Introduction to Transformers

What is a Transformer?

- Definition: A static (non-moving) electrical device that transfers electrical energy between two or more circuits.
- Core Function: It changes (steps up or steps down) the voltage and current levels of an alternating current (AC) system without changing the power or frequency.
- Static Nature: Because it has no moving parts, it is highly efficient and requires very little maintenance.

The Necessity of Transformers

- Power Generation: Electricity is generated at relatively low voltages .
- Transmission Challenge: Transmitting low voltage over long distances causes huge energy losses due to resistance .
- The Solution: Transformers step up the voltage for efficient transmission (reducing current) and then step down the voltage for safe use in homes and factories.

The Underlying Principle: Mutual Induction

- Principle: Transformers work purely on the principle of mutual induction, which is a consequence of Faraday's Law of Electromagnetic Induction.
- Mutual Induction: The phenomenon where a changing magnetic flux created by one coil (the primary) links to and induces a voltage in a nearby second coil (the secondary).

Faraday's Law of Electromagnetic Induction (Review)

- Statement: Whenever there is a change in the magnetic flux linking a circuit, an electromotive force (EMF) is induced in that circuit.
- Requirement for Transformers: The input must be Alternating Current (AC) because AC creates a continuously *changing* magnetic flux.
- DC Input: A transformer cannot operate on Direct Current (DC) because DC produces a steady magnetic field, meaning the flux is not changing , so no EMF is induced.

Essential Components of a Transformer

- A basic transformer consists of three main parts:

1. **Primary Winding:** The coil connected to the AC source (input side).
2. **Secondary Winding:** The coil connected to the load (output side).
3. **Core:** The soft iron magnetic path that links the two windings.

The Core: The Magnetic Link

- Function: Provides a low-reluctance (easy) path for the magnetic flux to flow between the primary and secondary windings, minimizing magnetic leakage.
- Material: Usually made of silicon steel because it has high permeability (can be easily magnetized) and low hysteresis loss.
- Structure: The core is not one solid piece of metal but is constructed from thin, insulated sheets called laminations.

The Windings (Coils)

- Material: Made of highly conductive material, typically copper or sometimes aluminum.
- Insulation: Each turn is electrically insulated from the adjacent turns and the core to prevent short circuits.
- Turns: The number of turns in the primary and secondary coils is the defining factor for the voltage transformation.

The Transformation Ratio

- The Transformation Ratio is the ratio of the secondary voltage to the primary voltage, which is equal to the ratio of the secondary turns to the primary turns.
- This is the most important formula for understanding transformer operation.

Step-Up Transformers

- Voltage: The secondary voltage is greater than the primary voltage.
- Turns: The number of secondary turns is greater than the number of primary turns .
- Transformation Ratio (K): .
- Application: Used at power generating stations to increase voltage for transmission.

Step-Down Transformers

- Voltage: The secondary voltage is less than the primary voltage .
- Turns: The number of secondary turns () is less than the number of primary turns .
- Transformation Ratio (K): .
- Application: Used near consumers and factories to reduce high transmission voltage to safe usage levels.

The Ideal Transformer: Assumptions

•An **ideal transformer** is a hypothetical model used to simplify initial analysis. It assumes:

1.No Winding Resistance: Windings have zero resistance.

2.No Core Losses: No eddy current or hysteresis losses.

3.Zero Leakage Flux: All flux produced by the primary links the secondary.

4.100% **Efficiency:** Output power equals input power.

Ideal Transformer Power Relation

- In an ideal transformer, the input power (P_{in}) must equal the output power (P_{out}).

$$P_{in} = P_{out}$$

$$V_p I_p = V_s I_s$$

- This relationship reveals a crucial inverse principle.

The Inverse Current Relationship

- From the power equation ($V_p I_p = V_s I_s$):

$$\frac{V_s}{V_p} = \frac{I_p}{I_s}$$

- **Conclusion:** If the voltage is stepped up (e.g., $V_s > V_p$), the current must be stepped down (e.g., $I_s < I_p$), and vice versa.
- The transformer conserves power: it trades voltage for current.

Voltage, Current, and Turns Ratios (Summary)

- All ratios are linked through the constant transformation ratio (K):

$$\mathrm{K} = \frac{N_s}{N_p} = \frac{V_s}{V_p} = \frac{I_p}{I_s}$$

- Note the inversion for the current ratio ($\frac{I_p}{I_s}$ versus $\frac{N_s}{N_p}$).

Real Transformers: Introduction to Losses

- In reality, no transformer is truly ideal; they all have losses. A typical large transformer has an efficiency of to .
- Transformer losses are categorized into two main types:
  - **Core Losses (Iron Losses):** Occur in the core material.
  - **Copper Losses:** Occur in the windings.

Core Losses: Hysteresis Loss

- Cause: The alternating magnetic flux repeatedly magnetizes and demagnetizes the iron core material.
- Mechanism: Energy is required to overcome the magnetic friction within the core material during each cycle.
- Minimization: Using high-grade silicon steel for the core, which has a narrow hysteresis loop, helps reduce this loss.

Core Losses: Eddy Current Loss

- Cause: Induced circulating currents within the core material
- Mechanism: These currents flow against the core's resistance, dissipating power as heat .
- Minimization: Using laminated core sheets (thin, insulated layers).

Summary of Core Losses

- Nature: Core losses are relatively constant for a given voltage and frequency, regardless of the load connected to the secondary side.
- Test: They are measured by the Open-Circuit Test (No-Load Test).

Copper Losses

- **Cause:** Power lost due to the **resistance** of the primary and secondary windings.
- **Mechanism:** When current flows through the windings, heat is dissipated according to the formula: $P_{Cu} = I_p^2 R_p + I_s^2 R_s$.
- **Nature:** Copper losses are **variable** because they are proportional to the square of the current, which changes with the load.

Minimization of Copper Losses

- Method: Using winding conductors with a large enough cross-sectional area (thick wire) to keep the resistance as low as possible.
- Test: They are measured by the Short-Circuit Test.

Efficiency of a Transformer

Definition: The ratio of the output power to the input power.

$$\text{Efficiency}(\eta) = \frac{\text{Output Power}}{\text{Input Power}}$$

Or, in terms of losses:

$$\eta = \frac{\text{Input Power} - \text{Losses}}{\text{Input Power}} = 1 - \frac{\text{Losses}}{\text{Input Power}}$$

Condition for Maximum Efficiency

- A transformer achieves its maximum efficiency when the variable losses (Copper Losses) are equal to the constant losses (Core Losses).
- This condition determines the optimal load at which the transformer should operate.

Types of Transformer Construction: Core Type

- Structure: The windings surround a central core column. The copper windings completely enclose the steel core.
- Shape: Typically has long, cylindrical coils.
- Application: Suitable for high-voltage, low-current power systems. Easier to repair and insulate.

Types of Transformer Construction: Shell Type

- Structure: The core completely surrounds the windings. The steel core encloses the copper windings.
- Shape: Windings are often short and stacked (sandwiched).
- Application: Suitable for low-voltage, high-current applications. Provides better mechanical protection and insulation.

Classification by Cooling Method

- Since losses produce heat, transformers need cooling.
- Air-Cooled (Dry Type): Used for small transformers. Air circulates naturally or by fans.
- Oil-Immersed: Used for large power transformers. The core and windings are immersed in insulating oil.

The Dual Role of Transformer Oil

- Cooling: The oil absorbs heat from the windings and core and transfers it to the tank walls, which then dissipates it to the atmosphere.
- Insulation: The oil provides excellent electrical insulation between the windings and the tank.

Applications in Power Systems (Generation to Home)

- Step 1: Generation: Generator produces power at power generating stations .
- Step 2: Transmission Substation: Step-Up transformer boosts voltage to extra-high levels
- Step 3: Receiving Substation: Step-Down transformer reduces voltage to a medium level
- Step 4: Distribution Substation: Further Step-Down to primary distribution levels
- Step 5: Pole/Pad Transformer: Final Step-Down to consumer voltage

Isolation Transformers

- Ratio: $N_p = N_s$, so $V_p = V_s$ ($\mathrm{K} = 1$).
- **Function:** Does not change the voltage, but provides **electrical isolation** between the input and output circuits.
- **Application:** Used for safety purposes in laboratories and specialized electronic equipment to prevent shock hazards.

Autotransformers

- Structure: Uses a single winding that acts as both the primary and secondary winding.
- Advantage: Smaller, cheaper, and more efficient than a two-winding transformer for a given rating.
- Limitation: Provides no electrical isolation between the primary and secondary circuits.

Instrument Transformers: Potential Transformer (PT)

- Function: A high-accuracy Step-Down transformer used to measure high AC voltages safely.
- Safety: Reduces the high system voltage down to a very low, safe, standard voltage for measurement instruments like voltmeters.

Instrument Transformers: Current Transformer (CT)

- Function: A high-accuracy Step-Up transformer used to measure high AC currents safely.
- Safety: Steps down the high system current to a very low, safe, standard current for measurement instruments like ammeters.

Inrush Current Phenomenon

- The Problem: When a transformer is first energized (switched on), it draws a large, momentary surge of current from the supply.
- Cause: This inrush current occurs because the magnetic core may have residual magnetism from previous operation, causing the flux to momentarily exceed its normal limit.
- Duration: Lasts only for a few cycles, but it is typically several times the normal full-load current.

Thank you

Shamna Subaida Khalid
shamnaplpy@gmail.com