Lecture 12: 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 design and operating principles of autotransformers.
- ❖ Analyse an autotransformer to determine the power transferred by induction and the power delivered by conduction.
- ❖ Explain how the autotransformers can transfer more power capacity than the conventional two-winding transformers.
- ❖ Apply the operating principles of three-phase transformer banks and three-phase transformers in power supply systems.

Autotransformer

- In normal transformers, the windings are electrically isolated and the energy transfer from one winding to another occurs completely through magnetic induction as shown in Fig. 44.

$$\frac{E_1}{E_2} = \frac{I_2}{I_1} = a = \frac{N_1}{N_2}, \text{ and } E_1 I_1 = E_2 I_2 = S$$

is the total power delivered through induction.

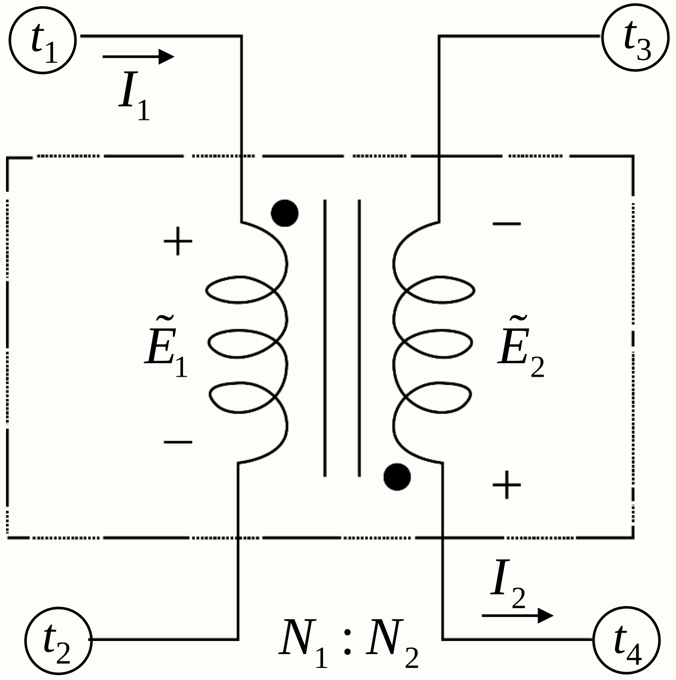


Fig. 44. Two-winding transformer.

Autotransformer

- The windings of a transformer can, however, be electrically connected, so that the energy transfer may occur both through **conduction**, as well as magnetic **induction**. Then, the total power delivered can be enhanced (increased) by making proper electrical connections between the two windings. Transformers with such connections are called **autotransformers**.

- Commonly, the two-windings are connected in series. Then
    - Any two terminals may be the input, and
    - Any two terminals may be the output.

- With proper connections, it is possible to achieve several combinations of input-output voltages from a single two-winding transformer.

Autotransformer

❖ Four common autotransformer configurations:

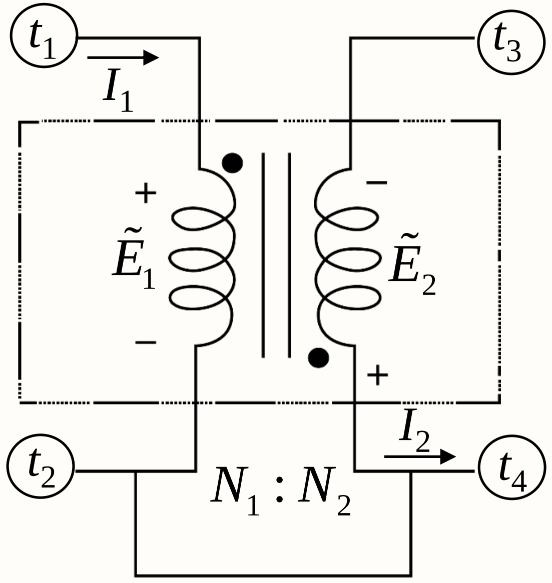


Fig. 45. Two-winding transformer.

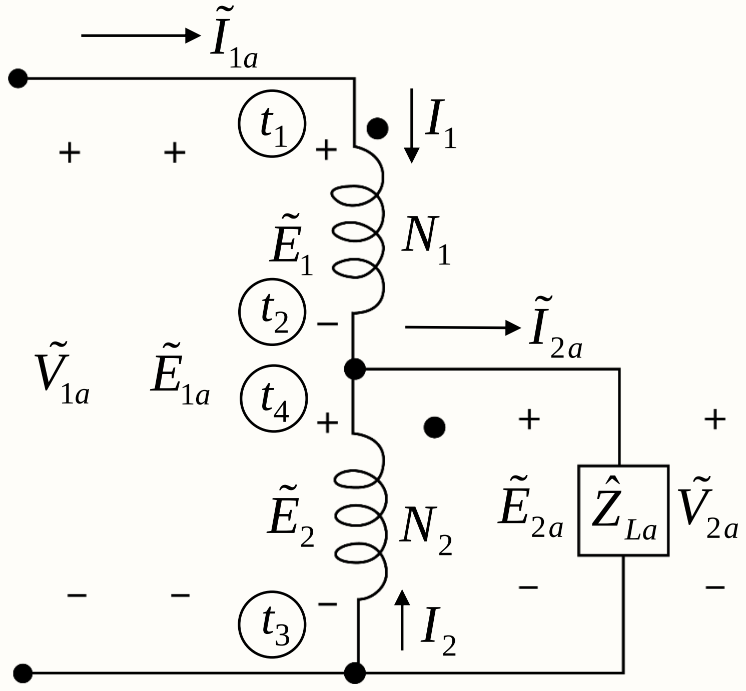


Fig. 46. Configuration 1: $(V_1+V_2)/V_2$ step-down connection.

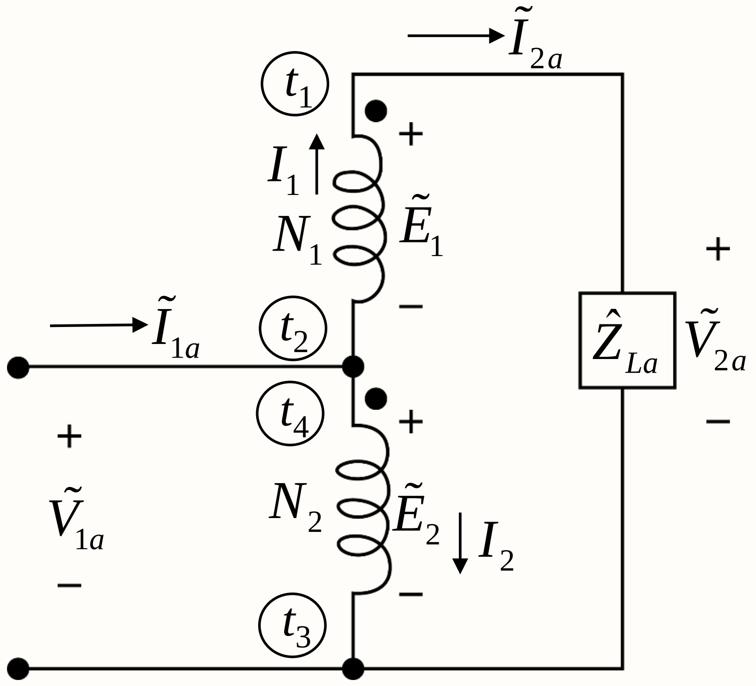


Fig. 47. Configuration 2: $V_2/(V_1+V_2)$ step-up connection.

Autotransformer

- Four common autotransformer configurations:

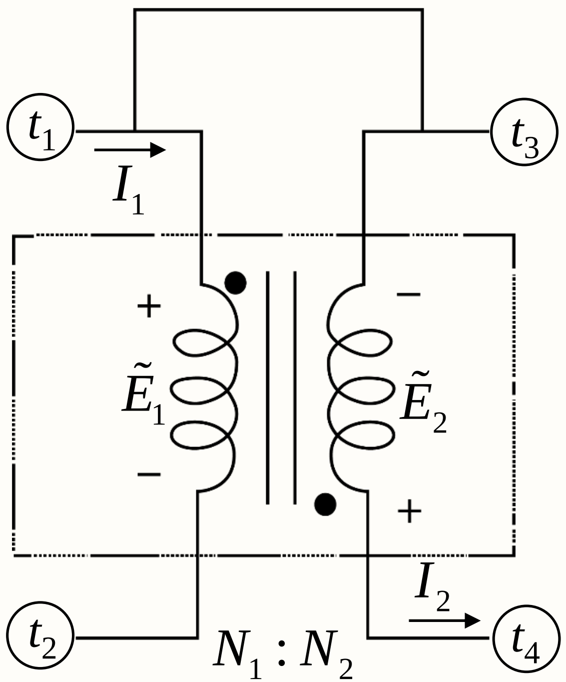


Fig. 48. Two-winding transformer.

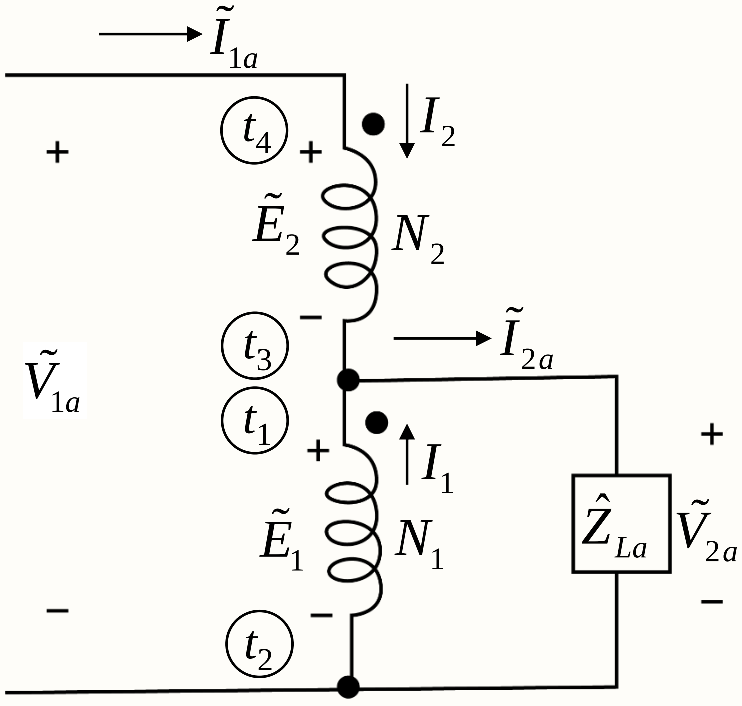


Fig. 49. Configuration 3: $(V_1+V_2)/V_1$ step-down connection.

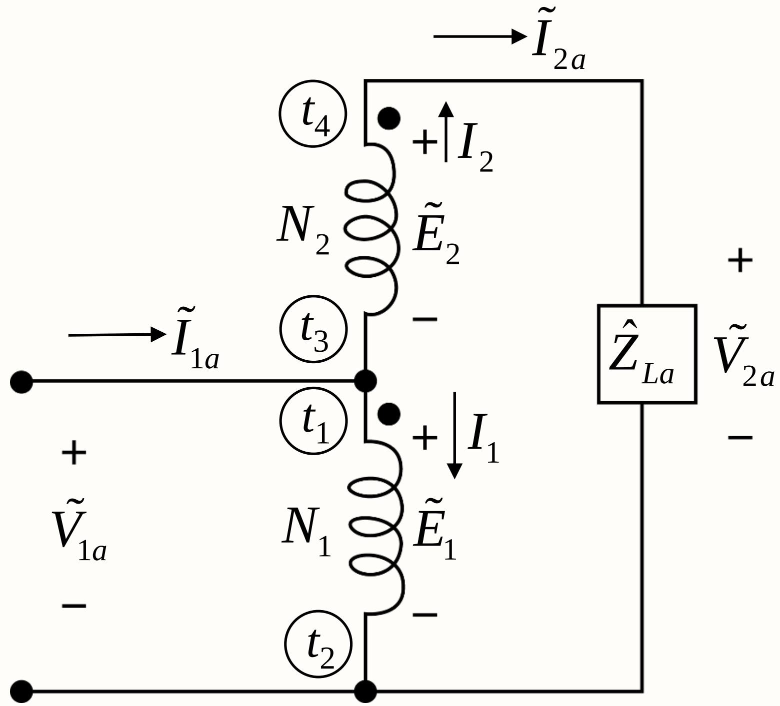


Fig. 50. Configuration 4: $V_1/(V_1+V_2)$ step-up connection.

Autotransformer

- One common form of autotransformer is a single winding transformer with a sliding point, with variable output voltage, as shown in Fig. 51.

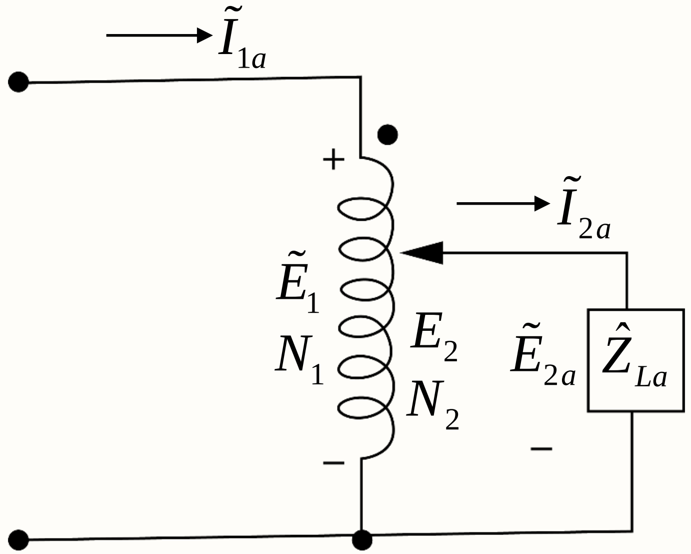


Fig. 51. A single winding transformer with variable output voltage.

Autotransformer

- Autotransformers offer several advantages:
  - They can deliver more power for the same size.
  - They provide several voltage transformation ratios - voltage flexibility.
  - They are more efficient.
  - They are cheaper.
  - They take lesser excitation current.
- Their main disadvantage is the loss of electrical isolation between the primary and the secondary windings.

Autotransformer Analysis

- Consider a particular autotransformer configuration, as shown in Fig. 53.

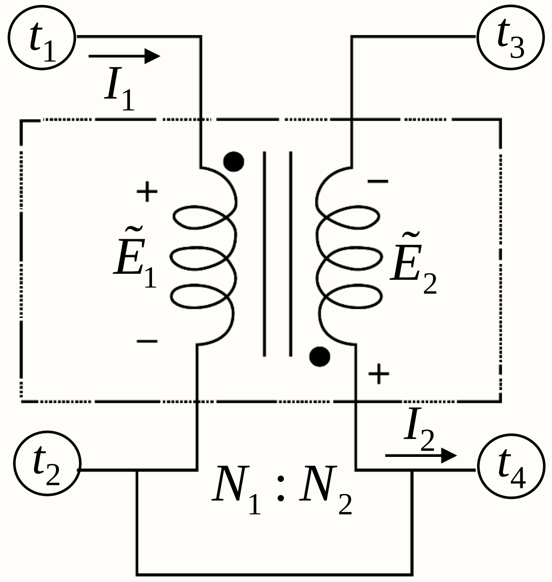


Fig. 52. Two-winding transformer.

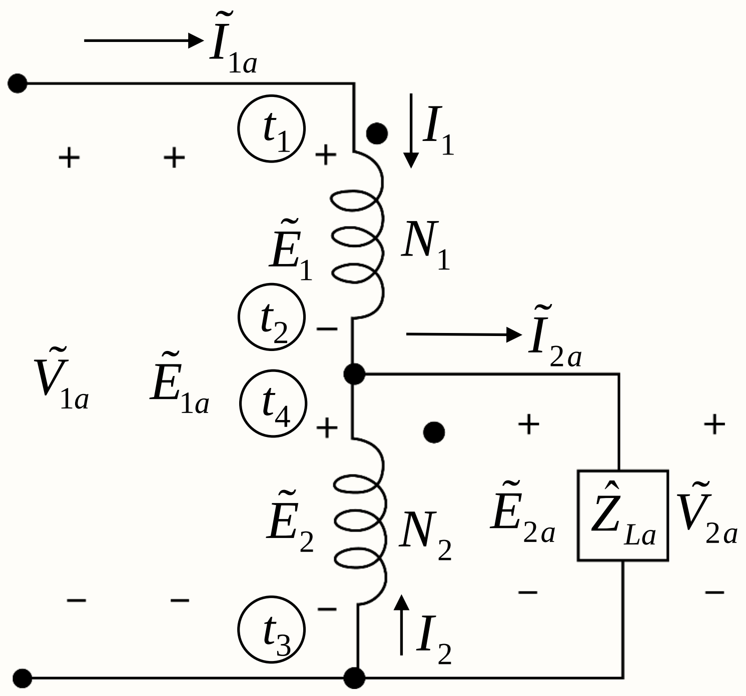


Fig. 53. Configuration 1: $(V_1+V_2)/V_2$ step-down connection.

Autotransformer Analysis

- The following notations are used in the analysis:
  - E_1 and I_1 are the winding 1 voltage and current.
  - E_2 and I_2 are the winding 2 voltage and current.
  - E_{1a} and I_{1a} are the autotransformer primary voltage and current.
  - E_{2a} and I_{2a} are the autotransformer secondary voltage and current.

Autotransformer Analysis

- For the two-winding transformer:
  - $$\frac{E_1}{E_2} = \frac{I_2}{I_1} = \frac{N_1}{N_2} = a$$
  - $$E_1 I_1 = E_2 I_2 = S$$
  - If current enters the dotted terminal in one coil, the currents must come out of the dotted terminal in the other coil.

Autotransformer Analysis

- For the autotransformer,

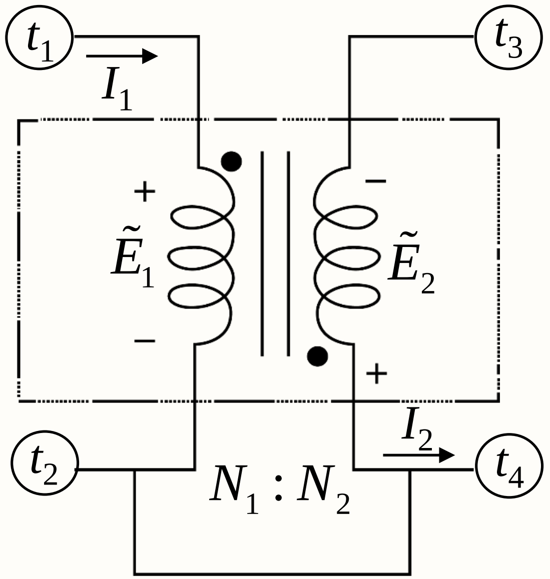


Fig. 54. Two-winding transformer.

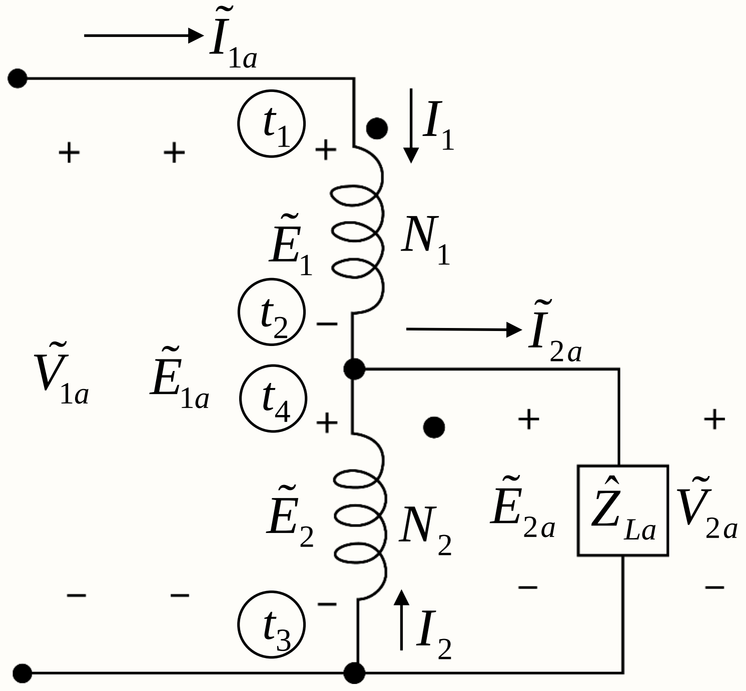


Fig. 55. Configuration 1: $(V_1+V_2)/V_2$ step-down connection.

Autotransformer Analysis

- The autotransformer voltage ratio is

$$\frac{V_{1a}}{V_{2a}} = \frac{E_1 + E_2}{E_2} = \frac{E_1}{E_2} + 1 = a + 1 \quad \left(\frac{E_{1a}}{E_{2a}} = \frac{E_1 + E_2}{E_2}\right)$$

- The autotransformer current ratio is

$$\frac{I_{2a}}{I_{1a}} = \frac{I_1 + I_2}{I_1} = 1 + \frac{I_2}{I_1} = 1 + a$$

Therefore,

$$\frac{V_{1a}}{V_{2a}} = \frac{I_{2a}}{I_{1a}} \Rightarrow V_{1a} I_{1a} = V_{2a} I_{2a}, \text{ i.e., } S_{1a} = S_{2a}$$

Autotransformer Analysis

- The input of the autotransformer is

$$S_{1a} = E_{1a} I_{1a} = (E_1 + E_2) I_1 = E_1 I_1 + E_2 I_1$$

- Similarly, the output of the autotransformer is

$$S_{2a} = E_{2a} I_{2a} = E_2 (I_1 + I_2) = E_2 I_2 + E_2 I_1$$

- The first terms of the input and the output of the autotransformer:

$$E_1 I_1 = E_2 I_2 = S$$

is the power transferred through regular transformer action, and is called the power transferred through **induction**.

Autotransformer Analysis

- The second term:

$$E_2 I_1 = (\frac{E_1}{a})\ I_1 = (\frac{1}{a}) E_1 I_1 = \frac{S}{a}$$

is the additional power delivered because of the connection as autotransformer. This is the power delivered by **conduction**.

- The total power delivered by the autotransformer is thus:

$$S_{1a} = S_{2a} = S + \frac{S}{a}$$

- It should be noted that the rating, i.e., the capacity of the transformer is apparently enhanced by an amount S/a when connected as an autotransformer as shown in Fig. 55.

Autotransformer Analysis

- It can be seen through similar analyses of other autotransformer configurations that the rated power transfer by induction remains the same S for all configurations, while the rated power transfer by conduction is different for different configurations.

- Exercise: Analyse configurations of Figs. 47, 49 and 50, and determine the general expressions for power delivered through conduction for these configurations.

Example 7

A 24-kVA, 2400/240-V transformer is to be connected as an autotransformer. Sketch the different possible connections. For each connection, determine

a) the input voltage,

b) the output voltage,

c) the nominal rating of the autotransformer,

d) the power delivered conductively, and

e) The power transformed magnetically.

(Solutions →)

Example 7 – Solutions

Consider a possible connection shown in Fig. 57.

$E_1 = 2400$ V, $E_2 = 240$ V

Turns ratio $a = \dfrac{2400}{240} = 10$

Power rating $S = 24$ kVA

Therefore, the current ratings of the two-windings are

$$I_1 = \frac{S}{E_1} = 10 \text{ A, and } I_2 = \frac{S}{E_2} = 100 \text{ A}$$

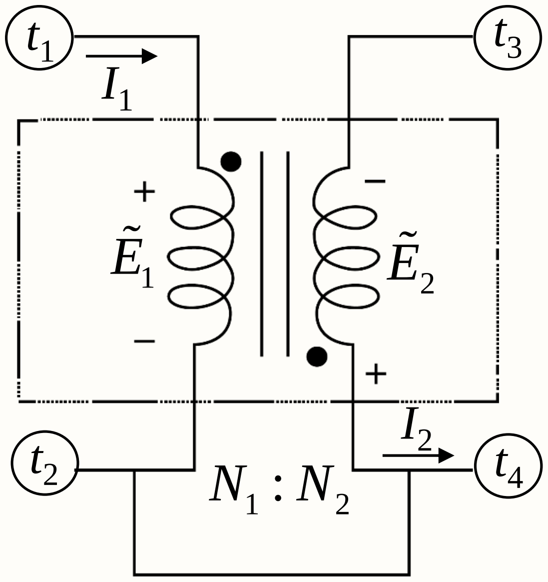


Fig. 56. Two-winding transformer.

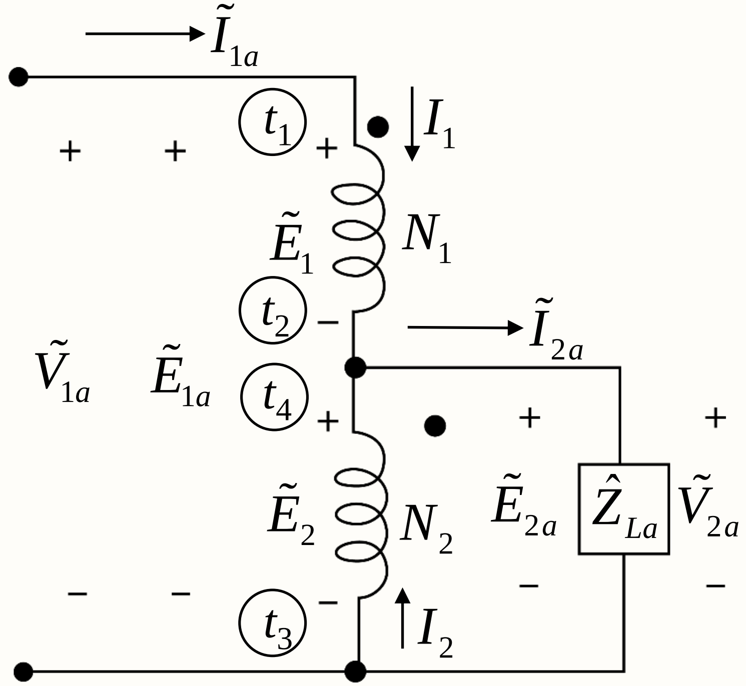


Fig. 57. Configuration 1: $(V_1+V_2)/V_2$ step-down connection.

Example 7 – Solutions

For the chosen configuration of the autotransformer:

a) Input voltage $= E_1 + E_2 = 2400 + 240 = 2640$ V

b) Output voltage $= E_2 = 240$ V

c) Rated value of the output current $I_{2a} = I_1 + I_2 = (10 + 100) = 110$ A

Rated output power $E_2 I_{2a} = 240 \times 110 = 26.4$ kVA

d) Power conducted directly $S_c = E_2 I_1 = 240 \times 10 = 2.4$ kVA

e) Power transformed magnetically $S_m = E_1 I_1 = 2400 \times 10 = 24$ kVA

Also, $S_m = E_2 I_2 = 240 \times 100 = 24$ kVA

Example 7 – Solutions

- Note: Power transferable through induction will always be the transformer rating, while the power transferred through conduction will vary with the autotransformer configuration.
- Complete the solutions for Figs. 47, 49, and 50. Refer to the textbook.

Three-Phase Transformer Banks

- Most power systems utilise three-phase systems. A number of single-phase transformers may be interconnected and used in three-phase systems. Such systems are called **Transformer Banks**.

- The simplest transformer bank utilises three identical single-phase transformers as shown in Fig. 58. The primary and secondary windings can be connected either in **Star** or **Delta** configuration as necessary.

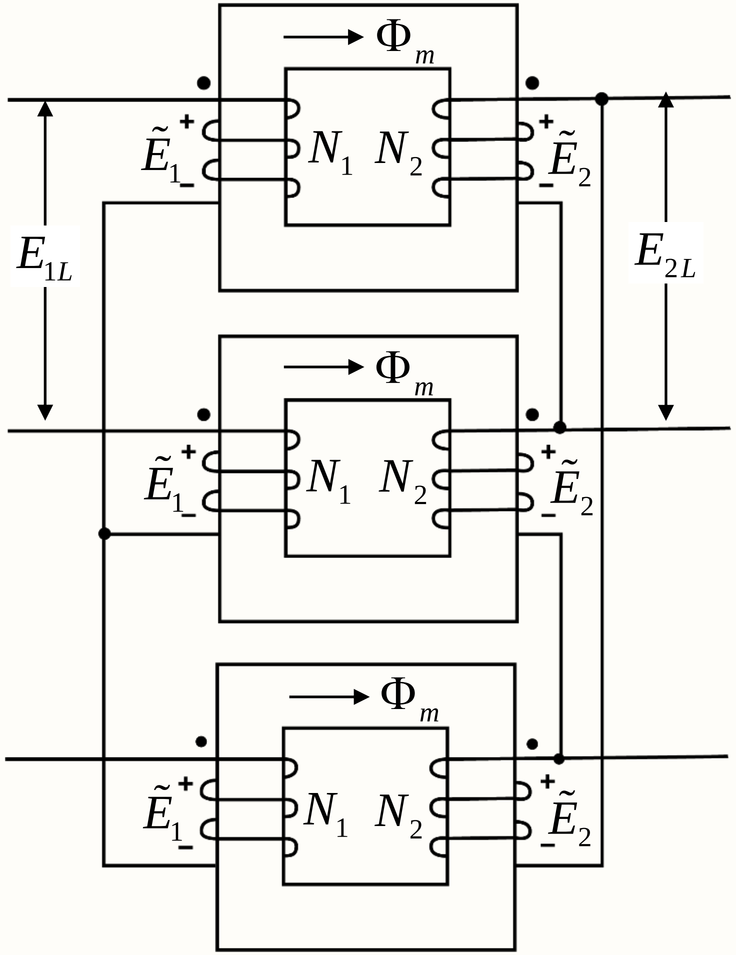


Fig. 58. Three-phase transformer bank.

Three-Phase Transformer Banks

- Note that a transformer bank consists of three separate one phase transformers. There is no common magnetic core. Electrical connections are made externally.

- The ratings of the transformer bank have to be specified by stating the rating of one of the three single-phase transformers.
  - E.g., a transformer bank of 3 x 1-phase, 10 kVA, 440/220 V transformers.

Three-Phase Transformers

- Three-phase transformer has a common magnetic core with three primary and three secondary windings so that they can be connected to three-phase systems, both at the input as well as the output terminals. The magnetic core may be of two types as shown in Figs. 59 and 60.
  - Shell Type
  - Core Type

Three-Phase Transformers

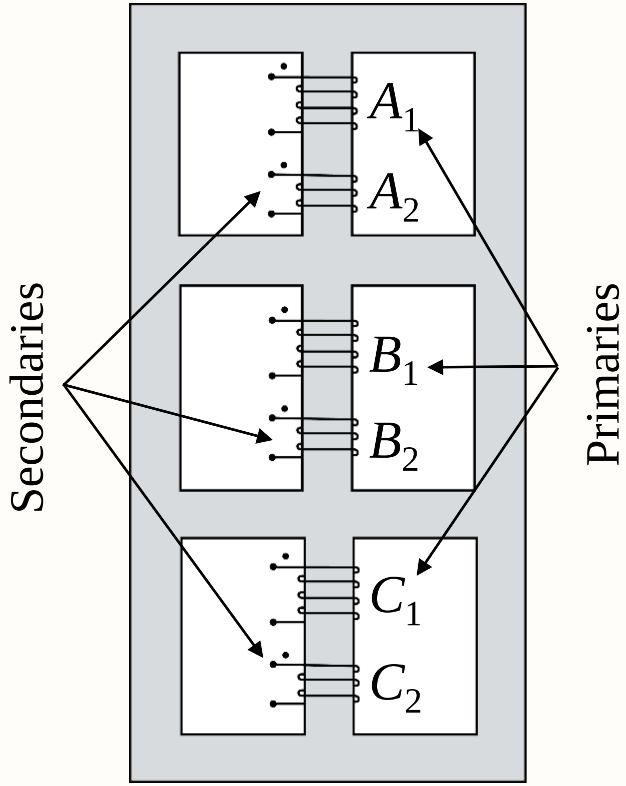


Fig. 59. Shell type three-phase transformer construction.

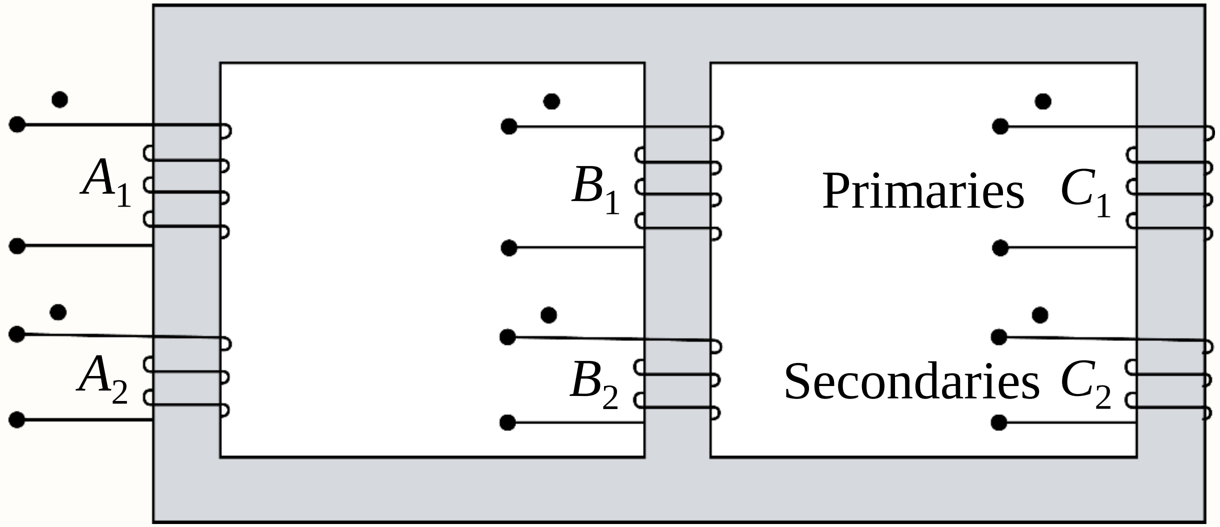


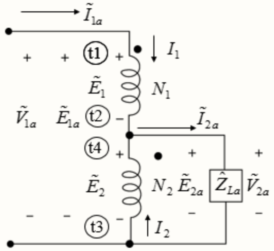
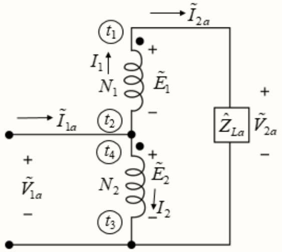
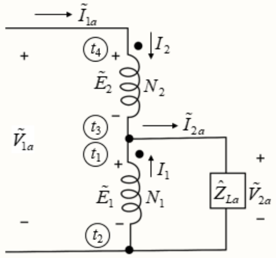
Fig. 60. Core type three-phase transformer construction.

Summary

In this lecture, you have learnt:

- The design and operating principles of autotransformers.
- Analysis of autotransformers to determine the power transferred by induction and the power delivered by conduction.
- The more power transfer capacity of autotransformers than the conventional two-winding transformers.
- The construction of three-phase transformer banks and three-phase transformers.

References

No.	Slide No.	Image	Reference
1	6, 10, 13 and 19		Reprinted from *Electric Machinery and Transformers, 3rd ed.*, (p. 246), by B. S. Guru, & H. R. Hiziroglu, 2001, New York, NY: Oxford University Press. Copyright 2001 by Oxford University Press.
2	6		Reprinted from *Electric Machinery and Transformers, 3rd ed.*, (p. 246), by B. S. Guru, & H. R. Hiziroglu, 2001, New York, NY: Oxford University Press. Copyright 2001 by Oxford University Press.
3	7		Reprinted from *Electric Machinery and Transformers, 3rd ed.*, (p. 246), by B. S. Guru, & H. R. Hiziroglu, 2001, New York, NY: Oxford University Press. Copyright 2001 by Oxford University Press.

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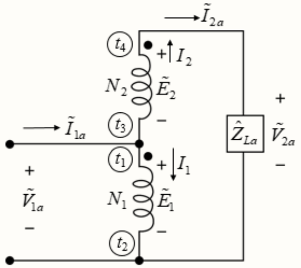
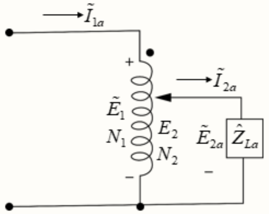
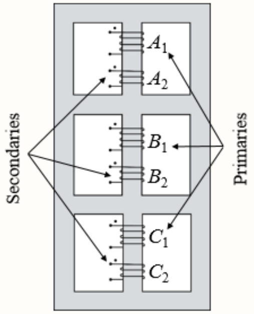
4	7		Reprinted from *Electric Machinery and Transformers, 3rd ed.*, (p. 246), by B. S. Guru, & H. R. Hiziroglu, 2001, New York, NY: Oxford University Press. Copyright 2001 by Oxford University Press.
5	8		Reprinted from *Electric Machinery and Transformers, 3rd ed.*, (p. 246), by B. S. Guru, & H. R. Hiziroglu, 2001, New York, NY: Oxford University Press. Copyright 2001 by Oxford University Press.
6	25		Reprinted from *Electric Machinery and Transformers, 3rd ed.*, (p. 254), by B. S. Guru, & H. R. Hiziroglu, 2001, New York, NY: Oxford University Press. Copyright 2001 by Oxford University Press.

References

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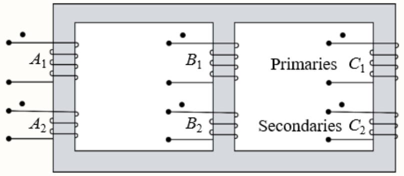
7	25		Reprinted from *Electric Machinery and Transformers, 3rd ed.*, (p. 254), by B. S. Guru, & H. R. Hiziroglu, 2001, New York, NY: Oxford University Press. Copyright 2001 by Oxford University Press.