POLYTECHNIC 2nd SEMESTER

Fundamentals of Electrical & Electronics Engineering

CHAPTER NOTES

TRANSFORMERS AND MACHINES

Unit Topics Covered

1. Introduction to Transformers and Machines
2. General Construction and Principle of Transformers
3. EMF Equation and Transformation Ratio
4. Auto Transformers
5. Construction and Working Principle of Motors
6. Types of Motors and Their Applications
7. Solved Problems on Transformers and Electrical Machines

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1. Introduction to Transformers and Machines

Transformers and electrical machines form the backbone of modern electrical engineering systems. From power generation to end-user distribution, these devices ensure efficient energy conversion and transmission. In the study of Fundamentals of Electrical and Electronics Engineering (FEEE), understanding transformers and machines is essential for grasping how electrical energy is harnessed, converted, and applied in real-world scenarios.

What is a Transformer?

A transformer is a static electromagnetic device that transfers electrical energy from one circuit to another through the principle of electromagnetic induction, without any physical electrical connection between the two circuits. It operates on alternating current (AC) only and can step up or step down voltages as required.

What is an Electrical Machine?

An electrical machine is a device that converts electrical energy into mechanical energy (motor) or mechanical energy into electrical energy (generator). Electrical machines are broadly classified as DC machines and AC machines, and they are fundamental to industrial and domestic applications alike.

> **Key Principle:** Both transformers and motors work on the principle of electromagnetic induction, as stated by Faraday's Laws of Electromagnetic Induction.

Importance in FEEE Syllabus

The study of transformers and machines in the Polytechnic 2nd Semester curriculum helps students:

- Understand how power is transmitted over long distances efficiently.
- Learn the construction and working of common electrical devices.
- Apply theoretical formulas to solve practical numerical problems.
- Gain a foundation for advanced subjects in electrical engineering.

2. General Construction and Principle of Different Types of Transformers

2.1 Basic Principle of a Transformer

A transformer works on the principle of Mutual Electromagnetic Induction. When an alternating current flows through the primary winding, it produces a changing magnetic flux in the core. This changing flux links with the secondary winding and induces an electromotive force (EMF) in it. If the secondary circuit is closed, current flows through it, thus transferring energy from primary to secondary.

Faraday's Law Applied: The induced EMF in any coil is directly proportional to the rate of change of magnetic flux linkage with the coil: $e = -N (d\Phi/dt)$

2.2 General Construction of a Transformer

A transformer primarily consists of three main parts — the magnetic core, the primary winding, and the secondary winding. These parts together facilitate the efficient transfer of electromagnetic energy.

(a) Magnetic Core

The core provides a low-reluctance path for the magnetic flux produced by the windings. It is made of high-grade silicon steel laminations to reduce eddy current losses. Laminations are insulated from each other by varnish or oxide coating.

- Material: Silicon steel (grain-oriented)
- Purpose: Low reluctance path for flux linkage
- Why laminated: To minimize eddy current losses

(b) Primary Winding

The primary winding is the input coil connected to the AC supply source. It consists of insulated copper conductors wound around the core. The number of turns in the primary winding (N1) determines the input voltage relationship.

(c) Secondary Winding

The secondary winding is the output coil from which the transformed voltage is taken. It is also wound on the same core and consists of insulated copper turns. The number of turns (N2) in the secondary determines the output voltage.

(d) Tank and Insulating Oil (for large transformers)

Large power transformers are enclosed in oil-filled tanks. The insulating oil (transformer oil) serves two purposes — it provides electrical insulation between windings and the core, and it acts as a cooling medium by carrying heat away from the windings.

2.3 Types of Transformers

Transformers can be classified based on construction, purpose, and voltage ratio. The major types are described below.

(a) Core Type Transformer

In a core-type transformer, the magnetic core forms a simple rectangular frame (like a window frame), and the windings surround the limbs of the core. Both primary and secondary windings are wound on different limbs or on the same limb in two halves, each half on a separate limb.

- Simple in design and easy to repair
- Better cooling due to exposed windings
- Used in high voltage applications

(b) Shell Type Transformer

In a shell-type transformer, the magnetic core surrounds the windings. The core has three limbs — the windings are placed on the central limb and the outer two limbs provide a return path for the flux. This type offers better mechanical support to the windings.

- Better short-circuit strength
- Used in low voltage, high current applications
- Windings are better protected against mechanical stress

(c) Step-Up Transformer

A step-up transformer increases the output voltage ($V2 > V1$). It has more turns in the secondary winding than in the primary winding ($N2 > N1$). These are used at power generation stations to increase voltage for long-distance transmission, reducing transmission losses.

(d) Step-Down Transformer

A step-down transformer decreases the output voltage ($V2 < V1$). It has fewer turns in the secondary winding than in the primary ($N2 < N1$). These are used at distribution substations to reduce voltage to safe levels for domestic and industrial use.

(e) Distribution Transformer

Distribution transformers are step-down transformers used at the final stage of power distribution to supply power to homes and small industries. They typically step down voltage from 11 kV to 400 V or 230 V.

(f) Power Transformer

Power transformers are large-capacity transformers used in transmission networks. They operate at full load continuously and are designed for high efficiency at full load. These are found at grid substations and power stations.

(g) Instrument Transformers

Instrument transformers are used to measure high voltages and currents by stepping them down to safe, measurable levels for use with meters and protective relays. There are two types:

- Current Transformer (CT): Steps down high current to measurable levels (e.g., 1000 A to 5 A).
- Potential Transformer (PT): Steps down high voltage to a safe measuring range (e.g., 11 kV to 110 V).

2.4 Losses in a Transformer

Although transformers are highly efficient devices, they are not 100% efficient. The following losses occur during operation:

- Iron/Core Losses (Pi): Consist of hysteresis loss and eddy current loss. These are constant losses, independent of load.
- Copper Losses (Pc): Also called I^2R losses, these occur in the resistance of primary and secondary windings. These vary with load current.

3. EMF Equation and Transformation Ratio of Transformers

3.1 EMF Equation of a Transformer

The EMF equation relates the induced voltage in the windings to the core flux, frequency, and number of turns. It is one of the most important equations in transformer theory and is derived from Faraday's Law of Electromagnetic Induction.

Derivation

Let the maximum core flux be Φm (in Webers), supply frequency be f (in Hz), and number of turns in the primary be N1 and in the secondary be N2. The core flux varies sinusoidally as:

$$\Phi = \Phi m \sin(2\pi f t)$$

Sinusoidal variation of core flux

The rate of change of flux is maximum when $\cos(2\pi f t) = 1$. So the maximum rate of change of flux = $2\pi f \times \Phi m$.

The maximum EMF induced in the primary winding is:

$$E1(max) = N1 \times 2\pi f \times \Phi m$$

Since the EMF is sinusoidal, the RMS value is obtained by dividing by $\sqrt{2}$:

$$E1 = (2\pi / \sqrt{2}) \times f \times N1 \times \Phi m = 4.44 \times f \times N1 \times \Phi m$$

EMF Equation for Primary Winding

$$E2 = 4.44 \times f \times N2 \times \Phi m$$

EMF Equation for Secondary Winding

Where: E1 = RMS EMF of primary (V) | E2 = RMS EMF of secondary (V) | f = Frequency (Hz) | N1, N2 = Number of turns | Φm = Maximum flux (Wb)

3.2 Transformation Ratio (K)

The transformation ratio, also called the turns ratio, is defined as the ratio of the number of turns in the secondary winding to the number of turns in the primary winding. It determines whether a transformer is step-up or step-down.

$$K = N2 / N1 = E2 / E1 = V2 / V1 = I1 / I2$$

Transformation Ratio Formula

For an ideal transformer (100% efficient), the voltage ratio equals the turns ratio and the current ratio is the inverse of the turns ratio. This means:

- If K > 1: Step-up transformer (N2 > N1, voltage is increased)
- If K < 1: Step-down transformer (N2 < N1, voltage is decreased)
- If K = 1: Isolation transformer (voltage unchanged, circuits isolated)

Power Relationship in Ideal Transformer

In an ideal transformer, input power equals output power (no losses). Therefore:

$$V1 \times I1 = V2 \times I2 \rightarrow (V1/V2) = (I2/I1) = (N1/N2)$$

Power Conservation in Ideal Transformer

3.3 Efficiency of a Transformer

The efficiency of a transformer is the ratio of output power to input power, expressed as a percentage. For maximum efficiency, the copper losses must equal the iron losses.

$$\eta = (\text{Output Power} / \text{Input Power}) \times 100\% = (V2\ I2\ \cos\varphi) / (V2\ I2\ \cos\varphi + Pi + Pc) \times 100\%$$

4. Auto Transformers

4.1 Introduction to Auto Transformer

An auto transformer is a special type of transformer that uses only a single winding, which serves as both the primary and secondary winding. Unlike a conventional two-winding transformer, the auto transformer has an electrical connection between the primary and secondary circuits in addition to the magnetic coupling. This makes it more compact, lighter, and economical, but it lacks electrical isolation between the circuits.

Key Difference: A conventional transformer has two separate windings (electrically isolated). An Auto Transformer has ONE winding that is tapped to give a different voltage — primary and secondary are electrically connected.

4.2 Construction of Auto Transformer

The auto transformer consists of a single continuous winding wound on a laminated silicon steel core. A sliding or fixed tap is taken from a point along the winding to serve as the secondary terminal. The entire winding is used as the primary (connected to AC supply), while a portion of it forms the secondary (connected to load).

- Core: Laminated silicon steel (similar to conventional transformer)
- Winding: Single winding — part of it is common to both primary and secondary
- Tapping: Fixed taps at different points or a variable sliding contact (Variac)

4.3 Working Principle

When AC supply is connected across the full winding (primary), the alternating flux is set up in the core. This flux induces EMF in the entire winding. Since the secondary is a part of the same winding, the voltage across the secondary terminals is proportional to the number of turns up to the tapping point.

The current in the common section of the winding is the difference of the primary and secondary currents (I2 - I1 for step-down). This means the common portion carries less current, allowing the use of a thinner wire and reducing copper volume.

4.4 Voltage and Current Relations

$$V2 / V1 = N2 / N1 = K \quad \text{and} \quad I1 / I2 = N2 / N1 = K$$

For a step-down auto transformer (K < 1), the current in the common winding section = (I2 - I1), which is much smaller than I2. This reduced current in the common section is why auto transformers save copper.

4.5 Advantages of Auto Transformer

- Smaller in size and lighter weight compared to two-winding transformer of same rating
- Lower leakage reactance and better voltage regulation
- Higher efficiency due to reduced copper losses
- Less expensive to manufacture
- Variable output voltage is possible (using Variac — variable auto transformer)

4.6 Disadvantages of Auto Transformer

- No electrical isolation between primary and secondary — this is a major safety concern
- If the common winding section breaks, full primary voltage appears at secondary terminals — hazardous
- Not suitable where isolation is essential (e.g., medical equipment, safety circuits)
- Short-circuit current is higher than in a two-winding transformer

4.7 Applications of Auto Transformer

- Starting of induction motors (to reduce starting current — auto transformer starter)
- Variac (variable voltage transformer) used in laboratories
- Power transmission interconnections between systems of slightly different voltages
- Railway traction systems
- Voltage stabilizers and AC voltage regulators

5. Construction and Working Principle of Motors

5.1 Introduction to Electric Motors

An electric motor is an electromechanical device that converts electrical energy into mechanical energy. This conversion is based on the principle that when a current-carrying conductor is placed in a magnetic field, it experiences a mechanical force (Lorentz force). Electric motors are among the most widely used electrical devices in industry, transportation, and household appliances.

Fundamental Principle: When a current-carrying conductor is placed in a magnetic field, it experiences a force $F = BIL \sin(\theta)$, where B = magnetic flux density, I = current, L = length of conductor, θ = angle between B and I.

5.2 Construction of DC Motor

A DC motor has several key components that work together to produce continuous rotational motion. The construction is described below:

(a) Yoke (Frame)

The yoke is the outer cylindrical frame of the motor made of cast iron or steel. It provides mechanical support to the internal parts and serves as a return path for the magnetic flux from the field poles.

(b) Field Poles and Field Winding

The field poles are projections from the inner surface of the yoke, made of silicon steel laminations. The field winding is wound around these poles and, when energized with DC, produces a stationary magnetic field inside the motor.

(c) Armature Core

The armature core is a cylindrical laminated silicon steel structure mounted on the shaft. The laminations reduce eddy current losses. Slots are cut on the periphery of the armature to accommodate the armature winding.

(d) Armature Winding

The armature winding consists of copper conductors placed in the slots of the armature core. It is the rotating part of the motor and carries the current that interacts with the magnetic field to produce rotation.

(e) Commutator

The commutator is a cylindrical assembly of copper segments (bars) insulated from each other and from the shaft by mica. It converts the alternating current induced in the armature winding into unidirectional

DC and maintains the direction of force on the armature conductors to ensure continuous rotation in one direction.

(f) Brushes

Carbon or graphite brushes press against the commutator segments and serve as the sliding electrical contacts between the external DC supply and the rotating armature winding.

(g) Shaft and Bearings

The shaft transmits the mechanical output torque of the motor to the load. Ball or roller bearings support the shaft and reduce friction.

5.3 Working Principle of DC Motor

When DC supply is connected to the field winding, it establishes a stationary magnetic field between the poles. When DC is also supplied to the armature winding through the brushes and commutator, the current-carrying armature conductors experience a force due to the interaction between the current and the magnetic field. This force produces a torque on the armature, causing it to rotate.

The direction of rotation is determined by Fleming's Left-Hand Rule: if the thumb, index finger, and middle finger of the left hand are held mutually perpendicular, with the index finger pointing in the direction of the magnetic field and the middle finger in the direction of current, the thumb points in the direction of the force (motion).

$$\text{Torque } (T) = BILAN \quad (N \cdot m)$$

Where B = flux density, I = armature current, L = conductor length, A = no. of conductors, N = speed

5.4 Back EMF in DC Motor

When the armature rotates in the magnetic field, an EMF is induced in it (by Faraday's Law). This induced EMF opposes the supply voltage and is called the Back EMF (Eb). The back EMF is what regulates and limits the armature current.

$$V = Eb + Ia \times Ra \quad \rightarrow \quad Ia = (V - Eb) / Ra$$

Where V = supply voltage, Ia = armature current, Ra = armature resistance

5.5 Construction and Working Principle of AC Induction Motor

The three-phase induction motor is the most widely used AC motor in industry. Its construction consists of two main parts: the stator (stationary part) and the rotor (rotating part).

Stator

The stator is the outer stationary part. It consists of a laminated cylindrical core with slots in which a three-phase winding is placed. When connected to a three-phase AC supply, the stator winding produces a rotating magnetic field (RMF) that rotates at synchronous speed Ns = 120f/P, where f is frequency and P is number of poles.

Rotor

The rotor is the inner rotating part. In a squirrel cage induction motor (the most common type), the rotor consists of copper or aluminium bars embedded in a laminated core and short-circuited at both ends by end rings, resembling a squirrel cage.

Working Principle of Induction Motor

The rotating magnetic field (RMF) produced by the stator cuts the stationary rotor conductors, inducing an EMF in them (by Faraday's Law). Since the rotor bars are short-circuited, current flows through them. The interaction between this rotor current and the stator's RMF produces a torque on the rotor, causing it to rotate in the same direction as the RMF. The rotor speed is always slightly less than the synchronous speed — this difference is called slip.

Slip (s) = (Ns - Nr) / Ns   and   % Slip = s × 100

Where Ns = Synchronous speed, Nr = Rotor speed

6. Types of Motors and Their Applications

6.1 Classification of Electric Motors

Electric motors are broadly classified based on the type of electrical supply they use — DC motors and AC motors. Each type has several subtypes suited to different applications.

6.2 Types of DC Motors

(a) DC Series Motor

In a DC series motor, the field winding is connected in series with the armature winding. Therefore, the field current is the same as the armature current, and the magnetic flux varies with load. This motor produces high starting torque but has poor speed regulation — the speed drops considerably with increased load.

- High starting torque
- Speed inversely proportional to load (dangerously high speed at no-load — never run without load)
- Applications: Electric traction (trains, trams), cranes, hoists, elevators, electric vehicles

(b) DC Shunt Motor

In a DC shunt motor, the field winding is connected in parallel (shunt) with the armature winding. The field current is independent of the armature current. The flux remains approximately constant, giving this motor nearly constant speed characteristics.

- Nearly constant speed from no-load to full load
- Good speed regulation
- Applications: Lathes, fans, blowers, centrifugal pumps, machine tools, printing presses

(c) DC Compound Motor

A compound motor has both a series field winding and a shunt field winding. It combines the characteristics of series and shunt motors. A cumulative compound motor has both windings aiding each other, while in a differential compound motor, they oppose each other.

- Good starting torque (from series component)
- Relatively stable speed (from shunt component)
- Applications: Rolling mills, presses, shears, elevators, heavy duty applications

6.3 Types of AC Motors

(a) Three-Phase Squirrel Cage Induction Motor

This is the most widely used motor in industry. The rotor has short-circuited bars with no external connections, resembling a squirrel cage. It is robust, requires little maintenance, and is self-starting.

- Rugged, simple, and low cost

- No brushes, commutator, or slip rings required
- Applications: Pumps, compressors, fans, conveyors, industrial drives

(b) Three-Phase Wound Rotor (Slip Ring) Induction Motor

The rotor has a three-phase winding connected through slip rings to external resistors. This allows control of starting torque and speed by varying the external resistance. It has higher starting torque than squirrel cage motors.

- Variable starting torque through external rotor resistance
- Applications: Cranes, crushers, lifts, cement mills

(c) Single-Phase Induction Motor

These motors use a single-phase AC supply and are commonly used in domestic applications. They are not self-starting and require auxiliary starting methods such as capacitor start, resistance start, or shaded pole.

- Types: Capacitor start, Capacitor run, Shaded pole, Split-phase
- Applications: Ceiling fans, water pumps, refrigerators, washing machines, mixer grinders, air coolers

(d) Synchronous Motor

A synchronous motor runs at exactly the synchronous speed ($N_s = 120f/P$) and does not have slip. It requires DC excitation for the rotor and is not self-starting. It is used where constant speed is essential.

- Operates at synchronous speed — no slip
- Can operate at unity or leading power factor (used for power factor correction)
- Applications: Compressors, large fans, pumps, power factor correction in power systems

(e) Universal Motor

A universal motor can operate on both AC and DC supply. It is essentially a series-wound DC motor that is designed to work on AC as well. It operates at high speed and produces high starting torque.

- Operates on both AC and DC
- Very high speed (up to 20,000 RPM)
- Applications: Portable drills, vacuum cleaners, mixers, food processors, hair dryers

6.4 Quick Reference: Motor Types and Applications

Motor Type	Key Feature	Applications
DC Series	High starting torque, variable speed	Traction, cranes, hoists
DC Shunt	Constant speed, good regulation	Lathes, pumps, machine tools
DC Compound	High torque + stable speed	Elevators, rolling mills
3-Ph Squirrel Cage IM	Rugged, self-starting, low cost	Pumps, fans, conveyors

3-Ph Slip Ring IM	High starting torque, variable	Cranes, crushers
1-Ph Induction	Simple, domestic use	Fans, refrigerators, washing machines
Synchronous	Constant speed, PF correction	Compressors, grid support
Universal Motor	AC/DC, very high speed	Drills, vacuum cleaners, mixers

7. Solved Problems on Transformers and Electrical Machines

This section contains step-by-step solved numerical problems covering transformers and electrical machines, as required for the FEEE Polytechnic 2nd Semester examination.

Problem 1: Find Secondary Voltage of a Transformer

Given	Primary voltage $V1 = 2200$ V Primary turns $N1 = 2000$ Secondary turns $N2 = 200$
To Find	Secondary voltage $V2 = ?$
Solution	Using transformation ratio: $V2/V1 = N2/N1$ $V2 = V1 \times (N2/N1) = 2200 \times (200/2000)$ $V2 = 2200 \times 0.1 = 220$ V
Answer	$V2 = 220$ V (Step-down transformer, $K = 0.1$)

Problem 2: Calculate Maximum Core Flux Using EMF Equation

Given	Primary EMF $E1 = 3300$ V Frequency $f = 50$ Hz Number of primary turns $N1 = 1500$
To Find	Maximum core flux $\Phi m = ?$
Solution	Using EMF equation: $E1 = 4.44 \times f \times N1 \times \Phi m$ $\Phi m = E1 / (4.44 \times f \times N1)$ $\Phi m = 3300 / (4.44 \times 50 \times 1500)$ $\Phi m = 3300 / 333000$ $\Phi m = 0.00991$ Wb ≈ 9.91 mWb
Answer	Maximum core flux $\Phi m = 9.91$ mWb

Problem 3: Find Number of Secondary Turns for Given Voltage

Given	Primary voltage $V1 = 440$ V Secondary voltage $V2 = 110$ V Primary turns $N1 = 400$
To Find	Number of secondary turns $N2 = ?$
Solution	Using: $N2/N1 = V2/V1$ $N2 = N1 \times (V2/V1) = 400 \times (110/440)$ $N2 = 400 \times 0.25 = 100$ turns
Answer	$N2 = 100$ turns (Step-down, $K = 0.25$)

Problem 4: Calculate Primary Current of a Transformer

Given	Primary voltage V1 = 11000 V Secondary voltage V2 = 440 V Load current I2 = 100 A Assume ideal transformer
To Find	Primary current I1 = ?
Solution	For ideal transformer: V1 × I1 = V2 × I2 I1 = (V2 × I2) / V1 = (440 × 100) / 11000 I1 = 44000 / 11000 = 4 A
Answer	Primary current I1 = 4 A

Problem 5: Calculate Efficiency of a Transformer

Given	Output power = 50 kW Power factor cosφ = 0.8 Iron losses Pi = 500 W Copper losses Pc = 800 W
To Find	Efficiency η = ?
Solution	Output power = 50,000 W Input power = Output + Total losses = 50000 + 500 + 800 = 51300 W η = (Output / Input) × 100 = (50000 / 51300) × 100 η = 97.46%
Answer	Efficiency η = 97.46%

Problem 6: Calculate Slip and Rotor Speed of Induction Motor

Given	Supply frequency f = 50 Hz Number of poles P = 4 Rotor speed Nr = 1440 RPM
To Find	Synchronous speed Ns and % Slip
Solution	Ns = 120 × f / P = 120 × 50 / 4 = 6000/4 = 1500 RPM Slip s = (Ns - Nr) / Ns = (1500 - 1440) / 1500 s = 60 / 1500 = 0.04 % Slip = 0.04 × 100 = 4%
Answer	Synchronous speed Ns = 1500 RPM | % Slip = 4%

Problem 7: Find EMF of Secondary Winding

Given	Core flux $\Phi m = 0.05$ Wb Frequency $f = 50$ Hz Secondary turns $N2 = 500$
To Find	Secondary EMF $E2 = ?$
Solution	Using EMF equation: $E2 = 4.44 \times f \times N2 \times \Phi m$ $E2 = 4.44 \times 50 \times 500 \times 0.05$ $E2 = 4.44 \times 50 \times 25$ $E2 = 4.44 \times 1250 = 5550$ V
Answer	Secondary EMF $E2 = 5550$ V

Problem 8: Auto Transformer — Find Secondary Voltage

Given	Auto transformer primary voltage $V1 = 230$ V Total turns $N = 460$ Tapping point at 200 turns ($N2 = 200$)
To Find	Secondary voltage $V2 = ?$
Solution	Turns ratio $K = N2/N1 = 200/460$ $V2 = V1 \times (N2/N1) = 230 \times (200/460)$ $V2 = 230 \times 0.4348 \approx 100$ V
Answer	Secondary voltage $V2 \approx 100$ V

7.1 Important Formulas Summary

Formula / Quantity	Expression
EMF Equation (Primary)	$E1 = 4.44 \times f \times N1 \times \Phi m$
EMF Equation (Secondary)	$E2 = 4.44 \times f \times N2 \times \Phi m$
Transformation Ratio	$K = N2/N1 = V2/V1 = I1/I2$
Efficiency	$\eta = Output / (Output + Pi + Pc) \times 100\%$
Synchronous Speed	$Ns = 120f / P$ (RPM)
Slip	$s = (Ns - Nr) / Ns$
% Slip	$\% Slip = s \times 100$
Back EMF (DC Motor)	$V = Eb + Ia \times Ra$
Force on Conductor	$F = BIL \sin(\theta)$ (Newton)

End of Chapter: Transformers and Machines
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