# EN 206 - Power Electronics and Machines

## Transformers

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# Lecture Organization - Modules



- Introduction and Power Semiconductor Switches
- Module 1: Transformers
- Module 2: AC/DC converter / Rectifier
- Module 3: DC machines and Drives
- Module 4: DC/DC converter
- Module 5: Induction Machine
- Module 6: DC/AC converter / Inverter
- Module 7: AC/AC converter / Cyclo converter
- Module 8: Synchronous Machine
- Module 9: Special Topics: Machines, HVDC, APF

# Definition

- Transformer is a device or a machine, that transfers electrical energy from one electrical circuit to another electrical circuit through the medium of magnetic field and without change in frequency.
- It is possible to step up or step down the voltage/current of a transformer, but the frequency remains constant.

# Types of Transformers

### Voltage Level

- Step Up
- Step Down
- Isolation

### Construction

- Core
- Shell

### Application

- Power Transformer
- Distribution Transformer
- Generation Transformer

### Connection

- Star-Star, Star-Delta
- Delta-Delta, Delta-Star

The principle of operation remains the same, irrespective of voltage level, type, size and usage pattern.

# Distribution Transformers

## Pole Mounted

## Features

- Ratings:CRGO Silicon Steel Transformers - Upto 167 kVA, Amorphous Metal Transformers - Upto 167 kVA
- Cooling : ONAN, OA

- Primary voltage (Upto 33 kV), Secondary Voltage (120, 120/240, 210-105, 250, 240/480 V)
- Winding material : Copper / Aluminium
- Tapping range : 5% in steps of 2.5%

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[1] Ref: http://www.vijaielectricals.com

# Power Transformers

EN 206
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Prof. Doolla

Introduction

Analysis

## Power Transformer

## Features

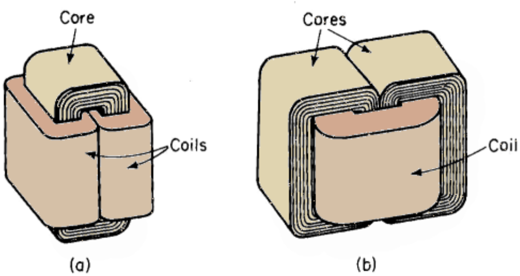
- Small (10-25MVA, 12-66kV)
- Medium (Up to 30 MVA, Up to 132 kV)
- Large (25 to 500 MVA, 11 to 765 kV)

- Cooling: ONAN, ONAF
- Winding material : Copper

[2]

[2] Ref: http://www.cgglobal.com

# Construction

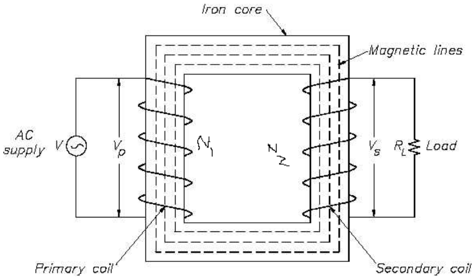



- Core type : Winding sorrounds majority part of the core; conentric coil type
- Shell type: Core surrounds majority part of the winding, interleaved or sandwich type
- For a given output and volage rating, core-type transformer requires less iron but more conductor material as compared to shell-type material

# Construction

- Magnetic core: Stack of thin silicon-steel laminations, about 0.35mm thick for 50 Hz transformers
- Cold-rolled grain oriented sheet - Steel (CRGO): Low core loss and high permiability. Typically used in large power and distribution transformers
- Amorophous Steel: Core loss one third of conventional steel. Typically used in distribution transformers

# Ideal Transformer



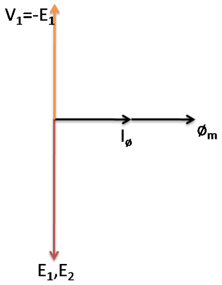

- Winding resistances are negligible.
- All flux setup by primary links the secondary.
- Core has constant permeability.
- The core losses (hysteresis and eddy current) are negligible.
- The magnetizing current and hence flux are sinusoidal in nature.

# Ideal Transformer- EMF Generation

- EMF inducted in the primary $e_1 = -N_1 \frac{d\phi}{dt}$
- If we assume that the flux is sinusoidal in nature ($\phi = \phi_m sin\omega t$), then:
  $e_1 = -N_1\omega\phi_m cos\omega t = N_1\omega\phi_m sin(\omega t - \frac{\pi}{2})$
- Rms value of $e_1 = E_1 = \frac{E_{1,max}}{\sqrt{2}} = \frac{N_1\omega\phi_m}{\sqrt{2}} = \sqrt{2}\pi f N_1 \phi_m$
- EMF inducted in the secondary
  $e_1 = -N_2 \frac{d\phi}{dt} = -N_2\omega\phi_m cos\omega t = E_{2max} sin(\omega t - \frac{\pi}{2})$
- Rms value of $e_2 = E_2 = \frac{E_{2,max}}{\sqrt{2}} = \frac{N_2\omega\phi_m}{\sqrt{2}} = \sqrt{2}\pi f N_2 \phi_m$

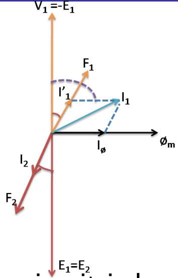
$\therefore \frac{E_1}{E_2} = \frac{N_1}{N_2}$, also $\frac{E_1}{N_1} = \frac{E_2}{N_2} = \sqrt{2}\pi f N_2 \phi_m$, i.e, emf per turn in primary is equal to emf per turn in secondary.

# Ideal Transformer- No Load - Phasor Diagram




- The core flux ($\phi_m$) lags the induced emf ($E_1$ , $E_2$) by $90^0$
- The no load current or magnetizing current ($I_\phi$)is inphase with the core flux ($\phi_m$)
- Supply voltage leads the magnetizing current ($I_\phi$) and core flux ($\phi_m$) by $90^0$, as the system is purely inductive.

# Ideal Transformer- Phasor Diagram - Secondary loaded




- When the secondary circuit is loaded, secondary mmf being opposite to $\phi_m$, tends to reduce the alternating mutual flux $\phi_m$.
- For an ideal transformer $|E_1| = |V_1|$, as the supply voltage remains constant, therefore more amount of power is drawn from primary.
- Compensating primary mmf = Secondary mmf i.e., $I_1^{'} N_1 = I_2 N_2$, where $I_1^{'}$ is load component of primary current $I_1$.

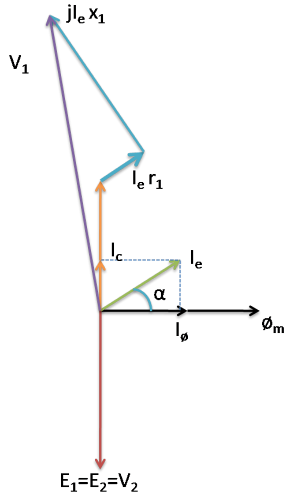
# Ideal Transformer- Phasor Diagram - Secondary loaded

- The total primary current $I_1$ is the phasor sum of $I_1^{'}$ and $I_\phi$.
- $\overline{I_1} = \overline{I_1^{'}} + \overline{I_\phi}$
- Power factor of the system is given by $\cos\phi$
- If $I_\phi$ is neglected, $I_1 N_1 = I_2 N_2 \implies \frac{E_1}{E_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1} = \frac{V_1}{V_2}$
- Total input power = Total output power $\implies V_1 I_1 = V_2 I_2$

# Impedance Transformation

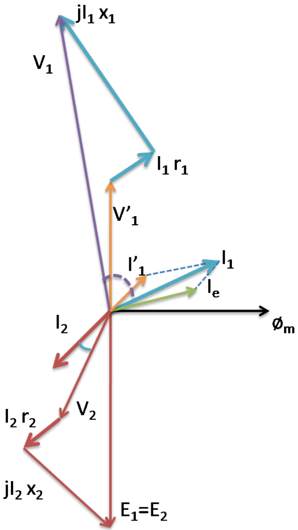
- Used to simplify the equivalent circuit
- If $Z_2$ is impedance of load connected, $V_2$ is the voltage of secondary, $I_2$ is current through the secondary winding, then $Z_2 = \frac{V_2}{I_2}$,
- Also, $\frac{V_1}{N_1} = \frac{V_2}{N_2}$; $I_1 N_1 = I_2 N_2$
- If the secondary impedance is transferred to primary side, then impedance seen by primary circuit is given by:
- $\frac{V_1}{I_1} = \frac{N_1}{N_2} V_2 \times \frac{N_1}{N_2} \frac{1}{I_2} \implies \frac{V_1}{I_1} = Z_2' = (\frac{N_1}{N_2})^2 Z_2$
- Similarly, when primary impedance is referred to secondary, $Z_1' = (\frac{N_2}{N_1})^2 Z_1$

# Phasor Diagram - No Load




- $\alpha$: Hysteresis angle, $I_e$: exciting current, $I_\phi$ : Magnetizing current, $I_c$: Core loss component
- $r_1$: primary resistance
- $x_1$: fictituous quantity introduced to represent the leakage flux in primary
- Primary leakage impedance drop is about 2 to 5% even at full load.
- The magnetizing current is typically 1% of full load current and hence is neglected.

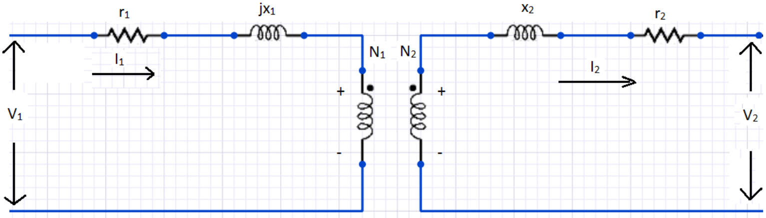
# Phasor Diagram - Lagging Load



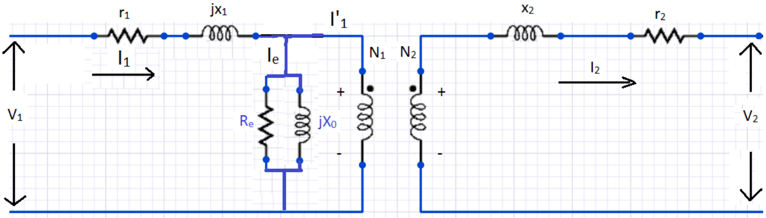

- $\theta_1$ and $\theta_2$ is the power factor of the load and source respectively.
- $r_1$: primary resistance
- $x_1$: fictitious quantity introduced to represent the leakage flux in primary
- Primary leakage impedance drop is about 2 to 5% even at full load.
- Phasor diagram is helpful only:
  - When a transformer is to be studied alone
  - When the internal behaviour of the transformer is to be understood

# Equivalent Circuit

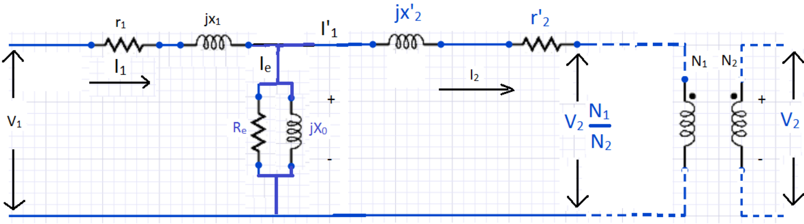
With Exciting current neglected:




Exact equivalent circuit:



Equivalent circuit referred to primary:



# Summary

- Transformers
  - Principle of operation
  - Equivalent Circuit

  **Next Class**
  - Testing of Transformer
  - Auto Transformer
- Thank you!!

For Further Reading:

- Transformer Engineering: Design and Practice Authors: S.V. Kulkarni and S.A. Khaparde Publisher: Marcel Dekker (Taylor & Francis Group), New York, May 2004 ISBN: 0-8247-5653-3
- Electric Machinery: A. E. Fitzgerald, C. Kingsley, S. D. Umans. Publisher: TMH, New Delhi, India, 2009