Lecture 11: 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:

- Explain how open-circuit test and short-circuit test are carried out to determine the transformer shunt parameters R_c and X_m and the transformer series parameters R_e and X_e respectively.

- Apply the shunt and series parameters obtained to develop the approximate equivalent circuits referred to the low-voltage side and the high-voltage side.

- Perform analysis on the approximate equivalent circuits to evaluate the transformer performance.

Transformer Testing: Determination of Parameters

❖ **Open-circuit (OC) Test**

- This test is carried out to determine the shunt parameters $\boldsymbol{R_c}$ and $\boldsymbol{X_m}$ of the transformer. The connection diagram of the test setup is shown in Fig. 37.

- One winding, usually the high-voltage side, is left open. The low-voltage side is supplied with rated voltage at rated frequency.

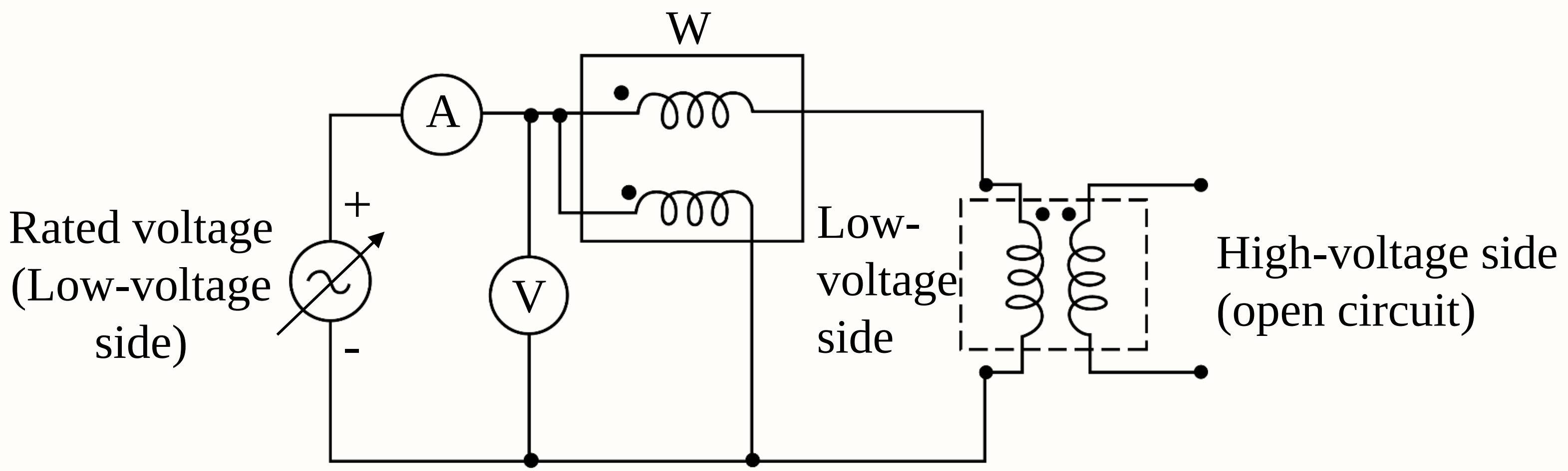

Fig. 37. The connection diagram of the test setup.

Transformer Testing: Determination of Parameters

- The wattmeter, the voltmeter, and the ammeter connected as shown in Fig. 37 are used to record:
  - The applied rated voltage (V_{oc}) V
  - The power input (P_{oc}) W
  - The current drawn (I_{oc}) A

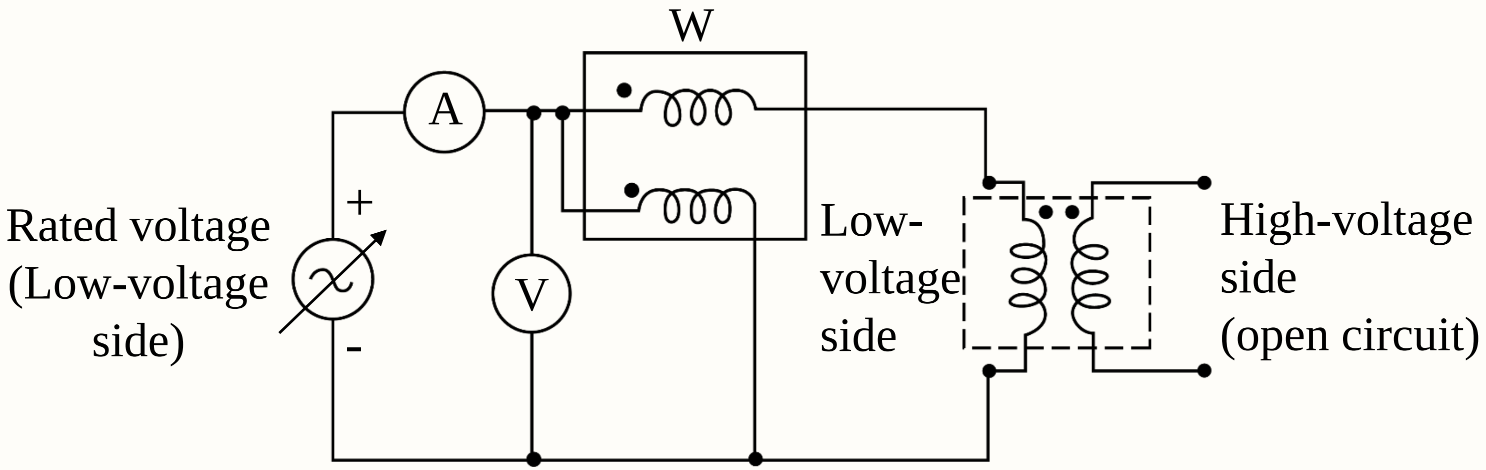

Fig. 37. The connection diagram of the test setup.

Transformer Testing: Determination of Parameters

- The approximate equivalent circuit for the circuit connection during OC test is shown in Fig. 38. Since the test is conducted on the low-voltage (lv) side, the parameters obtained will be the effective value referred to the lv (L) side.

- All the power input during the test is consumed by R_{cL}. Since

$$P_{oc} = \frac{V_{oc}^2}{R_{cL}} \Rightarrow R_{cL} = \frac{V_{oc}^2}{P_{oc}}$$

Then, $I_c = \dfrac{V_{oc}}{R_{cL}}$ A

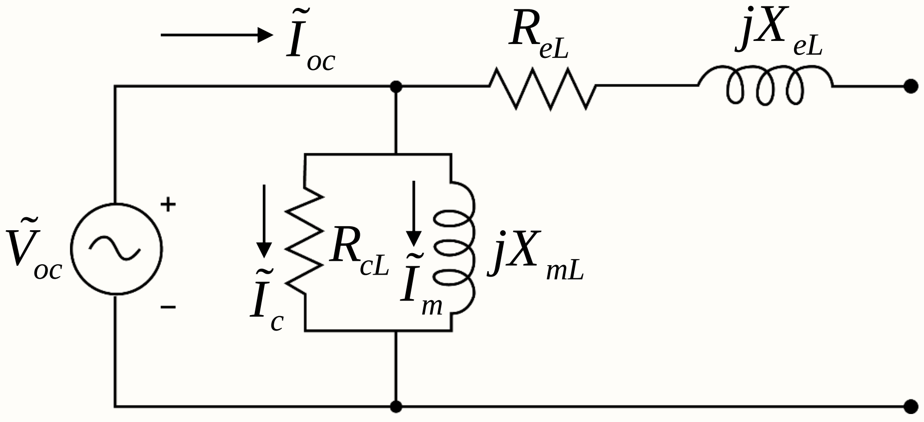

Fig. 38. The approximate equivalent circuit for the circuit connection during OC test.

Transformer Testing: Determination of Parameters

- The phasor relationship between the currents I_c, I_m, and I_{oc} is shown in Fig. 39. Clearly,

$$I_{oc}^2 = I_c^2 + I_m^2 \;\Rightarrow\; I_m = \sqrt{I_{oc}^2 - I_c^2}$$

- Then, $X_{mL} = \dfrac{V_{oc}}{I_m}$

- Thus, the simple data collected from the OC test, V_{oc}, P_{oc} and I_{oc}, can be easily used to calculate the shunt parameters $\boldsymbol{R_{cL}}$ and $\boldsymbol{X_{mL}}$ of the transformer approximate equivalent circuit.

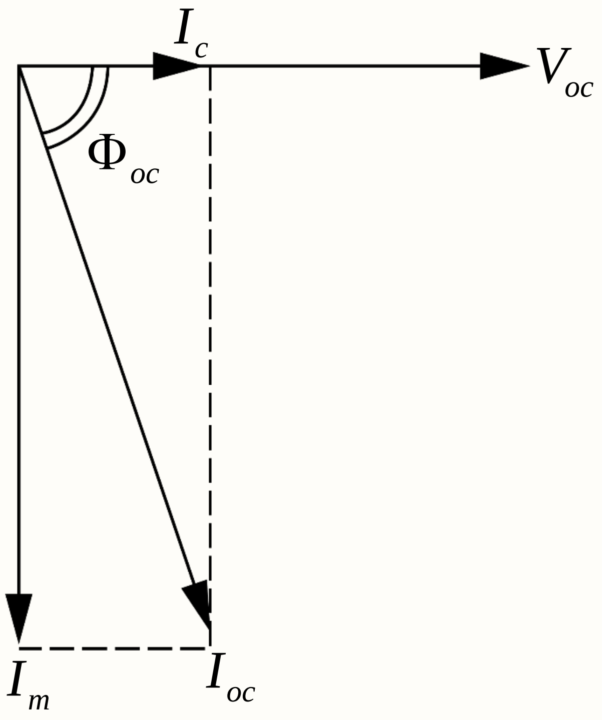

Fig. 39. The phasor diagram.

Transformer Testing: Determination of Parameters

❖ Short-circuit (SC) Test

- This test is carried out to determine the series parameters $\boldsymbol{R_e}$ and $\boldsymbol{X_e}$ of the transformer. The connection diagram of the test setup is shown in Fig. 40.

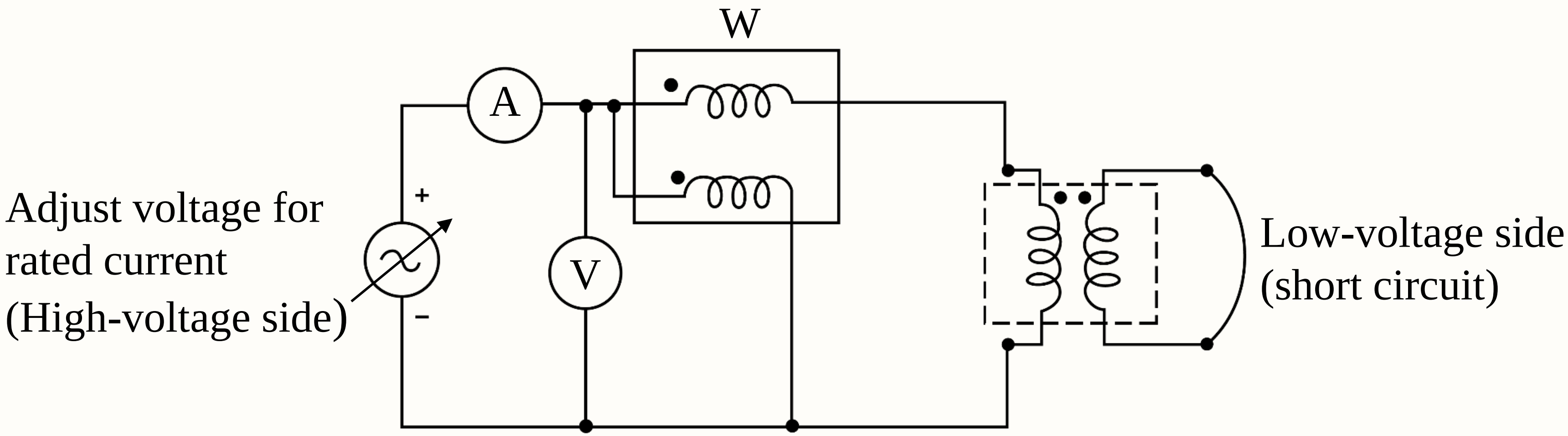

Fig. 40. The connection diagram of the test setup.

Transformer Testing: Determination of Parameters

- One winding, usually the low-voltage side, is short-circuited. The high-voltage side is supplied with a variable voltage source of the rated frequency. The input voltage is kept low ($\approx$5 % of rated voltage), such that rated currents flow in the primary and secondary windings under the short-circuit test condition.

- The wattmeter, the voltmeter, and the ammeter connected as shown in Fig. 40 are used to record:
    - The applied **reduced** voltage (V_{sc}) V
    - The power input (P_{sc}) W
    - The current drawn (I_{sc}) A

Transformer Testing: Determination of Parameters

- The approximate equivalent circuit for the circuit connection during SC test is shown Fig. 41. The test is conducted on the high-voltage (hv) side, so the parameters obtained will be the effective values referred to the hv (H) side.

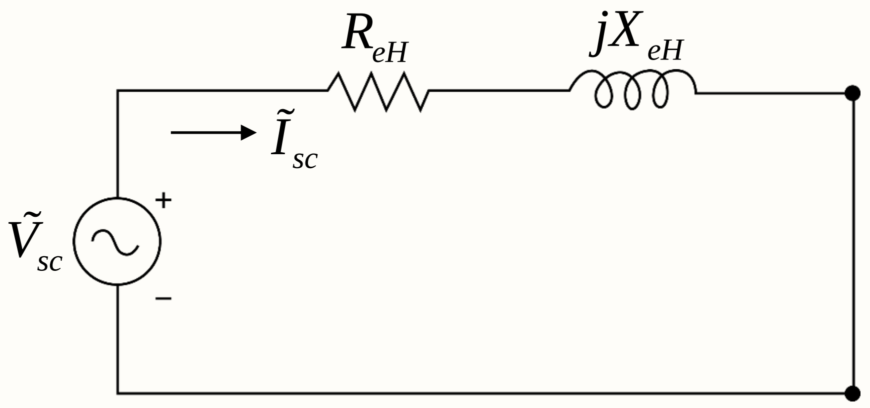

Fig. 41. The approximate equivalent circuit for the circuit connection during SC test.

- All the power input during the test is consumed by R_{eH}:

$$P_{sc} = I_{sc}^2 R_{eH} \Rightarrow R_{eH} = \frac{P_{sc}}{I_{sc}^2}$$

- Also, $Z_{eH} = \dfrac{V_{sc}}{I_{sc}}$, then, clearly: $Z_{eH}^2 = R_{eH}^2 + X_{eH}^2 \Rightarrow X_{eH} = \sqrt{Z_{eH}^2 - R_{eH}^2}$

Transformer Testing: Determination of Parameters

- Thus, the simple set of data collected from the SC test, V_{sc}, P_{sc} and I_{sc}, can be easily used to calculate the total effective values of the series parameters $\boldsymbol{R_{eH}}$ and $\boldsymbol{X_{eH}}$ of the transformer equivalent circuit.

- It must be noted that these two tests are generally conducted on two different sides of the transformer. Therefore, appropriate adjustments of the parameters are required to use them in the same common circuit.

Example 6

The following test data were collected from a 48-kVA, 4800/240-V, 50-Hz transformer:

	Voltage (V)	Current (A)	Power (W)
Open-circuit test	240	2	120
Short-circuit test	150	10	600

Determine the equivalent circuit of the transformer:

a) Referred to the low-voltage side.

b) Referred to the high-voltage side.

(Solutions →)

Example 6 – Solutions

OC test must be done at **rated voltage**.

Therefore, the OC test is conducted on the low-voltage (L) side, and

$V_{oc} = 240$ V, $I_{oc} = 2$ A, and $P_{oc} = 120$ W.

$$P_{oc} = \frac{V_{oc}^2}{R_{cL}} \Rightarrow R_{cL} = \frac{V_{oc}^2}{P_{oc}} = \frac{240^2}{120} = 480\ \Omega, \text{ and } I_c = \frac{V_{oc}}{R_{cL}} = \frac{240}{480} = 0.5\text{ A}$$

Then,

$$I_m = \sqrt{I_{oc}^2 - I_c^2} = \sqrt{2^2 - 0.5^2} = 1.9365\text{ A}, \text{and}$$

$$X_{mL} = \frac{V_{oc}}{I_m} = \frac{240}{1.9365} = 123.94\ \Omega$$

Example 6 – Solutions

SC test is done on the high-voltage (H) side, and

$V_{sc} = 150$ V, $I_{sc} = 10$A, and $P_{sc} = 600$ W

$$R_{eH} = \frac{P_{sc}}{I_{sc}^2} = \frac{600}{10^2} = 6\ \Omega, \text{ and } Z_{eH} = \frac{V_{sc}}{I_{sc}} = \frac{150}{10} = 15\ \Omega$$

$$X_{eH} = \sqrt{Z_{eH}^2 - R_{eH}^2} = \sqrt{15^2 - 6^2} = 13.75\ \Omega$$

Now, the turns ratio of the transformer $a = \frac{4800}{240} = 20$

Therefore, $R_{eH} = 6\ \Omega \Rightarrow R_{eL} = \left(\frac{1}{a^2}\right) R_{eH} = \frac{1}{20^2} \times 6 = 0.015\ \Omega = 15\ \text{m}\Omega$

Example 6 – Solutions

$$X_{eH} = 13.75\ \Omega \Rightarrow X_{eL} = \left(\frac{1}{a^2}\right) X_{eH} = \frac{1}{20^2} \times 13.75 = 0.0344\ \Omega = 34.4\ \text{m}\Omega$$

$$R_{cL} = 480\ \Omega \Rightarrow R_{cH} = a^2 R_{cL} = 20^2 \times 480 = 192\ \text{k}\Omega$$

$$X_{mL} = 123.94\ \Omega \Rightarrow X_{mH} = a^2 X_{mL} = 20^2 \times 123.94 = 49.58\ \text{k}\Omega$$

The approximate equivalent circuits can now be drawn (see Figs. 42 and 43) as follows:

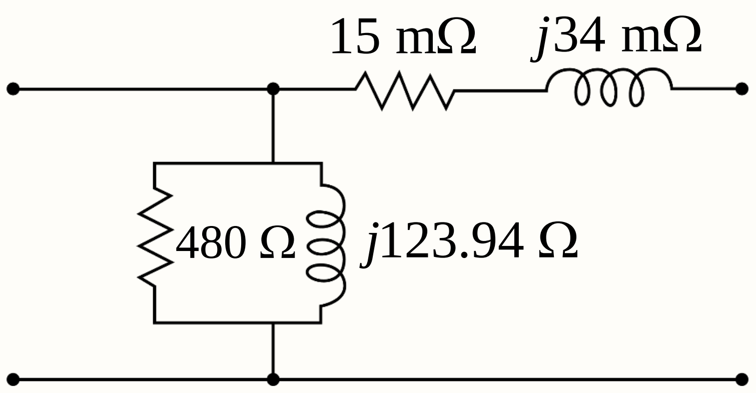

Fig. 42. Referred to low-voltage side.

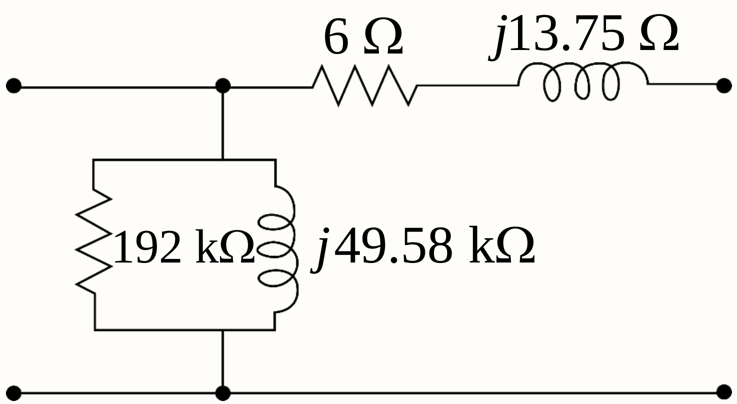

Fig. 43. Referred to high-voltage side.

Summary

In this lecture, you have learnt:

- The transformer testing on open-circuit test and short-circuit test to determine the transformer shunt parameters R_c and X_m and the transformer series parameters R_e and X_e .

- The concepts of using the shunt and series parameters to develop the approximate equivalent circuits referred to the low-voltage side and the high-voltage side.

- Analysis on the approximate equivalent circuits to evaluate the transformer performance.

References

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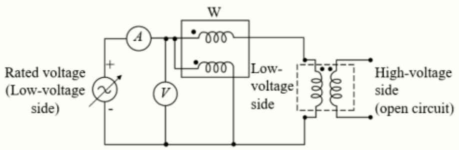
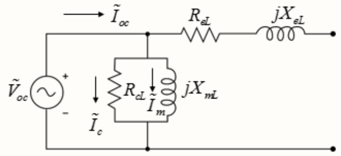
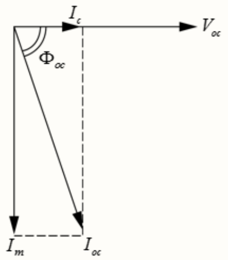
1	4 and 5		Reprinted from *Electric Machinery and Transformers, 3rd ed.*, (p. 233), by B. S. Guru, & H. R. Hiziroglu, 2001, New York, NY: Oxford University Press. Copyright 2001 by Oxford University Press.
2	6		Reprinted from *Electric Machinery and Transformers, 3rd ed.*, (p. 233), by B. S. Guru, & 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. 234), by B. S. Guru, & H. R. Hiziroglu, 2001, New York, NY: Oxford University Press. Copyright 2001 by Oxford University Press. Reprinted with permission.

References

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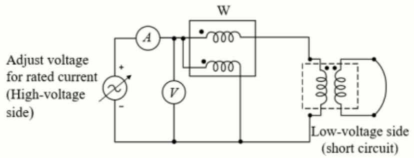
<tr><td>4</td><td>8</td><td>
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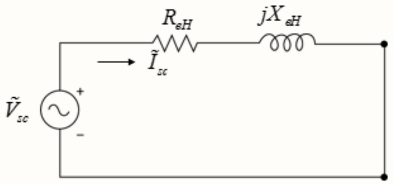
<tr><td>5</td><td>10</td><td>
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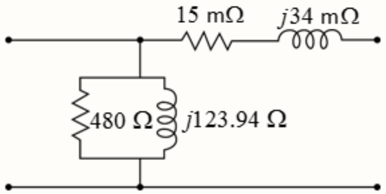
<tr><td>6</td><td>15</td><td>
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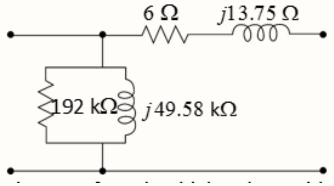
7	15		Reprinted from *Electric Machinery and Transformers, 3rd ed.*, (p. 238), by B. S. Guru, & H. R. Hiziroglu, 2001, New York, NY: Oxford University Press. Copyright 2001 by Oxford University Press.