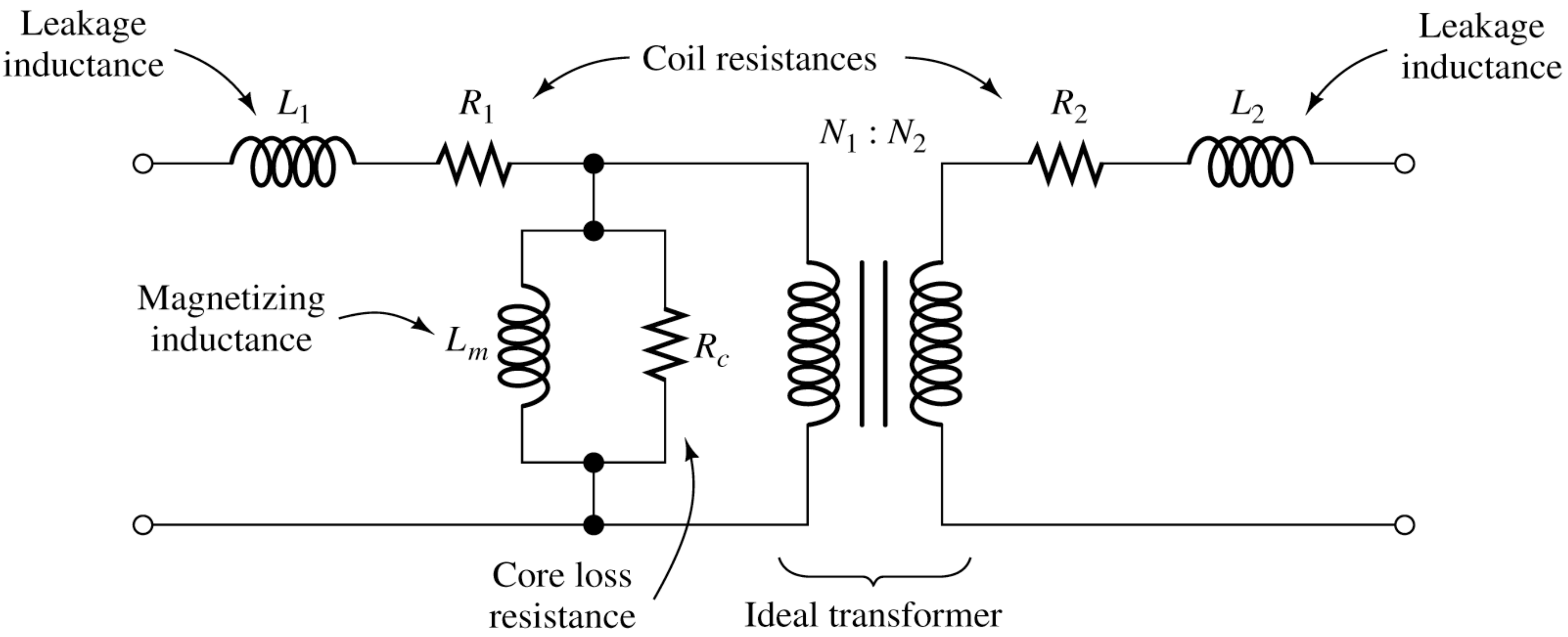
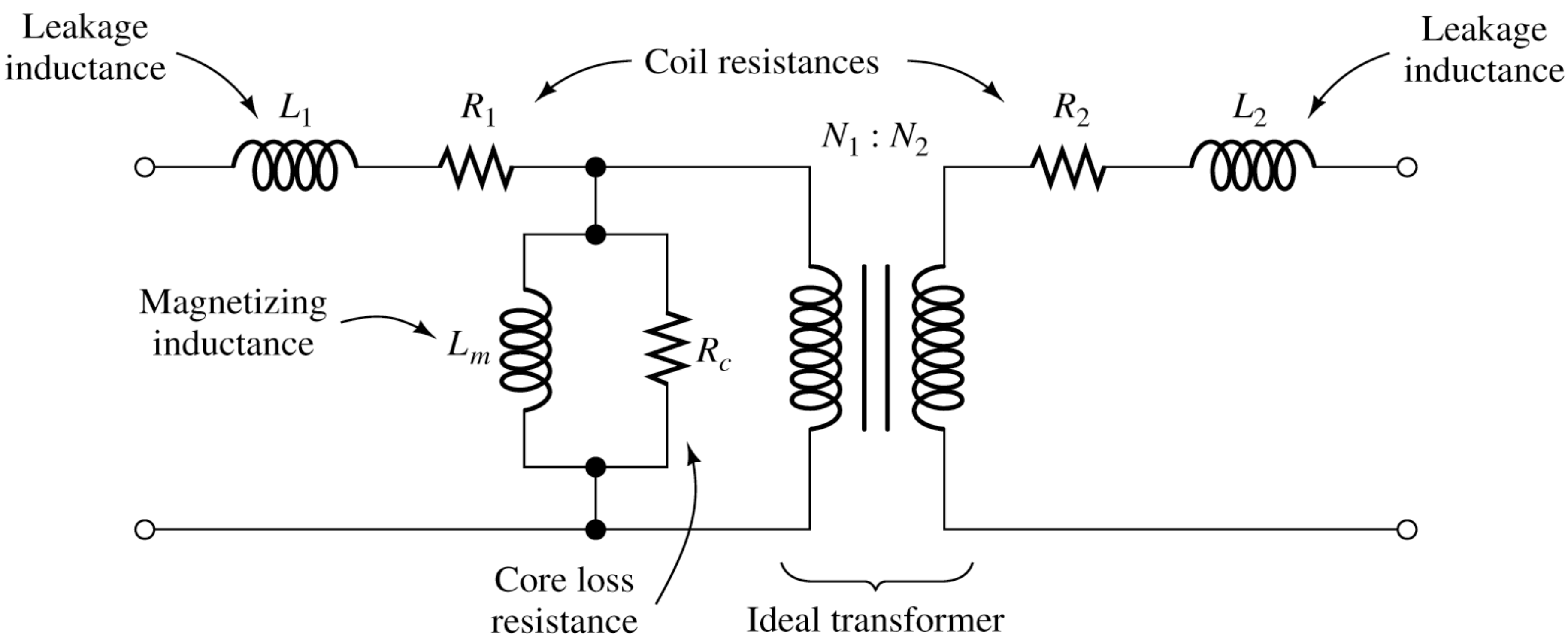


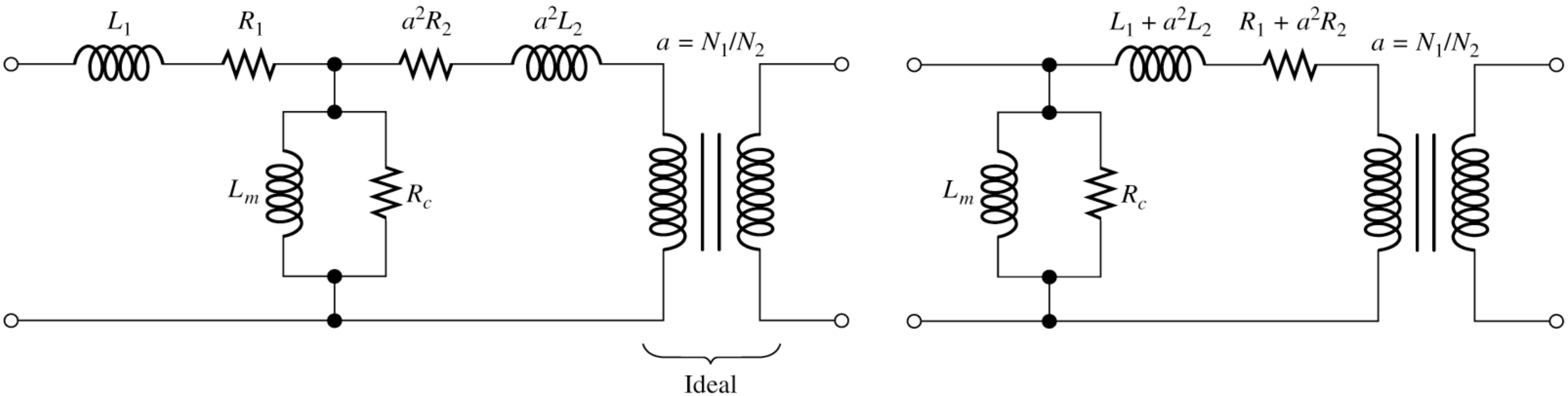
Figure 15.28 The equivalent circuit of a real transformer.

REAL TRANSFORMERS



METU

Transformers



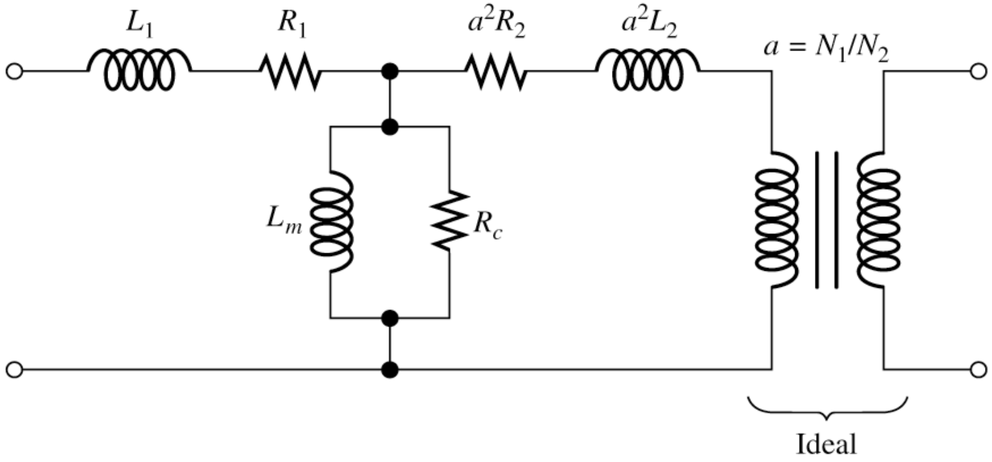
(a) All elements referred to the primary side

(b) Approximate equivalent circuit that is sometimes more convenient to use than that of part (a)

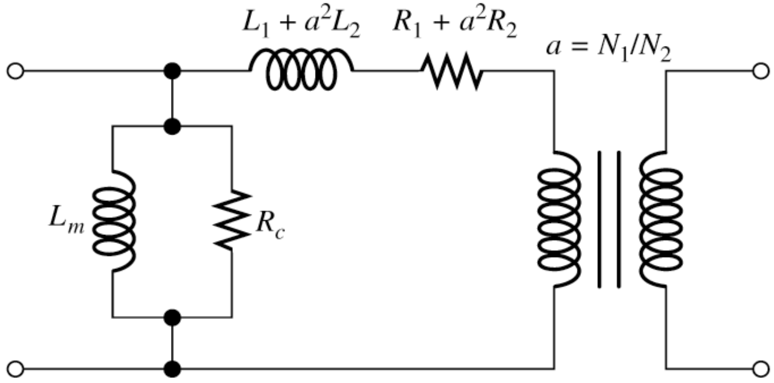
Figure 15.29 Variations of the transformer equivalent circuit. The circuit of (b) is not exactly equivalent to that of (a) but is sufficiently accurate for practical applications.

Transformers

Variations of the Transformer Model



(a) All elements referred to the primary side



(b) Approximate equivalent circuit that is sometimes more convenient to use than that of part (a)

Transformers

Table 15.1. **Circuit Values of a 60-Hz 20-kVA 2400/240-V Transformer Compared to Those of an Ideal Transformer**

Element Name	*Symbol*	*Ideal*	*Real*
Primary resistance	R_1	0	3.0 Ω
Secondary resistance	R_2	0	0.03 Ω
Primary leakage reactance	$X_1 = \omega L_1$	0	6.5 Ω
Secondary leakage reactance	$X_2 = \omega L_2$	0	0.07 Ω
Magnetizing reactance	$X_m = \omega L_m$	∞	15 kΩ
Core-loss resistance	R_c	∞	100 kΩ

Regulation and Efficiency

$$\text{percent regulation} = \frac{V_{\text{no-load}} - V_{\text{load}}}{V_{\text{load}}} \times 100\%$$

$$\text{power efficiency} = \frac{P_{\text{load}}}{P_{\text{in}}} \times 100\% = \left(1 - \frac{P_{\text{loss}}}{P_{\text{in}}}\right) \times 100\%$$

Transformers

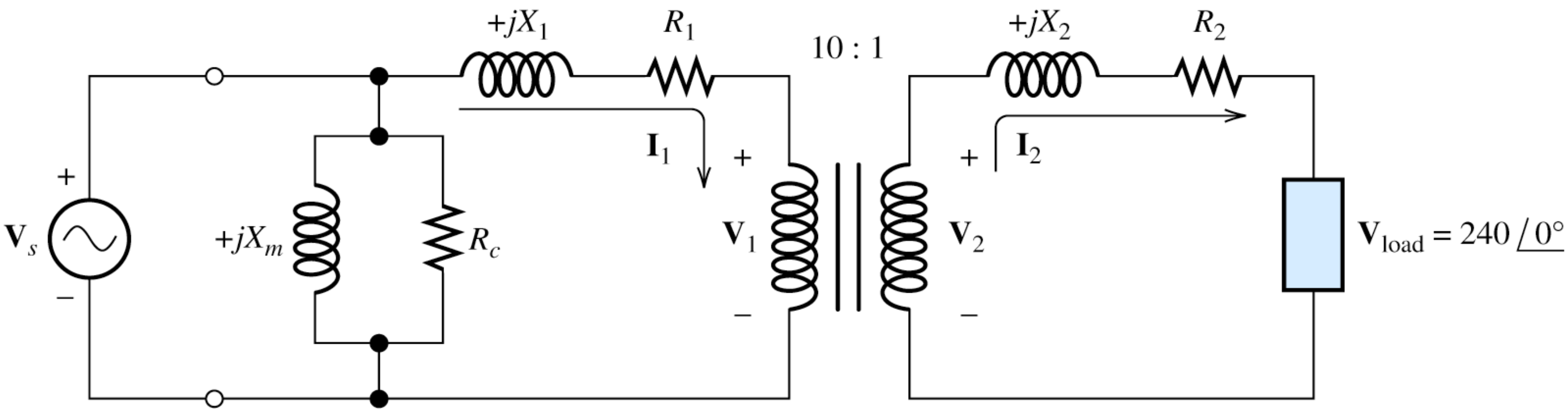


Figure 15.30 Circuit of Example 15.13.