# Lecture 7: Transformers

## EE3010: Electrical Devices and Machines

School of Electrical and Electronic Engineering

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# Learning Objectives

By the end of this lecture, you should be able to:

- Describe the operating principles and basic construction of a single-phase transformer.

- Explain the basic assumptions of an ideal transformer and apply the concepts learnt to derive equations related to the turns ratio.

- Identify the concepts of referred values and dot convention of a single-phase transformer.

# Topics

(**Chapter 4 - Bhag S. Guru, Electric Machinery and Transformers**)

1. Introduction: Construction
2. Basic Principles: Ideal Transformer
3. Practical Transformer: Equivalent Circuit
4. Performance Analysis:
   i. Regulation
   ii. Losses and Efficiency

# Topics

5. Testing: Determination of Parameters
6. Autotransformers
7. Three-phase Transformers:
   i. Three-phase Transformer Banks
   ii. Three-phase Transformers

# Notations

| Notations | Description |
|---|---|
| $\mathrm{V}, \mathrm{I}$, or $\tilde{\mathrm{V}}, \tilde{\mathrm{I}}$ | Normal letters or letters with the **tilde** signs above them indicate phasor quantities. The phase angles of these quantities may change with respect to the reference quantity. |
| $\mathrm{S}, \mathrm{Z}$, or $\hat{\mathrm{S}}, \hat{\mathrm{Z}}$ | Normal letters or letters with the **hat** signs above them indicate complex (vector) quantities. The phase angles of these quantities are independent of the reference quantity. |
| $V, I, S, Z$ | Italic letters indicate the magnitudes of the corresponding phasors or vectors. |

# Notations

- Revision of concepts on '**Electric Circuits**', '**Three-phase Systems**' and '**Magnetic Circuits**' would be very helpful for this topic.

- Please refer to the notes on those topics to recall important quantities, their symbols and their units.

# Introduction

- A simplest transformer shown in Fig. 1 consists of two coils wound on a common magnetic core:
  - Primary winding
  - Secondary winding

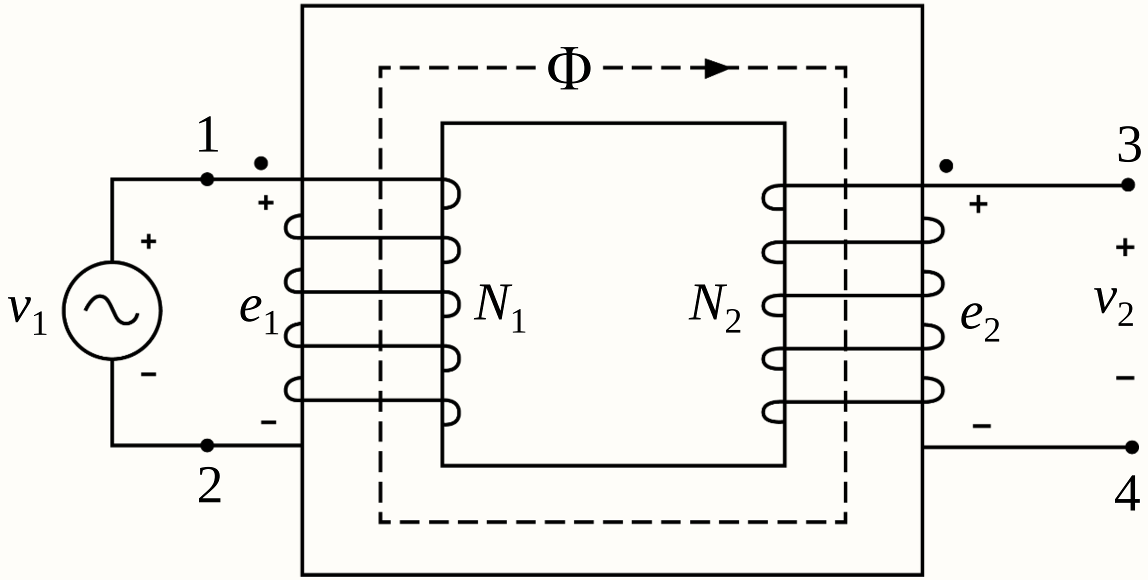


Fig. 1. The simplest transformer.

# Introduction

- A time varying current produced by a time varying voltage connected to one winding establishes a time varying flux in the coil. The flux links the secondary winding inducing a voltage in the secondary winding.
  - Step-up transformer, e.g., 110 Vac ⇒ 220 Vac
  - Step-down transformer, e.g., 220 Vac ⇒ 110 Vac
- Either winding can be connected to the source or the load.
- Power transfer from one winding to the secondary winding occurs through the magnetic field or magnetic flux in the core.
- The frequency in the secondary winding is the same as in the primary winding, i.e., $f_1 = f_2$

# Construction

❖ The core is made of thin 'electrical steel' laminations in order to reduce the core (eddy current and hysteresis) losses. The core is of two types (see Figs. 2 and 3):

- Shell type
- Core type

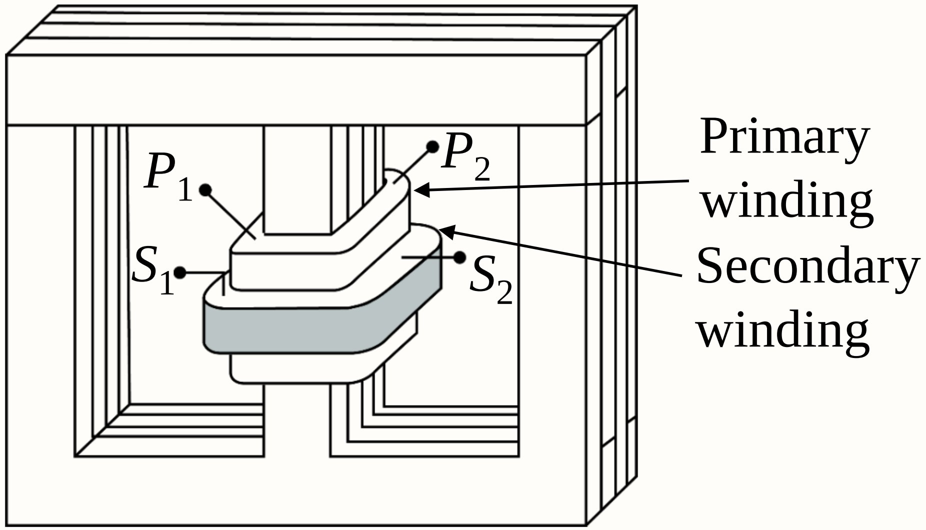


Fig. 2. Shell type transformer.

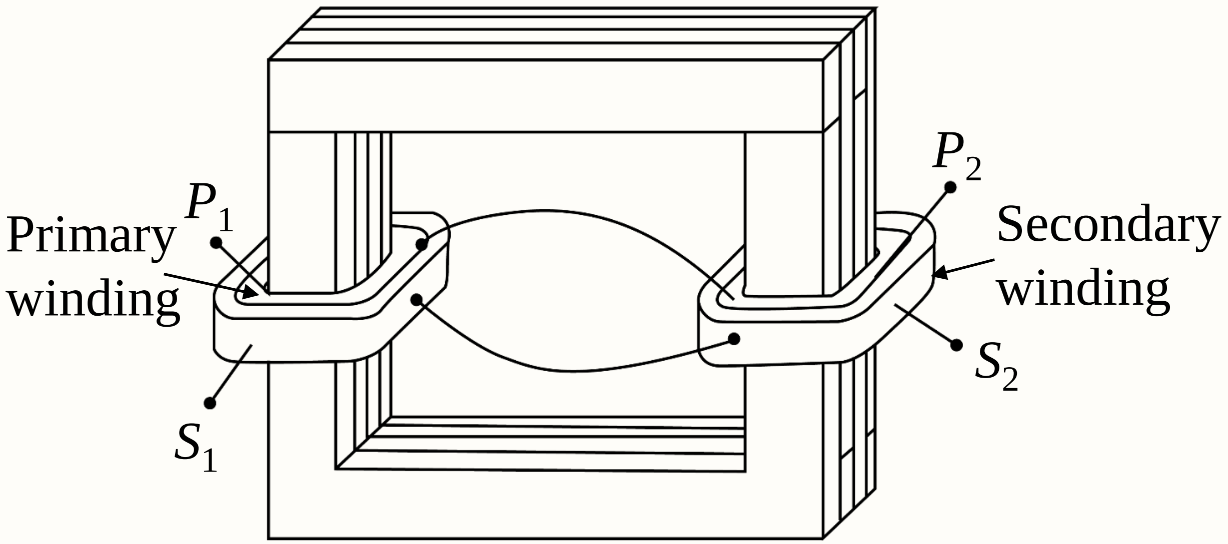


Fig. 3. Core type transformer.

# Construction

- The windings may be directly wound on the core in small transformers. However, for high-power transformers, the windings are usually form-wound and then assembled over the core.

- A cooling system is an integral part of the transformer. Usually, a transformer may be cooled by natural air or forced air circulation. When natural air or forced air circulation is not enough, the whole transformer is immersed in a transformer oil tank.

# Construction

# Ideal Transformer

- The ideal condition assumptions are:
  - The windings have negligible resistance ⇒ no copper losses in the windings, no voltage drops.
  - All the flux is confined to the core and therefore the same flux links both the windings.
  - The permeability of the core is infinitely high, which implies that a vanishingly small mmf (current) is required to set up the flux $\varphi$.

    As $\mu_c \to \infty,\ R_c = \left(\dfrac{l}{\mu_c A}\right) \to 0,\quad Ni \downarrow = \varphi R_c \downarrow$
  - The core does not incur any hysteresis or eddy current loss ⇒ no core losses.

# Ideal Transformer

- If the number of turns in the two windings are $N_1$ and $N_2$ as shown in Fig. 4, Faraday's Law gives

$$v_1 = e_1 = N_1 \frac{d\varphi}{dt}$$

$$v_2 = e_2 = N_2 \frac{d\varphi}{dt}$$

$$\frac{v_1}{v_2} = \frac{e_1}{e_2} = \frac{N_1}{N_2} = a$$

where '$\boldsymbol{a}$' is called the turns ratio.

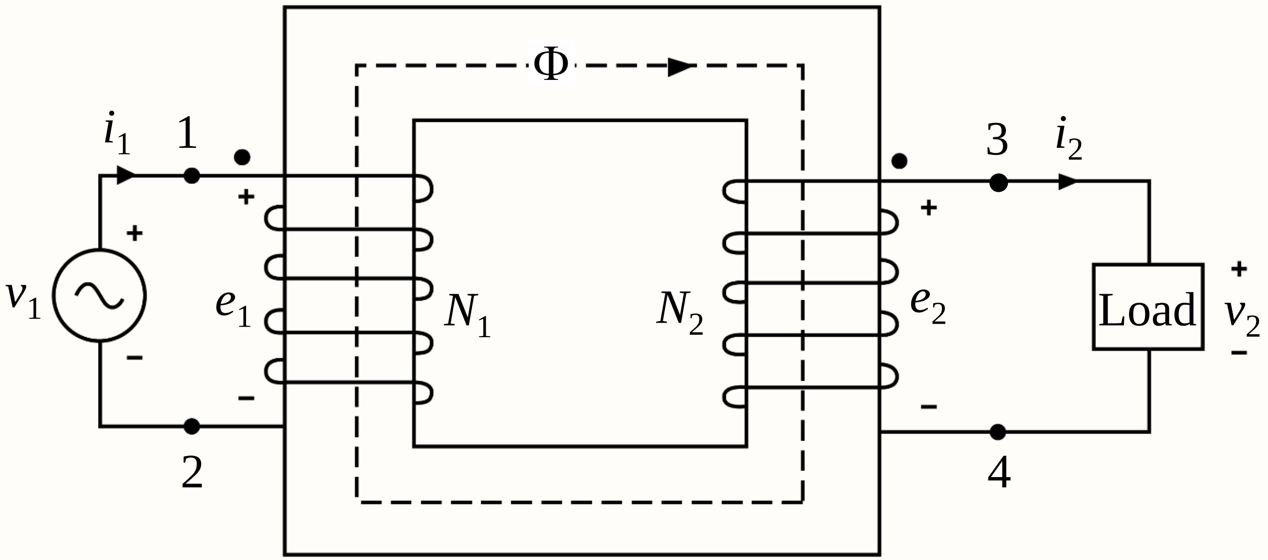


Fig. 4. An ideal transformer under load.

# Ideal Transformer

- As the core material is ideal, the total mmf required to create the flux would be vanishingly small, so that

$$N_1 i_1 - N_2 i_2 = 0 \Rightarrow N_1 i_1 = N_2 i_2 \Rightarrow \frac{i_2}{i_1} = \frac{N_1}{N_2} = a$$

- From the above two equations,

$$\frac{v_1}{v_2} = a = \frac{i_2}{i_1} \Rightarrow v_1 i_1 = v_2 i_2$$

- Expressing these equations in effective or rms quantities,

$$\frac{V_1}{V_2} = a, \ \frac{I_2}{I_1} = a, \text{ and, } V_1 I_1 {*} = V_2 I_2 {*} \ \text{(also } V_1 I_1 = V_2 I_2\text{)}$$

# Ideal Transformer

- An ideal transformer connected to a source on one side and a load on the other side can be schematically represented as shown in Fig. 5, where

$$\frac{V_1}{V_2} = \frac{E_1}{E_2} = a, \text{ and } \frac{I_2}{I_1} = a \Rightarrow \frac{I_2}{a} = I_1$$

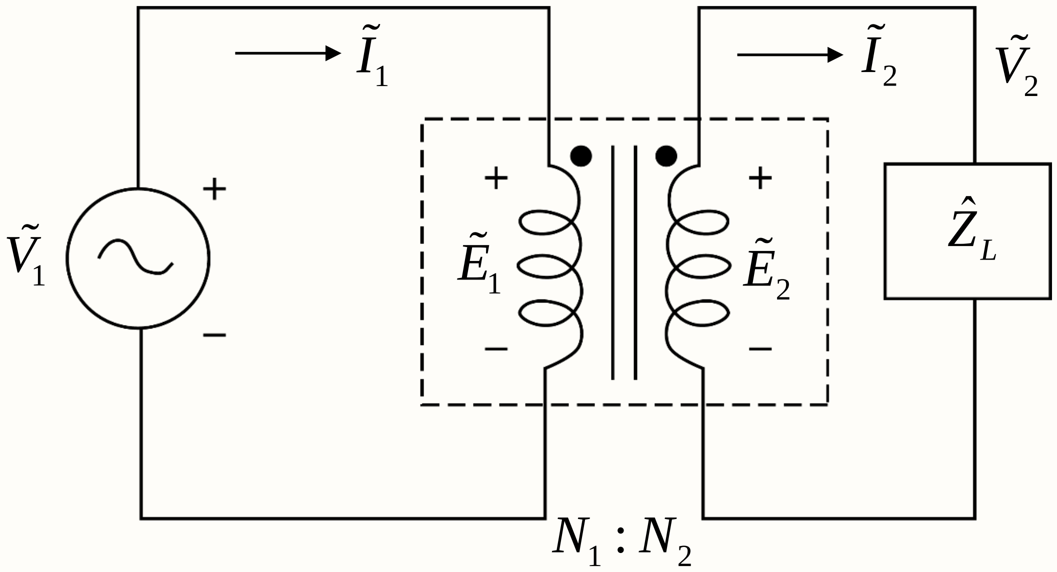


Fig. 5. An ideal transformer connected to a source and a load.

# Referred Values

- As shown in Fig. 6, for a voltage $V_2$ in the secondary side of the transformer, the primary voltage will be: $V_1 = aV_2 = V_2'$
- For a current $I_2$ in the secondary side, the current in the primary will be:

$$I_1 = \frac{I_2}{a} = I_2'$$

- $V_2'$ and $I_2'$ are called the referred values of $V_2$ and $I_2$ referred to the primary side respectively.

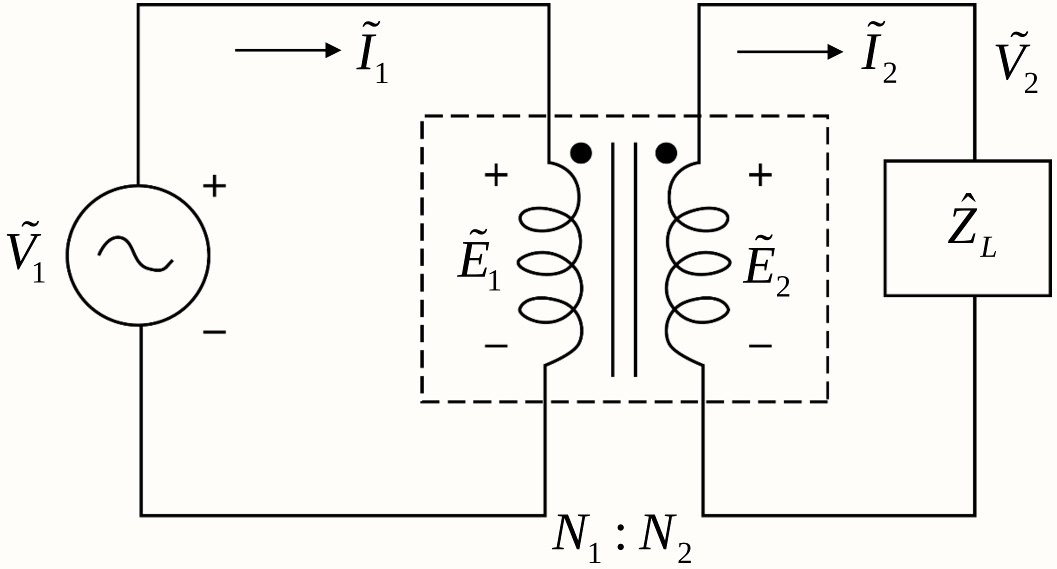


Fig. 6. An ideal transformer.

# Referred Values

- If $Z_2$ is the load impedance on the secondary side, then

$$Z_2 = \frac{V_2}{I_2}$$

- On the primary side the impedance will appear to be

$$Z_1 = \frac{V_1}{I_1} = \frac{aV_2}{I_2 / a} = a^2 \frac{V_2}{I_2} = a^2 Z_2 = Z_2'$$

$Z_2'$ is the referred value of $Z_2$ referred to the primary side.

- Similarly, $V_1$, $I_1$, and $Z_1$ when referred to the secondary side become

$$V_1' = \frac{V_1}{a},\ \ I_1' = aI_1,\ \text{ and }\ Z_1' = \frac{Z_1}{a^2}$$

# Transformer Polarity – Dot Convention

- It is very important to know the polarity (i.e., the relative direction of induced voltages) of transformer windings to make proper circuit connections.

- For the connections shown in Fig. 7:
  - $e_1$ has to oppose $v_1$, and so terminal **1** is positive with respect to terminal **2** on side 1.

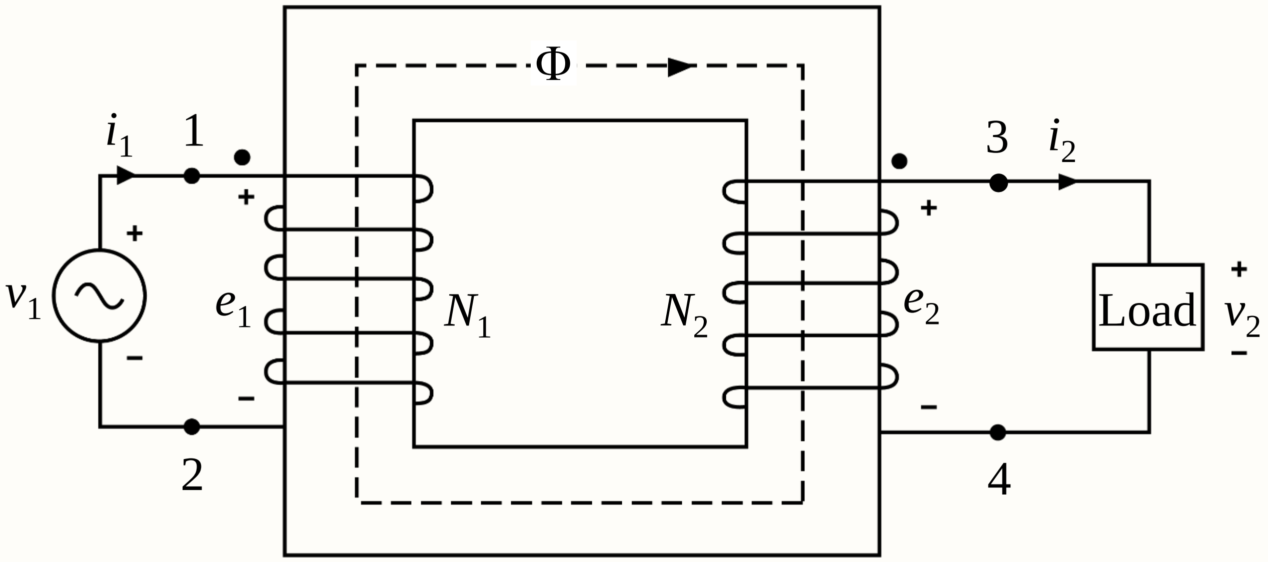


Fig. 7. An ideal transformer under load.

# Transformer Polarity – Dot Convention

- The current $i_2$ on side 2 has to oppose the flux $\varphi$ created by $i_1$, so that $i_2$ will flow in the direction as shown in Fig. 7, for the direction of the winding shown in Fig. 6. Therefore, terminal **3** is positive with respect to terminal **4** on side 2.
- Thus, terminals **1** and **3** are of like polarity (positive in this case), and so are terminals **2** and **4** (negative).

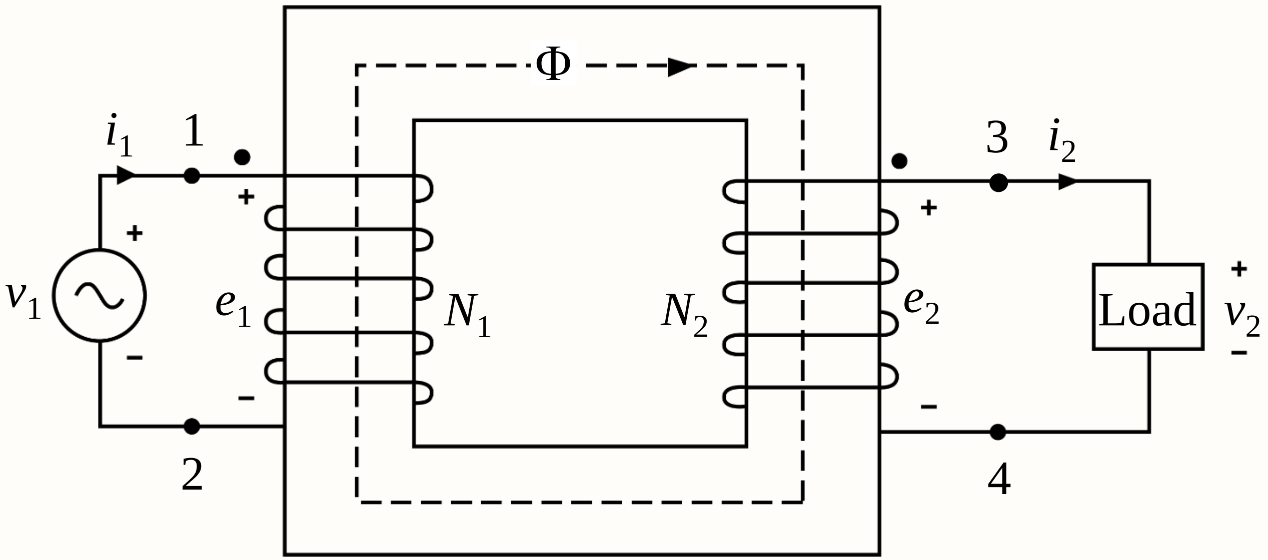


Fig. 7. An ideal transformer under load.

❖ Therefore, terminals **1** and **3** are marked by similar 'dots' as shown.

# Transformer Polarity – Dot Convention

- It should be noted that the terminal polarity depends on actual directions of the windings on the core. If the direction of the secondary winding is changed as shown in Fig. 8, the direction of the secondary current and therefore the polarity of the secondary terminals will change as shown.

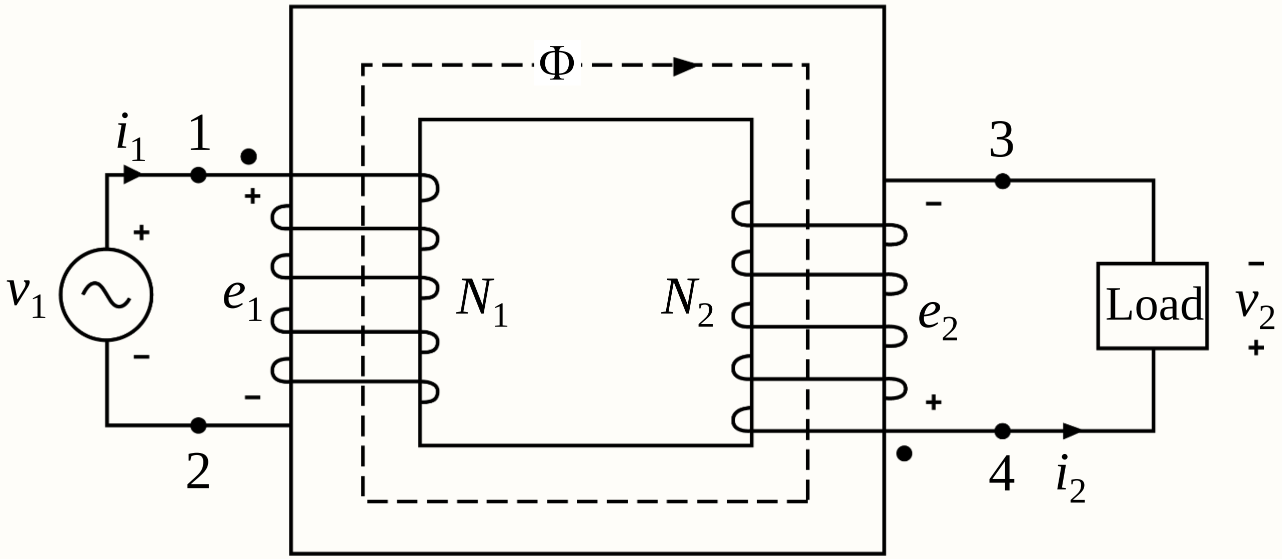


Fig. 8. An ideal transformer under load.

# Transformer Polarity – Dot Convention

- But the windings are hidden inside the tank and the winding directions will not be visible in practice. Therefore, terminals with like polarities are indicated by similar ‘dots’ as shown, outside the transformer tank itself. This practice is known as ‘**Dot-convention**’, which basically means that the terminals with similar ‘dots’ will have the same polarity.
- It should also be noted that, while the current enters the positive terminal of transformer winding on the source side, the current comes out of the positive terminal on the load side.

# Summary

In this lecture, you have learnt:

- The operating principles and basic construction of a single-phase transformer.
- The basic assumptions of an ideal transformer and the concepts learnt to derive equations related to the turns ratio.
- The concepts of referred values and dot convention of a single-phase transformer.

# References

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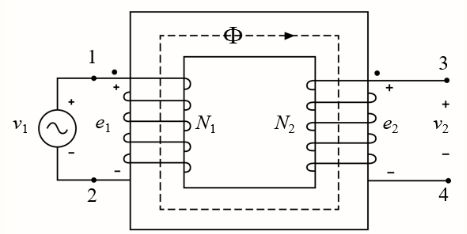
<tr><td>1</td><td>8</td><td>
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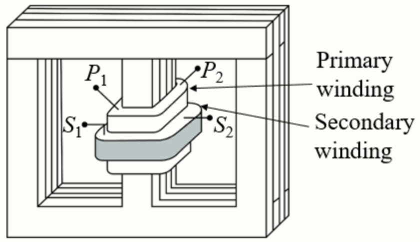
<tr><td>2</td><td>10</td><td>
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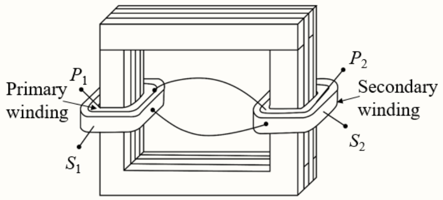
<tr><td>3</td><td>10</td><td>
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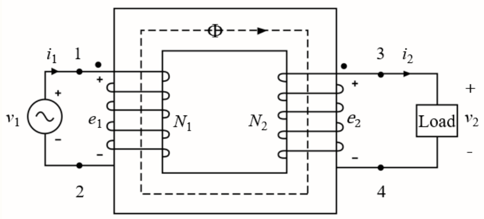
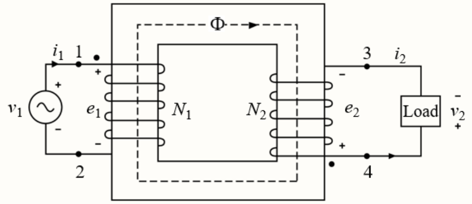
| 4 | 14, 19 and 20 |  | Reprinted from *Electric Machinery and Transformers, 3rd ed.*, (p. 207), by B. S. Guru, & H. R. Hiziroglu, 2001, New York, NY: Oxford University Press. Copyright 2001 by Oxford University Press. Reprinted with permission. |
| 5 | 21 |  | Reprinted from *Electric Machinery and Transformers, 3rd ed.*, (p. 207), by B. S. Guru, & H. R. Hiziroglu, 2001, New York, NY: Oxford University Press. Copyright 2001 by Oxford University Press. Reprinted with permission. |