Unit 4
Transformer and DC Machines

TRANSFORMER

FARADAY'S LAWS OF ELECTROMAGNETIC INDUCTION

Faraday's laws form the basis of the operation of electrical machines like transformers, generators, and motors.

Faraday's First Law

It states that:

"Whenever there is a change in magnetic flux linked with a coil, an EMF is induced in the coil."

Mathematically,

If a magnetic flux Φ (in Weber) changes with time, the induced EMF (electromotive force) is:

$$EMF \propto \frac{d\phi}{dt}$$

Faraday's Second Law

"The magnitude of the induced EMF is directly proportional to the rate of change of magnetic flux."

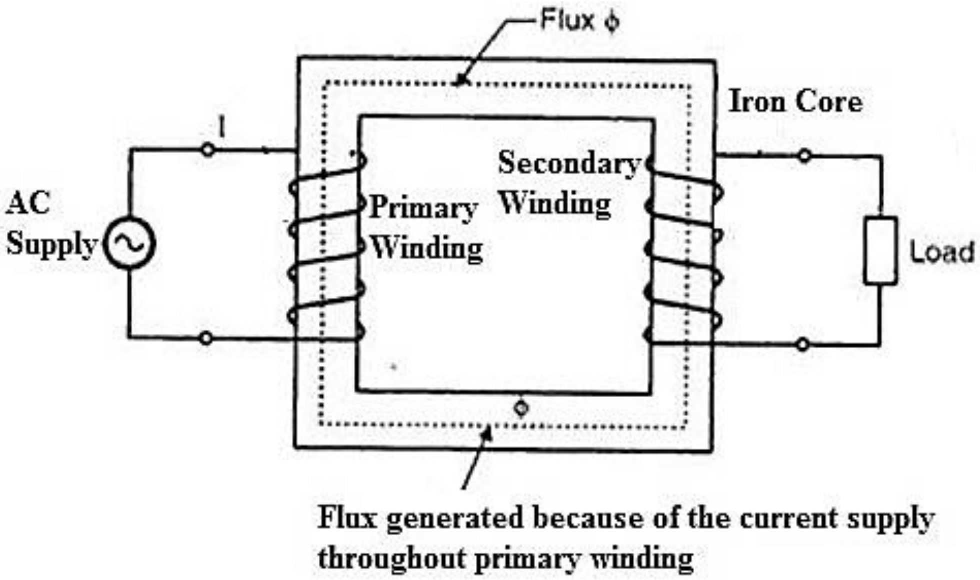
$$e = -N\frac{d\phi}{dt}$$

Where:

- e = induced EMF (Volts)
- N = number of turns in the coil
- $\frac{d\phi}{dt}$ = rate of change of flux
- Minus sign (–) represents Lenz's Law (induced EMF opposes the change in flux).

CONSTRUCTION AND OPERATION OF SINGLE-PHASE TRANSFORMER

A single-phase transformer is a static electrical device that transfers electrical energy between two circuits through electromagnetic induction.



Construction of Single-Phase Transformer

A single-phase transformer mainly consists of the following parts:

Core:

- Made of laminated soft iron sheets.
- Provides a low reluctance path for magnetic flux.
- Laminations reduce eddy current losses.

Windings (Primary and Secondary):

- Primary winding: Connected to the AC power source.
- Secondary winding: Connected to the load.
- Made of copper and insulated properly.
- Both windings are wound on the same core limbs but insulated from each other.

Insulation:

- Electrical insulation (like varnish or paper) is used to avoid short-circuits.
- Insulation is between layers of windings and core.

Tank and Cooling System:

- The whole unit is enclosed in a steel tank.
- Filled with transformer oil (for insulation and cooling).
- Cooling provided by radiators, fins, or fans in large transformers.

Bushings and Terminals:

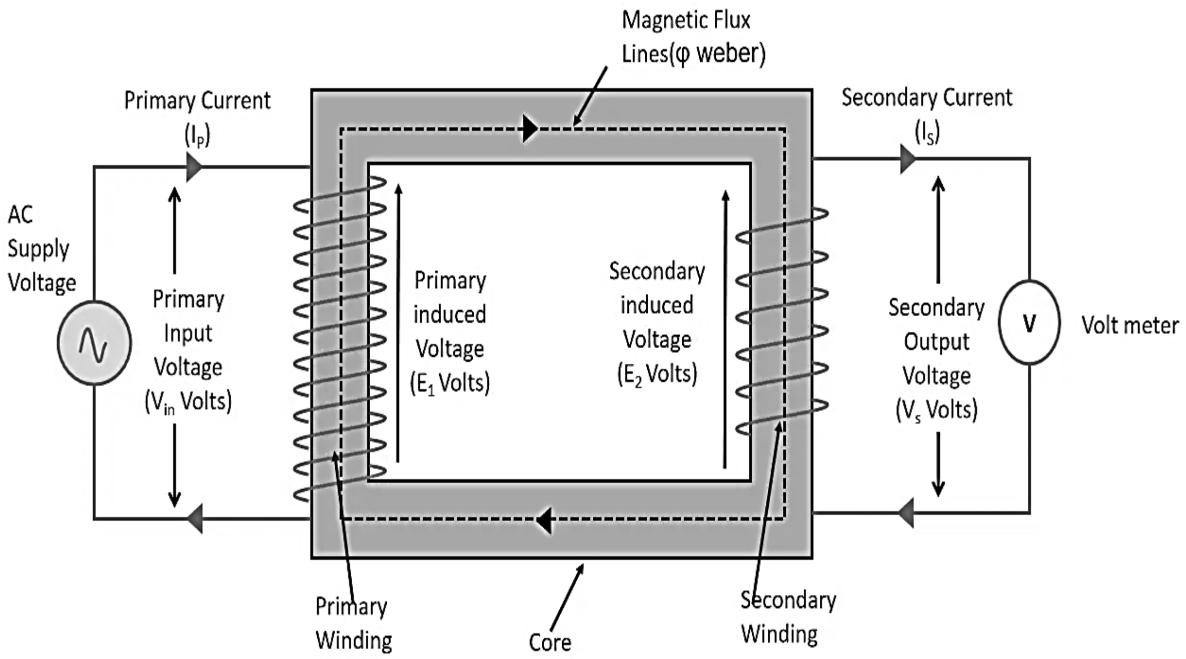
- High-voltage ceramic insulators allow wire connections through the tank safely.
- Terminals provided for connection of primary and secondary wires.

Operation of Single-Phase Transformer

The transformer works on the principle of mutual induction, which depends on Faraday's Law of Electromagnetic Induction.

Depending on winding turns:

- Step-Up Transformer: Increases voltage.
- Step-Down Transformer: Decreases voltage.



Step-by-step operation:

1. AC supply is given to the primary coil.
2. This produces an alternating magnetic flux in the core.

3. The flux links both windings through the core.
4. According to Faraday's Law, an EMF is induced in the secondary winding.
5. If the secondary circuit is connected to a load, current flows due to the induced EMF.
6. The voltage is either stepped up or stepped down depending on the turn ratio.

$$\frac{\mathrm{E}_1}{\mathrm{E}_2} = \frac{\mathrm{V}_1}{\mathrm{V}_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1}$$

Where:

- $\mathrm{E}_1, \mathrm{E}_2$: Primary and Secondary EMF
- $\mathrm{V}_1, \mathrm{V}_2$: Primary and Secondary Voltages
- $\mathrm{N}_1, \mathrm{N}_2$: Number of Turns in Primary and Secondary Coils
- $\mathrm{I}_1, \mathrm{I}_2$: Currents in Primary and Secondary Coils

EMF EQUATION

Let

- $\mathrm{N}_1 =$ number of turns in primary winding
- $\mathrm{N}_2 =$ number of turns in secondary winding
- $\phi_\mathrm{m} =$ maximum value of mutual flux (in Weber)
- f = frequency of AC supply (in Hz)

The flux ϕ is assumed sinusoidal:

$$\phi(t) = \phi_m \, sin(\omega t)$$

From Faraday's law of electromagnetic induction,

$$e = -N\frac{d\phi}{dt}$$

For sinusoidal flux:

$$\frac{d\phi}{dt} = \phi_m \cos(\omega t)$$

As $cos(\omega t) = sin(\omega t + 90°)$

This means EMF is also sinusoidal and leads flux by 90°.

Peak value of EMF:

$$E_{max} = \mathrm{N} \cdot \omega \cdot \phi_m = 2\pi f \mathrm{N} \phi_m \qquad [\because \omega = 2\pi f]$$

RMS value:

$$\mathrm{E} = \frac{E_{max}}{\sqrt{2}} = \frac{2\pi f \mathrm{N}\phi_m}{\sqrt{2}} = 4.44 f \mathrm{N} \phi_m$$

Final EMF Equations:

- Primary EMF (E_1):

$$E_1 = 4.44 f N_1 \phi_m$$

- Secondary EMF (E_2):

$$E_2 = 4.44 f N_2 \phi_m$$

Transformer Turn Ratio (k):

$$k = \frac{\mathrm{E}_1}{\mathrm{E}_2} = \frac{N_1}{N_2}$$

VOLTAGE AND CURRENT RELATIONSHIPS

A transformer works on the principle of electromagnetic induction and has two windings:

- Primary winding (connected to supply)
- Secondary winding (connected to load)

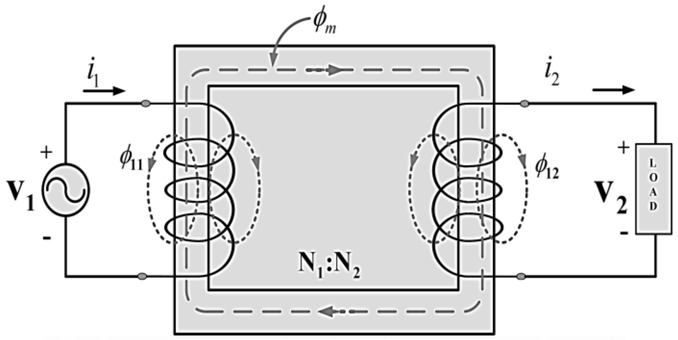
Voltage Relationship (Assuming an ideal transformer)

$$\frac{V_1}{V_2} = \frac{N_1}{N_2}$$

Where:

- V_1: Primary voltage
- V_2: Secondary voltage
- N_1: Number of primary turns
- N_2: Number of secondary turns

Step-up transformer: $N_2 > N_1 \rightarrow V_2 > V_1$
Step-down transformer: $N_2 < N_1 \rightarrow V_2 < V_1$



Current Relationship (Assuming ideal and lossless transformer)

$$\frac{I_2}{I_1} = \frac{N_1}{N_2} \quad \text{or} \quad V_1 I_1 = V_2 I_2$$

Power is conserved in an ideal transformer:

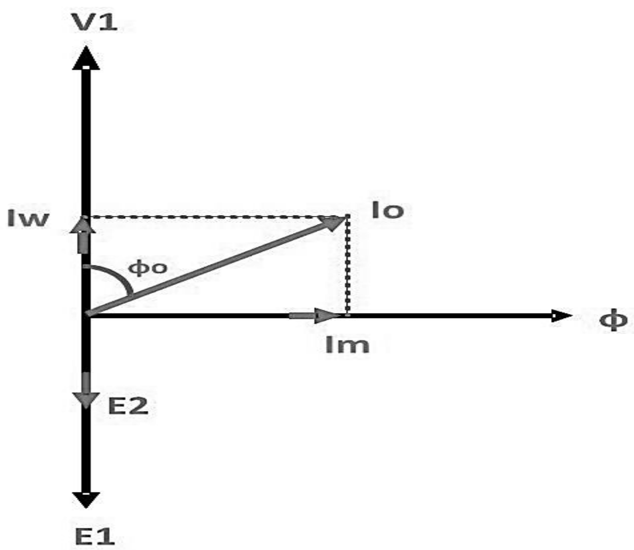
$$Input\ Power = Output\ Power$$

PHASOR DIAGRAM OF IDEAL TRANSFORMER AT NO-LOAD AND LOADED CONDITIONS

For No-Load

The secondary winding is open, i.e., $I_2 = 0$, and only a small no-load current (I_0) flows in the primary.

- V_1: Primary voltage (Reference phasor)
- I_0: No-load current, lags behind V_1 by a large angle (because of core inductance)
- Φ_m: Mutual flux, in phase with emf E_1 and E_2
- E_1: Induced emf in primary
- E_2: Induced emf in secondary

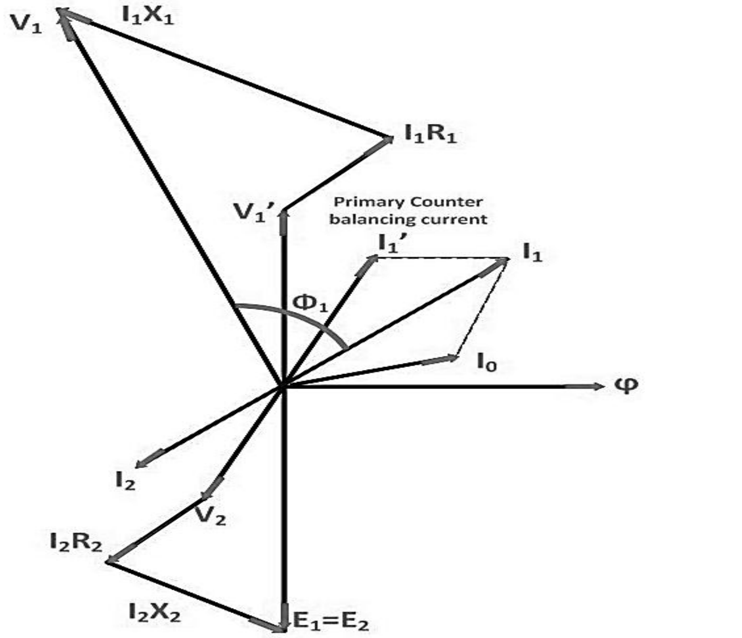


Phasor Diagram at Loaded Condition

The secondary is connected to load, and current I_2 flows.

- I_2 depends on the type of load:
  - Purely Resistive → I_2 in phase with E_2
  - Inductive → I_2 lags E_2
  - Capacitive → I_2 leads E_2
- I_1 adjusts to balance the ampere-turns:

$$I_1N_1 = I_2N_2\ (i.e., I_1 = K \times I_2, where\ K = N_2/N_1)$$



DC MACHINES

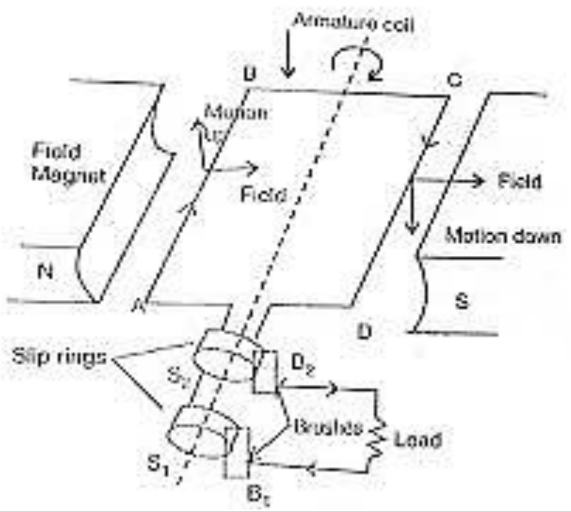
PRINCIPLE OF DC MACHINES

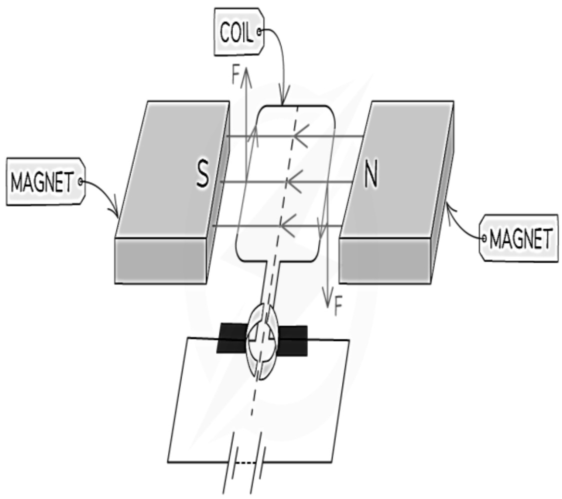
DC machines work on the principle of Electromagnetic Induction, which was discovered by Michael Faraday. The principle states that:

"When a conductor cuts the magnetic field, an EMF is induced in it. If the circuit is closed, current flows."

In DC machines:

- Generators convert mechanical energy into DC electrical energy.
- Motors convert DC electrical energy into mechanical energy.





The basic working principle of both DC motors and DC generators is the same, i.e., electromagnetic induction. The difference lies in energy conversion.

Key Concepts

- When conductor moves in a magnetic field, it cuts magnetic flux and an EMF is induced.
- Direction of EMF is given by Fleming's Right Hand Rule for generators and Fleming's Left Hand Rule for motors.

TYPES OF DC MACHINES

DC machines are generally classified based on field excitation method.

A. **Separately Excited DC Machines**
    - The field winding is powered by an external DC source.
    - Armature and field circuits are electrically independent.

B. **Self-Excited DC Machines**
    - The field winding gets power from the generated EMF of the machine itself.
    - These are further classified as:

I. *Shunt-Wound DC Machine*
    - Field winding is connected parallel to the armature.
    - High field resistance, low field current.
    - Used where constant speed is required.

II. *Series-Wound DC Machine*
    - Field winding is connected in series with the armature.
    - Low field resistance, high field current.
    - Suitable for high starting torque applications.

III. *Compound-Wound DC Machine*
    - Has both shunt and series field windings.
    - Combines advantages of both.

Two types:

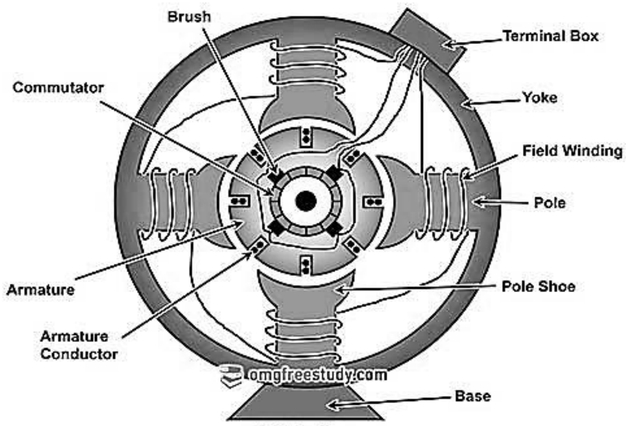
- *Short Shunt:* Shunt field connected across armature only.
- *Long Shunt:* Shunt field connected across both armature and series field.

CONSTRUCTION AND OPERATION

DC Machines are electromechanical energy conversion devices. They convert mechanical energy into electrical energy (when used as a generator) and vice versa (when used as a motor).

Construction of DC Machines

A DC machine (motor or generator) consists of the following main parts:



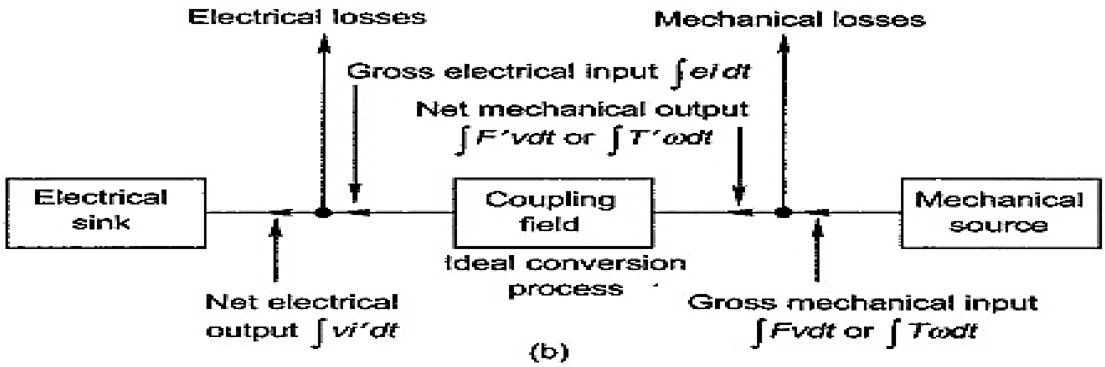
DC Machine

1. *Yoke (Frame):*
   Outer body of the machine made of cast iron or steel.
   Provides mechanical support and carries magnetic flux.
2. *Pole Core and Pole Shoe:*
   Bolted to the yoke.
   Made of laminated steel.
   Increases the area of the magnetic field and holds field windings.
3. *Field Windings (Exciting Coils):*
   Wound around poles.
   Carries DC to produce the magnetic field.
4. *Armature Core:*
   Cylindrical drum made of laminated steel.
   Houses slots for armature winding and reduces eddy current losses.
5. *Armature Windings:*
   Copper wires placed in the slots of armature core.
   Cuts magnetic field and induces EMF (in generator) or carries current (in motor).
6. *Commutator:*
   Converts AC induced in the armature to DC output.
   Made of copper segments insulated by mica.
7. *Brushes:*
   Usually made of carbon.
   Maintain electrical contact between armature and external circuit via commutator.

Operation of DC Machines

A. *As DC Generator:*

- The armature rotates in magnetic field created by field winding.
- As armature conductors cut magnetic lines of force, EMF is induced.
- EMF is collected via commutator and brushes.
- If external load is connected, current flows.



(b)

EMF Equation:

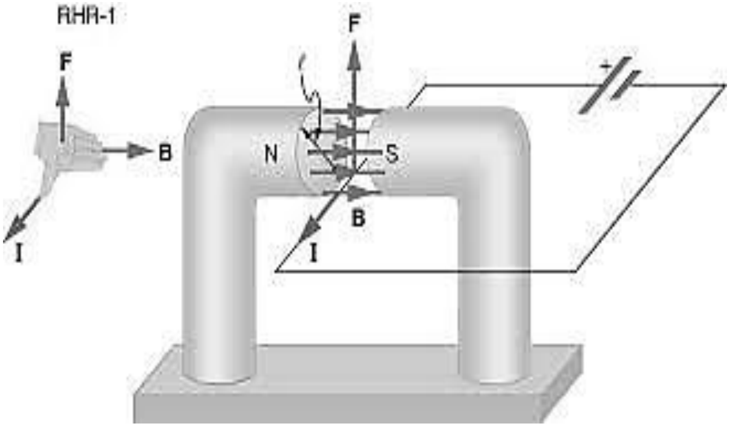
$$E = \frac{P \cdot \phi \cdot Z \cdot N}{60 \cdot A}$$

Where:

- E = Generated EMF
- P = No. of poles
- ϕ = Flux per pole (Wb)
- Z = Total armature conductors
- N = Speed in RPM
- A = No. of parallel paths

B. As DC Motor:

- When voltage is applied, current flows through the armature.
- Interaction of magnetic field and current produces torque.
- The motor starts rotating.
- Back EMF is produced, which opposes the supply voltage.



Back EMF Equation:

$$E_b = V - I_a R_a$$

Where:

- E_b = Back EMF
- V = Supply voltage
- I_a = Armature current
- R_a = Armature resistance