Universiti Malaysia PAHANG
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DEE 3143 BASIC ELECTRICAL MACHINE & POWER SYSTEMS

CHAPTER 1
TRANSFORMER

by
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Chapter Outline

1.1 Review of electromagnetism
1.2 Single-phase transformer
- 1.2.1 Transformer
- 1.2.2 Construction & transformer equations
- 1.2.3 Equivalent circuit
- 1.2.4 Losses, voltage regulation & efficiency
- 1.2.5 Open circuit test & short circuit test

1.3 Three-phase transformer
- 1.3.1 Construction
- 1.3.2 Three-phase connection

1.4 Auto-transformer & instrument transformer

Learning Outcomes

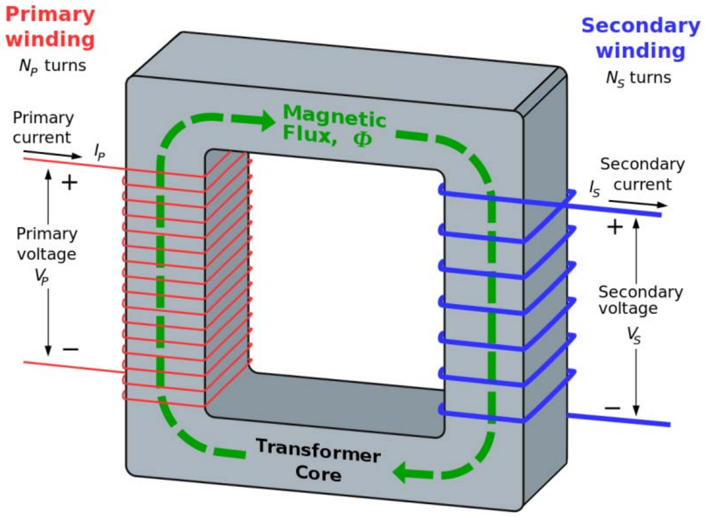
After complete this chapter, students should be able to:

1) Understand magnetic fields with its interactions with moving charges/part.
2) Understand single phase transformer which cover the transformer construction, transformer equations, and equivalent circuit.
3) Describe the circuit test such as open and short circuit test.
4) Apply the construction and understand the three-phase connection of the three phase transformer circuit.
5) Understand the concept of auto transformer.

1.1 REVIEW OF ELECTROMAGNETISM

Electromagnetism

- Magnetic field is a mechanism that convert energy to another form.
- Electromagnetism is a current-carrying conductor that energize magnetic field within the vicinity of conductor



Source: Wikipedia

Magnetic Field

- Electric current that produce magnetic field is express through **Ampere's law**:

$$\oint H dl = I_{net}$$

Magnetomotive force:

$$F = Ni$$

Unit :Ampere-turns (At)

Magnetic field intensity:

$$H = Ni/l_c$$

Unit: Ampere-turns per meter (At/m)

Magnetic Flux

- Magnetic field strength depend on type of material:

Magnetic flux density:

$$B = \mu H$$

μ = magnetic permeability of material

$$\mu = \mu_0 \mu_r$$

$$\mu_0 = 4\pi \times 10^{-7}\,\mathrm{H/m}$$

μ_0 = permeability of free space
μ_r = relative permeability of material

Unit for magnetic flux intensity, B: Tesla (T)

Total flux

- The total flux:

Total flux:

$$\phi = BA \quad where \quad B = \mu H = \frac{\mu N i}{l_c}$$

$$\phi = \mu HA = \frac{Ni}{l_c / \mu A} \quad or \quad \phi = \frac{F}{R} = FP$$

Unit : Webers (Wb)

Reluctance:

$$R = \frac{F}{\phi}$$

Unit :Ampere-turns per Webers (At/Wb)

FARADAY'S LAW & LENZ'S LAW

- Faraday's Law: If a flux passes through a turn of a coil of wire, a voltage will be induced in the turn of wire that directly proportional to the rate of change in the flux with respect to time.

$$e_{ind} = -N \frac{d\phi}{dt}$$

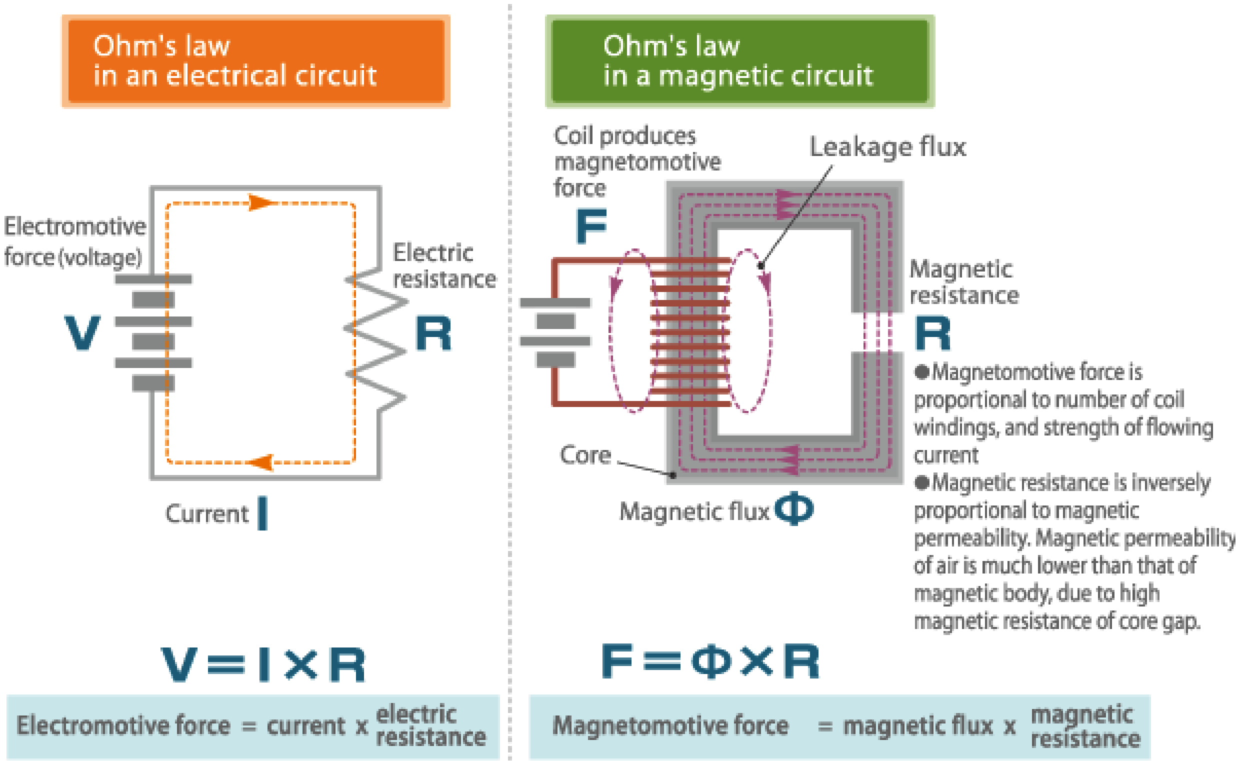
e_{ind} = induced voltage
N = no of turns in coil
$d\Phi$ = change of flux in coil
dt = time interval

- Lenz's Law: Determine the polarity of the induced voltage.

Magnetic Circuit

Magnetic circuit representation = Electric circuit representation

Ohm's law in electrical and magnetic circuits



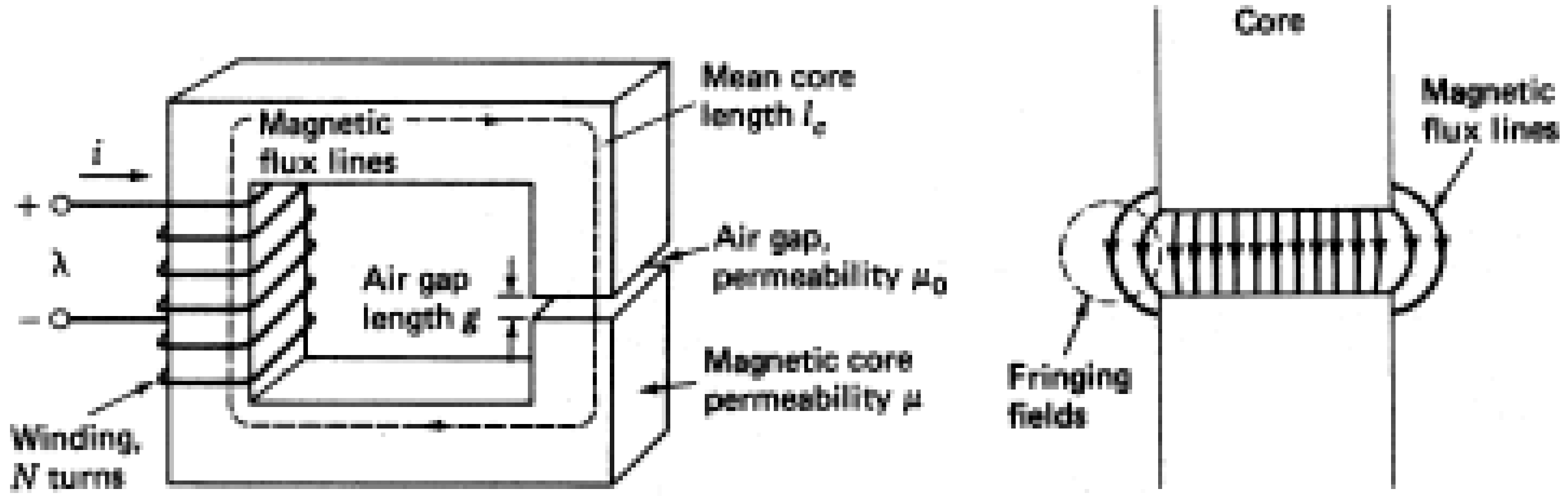
Source: http://www.global.tdk.com/techmag/inductive/vol5/index.htm

Analogy Of Magnetic Circuit vs Electric Circuit

ELECTRICAL	MAGNETIC	MAGNETICS UNITS
Voltage, V	Magnetomotive force, F	At
Current, I	Magnetic flux,	Webers, Wb
Resistance, R	Reluctance, R	At/Wb
Conductivity, 1/p	Permeability, µ	Wb/Atm
Current density, J	Magnetic flux density, B	Tesla, T
Electric field, E	Magnetic field intensity, H	At/m

Fringing Effect

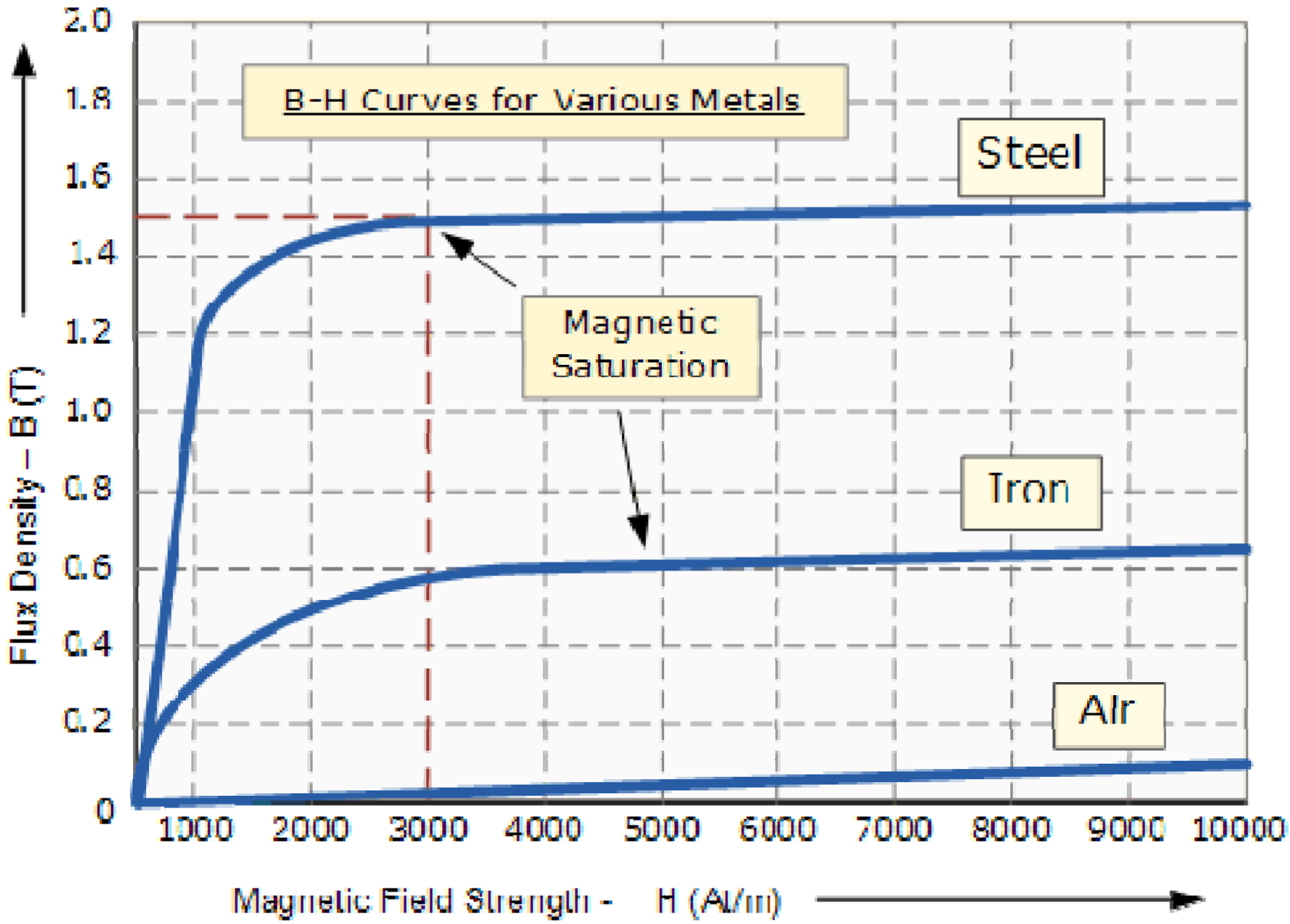
Source: https://www.slideshare.net/NikDinEduJke/chapter1-part1
http://slideplayer.com/slide/5732227/



A simple magnetic circuit with an air gap

- Fringing field – spreading of magnetic field flux outside core area within the air gap
- Approximately calculation of fringing by aggregating the depth and width of gap area

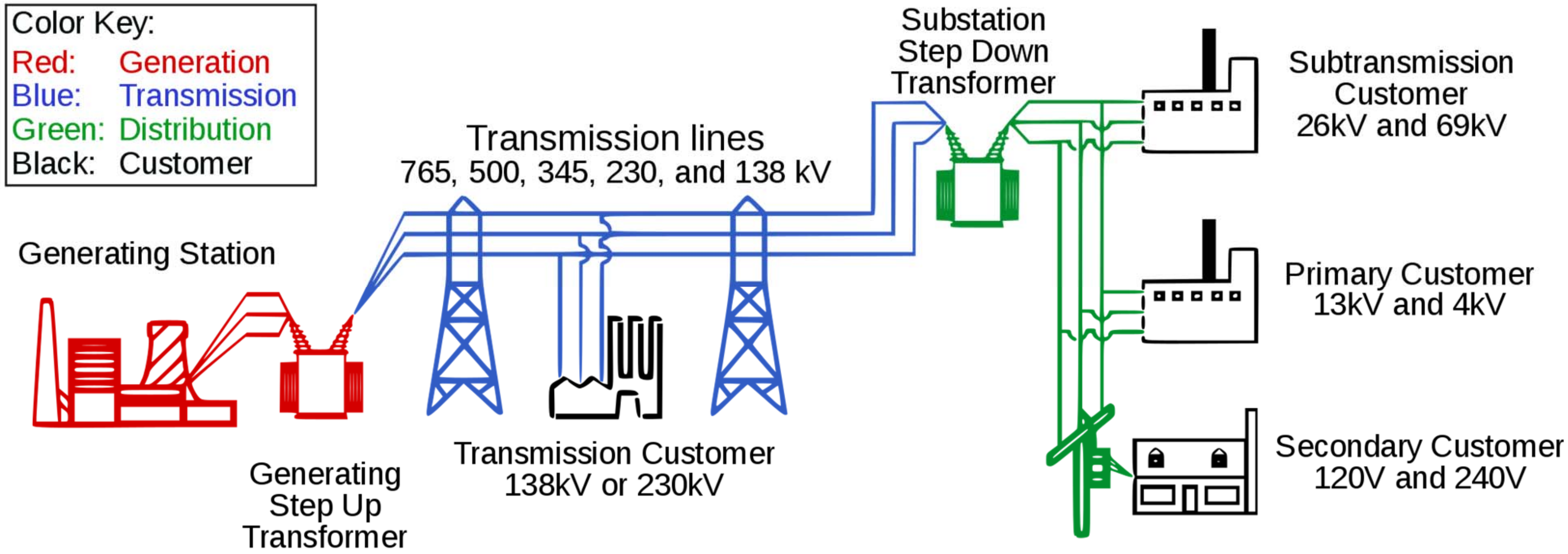
Magnetizaton Characteristics (B-H Loop)



Source: http://www.electronics-tutorials.ws/electromagnetism/magnetic-hysteresis.html

1.2 SINGLE-PHASE TRANSFORMER

Power Distribution System



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Transformer

A transformer is an equipment that convert certain an ac voltage to another ac voltage level

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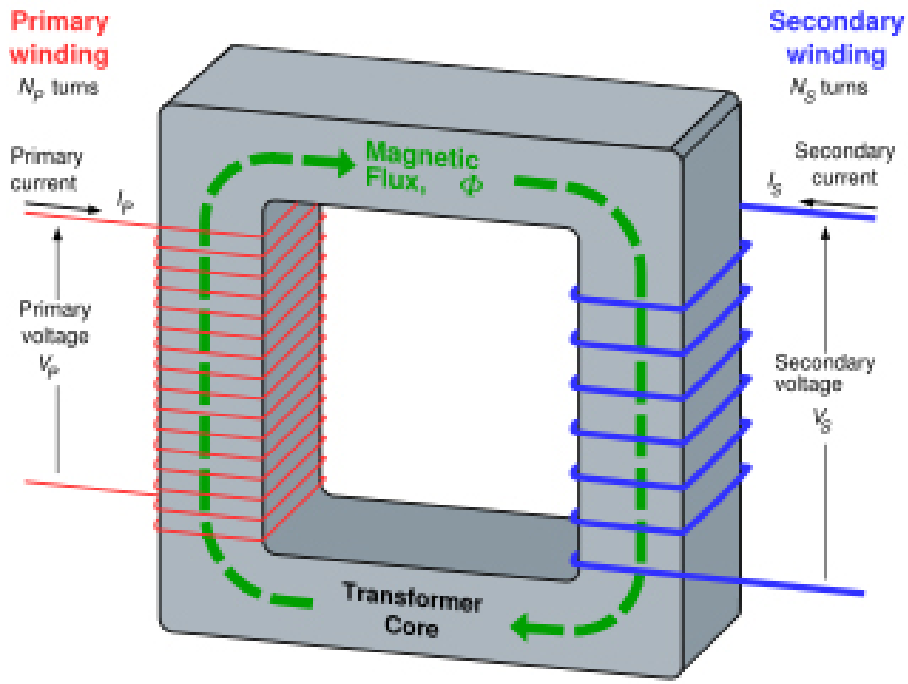
Transformer Construction: Basic

Basic construction of transformer:

i. A primary winding/coil

ii. A secondary winding/coil

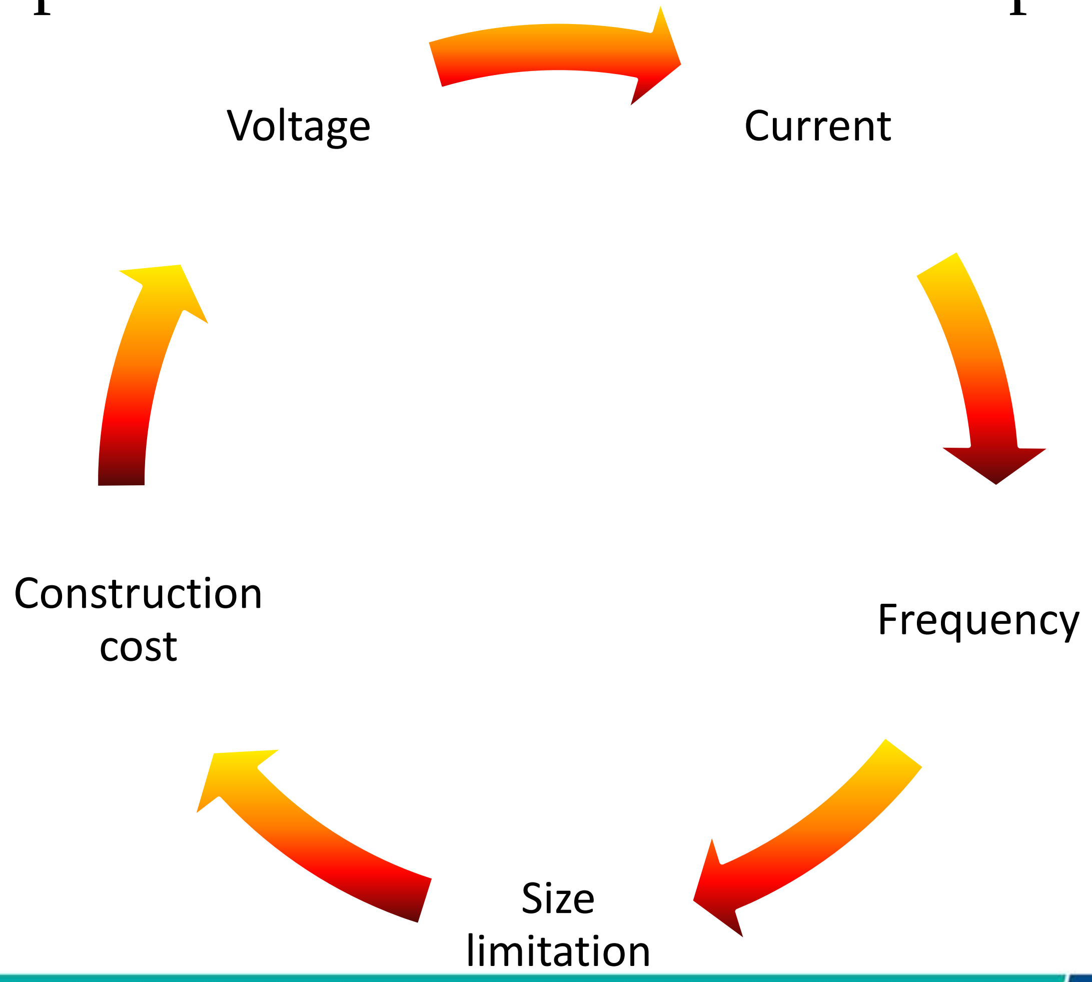
iii. A transformer core



Source: Wikipedia

Transformer Construction: Core

- The composition of a transformer core depends on:



Transformer Construction: Core

- Transformer core material commonly are air, soft iron, and steel material.
- The iron-core type gives better power transfer than the air-core type.

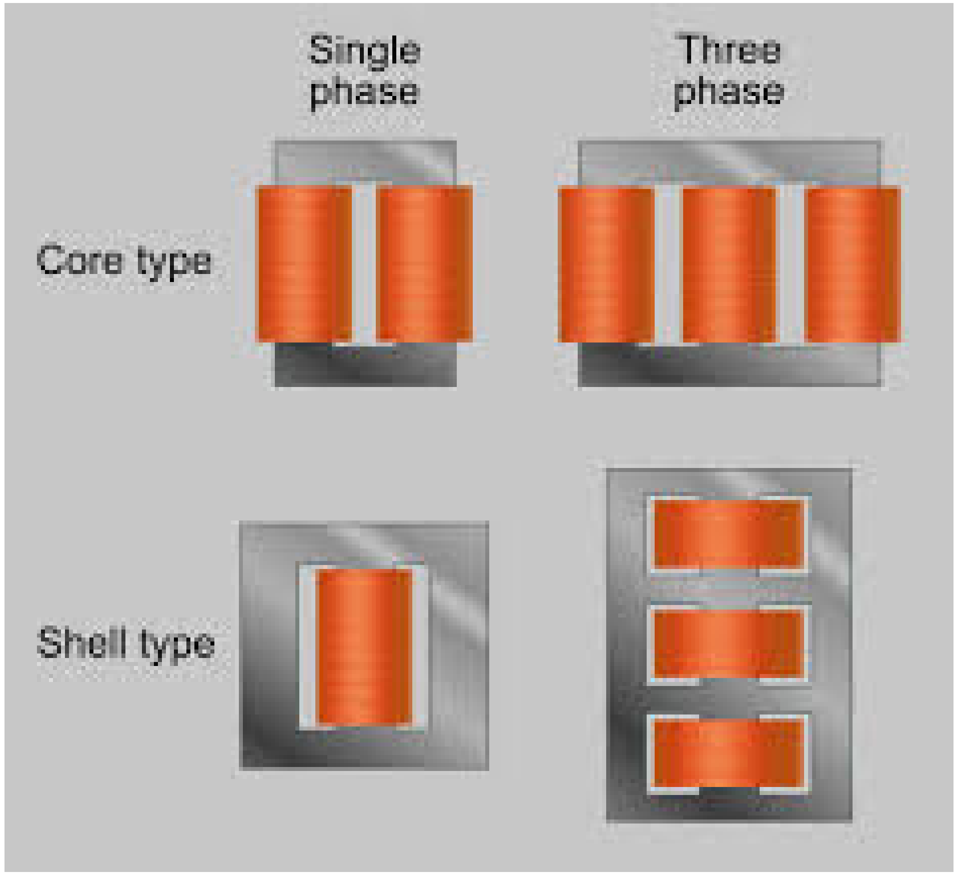
MATERIAL	FREQUENCY	SIZE
Air-core	> 20 kHz	
Iron-core	< 20 kHz	
Soft iron-core		Small

TRANSFORMER CONSTRUCTION: TYPES

Source: https://en.wikipedia.org/wiki/Transformer

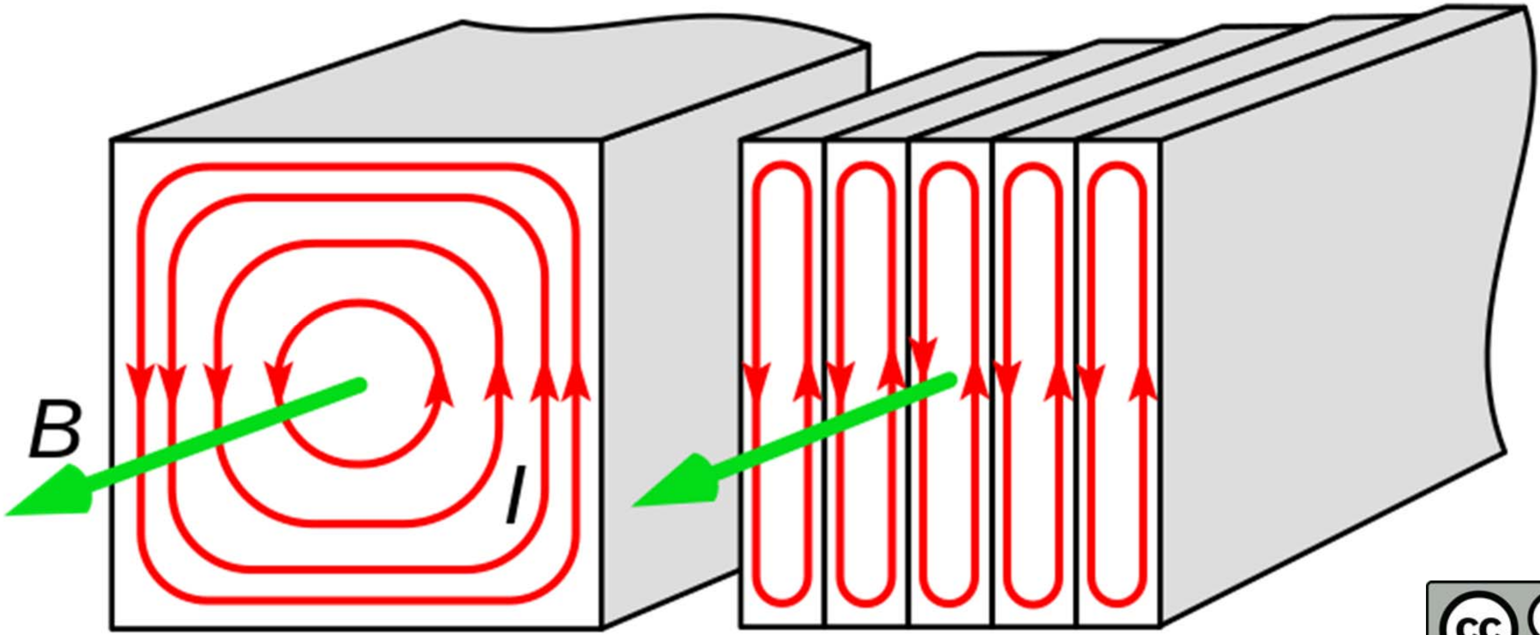
- Core type - Windings are wrapped around two sides (for single phase) and three sides (for three phases) of a laminated core .

- Shell type - Windings are wrapped within the center of laminated core.



➢ The most efficient transformer is Shell form transformer.

Transformer Construction: Lamination

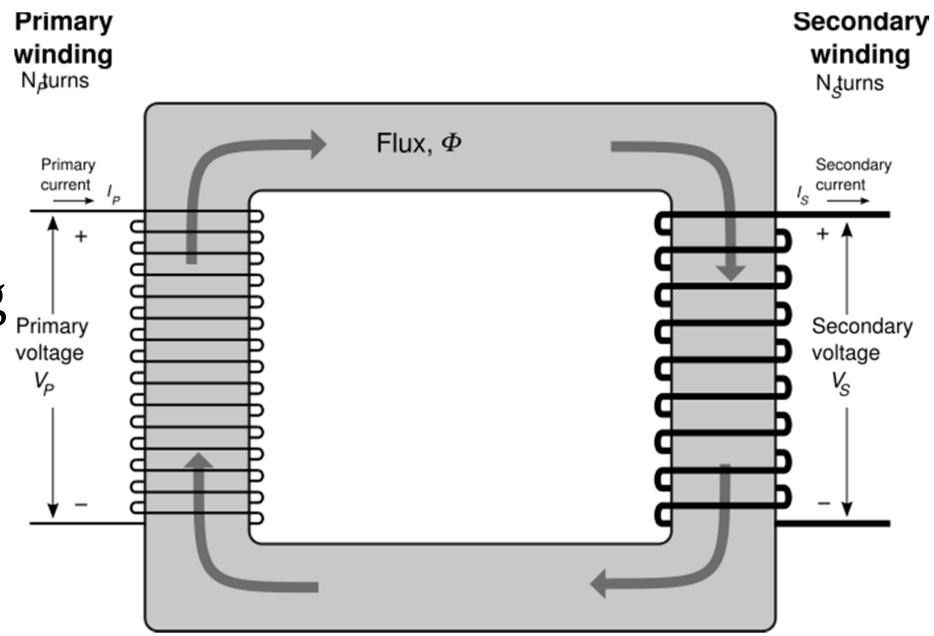


- The purpose of lamination within every core is to reduce eddy-current losses.

Ideal Transformer

Below are the assumption made for an ideal transformer:

- The transformer windings made from perfect conductors with zero winding resistance.
- The core permeability is infinite (the reluctance of the core is zero).
- All magnetic flux is within the transformer core with no leakage flux.
- Zero core losses.



Source: https://commons.wikimedia.org/wiki/File:Single-phase_transformer.svg

Transformer Equations

- The sinusoidal primary current produces a sinusoidal flux:

$$\Phi = \Phi_m \sin \omega t$$

- Therefore,

$$V_{ind} = emf_{ind} = -N_1 \frac{d\Phi}{dt}\left(\Phi_m \sin \omega t\right)$$
$$= -N_1 \Phi_m \cos \omega t$$

- Thus,

$$V_{ind} = emf_{ind\,(\max)} = N_1 \omega \Phi_m = 2\pi f N_1 \Phi_m$$

$$Emf_{ind\,(rms)} = \frac{N_1 \omega \Phi_m}{\sqrt{2}} = \frac{2\pi f N_1 \Phi_m}{\sqrt{2}} = 4.44\, f N_1 \Phi_m$$

Transformer Equations

- For an ideal transformer

$$E_1 == 4.44\, fN_1\Phi_m$$
$$E_2 == 4.44\, fN_2\Phi_m \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(i)}$$

- In the equilibrium condition (ideal condition of a transformer):

$$Input\ power = output\ power$$
$$V_1 I_1 \cos\theta = V_2 I_2 \cos\theta$$
$$\therefore \frac{V_1}{V_2} = \frac{I_2}{I_1}$$

- From the ideal transformer circuit,

$$E_1 = V_1\ and\ E_2 = V_2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(ii)}$$

Transformer Equations

- Substitute (ii) into (i), therefore,

$$\frac{E_1}{E_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1} = a$$

- 'a' = Voltage Transformation Ratio.
- Voltage Transformation Ratio (a) will determine the transformer type (step-up or step down).

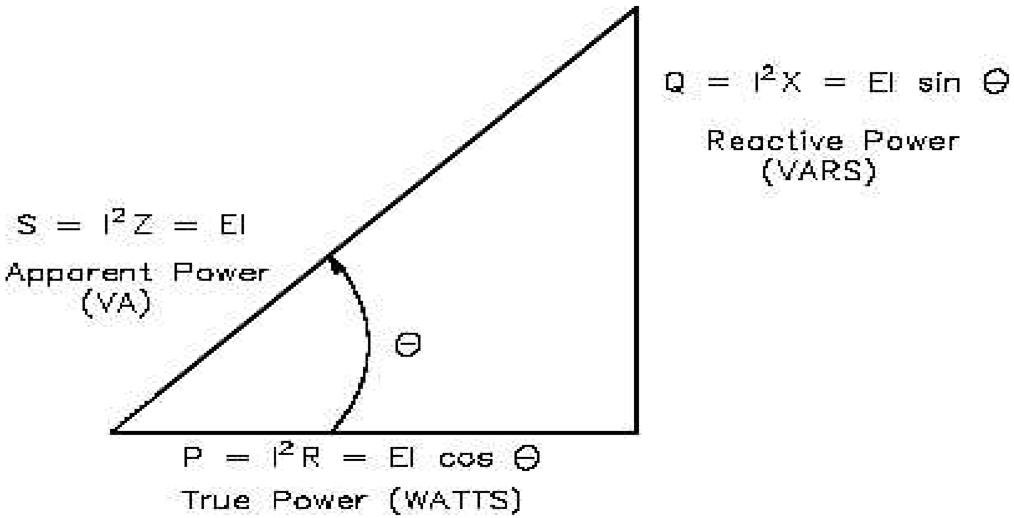
Voltage transformation ratio	Number of wire winding	Types of transformer
$a > 1$	$N_1 > N_2$	Step-down
$a < 1$	$N_1 < N_2$	Step-up

Power in Ideal Transformer

Output Power $$P_{out} = P_{in} = V_p I_p \cos\theta$$

Reactive Power $$Q_{out} = Q_{in} = V_p I_p \sin\theta$$

Apparent Power $$S_{out} = S_{in} = V_p I_p$$



Alternative Forms of Power Equations

- The value of voltage across impedance: $V = IZ$
- Output - Real and Reactive power expressed in term of current and impedance:

$$P_{out} = P_{in} = I^2 Z \cos\theta$$
$$Q_{out} = Q_{in} = I^2 Z \sin\theta$$
$$S_{out} = S_{in} = I^2 Z$$

- Impedance of the load Z: $Z = R + jX = |Z|\cos\theta + j|Z|\sin\theta$
- Output – Real and Reactive power are represented together as apparent power, S

$$S = P + jQ = VI\cos\theta + jVI\sin\theta$$

Real Practical of Transformer

- In real practical of transformer
  - Finite permeability
  - Eddy current and hysteresis are included in the losses
  - Leakage fluxes
  - Finite winding of resistances

Transformer Losses

- Small power transformer has efficiency around 80 to 90%.
- Commercial power transformer may reach up to 98% efficiency
- The losses of transformer consists of 3 type of losses:

  - Copper loss
  - Eddy-current loss
  - Hysteresis loss

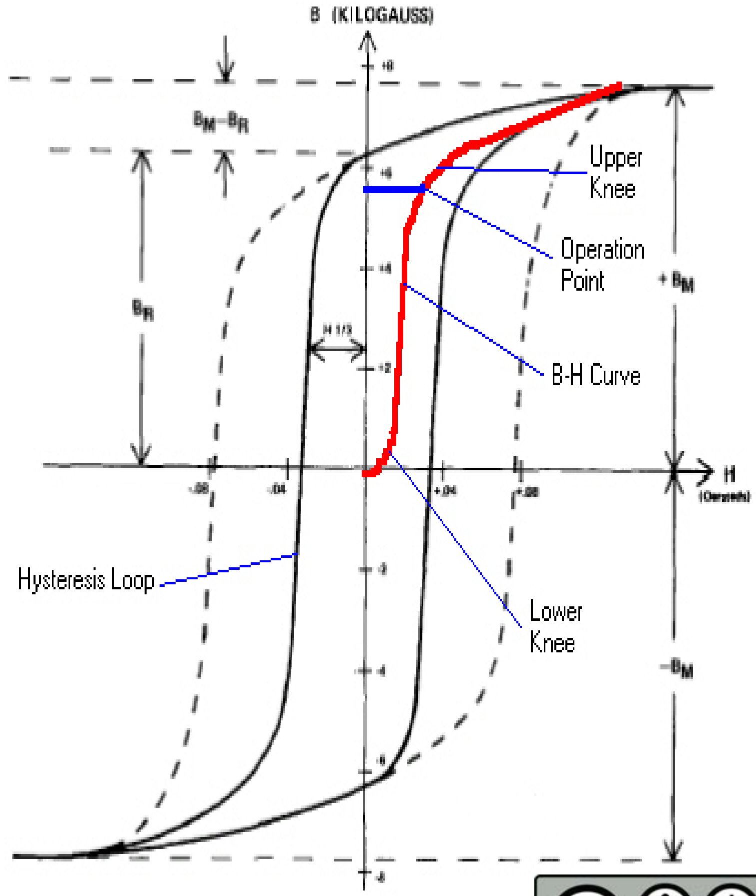
Copper Loss

- Copper losses is the loss of power in the form I^2R by the resistance within the primary and secondary windings.
- The copper loss depends the magnitude of current flowing through the windings.
- The total copper loss is given by:

$$P_{cu} = I_1^2 R_{cu}$$

Hysteresis Loss

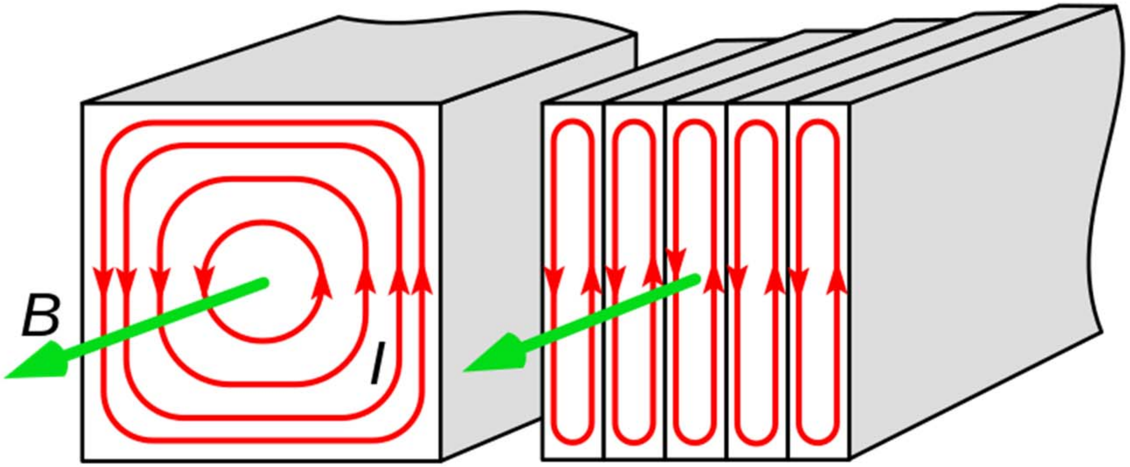
- The direction of the magnetic flux in the core changes every cycle.
- Power is consumed to move around the magnetic dipoles in the core material, and energy is dissipated as heat.



Source: https://commons.wikimedia.org/wiki/File:BH_Loop1a.jpg

Eddy-Current Loss

- EMF induced in core generates eddy currents which circulate in the core material, generating heat.
- Laminations (silica sheets between core layers) – to reduce eddy current, and minimize loss.



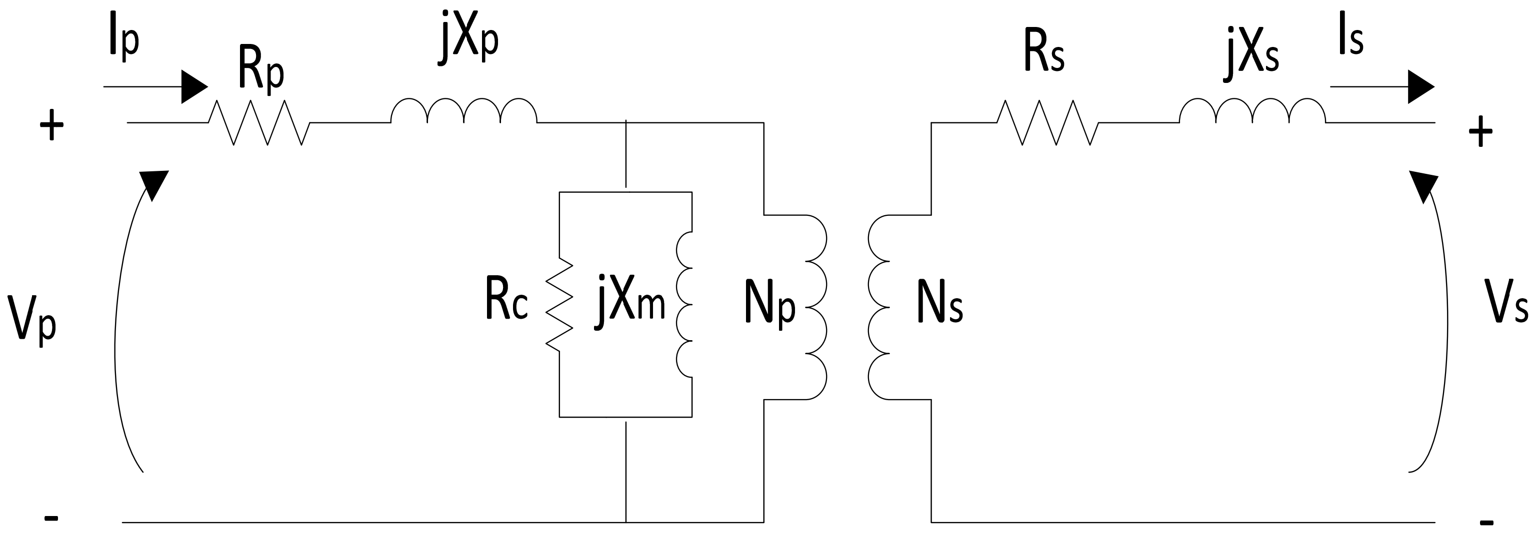
Source: https://commons.wikimedia.org/wiki/File:Laminated_core_eddy_currents.svg

The transformer's Equivalent Circuit

To model a real transformer accurately, we need to account for the following losses:

PROBLEM	SOLUTION
Copper losses due to resistance of the wires	modeled by the resistors R_p and R_s
Core losses due to Eddy current loss & Hysteresis loss	designed by a resistance R_C connected across the primary voltage source
Magnetization current necessary to produce magnetic flux within the transformer core	designed by a reactance X_M connected across the primary voltage source
Losses due to flux leakage out of the transformer core	modeled by primary and secondary reactance X_P , X_S

Exact Equivalent Circuit Of A Real Transformer



V_p = primary terminal voltage

V_s = secondary terminal voltage

I_p = primary current

I_s = secondary current

X_s = secondary leakage reactance

R_p = resistance of primary winding

R_s = resistance of the secondary winding

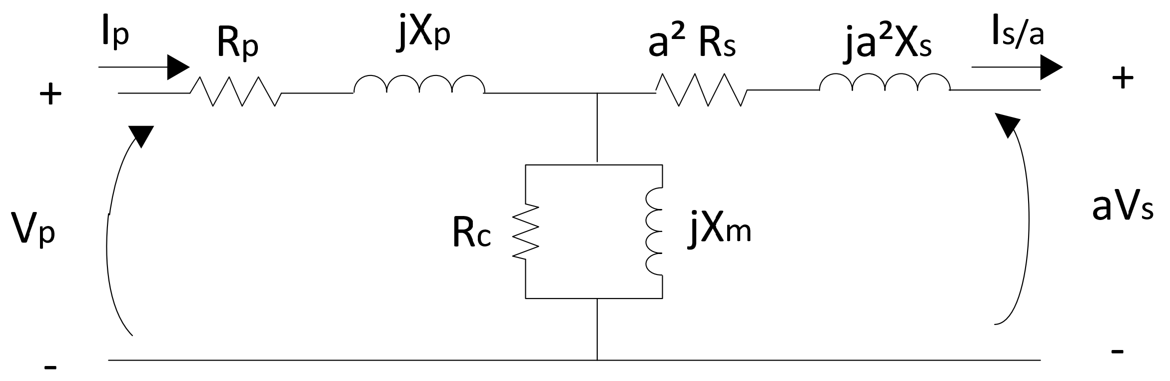
R_C = core resistance

X_M = magnetizing reactance

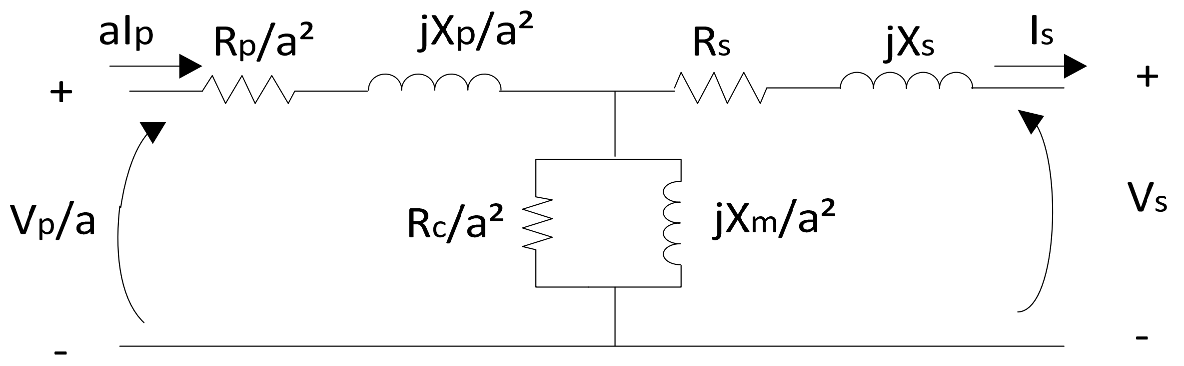
X_p = primary leakage reactance

Exact Equivalent Circuit Of A Real Transformer

- The equivalent circuit of transformer may refer to primary or secondary side:



Refer to primary side of transformer

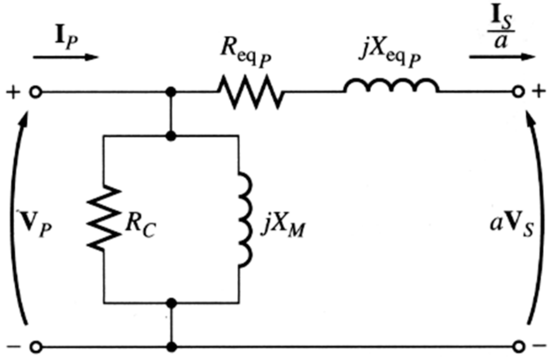


Refer to secondary side of transformer

Approximate Equivalent Circuit of Transformer

- For many practical applications, approximate models of transformers are used.

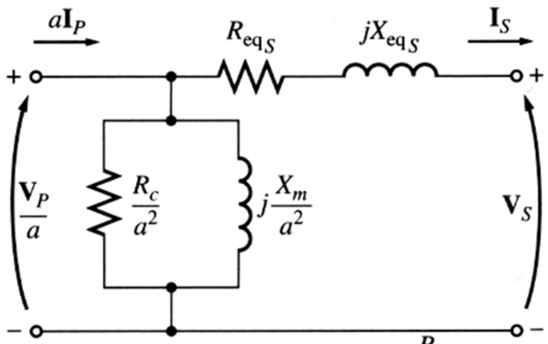
Refer to primary side of transformer



$$R_{eq\,P} = R_P + a^2 R_S$$

$$X_{eq\,P} = X_P + a^2 X_S$$

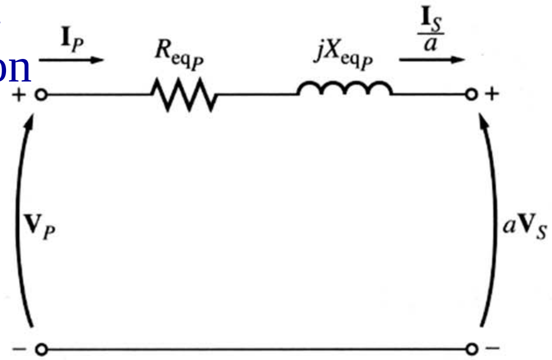
Refer to secondaryside of transformer

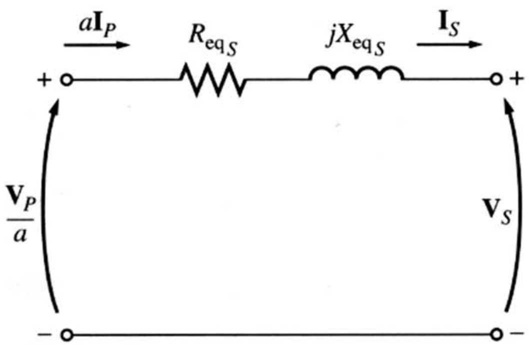


$$R_{eq\,S} = \frac{R_P}{a^2} + R_S$$

$$X_{eq\,S} = \frac{X_P}{a^2} + X_S$$

Equivalent circuit without an excitation branch





Equivalent circuit without an excitation branch

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Research interest: Reliability, Distribution network, smart grid, risk asessment