Lecture Three

Practical Transformer

Single Phase Transformer

1. Practical Transformer

Practical transformers are quite different from the ideal transformers which are studied in theory. .

Parameter	Ideal	Practical
Efficiency	100%	95-99%
Losses	None	Present
Voltage regulation	0%	2-5%
Winding resistance	Zero	Non-zero

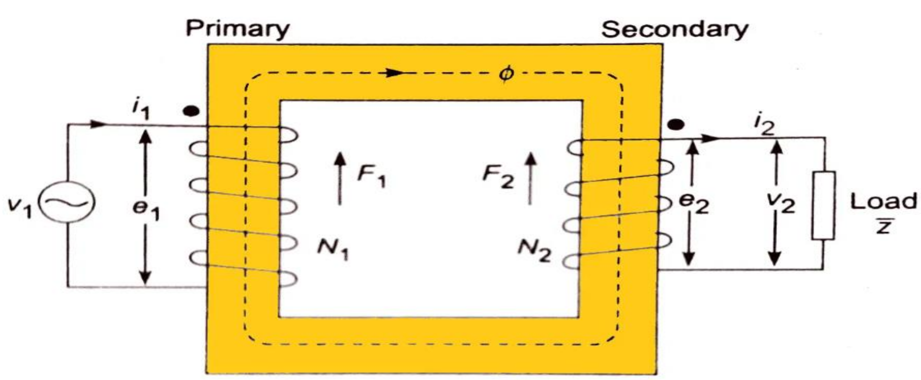


Fig.(1.a)

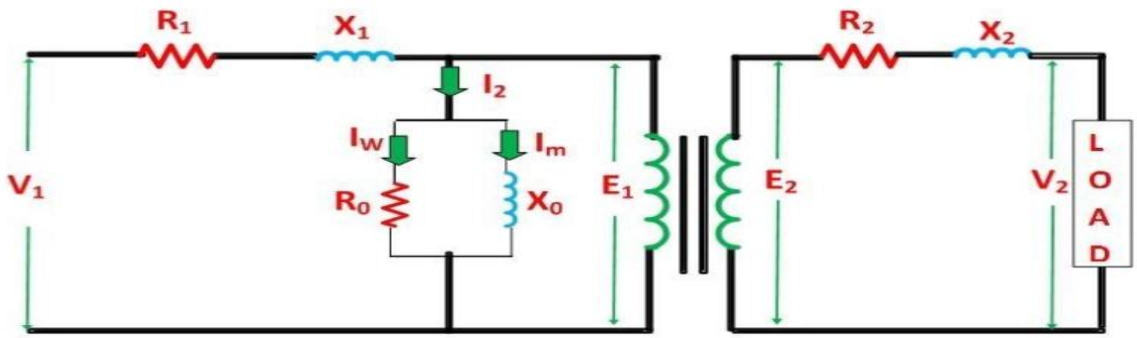


Fig.(1.b)

Fig.(1,a,b) the equivalent circuit of transformer

2. Losses in Practical Transformers

a) Copper Losses (I^2R Losses)

Copper losses occur due to the resistance of the transformer windings. When current flows through the primary and secondary windings, power is lost as heat according to the formula $I_1^2R_1 + I_2^2R_2$. These losses are called variable losses because they change with the load current. As the load increases, the current increases, and since the loss is proportional to the square of the current, copper losses increase rapidly with load.

b) Iron Losses (Core Losses)

Iron losses occur in the transformer core and consist of two components. Hysteresis loss happens due to the repeated magnetization and demagnetization of the core material as the AC magnetic field alternates. Eddy current loss is caused by small circulating currents that flow within the core material itself. These losses are constant and independent of the load because they depend only on the applied voltage and frequency. To reduce eddy current losses, transformer cores are made from thin laminated steel sheets that are insulated from each other.

3. Voltage Regulation

Voltage regulation describes how much the secondary voltage drops when load is applied to the transformer. It is calculated using the formula: % Voltage Regulation = $[(V_{20} - V_2)/V_2] \times 100$, where V_{20} is the no-load voltage and V_2 is the full-load voltage. Several factors affect voltage regulation, including the load current (higher current causes more voltage drop) and the power factor of the load (lagging power factor gives the highest voltage regulation, while leading power factor may even give negative regulation).

Voltage Regulation:

$$VR\% = (V_{20} - V_2)/V_2 \times 100$$

4. Efficiency

Transformer efficiency is the ratio of output power to input power, expressed as a percentage. It can be calculated using the formula: η = (Output Power)/(Output Power + Total Losses) × 100. The efficiency of a transformer varies with load, and there is a specific load at which efficiency is maximum. This maximum efficiency occurs when the copper losses equal the iron losses. At light loads, iron losses dominate, while at heavy loads, copper losses become more significant.

Efficiency: $\eta = \text{Output}/(\text{Output} + \text{Losses}) \times 100$

Maximum Efficiency Load:

$$\text{Load fraction} = \sqrt{(\text{Iron losses}/\text{Full} - \text{load copper losses})}$$

Ex.1: Consider a 50 kVA transformer with copper losses of 800W and iron losses of 600W, operating at 0.8 power factor. find the efficiency at full load,

Solution:

- Output = 50 × 0.8 = 40 kW
- Total losses = 800 + 600 = 1400W
- Efficiency = 40000/(40000 + 1400) × 100 = **96.6%**

Ex.2: For a transformer with iron losses of 500W and full-load copper losses of 800W, find the load at which efficiency is maximum.

Solution: Load for max efficiency = √(500/800) = 0.79 = 79% of full load

Theory of Operation: The transformer operates on two main phenomena:

1. Electromagnetic Induction: When AC current flows through the primary winding, it creates a varying magnetic flux in the core.
2. Mutual Induction: The varying flux links the secondary winding and induces an EMF according to Faraday's law.

The instantaneous EMF is given by: $\boldsymbol{e = 2\pi \emptyset f \cdot N \cdot \sin\theta}$

The RMS value is: $E = 4.44 \cdot \emptyset_{\mathrm{m}} \cdot f \cdot N$

Where:

- Ø = Magnetic flux
- f = Frequency
- N = Number of turns
- $Ø_m$ = Maximum flux

✓ For the primary: $E_1 = 4.44 \cdot Ø_m \cdot f \cdot N_1$ For the secondary: $E_2 = 4.44 \cdot Ø_m \cdot f \cdot N_2$

Ex.:A single-phase transformer rated 50 kVA, 2200/250V, 50Hz has core cross-sectional area 36 cm^2 and maximum flux density 1.2 T.

Find: Number of primary and secondary turns, and transformation ratio.

Solution: $Øm = B \times A = 1.2 \times 36 \times 10^{-4} = 0.0432$ Wb

$N_1 = E_1/(4.44 \times Øm \times f) = 2200/(4.44 \times 0.0432 \times 50) = 229$ turns

$N_2 = E_2/(4.44 \times Øm \times f) = 250/(4.44 \times 0.0432 \times 50) = 26$ turns

$K = N_1/N_2 = 229/26 = 8.8$

5. Types of Practical Transformers

5.1 Power Transformers

Power transformers are used in electrical power transmission systems to step up voltage for efficient long-distance transmission or step down voltage for distribution. These large transformers range from 1 MVA to 1000 MVA and achieve very high efficiencies of 98-99.5%. They are typically oil-immersed and use sophisticated cooling systems to handle the large amounts of power they process.

5.2 Distribution Transformers

Distribution transformers are used in the final stages of power distribution to provide the appropriate voltage levels for end users. They typically range from 25 kVA to 2.5 MVA and achieve efficiencies of 96-98%. These transformers may be oil-filled for outdoor installations or dry-type for indoor use where fire safety is a concern.

6. Open-Circuit and Short-Circuit Tests on a Transformer

A transformer's efficiency and voltage regulation depend on its equivalent circuit parameters. To determine these parameters practically, two standard tests are performed:

1. **Open-Circuit (OC) Test** – determines **core (iron) losses** and **magnetizing parameters**.
2. **Short-Circuit (SC) Test** – determines **copper losses** and **series parameters**.

1. Open-Circuit Transformer (Theory)

When a transformer operates under **open-circuit conditions**, one of its windings (usually the secondary) is left **open**, meaning **no load** is connected to it. In this state, the transformer draws only a **small current** from the supply connected to the primary winding.

1. Definition

A **transformer is said to be open-circuited** when the secondary winding is not connected to any external circuit, while the primary winding is connected to its rated voltage source.

This condition is also called the **no-load condition**, because no current flows in the secondary winding, and therefore, no load power is delivered.

When the primary winding of the transformer is connected to an AC supply and the secondary winding is open:

- A **small current** called the **no-load current (I_0)** flows in the primary.
- This current produces an **alternating magnetic flux (Φ)** in the transformer core.
- The alternating flux links both windings and induces:
  - **Primary induced emf (E_1)**
  - **Secondary induced emf (E_2)**

3. Phasor Diagram

The no-load current (I_0) in the primary has two components:

1. **Magnetizing component ((Im))** produces the mutual flux in the core.
2. **Core loss component ((Iw))** accounts for hysteresis and eddy current losses in the core.

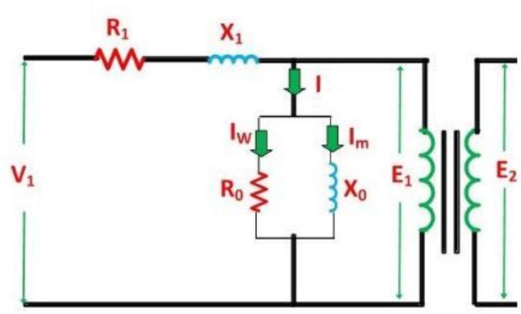
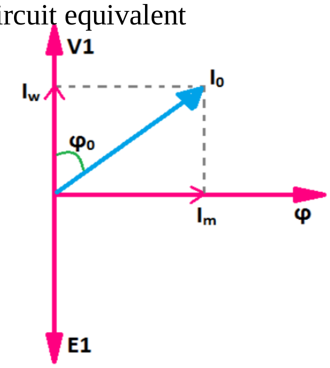


Fig.(2) the open circuit equivalent



Thus, $I_0 = \sqrt{Im^2 + Iw^2}$

$$Im = I_0 \times \sin \varphi_0$$
$$Iw = I_0 \times \cos \varphi_0$$

The input power under open-circuit condition mainly covers the **iron losses** (core losses) and a very small amount of **copper loss** due to (I_0).

4. Power Flow under Open Circuit

Since the secondary side is open:

- **No power** is transferred to the secondary circuit.
- The **input power** is only used to supply:
  - **Core (iron) losses** in the transformer.
  - **Negligible copper losses** in the primary winding.

Hence, total input power ≈ iron loss.

5. Equivalent Circuit under Open Circuit

In the equivalent circuit representation:

- The **magnetizing branch** (containing (Rc) and (Xm) is considered.
- The **load branch** is absent since the secondary current is zero as shown Fig.2.
- Therefore, the transformer behaves as a **magnetizing circuit** drawing a small current to maintain the alternating flux.

Ex. A **50 kVA, 2400/240 V, 60 Hz** single-phase transformer is subjected to an open circuit test. The following readings are obtained when rated voltage is applied to the **low-voltage side**: Voltage: $V_0 = 240$ V, Current: $I_0 = 1.2$ A, Power: $P_0 = 120$ W

Find:

1. The core loss
2. The no-load power factor
3. The core loss component of current (Iw)
4. The magnetizing component of current (Im)

Sol.

1. Core Loss:

$$Core\ Loss = P_0 = 120\ W$$

2. No-Load Power Factor:

$$\cos\varphi_0 = P_0 / (V_0 \times I_0)$$

$$\cos\varphi_0 = 120 / (240 \times 1.2)$$

$$\cos\varphi_0 = 120 / 288$$

$$\cos\varphi_0 = 0.417\ (lagging)$$

3. Core Loss Component:

$$Iw = I_0 \times \cos\varphi_0$$

$$Iw = 1.2 \times 0.417$$

$$Iw = 0.50\ A$$

4. Magnetizing Component:

$$\sin\varphi_0 = \sqrt{(1 - \cos^2\varphi_0)} = \sqrt{(1 - 0.417^2)} = 0.909$$

$$Im = I_0 \times \sin\varphi_0$$

$$Im = 1.2 \times 0.909$$

$$Im = 1.09\ A$$

Alternative Method for Im:

$$Im = \sqrt{(I_0{}^2 - Ic^2)}$$

$$Im = \sqrt{(1.2^2 - 0.50^2)}$$

$$Im = \sqrt{(1.44 - 0.25)}$$

$$Im = 1.09\ A$$

Ex. A **25 kVA, 2000/200 V, 50 Hz** transformer is tested with the following results:

Open Circuit Test (LV side): Voltage: 200 V, Current: 1.5 A, Power: 90 W

Find:

1. The core loss resistance (Rc) referred to LV side
2. The magnetizing reactance (Xm) referred to LV side

Sol.:

Step 1: Calculate Power Factor and Current Components

$$\cos\varphi_0 = P_0 / (V_0 \times I_0)$$

$$\cos\varphi_0 = 90 / (200 \times 1.5) = 90 / 300 = 0.30$$

$$Ic = I_0 \times \cos\varphi_0 = 1.5 \times 0.30 = 0.45\ A$$

$$\sin\varphi_0 = \sqrt{}(1 - 0.30^2) = \sqrt{}(1 - 0.09) = 0.954$$

$$Im = I_0 \times \sin\varphi_0 = 1.5 \times 0.954 = 1.43\ A$$

Step 2: Calculate Core Loss Resistance (Rc)

Method 1:

$$Rc = V_0 / Ic$$

$$Rc = 200 / 0.45$$

$$Rc = 444.4\,\Omega$$

Method 2:

$$Rc = {V_0}^2 / P_0$$

$$Rc = 200^2 / 90 = 40{,}000 / 90$$

$$Rc = 444.4\,\Omega$$

Step 3: Calculate Magnetizing Reactance (Xm)

$$Xm = V_0 / Im$$

$$Xm = 200 / 1.43$$

$$Xm = 139.9\,\Omega$$

Final Answer:

- **Rc = 444.4 Ω** (referred to LV side)
- **Xm = 139.9 Ω** (referred to LV side)

Problems

- **PROBLEM 1:** A **75 kVA, 3300/400 V, 50 Hz** single-phase transformer is tested under open circuit conditions. The test is performed on the **low-voltage side** with the following readings:

Given:

- Voltage: $V_0 = 400$ V
- Current: $I_0 = 3.5$ A
- Power: $P_0 = 350$ W

Calculate:

1. The core loss
2. The no-load power factor
3. The working component of current (Iw)
4. The magnetizing component of current (Im)
5. Verify $I_0 = \sqrt{(Iw^2 + Im^2)}$

- **PROBLEM 2:** A **40 kVA, 4000/200 V, 60 Hz** transformer gave the following results during an open circuit test conducted on the **LV side**:

Given:

- Voltage: $V_0 = 200$ V
- Current: $I_0 = 2.8$ A

- Power: P_0 = 180 W

Calculate:

1. The working component (Iw) and magnetizing component (Im) of no-load current
2. The core loss resistance (Rc) referred to the LV side using both methods:
   - Method 1: $Rc = V_0/Iw$
   - Method 2: $Rc = V_0^2/P_0$
3. The magnetizing reactance (Xm) referred to the LV side ($Xm = V_0/Im$)
4. Verify your answer by calculating I_0 from Rc and Xm

- **PROBLEM 3:** A **50 kVA, 6600/660 V, 50 Hz** transformer is tested:

Open Circuit Test (performed on LV side):

- Voltage: 660 V
- Current: 2.0 A
- Power: 500 W

Calculate:

1. Iw and Im components
2. Rc and Xm referred to the **LV side**
3. Calculate the turns ratio (a)
4. Rc and Xm referred to the **HV side**

Hint: Use the transformation formula: $Z\_HV = a^2 \times Z\_LV$

- **PROBLEM 6:** A **20 kVA, 2200/220 V, 50 Hz** transformer gives the following OC test results on LV side:

Given:

- $V_0 = 220$ V
- $I_0 = 1.8$ A
- $P_0 = 150$ W

Calculate:

1. $\cos \varphi_0$ and $\sin \varphi_0$
2. Iw and Im
3. Rc and Xm referred to LV side
4. Refer Rc and Xm to HV side