DI03000081: Electrical Machines - I

GTU Course Presentation

July 25, 2026

Course Contents I

Introduction to D.C. Machines I

A D.C. machine is an electromechanical energy conversion device that operates as either a generator (mechanical to electrical) or a motor (electrical to mechanical).

Key Points:

- The fundamental construction of a D.C. generator and a D.C. motor is identical.
- Major components are divided into two main categories: Stator (stationary part) and Rotor (rotating part).
- The stationary parts include the yoke, field poles, and brushes.
- The rotating parts include the armature core, armature winding, and commutator.

Yoke (Magnetic Frame) I

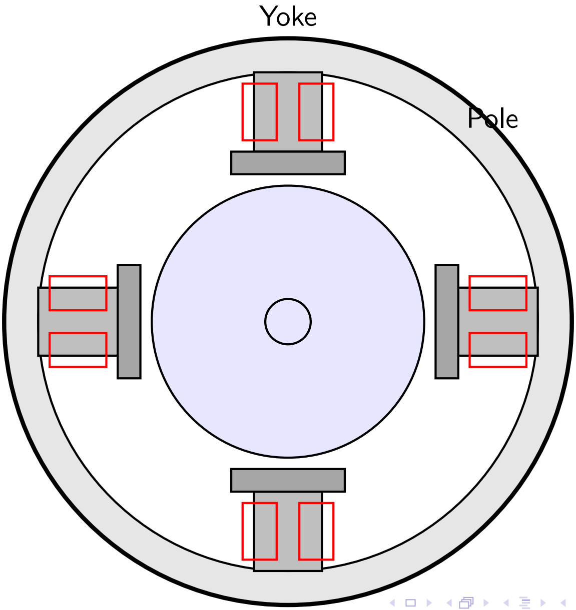
The yoke is the outer frame of the D.C. machine, providing mechanical protection and a path for the magnetic flux.

Key Points:

- Function 1: Serves as the outer protective cover for the inner working parts of the machine against moisture, dust, and mechanical damage.
- Function 2: Provides a return path for the magnetic flux produced by the field poles, carrying half of the pole flux ($\Phi/2$).
- Material for small machines: Cast iron, due to lower cost and sufficient permeability for low-flux applications.
- Material for large machines: Cast steel or rolled steel, which offers higher mechanical strength and higher permeability to reduce the size and weight of the frame.

Cross-sectional View of a 4-Pole D.C. Machine I

Cross-sectional View of a 4-Pole D.C. Machine II



Pole Cores and Pole Shoes I

Poles are electromagnets fixed to the inner surface of the yoke. They consist of a pole core and a pole shoe.

Key Points:

- Pole Core Function: To carry the field winding which produces the magnetic flux when energized.
- Pole Shoe Function: It is wider than the core to spread the magnetic flux uniformly over the armature periphery and to provide mechanical support for the field coils.
- Material: Constructed from thin laminations (about 1mm thick) of annealed steel or wrought iron.
- Lamination Purpose: Laminations are used to minimize eddy current losses caused by variations in magnetic flux due to the slotted armature.

Field Winding (Exciting Winding) I

The field winding consists of coils of wire placed on the pole cores.

Key Points:

- Function: When direct current is passed through these coils, they electromagnetize the poles, producing the necessary magnetic flux for energy conversion.
- Configuration: The coils are connected in series in such a way that adjacent poles have opposite polarities (N-S-N-S).
- Material: Enamelled copper wire is almost exclusively used due to its high electrical conductivity and excellent thermal properties.
- The windings are carefully insulated with mica or synthetic varnishes to prevent short circuits.

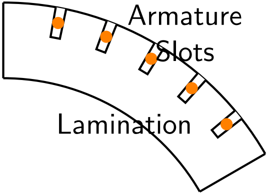
Armature Core I

The armature core is the rotating, cylindrical part of the machine mounted on the shaft.

Key Points:

- Function 1: Houses the armature conductors (windings) in slots cut into its outer periphery.
- Function 2: Provides a low-reluctance path for the magnetic flux from the North pole to the South pole.
- Material: Made of high-permeability, low-hysteresis silicon steel laminations (0.35 mm to 0.5 mm thick).
- Silicon content (about 3-4

Armature Slots and Laminations I



Key Points:

- Slots can be open, semi-closed, or closed depending on the machine design.
- Conductors are placed in these slots and are secured by wedges.
- Air ducts are often provided radially and axially within the core to facilitate cooling.

Armature Winding I

The armature winding is the heart of the D.C. machine where the actual electromechanical energy conversion takes place.

Key Points:

- Function in Generator: It is the winding where the electromotive force (EMF) is induced due to electromagnetic induction.
- Function in Motor: It carries the input current which interacts with the magnetic field to produce electromagnetic torque.
- Material: High-conductivity electrolytic copper.
- Types: Generally classified into Lap winding (for high current, low voltage) and Wave winding (for high voltage, low current).

Commutator and Brushes I

The commutator and brush assembly is a unique mechanical rectifier/inverter system crucial for D.C. machines.

Key Points:

- Commutator Function: Converts the alternating current (AC) induced in the rotating armature conductors into direct current (DC) at the external terminals (in a generator).
- Commutator Material: Made of wedge-shaped, hard-drawn copper segments, insulated from each other by thin layers of mica (0.8 mm thick).
- Brushes Function: To collect current from the rotating commutator and deliver it to the stationary external circuit, or vice-versa.

Commutator and Brushes II

- Brushes Material: High-grade carbon or electro-graphite. Carbon is used because it is self-lubricating, has a negative temperature coefficient of resistance, and is softer than copper (minimizing commutator wear).

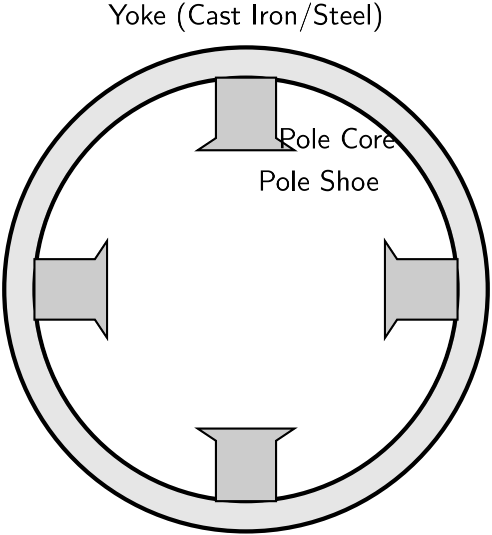
Introduction to DC Machine Construction I

A DC machine essentially consists of a stator (stationary part) and a rotor (rotating part, specifically the armature).

Key Points:

- The stator provides the mechanical support and produces the working magnetic flux.
- The rotor consists of the armature core, armature windings, and commutator.
- A small air gap separates the stator and rotor to allow free rotation while minimizing magnetic reluctance.
- Fundamental principle: Electromechanical energy conversion relies on the interaction between the stator's magnetic field and the armature currents.

Yoke (Magnetic Frame) I



Yoke (Magnetic Frame) II

Key Points:

- Function: Serves as the outer protecting cover for the machine and carries the magnetic flux produced by the poles.
- Material for small machines: Cast iron due to lower cost and sufficient mechanical strength.
- Material for large machines: Cast steel or rolled steel to handle higher flux densities and provide greater mechanical strength.
- Its cross-sectional area must be sufficient to carry half the flux per pole ($\Phi/2$).

Pole Cores and Pole Shoes I

The magnetic poles are bolted to the inner periphery of the yoke and consist of two main parts: the pole core and the pole shoe.

Key Points:

- Function of Pole Core: Supports the field winding and directs the magnetic flux towards the armature.
- Function of Pole Shoe: Enlarges the area of the pole to spread the flux evenly over the air gap and physically retains the field coil.
- Material: Typically made from laminated cast steel or silicon steel stampings (approx. 1 mm thick) to reduce eddy current losses when subjected to flux pulsations.
- The laminated structure is riveted together under hydraulic pressure.

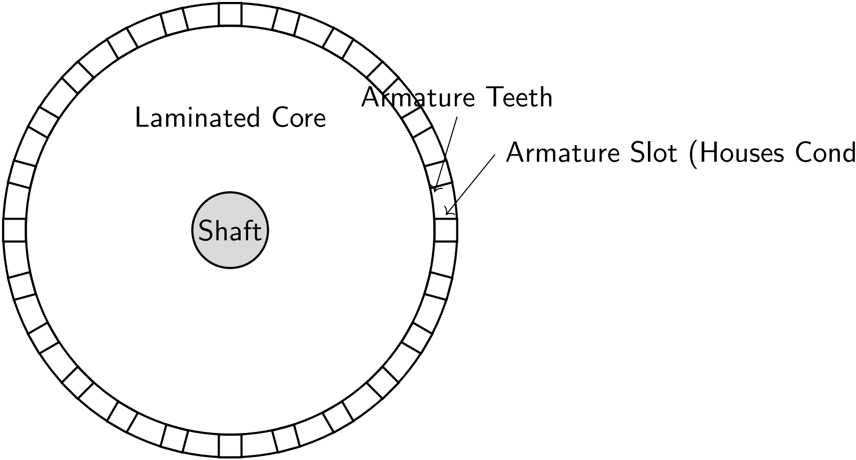
Field Windings (Exciting Coils) I

Field coils are placed around the pole cores to create the electromagnet that produces the working flux.

Key Points:

- Function: To produce the required magnetomotive force (MMF) for establishing the main magnetic field in the air gap.
- Material: Enamelled copper wire (or sometimes aluminum in cost-sensitive designs).
- Construction: Wound on a former and then placed over the pole core. The coils of all poles are connected in series.
- Connections are made such that adjacent poles acquire opposite magnetic polarities (N-S-N-S) when energized.

Armature Core I



Key Points:

Armature Core II

- Function: Houses the armature conductors (windings) in slots and provides a low reluctance path for the magnetic flux.
- Material: High-grade silicon steel laminations (0.35 mm to 0.5 mm thick) to minimize eddy current and hysteresis losses.
- Construction: The laminations are insulated from each other using a thin coating of varnish.
- Slots are punched on the outer periphery to hold the armature conductors, with air ducts incorporated for cooling.

Armature Windings I

The armature winding is the heart of the DC machine where the actual electromechanical energy conversion takes place.

Key Points:

- Function: Conductors cut the magnetic field to induce EMF (generator) or produce electromagnetic torque (motor).
- Material: High-conductivity copper.
- Types: Primarily classified into Lap winding (A=P, suitable for high current, low voltage) and Wave winding (A=2, suitable for high voltage, low current).
- The coils are insulated from the slots using materials like mica, nomex, or glass tape.

Commutator I

The commutator is a mechanical rectifier or inverter, which is a unique and essential part of a DC machine.

Key Points:

- Function in Generator: Converts the alternating current (AC) induced in the armature conductors into direct current (DC) in the external circuit.
- Function in Motor: Reverses the current direction in armature coils as they pass under opposite poles to maintain unidirectional torque.
- Material: Hard-drawn copper segments insulated from each other by thin layers of mica (about 0.8 mm thick).
- Structure: Cylindrical shape built up of wedge-shaped copper segments, tightly clamped together.

Brushes and Brush Gear I

Brushes establish electrical connection between the rotating commutator and the stationary external circuit.

Key Points:

- Function: To collect current from the commutator (generator) or feed current to it (motor).
- Material: Carbon or graphite is most common due to self-lubricating properties, negative temperature coefficient of resistance, and relatively soft nature which minimizes commutator wear.
- Metal-graphite brushes are used for low-voltage, high-current machines to reduce voltage drop.
- Brush Gear: Consists of brush holders, springs to maintain uniform pressure (approx. 0.1 to 0.2 kg/cm^2), and flexible copper pigtails.

Bearings and Shaft I

These mechanical components support the rotor and ensure smooth rotation with minimal friction.

Key Points:

- Function of Bearings: Support the rotating shaft and reduce rotational friction.
- Material for Bearings: Ball bearings (carbon steel) are used for small machines; roller or sleeve bearings (babbitt metal/white metal) are used for large machines handling heavier loads.
- Function of Shaft: Transfers mechanical power to or from the machine.
- Material for Shaft: Mild steel, designed with maximum stiffness to withstand torsional and bending stresses during operation.

A D.C. generator is an electrical machine that converts mechanical energy into direct current (D.C.) electrical energy. This conversion is based on the principle of dynamically induced EMF.

Key Points:

- Mechanical energy input is typically provided by a prime mover (e.g., steam turbine, diesel engine or electric motor).
- The output is unidirectional electrical power (D.C.).
- The generator relies on the physical interaction between a static magnetic field and a moving conductor (armature).

Principle of Operation: Electromagnetic Induction I

The fundamental principle behind the operation of a D.C. generator is electromagnetic induction, where an electromotive force (EMF) is induced in a conductor when it cuts magnetic flux lines.

Key Points:

- When an armature is rotated within a uniform magnetic field, the flux linked with its coils changes continuously.
- Due to this continuous changing flux linkage, an EMF is induced in the armature conductors.
- The nature of this induced EMF in the armature is fundamentally alternating (A.C.) because the conductors pass alternately under North and South poles.
- A commutator is required to convert this alternating internal EMF into a unidirectional EMF (D.C.) across the external load.

Faraday's First Law of Electromagnetic Induction I

Faraday's First Law states the primary condition under which an electromotive force is induced in a circuit.

Key Points:

- Statement: Whenever a conductor is placed in a varying magnetic field, an EMF is induced in the conductor.
- Alternatively: Whenever a moving conductor cuts stationary magnetic flux, a dynamically induced EMF is generated.
- If the conductor forms a closed electrical circuit, this induced EMF causes a current to flow, known as induced current.
- In a typical D.C. generator, the magnetic field is stationary (stator), and the armature conductors rotate (rotor) to cut the flux.

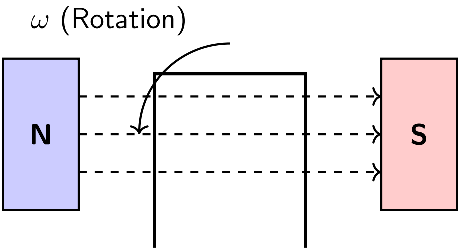
Faraday's Second Law of Electromagnetic Induction I

Faraday's Second Law quantifies the magnitude of the dynamically induced EMF.

Key Points:

- Statement: The magnitude of the induced EMF is directly proportional to the rate of change of flux linkages.
- Mathematically: E = -N * $(\mathrm{d}\Phi/dt), where'N'isthenumberofturnsand'd\Phi/dt'isthetimerateofc$
- The negative sign (derived from Lenz's Law) indicates that the induced EMF drives a current that opposes the change in flux producing it.
- In generators, for a single conductor moving with velocity 'v' in a magnetic field density 'B' of length 'l', the dynamically induced EMF is E = B * l * v * sin(θ).

Schematic of D.C. Generator Principle I



Key Points:

- The diagram shows a simplified single-turn armature coil placed between the North and South poles of a field magnet.
- The horizontal dashed lines represent the uniform magnetic flux flowing from North to South.
- Mechanical rotation (ω) of the coil cuts these flux lines, dynamically inducing an EMF.

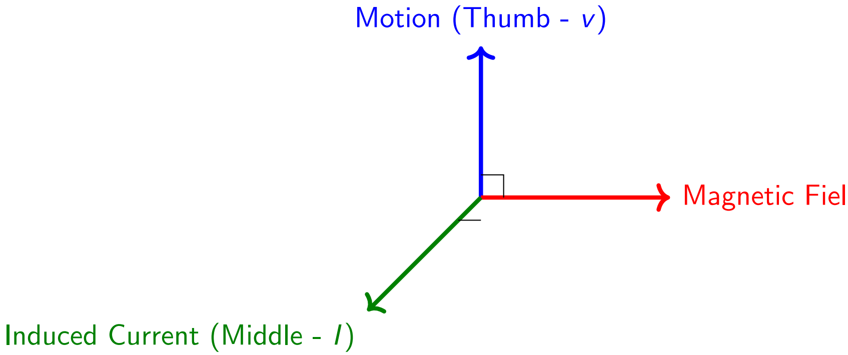
Fleming's Right-Hand Rule I

Fleming's Right-Hand Rule is a mnemonic used to determine the exact direction of the dynamically induced EMF and the resulting current in a generator's conductor.

Key Points:

- Stretch the thumb, forefinger, and middle finger of the right hand so they are mutually orthogonal (at right angles to each other).
- Thumb: Aligned with the direction of the mechanical motion of the conductor relative to the magnetic field.
- Forefinger: Aligned with the direction of the magnetic field (flux lines from North to South).
- Middle Finger: Automatically points in the direction of the induced EMF or conventional current flow within the conductor.

Vector Representation of Fleming's Right-Hand Rule I



Key Points:

Vector Representation of Fleming's Right-Hand Rule II

- This mutually orthogonal system defines the vector cross product relationship: E $=$ l * (v $\times B$).
- It is essential for mapping armature winding connections, calculating commutator pitch, and determining generator polarity.
- Remember: Right hand rule is exclusively for generators (determining induced current), Left hand rule is for motors (determining force).

The Role of the Commutator I

While the armature naturally generates an alternating EMF due to its rotation in a stationary magnetic field, a D.C. generator must provide direct current to the load.

Key Points:

- The induced EMF in any individual armature coil reverses its direction every half-revolution as it passes under alternate polarity poles.
- The commutator acts as a synchronized mechanical rectifier, reversing the electrical connections of the armature coils to the external circuit at the exact moment the EMF reverses.
- This process ensures that the current supplied to the external load circuit always flows in a single, unidirectional manner.
- Stationary carbon brushes rest on the rotating commutator segments to continuously collect this unidirectional current.

Summary and Practical Machine Considerations I

Understanding the core principles of Faraday's and Fleming's laws is the foundation for scaling a single-loop generator up to a complex, multi-pole industrial D.C. machine.

Key Points:

- A practical D.C. generator features numerous coils wound in slots on a laminated cylindrical iron armature core, which maximizes flux linkage and minimizes output voltage ripple.
- The magnetic field is typically produced by electromagnets (field coils) rather than permanent magnets, allowing for precise voltage control via field current regulation.

Summary and Practical Machine Considerations II

- The total generated EMF equation is E_g $= (\text{P * } \Phi * Z * N)/(60 * A), whichintegratesFaraday'slawovertheentiremachine'swindingcor$
- Next lecture: We will dive into the constructional details of D.C. Machines (Yoke, Armature core, Commutator design, and Brush gear).

Fundamental Principle of E.M.F. Generation I

According to Faraday's Laws of Electromagnetic Induction, an electromotive force (e.m.f.) is induced in a conductor whenever it cuts across a magnetic field.

Key Points:

- The magnitude of the induced e.m.f. depends on the rate of change of flux linkage ($e = -N * d\Phi/dt$).
- In a DC generator, the armature rotates within a stationary magnetic field produced by the field poles.
- As the armature conductors sweep past the magnetic poles, they experience a changing magnetic flux, inducing an alternating e.m.f.
- The commutator then converts this internal alternating e.m.f. into a unidirectional (DC) voltage at the external terminals.

Key Variables and Terminology I

To derive the E.M.F. equation, we must define the critical parameters governing the generator's physical and electrical characteristics.

Key Points:

- P = Number of field poles in the generator.
- Φ (Phi) = Useful magnetic flux produced per pole, measured in Webers (Wb).
- Z = Total number of armature conductors on the rotor.
- N = Rotational speed of the armature, measured in revolutions per minute (RPM).
- A = Number of parallel paths into which the armature winding is divided.

Flux Cut by a Single Conductor I

Consider a single armature conductor mounted on the rotor. We calculate the total flux it cuts during one complete revolution.

Key Points:

- During one revolution, the conductor passes by all 'P' poles.
- Since each pole produces a flux of 'Φ' Webers, the total flux cut by one conductor in one revolution is $d\Phi = P * \Phi$ Webers.
- This forms the numerator in our rate-of-change of flux equation ($d\Phi/dt$).
- The flux distribution is typically assumed to be sinusoidal or trapezoidal, but the average e.m.f. depends only on the total flux per pole.

Time of One Revolution I

Next, we determine the time interval 'dt' required for the armature to complete one single revolution.

Key Points:

- The armature rotates at 'N' revolutions per minute (RPM).
- Therefore, the number of revolutions per second is N / 60.
- The time taken to complete exactly one revolution is the reciprocal of the speed in rev/sec.
- Thus, $dt = 60 / N$ seconds. This is the denominator for our Faraday's Law application.

Average E.M.F. Induced in One Conductor I

Using Faraday's law of induction ($E = d\Phi/dt$), we can now calculate the average e.m.f. generated in a single armature conductor.

Key Points:

- Average e.m.f. per conductor = Total flux cut / Time taken.
- $e = d\Phi / dt = (P * \Phi) / (60 / N)$.
- Simplifying the expression yields: $e = (P * \Phi * N) / 60$ Volts.
- This is the voltage generated by just one conductor. However, the armature consists of 'Z' conductors connected in series-parallel combinations.

Armature Windings and Parallel Paths (A) I

The total generated E.M.F. (Eg) depends on how the conductors are interconnected. The total conductors 'Z' are divided into 'A' parallel paths.

Key Points:

- The number of conductors connected in series in each parallel path is Z / A.
- Voltages in series add up. Parallel paths determine the current capacity but not the total voltage.
- For Lap Winding: The number of parallel paths equals the number of poles ($A = P$). Often used for high current, low voltage machines.
- For Wave Winding: The number of parallel paths is always two ($A = 2$). Often used for high voltage, low current machines.

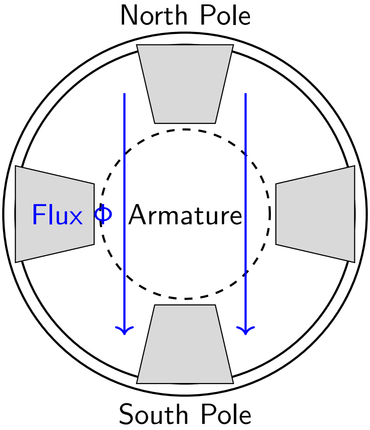
Final Derivation of the E.M.F. Equation I

By combining the e.m.f. per conductor with the number of series conductors per path, we arrive at the standard D.C. Generator E.M.F. equation.

Key Points:

- Total Generated E.M.F. (Eg) = (Average e.m.f. per conductor) * (Number of conductors in series per path).
- $Eg = [(P * \Phi * N) / 60] * (Z / A)$.
- Rearranging gives the fundamental equation: $Eg = (\Phi * Z * N * P) / (60 * A)$ Volts.
- For a given machine, Z, P, and A are constant. Thus, Eg is directly proportional to the flux per pole (Φ) and the speed (N): $Eg = k * \Phi * N$, where $k = (Z * P) / (60 * A)$.

Diagram: D.C. Machine Cross-Section I

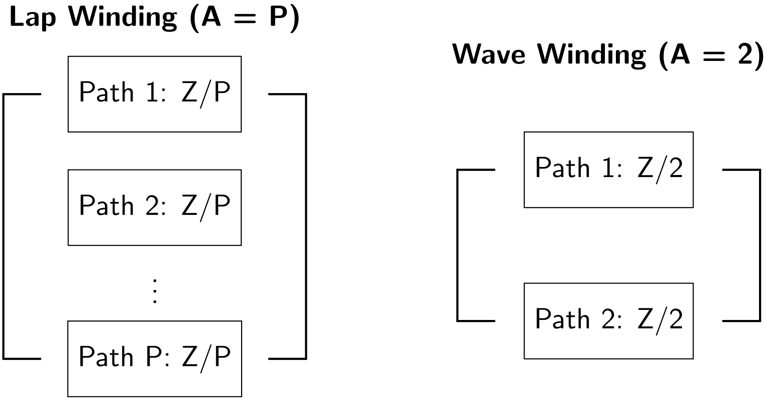


Key Points:

Diagram: D.C. Machine Cross-Section II

- This diagram illustrates a 4-pole DC machine with primary magnetic poles.
- Magnetic flux (Φ) travels from the North poles, across the air gap, through the armature, and into the South poles.
- The armature rotates within this magnetic field, causing the conductors to cut the flux lines.

Diagram: Armature Parallel Paths (Lap vs Wave) I



Key Points:

- Lap Winding creates $A = P$ parallel paths. Voltage is lower, but current capacity is higher due to multiple parallel branches.

Diagram: Armature Parallel Paths (Lap vs Wave) II

- Wave Winding creates strictly $A = 2$ parallel paths regardless of the number of poles. Voltage is higher, but current capacity is lower.
- The generated e.m.f. across the external terminals is equal to the e.m.f. generated across any single parallel path.

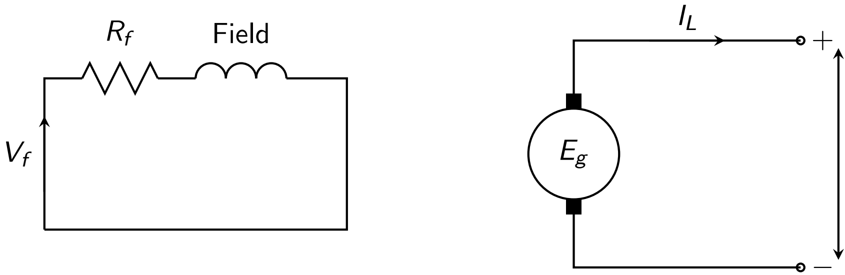
Classification of D.C. Generators I

DC generators are primarily classified based on the method of field excitation.

Key Points:

- Excitation is the process of establishing a magnetic field by passing a direct current through the field winding.
- Generators are broadly classified into two main categories: Separately Excited and Self-Excited.
- In Self-excited generators, the field winding is energized by the current produced by the generator itself.
- Self-excited generators are further divided into Series, Shunt, and Compound wound generators based on armature and field connections.
- Compound generators can be short-shunt or long-shunt, and cumulatively or differentially compounded.

Separately Excited D.C. Generator I



Key Points:

- The field winding is energized from an independent external DC source, such as a battery or another DC generator.
- The field current (If) is completely independent of the armature current (Ia) and load variations.

Separately Excited D.C. Generator II

- Armature current equals load current: Ia = IL.
- Terminal voltage equation: V = Eg - Ia*Ra - V_brush, where Eg is the generated EMF and Ra is armature resistance.
- Applications: Used in Ward-Leonard speed control systems and for testing purposes in laboratories where a wide range of output voltages is required.

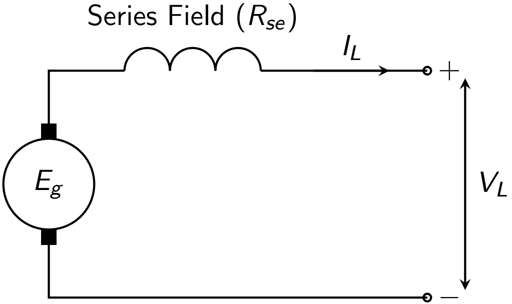
Voltage Buildup in Self-Excited Generators I

Self-excited generators rely on residual magnetism to initiate the voltage generation process.

Key Points:

- The field poles must possess some residual magnetism to induce a small initial EMF when the armature rotates.
- This initial EMF drives a small current through the field winding, which must be connected such that it aids the residual flux.
- An increase in flux leads to a higher induced EMF, causing a cumulative buildup of voltage until magnetic saturation limits it.
- Critical Resistance: The field circuit resistance must be less than a critical value for the generator to build up voltage.
- Critical Speed: The armature must rotate at a speed above a certain critical threshold for successful voltage buildup.

Series Wound D.C. Generator I



Key Points:

- The field winding is connected in series with the armature winding.

Series Wound D.C. Generator II

- The series field winding carries the full load current, so it is constructed with a few turns of thick wire to keep resistance (Rse) low.
- Current equation: Series field current (Ise) = Armature current (Ia) = Load current (IL).
- Voltage characteristics: Terminal voltage rises as load current increases until the magnetic circuit saturates.
- Applications: Employed as voltage boosters in DC distribution systems to compensate for voltage drops in long feeders.

The field winding is connected in parallel (shunt) with the armature winding.

Key Points:

- The shunt field winding has many turns of fine wire, resulting in a high resistance (Rsh) to limit the field current to a fraction of the total current.
- Current equation: Armature current Ia = Load current IL + Shunt field current Ish.
- The shunt field current is given by Ish = V / Rsh, meaning it depends on the terminal voltage.
- Voltage characteristics: It acts as a relatively constant voltage source. Terminal voltage drops slightly (due to IaRa drop and armature reaction) as load increases.
- Applications: Widely used for battery charging, ordinary lighting circuits, and providing excitation for AC generators.

Compound Wound D.C. Generator I

Compound generators are equipped with both series and shunt field windings on each main pole.

Key Points:

- This design combines the rising voltage characteristic of a series generator with the drooping characteristic of a shunt generator.
- The series field winding is placed over the shunt field winding.
- They can be classified by wiring layout into Long-shunt (shunt field is parallel to both armature and series field) and Short-shunt (shunt field is parallel only to armature).
- They can also be classified by magnetic polarity into Cumulative (fluxes aid each other) and Differential (fluxes oppose each other).
- The compounding degree can be adjusted by using a variable diverter resistance in parallel with the series field.

Long Shunt and Short Shunt Connections I

The differences in connection primarily affect the mathematical formulation for currents and voltages.

Key Points:

- Long-shunt Equation: Ise = Ia = IL + Ish. Field current Ish = V / Rsh. Terminal voltage V = Eg - Ia(Ra + Rse).
- Short-shunt Equation: Ise = IL, and Ia = IL + Ish. Field current Ish = (V + IL*Rse) / Rsh. Terminal voltage V = Eg - Ia*Ra - IL*Rse.
- Under load, a short-shunt machine has a slightly higher shunt field current than a long-shunt machine for the same terminal voltage.
- In practical applications, the external V-I characteristics of both configurations are nearly identical if the machine is well-designed.

Long Shunt and Short Shunt Connections II

- The choice between short and long shunt is often dictated by constructional convenience or specific switchgear arrangements.

Cumulative and Differential Compounding I

The magnetic interaction between the series and shunt fluxes defines the voltage regulation of the machine.

Key Points:

- Over-compounded (Cumulative): Full-load voltage is higher than no-load voltage. Used to compensate for significant line voltage drops.
- Flat-compounded (Cumulative): Full-load voltage approximately equals no-load voltage. Ideal for loads located near the generator.
- Under-compounded (Cumulative): Full-load voltage is slightly lower than no-load voltage, sharing similarities with shunt generators.
- Differential Compounding: The series flux opposes the shunt flux, leading to a drastically drooping voltage characteristic as load increases.

Cumulative and Differential Compounding II

- Differential generators act as almost constant-current sources when heavily loaded, preventing large current spikes.

Summary of Industrial Applications I

Generator selection is strictly driven by the voltage and current requirements of the target application.

Key Points:

- Separately Excited: Electroplating, refining processes, and Ward-Leonard speed control systems.
- Shunt Generators: Constant voltage applications like battery charging stations, synchronous machine excitation, and general lighting.
- Series Generators: Voltage boosters in long DC transmission lines and constant current supply for specialized heating.
- Cumulative Compound: Heavy machinery, DC traction systems (railways), elevators, and loads requiring steady voltage across long distances.

Summary of Industrial Applications II

- Differential Compound: Exclusively dominant in arc welding, where a drooping voltage is required to maintain a stable, constant-current arc.

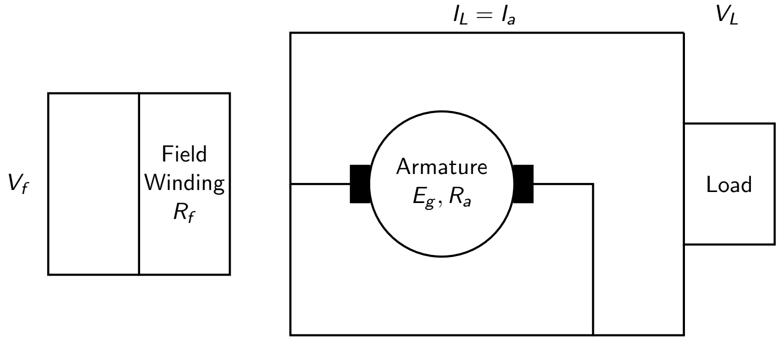
Classification of D.C. Generators I

D.C. generators are classified based on the methods of field excitation. The magnetic field in a DC machine is produced by electromagnets, which require a direct current for excitation.

Key Points:

- Separately Excited D.C. Generators: The field winding is supplied from an independent external D.C. source (like a battery or another generator).
- Self-Excited D.C. Generators: The field winding is supplied by the current produced by the generator itself.
- Self-excited generators require residual magnetism in the field poles to initiate voltage build-up.
- Types of Self-Excited Generators: Shunt, Series, and Compound wound.

Separately Excited D.C. Generator Diagram I



Key Points:

- The field winding is isolated electrically from the armature circuit.
- Field current (I_f) is determined by external supply (V_f) and field resistance (R_f): $I_f = V_f / R_f$.

Separately Excited D.C. Generator Diagram II

- Armature current (I_a) equals load current (I_L).
- Terminal voltage $V = E_g - I_a R_a - V_{brush}$, where E_g is generated EMF.

Applications of Separately Excited Generators I

Since the field excitation is independent of load current, these generators offer excellent voltage control and can operate in a stable manner over a wide range of output voltages.

Key Points:

- Ward-Leonard System: Widely used in speed control of D.C. motors where a broad and sensitive range of speed control is necessary.
- Used in testing laboratories where a wide range of DC voltages is required.
- Used as supply sources for other DC generators (exciters).
- Advantage: Capable of operating stably at very low field excitations.
- Disadvantage: Requires an external DC power source, making it more expensive and less portable.

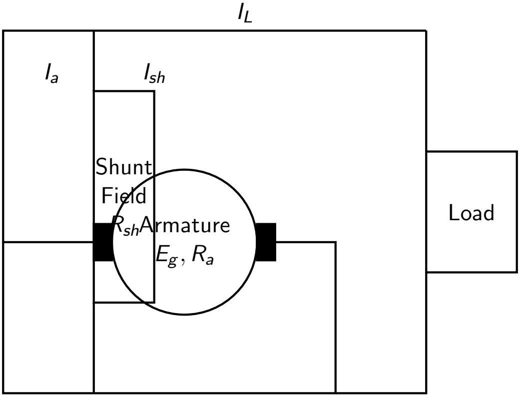
Self-Excited D.C. Generators: Introduction I

In self-excited generators, the residual magnetism in the field poles provides the initial flux. When the armature rotates, a small EMF is induced, causing a small field current, which in turn strengthens the magnetic flux.

Key Points:

- Requires residual magnetism in the poles to start the voltage build-up process.
- D.C. Shunt Generator: Field winding is connected in parallel with the armature.
- D.C. Series Generator: Field winding is connected in series with the armature.
- D.C. Compound Generator: Contains both series and shunt field windings on the poles.
- The process of voltage build-up is cumulative until magnetic core saturation is reached.

D.C. Shunt Generator Diagram I



Key Points:

- The shunt field winding consists of many turns of fine wire and has high resistance (R_{sh}).

D.C. Shunt Generator Diagram II

- Armature current divides into field current and load current: $I_a = I_L + I_{sh}$.
- Field current $I_{sh} = V/R_{sh}$, where V is the terminal voltage.
- Terminal voltage $V = E_g - I_a R_a$.
- Considered a constant-voltage generator because V drops only slightly from no-load to full-load.

Applications of D.C. Shunt Generators I

Because of their relatively constant voltage characteristics, shunt generators are utilized where a steady supply voltage is required under varying load conditions.

Key Points:

- Battery Charging: Provides a stable voltage essential for properly charging batteries without overcurrent.
- General Lighting: Used for lighting circuits where voltage consistency prevents flickering.
- Excitation: Acts as exciters for the field windings of large AC alternators.
- Portable DC power sources for tools and equipment requiring stable DC.
- Highly effective in applications where load is situated near the generator to minimize line voltage drop.

D.C. Series Generator Characteristics I

In a series generator, the field winding is connected in series with the armature and the load. It carries the full load current and is wound with a few turns of thick wire.

Key Points:

- Series field current (I_{se}) equals armature current (I_a) and load current (I_L): $I_a = I_{se} = I_L$.
- Generated EMF E_g increases with the load because field flux increases with load current.
- Terminal voltage $V = E_g - I_a(R_a + R_{se})$.
- It is a variable voltage generator; voltage is minimum at no load and increases with load.
- Application: Used as voltage boosters in DC transmission systems to compensate for line drop.
- Application: Historically used for constant-current arc lighting (now mostly obsolete).

D.C. Compound Generators I

Compound generators possess both series and shunt field windings. They combine the characteristics of both to achieve specific voltage regulation curves.

Key Points:

- Cumulative Compound: The series field flux aids the shunt field flux ($\Phi_{total} = \Phi_{sh} + \Phi_{se}$).
- Differential Compound: The series field flux opposes the shunt field flux ($\Phi_{total} = \Phi_{sh} - \Phi_{se}$).
- Long-Shunt Connection: Shunt field is connected across both armature and series field.
- Short-Shunt Connection: Shunt field is connected only across the armature.
- Degree of compounding (over, flat, or under-compounded) determines how terminal voltage varies with load.

Applications of D.C. Compound Generators I

The versatility of compound generators allows them to be tailored for specific industrial needs by adjusting the series field turns (compounding).

Key Points:

- Cumulative (Flat-Compounded): Used for general power and lighting loads where voltage must be constant irrespective of load variations.
- Cumulative (Over-Compounded): Used to supply power over long DC transmission lines to compensate for severe line voltage drops.
- Cumulative (Under-Compounded): Sometimes used for parallel operation of DC generators.
- Differential Compound: Has a steeply drooping voltage characteristic; voltage drops rapidly with increasing load.

Applications of D.C. Compound Generators II

- Differential Compound Application: Used in DC welding to provide a constant current characteristic preventing excessive current during short circuits.

Introduction to DC Generator Characteristics I

Operating characteristics define the behavior of a DC generator under varying load conditions.

Key Points:

- They graphically represent the relationships between various electrical and magnetic quantities.
- The most important quantities are field current (If), armature current (Ia), load current (IL), generated EMF (E), and terminal voltage (V).
- Understanding these curves is essential for selecting the appropriate generator for a specific application.
- The speed of the generator is generally assumed to be constant during these characteristic tests.

The Three Primary Characteristics I

There are three fundamental characteristics that completely describe the performance of a DC generator.

Key Points:

- 1. Open Circuit Characteristic (OCC) or Magnetic Characteristic: Relates no-load EMF (E0) to field current (If) at constant speed.
- 2. Internal Characteristic or Total Characteristic: Relates the actually generated EMF (E) to the armature current (Ia).
- 3. External Characteristic: Relates the terminal voltage (V) to the load current (IL).
- The external characteristic is the most practically important as it determines the suitability of a generator for a given load.

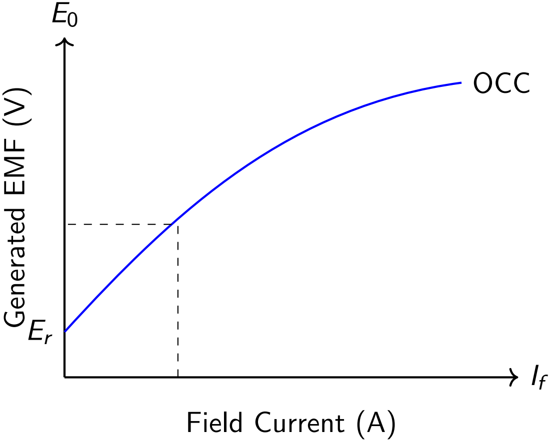
Open Circuit Characteristic (OCC) I

The OCC is also known as the magnetization curve or no-load characteristic.

Key Points:

- It shows the variation of no-load generated EMF (E0) with field current (If) when the machine is driven at a constant rated speed.
- For low values of If, E0 is proportional to If because the magnetic circuit is unsaturated and reluctance is mainly due to the air gap.
- At higher field currents, the iron parts of the magnetic circuit (armature core, pole core) start to saturate, causing the curve to bend and flatten.
- Even when If $= 0$, a small EMF (Er) is generated due to the residual magnetism in the poles.

OCC Diagram I



Key Points:

OCC Diagram II

- The curve starts from a point slightly above the origin due to residual magnetism (Er).
- The initial linear portion represents the air gap line where permeability is practically constant.
- The knee of the curve indicates the onset of magnetic saturation in the iron core.

Internal Characteristic (E vs Ia) I

The internal characteristic plots the generated EMF on load (E) against the armature current (Ia).

Key Points:

- It is obtained by subtracting the voltage drop due to armature reaction from the no-load EMF (E0).
- Armature reaction has a demagnetizing effect that reduces the net main pole flux, thereby reducing the generated EMF.
- Therefore, E is always less than E0 under loaded conditions, provided the field excitation remains constant.
- This curve lies below the OCC and is primarily of theoretical interest to determine internal voltage drops.

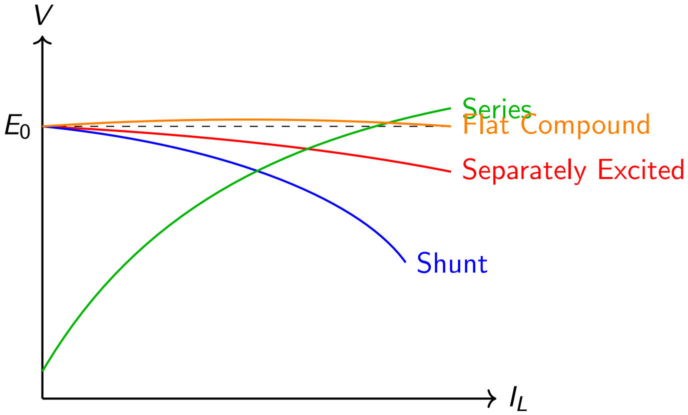
External Characteristic (V vs IL) I

The external characteristic plots the terminal voltage (V) against the load current (IL).

Key Points:

- It is obtained from the internal characteristic by subtracting the armature circuit voltage drop (IaRa) from the generated EMF (E).
- $V = E - IaRa$ (for a separately excited or shunt generator).
- The external characteristic curve always lies below the internal characteristic curve.
- This is the most important characteristic for practical purposes as it shows how the voltage delivered to the load varies with the load current.

External Characteristics of Different Generators I



Key Points:

External Characteristics of Different Generators II

- Shunt generators show a greater voltage drop than separately excited generators due to the reduction in field current as terminal voltage drops.
- Series generators show an increasing voltage with load up to magnetic saturation, after which it drops due to armature reaction and resistance.
- Compound generators can be designed for flat, over, or under-compounding based on the series field amp-turns.

Factors Affecting Terminal Voltage Drop I

In self-excited generators, the drop in terminal voltage from no-load to full-load is caused by multiple interacting factors.

Key Points:

- 1. Armature Circuit Resistance Drop (IaRa): The direct ohmic voltage drop across the armature winding, brushes, and contact resistance.
- 2. Armature Reaction Drop: The demagnetizing effect of armature flux reduces the main flux, lowering the induced EMF.
- 3. Decreased Field Current (Shunt only): As V drops due to the first two reasons, the shunt field current (If = V/Rsh) also decreases, further reducing flux and EMF.
- This cumulative effect leads to the more pronounced 'drooping' characteristic of a shunt generator compared to a separately excited one.

The external characteristic dictates the appropriate application domain of each type of DC generator.

Key Points:

- Shunt generators are suitable for reasonably constant voltage applications like battery charging and lighting circuits.
- Series generators have limited direct application but are used as voltage boosters in DC distribution systems.
- Compound generators (especially flat-compounded) are used where a constant voltage over a wide load range is required, such as in DC power supplies for heavy motor loads.
- Understanding these characteristics allows engineers to predict system performance and design appropriate control and regulation mechanisms.

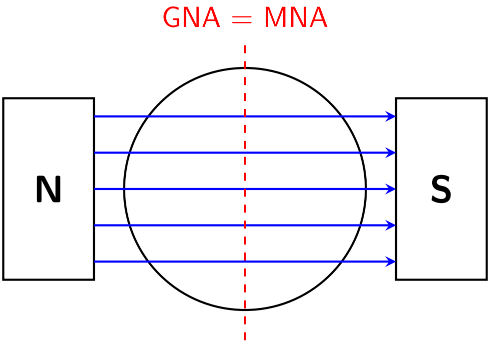
What is Armature Reaction? I

In a DC machine, two magnetic fluxes are present: the main flux produced by the field poles, and the armature flux produced by the current flowing through the armature conductors.

Key Points:

- Armature reaction is the effect of the armature magnetic field on the main magnetic field.
- When the armature is loaded and carries current, it sets up its own magnetic field (armature mmf).
- This armature mmf distorts and weakens the main field flux.
- The Geometrical Neutral Axis (GNA) is the axis of symmetry between poles.
- The Magnetic Neutral Axis (MNA) is the axis perpendicular to the resultant flux passing through the armature.

Magnetic Field Distribution on No-Load I



Key Points:

- Under no-load conditions, the armature current is zero (or negligible).

Magnetic Field Distribution on No-Load II

- The only mmf acting is the main field mmf, producing a uniform, symmetrical flux.
- The magnetic lines of force are parallel to the polar axis.
- Because the flux is horizontal and symmetrical, the MNA coincides perfectly with the GNA.
- Brushes are optimally placed along the MNA to achieve zero induced EMF in the commutated coil.

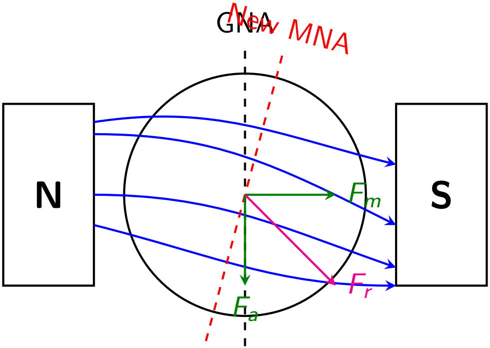
Armature MMF (Cross-Magnetization) I

Consider the armature carrying current while the main field is unexcited. The current direction in conductors under the N-pole is inwards (cross) and under the S-pole is outwards (dot) for a generator.

Key Points:

- According to the right-hand grip rule, the armature sets up a magnetic field that is perpendicular (at 90 degrees) to the main field axis.
- The armature flux is directed downward along the GNA (for a clockwise rotating generator).
- This transverse field causes a pure cross-magnetizing effect.
- The MMF wave of the armature is triangular in space, peaking at the interpolar axis (GNA) and zero at the center of the poles.

Resultant Magnetic Field Under Load I



Key Points:

- The main field and armature field interact to form a resultant field.

Resultant Magnetic Field Under Load II

- Flux lines are crowded at the trailing pole tips and thinned out at the leading pole tips for a generator.
- This distortion shifts the resultant flux axis forward in the direction of rotation.
- Consequently, the Magnetic Neutral Axis (MNA) shifts forward by an angle theta.
- Brushes must be shifted to the new MNA to achieve sparkless commutation.

Demagnetizing and Cross-Magnetizing Effects I

When the brushes are shifted to the new MNA to avoid sparking, the armature MMF vector also shifts by the same angle.

Key Points:

- The armature MMF can now be resolved into two orthogonal components.
- Demagnetizing Component: Acts in direct opposition to the main field poles, reducing total flux and generated EMF.
- Cross-magnetizing Component: Acts perpendicular to the main field, distorting it.
- Conductors lying within twice the brush shift angle constitute the demagnetizing ampere-turns.
- The remaining conductors constitute the cross-magnetizing ampere-turns.

Remedies for Armature Reaction I

To maintain efficient operation and avoid voltage drop and sparking, the effects of armature reaction must be mitigated.

Key Points:

- Brush Shifting: Shifting brushes to the new MNA, but this is impractical for variable loads as the MNA shifts with load current.
- Interpoles (Commutating Poles): Small narrow poles placed in the interpolar regions to neutralize cross-magnetizing MMF at any load.
- Compensating Windings: Embedded in the main pole faces carrying armature current in the opposite direction to adjacent conductors.
- High Reluctance Pole Tips: Chamfering pole tips to increase air gap reluctance, reducing flux crowding.

Introduction to Commutation I

Commutation is the process by which current in the short-circuited coil reverses its direction as the coil passes the MNA.

Key Points:

- In a DC machine, the generated alternating current in the armature is converted to direct current by the commutator and brushes.
- A coil undergoes commutation when it is short-circuited by a carbon brush bridging two adjacent commutator segments.
- During this short time (Time of Commutation), the current must reverse from +Ic to -Ic.
- Ideal (Linear) Commutation: Current changes linearly from +Ic to -Ic without any sparking.

Reactance Voltage and Delayed Commutation I

In practice, the reversal of current is opposed by the coil's self-inductance.

Key Points:

- The short-circuited coil possesses self-inductance (L).
- The rapid change of current (di/dt) induces a self-induced EMF, given by e = L * (di/dt).
- This induced EMF is called the 'Reactance Voltage'.
- According to Lenz's Law, Reactance voltage opposes the reversal of current, causing 'under-commutation' or delayed commutation.
- As the trailing edge of the brush leaves the commutator segment, unreversed current arcs across the air gap, causing severe sparking.

Methods to Improve Commutation I

To achieve sparkless commutation, the reactance voltage must be neutralized.

Key Points:

- Resistance Commutation: Using high-resistance carbon brushes. The increasing contact resistance at the trailing edge forces current into the next coil.
- Voltage Commutation (EMF Commutation): Inducing a reversing EMF in the short-circuited coil to cancel the reactance voltage.
- Brush Shift: Shifting brushes slightly ahead of MNA (in generators) so the coil enters the fringe field of the next pole.
- Interpoles: Providing a dynamic neutralizing field exactly at the commutating zone, which is the most effective and widely used method.

Introduction to Losses in DC Machines I

A DC machine converts mechanical energy into electrical energy (generator) or vice-versa (motor). During this conversion, not all input energy is transferred to the output due to various losses within the machine.

Key Points:

- Losses reduce the efficiency of the DC machine.
- They dictate the temperature rise, which determines the rating of the machine.
- Major categories of losses: Copper Losses, Iron (Core) Losses, and Mechanical Losses.
- Stray load losses account for additional losses not covered by the main categories, usually taken as 1

Copper Losses in DC Machines I

Copper losses occur due to the resistance of the various windings in the DC machine when current flows through them. They are proportional to the square of the current (I^2R losses).

Key Points:

- Armature Copper Loss (I_a^2 R_a): The most significant copper loss, varying with the square of armature current. Usually 30-40
- Field Copper Loss (I_f^2 R_f): Constant for shunt machines (V^2/R_sh) but varies with load for series machines. Typically 20-30
- Brush Contact Loss: Voltage drop across the brush contacts, often taken as 2V total (1V per brush) times I_a.
- Total Copper Loss = Armature Cu Loss + Field Cu Loss + Brush Contact Loss.

Iron (Core) and Mechanical Losses I

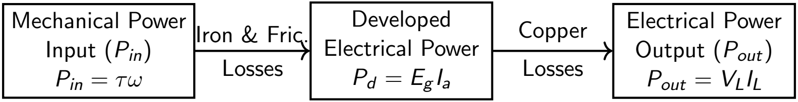
Iron losses occur in the armature core since it rotates in a magnetic field, whereas mechanical losses are due to physical movement. Both are generally considered constant losses.

Key Points:

- Hysteresis Loss (P_h): Occurs due to magnetic reversal in the armature core. P_h = $\eta B\_max^{1.6} fV.Reducedbyusingsiliconsteel.$
- Eddy Current Loss (P_e): Due to induced currents in the core. P_e = K_e B_max^{2}f^2 t^2 V. Minimized by laminating the armature core.
- Friction Losses: Bearing friction and brush friction against the commutator.
- Windage Losses: Aerodynamic drag on the rotating armature.

Iron (Core) and Mechanical Losses II

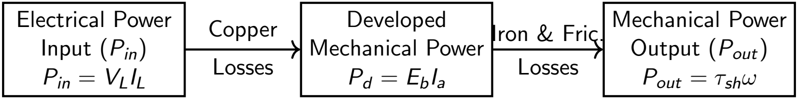
- Together, Iron and Mechanical losses form the Constant Losses (or Rotational Losses), about 10-20



Key Points:

- Mechanical Power Input (P_in): Driving power from prime mover.
- Iron and Friction Losses: Subtracted from mechanical input to get electrical power generated in armature.
- Electrical Power Developed (E_g I_a): Internal electrical power converted from mechanical power.
- Copper Losses: Subtracted from developed electrical power.
- Electrical Power Output (V I_L): Usable electrical power delivered to the load.

Power Stages in DC Motor I



Key Points:

- Electrical Power Input (V I_L): Power supplied from the mains.
- Copper Losses: Subtracted from electrical input to get developed mechanical power.
- Mechanical Power Developed (E_b I_a): Internal mechanical power converted from electrical power.
- Iron and Friction Losses: Subtracted from developed mechanical power.
- Mechanical Power Output (P_out): Useful power available at the motor shaft (BHP).

Efficiency of DC Machines I

Efficiency is the ratio of useful output power to total input power. It evaluates how effectively the machine converts energy.

Key Points:

- Mechanical Efficiency (η_m) : $Ratioofdevelopedelectricalpowertomechanicalinput(generator)orus$
- Electrical Efficiency (η_e) : $Ratioofelectricaloutputtodevelopedelectricalpower(generator)orde$
- Commercial/Overall Efficiency (η_c) : $\eta\_c = \eta\_m \times \eta\_e.Ratioofnetoutputpowertonetinputpower.$
- Overall Efficiency is always lower than both mechanical and electrical efficiencies due to cumulative losses.

Condition for Maximum Efficiency I

A DC machine attains its highest efficiency when its variable losses are exactly equal to its constant losses.

Key Points:

- Generator input power: P_in = V I_L + I_a^2 R_a + W_c, where W_c is constant losses.
- Assuming I_a $\approx I_L(shuntmachine), Totallosses = I_$a^2 R_a + W_c.
- Efficiency $\eta = (VI_a)/(VI_a + I_$a^2 R_a + W_c).
- Differentiating $\eta withrespecttoI_aandequatingtozeroyields : I_$a^2 R_a = W_c.
- Therefore, Maximum Efficiency occurs when Variable Losses (Copper) = Constant Losses (Iron + Mechanical).
- The load current at maximum efficiency: I = $\sqrt{W\_c/R\_a}$.

Voltage Regulation of DC Generator I

Voltage regulation indicates the change in terminal voltage from no-load to full-load condition, expressed as a percentage of the full-load voltage.

Key Points:

- Voltage Regulation (
- V_NL is the No-Load terminal voltage.
- V_FL is the Full-Load terminal voltage.
- A smaller percentage indicates better voltage regulation, meaning the voltage remains relatively stable under varying loads.
- Factors affecting regulation: Armature resistance drop (I_a R_a) and Armature Reaction drop.
- Series generators have negative regulation, while shunt and compound generators have positive regulation.

Summary and Key Takeaways I

Understanding power stages, losses, and efficiency is crucial for evaluating and optimizing the performance of DC machines.

Key Points:

- Losses are categorized into variable (copper) and constant (iron + mechanical).
- Power stages clearly trace energy conversion, highlighting points of loss.
- Overall efficiency peaks when variable losses equate to constant losses.
- Voltage regulation is a key metric for generators, indicating voltage stability under load variations.
- Proper design (laminations, high-quality steel) minimizes constant losses, improving overall performance.

Principle of D.C. Motor Operation I

A direct current (DC) motor converts electrical energy into mechanical energy based on the principle of electromagnetic induction and magnetic force.

Key Points:

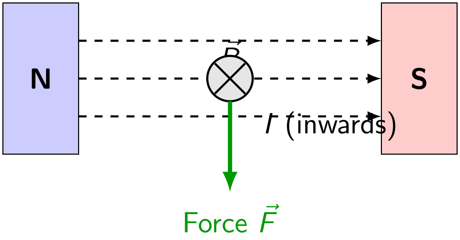
- When a current-carrying conductor is placed in a magnetic field, it experiences a mechanical force.
- The direction of this force is mutually perpendicular to both the magnetic field and the direction of the current.
- In a DC motor, the stator provides a stationary magnetic field, and the armature (rotor) carries the current.
- The interaction between the main magnetic flux and the armature flux produces a driving torque that rotates the armature.

The Lorentz Force Law I

The fundamental principle driving the motor is the Lorentz force. It describes the force exerted on a charged particle moving through an electromagnetic field.

Key Points:

- The total force F on a point charge q is given by $F = q(E + v \times B)$, where E is the electric field, v is the velocity, and B is the magnetic field.
- For a straight current-carrying conductor of length L in a uniform magnetic field, this simplifies to $F = I(L \times B)$.
- The magnitude of the force is $F = B \cdot I \cdot L \cdot \sin(\theta)$, where θ is the angle between the current direction and the magnetic field.
- Maximum force is generated when the conductor is strictly perpendicular to the magnetic field ($\theta = 90$ degrees, $\sin(\theta) = 1$).



Key Points:

- Magnetic field (B) flows from North to South.
- The cross (X) inside the conductor indicates current (I) flowing into the page.
- According to the interaction of the main field and the field around the conductor, flux density increases above the conductor and decreases below it.

Diagram: Conductor in a Magnetic Field II

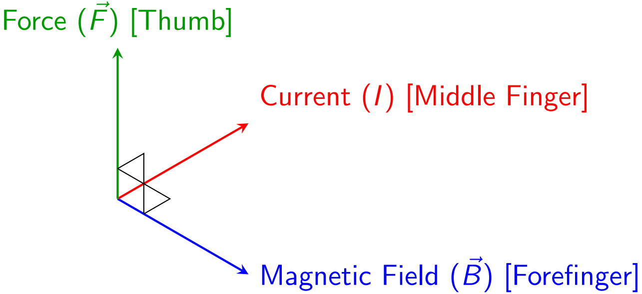
- This creates a downward net mechanical force (F) on the conductor.

Fleming's Left-Hand Rule I

Fleming's Left-Hand Rule is a visual mnemonic used to determine the direction of the force experienced by a current-carrying conductor in a magnetic field.

Key Points:

- Stretch the thumb, forefinger (index finger), and middle finger of your left hand such that they are mutually perpendicular.
- Forefinger represents the direction of the Magnetic Field (B), pointing from North to South.
- Middle finger represents the direction of the Current (I), flowing from positive to negative.
- Thumb will then point in the direction of the resulting mechanical Force (F) or motion.



Key Points:

- The 3D vector diagram illustrates the mutually orthogonal relationship of B, I, and F.
- If the current or the magnetic field reverses direction, the force vector will also reverse its direction.

Diagram: Fleming's Left-Hand Rule Vectors II

- If both current and magnetic field are reversed simultaneously, the direction of the force remains unchanged.

Role of the Commutator I

To maintain continuous unidirectional rotation, the direction of current in the armature conductors must be reversed as they pass from the influence of one pole to the next.

Key Points:

- The commutator acts as a mechanical rotary switch, reversing the current direction in the armature coils at specific rotational positions.
- As a coil moves past the neutral axis (between N and S poles), the commutator segments connected to that coil switch their contact with the stationary carbon brushes.
- This ensures that conductors under the North pole always carry current in one direction, while those under the South pole carry it in the opposite direction.
- The result is a continuous, unidirectional torque on the rotor shaft, rather than an oscillating force.

Concept of Back EMF I

When the armature of a DC motor rotates under the influence of the driving torque, its conductors cut the magnetic flux of the stator.

Key Points:

- According to Faraday's Law of Electromagnetic Induction, this flux cutting action induces an electromotive force (EMF) in the armature conductors.
- By Lenz's Law, the direction of this induced EMF opposes the very cause producing it, which is the applied supply voltage (V).
- Because it opposes the supply voltage, this induced EMF in a motor is known as Back EMF or Counter EMF, denoted as Eb.
- The motor armature behaves like a battery connected in series-opposition to the main electrical supply.

Significance of Back EMF I

Back EMF is not an undesirable byproduct; it is the fundamental mechanism that allows a DC motor to be a self-regulating machine.
Key Points:

- Self-Regulation: Eb dynamically adjusts the armature current to meet the mechanical load requirements.
- When load increases, motor speed drops, Back EMF decreases, allowing more armature current to flow from the supply to produce the required higher torque.
- When load decreases, motor speed rises, Back EMF increases, reducing the armature current to match the lower torque demand.
- Without Back EMF (e.g., at startup when speed is zero), the armature current would be dangerously high, necessitating a starting resistor to prevent motor winding damage.

Voltage Equation of a DC Motor I

The relationship between the applied voltage, Back EMF, and armature resistance drop is given by the fundamental voltage equation of the motor.

Key Points:

- The Back EMF equation is $Eb = (P \cdot \Phi \cdot Z \cdot N) / (60 \cdot A)$, where P=poles, Φ=flux/pole, Z=total armature conductors, N=speed in RPM, A=parallel paths.
- The applied voltage V must overcome the Back EMF (Eb) and the ohmic voltage drop in the armature winding $(Ia \cdot Ra)$.
- Therefore, the motor voltage equation is: $V = Eb + Ia \cdot Ra$, where Ia is armature current and Ra is armature circuit resistance.

Voltage Equation of a DC Motor II

- Multiplying the equation by Ia yields $V \cdot Ia = Eb \cdot Ia + Ia^2 \cdot Ra$, demonstrating that electrical input power equals mechanical power developed ($Eb \cdot Ia$) plus copper losses ($Ia^2 \cdot Ra$).

Introduction to D.C. Motor Principle I

A direct current (D.C.) motor operates on the fundamental electromagnetic principle that whenever a current-carrying conductor is placed in a magnetic field, it experiences a mechanical force.

Key Points:

- Converts electrical energy into mechanical energy.
- The construction of a D.C. motor is fundamentally the same as that of a D.C. generator.
- The interaction between the main magnetic field and the magnetic field established by the armature current produces torque.
- The magnitude and direction of the force depend on the magnetic flux density, the current, and the orientation of the conductor.

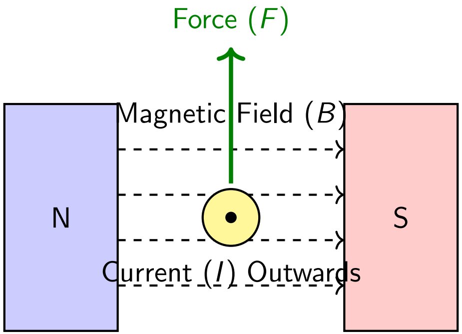
Lorentz Force Law I

The Lorentz force is the combination of electric and magnetic force on a point charge due to electromagnetic fields. In a D.C. motor, the focus is on the magnetic force component acting on a current-carrying conductor.

Key Points:

- Equation: $F = B\ I\ L\ \sin(\theta)$
- F is the mechanical force in Newtons (N).
- B is the magnetic flux density in Teslas (T) or Webers/m^2.
- I is the magnitude of the electric current in Amperes (A).
- L is the active length of the conductor in the magnetic field in meters (m).
- θ is the angle between the conductor and the magnetic field vectors.

Diagram: Conductor in a Magnetic Field I



Key Points:

- The N and S poles establish a uniform magnetic field from left to right.
- The central conductor carries a current directed out of the slide plane.

Diagram: Conductor in a Magnetic Field II

- The interaction of the two magnetic fields (main field and conductor field) pushes the conductor upwards.
- This upward thrust is governed by the Lorentz force law.

Fleming's Left-Hand Rule I

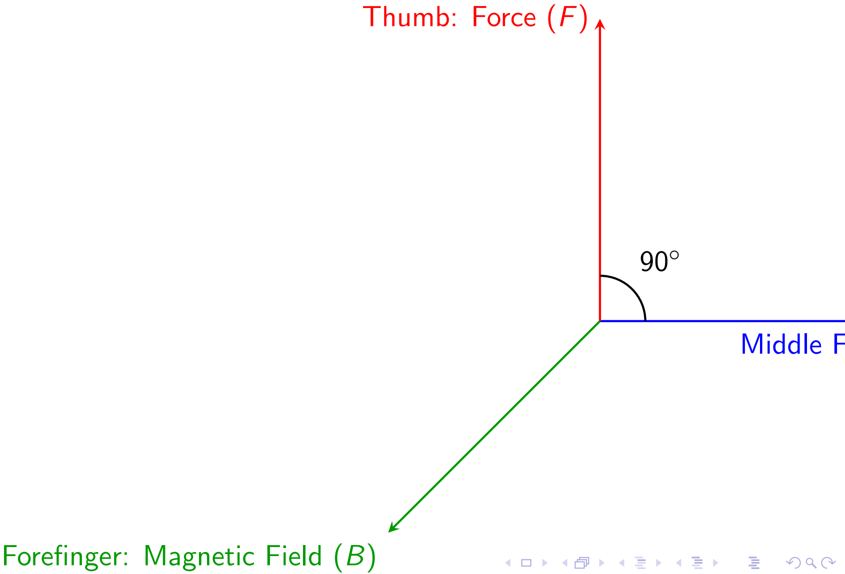
Fleming's Left-Hand Rule is a mnemonic used to determine the direction of the mechanical force (or motion) experienced by a current-carrying conductor in a magnetic field.

Key Points:

- Stretch the thumb, forefinger, and middle finger of the left hand so they are mutually perpendicular.
- Forefinger (First finger) points in the direction of the Magnetic Field (B).
- Middle finger (seCond finger) points in the direction of the Current (I).
- Thumb then points in the direction of the mechanical Force (F) or Thrust.

Diagram: Fleming's Left-Hand Rule I

Diagram: Fleming's Left-Hand Rule II



Motor Action in a D.C. Machine I

In a practical D.C. motor, the armature winding consists of many coils placed in slots on the armature core. Commutator action ensures continuous unidirectional torque.

Key Points:

- When D.C. supply is given, conductors under the N-pole carry current in one direction, while those under the S-pole carry current in the opposite direction.
- Applying Fleming's Left-Hand rule shows that force on all conductors under N-poles and S-poles acts in the same rotational direction.
- This continuous unidirectional force produces a driving torque.
- The commutator acts as a mechanical inverter, reversing armature coil currents as they cross the magnetic neutral axis to maintain continuous rotation.

Introduction to Back E.M.F. I

When the armature of a D.C. motor rotates under the influence of the driving torque, its conductors cut the magnetic flux of the field poles.

Key Points:

- According to Faraday's Laws of Electromagnetic Induction, an electromotive force (E.M.F.) is induced in these conductors.
- By Lenz's Law, the direction of this induced E.M.F. is such that it opposes the cause producing it (i.e., the applied voltage).
- Therefore, this induced E.M.F. is known as Back E.M.F. or Counter E.M.F. (Eb).
- Eb $= (P\ \Phi\ Z\ N)\ /\ (60\ A)$, the same formula as the generated E.M.F. in a D.C. generator.

Significance of Back E.M.F. I

The presence of back E.M.F. makes the D.C. motor a self-regulating machine, automatically adjusting its armature current to meet the mechanical load requirements.

Key Points:

- Armature current Ia = (V - Eb) / Ra, where V is supply voltage and Ra is armature resistance.
- When running at no load, motor requires small torque to overcome friction. Speed is high, Eb is high, hence Ia is small.
- If mechanical load is suddenly increased, motor speed decreases, which reduces Eb.
- Reduced Eb results in a larger armature current (Ia), increasing the motor's torque to match the new mechanical load.

Voltage Equation of D.C. Motor I

The voltage equation governs the relationship between the applied voltage, back E.M.F., and the voltage drop across the armature resistance.

Key Points:

- V = Eb + Ia * Ra
- V is the applied supply voltage to the motor terminals.
- Eb is the back E.M.F. induced in the armature.
- Ia * Ra is the voltage drop due to the internal armature circuit resistance.
- Multiplying the equation by Ia yields the power equation: V*Ia = Eb*Ia + Ia^2*Ra.
- Here, V*Ia is electrical input, Eb*Ia is mechanical power developed, and Ia^2*Ra is copper loss.

Introduction to Torque I

Torque is the turning or twisting moment of a force about an axis. It is measured by the product of the force and the radius at which this force acts.

Key Points:

- Mathematical definition: $T = F \times r$, where F is the force and r is the radius of the armature.
- In a DC motor, each conductor is acted upon by a circumferential force $F = B \times I \times L$.
- Since the conductors are placed on the surface of the armature of radius r, they exert a turning moment.
- Total torque depends on the cumulative effect of all current-carrying conductors in the magnetic field.

Armature Torque (Ta) Derivation I

The torque developed by the armature of a motor is called Armature Torque. It is derived from the mechanical power developed.

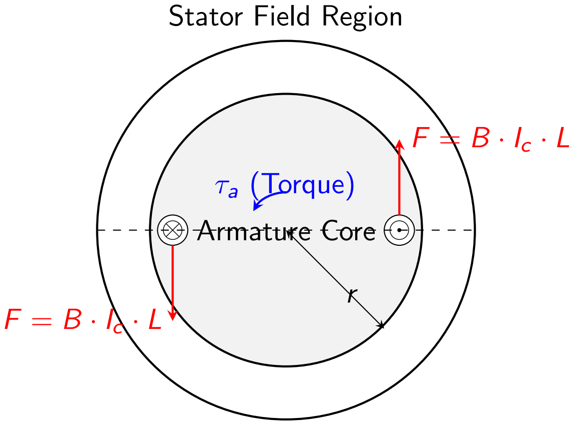
Key Points:

- Let Ta be the armature torque in N-m, and N be the speed in RPM.
- Mechanical power developed in the armature = Ta $\times$ (2 $\times$ π $\times$ N / 60) Watts.
- Electrically, the mechanical power developed is also given by Pm = Eb $\times$ Ia, where Eb is back EMF and Ia is armature current.
- Equating both: Ta $\times$ (2 $\times$ π $\times$ N / 60) = Eb $\times$ Ia.
- Since Eb = (Φ $\times$ Z $\times$ N $\times$ P) / (60 $\times$ A), substituting this gives Ta = 0.159 $\times$ Φ $\times$ Z $\times$ Ia $\times$ (P / A) N-m.

Armature Torque (Ta) Derivation II

- For a given motor, Z, P, and A are constant, hence Ta $\propto \Phi \times$ Ia.

Armature Forces and Torque Diagram I



Key Points:

Armature Forces and Torque Diagram II

- The diagram shows a cross-section of the armature with two conductors carrying current in opposite directions.
- The interaction between the magnetic field (B) and conductor current (Ic) produces a force (F).
- The tangential forces on the conductors create a twisting moment (torque) around the shaft axis.
- The sum of all these individual conductor torques constitutes the total Armature Torque (Ta).

Shaft Torque (Tsh) I

The torque which is available at the motor shaft for doing useful work is known as shaft torque.

Key Points:

- It is always less than the armature torque (Ta) due to mechanical losses.
- Mechanical losses include friction (at bearings and commutator) and windage (air friction) losses.
- The relationship is given by: Tsh = Ta - Tf, where Tf is the lost torque due to friction and windage.
- Shaft torque represents the net useful rotational force transmitted to the mechanical load.
- Tsh = Output Power / (2 $\times$ π $\times$ N / 60).

Lost Torque (Tf) I

Lost torque accounts for the internal mechanical and iron losses in the machine that prevent all generated torque from reaching the shaft.

Key Points:

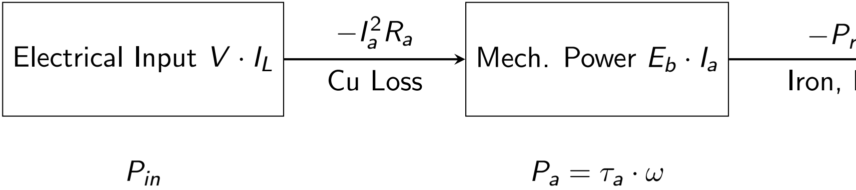
- Lost Torque (Tf) = Ta - Tsh.
- Alternatively, Tf can be calculated from rotational losses: Tf = Rotational Losses / (2 $\times$ π $\times$ N / 60).
- Rotational losses = Friction Windage losses + Iron (core) losses.
- Iron losses occur in the armature core due to hysteresis and eddy currents as it rotates in the magnetic field.
- In a no-load condition, the motor only develops enough torque to overcome these rotational losses (i.e., Ta = Tf and Tsh = 0).

Brake Horse Power (BHP) I

Brake Horse Power is the measure of the motor's useful mechanical power output available at the shaft.

Key Points:

- It is termed 'Brake' because it was originally measured using a Prony brake or dynamometer connected to the shaft.
- 1 Horse Power (HP) in electrical engineering (imperial) is generally equivalent to 746 Watts, or 735.5 Watts in the metric system.
- BHP is directly related to Shaft Torque (Tsh): Output Power (in Watts) = BHP $\times$ 746.
- Therefore, Tsh = (BHP $\times$ 746 $\times$ 60) / (2 $\times$ π $\times$ N) N-m.
- BHP is the standard rating printed on the nameplate of industrial motors to denote their mechanical capability.



Key Points:

- The diagram illustrates the flow of energy from electrical input to mechanical output in a DC motor.
- Initial loss is the copper loss (I^2R) in the armature and field windings, leaving the mechanical power developed (Eb × Ia).
- The mechanical power developed is proportional to the internal Armature Torque (Ta).

Power Flow and Conversion Diagram II

- Rotational losses (iron, friction, windage) further reduce the power, resulting in the final mechanical output at the shaft.
- The final output corresponds to the Shaft Torque (Tsh) and defines the motor's Brake Horse Power (BHP).

Torque Characteristics and Efficiency I

The relationships between armature torque, shaft torque, and different speeds dictate the performance and efficiency of the motor.

Key Points:

- Mechanical Efficiency (m) = Output Mechanical Power / Internal Mechanical Power Developed = (Tsh $\times$ ω) / (Ta $\times$ ω) = Tsh / Ta.
- Electrical Efficiency (e) = Internal Mechanical Power Developed / Electrical Input Power = (Eb $\times$ Ia) / (V $\times$ IL).
- Overall Efficiency () = m $\times$ e = Mechanical Output Power / Electrical Input Power.
- As load increases, both Ta and Tsh increase, but efficiency peaks at a specific load where constant losses equal variable losses.
- Starting torque must be significantly higher than full-load torque to overcome high static friction and inertia.

Summary and Key Takeaways I

A clear understanding of the various torque definitions is essential for motor selection and application engineering.

Key Points:

- Armature Torque (Ta) is the gross torque developed internally by electromagnetic induction.
- Shaft Torque (Tsh) is the net useful torque available at the rotor shaft, reduced by mechanical and iron losses.
- Lost Torque (Tf) accounts for the difference between Ta and Tsh (Tf = Ta - Tsh).
- Brake Horse Power (BHP) is the industrial unit of mechanical output power, directly linked to Shaft Torque and angular velocity.
- Motor sizing for a specific industrial application is primarily determined by the required BHP and nominal operating speed.

Introduction to Torque I

Torque in a DC motor is the turning or twisting moment of a force about an axis.

Key Points:

- Torque (T) is defined as the product of force (F) and the perpendicular distance (r) from the axis of rotation: $T = F \times r$.
- In a DC motor, the torque is produced by the electromagnetic interaction between the magnetic field of the stator and the current-carrying conductors in the armature.
- When an armature conductor carries current in a magnetic field, it experiences a mechanical force (Lorentz force) $F = B\ I\ L$.

Introduction to Torque II

- The cumulative effect of all forces acting on the individual conductors, at a radius R from the shaft center, creates a net turning moment called the electromagnetic torque or armature torque.

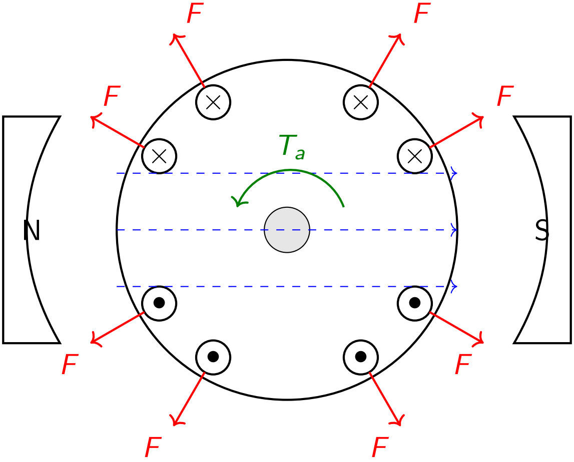
Derivation of Armature Torque (Ta) I

The gross mechanical power developed by the armature is given by the product of the back EMF (Eb) and the armature current (Ia).

Key Points:

- Electrical power converted into mechanical power: P_mech = Eb $\times$ Ia.
- Mechanical power can also be expressed as the product of armature torque (Ta) and angular velocity (ω): $P_mech = Ta\omega$.
- Equating both expressions: Ta $\times$ (2πN / 60) = Eb $\times$ Ia, where N is the speed in Revolutions Per Minute (RPM).
- Substituting Eb = (Φ Z N P) / (60 A), we get Ta $\times$ (2πN / 60) = (Φ Z N P Ia) / (60 A).
- Simplifying yields the fundamental torque equation: Ta = (1 / 2π) $\times$ (Φ Z P Ia / A) = 0.159 Φ Z P Ia / A (N-m).

Visualizing Armature Torque I



Key Points:

Visualizing Armature Torque II

- The diagram illustrates a cross-section of a 2-pole DC motor.
- Conductors under the N-pole carry current inward ($\times$), while conductors under the S-pole carry current outward ($\bullet$).
- According to Fleming's Left-Hand Rule, a unidirectional force F is exerted on all conductors, producing a net counter-clockwise torque Ta.

Dependence of Armature Torque on Flux and Current I

From the torque equation $Ta = (P\ Z\ /\ 2\pi\ A) \times \Phi \times Ia$, we can identify constants and variables for a specific motor.

Key Points:

- For a given, manufactured DC motor, the number of poles (P), total armature conductors (Z), and parallel paths (A) are constant.
- Therefore, $Ta \propto \Phi\ Ia$ (Armature torque is directly proportional to the product of flux per pole and armature current).
- In a D.C. Shunt Motor: The field flux Φ is practically constant, so $Ta \propto Ia$. The torque-current characteristic is a straight line through the origin.
- In a D.C. Series Motor: Before magnetic saturation, field flux Φ is proportional to the series field current, which is equal to Ia ($\Phi \propto Ia$). Thus, $Ta \propto Ia^2$. The characteristic is a parabola.

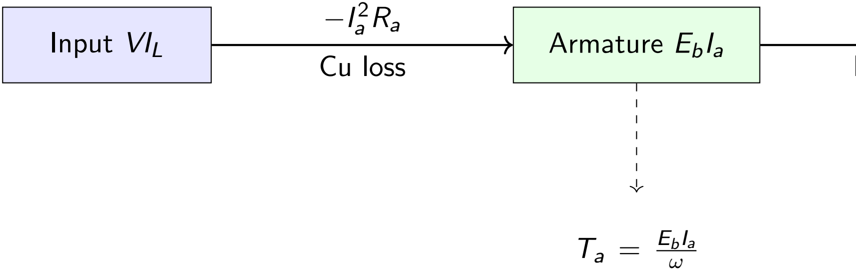
Shaft Torque (Tsh) I

The torque actually available at the motor shaft for doing useful mechanical work is called the shaft torque (Tsh).

Key Points:

- The gross armature torque (Ta) developed internally is not fully available at the shaft pulley to drive the mechanical load.
- A portion of the armature torque is consumed in overcoming rotational losses, specifically friction and windage losses, as well as iron (core) losses in the armature.
- The torque corresponding to these rotational losses is known as Lost Torque (T_lost).
- Therefore, the relationship is: Shaft Torque (Tsh) = Armature Torque (Ta) - Lost Torque (T_lost).
- Tsh is always less than Ta in a practical, running motor.

Power Flow and Torque Relationships I



Key Points:

- This block diagram represents the power flow in a DC motor from electrical input to mechanical output.
- Gross mechanical power developed in the armature is Eb × Ia, corresponding to Armature Torque (Ta).

Power Flow and Torque Relationships II

- Net mechanical power output available at the shaft is P_sh, corresponding to Shaft Torque (Tsh).
- The difference between Eb·Ia and P_sh is the rotational power loss (P_rot).

Lost Torque and Rotational Losses I

Lost torque is the equivalent torque that represents the motor's internal mechanical and magnetic losses.

Key Points:

- Rotational losses (P_rot) = Friction loss (bearings, commutator/brushes) + Windage loss (air resistance to rotation) + Iron/Core loss (hysteresis and eddy currents in the rotating armature).
- Power associated with rotational losses can be written as: $P_rot = T_lost\omega$.
- Lost Torque can be calculated as: $T_lost = P_rot/\omega = (P_rot60)/(2\pi N)$.
- T_lost is relatively constant in shunt motors since speed N is roughly constant, but varies significantly in series motors where speed changes drastically with load.

Brake Horse Power (BHP) I

Brake Horse Power is the measure of the motor's useful mechanical output power, traditionally measured using a mechanical brake.

Key Points:

- The output power at the shaft is commonly expressed in Horse Power (HP). 1 Imperial HP = 746 W, and 1 Metric HP = 735.5 W. The standard in electrical engineering typically assumes 1 HP = 746 Watts.
- Shaft Output Power (P_sh) = BHP × 746 (in Watts).
- The relationship between Shaft Torque (Tsh) in N-m and BHP is: $\mathrm{P}_s h = Tsh(2\pi\mathrm{N}\ /\ 60) = \mathrm{BHP} \times 746$.
- Therefore, Shaft Torque can be explicitly calculated from BHP: Tsh = (BHP × 746 × 60) / (2πN) = 7123.6 × BHP / N (N-m).
- BHP is a critical rating on a motor's nameplate, defining its continuous mechanical load capability without overheating.

Summary and Conclusion I

Understanding the distinction between generated armature torque and available shaft torque is crucial for motor selection and application.

Key Points:

- Armature Torque (Ta) is the total internal electromagnetic torque generated: Ta $\propto$ Φ Ia.
- Shaft Torque (Tsh) is the net useful torque available to drive the load: Tsh = Ta - T_lost.
- Break Horse Power (BHP) is the rating of this useful mechanical power output.
- The ratio of useful output power (BHP $\times$ 746) to electrical input power (VI) dictates the overall commercial efficiency of the motor.

Summary and Conclusion II

- Next Lecture: We will analyze Speed-Torque and Torque-Current characteristics for various DC motor types based on these fundamental torque equations.

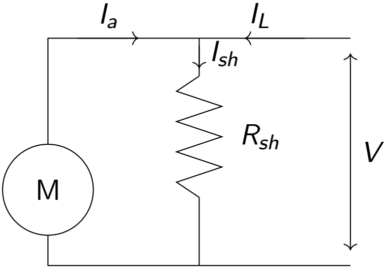
Types of D.C. Motors I

D.C. Motors are classified based on the method of field excitation. The interconnection of the field winding with the armature determines the motor's operating characteristics.

Key Points:

- Separately Excited DC Motor: The field winding is excited from a separate and independent DC voltage source.
- Self-Excited DC Motor: The field winding is connected in series, in parallel, or a combination of both, with the armature.
- DC Shunt Motor: The field winding is connected in parallel with the armature, resulting in a constant flux operation.
- DC Series Motor: The field winding is connected in series with the armature, carrying the full armature current.
- DC Compound Motor: Contains both series and shunt field windings, further divided into cumulative and differential compound motors based on flux direction.

DC Shunt Motor: Equivalent Circuit I



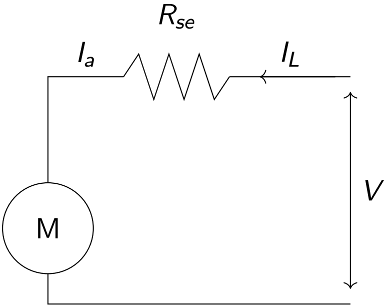
Key Points:

- The field winding is connected in parallel with the armature.
- Line current IL = Ia + Ish, where Ish = V / Rsh.
- Since the supply voltage V is assumed constant, the shunt field current Ish and thus the field flux remain practically constant.

DC Shunt Motor: Equivalent Circuit II

- Back EMF: $Eb = V - IaRa$, where Ra is the armature resistance.
- Used for applications requiring a relatively constant speed regardless of the load, such as machine tools and centrifugal pumps.

DC Series Motor: Equivalent Circuit I



Key Points:

- The series field winding is connected in series with the armature.
- Therefore, the line current, series field current, and armature current are all equal: IL = Ise = Ia.

DC Series Motor: Equivalent Circuit II

- The field flux is directly proportional to the armature current prior to magnetic saturation.
- Voltage equation: $V = Eb + Ia(Ra + Rse)$, where Rse is the series field resistance.
- Produces very high starting torque but its speed drops significantly with an increase in load. Used in hoists, cranes, and electric traction.

DC Compound Motors I

Compound motors incorporate both series and shunt field windings to combine the characteristics of both types. They are classified by how the two fields interact.

Key Points:

- Cumulative Compound Motor: The flux produced by the series field aids (adds to) the flux produced by the shunt field.
- Cumulative compound motors provide high starting torque (like series) and a finite no-load speed (like shunt).
- Differential Compound Motor: The flux produced by the series field opposes (subtracts from) the flux produced by the shunt field.
- Differential compound motors try to maintain a very constant speed as load increases, but they are prone to instability and are rarely used.

DC Compound Motors II

- Connections can be 'Long Shunt' (shunt field in parallel with both armature and series field) or 'Short Shunt' (shunt field in parallel with armature only).

Governing Equations for DC Motor Characteristics I

The behavior of any DC motor under load is governed by three fundamental equations relating torque, speed, and armature current.

Key Points:

- Voltage Equation: V = Eb + IaRa, where Eb is the back EMF.
- Speed Equation: Since Eb = (P*Phi*Z*N) / (60*A), we can express speed as N = K * (Eb / Phi).
- Substituting Eb gives the Speed Formula: N = K * (V - IaRa) / Phi. Speed is directly proportional to Back EMF and inversely proportional to flux.
- Torque Equation: T = K' * Phi * Ia. The electromagnetic torque is directly proportional to the product of magnetic flux and armature current.

- By analyzing how Phi changes with Ia, we can determine the Speed-Ia, Torque-Ia, and Speed-Torque characteristics for any motor type.

DC Shunt Motor Characteristics I

In a DC shunt motor, assuming a constant supply voltage, the field current and consequently the flux (Phi) are practically constant.

Key Points:

- Torque vs. Armature Current (T-Ia): Since Phi is constant, T is directly proportional to Ia. The characteristic is a straight line passing through the origin.
- Speed vs. Armature Current (N-Ia): N is proportional to (V - IaRa). As Ia increases, the IaRa drop increases slightly, causing a minor, linear drop in speed. It's considered a 'constant speed' motor.
- Speed vs. Torque (N-T): Derived from the above two. As torque demand increases (and Ia increases), the speed drops slightly from no-load to full-load.

DC Shunt Motor Characteristics II

- Armature Reaction at high loads can weaken the main flux slightly, which might counteract the IaRa drop, flattening the speed curve further.

DC Series Motor Characteristics I

In a DC series motor, the field winding is in series with the armature, so the flux (Phi) is directly proportional to the armature current (Ia) before saturation.

Key Points:

- Torque vs. Armature Current (T-Ia): Since Phi proportional to Ia, T is proportional to Ia^2 before magnetic saturation. The curve is a parabola. After saturation, Phi is constant, and T becomes linearly proportional to Ia.
- Speed vs. Armature Current (N-Ia): N is proportional to 1 / Phi, hence N is proportional to 1 / Ia. The characteristic is a rectangular hyperbola.
- Warning: At very low armature currents (light load), speed approaches dangerously high values. A series motor must NEVER be started on no-load.

DC Series Motor Characteristics II

- Speed vs. Torque (N-T): Similarly follows an inverse square-root relationship. High torque occurs at low speeds, making it ideal for high-inertia loads like trains.

DC Compound Motor Characteristics I

The characteristics of a compound motor depend on whether it is cumulatively or differentially compounded.

Key Points:

- Cumulative T-Ia: Series flux aids shunt flux. As Ia increases, total flux increases. Torque is greater than a shunt motor but less than a series motor for a given current.
- Cumulative N-Ia: As load (Ia) increases, total flux increases, causing the speed to drop more sharply than a shunt motor, but providing a safe, defined no-load speed unlike a series motor.
- Differential N-Ia: Series flux opposes shunt flux. As load increases, net flux decreases. This increases the speed, compensating for the IaRa drop, leading to nearly perfectly constant speed.

- Differential Instability: At severe overloads in a differential motor, the series field can overpower the shunt field, reversing the motor's rotation. Hence, differential compounding is very rare.

Summary and Industrial Applications I

Matching the motor's mechanical characteristics to the load requirements is a crucial engineering task in drive systems.

Key Points:

- DC Shunt Motors: Used where constant speed is required and starting conditions are not severe (e.g., Lathes, centrifugal pumps, fans, blowers, conveyors).
- DC Series Motors: Used where high starting torque is essential and speed can vary with load (e.g., Electric locomotives, cranes, hoists, elevators).
- Cumulative Compound Motors: Used for loads involving heavy intermittent impacts or high starting torque where a no-load run might occur (e.g., Rolling mills, punches, shears, heavy planers).

Summary and Industrial Applications II

- Differential Compound Motors: Historically used for constant speed battery-driven applications, but largely replaced by electronically controlled shunt motors today due to instability risks.

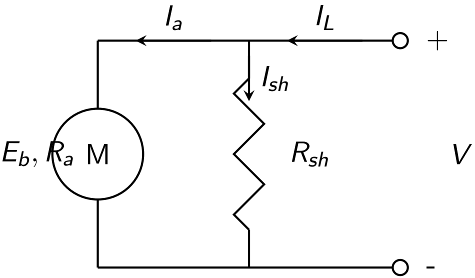
Classification of D.C. Motors I

D.C. motors are classified based on how their field windings are excited. The field winding provides the necessary working magnetic flux.

Key Points:

- Separately Excited D.C. Motor: The field winding is supplied from a separate, independent D.C. voltage source.
- Self-Excited D.C. Motor: The field winding is connected to the same supply voltage as the armature.
- Based on the field winding connection relative to the armature, self-excited motors are divided into three types: Shunt, Series, and Compound.
- Compound motors are further classified into Cumulative Compound and Differential Compound motors based on flux direction.

D.C. Shunt Motor Schematic I



Key Points:

- In a shunt motor, the field winding is connected in parallel (shunt) with the armature.
- The supply voltage V is applied directly across both the armature and the field winding.

D.C. Shunt Motor Schematic II

- The shunt field current Ish = V / Rsh. Since V and Rsh are practically constant, the working flux Φ remains practically constant.
- Therefore, a D.C. shunt motor operates essentially as a constant-flux machine.

Governing Equations of D.C. Motors I

The steady-state behavior of any D.C. motor is fundamentally governed by three principal equations involving Voltage, Back EMF, and Torque.

Key Points:

- Voltage Equation: V = Eb + Ia * Ra (where V is terminal voltage, Ia is armature current, Ra is armature resistance).
- Back EMF Equation: Eb = (P * Φ * Z * N) / (60 * A), meaning Back EMF is directly proportional to flux and speed (Eb $\propto$ Φ * N).
- Torque Equation: T = (P * Z / (2 * π * A)) * Φ * Ia, meaning developed torque is directly proportional to flux and armature current (T $\propto$ Φ * Ia).
- Speed Equation: Rearranging the EMF equation yields N $\propto$ Eb / Φ. Substituting Eb gives N $\propto$ (V - Ia * Ra) / Φ.

Motor Characteristics Overview I

The practical application of a D.C. motor is determined by analyzing three crucial characteristic curves under varying mechanical loads.

Key Points:

- Torque vs. Armature Current (T vs. Ia): Also known as the 'Electrical Characteristic'. It illustrates how the developed torque responds to current changes.
- Speed vs. Armature Current (N vs. Ia): Shows how motor speed fluctuates as the load (and consequently armature current Ia) changes.
- Speed vs. Torque (N vs. T): Also known as the 'Mechanical Characteristic'. Derived from the first two curves, it is the most critical curve for matching a motor to its mechanical load.

D.C. Shunt Motor Characteristics I

Analyzing the electrical (T vs. Ia) and mechanical (N vs. T) characteristics of the practically constant-flux shunt motor.

Key Points:

- Torque vs Ia (Electrical): Since Φ is constant, T $\propto$ Ia. The theoretical characteristic is a straight line passing through the origin. At heavy loads, armature reaction slightly demagnetizes the field, causing actual torque to droop slightly below the line.
- Speed vs Ia: N $\propto$ (V - Ia*Ra) / Φ. As Ia increases with load, the resistive voltage drop (Ia*Ra) increases, causing a slight, linear decrease in speed.
- Speed vs Torque (Mechanical): As torque demand increases, the speed slightly drops. The total speed variation from no-load to full-load is typically only 3-5
- Conclusion: The D.C. shunt motor is considered a 'constant speed' motor suitable for steady continuous loads.

D.C. Series Motor Introduction I

In a series motor, the field winding is connected in series with the armature, meaning the entire armature current provides the field excitation.

Key Points:

- Current relationship: The load current from the supply equals the armature current and the series field current ($IL = Ia = Ise$).
- Voltage Equation: $V = Eb + Ia(Ra + Rse)$, where Rse is the series field resistance.
- Flux relationship (Linear Region): Before magnetic saturation of the iron poles, the field flux Φ is directly proportional to the armature current ($\Phi \propto Ia$).
- Flux relationship (Saturation Region): At high currents, the iron core saturates, and flux Φ becomes practically constant, independent of further increases in Ia.

D.C. Series Motor Characteristics: Torque vs Current I

The electrical characteristic (T vs Ia) defines the series motor's exceptional heavy starting torque capability.

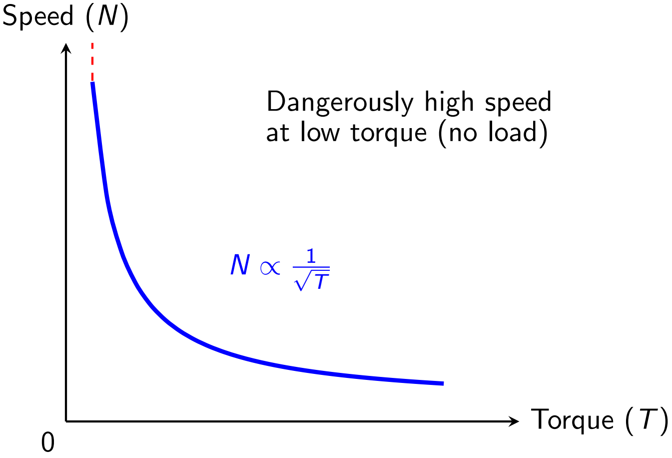
Key Points:

- From the basic torque equation, $T \propto \Phi * Ia$. In a series motor before saturation, $\Phi \propto Ia$, which results in $T \propto Ia^2$.
- The initial segment of the T-Ia curve is a parabola. This square relationship means the motor produces exponentially higher torque at high starting currents.
- This property makes series motors ideal for applications requiring massive starting torque, such as electric locomotives, cranes, and heavy hoists.

D.C. Series Motor Characteristics: Torque vs Current II

- After magnetic saturation, Φ becomes constant, reducing the relationship to T $\propto$ Ia. The curve transitions from a parabola to a straight line.

D.C. Series Motor Characteristics: Speed-Torque I



Key Points:

D.C. Series Motor Characteristics: Speed-Torque II

- Speed is inversely proportional to flux (N $\propto$ Eb / Φ). Since Φ $\propto$ Ia (before saturation) and T $\propto$ Ia^2, $we derive that N \propto$ 1 / T.
- The N-T mechanical characteristic takes the shape of a rectangular hyperbola.
- At low torque (light load condition), the current and flux are small, causing the speed to approach dangerously high, theoretically infinite values.
- Centrifugal forces at such speeds can mechanically destroy the armature. Therefore, series motors must NEVER be started on no-load and are always directly coupled to their loads.

Summary and Applications I

Matching motor characteristics to specific load requirements is the primary principle of electrical drive system design.

Key Points:

- Shunt Motors: Provide almost constant speed from no-load to full-load. Widely used where strict constant speed is required: lathes, centrifugal pumps, machine tools, and blowers.
- Series Motors: Feature variable speed and extremely high starting torque. Used for heavy-duty applications: electric traction (trains), cranes, hoists, and elevators.
- Cumulative Compound Motors: Combine shunt and series traits, offering high starting torque without the danger of overspeeding at no load. Used for rolling mills, shears, and punches.

Summary and Applications II

- Differential Compound Motors: Exhibit unstable speed characteristics at high loads and have very few practical industrial applications.

Basics of DC Motor Speed Control I

The fundamental EMF equation dictates the speed of a DC motor: N = (V - I_a R_a) / (k * Φ).

Key Points:

- From the back EMF equations E_b = V - I_a R_a and E_b = (P $\Phi NZ)/(60A), *wecandeducetheprimaryspeedequation*.
- Speed N is directly proportional to the back EMF (E_b) and inversely proportional to the air-gap flux (Φ).
- Equation representation: N $\propto (V - I\_aR\_a)/\Phi$
- Therefore, speed can be controlled by varying one of three parameters: 1) Flux $\Phi(FluxControlMethod), 2) ArmatureResistanceR\_a(RheostaticCon$

Speed Control of DC Shunt Motors: Flux Control Method I

By adding a variable external resistance in series with the shunt field winding, we can decrease the field current and thereby reduce the flux.

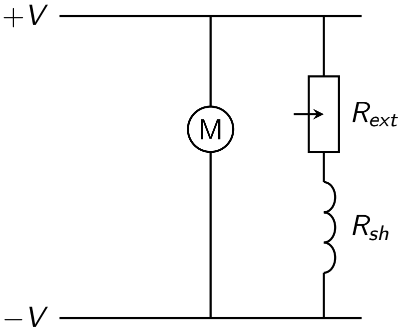
Key Points:

- In a shunt motor, the field winding is connected in parallel with the armature. Flux $\Phi is directly proportional to the field current I\_sh$.
- By increasing the external resistance (R_ext) in the field circuit, the field current decreases (I_sh = V / (R_sh + R_ext)).

Speed Control of DC Shunt Motors: Flux Control Method II

- A decrease in flux $\Phi causesanincreaseinspeedabovetherated(base)speed.$
- This method is highly efficient because the field current is a small fraction of the total current, resulting in minimal I^2R power loss in the control rheostat.
- It provides a constant power drive; as speed increases, permissible torque decreases since Torque T $\propto \Phi I\_a$.

Circuit Diagram: Flux Control of Shunt Motor I



Key Points:

- The diagram illustrates a DC Shunt Motor with an external variable rheostat (R_ext) connected in series with the shunt field winding (R_sh).

Circuit Diagram: Flux Control of Shunt Motor II

- Adjusting R_ext modulates the field current independently of the armature voltage.
- Crucial Note: Only speeds ABOVE the base speed can be achieved because flux can only be reduced below its rated value, never increased.

Speed Control of DC Shunt Motors: Armature Control I

By inserting a variable resistance in series with the armature, the effective voltage across the armature can be reduced, which decreases the motor speed.

Key Points:

- A heavy-duty rheostat is connected in series with the armature winding to absorb excess voltage.
- The voltage available at the armature terminals becomes V_a = V - I_a R_ext. This directly reduces back EMF (E_b) and consequently the speed N.
- Unlike flux control, this method allows for speed control strictly BELOW the base (rated) speed.
- It acts as a constant torque drive method but is highly inefficient due to large power dissipation (I_a^2 R_ext) as heat in the series resistor.

Speed Control of DC Shunt Motors: Armature Control II

- Speed regulation is poor because the voltage drop across R_ext heavily depends on the load demand (armature current I_a).

Speed Control of DC Series Motors: Flux Control Methods I

Since the field winding is in series with the armature, controlling flux requires bypassing current away from the field or modifying the field turns.

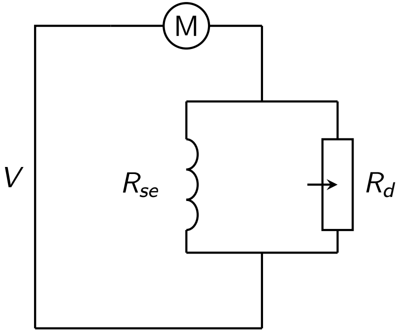
Key Points:

- Field Diverter Method: A variable resistance (diverter) is connected in parallel with the series field winding to bypass a portion of the main line current.
- By decreasing the diverter resistance, more current bypasses the field, reducing the flux $(\Phi) and increasing the speed above base speed.$
- Tapped Field Method: The series field winding is provided with several taps. Changing the tap selection alters the number of active turns, thus varying the MMF and flux.

Speed Control of DC Series Motors: Flux Control Methods II

- Series-Parallel Field Method: The field coil is divided into two halves which can be connected in series (for normal rated speed) or parallel (for higher speeds due to halved flux).

Circuit Diagram: Field Diverter Control I



Key Points:

- The schematic shows a diverter resistance R_d connected in parallel with the series field winding R_se.
- The total armature line current divides between the series field R_se and the diverter R_d.

Circuit Diagram: Field Diverter Control II

- Decreasing R_d diverts more current away from the field coil, effectively decreasing flux and increasing motor speed.

Speed Control of DC Series Motors: Armature Control I

A variable resistance can be placed in series with the entire motor circuit to control the voltage applied to both the armature and the field.

Key Points:

- A variable resistor (R_ext) is connected in series with the entire motor (armature + series field) across the DC supply.
- This reduces the voltage available across the motor, changing the back EMF: E_b $\propto V - I\_a(R\_a + R\_se + R\_ext)$.
- This method is exclusively used for obtaining speeds below the normal base speed.
- Because the full load current passes through the control resistor, considerable electrical power is wasted as heat (I^2R loss).

Speed Control of DC Series Motors: Armature Control II

- Despite its inefficiency, it is commonly used for intermittent duty applications like electric traction, hoists, or cranes where robust, simple control at start-up is critical.

Numerical Problem: DC Shunt Motor I

A 220V DC shunt motor runs at 500 rpm when armature current is 50A. Calculate the speed if torque is doubled. (R_a = 0.2 Ω)

Key Points:

- Given: V = 220V, N1 = 500 rpm, Ia1 = 50A, Ra = 0.2 Ω.
- Calculate Initial back EMF: Eb1 = V - Ia1*Ra = 220 - (50 * 0.2) = 210 V.
- In a shunt motor without field control, flux $\Phi remainsconstant. Therefore, TorqueT \propto I\_a$.
- If torque is doubled, T2 = 2 * T1, which implies Ia2 = 2 * Ia1 = 100A.
- Calculate New back EMF: Eb2 = V - Ia2*Ra = 220 - (100 * 0.2) = 200 V.

Numerical Problem: DC Shunt Motor II

- Since N $\propto Eb(forconstantflux), N2/N1 = Eb2/Eb1. Solvingyields N2 = 500 * (200/210) = 476.19 rpm.$

Numerical Problem: DC Series Motor I

A 250V DC series motor takes 40A and runs at 1000 rpm. If load torque is halved, calculate the new speed.
(Ra=0.2Ω, $Rse = 0.3\Omega, unsaturatedcore$)
Key Points:

- Given parameters: V = 250V, I1 = 40A, N1 = 1000 rpm, total resistance (Ra+Rse) = 0.5 Ω.
- Initial back EMF: Eb1 = V - I1(Ra+Rse) = 250 - 40(0.5) = 230V.
- For an unsaturated series motor, flux $\Phi \propto I\_a. Therefore, Torque T \propto \Phi I\_a \propto I\_a^2$.
- If torque is halved (T2 = 0.5 T1), then $(I2/I1)^2 = 0.5, giving I2 = I1/\sqrt{2} = 40/1.414 = 28.28A$.
- Calculate New back EMF: Eb2 = 250 - 28.28(0.5) = 235.86V.

Numerical Problem: DC Series Motor II

- Speed N $\propto Eb/\Phi \propto Eb/I. Thus, (N2/N1) = (Eb2/Eb1) * (I1/I2).$
- Solving for N2: 1000 * (235.86 / 230) * (40 / 28.28) = 1000 * 1.0255 * 1.414 = 1450 rpm.

Necessity of DC Motor Starters I

At standstill, a DC motor lacks back EMF, making the initial armature current dangerously high.

Key Points:

- Armature current is governed by the equation: I_a = (V - E_b) / R_a.
- At the moment of starting, motor speed N = 0, which means back EMF $E_b = (P\Phi$ Z N) / (60 A) = 0.
- The armature resistance R_a is typically very small (usually between 0.1 to 1 ohm) to keep copper losses low.
- If full supply voltage V is applied directly to the armature, $I_a becomesastronomicallyhigh(e.g., 220V/0.5\Omega =$ 440A).
- This initial starting current can be 10 to 15 times the rated full-load current of the machine.

Consequences of Direct-On-Line Starting I

The immense inrush of current can cause severe electrical, thermal, and mechanical damage to the machine.

Key Points:

- Electrical Damage: Destructive sparking occurs at the commutator and brush gear due to the poor commutation of massive currents.
- Thermal Damage: Rapid overheating can quickly burn out the armature windings and severely degrade or melt the insulation.
- Mechanical Damage: An extremely high starting torque (since T $\propto$ I_a)*generatessuddenandseveremechanicalstressontheshaft*, *coupling*
- System Impact: Heavy current draw from the mains can cause a massive voltage dip in the supply lines, affecting other parallel connected loads.

Consequences of Direct-On-Line Starting II

- Protection Tripping: Supply fuses will blow instantly or circuit breakers will trip, abruptly halting operations.

Functions of a DC Motor Starter I

A starter safely accelerates the motor to its base speed and provides essential operational protective mechanisms.

Key Points:

- Current Limiting: It inserts a variable external resistance in series with the armature to restrict the starting current to safe limits (usually 1.5 to 2 times full load).
- Resistance Cut-out: As the motor accelerates and E_b progressively builds up, the external resistance is gradually removed in steps via the starter handle.
- No-Volt Protection: The No-Volt Coil (NVC) automatically disconnects the motor if the supply voltage fails, preventing a dangerous direct re-start when power is restored.
- Overload Protection: The Overload Release (OLR) trips the circuit if the motor draws excessive current due to mechanical overloading or an internal electrical fault.

Functions of a DC Motor Starter II

- Therefore, a motor starter is not just a starting resistor, but a comprehensive control, starting, and protection unit.

Two-Point Starter: Working Principle I

The Two-Point Starter is exclusively designed and utilized for starting and protecting DC Series Motors.

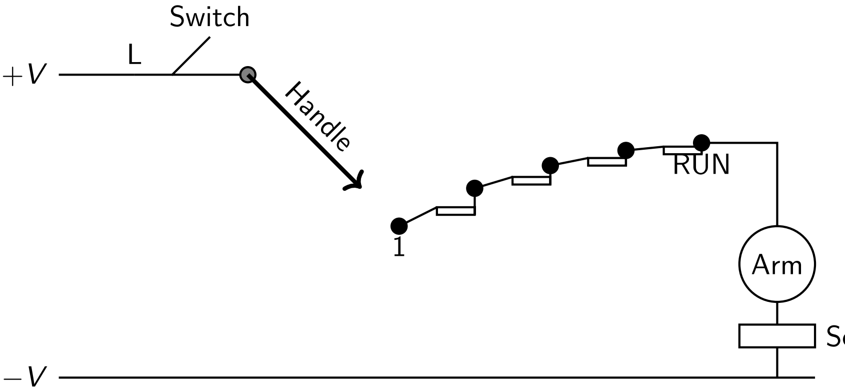
Key Points:

- It consists of only two main terminals connecting to the external electrical circuit: L (Line) and F (Field/Motor).
- The starting resistance, the No-Volt Coil (NVC), the motor armature, and the series field winding are all connected in series.
- Because the NVC is placed directly in the main series circuit, it carries the full motor current at all times.
- The electromagnetic holding force of the NVC is directly dependent on the load current. If the mechanical load drops significantly, current falls.

Two-Point Starter: Working Principle II

- If current drops too low, the NVC releases the handle. This is an intended safety feature for series motors, which can race to destructively high speeds at no-load.

Two-Point Starter Circuit Diagram I



Key Points:

Two-Point Starter Circuit Diagram II

- Terminal L connects to the positive supply, and the handle connects to the sequence of starting resistance studs.
- As the user sweeps the handle from stud 1 to the RUN position, the resistance is gradually bypassed.
- The holding coil (NVC) is integrated into this series path, holding the handle magnetically against spring tension in the RUN position.
- The series field winding and the motor armature remain in series with the entire starting resistor network.

Three-Point Starter: Working Principle I

The Three-Point Starter is the standard device used for starting DC Shunt and Compound Motors.

Key Points:

- It features three distinct external terminals: L (Line), F (Field), and A (Armature).
- The Line terminal (L) connects to the positive DC supply via a protective Overload Release (OLR) coil.
- The Armature terminal (A) connects the starting resistance array directly to the motor's armature circuit.
- The Field terminal (F) connects the No-Volt Coil (NVC) in series with the shunt field winding of the motor.
- When the handle touches the first stud, full starting resistance is in series with the armature, but the field circuit gets direct full voltage, ensuring maximum starting torque.

Protective Mechanisms in Three-Point Starters I

The 3-point starter integrates robust electromagnetic relays for No-Volt and Overload protection.

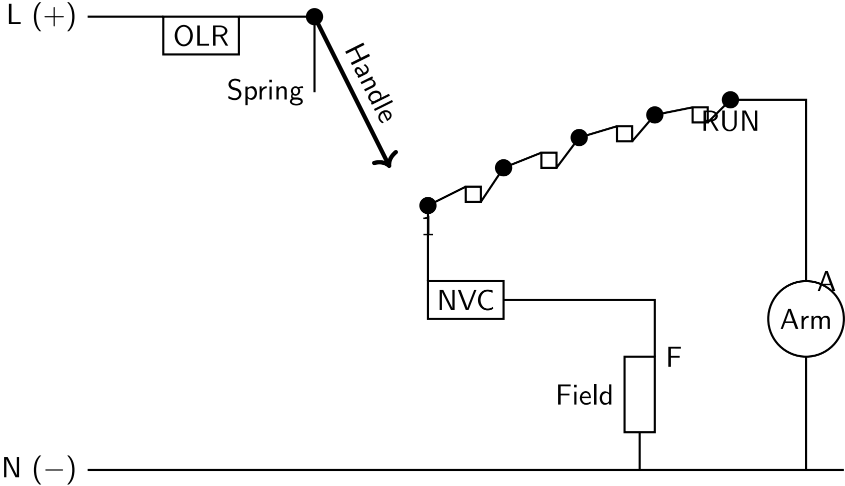
Key Points:

- No-Volt Release (NVC): An electromagnet energized continuously by the shunt field current. It physically holds the starter handle in the 'RUN' position.
- If the supply voltage fails, the NVC loses its magnetism. A mechanical spring then forcibly pulls the handle back to 'OFF', ensuring safe shutdown.
- Overload Release (OLR): An electromagnet coil consisting of a few turns of thick wire, connected in series with the main supply line (carrying total motor current).
- Under overload conditions, the OLR's strong magnetic field lifts an iron piece that electrically short-circuits the NVC terminals.

Protective Mechanisms in Three-Point Starters II

- This instantly demagnetizes the NVC, causing the spring to pull the handle to the 'OFF' position, isolating the overloaded motor.

Three-Point Starter Circuit Diagram I



Three-Point Starter Circuit Diagram II

Key Points:

- The L terminal enters through the OLR, meaning it carries the total line current.
- The NVC is uniquely placed in series with the shunt field winding, getting current via stud 1.
- As the handle advances from 1 to RUN, the starting resistance is progressively cut out of the armature circuit and added to the field circuit.
- Because shunt field resistance is very high, adding the comparatively small starting resistance to it does not significantly alter the field flux.
- If OLR actuates, it provides a short circuit path across the NVC, immediately tripping the starter.

Drawbacks of the Three-Point Starter I

Implementing flux control for speed variation exposes a critical functional flaw in the 3-point starter design.

Key Points:

- For above-normal speed control, an external rheostat is inserted in the shunt field circuit to intentionally weaken the flux.
- Increasing this field resistance significantly decreases the field current. Because the NVC is in series with the field, the NVC current also drops.
- If the field current drops below the minimum hold-in threshold of the NVC electromagnet, it loses its grip.
- The restoring spring then overrides the weak NVC, pulling the handle back to OFF and stopping the motor under normal running conditions.

Drawbacks of the Three-Point Starter II

- To resolve this, the Four-Point Starter was developed, which isolates the NVC into its own independent parallel circuit.

The Necessity of Starters in DC Motors I

At the moment of starting a DC motor, the armature is stationary, meaning the back EMF (E_b) is zero.

Key Points:

- The voltage equation of a DC motor is $V = E_b + I_a R_a$.
- At standstill ($N = 0$), the back EMF $E_b = \frac{P\Phi ZN}{60A} = 0$.
- Therefore, the starting armature current is $I_{a(start)} = \frac{V}{R_a}$.
- Since the armature resistance R_a is typically very small (0.1 to 1 ohm), applying full supply voltage V results in dangerously high starting current.
- This excessive current can blow fuses, damage the commutator through heavy sparking, and burn the armature winding.

Mathematical Proof of High Starting Current I

Example calculation demonstrating the magnitude of starting current without a starter.

Key Points:

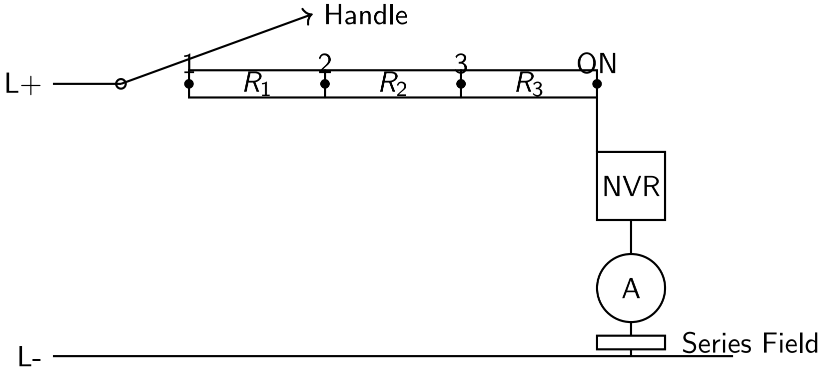
- Consider a 220 V DC motor with an armature resistance $R_a = 0.5\Omega$.
- If connected directly to the supply, $I_a = \frac{220}{0.5} = 440$ Amperes.
- The full-load current of this motor might only be around 40 Amperes.
- Starting current is 11 times the full-load current, creating massive thermal and mechanical stress (I^2R losses).
- To restrict this initial rush of current, an external resistance must be inserted in series with the armature.

Basic Principle of a DC Starter I

A starter is essentially a variable resistance in series with the armature circuit, equipped with protective mechanisms.

Key Points:

- At the instant of starting, maximum resistance is kept in the armature circuit to limit I_a.
- As the motor accelerates, it develops back EMF ($E_b \propto N$), which naturally opposes the supply voltage.
- With increasing back EMF, the external resistance is gradually cut out of the circuit in steps.
- When the motor reaches rated speed, the entire starting resistance is bypassed, and the motor runs directly on the supply voltage.
- Modern starters also include protective devices like No-Volt Release (NVR) and Over-Load Release (OLR).



Key Points:

- The 2-point starter is exclusively used for starting DC series motors.

Two-Point Starter Schematic II

- It has only two terminals connecting to the external circuit: Line (L) and Field/Armature (F/A).
- The No-Volt Release (NVR) coil is connected in series with the motor armature and series field.

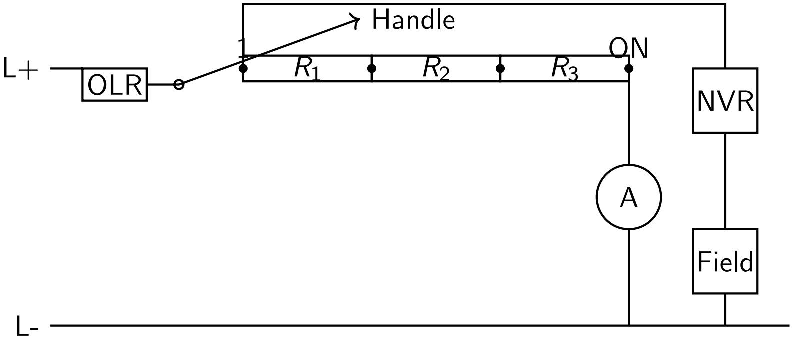
Operation of the Two-Point Starter I

The functional mechanism of limiting current and maintaining the handle position in a 2-point starter.

Key Points:

- The starting arm is moved against spring tension to stud 1, placing total resistance $(R_1 + R_2 + R_3)$ in series with the motor.
- As speed and back EMF build up, the handle is manually moved across the studs, cutting out resistance.
- At the 'ON' position, all starting resistance is removed, and the motor operates at full line voltage.
- The NVR coil is energized by the full motor current. It electromagnetically holds the iron armature on the handle at the ON position.
- If the supply fails, the NVR loses magnetism, and the return spring pulls the handle back to the OFF position, preventing a sudden full-voltage restart.

Three-Point Starter Schematic I



Key Points:

- The 3-point starter is used for DC shunt and compound motors.

Three-Point Starter Schematic II

- It has three terminals: L (Line), Z or F (Field), and A (Armature).
- The starting resistance is in series with the armature, while the NVR coil is in series with the shunt field circuit.

Operation of the Three-Point Starter I

Circuit behavior during the starting phase of a DC shunt/compound motor.

Key Points:

- Moving the handle to the first stud connects the full resistance in series with the armature, limiting I_a.
- Simultaneously, the shunt field circuit is connected directly across the supply via the NVR coil, ensuring maximum field current and starting torque.
- As the handle advances, armature resistance is decreased, and the cut-out resistance is added to the field circuit.
- The added resistance in the field circuit is negligible compared to the high resistance of the shunt field winding itself.
- At the final ON stud, the armature receives full voltage, and the NVR coil holds the handle magnetically.

Protective Devices: NVR and OLR I

Ensuring safety of the motor under abnormal operating conditions.
Key Points:

- No-Volt Release (NVR): In a 3-point starter, the NVR coil is in series with the shunt field. If the field circuit opens or supply fails, NVR loses magnetism, dropping the handle to OFF.
- Loss of field in a shunt motor causes dangerous overspeed ($N \propto 1/\Phi$). The NVR prevents this by immediately disconnecting the motor.
- Over-Load Release (OLR): Connected in series with the main line. It carries the total motor current.
- If the motor draws excessive current due to mechanical overload, the OLR's electromagnet becomes strong enough to pull a small lever.

Protective Devices: NVR and OLR II

- This lever short-circuits the NVR coil, instantly demagnetizing it and allowing the spring to throw the handle back to the OFF position.

Limitations of the Three-Point Starter I

Why the three-point starter is unsuitable for wide-range speed control.

Key Points:

- Speed control of a DC shunt motor above base speed is achieved by field weakening (adding a rheostat in the field circuit).
- In a 3-point starter, the NVR coil is in series with the shunt field.
- Adding resistance to the field to increase speed significantly reduces the field current.
- This reduced current can weaken the NVR electromagnet so much that it cannot overcome the spring tension.
- Consequently, the handle may fly back to the OFF position even under normal operating conditions. This necessitates the use of a Four-Point Starter.

Introduction to Testing of D.C. Machines I

To ensure reliable operation and verify design specifications, D.C. machines must be tested for efficiency, temperature rise, and commutation under working conditions.

Key Points:

- Direct Method: The machine is loaded directly (e.g., Brake test). It is suitable only for small capacity machines because the entire output power is wasted.
- Indirect Method: The machine is operated at no-load to determine constant losses (e.g., Swinburne's test). Efficiency is then pre-determined without full loading.
- Regenerative Method: Two identical machines are mechanically and electrically coupled (e.g., Hopkinson's test). Power drawn from the supply is only to overcome losses.

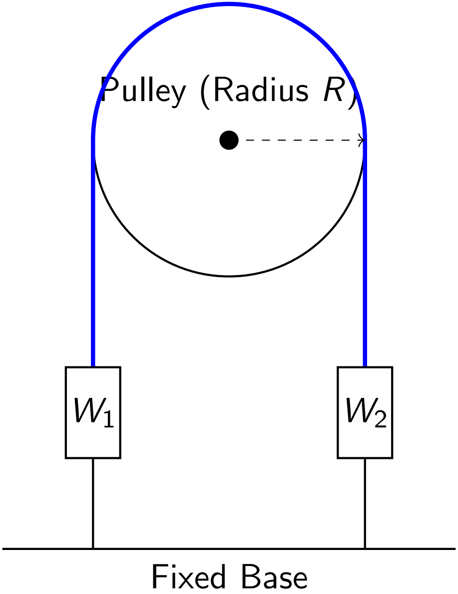
The Brake Test - Principle of Operation I

The brake test is a direct mechanical testing method primarily applied to small D.C. motors to determine their output torque and efficiency.

Key Points:

- A water-cooled, flanged pulley is mounted securely on the motor shaft.
- A friction band or belt passes over the pulley, with its ends connected to two spring balances, W1 and W2.
- By tightening the belt, mechanical load (friction) is progressively applied, thus directly loading the motor.
- The heat generated by the friction is dissipated by continuously circulating water inside the hollow rim of the pulley.
- Input electrical power is simultaneously measured using a voltmeter across the armature and an ammeter in the line.

Brake Test Mechanical Setup I


Pulley (Radius R)
W_1
W_2
Fixed Base

Brake Test - Efficiency Calculation I

The mechanical output power is calculated from the shaft torque and rotational speed, allowing determination of the exact efficiency.

Key Points:

- Net pull on the belt = (W1 - W2) kg, which is equivalent to (W1 - W2) * 9.81 Newtons.
- Shaft Torque (T_sh) = Force * Radius = (W1 - W2) * 9.81 * R (N-m).
- Angular Velocity (omega) = (2 * pi * N) / 60 rad/s, where N is motor speed in RPM.
- Mechanical Output Power (P_out) = T_sh * omega = (W1 - W2) * 9.81 * R * (2 * pi * N) / 60 Watts.
- Electrical Input Power (P_in) = V * I (where V is terminal voltage and I is total line current).
- Overall Efficiency (eta) = P_out / P_in.

Swinburne's Test - Fundamentals I

Swinburne's test is a widely used indirect, no-load testing method for predicting the efficiency of D.C. shunt and compound machines.

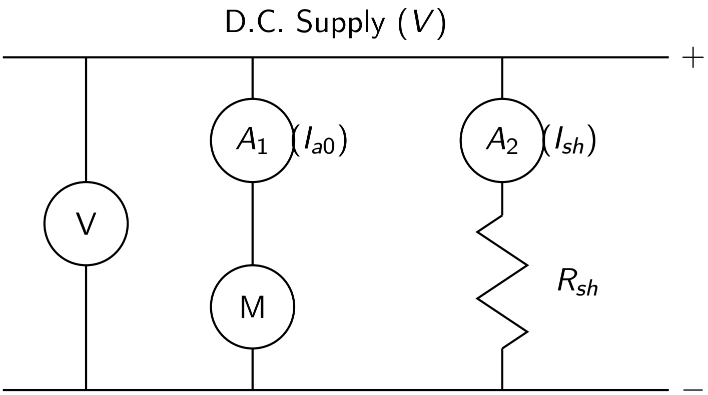
Key Points:

- The machine is operated strictly as a motor at no-load, supplied with its rated voltage and adjusted to run at rated speed.
- It is a highly economical test because the input power required is only equal to the no-load losses (which is a fraction of full-load power).
- The primary goal is to isolate and calculate the constant losses (iron loss, friction, and windage loss).
- Once the constant losses are determined, the efficiency can be pre-determined at any arbitrary load for both motor and generator operations.

Swinburne's Test - Fundamentals II

- CRITICAL LIMITATION: This test cannot be performed on D.C. series motors, as they can achieve dangerously high speeds at no-load.

Swinburne's Test Circuit Diagram I



Key Points:

- Ammeter A1 measures the no-load armature current (I_a0), which is typically very small.

Swinburne's Test Circuit Diagram II

- Ammeter A2 measures the shunt field current (I_sh), determining the constant field copper loss.
- Voltmeter V ensures the machine is tested precisely at its rated supply voltage.
- An external rheostat in the field circuit may be used to bring the motor speed to the exact rated RPM.

Swinburne's Test - Determining Constant Losses I

By analyzing the power consumed during no-load operation, the constant rotational losses are mathematically separated from the variable copper losses.

Key Points:

- Let V = Supply voltage, I_a0 = No-load armature current, I_sh = Shunt field current.
- Total no-load input power = V * (I_a0 + I_sh).
- This input power is entirely consumed by two components: No-load armature copper loss + Constant losses.

Swinburne's Test - Determining Constant Losses II

- No-load armature copper loss = $(\text{I\_a0})^2 * R\_a, where R\_a is the measured armature resistance.$
- Constant losses (P_c) = Total input power - No-load armature copper loss = V * (I_a0 + I_sh) - $(\text{I\_a0})^2 * R\_a.$
- Because the machine operates at constant speed and near-constant flux, P_c remains practically constant across all future load conditions.

Swinburne's Test - Efficiency at Any Load I

Using the previously determined constant losses (P_c), we can pre-calculate the machine's efficiency for any assumed load current 'I'.

Key Points:

- MOTOR MODE Calculation: Assume a total load line current I.
- Armature current I_a = I - I_sh. Total Motor Input Power = V * I.
- Total Motor Losses = Constant Losses (P_c) + Variable Copper Loss ($(I\_a)^2 * R\_a$).
- Motor Efficiency = (Input Power - Total Losses) / Input Power.
- GENERATOR MODE Calculation: Assume a total output load current I.

Swinburne's Test - Efficiency at Any Load II

- Armature current $I_a = I + I_{sh}$. Total Generator Output Power = V * I.
- Total Generator Losses = $P_c + (I_a)^2 * R_a$.
- Generator Efficiency = Output Power / (Output Power + Total Losses).

Comparison, Advantages and Disadvantages I

While Swinburne's test provides mathematical elegance and economy, the Brake test provides realistic operational data.

Key Points:

- Swinburne's Advantage: Extremely low power requirement, enabling testing of high-capacity machines that cannot be tested by direct loading.
- Swinburne's Advantage: Convenience of pre-determining efficiency at fractional or overload conditions without physical stress.
- Swinburne's Disadvantage: Ignores stray load losses, which actually increase with load, meaning the real efficiency is slightly lower than calculated.
- Swinburne's Disadvantage: Cannot verify if full-load temperature rise remains within safe insulation limits.

Comparison, Advantages and Disadvantages II

- Brake Test Advantage: Being a direct load test, it provides exact full-load parameters, true commutation behavior, and actual thermal conditions.

Introduction to Testing of DC Machines I

Testing is essential to determine the performance characteristics, efficiency, losses, and temperature rise of DC machines.

Key Points:

- Direct Method: The machine is fully loaded. Only suitable for fractional horsepower or small capacity machines.
- Indirect Method: Determines constant losses without loading the machine. Highly suitable for large capacity machines.
- Regenerative Method: Two identical machines are coupled. The power drawn from the supply just meets the losses.

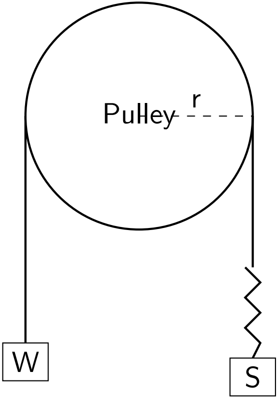
Direct Method: Brake Test I

The brake test is a direct measurement technique where a mechanical load is applied to the motor shaft via a friction band or belt.

Key Points:

- A belt or rope is wound around a water-cooled pulley keyed to the motor shaft.
- One end of the belt connects to a suspended dead weight (W) and the other to a spring balance (S).
- The net effective pull on the pulley is (W - S) in Newtons or kg-wt.
- Mechanical power output is calculated by measuring the tension difference and the shaft speed in RPM.

Brake Test Schematic Diagram I



Key Points:

- The pulley of radius 'r' is attached to the motor shaft.
- 'W' is the suspended dead weight in Newtons.

Brake Test Schematic Diagram II

- 'S' is the reading of the spring balance in Newtons.
- Net force on the pulley is (W - S).

Brake Test Analysis and Limitations I

Efficiency is calculated as the ratio of mechanical output power to electrical input power.

Key Points:

- Input Power (Pin) = V * I (Supply voltage * Total current).
- Output Power (Pout) = Torque * Angular Velocity = [(W - S) * r] * [2 * $\pi * N/60$].
- Efficiency (η) = $Pout/Pin$.
- Limitations: Large power is wasted as heat at the friction surface, cooling the pulley is difficult, and spring readings fluctuate wildly.

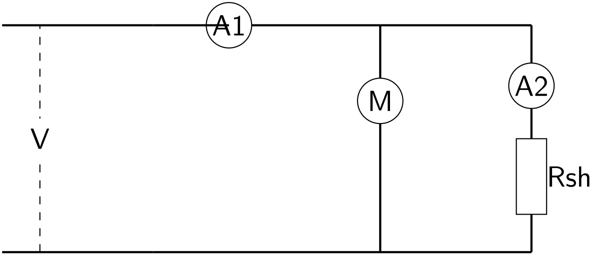
Indirect Method: Swinburne's Test I

Swinburne's test is an indirect, no-load test used to determine the efficiency of a DC machine without actually applying a load.

Key Points:

- The DC machine is run as a motor on no-load at its rated voltage and rated speed.
- It measures the constant losses (core losses, friction, and windage) directly.
- It is highly economical since power is not wasted in loading the machine.
- Crucially, it cannot be performed on DC series motors because they overspeed dangerously at no-load.

Swinburne's Test Circuit Diagram I



Key Points:

- Ammeter A1 measures the main no-load line current (Io).
- Ammeter A2 measures the shunt field current (Ish).
- The Voltmeter (V) monitors the rated supply voltage.
- No-load armature current Iao = Io - Ish.

Calculation of Constant Losses in Swinburne's Test I

The total no-load power input supplies both the constant losses and the no-load armature copper loss.

Key Points:

- Total no-load power input = V * Io.
- No-load armature copper loss = $Iao^2 * Ra$, where Ra is the armature resistance.
- Constant losses (Pc) = (V * Io) - ($Iao^2 * Ra$).
- Constant losses include iron losses in the core, mechanical friction at bearings, and windage losses.

Pre-determination of Efficiency I

Once constant losses are known, efficiency can be calculated for any arbitrary load current.

Key Points:

- For a motor at load current I: Armature current Ia = I - Ish. Total loss = Pc + Ia^2 * Ra.
- Motor Efficiency = (V*I - Total Loss) / (V*I).
- For a generator at load current I: Armature current Ia = I + Ish. Total loss = Pc + Ia^2 * Ra.
- Generator Efficiency = (V*I) / (V*I + Total Loss).

Merits and Demerits of Swinburne's Test I

A summary of why Swinburne's test is preferred for large machines, despite some theoretical inaccuracies.

Key Points:

- Advantage: Power required is minimal (only enough to supply no-load losses), making it economical for large machines.
- Advantage: Efficiency can be predetermined at any desired load condition.
- Disadvantage: Does not account for stray load losses, leading to a slightly overestimated actual efficiency.
- Disadvantage: Cannot observe full-load commutation behavior or actual temperature rise under operating load.

Introduction to DC Motor Classifications I

Overview of DC motor types based on field excitation methods and their implications for performance.

Key Points:

- DC motors are classified primarily by how their field windings are connected relative to the armature circuit.
- The three main classifications for self-excited motors are Shunt, Series, and Compound wound.
- Each specific configuration yields entirely unique speed-torque and torque-current characteristics.
- The selection of a specific DC motor type for an industrial application is dictated by the mechanical load requirements.
- Separately excited motors are also utilized but require an independent, external DC voltage source for the field winding.

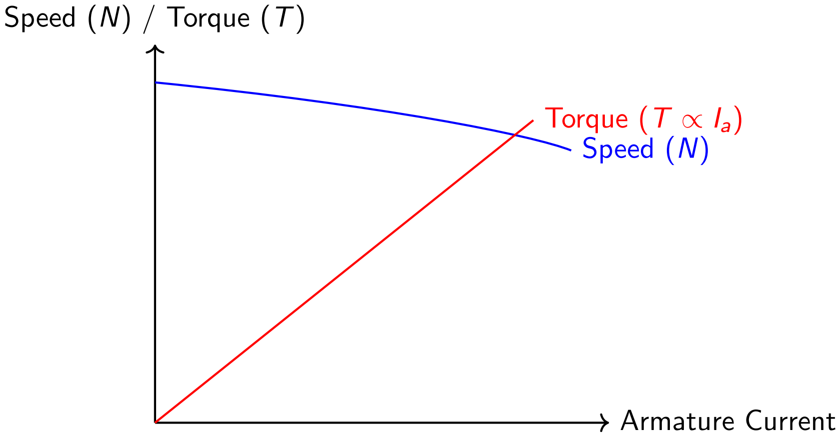
DC Shunt Motors: Characteristics and Advantages I

Analysis of the DC shunt motor where the field winding is connected in parallel with the armature.

Key Points:

- The field winding has high resistance, drawing a relatively small, constant current, leading to a constant flux operation ($\Phi \approx$ constant).
- Exhibits excellent intrinsic speed regulation; the speed drops only slightly (typically 2-5
- Considered a constant-speed motor under normal operating conditions, making it predictable for steady loads.
- Starting torque is moderate, typically limited to 1.5 times the full-load running torque.
- Advantageous where precise speed control is required over a wide range using either armature voltage control (below base speed) or field weakening methods (above base speed).

DC Shunt Motor: Torque-Speed Characteristic I



Constant flux operation ($\Phi \approx$ constant)

DC Shunt Motor: Torque-Speed Characteristic II

Key Points:

- The speed curve (blue) shows a slight droop due to the internal armature resistance drop ($I_a R_a$) and the demagnetizing effect of armature reaction.
- The torque curve (red) is a straight line passing through the origin since $T \propto \Phi I_a$ and Φ is effectively constant.
- The slight deviation from linearity at very high armature currents is exclusively due to armature reaction weakening the main pole flux.
- This characteristic makes the shunt motor suitable for applications where speed must remain relatively constant regardless of load torque variations.
- The intersection of the speed curve with the y-axis represents the theoretical no-load speed of the motor.

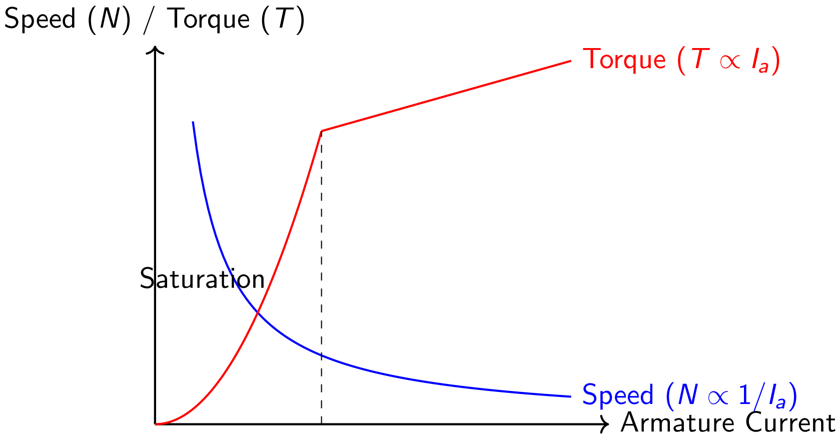
DC Shunt Motors: Industrial Applications I

Commercial and industrial applications leveraging the constant speed and controllable nature of shunt motors.

Key Points:

- Extensively used in machine tools such as lathes, drills, milling machines, and grinders where cutting speed must be maintained for precision.
- Ideal for centrifugal pumps and blowers which require a predictable and constant continuous driving speed.
- Employed in weaving machines and textile looms to ensure uniform fabric tension and consistent manufacturing quality.
- Frequently used to drive line shafts, small printing presses, and paper machines.
- Their ability to easily and predictably reverse rotational direction (by reversing field or armature polarity) adds to their versatility.

DC Series Motor: Torque-Speed Characteristic I



Key Points:

DC Series Motor: Torque-Speed Characteristic II

- Before magnetic saturation of the iron core, field flux Φ is proportional to I_a, making torque $T \propto I_a^2$ (a parabolic curve).
- After saturation, Φ becomes constant, and torque transitions to a linear relationship ($T \propto I_a$).
- Speed $N \propto E_b/\Phi$. Since $\Phi \propto I_a$, speed is inversely proportional to armature current ($N \propto 1/I_a$).
- At very low loads or no-load, I_a is tiny, causing the speed to theoretically approach infinity, reaching dangerously high (runaway) mechanical limits.
- Consequently, a series motor must absolutely never be started without a solid mechanical load coupled to it (e.g., via gears, never belts).

DC Series Motors: Characteristics and Applications I

Analysis of the DC series motor where the thick field winding is in series with the armature, carrying the full load current.

Key Points:

- Provides exceptionally high starting torque, often 5 to 6 times the full-load running torque, due to the $T \propto I_a^2$ initial relationship.
- Speed regulation is inherently very poor; speed changes drastically with load variations, classifying it strictly as a variable speed motor.
- Automatically adjusts its speed to the demanded load: it slows down heavily under large loads (increasing torque) and speeds up significantly with light loads.
- Widely and historically used in electric traction systems (trains, trams, trolleybuses) due to the immense low-speed torque required to accelerate heavy masses.

- Employed in industrial cranes, hoists, and elevators where high starting torque is essential for lifting heavy weights from a standstill.

DC Compound Motors: Characteristics and Types I

Motors featuring both series and shunt field windings on the main poles to combine the characteristics of both base types.

Key Points:

- Cumulative Compound: The series field flux aids the shunt field flux ($\Phi_{total} = \Phi_{shunt} + \Phi_{series}$). This is the most common configuration.
- Differential Compound: The series field flux opposes the shunt field flux ($\Phi_{total} = \Phi_{shunt} - \Phi_{series}$). Rarely used due to instability.
- Cumulative compound motors offer high starting torque (like a series motor) but feature a finite, safe no-load speed limit (like a shunt motor).
- Differential compound motors can theoretically maintain an almost perfectly constant speed regardless of load, but can become dangerously unstable at heavy loads as flux collapses.

DC Compound Motors: Characteristics and Types II

- The exact degree of compounding (over-compounded, flat-compounded, under-compounded) determines the specific speed-load drooping characteristic.

DC Compound Motors: Industrial Applications I

Specific heavy-industry use cases for cumulative compound DC motors where neither pure shunt nor pure series motors suffice.

Key Points:

- Ideal for driving mechanical loads subjected to sudden, heavy impacts, intermittent loading, or pulsating torques.
- Widely used in punch presses, shears, and heavy stamping machines where large mechanical flywheels are utilized to store and release kinetic energy.
- During the heavy punch cycle, the motor intentionally slows down (droops), allowing the flywheel to deliver the bulk of the required energy, preventing massive current spikes from the electrical supply.
- Frequently used in heavy rolling mills, large duty conveyors, and deep mining hoists.

DC Compound Motors: Industrial Applications II

- Suitable for certain types of large elevators and passenger lifts that require smooth, high-torque acceleration combined with a definite maximum speed limitation.

General Advantages and Disadvantages of DC Motors I

A summary of the overarching pros and cons of using direct current motors compared to modern AC induction and synchronous alternatives.

Key Points:

- Advantage: Unmatched, simple, and linear speed control capabilities; speed can be adjusted smoothly down to absolute zero and well above base speed.
- Advantage: Provide extremely high starting torques and possess excellent accelerating/decelerating dynamic capabilities.
- Advantage: Rapid and precise dynamic response, making them historically the preferred choice in high-performance servo systems.

General Advantages and Disadvantages of DC Motors II

- Disadvantage: High mechanical maintenance requirements due to the presence of the commutator and carbon brushes which wear out and require replacement.
- Disadvantage: Sparking at the commutator brushes strictly limits their use in explosive or hazardous chemical environments.
- Disadvantage: Generally larger, heavier, and more expensive to manufacture than equivalent-power AC induction motors.

Introduction to Transformers I

A transformer is a static electrical device that transfers electrical energy between two or more circuits through electromagnetic induction.

Key Points:

- Operates on Faraday's law of electromagnetic induction.
- Steps up or steps down alternating voltage levels while keeping the frequency constant.
- Has no moving parts, resulting in extremely high efficiency (often ¿98
- Consists primarily of two inductively coupled coils: the primary winding (connected to the source) and the secondary winding (connected to the load).
- Magnetic coupling is enhanced by using a low-reluctance magnetic core made of laminated steel.

Types of Transformers based on Construction I

Transformers are broadly classified into Core Type and Shell Type based on how the primary and secondary windings are placed around the magnetic core.

Key Points:

- The choice between core and shell type depends on voltage ratings, kVA ratings, and cooling requirements.
- Core Type: The windings surround a considerable part of the magnetic core. The core forms a single continuous magnetic path.
- Shell Type: The magnetic core surrounds a considerable portion of the windings. The core provides two parallel magnetic paths.
- Both types aim to minimize magnetic leakage flux and maximize coupling between primary and secondary windings.

Types of Transformers based on Construction II

- Berry Type is another less common construction, similar to the shell type but with cores distributed radially.

Core Type Transformer Construction I

In a core type transformer, the core is in the form of a rectangular frame with two vertical limbs and two horizontal yokes.

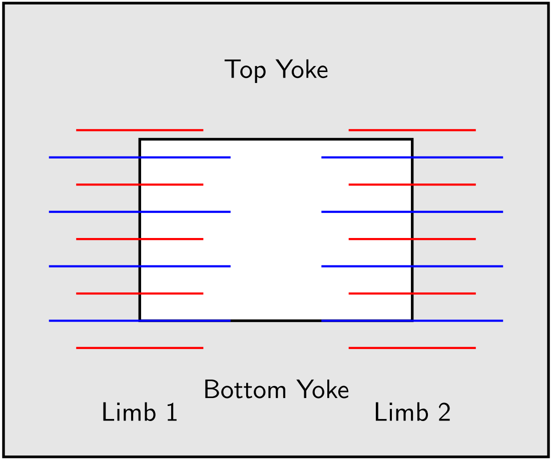
Key Points:

- The core has a simple rectangular shape with a single magnetic circuit.
- Windings are cylindrical and are placed on the two vertical limbs to reduce leakage flux.
- To maximize coupling, half of the primary and half of the secondary windings are placed on each limb (forming concentric windings).
- Low Voltage (LV) winding is placed nearer to the core to minimize the insulation requirements.
- High Voltage (HV) winding is placed outside the LV winding, separated by insulating cylinders.

Core Type Transformer Construction II

- Maintenance, inspection, and repair are easier as the windings are more accessible.

Core Type Transformer Schematic



Core Type Transformer Diagram II

Key Points:

- The diagram shows a core type transformer with concentric windings.
- Red lines represent Low Voltage (LV) windings placed closely to the core.
- Blue lines represent High Voltage (HV) windings placed on the outside.
- Notice the single, continuous magnetic path circulating through the vertical limbs and horizontal yokes.

Shell Type Transformer Construction I

In a shell type transformer, the core has three limbs, and both primary and secondary windings are placed entirely on the central limb.

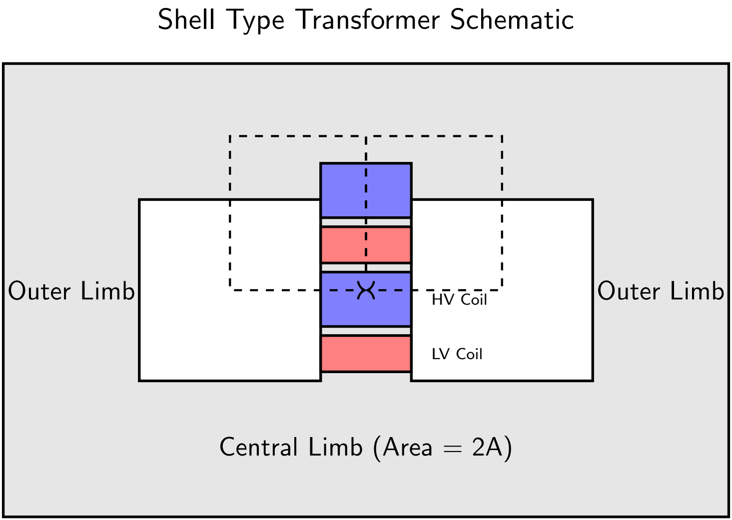
Key Points:

- The core surrounds a major portion of the windings, providing physical protection and two parallel paths for the magnetic flux.
- The central limb carries the total flux (Φ), while the two outer limbs each carry half of the flux ($\Phi/2$).
- Consequently, the cross-sectional area of the central limb is designed to be twice that of the outer limbs.
- Windings are of the interleaved or 'sandwich' type, which significantly reduces leakage reactance.

Shell Type Transformer Construction II

- HV and LV coils are arranged alternately on the central limb, with LV coils placed at the very top and bottom to minimize insulation requirements to the yokes.
- Shell type is often preferred for low voltage, high-current applications due to better mechanical protection and bracing against short-circuit forces.

Shell Type Transformer Diagram I



Shell Type Transformer Diagram II

Key Points:

- The diagram illustrates a shell type transformer with interleaved (sandwich) windings.
- Both HV (blue) and LV (red) windings are placed on the central limb only.
- Dashed lines indicate the parallel flux paths splitting from the central limb into the two outer limbs.
- The outer limbs require only half the cross-sectional area of the central limb because they carry half the flux.

Materials Used: The Magnetic Core I

The magnetic core is the foundation of the transformer, designed to provide a continuous, low-reluctance path for the magnetic flux.

Key Points:

- Material: Cold Rolled Grain Oriented (CRGO) Silicon Steel is predominantly used.
- Silicon Content: About 3
- Grain Orientation: Cold rolling aligns the steel grains parallel to the direction of magnetic flux, greatly reducing hysteresis loss and increasing permeability.
- Laminations: The core is built from thin sheets or laminations (typically 0.25mm to 0.35mm thick) to further suppress the formation of large eddy currents.
- Varnish: Each lamination is coated with a thin layer of insulating varnish or oxide to electrically isolate it from adjacent sheets.

Materials Used: The Magnetic Core II

- Joints: Mitred (stepped) joints are often used at the corners to reduce reluctance and the magnetizing current at the yoke-limb junctions.

Materials Used: Windings and Insulation I

The windings carry the electrical current and must be highly conductive and rigorously insulated.

Key Points:

- Conductor Material: High-grade electrolytic copper is widely used due to its excellent electrical conductivity and mechanical strength.
- Aluminum is sometimes used in smaller distribution transformers to reduce weight and cost, despite having lower conductivity than copper.
- Conductor Shape: Conductors can be round wire for small currents, or rectangular strips/strands for higher currents to maximize space factor and minimize skin effect.
- Solid Insulation: Kraft paper, pressboard, and enamel (for thin wires) are used for insulating individual conductors from each other and from the grounded core.

Materials Used: Windings and Insulation II

- Liquid Insulation: Mineral oil (transformer oil) serves a dual purpose: it acts as a highly effective dielectric insulator and as a primary coolant to dissipate heat.
- Insulation Classes: Materials are chosen based on their thermal class (e.g., Class A for 105°C, Class B for 130°C) corresponding to the maximum allowable operating temperature.

Other Key Parts and Functions I

A complete practical transformer assembly includes several auxiliary components essential for protection, monitoring, and cooling.

Key Points:

- Conservator Tank: An expansion tank located above the main tank; it accommodates the volumetric expansion and contraction of transformer oil due to load and temperature variations.
- Breather: Attached to the conservator, it contains silica gel to absorb moisture from the atmospheric air entering the tank as the oil contracts, preventing dielectric breakdown.
- Buchholz Relay: A gas-actuated protection relay installed on the pipe between the main tank and conservator; it detects internal faults by accumulating gases produced by arcing or overheating in the oil.

Other Key Parts and Functions II

- Radiators / Cooling Tubes: Provide an increased surface area for the hot transformer oil to dissipate heat to the surrounding ambient air via natural or forced convection.
- Bushings: Insulators (usually made of porcelain or epoxy resin) that allow the high-voltage and low-voltage connections to pass safely through the grounded metallic transformer tank.
- Explosion Vent: A safety diaphragm that ruptures to release excessive internal pressure in the event of a severe internal fault, preventing catastrophic tank failure.

Introduction to Transformers I

A transformer is a static electrical device that transfers electrical energy between two or more circuits through electromagnetic induction.

Key Points:

- Operates strictly on Faraday's Law of Electromagnetic Induction.
- Transfers AC electrical power from one circuit to another at the same frequency.
- Used for stepping up or stepping down voltage levels to facilitate efficient transmission and distribution.
- Provides electrical isolation while remaining magnetically linked via a core.

Classification Based on Construction I

Transformers are primarily classified into two main types based on the arrangement of the magnetic core and the windings.

Key Points:

- Core Type Transformer: The windings surround a considerable portion of the magnetic core.
- Shell Type Transformer: The magnetic core surrounds a considerable portion of the windings.
- The choice between core and shell types depends on voltage rating, kVA rating, and specific application requirements.
- Fundamental differences lie in the flux path, winding placement, and mechanical robustness against short-circuit forces.

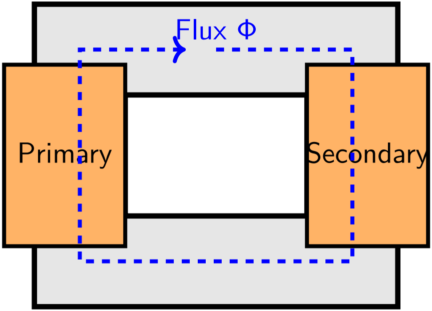
Core Type Transformer Construction I

In a core type transformer, the magnetic circuit consists of two vertical limbs (legs) and two horizontal yokes joining them.

Key Points:

- Windings are typically concentric (cylindrical) and placed on the two vertical limbs.
- In practice, half of the primary and half of the secondary windings are placed on each limb to significantly reduce leakage flux.
- The Low Voltage (LV) winding is placed closest to the core to minimize insulation requirements and ease of design.
- The High Voltage (HV) winding is placed concentrically outside the LV winding, separated by an insulation cylinder.
- The core type provides a single, series path for the magnetic flux.

Core Type Transformer Diagram I



Key Points:

- Schematic representation of a Core Type Transformer.
- Notice the single continuous magnetic flux path.
- For simplicity, primary and secondary are shown on opposite limbs, though practically they are interleaved concentrically.

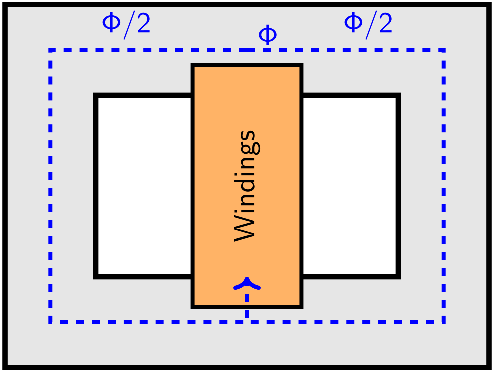
Shell Type Transformer Construction I

In a shell type transformer, the magnetic core consists of three limbs. Both the primary and secondary windings are placed on the central limb.

Key Points:

- The central limb carries the entire main flux, which then splits equally into the two outer limbs.
- The cross-sectional area of the central limb is twice that of the outer limbs.
- Windings are typically of the sandwich (or disc) type, where LV and HV coils are stacked alternately.
- Provides excellent mechanical protection to the windings as they are surrounded by the heavy steel core.
- Often preferred for low voltage, high output current applications due to better cooling of windings.

Shell Type Transformer Diagram I



Key Points:

- Schematic representation of a Shell Type Transformer.
- The central limb carries the total flux Φ.

Shell Type Transformer Diagram II

- The outer limbs act as return paths, each carrying half the flux ($\Phi/2$).
- Windings are structurally protected within the core windows.

Major Parts and their Functions I

A commercial power or distribution transformer requires several essential components beyond just the core and windings to operate safely and efficiently.

Key Points:

- Magnetic Core: Provides a low-reluctance path for the mutual magnetic flux coupling the windings.
- Windings (Coils): Conductors that form the electrical circuits; carrying current and inducing voltage.
- Transformer Tank: The main enclosure that houses the active parts (core and windings) and contains the insulating oil.
- Conservator Tank: A cylindrical tank mounted above the main tank to accommodate the expansion and contraction of oil due to load and temperature variations.

Auxiliary Components for Safety and Cooling I

Additional monitoring and cooling components ensure the longevity of the transformer under operational stresses.

Key Points:

- Breather: Attached to the conservator, containing silica gel (changes from blue to pink when saturated) to absorb moisture from air entering the tank.
- Buchholz Relay: A gas-actuated mechanical relay installed in the pipe between the main tank and conservator to detect internal faults (like incipient arcs).
- Radiators/Cooling Tubes: Finned structures welded to the tank that increase surface area for the transformer oil to dissipate heat.
- Bushings: Insulating structures (typically porcelain or epoxy) that allow high-voltage connections to safely pass through the grounded steel tank.

Materials Used in Transformer Construction I

The selection of highly specialized materials is critical to minimizing losses (core and copper losses) and ensuring structural integrity.

Key Points:

- Core Material: Cold-Rolled Grain-Oriented (CRGO) Silicon Steel. The addition of 3-4
- Winding Material: High-conductivity Copper or Aluminum. Copper is strictly preferred for large power transformers due to its superior current density and mechanical strength.
- Insulating Oil: Highly refined Mineral oil (naphthenic or paraffinic base) provides high dielectric strength and acts as a primary cooling medium.
- Solid Insulation: Kraft paper, pressboard, and enamel coatings are used directly on the conductors and between layers to prevent internal short circuits.

Introduction to Transformers I

A transformer is a static electrical device that transfers electrical energy between two or more circuits through electromagnetic induction, without any change in frequency.

Key Points:

- Operates strictly on Faraday's Law of Electromagnetic Induction.
- Comprises two or more magnetically coupled coils (windings) sharing a common magnetic flux.
- Provides galvanic isolation between circuits while altering voltage and current levels.
- Step-up transformers increase voltage (decrease current); Step-down decrease voltage (increase current).
- Fundamental EMF equation: $E = 4.44 * f * N * Phi\_m$, where E is induced EMF, f is frequency, N is number of turns, and Phi_m is peak magnetic flux.

Fundamental Circuits of a Transformer I

The construction of any practical transformer essentially involves three interacting physical circuits.

Key Points:

- 1. Magnetic Circuit: Comprises the core, which provides a low-reluctance path for the mutual magnetic flux (Phi). Built from laminated ferromagnetic materials.
- 2. Electric Circuit: Comprises the primary and secondary windings (usually copper or aluminum conductors) that carry the load and magnetizing currents.
- 3. Dielectric Circuit: Comprises the insulation system (transformer oil, Kraft paper, pressboard) that prevents electrical breakdown between windings, phases, and the core.
- The primary engineering design challenge is to optimize these three circuits concurrently for maximum efficiency, thermal stability, and mechanical strength under fault conditions.

Types of Transformers based on Construction I

Transformers are broadly classified into two main types based on the geometric arrangement of the magnetic core relative to the electrical windings.

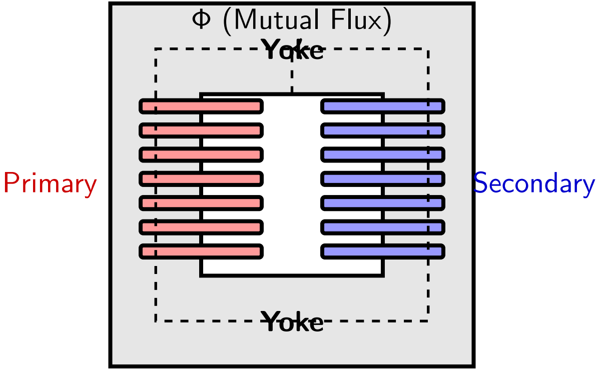
Key Points:

- Core Type Transformer: The electrical windings surround a considerable portion of the magnetic core. The core forms a single continuous magnetic circuit.
- Shell Type Transformer: The magnetic core surrounds a considerable portion of the electrical windings. The core forms a multiple-path (usually double-path) magnetic circuit.
- The selection between core and shell type depends on voltage rating, KVA capacity, manufacturing constraints, and cooling requirements.

Types of Transformers based on Construction II

- Core type is generally preferred for high voltage, high power applications because the windings are more accessible, making them easier to insulate.
- Shell type is often used for low voltage, low power applications, and for very large power transformers where transportation height restrictions exist.

Core Type Transformer Construction I



Key Points:

- In a core-type transformer, the windings are wound around the two vertical legs (limbs) of a rectangular magnetic core.

Core Type Transformer Construction II

- The core has a single magnetic path, meaning the same total flux (Φ) flows through both limbs and yokes in series.
- To minimize magnetic leakage flux, half of the primary and half of the secondary windings are placed on each limb (known as concentric winding).
- The Low Voltage (LV) winding is always placed closest to the core to minimize core-to-winding insulation requirements, with the High Voltage (HV) winding placed concentrically outside.

Characteristics of Core Type Transformers I

The structural arrangement of the core type gives it distinct electrical and mechanical properties.

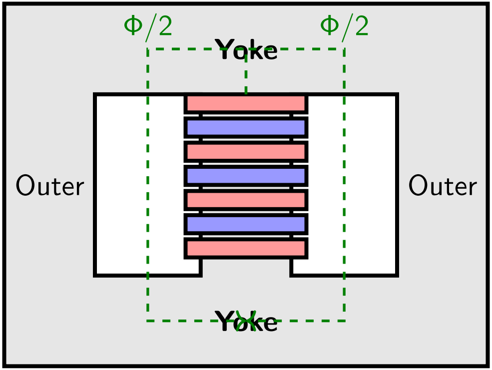
Key Points:

- Cylindrical coils are used, which naturally possess high mechanical robustness against radial electro-dynamic forces during short-circuits.
- Relatively simpler to manufacture and repair; windings are easily accessible for inspection and maintenance.
- Possesses a higher natural leakage reactance compared to the shell type, primarily because the magnetic flux paths in air are longer.
- Provides excellent cooling for windings since they form the outermost layer and are directly exposed to the surrounding cooling medium (air or transformer oil).

Characteristics of Core Type Transformers II

- Laminations are typically L-shaped, or a combination of U-shaped and I-shaped, interleaved at the joints to eliminate continuous air gaps and reduce reluctance.

Shell Type Transformer Construction I



Key Points:

- In a shell-type transformer, the multi-limb core heavily encapsulates the windings. Both primary and secondary coils are wound exclusively on the central limb.

Shell Type Transformer Construction II

- The core provides two parallel paths for the magnetic flux. The total flux Φ generated in the central limb divides equally ($\Phi/2$) into the two outer limbs.
- Consequently, the cross-sectional area of the central limb must be exactly twice that of the outer limbs and yokes to maintain a uniform flux density (B) throughout the core.
- Utilizes a sandwiched (or interleaved) winding arrangement: disc-shaped LV and HV coils are stacked alternately along the central limb, with LV coils positioned closest to the yokes.

Characteristics of Shell Type Transformers I

The multi-path magnetic circuit and interleaved windings define the operational characteristics of shell-type transformers.

Key Points:

- Achieves significantly lower leakage reactance due to the very close magnetic coupling provided by the sandwiched LV/HV coil arrangement.
- Mechanically highly rigid; the massive core braces the windings externally, making it extremely resistant to axial short-circuit electro-dynamic forces.
- Cooling of the outer core is excellent as it is completely exposed, but effective cooling of the deeply embedded internal windings requires careful thermal design.
- Requires highly specialized manufacturing and assembly techniques compared to the core type.
- Laminations are typically E and I shaped for small units.

- Preferred for low voltage/high current furnace transformers, and very large step-up generator transformers.

Transformer Parts, Functions & Materials - I I

Active materials in a transformer are fundamentally responsible for the primary electromagnetic energy conversion.

Key Points:

- Magnetic Core: Function is to carry the main alternating flux with minimum reluctance. Material: Cold Rolled Grain Oriented (CRGO) Silicon Steel. Silicon addition increases resistivity (reducing eddy currents), while CRGO processing provides exceptionally high permeability in the rolling direction.
- Laminations: The core is built of ultra-thin laminations (typically 0.23mm to 0.30mm thick), individually coated with an inorganic insulating varnish (e.g., Carlite) to restrict eddy current paths and drastically reduce core losses.

Transformer Parts, Functions & Materials - I II

- Windings (Coils): Function is to establish the MMF and induce EMF. Material: Electrolytic grade Copper or Aluminum. Copper provides lower I^2R losses and higher tensile strength, whereas aluminum offers weight and cost advantages.
- Conductor Insulation: Individual wire turns are insulated using synthetic enamel (for small units) or spirally wrapped Kraft paper (for high voltage power transformers).

Ancillary mechanical and chemical components are crucial for the insulation, cooling, and long-term operational safety of the transformer.

Key Points:

- Transformer Oil (Mineral Oil or Synthetic Ester): Serves a dual critical purpose as an excellent liquid dielectric (preventing arcing) and a primary coolant (convecting heat from the active parts to the tank walls).
- Main Tank: Houses the core-winding assembly and bulk oil. Material: Welded mild steel plates. Usually fitted with external pressed-steel radiators or cooling fins to maximize surface area for heat dissipation.

Transformer Parts, Functions & Materials - II II

- Conservator Tank: A small cylindrical drum mounted above the main tank. It accommodates the natural volumetric expansion and contraction of the transformer oil due to load cycling, ensuring the main tank remains completely filled.
- Breather: Attached to the conservator's air vent. It contains moisture-absorbing Silica gel crystals. As the transformer 'breathes' air in, the gel absorbs ambient humidity, preventing moisture ingress which would otherwise rapidly degrade the oil's dielectric strength (crystals turn from blue to pink when saturated).

Principle of Operation I

A transformer operates on the fundamental principle of mutual electromagnetic induction between two or more magnetically coupled coils.

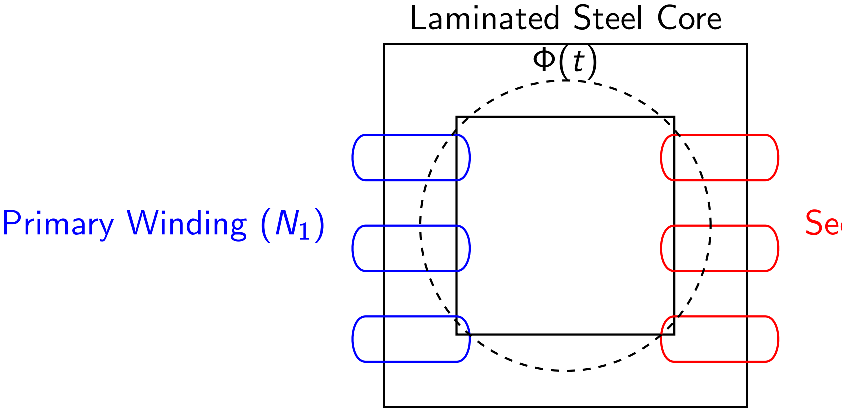
Key Points:

- When an alternating voltage V_1 is applied to the primary winding, an alternating exciting current flows, establishing an alternating magnetic flux Φ in the core.
- This mutually shared alternating flux links with both the primary and secondary windings.
- According to Faraday's Law of Electromagnetic Induction, the rate of change of flux linkages induces an electromotive force (EMF) in both windings.
- The induced EMF in the primary winding (E_1) opposes the applied voltage V_1, satisfying Lenz's Law.

Principle of Operation II

- The induced EMF in the secondary winding (E_2) drives a load current if an external circuit is closed across its terminals.
- Electrical energy is thereby transferred from the primary circuit to the secondary circuit entirely through the magnetic medium, with no direct galvanic connection.

Transformer Construction and Magnetic Circuit I



Key Points:

Transformer Construction and Magnetic Circuit II

- The ferromagnetic core provides a tightly confined, low-reluctance path for the mutual flux Φ.
- The core is constructed from thin silicon-steel laminations to minimize eddy current losses.
- The primary winding consists of N_1 turns, while the secondary winding consists of N_2 turns.

Faraday's Law and Induced EMF Derivation I

The instantaneous equations governing the induced EMFs are derived directly from Faraday's law of induction.

Key Points:

- Assume the alternating flux in the transformer core is purely sinusoidal: $\Phi = \Phi_m \sin(\omega t)$, where Φ_m is the peak flux in Webers.
- Instantaneous EMF induced in the primary winding: $e_1 = -N_1 \frac{d\Phi}{dt} = -N_1 \omega \Phi_m \cos(\omega t)$.
- Using trigonometric identities, this can be written as: $e_1 = N_1 \omega \Phi_m \sin(\omega t - 90^\circ)$.
- Similarly, the instantaneous EMF induced in the secondary: $e_2 = -N_2 \frac{d\Phi}{dt} = N_2 \omega \Phi_m \sin(\omega t - 90^\circ)$.
- The negative sign is a mathematical expression of Lenz's law, indicating the induced EMF opposes the flux variations.

Faraday's Law and Induced EMF Derivation II

- Crucial observation: Both induced EMFs (e_1 and e_2) lag the main core flux (Φ) by exactly 90° in time.

The Universal EMF Equation of a Transformer I

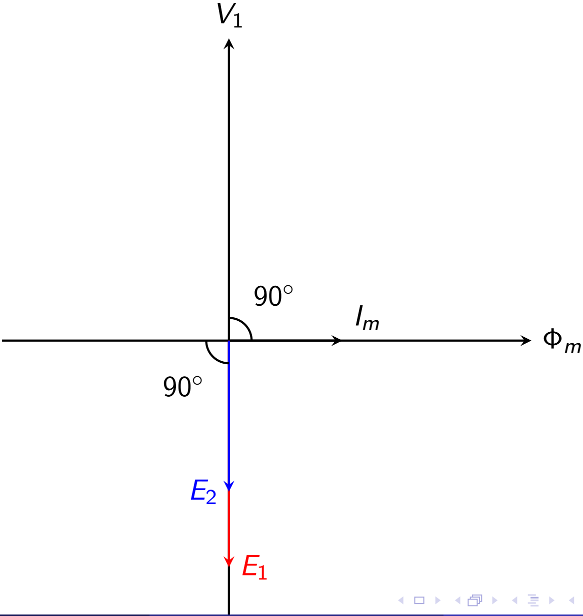
The Root Mean Square (RMS) values of the induced EMFs give us the standard design equation for transformers.

Key Points:

- The maximum (peak) value of the induced primary EMF is $E_{1m} = N_1 \omega \Phi_m = 2\pi f N_1 \Phi_m$.
- The RMS value of the primary EMF is $E_1 = \frac{E_{1m}}{\sqrt{2}} = \frac{2\pi}{\sqrt{2}} f N_1 \Phi_m \approx 4.44 f N_1 \Phi_m$.
- Following the exact same logic, the RMS value of the secondary EMF is $E_2 = 4.44 f N_2 \Phi_m$.
- In these equations, f is the AC supply frequency in Hertz (Hz), and $\Phi_m = B_m \times A_i$ (peak flux density times net core area).
- The quantity $\frac{E_1}{N_1} = \frac{E_2}{N_2} = 4.44 f \Phi_m$ represents the EMF induced per turn, which remains strictly identical for both windings in an ideal transformer.

Phasor Diagram of Ideal Transformer (No Load) I

Phasor Diagram of Ideal Transformer (No Load) II



Voltage Transformation Ratio (K) I

The voltage transformation ratio dictates the primary function of the transformer in a power network.

Key Points:

- The ratio of the secondary RMS voltage to the primary RMS voltage is designated by the constant K.
- For an ideal transformer, $K = \frac{E_2}{E_1} = \frac{V_2}{V_1}$ (ignoring resistive and leakage reactance voltage drops).
- Substituting the EMF equations: $\frac{E_2}{E_1} = \frac{4.44 f N_2 \Phi_m}{4.44 f N_1 \Phi_m} = \frac{N_2}{N_1}$.
- If $K > 1$ ($N_2 > N_1$), the secondary voltage is higher; this is a Step-Up transformer.
- If $K < 1$ ($N_2 < N_1$), the secondary voltage is lower; this is a Step-Down transformer.
- If $K = 1$ ($N_2 = N_1$), the voltages are equal; this is an Isolation transformer, used primarily for electrical safety and noise decoupling.

Turns Ratio and Current Ratio I

The principles of energy conservation and Ampere-turn balance establish the relationship between primary and secondary currents.

Key Points:

- The 'turns ratio' is standardly defined as $a = \frac{N_1}{N_2}$, which is the inverse of the transformation ratio ($a = 1/K$).
- Assuming an ideal transformer with 100
- Rearranging yields the current ratio: $\frac{I_1}{I_2} = \frac{V_2}{V_1} = \frac{N_2}{N_1} = K$.
- This implies the primary Magnetomotive Force (MMF) balances the secondary MMF: $I_1 N_1 = I_2 N_2$.
- Crucial takeaway: A transformer that steps up voltage ($V_2 > V_1$) must proportionately step down current ($I_2 < I_1$) to satisfy the conservation of energy.

Numerical Problem Formulation I

Let's apply the derived EMF equation and transformation ratio principles to a practical design calculation.

Key Points:

- Problem Statement: A 3300/220 V, 50 Hz, single-phase core-type transformer has a net core cross-sectional area of 125 cm^2.
- If the maximum operating flux density in the steel core is designed to be 1.2 Wb/m^2 (Tesla), calculate:
- 1. The required number of turns on the primary high-voltage winding (N_1).
- 2. The required number of turns on the secondary low-voltage winding (N_2).
- Extracted Given Data: $V_1 = 3300$ V, $V_2 = 220$ V, $f = 50$ Hz.
- Core Area $A = 125 \text{ cm}^2 = 125 \times 10^{-4} \text{ m}^2$.
- Maximum core flux density $B_m = 1.2$ T.

Numerical Problem Solution I

Step-by-step calculation executing the fundamental electrical machine formulas.

Key Points:

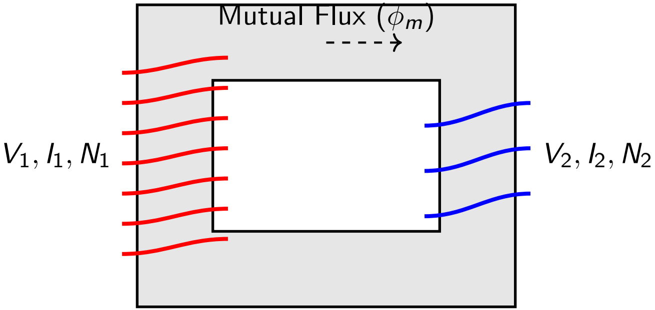
- Step 1: Calculate the peak mutual flux Φ_m in the core.
- $\Phi_m = B_m \times A = 1.2 \times (125 \times 10^{-4}) = 0.015$ Wb (Webers).
- Step 2: Utilize the primary EMF equation to determine N_1.
- $E_1 \approx V_1 = 4.44 f N_1 \Phi_m \implies 3300 = 4.44 \times 50 \times N_1 \times 0.015$
- $N_1 = \frac{3300}{4.44 \times 50 \times 0.015} = \frac{3300}{3.33} \approx 990.99 \implies 991$ turns.
- Step 3: Apply the voltage transformation ratio K to deduce N_2.
- $\frac{N_2}{N_1} = \frac{V_2}{V_1} \implies N_2 = N_1 \times \left(\frac{V_2}{V_1}\right) = 991 \times \left(\frac{220}{3300}\right)$
- $N_2 = 991 \times \left(\frac{1}{15}\right) = 66.06 \implies 66$ turns.
- Final Engineering Conclusion: The primary winding requires 991 turns, and the secondary winding requires 66 turns to satisfy the design specifications.

Principle of Operation I

The single-phase transformer operates on the principle of Faraday's Law of Electromagnetic Induction, specifically mutual induction between two magnetically coupled coils.

Key Points:

- A time-varying alternating voltage V1 applied to the primary winding creates an alternating current.
- This current produces an alternating magnetic flux in the highly permeable core.
- The flux links with both the primary and secondary windings, establishing mutual flux Φm.
- According to Faraday's law ($e = -N * d\Phi/dt$), an EMF is induced in both windings due to this changing flux.



Key Points:

- The laminated silicon steel core provides a low-reluctance path for the magnetic flux.
- Primary winding (N1 turns) is connected to the AC source.
- Secondary winding (N2 turns) is connected to the load.

Transformer Magnetic Circuit II

- The mutual flux Φm links both windings, facilitating energy transfer without electrical connection.

Induced EMFs: Self and Mutual I

The changing flux induces voltage in both the primary and secondary coils.

Key Points:

- Self-induced EMF (E1) in the primary: $E1 = -N1 * (d\Phi/dt)$. By Lenz's law, it opposes the applied voltage V1.
- Mutually-induced EMF (E2) in the secondary: $E2 = -N2 * (d\Phi/dt)$.
- Since the same flux Φ links both windings, the induced EMF per turn is identical for both primary and secondary: $E1/N1 = E2/N2$.

Derivation of the EMF Equation I

Let the alternating flux be sinusoidal: $\Phi = \Phi m * \sin(\omega t)$ where Φm is the maximum flux in Webers (Wb).

Key Points:

- Angular frequency $\omega = 2\pi f$, where f is the supply frequency in Hertz (Hz).
- Instantaneous induced EMF in a coil of N turns: $e = -N * (d\Phi/dt)$.
- Substituting Φ: $e = -N * (d/dt)[\Phi m * \sin(\omega t)] = -N\omega\Phi m * \cos(\omega t)$.
- Using trigonometric identity: $e = N\omega\Phi m * \sin(\omega t - \pi/2)$. This shows the induced EMF lags the flux by 90 degrees.

RMS Value of Induced EMF I

The maximum value of the induced EMF is $E_max = N\omega\Phi m$ = N * 2πf * Φm.

Key Points:

- For a sinusoidal wave, the RMS value is E_rms = E_max / 2.
- E = (2πf * N * Φm) / 2 = 4.44 * f * N * Φm.
- Primary RMS Voltage: E1 = 4.44 * f * N1 * Φm.
- Secondary RMS Voltage: E2 = 4.44 * f * N2 * Φm.
- Using maximum flux density Bm and core area A: Φm = Bm * A. Thus, E = 4.44 * f * N * Bm * A.

Voltage Transformation Ratio (K) I

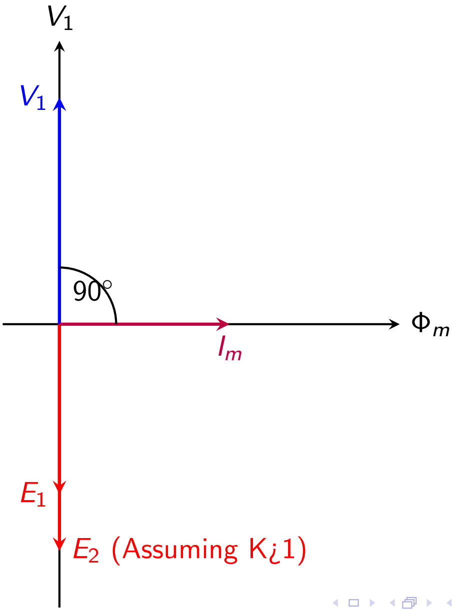
The voltage transformation ratio (K) relates the secondary and primary parameters.

Key Points:

- From the EMF equations, E2 / E1 = (4.44 * f * N2 * Φm) / (4.44 * f * N1 * Φm) = N2 / N1.
- The constant K = N2 / N1 is defined as the voltage transformation ratio or turns ratio.
- If K ¿ 1 (N2 ¿ N1), the transformer is a Step-Up transformer.
- If K ¡ 1 (N2 ¡ N1), the transformer is a Step-Down transformer.
- For an ideal transformer, V1 E1 and V2 E2, so K = V2 / V1 = N2 / N1 = I1 / I2.

No-Load Phasor Diagram I

No-Load Phasor Diagram II



Numerical Problem: EMF Equation I

Problem Statement: A 25 kVA, 2200/220 V, 50 Hz single-phase transformer has a primary winding with 2000 turns.

Key Points:

- Calculate the number of turns on the secondary winding (N2).
- Calculate the maximum value of the core flux (Φm).
- Given Data: Primary Voltage V1 = 2200 V, Secondary Voltage V2 = 220 V.
- Frequency f = 50 Hz, Primary Turns N1 = 2000.

Numerical Problem: Solution I

Solution breakdown applying the transformation ratio and EMF equation.

Key Points:

- 1. Secondary Turns (N2): Using the transformation ratio K = V2/V1 = N2/N1.
- K = 220 / 2200 = 0.1. Thus, N2 = K * N1 = 0.1 * 2000 = 200 turns.
- 2. Maximum Core Flux (Φm): Using the primary EMF equation V1 E1 = 4.44 * f * N1 * Φm.
- 2200 = 4.44 * 50 * 2000 * Φm.
- Φm = 2200 / (4.44 * 50 * 2000) = 2200 / 444000 0.00495 Webers (or 4.95 mWb).

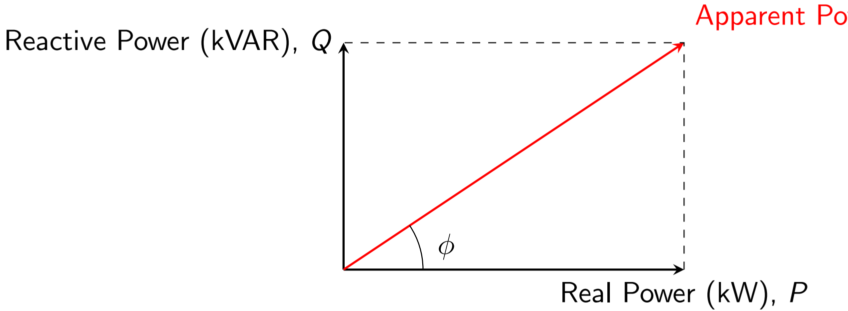
Introduction to Transformer Ratings I

A transformer's nameplate provides critical operating boundaries established by the manufacturer.

Key Points:

- Ratings define the maximum safe continuous operating conditions under which a transformer can perform without suffering damage or accelerated aging.
- They ensure the machine operates within thermally acceptable temperature rise limits.
- The primary ratings include Apparent Power (kVA/MVA), Primary/Secondary Voltage, Current, Frequency, and Per Unit Impedance.
- Exceeding these limits leads to accelerated insulation degradation, core saturation, or catastrophic failure.

Why is the Rating in kVA instead of kW? I



$$S = \sqrt{P^2 + Q^2}$$

Key Points:

Why is the Rating in kVA instead of kW? II

- Transformer losses fundamentally consist of copper losses and iron (core) losses.
- Copper losses depend exclusively on the current (I) flowing through the windings, while iron losses depend on the applied voltage (V).
- Total losses, therefore, depend on Voltage and Current ($V \times I$), and are entirely independent of the load's power factor ($\cos \phi$).
- Since the manufacturer cannot predict the power factor of the load that will be connected, the rating is specified in kVA (Apparent Power) rather than kW (Real Power).

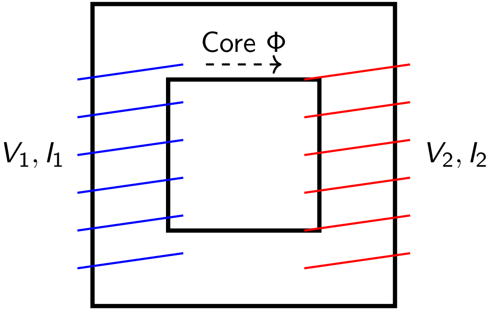
Rated Voltage (Primary and Secondary) I

Voltage ratings dictate the dielectric insulation level and the operating magnetic flux density.

Key Points:

- Rated primary voltage (V1) is the voltage for which the primary winding is designed to be connected for normal operation.
- Rated secondary voltage (V2) is the no-load terminal voltage at the secondary when V1 is applied to the primary.
- The ratio of these voltages (V1/V2) approximately establishes the physical turns ratio (N1/N2) of the windings.
- Exceeding the rated voltage pushes the magnetic core into deep saturation, resulting in high magnetizing currents, excessive harmonics, and dangerous core heating.

Physical Implications of Ratings on Core and Windings I



Key Points:

- The Voltage rating directly determines the number of winding turns required to keep the magnetic flux within safe limits.

Physical Implications of Ratings on Core and Windings II

- The Current rating directly dictates the cross-sectional area of the copper or aluminum conductors to prevent excessive I^2R heating.
- The core cross-section is sized to carry the mutual flux (Φ) without reaching the saturation region of the B-H curve.
- A properly rated transformer perfectly balances electrical capability with thermal dissipation.

Rated Current (I1 and I2) I

Current ratings represent the maximum continuous RMS currents the windings can safely carry.

Key Points:

- These values are mathematically derived from the kVA rating and the respective nominal voltages: I = (kVA * 1000) / V.
- They determine the full-load operating state of the transformer.
- Exceeding rated current results in copper losses (I^2R) that exceed the thermal dissipation capacity of the transformer's cooling system.
- Sustained overcurrent (overloading) causes thermal degradation of the cellulose insulation, drastically reducing transformer lifespan.

Rated Frequency I

The designated operating frequency of the AC supply system (typically 50 Hz or 60 Hz).

Key Points:

- According to the EMF equation (E = 4.44 * f * N * $\Phi_max), foraconstantappliedvoltage, themaximumflux(\Phi_max)isinve$
- Operating a 60 Hz transformer on a 50 Hz supply at its rated voltage increases core flux by 20
- Operating a 50 Hz transformer on a 60 Hz supply reduces the flux, safely avoiding saturation, but may alter eddy current losses.
- The frequency rating critically influences the physical volume and weight of the ferromagnetic core material required.

Per Unit Impedance (%Z) I

The internal equivalent impedance specified as a percentage of the base impedance.

Key Points:

- Percentage impedance (
- It is a crucial parameter for power system fault analysis; it limits the maximum short-circuit current during a secondary fault ($I_{sc} = I_{rated} / Z_{pu}$).
- A higher
- When connecting transformers in parallel, they must possess identical or very similar

Insulation Class and Temperature Rise I

Defines the thermal endurance and cooling requirements of the transformer components.

Key Points:

- Nameplates strictly specify allowable temperature rise (e.g., 55°C or 65°C rise above a specified ambient temperature, usually assumed as 40°C).
- Standardized insulation classes (such as A, B, F, H) dictate the maximum absolute "hot-spot" temperature the winding insulation can physically withstand.
- Following the Arrhenius equation principle, for every 10°C increase above the rated continuous insulation temperature, the life expectancy of the transformer is approximately halved.
- Cooling methods (ONAN, ONAF, OFAF) are engineered precisely to maintain temperatures within these defined limits under full kVA load.

Summary: The Practical Importance of Ratings I

Transformer ratings form the foundational blueprint for safe, efficient, and reliable power system operation.

Key Points:

- kVA defines overall thermal and power capacity; Voltage defines dielectric stress and magnetic flux limits; Current dictates conductor sizing.
- Frequency must match system design to prevent magnetic saturation or excessive core losses.
- Impedance (
- Strict adherence to all specified ratings is paramount in electrical engineering to prevent catastrophic equipment failure and guarantee continuous power delivery.

Introduction to Transformer Ratings I

A transformer's rating specifies the operating limits within which it can perform continuously without exceeding safe temperature limits or suffering insulation degradation.

Key Points:

- Ratings dictate the maximum voltage, current, and apparent power a transformer can handle safely in steady-state operation.
- They are determined primarily by the thermal limits of the internal winding insulation and the heat dissipation capacity of the cooling system.
- Exceeding nameplate ratings (overloading) accelerates insulation aging. According to Arrhenius theory, insulation life is roughly halved for every 8°C rise beyond its operational limit.

Introduction to Transformer Ratings II

- The primary ratings found on a nameplate include Apparent Power (kVA/MVA), Voltage Levels, Frequency, and Percentage Impedance.

Why is a Transformer Rated in kVA and not kW? I

The rating of a transformer is expressed in Apparent Power (VA, kVA, or MVA), remaining independent of the connected load's power factor.

Key Points:

- Total transformer losses are the sum of Core (Iron) losses and Copper (Winding) losses.
- Core loss (P_i) is dependent on the core flux density, which is proportional to the applied voltage (V).
- Copper loss (P_{cu}) is dependent on the square of the current (I^2R), irrespective of the phase angle between voltage and current.
- Since the temperature rise depends purely on the magnitudes of V and I (and not the load power factor $\cos\phi$), the rating is inherently Apparent Power ($V \times I$).

Voltage Ratings (V_1 / V_2) I

Voltage ratings specify the RMS line-to-line voltages for which the primary and secondary windings are designed.

Key Points:

- The primary voltage rating limits the maximum flux density (B_m) in the core, based on the EMF equation: $V \approx 4.44 f N \phi_m$.
- Applying a voltage significantly higher than the rated value drives the core into magnetic saturation, producing severe harmonic distortion, high magnetizing current, and excessive core heating.
- The secondary voltage rating is defined as the open-circuit terminal voltage when the rated primary voltage is applied at rated frequency.
- Under actual load conditions, the secondary voltage will drop below the rated value due to the internal leakage impedance (measured as voltage regulation).

Current Ratings (I_1 / I_2) I

Full-load currents for both primary and secondary sides are derived algebraically from the kVA and Voltage ratings.

Key Points:

- For a single-phase transformer: $I = \frac{\text{kVA} \times 1000}{V}$.
- For a three-phase transformer: $I = \frac{\text{kVA} \times 1000}{\sqrt{3} \times V_{\text{line}}}$.
- The rated current dictates the required cross-sectional area of the winding conductors to maintain safe current density limits (typically 2.5 to 4.0 A/mm^2 in copper) to limit I^2R heating.
- Operating continuously above the rated current leads to thermal breakdown of cellulose insulation (Kraft paper), forming water and gases, further accelerating failure.

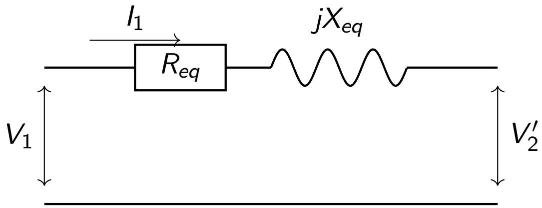
Frequency Rating (Hz) I

Transformers are designed and optimized for specific alternating current operating frequencies, standardly 50 Hz or 60 Hz.

Key Points:

- From the generalized EMF equation, $E = 4.44 f N B_m A_c$, flux density B_m is inversely proportional to frequency for a given voltage: $B_m \propto \frac{V}{f}$.
- Operating a 60 Hz transformer on a 50 Hz supply at the rated 60 Hz voltage increases the flux density by 20
- Conversely, operating a 50 Hz transformer on a 60 Hz supply reduces flux density, but increases frequency-dependent eddy current losses ($P_e \propto f^2$).
- Aviation and military transformers are often rated at 400 Hz to drastically reduce core cross-sectional area and weight for the same power rating.

Impedance Rating (Percentage Impedance %Z) I



Key Points:

-
- It characterizes the internal voltage drop (leakage reactance and winding resistance) during normal operation, dictating voltage regulation.
- Crucially,
- A high

Temperature Rise and Cooling Classifications I

The power rating is inextricably linked to the permissible temperature rise above ambient (e.g., 55°C or 65°C) and the cooling methodology.

Key Points:

- Insulation classes (A, B, F, H, etc.) establish the maximum absolute operating hotspot temperature (e.g., Class A is 105°C max).
- Cooling mechanisms are designated by standardized IEC/IEEE four-letter codes: ONAN (Oil Natural Air Natural), ONAF (Forced Air), OFAF (Forced Oil Air), etc.
- Power transformers frequently feature multi-stage ratings (e.g., 20/26.6/33.3 MVA ONAN/ONAF1/ONAF2) where fans and oil pumps activate to increase the rating dynamically.

Temperature Rise and Cooling Classifications II

- Prolonged operation beyond the thermal rating without adequate cooling leads to breakdown of the dielectric mineral oil and sludging.

Basic Impulse Insulation Level (BIL) & Transients I

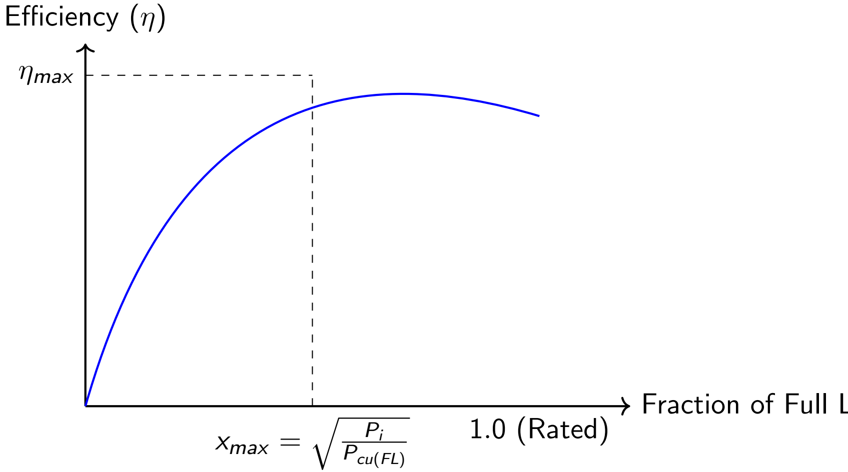
Beyond steady-state AC operation, the transformer rating must include its ability to withstand transient overvoltages and external faults.

Key Points:

- BIL (Basic Impulse Insulation Level) is the maximum crest voltage of a standard simulated lightning impulse (1.2/50 μs wave) the insulation can survive without flashover.
- Higher primary operating voltage ratings require exponentially higher BIL ratings, significantly dictating the physical size and cost of the bushings and internal insulation.
- Nameplates also specify the vector group (e.g., Dyn11), which describes the primary-secondary phase shift and is a strict prerequisite for parallel operation.

- The short-circuit withstand duration rating (typically 2 seconds) guarantees the transformer will not suffer mechanical deformation from Lorentz forces during external faults.

Impact of Rating on Operating Efficiency I



Impact of Rating on Operating Efficiency II

Key Points:

- A transformer's operational efficiency is a nonlinear curve that is heavily dependent on the percentage of rated load it is carrying.
- Maximum efficiency (η_{max}) theoretically occurs at the specific load fraction (x) where variable copper losses equal constant core losses: $x^2 P_{cu(FL)} = P_i$.
- Distribution transformers are designed with very low core losses (P_i), ensuring maximum efficiency occurs at typical average loads (often 50
- Conversely, large generator step-up (GSU) power transformers operate near full load constantly, and are therefore designed to have peak efficiency near 100

Introduction to Transformer Testing I

Why do we perform tests on transformers?

Key Points:

- To determine the parameters of the equivalent circuit (Ro, Xo, Req, Xeq).
- To predetermine the efficiency of the transformer at various loads without actual loading.
- To calculate the voltage regulation at any given load and power factor.
- Direct loading of large transformers is highly impractical and consumes massive amounts of power, hence open-circuit (O.C.) and short-circuit (S.C.) tests are preferred.

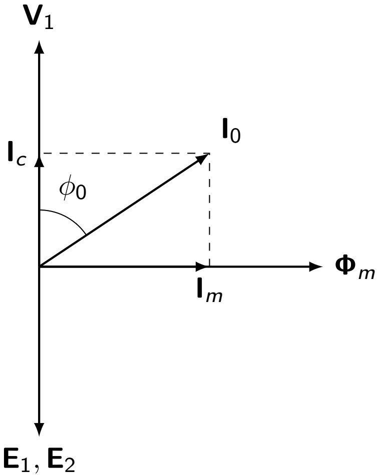
Open-Circuit (No-Load) Test I

Procedure and observations of the Open-Circuit Test.

Key Points:

- The test is usually performed on the Low Voltage (LV) side with the High Voltage (HV) side kept open-circuited.
- Rated voltage and rated frequency are applied to the primary (LV) winding.
- Since the secondary is open, the current drawn is the no-load current (I0), which is typically 2-5
- The wattmeter reads the no-load power (W0), which consists entirely of core loss (iron loss) as copper loss is negligible ($I_0^2 R_1 \approx 0$).
- Voltmeter reads rated primary voltage V_1, ammeter reads no-load current I_0.

No-Load Phasor Diagram I



Key Points:

No-Load Phasor Diagram II

- The applied voltage V_1 leads the mutual flux Φ_m by 90 degrees.
- Induced EMFS E_1 and E_2 lag the flux Φ_m by 90 degrees.
- The magnetizing current component I_m is in phase with the flux.
- The core loss component I_c is in phase with the applied voltage V_1.
- The total no-load current I_0 is the phasor sum of I_m and I_c.

Calculations from Open-Circuit Test I

Determining the shunt branch parameters of the equivalent circuit.
Key Points:

- No-load power factor: $\cos(\phi_0) = W_0/(V_1 \cdot I_0)$.
- Core loss component of current: $I_c = I_0 \cos(\phi_0)$.
- Magnetizing component of current: $I_m = I_0 \sin(\phi_0)$.
- Equivalent core-loss resistance: $R_0 = V_1/I_c = V_1/(I_0 \cos(\phi_0))$.
- Equivalent magnetizing reactance: $X_0 = V_1/I_m = V_1/(I_0 \sin(\phi_0))$.

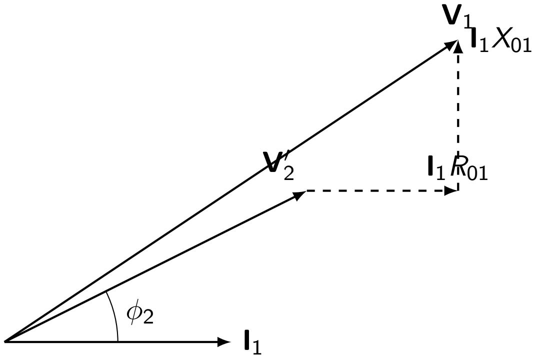
Short-Circuit (On-Load) Test I

Procedure and observations of the Short-Circuit Test.

Key Points:

- This test is typically performed on the High Voltage (HV) side with the Low Voltage (LV) side solidly short-circuited.
- A reduced voltage (usually 5-10
- Since the applied voltage is very low, the mutual flux is very small, making core loss negligible.
- The wattmeter primarily measures the full-load copper loss ($W_{sc} = I_{sc}^2 R_{eq}$).
- Voltmeter measures short-circuit voltage (V_{sc}), and ammeter measures full-load short-circuit current (I_{sc}).

Simplified On-Load Phasor Diagram (Lagging PF) I



Key Points:

- Phasor diagram is shown referred to the primary side for an inductive (lagging) load.

Simplified On-Load Phasor Diagram (Lagging PF) II

- $\mathbf{I}_1$ is the primary current. $\mathbf{V}_2'$ is the referred secondary terminal voltage.
- $\mathbf{I}_1 R_{01}$ represents the voltage drop across the total equivalent resistance, drawn parallel to $\mathbf{I}_1$.
- $\mathbf{I}_1 X_{01}$ represents the voltage drop across the total equivalent reactance, drawn perpendicular to $\mathbf{I}_1$.
- The primary voltage $\mathbf{V}_1$ is the phasor sum of $\mathbf{V}_2'$, $\mathbf{I}_1 R_{01}$, and $\mathbf{I}_1 X_{01}$.

Calculations from Short-Circuit Test I

Determining the series branch parameters of the equivalent circuit.
Key Points:

- Equivalent resistance referred to the measuring side: $R_{eq} = W_{sc}/I_{sc}^2$.
- Equivalent impedance referred to the measuring side: $Z_{eq} = V_{sc}/I_{sc}$.
- Equivalent leakage reactance referred to the measuring side: $X_{eq} = \sqrt{Z_{eq}^2 - R_{eq}^2}$.
- Short-circuit power factor: $\cos(\phi_{sc}) = W_{sc}/(V_{sc} \cdot I_{sc}) = R_{eq}/Z_{eq}$.
- These parameters are used to determine voltage regulation.

Transformer Leakage Reactance I

Understanding the physical significance of leakage flux and reactance.

Key Points:

- In a real transformer, not all flux produced by the primary links with the secondary, and vice versa.
- Flux that links only with the primary winding is primary leakage flux (Φ_{l1}), creating primary leakage reactance (X_1).
- Flux that links only with the secondary winding is secondary leakage flux (Φ_{l2}), creating secondary leakage reactance (X_2).
- Leakage flux paths are primarily through air, which has constant reluctance, so leakage reactance is constant regardless of saturation.
- Leakage reactance causes a voltage drop in the transformer under load, leading to poor voltage regulation if it is too high.

Summary of Testing and Parameters I

Recap of O.C. and S.C. test significance.

Key Points:

- O.C. test yields core loss (P_i) and shunt branch parameters (R_0, X_0). Usually done on LV side.
- S.C. test yields full-load copper loss (P_c) and series branch parameters (R_{eq}, X_{eq}). Usually done on HV side.
- Combining these tests gives the complete exact or approximate equivalent circuit of the transformer.
- With the equivalent circuit, one can calculate efficiency at any load and power factor: $\eta = \frac{xS \cos\phi}{xS \cos\phi + P_i + x^2 P_c}$.
- Voltage regulation can also be accurately computed as $V_r = \frac{I_2 R_{eq2} \cos\phi \pm I_2 X_{eq2} \sin\phi}{E_2}$.

Introduction to Transformer Testing I

Direct loading of large power transformers to determine efficiency and regulation is impractical due to massive power consumption and heat dissipation requirements.

Key Points:

- Instead of direct loading, we use indirect testing methods: Open-Circuit (No-load) and Short-Circuit tests.
- These tests allow us to determine the equivalent circuit parameters without loading the transformer to its rated capacity.
- The parameters obtained are then used to calculate performance indices like efficiency and voltage regulation at any load condition.
- Testing also helps in verifying design specifications and ensuring operational safety.

No-Load Test (Open Circuit Test) Setup I

The No-Load test is performed to determine the core loss (iron loss) and the shunt branch parameters of the equivalent circuit (magnetizing reactance and core-loss resistance).

Key Points:

- The test is typically conducted on the Low Voltage (LV) side because a lower rated voltage source and standard low-range meters can be used safely.
- The High Voltage (HV) side is left completely open-circuited.
- Rated voltage at rated frequency is applied to the primary (LV) winding.
- Instruments used: Voltmeter (measures applied rated voltage V1), Ammeter (measures no-load current I0), and Wattmeter (measures no-load input power P0).
- Since the secondary is open, primary current I0 is very small (2-5

No-Load Test Measurements and Calculations I

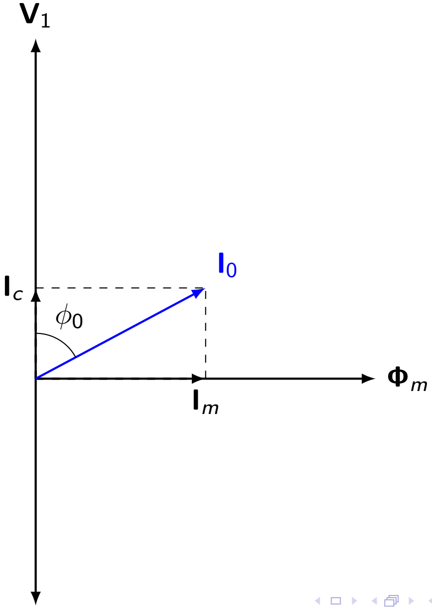
From the readings V0 (rated voltage), I0 (no-load current), and P0 (no-load power), we can calculate the core-loss resistance (Rc) and magnetizing reactance (Xm).

Key Points:

- No-load power factor: cos(ϕ0) = P0 / (V0 * I0). The power factor is usually very low (around 0.2 lagging).
- Core-loss component of current: Ic = I0 * cos(ϕ0). This current represents the active power required to overcome hysteresis and eddy current losses.
- Magnetizing component of current: Im = I0 * sin(ϕ0). This is the reactive component responsible for establishing the mutual flux in the core.
- Core-loss resistance (referred to primary): Rc = V0 / Ic = $V0^2$ / P0.
- Magnetizing reactance (referred to primary): Xm = V0 / Im.

No-Load Phasor Diagram I

No-Load Phasor Diagram II



Transformer on Load and Leakage Reactance I

When a load is connected to the secondary, a secondary current I2 flows, creating its own MMF (N2*I2) which opposes the primary mutual flux.

Key Points:

- To maintain the mutual flux constant (as determined by V1), the primary draws additional current I2' = I2 * (N2/N1) to balance the secondary MMF.
- Not all flux produced by the primary links with the secondary, and vice versa. This flux that links only one winding is called leakage flux.
- Primary leakage flux (ΦI1) links only the primary winding and induces a voltage drop proportional to the rate of change of primary current.

Transformer on Load and Leakage Reactance II

- Secondary leakage flux (Φl2) links only the secondary winding and induces a voltage drop proportional to the secondary current.

Modeling Leakage Reactance I

Leakage flux paths are primarily through air, meaning their reluctance is high and constant, so leakage fluxes are linearly proportional to the currents producing them.

Key Points:

- The effect of primary leakage flux is modeled as a primary leakage reactance, X1 = 2πf * $L1_leakage$.
- The effect of secondary leakage flux is modeled as a secondary leakage reactance, X2 = 2πf * $L2_leakage$.
- These leakage reactances cause voltage drops inside the transformer when it is loaded: I1*X1 in the primary and I2*X2 in the secondary.
- Leakage reactance is a crucial parameter affecting the voltage regulation of the transformer under load.

Short-Circuit Test Setup I

The Short-Circuit test is performed to determine the full-load copper losses (I^2*R) and the series branch parameters (equivalent resistance and equivalent leakage reactance).

Key Points:

- The test is typically conducted on the High Voltage (HV) side because the rated current on the HV side is lower, making it easier to supply from a standard AC source.
- The Low Voltage (LV) side is solidly short-circuited with a thick wire to ensure zero secondary voltage.
- A reduced voltage (usually 5
- Instruments used: Voltmeter (measures short-circuit voltage Vsc), Ammeter (measures short-circuit current Isc), and Wattmeter (measures short-circuit power Psc).

Short-Circuit Test Measurements and Calculations I

Since the applied voltage Vsc is very small, the mutual flux is very small (core losses are negligible). Thus, the wattmeter reading Psc represents almost entirely the total copper losses.

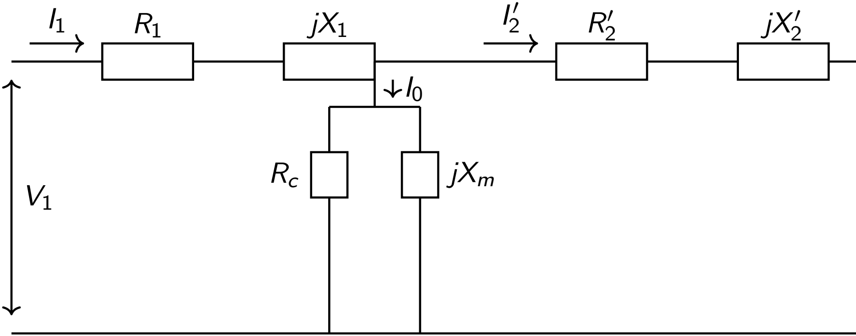
Key Points:

- Equivalent impedance referred to the test side: Zeq = Vsc / Isc.
- Equivalent resistance referred to the test side: Req = Psc / (Isc^2). This includes the AC resistance of both primary and secondary windings.
- Equivalent leakage reactance referred to the test side: Xeq = sqrt(Zeq^2 - Req^2).
- Short-circuit power factor: cos(ϕsc) = Req / Zeq = Psc / (Vsc * Isc).

Short-Circuit Test Measurements and Calculations II

- These parameters (Req and Xeq) are essential for calculating voltage regulation and efficiency under different load conditions.

Exact Equivalent Circuit Referred to Primary I



Key Points:

- R1 and X1 represent primary resistance and leakage reactance.

Exact Equivalent Circuit Referred to Primary II

- R'2 and X'2 represent secondary resistance and leakage reactance referred to the primary.
- Rc represents core-loss equivalent resistance, accounting for hysteresis and eddy current losses.
- Xm represents magnetizing reactance, accounting for the reactive power needed to magnetize the core.
- The shunt branch (Rc —— Xm) accounts for the no-load current I0 which produces the mutual flux and supplies core losses.

Introduction to the Equivalent Circuit I

The equivalent circuit is a simplified mathematical and electrical model used to predict the performance of a real transformer under various operating conditions.

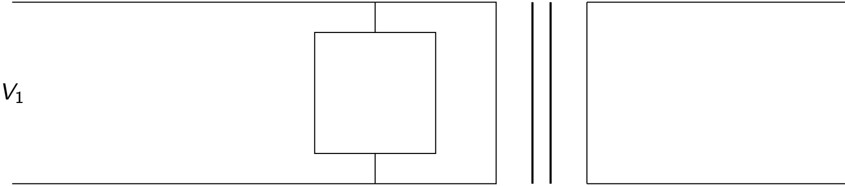
Key Points:

- A practical transformer has winding resistances, leakage reactances, and core losses, which distinguish it from an ideal transformer.
- To analyze the behavior of the transformer computationally, we replace the magnetic coupling with an equivalent electrical circuit.
- The model incorporates the primary and secondary resistances (R1, R2) representing ohmic copper losses.
- Leakage fluxes, which do not link both windings, are represented by series leakage reactances (X1, X2).

Introduction to the Equivalent Circuit II

- The non-ideal core behavior is modeled by a parallel shunt branch representing core losses and magnetization.

Exact Equivalent Circuit Model I



Key Points:

- The primary side includes the series combination of R1 and X1, representing primary copper loss and primary leakage flux.
- The excitation branch is placed parallel to the ideal transformer primary, accounting for no-load current (Io), which comprises core-loss current (Ic) and magnetizing current (Im).

Exact Equivalent Circuit Model II

- The core is represented by a parallel combination of Rc (eddy current and hysteresis losses) and Xm (finite permeability of the core).
- The secondary side includes R2 and X2, representing secondary copper loss and leakage flux.
- The ideal transformer in the center maintains the voltage transformation ratio $K = N2/N1$.

Components of the Excitation Branch I

The excitation branch models the non-ideal behavior of the transformer core and draws the no-load current from the source.

Key Points:

- Core Loss Resistance (Rc): Represents the active power dissipated as heat in the core due to hysteresis and eddy currents.
- Magnetizing Reactance (Xm): Represents the reactive power required to establish the mutual magnetic flux in the core.
- No-load Current (Io): The phasor sum of the core loss current (Ic = V1/Rc) and the magnetizing current (Im = V1/jXm).
- Io is typically very small, about 2
- This validates shifting the excitation branch to the primary terminals in the approximate equivalent circuit for simplified calculations.

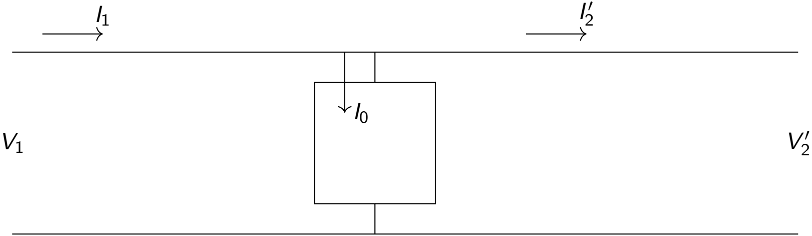
Impedance Transfer: Referring Parameters I

To simplify calculations, the entire circuit is often referred to a single side (either primary or secondary) by mathematically removing the ideal transformer and adjusting impedance values.

Key Points:

- The turns ratio is defined as a = N1 / N2, and transformation ratio as K = N2 / N1 = V2 / V1 = I1 / I2.
- When transferring an impedance from the secondary to the primary side, it is divided by K squared (Z2' = Z2 / K^2).
- Secondary resistance referred to primary: R2' = R2 / K^2.
- Secondary reactance referred to primary: X2' = X2 / K^2.
- Secondary voltage referred to primary: V2' = V2 / K.
- Secondary current referred to primary: I2' = K * I2.

Equivalent Circuit Referred to Primary I



Key Points:

- The ideal transformer has been mathematically eliminated by referring secondary quantities to the primary.
- R2' and X2' represent the secondary winding resistance and reactance as seen from the primary side.

Equivalent Circuit Referred to Primary II

- The load impedance (ZL) must also be referred to the primary as ZL' = ZL / K^2.
- The primary current I1 is the phasor sum of the no-load current Io and the referred load current I2'.
- This continuous circuit can be easily solved using standard nodal or mesh analysis techniques.

Total Equivalent Resistance and Reactance I

By combining the primary parameters with the referred secondary parameters, we define total equivalent values.

Key Points:

- Equivalent resistance referred to primary (Re1): Re1 = R1 + R2' = R1 + (R2 / K^2).
- Equivalent reactance referred to primary (Xe1): Xe1 = X1 + X2' = X1 + (X2 / K^2).
- Equivalent impedance referred to primary (Ze1): Ze1 = Re1 + jXe1.
- Similarly, we can refer to the secondary side: Re2 = R2 + (K^2 * R1) and Xe2 = X2 + (K^2 * X1).
- These equivalent values are crucial for calculating voltage regulation and efficiency under different load conditions.

Approximate Equivalent Circuit I

For most practical power transformers, the exact equivalent circuit is unnecessarily complex. An approximate circuit is widely used in engineering calculations.

Key Points:

- Since the no-load current Io is very small, the voltage drop it causes across R1 and X1 is minimal.
- By moving the shunt excitation branch (Rc —— jXm) to the input terminals, the series impedances (R1, X1) and (R2', X2') can be directly added together.
- The primary and secondary series branches merge into a single equivalent impedance: Ze1 = Re1 + jXe1.
- This significantly simplifies the circuit to a parallel excitation branch and a series equivalent impedance.
- The error introduced in calculating voltage drop and efficiency is typically less than 1

Determining Parameters via Testing I

The values for the equivalent circuit parameters (R1, X1, R2, X2, Rc, Xm) are experimentally determined using standardized transformer tests.

Key Points:

- Open-Circuit (OC) Test: Usually performed on the low-voltage side. It determines the core loss resistance (Rc) and magnetizing reactance (Xm).
- In the OC test, the current drawn is just the no-load current (Io), and copper losses are negligible.
- Short-Circuit (SC) Test: Usually performed on the high-voltage side with a reduced voltage. It determines the equivalent series resistance (Re) and reactance (Xe).
- In the SC test, the applied voltage is small, making the core flux very low; thus, core losses and the excitation branch can be practically ignored.

Determining Parameters via Testing II

- The parameters obtained from these tests allow engineers to construct the complete equivalent circuit for performance evaluation.

Summary and Importance I

The equivalent circuit is the foundational tool for analyzing transformer operation and predicting performance metrics.

Key Points:

- It translates the magnetic and electrical interactions of a transformer into a purely electrical circuit.
- Referring parameters to a single side eliminates the complexity of the ideal transformer step-up/step-down action.
- The equivalent parameters allow for precise calculation of voltage regulation, identifying how output voltage changes with load.
- Efficiency calculations rely heavily on the separation of core losses (excitation branch) and copper losses (series resistance).
- Mastering the equivalent circuit is essential for power system analysis and the study of all other AC electrical machines.

Purpose of the Equivalent Circuit I

An equivalent circuit models the physical phenomena within a transformer using standard electrical circuit components.

Key Points:

- Transforms a complex magnetic coupling problem into a standard electrical circuit problem.
- Facilitates performance analysis, including voltage regulation and efficiency calculations.
- Allows prediction of behavior under various load conditions without requiring the physical device.
- Parameters can be determined experimentally via open-circuit and short-circuit tests.

Practical vs. Ideal Transformer I

A practical transformer deviates from an ideal transformer due to physical imperfections in its materials and construction.

Key Points:

- Ideal transformers assume zero winding resistance, infinite core permeability, no leakage flux, and zero core loss.
- Practical transformers have finite winding resistance causing I^2R (copper) losses.
- Not all magnetic flux links both windings; leakage flux exists, creating leakage reactance.
- Finite permeability of the core requires a magnetizing current to establish mutual flux.
- Core materials exhibit hysteresis and eddy current losses under alternating magnetic fields.

Accounting for Winding Resistances I

Both primary and secondary windings are constructed from conductive materials (usually copper) that possess inherent ohmic resistance.

Key Points:

- Primary winding resistance is denoted as R.
- Secondary winding resistance is denoted as R.
- These resistances cause active voltage drops (IR and IR) in phase with the current.
- They are responsible for the load-dependent copper losses (I^2R and I^2R).
- In the equivalent circuit, R and R are modeled as discrete resistors in series with the ideal transformer windings.

Accounting for Leakage Reactances I

Leakage flux is the magnetic flux that links only one winding and completes its path primarily through the surrounding air.

Key Points:

- Primary leakage flux (Φ) links only the primary, inducing a self-voltage drop modeled by leakage reactance X.
- Secondary leakage flux (Φ) links only the secondary, modeled by leakage reactance X.
- Because leakage flux paths are mostly through non-magnetic air, they do not saturate, making X and X linear.
- These reactances cause reactive voltage drops (IX and IX) leading the current by 90 degrees.
- Modeled as discrete inductors in series with the respective winding resistances.

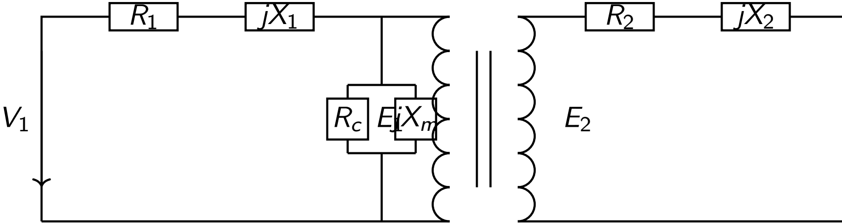
The Core Excitation Branch I

The excitation branch models the non-ideal characteristics of the ferromagnetic core under no-load conditions.

Key Points:

- Consists of a core-loss resistance (R_c) and a magnetizing reactance (X_m) connected in parallel.
- R_c models the active power losses in the core due to hysteresis and eddy currents.
- X_m models the reactive power (magnetizing current) required to establish the mutual flux in the core.
- The total no-load excitation current (I) is the phasor sum of the core-loss current (I_c) and magnetizing current (I_m).
- Typically placed on the primary side, effectively in parallel with the primary winding of the ideal transformer component.

Exact Equivalent Circuit Diagram I



Key Points:

- Depicts primary resistance and leakage reactance in series with the source.
- The parallel excitation branch accounts for core losses and magnetization.

Exact Equivalent Circuit Diagram II

- An ideal transformer component (with turns ratio a = N/N) magnetically couples the primary and secondary circuits.
- Secondary resistance and leakage reactance are in series with the load terminals.

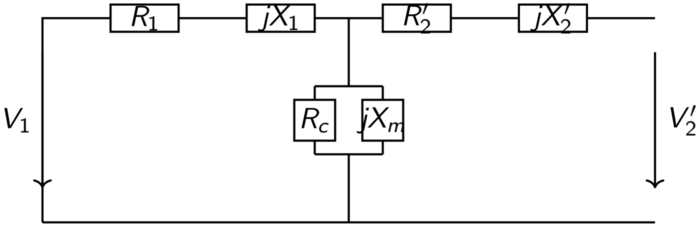
Referring Parameters to One Side I

To simplify circuit analysis, the ideal transformer can be analytically removed by referring all parameters to a single side.

Key Points:

- This relies on the turns ratio, defined as a = N / N.
- Impedances transferred from secondary to primary are multiplied by a^2 (e.g., R' = a^2R, X' = a^2X).
- Voltages referred to the primary are multiplied by a (e.g., V' = aV).
- Currents referred to the primary are divided by a (e.g., I' = I/a).
- Active power, reactive power, and apparent power remain invariant across the ideal transformer boundaries.

Equivalent Circuit Referred to Primary I



Key Points:

- The ideal transformer is mathematically eliminated from the physical diagram.
- Secondary parameters are now represented as R', X', and V', integrated directly into the primary circuit.
- The total equivalent primary series impedance becomes Z_eq1 = (R + R') + j(X + X').

Equivalent Circuit Referred to Primary II

- This merged circuit perfectly models the terminal electrical behavior of the actual transformer.

Approximate Equivalent Circuit I

For practical power transformers, further simplifications are often made with negligible loss of accuracy.

Key Points:

- The excitation current is very small (typically 2-5
- The shunt excitation branch (R_c and X_m) is shifted to the primary terminals, preceding R and X.
- This approximation introduces minimal error because the primary voltage drop (IZ) is very small compared to V.
- It allows for simple addition of primary and referred secondary impedances: R_eq1 = R + R' and X_eq1 = X + X'.
- Greatly simplifies manual calculations for voltage regulation and full-day efficiency.

Voltage Regulation of a Transformer I

Voltage regulation determines how well a transformer maintains constant secondary voltage under varying load conditions.

Key Points:

- Defined as the arithmetic difference in secondary terminal voltage between no-load and full-load, expressed as a fraction or percentage of full-load voltage.
- Formula:
- A lower voltage regulation indicates better performance. An ideal transformer has 0
- Lagging power factor loads cause positive regulation (voltage drop), while leading power factor loads can cause negative regulation (voltage rise).
- Can be computed using equivalent circuit parameters referred to secondary:

Transformer Efficiency and Losses I

Efficiency is the ratio of output power to input power. In a static transformer, the only losses are core and copper losses.

Key Points:

- Core Losses (Iron Losses): Consist of hysteresis and eddy current losses. These remain constant regardless of the load because the mutual flux is practically constant.
- Copper Losses (I^2*R Losses): Variable losses occurring in primary and secondary windings, directly proportional to the square of the load current.
- Formula: Efficiency () = Output Power / (Output Power + Core Loss + Copper Loss).
- Maximum efficiency occurs at a specific fractional load where constant losses (Core Loss) exactly equal variable losses (Copper Loss).

- Commercial efficiency is calculated for a particular load and power factor, typically defined at full load or half load.

Direct Load Test I

The direct load test involves physically connecting a variable load to the transformer's secondary to measure performance.

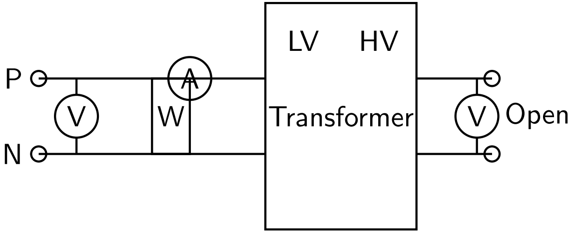
Key Points:

- Primary is connected to rated voltage and frequency, while secondary is connected to a variable load (resistive, inductive, or capacitive).
- Meters (Voltmeter, Ammeter, Wattmeter) are placed on both sides to measure input and output power accurately.
- Efficiency = (W_out / W_in) * 100. Voltage regulation is calculated directly from secondary voltmeter readings at no-load and full-load.
- Pros: Gives exact performance characteristics under actual load conditions, including the true temperature rise of the transformer.

Direct Load Test II

- Cons: Highly impractical for large power transformers due to massive power consumption and difficulty in safely dissipating the heat generated by the load.

Open Circuit (O.C.) Test I



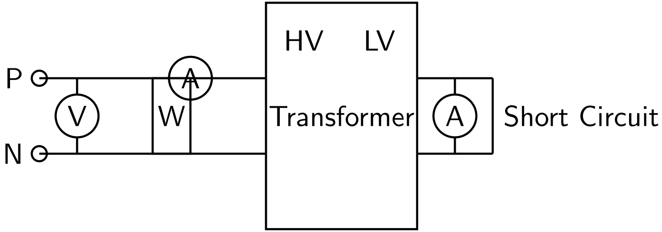
Key Points:

- Purpose: To determine the constant no-load losses (Core losses) and the parameters of the exciting branch (R0 and X0).
- Conducted on the Low Voltage (LV) side with the High Voltage (HV) side kept completely open to minimize hazardous voltages.

Open Circuit (O.C.) Test II

- Rated voltage and frequency are applied to the LV side. Since no-load current I0 is very small (2-5
- Wattmeter reading (W0) represents the total core loss (Pc). Voltmeter (V0) and Ammeter (I0) readings give no-load power factor: cos(ϕ0) = W0 / (V0 * I0).
- Working current Iw = I0 * cos(ϕ0) allows calculating R0 = V0 / Iw. Magnetizing current I = I0 * sin(ϕ0) allows calculating X0 = V0 / I.

Short Circuit (S.C.) Test I



Key Points:

- Purpose: To determine the full-load copper losses and the equivalent series parameters (Req and Xeq) referred to the primary.
- Conducted on the High Voltage (HV) side with the Low Voltage (LV) side securely short-circuited via a thick solid wire.
- A reduced voltage (usually 5-10

Short Circuit (S.C.) Test II

- Core losses are virtually zero due to the very low applied voltage and consequently negligible mutual core flux.
- Wattmeter reading (Wsc) represents full-load copper losses. Series Impedance Zeq = Vsc / Isc, and Equivalent Resistance Req = Wsc / (Isc^2).

Polarity Test I

A polarity test determines the relative instantaneous polarities of the primary and secondary terminals of the transformer.

Key Points:

- Crucial verification required before attempting parallel operation of single-phase transformers or making 3-phase bank connections (Star/Delta).
- Procedure: Connect one adjacent terminal of the primary and secondary together. Apply a small AC voltage (V1) to the primary winding.
- Measure the voltage (V3) across the remaining two open terminals using a high-impedance AC voltmeter.
- Additive Polarity: If $V3 = V1 + V2$ (where V2 is secondary induced voltage). The connected terminals have opposite instantaneous polarities.

Polarity Test II

- Subtractive Polarity: If V3 = V1 - V2. The connected terminals have the same instantaneous polarity. This is standard in modern manufacturing to reduce voltage stress.

All-Day Efficiency I

Also known as Energy Efficiency, it measures the energy performance of a transformer over a standard 24-hour cycle.

Key Points:

- Critical metric for distribution transformers which remain continuously energized (incurring core loss 24/7) but are loaded intermittently by consumers.
- Defined as the ratio of total energy output (in kWh) to the total energy input (in kWh) over an entire 24-hour period.
- Distribution transformers are specifically designed to have maximum efficiency at a low fraction of full load (e.g., 50-70
- Formula: All-Day Efficiency = (Total Output kWh in 24 hrs) / (Total Output kWh + 24*Pc + Total Pcu over 24 hrs).
- A transformer may boast high commercial (power) efficiency at full load, but possess poor all-day efficiency if its constant core losses are relatively high.

Numerical Example I

Calculating maximum efficiency point and voltage regulation using indirect OC and SC test data.

Key Points:

- Given: A 10 kVA, 2300/230V transformer. OC test (LV side): 230V, 1.2A, 50W. SC test (HV side): 50V, 4.34A, 100W.
- From OC Test: Core Loss Pc = 50W. (Since rated voltage was applied, this represents normal operational core loss).
- From SC Test: Full load copper loss Pcu = 100W at rated HV current Isc = 10000VA / 2300V = 4.34A.
- Max Efficiency Load Point: Fractional load x = (Pc / Pcu) = (50/100) = 0.707. Therefore, max efficiency occurs at 7.07 kVA.
- For Voltage Regulation at 0.8 PF lagging: Req = 100 / $(4.34)^2 = 5.3\Omega$, Zeq = 50 / 4.34 = 11.52Ω, yielding Xeq = $(11.52^2 - 5.3^2) = 10.2\Omega$.

Applications and Summary I

Understanding transformer testing and precise performance metrics is fundamentally vital for power system design and operation.

Key Points:

- OC and SC tests are standardized 'indirect' tests that allow full characterization of massive grid transformers without requiring MVA-level load banks.
- Voltage regulation dictates load-serving stability; excessive voltage drop across the transformer can cause undervoltage issues for downstream consumers.
- Efficiency dictates long-term operating costs. Minimizing core losses is strictly prioritized for distribution networks, while power transformers balance both loss types.
- Polarity tests are an absolute safety mandate before connecting any two transformers in parallel to prevent catastrophic dead short circuits.

Applications and Summary II

- Mastering these concepts allows engineers to appropriately specify the exact transformer design requirements based on grid integration needs.

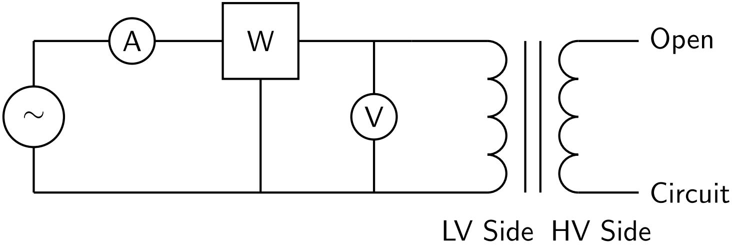
Voltage Regulation of a Transformer I

Voltage regulation is defined as the change in secondary terminal voltage from no load to full load, expressed as a percentage of the no-load or full-load voltage.

Key Points:

- Formula:
- V2_noload = E2, which is the induced EMF in the secondary winding.
- Voltage drop is caused by the internal impedance (R_eq + jX_eq) of the transformer.
- For a lagging power factor (inductive load), voltage regulation is typically positive.
- For a leading power factor (capacitive load), voltage regulation can be negative (terminal voltage rises).
- Approximate formula:

Open Circuit (O.C.) Test - Circuit Diagram I



Key Points:

- Instruments (Ammeter, Voltmeter, Wattmeter) are connected on the Low Voltage (LV) side.
- The High Voltage (HV) side is left open-circuited.
- Rated voltage at rated frequency is applied to the LV side.

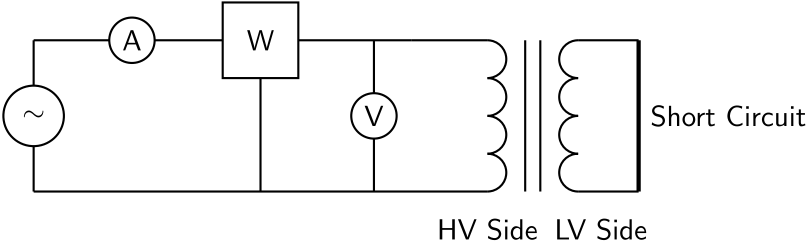
Open Circuit (O.C.) Test - Analysis I

The primary purpose of the O.C. test is to determine the no-load losses (core or iron losses) and the no-load branch parameters of the equivalent circuit.

Key Points:

- Since the secondary is open (I2 = 0), the primary draws only the no-load current (I0), which is typically 2-5
- Copper loss during this test is negligible ($I0^2$ * R1 is very small).
- The wattmeter reading primarily indicates the core losses (Hysteresis and Eddy current losses), denoted as Pi.
- Core Loss Pi = V1 * I0 * cos(phi_0), allowing calculation of the no-load power factor cos(phi_0).
- Magnetizing current Im = I0 * sin(phi_0) and Core-loss component Ic = I0 * cos(phi_0).
- Shunt branch parameters: R0 = V1 / Ic and X0 = V1 / Im.

Short Circuit (S.C.) Test - Circuit Diagram I



Key Points:

- Instruments are connected on the High Voltage (HV) side.
- The Low Voltage (LV) side is short-circuited using a thick conductor.
- A reduced voltage (5-10

Short Circuit (S.C.) Test - Analysis I

The S.C. test is conducted to determine the full-load copper losses and the equivalent series resistance and reactance of the transformer.

Key Points:

- The applied voltage (Vsc) is very small to force rated current; hence, core flux is very low and core losses are negligible.
- The wattmeter reading gives the full-load copper losses (Pc) since rated current flows through the windings.
- Pc = Isc^2 * Req, where Req is the equivalent resistance referred to the measuring side (usually HV).
- Equivalent Impedance Zeq = Vsc / Isc.
- Equivalent Reactance Xeq = sqrt(Zeq^2 - Req^2).
- These parameters are crucial for calculating voltage regulation at any load and power factor.

Transformer Efficiency I

Commercial efficiency of a transformer is the ratio of output power to input power, usually calculated at a specific load and power factor.

Key Points:

- Efficiency (eta) = Output Power / (Output Power + Total Losses).
- Total Losses = Core Loss (Pi) + Copper Loss (Pc).
- Core loss Pi is constant at all loads, whereas copper loss varies with the square of the load current (Pc = x^2 * Pcfull_load, where x is fraction of full load).
- Efficiency (eta) = (x * V2 * I2_fl * cos(phi)) / (x * V2 * I2_fl * cos(phi) + Pi + x^2 * Pcfull_load).
- Condition for Maximum Efficiency: Copper Loss = Core Loss (x^2 * Pcfull_load = Pi).

Transformer Efficiency II

- The load at which maximum efficiency occurs: x = sqrt(Pi / Pcfull_load).

All-Day Efficiency I

All-day efficiency (or energy efficiency) is calculated based on the energy consumed and delivered over a 24-hour period, critical for distribution transformers.

Key Points:

- All-day Efficiency = Output Energy in kWh in 24 hours / Input Energy in kWh in 24 hours.
- Distribution transformers have primary energized 24 hours a day, so core losses occur continuously throughout the day.
- They do not supply full load all day; the load varies significantly.
- To maximize all-day efficiency, distribution transformers are designed to have very low core losses.
- Their maximum efficiency is designed to occur at a fraction of full load (e.g., 50-70

Polarity Test of Transformers I

The polarity test determines the relative instantaneous voltage directions in primary and secondary windings, vital for paralleling transformers.

Key Points:

- When paralleling single-phase transformers or banking 1-phase units into 3-phase, identical polarity is mandatory to avoid catastrophic short circuits.
- Connect one primary terminal to one secondary terminal, apply voltage to the primary, and measure voltage across the remaining two open terminals.
- Additive Polarity: The measured voltage (V3) is the sum of primary (V1) and secondary (V2) voltages (V3 = V1 + V2).
- Subtractive Polarity: The measured voltage is the difference (V3 = V1 - V2).

Polarity Test of Transformers II

- Subtractive polarity is standard in modern power transformers to reduce voltage stress between adjacent external terminals.

Direct Load Test & Applications I

Direct load testing involves physically loading the transformer and measuring input/output directly, while O.C. and S.C. tests are indirect methods.

Key Points:

- Direct Load Test: Connect rated voltage to primary and apply physical electrical loads to the secondary. Measure input and output power.
- Impractical for large transformers due to immense power consumption and difficulty in dissipating massive amounts of heat.
- Hence, O.C. and S.C. indirect tests are predominantly used as they consume power equal only to the internal losses.
- Applications of parameters: Used to build phasor diagrams, predict voltage drops in distribution networks, and size protection relays.

Direct Load Test & Applications II

- Numerical problem approach: Convert all parameters to a common base (HV or LV), calculate Req and Xeq from S.C. test, and use the regulation formula.

Introduction to Auto Transformers I

An auto transformer is a type of electrical transformer with only one winding.

Key Points:

- Unlike a conventional two-winding transformer, the primary and secondary share a common winding.
- The primary and secondary are both electrically and magnetically coupled.
- It provides voltage regulation in applications where electrical isolation is not strictly required.
- Can be used as a step-up or step-down transformer depending on the tapping.

Construction of Single Phase Auto Transformer I

Constructed with a continuous winding on a laminated magnetic core.

Key Points:

- A single continuous winding is wound on a laminated silicon steel core to minimize eddy current and hysteresis losses.
- One portion of the winding acts as the primary, and the other as the secondary.
- Multiple tapings may be provided along the winding to obtain variable output voltages.
- Core construction is generally similar to standard transformers, often using core-type or shell-type geometries.

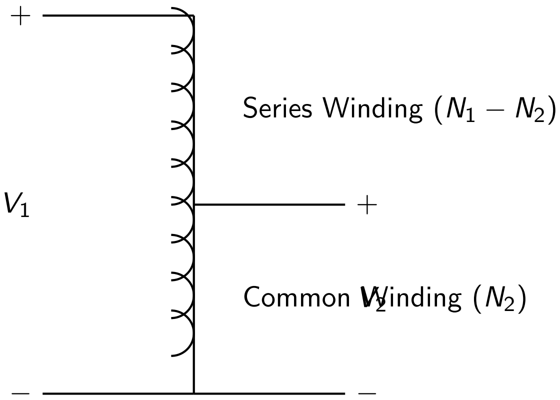
Working Principle I

Operates on the principle of Faraday's laws of electromagnetic induction.

Key Points:

- When an AC voltage is applied to the primary, it sets up an alternating magnetic flux in the core.
- This flux links with the entire winding, inducing an EMF (self-induction in the common part, mutual induction in the rest).
- The secondary voltage is obtained by tapping a specific portion of the continuous winding.
- Power is transferred from primary to secondary both conductively (directly through the wire) and inductively (via the magnetic core).

Circuit Diagram (Step-Down Auto Transformer) I



Key Points:

- The diagram illustrates a step-down auto transformer configuration.

Circuit Diagram (Step-Down Auto Transformer) II

- The entire winding has N1 turns across which the primary voltage V1 is applied.
- The common winding has N2 turns across which the secondary voltage V2 is obtained.
- The current in the common winding is the phasor difference between secondary and primary currents $(I_2 - I_1)$.

Voltage and Current Relations I

Analyzing the step-down configuration with V1 ¿ V2 and N1 ¿ N2.
Key Points:

- The transformation ratio (K) is defined as $K = V_2/V_1 = N_2/N_1 = I_1/I_2$ (for step-down, $K < 1$).
- Current in the series portion of the winding is I_1.
- Current in the common portion of the winding is $(I_2 - I_1)$.
- Apparent power input $(V_1 I_1)$ equals apparent power output $(V_2 I_2)$ when neglecting losses.

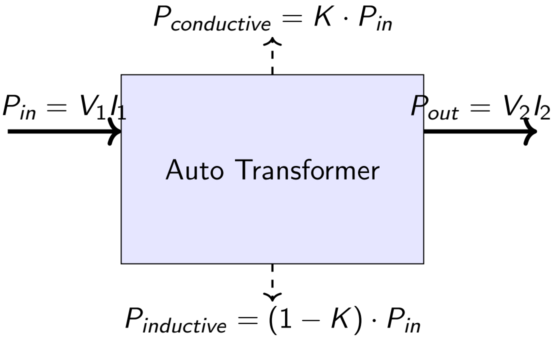
Copper Savings in Auto Transformer I

Significant copper material is saved compared to an equivalent two-winding transformer.

Key Points:

- The weight of copper in a winding is proportional to the product of its current and number of turns.
- Weight of auto transformer = Weight of series section + Weight of common section.
- Ratio of copper weight in auto transformer to two-winding transformer is $(1 - K)$.
- Maximum copper saving occurs when the transformation ratio K is close to 1 (e.g., K = 0.9 yields 90

Power Transfer Modalities I



Key Points:

- Power is transferred via two simultaneous paths: conductively and inductively.

Power Transfer Modalities II

- Conductively transferred power $= K \times$ Input Power. This power is transferred directly without electromagnetic transformation.
- Inductively transferred power (transformed power) $= (1 - K) \times$ Input Power.
- High overall efficiency is achieved because a significant portion of power is transferred conductively.

Advantages and Disadvantages I

Key trade-offs of using auto transformers in electrical systems.
Key Points:

- Advantages: Requires less copper, resulting in lower cost, smaller physical size, and lower weight.
- Advantages: Superior voltage regulation due to lower leakage reactance and lower ohmic losses.
- Disadvantages: Complete lack of electrical isolation between the primary and secondary circuits.
- Disadvantages: Extremely high short-circuit currents due to the low series impedance of the transformer.

Applications I

Common practical uses in electrical engineering and bulk power systems.

Key Points:

- Used as starting compensators to reduce the inrush current for induction motors and synchronous motors.
- Employed in railway electric traction systems to regulate voltage drop across long transmission lines.
- Used as continuously variable voltage sources (commonly known as Variacs) in electrical laboratories.
- Used for interconnecting high voltage power systems with similar voltage levels (e.g., 220kV and 132kV networks).

Introduction to Autotransformers I

An overview of the single-winding transformer topology.

Key Points:

- An autotransformer is an electrical transformer with only one continuous winding wound on a laminated magnetic core.
- Unlike standard two-winding transformers, the primary and secondary circuits share common turns and are not electrically isolated.
- Power is transferred from primary to secondary through both conductive (direct electrical connection) and inductive (magnetic coupling) action.
- It provides a mechanism to obtain a variable or fixed alternating voltage from a constant voltage AC supply efficiently.

Constructional Features I

Physical design and core characteristics.

Key Points:

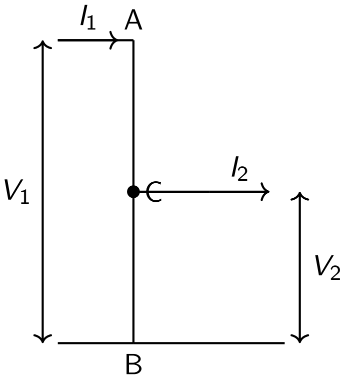
- The device is constructed using a single continuous winding of high-conductivity copper wire.
- The winding is mounted on a closed magnetic circuit made of silicon steel laminations to minimize eddy current and hysteresis losses.
- A portion of the single winding acts as part of both the primary and secondary circuits, referred to as the common winding.
- Fixed or sliding tapings (using carbon brushes) are provided along the winding to achieve specific voltage transformation ratios.

Principle of Operation I

Electromagnetic induction in a shared winding.

Key Points:

- The operation is governed by Faraday's laws of electromagnetic induction.
- Applying an alternating voltage to the primary terminals sets up a constantly changing alternating flux in the magnetic core.
- This main flux links with the entire winding, inducing an electromotive force (EMF) strictly proportional to the number of turns.
- The secondary voltage is tapped across a subset of the total turns, outputting a stepped-down or stepped-up voltage.



Key Points:

- In step-down mode, the entire winding AB acts as the primary winding with N1 turns.

Autotransformer as Step-Down Transformer II

- The tapped lower section CB acts as the secondary winding with N2 turns, satisfying N2 ¡ N1.
- The common portion of the winding (CB) carries the difference between secondary and primary currents (I2 - I1) acting in phase opposition.
- Source primary voltage V1 is applied across AB, while the secondary load voltage V2 is derived across terminals C and B.

Voltage and Current Relations I

Mathematical derivations of transformation ratios.

Key Points:

- The transformation ratio (K) is defined as K = V2 / V1 = N2 / N1, similar to a two-winding transformer.
- Assuming an ideal transformer with zero losses, input apparent power equals output apparent power: V1 * I1 = V2 * I2.
- The current ratio is inversely proportional to the voltage ratio: I1 / I2 = V2 / V1 = K.
- For a step-down unit, the current in the shared winding section is (I2 - I1), which reduces I^2R losses significantly when K is close to 1.

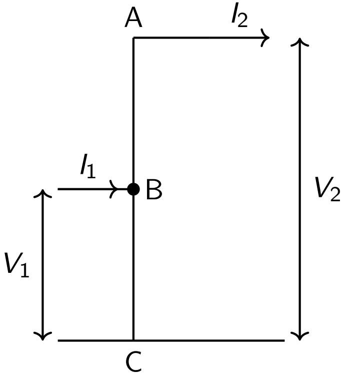
Copper Savings in Autotransformer I

Economic advantages due to reduced material volume.

Key Points:

- The volume and weight of copper wire required are directly proportional to the product of turns and current (ampere-turns).
- Weight of copper in an autotransformer (Wa) relates to primary (N1-N2)I1 plus common winding N2(I2-I1).
- Compared to a two-winding transformer (Wtw), the ratio of copper weights is Wa / Wtw = 1 - K.
- The actual saving in copper mass is K * Wtw. This economic advantage is highest when the transformation ratio K approaches unity.

Autotransformer as Step-Up Transformer I



Key Points:

- In step-up mode, the tapped section BC acts as the primary winding fed with voltage V1, consisting of N1 turns.

Autotransformer as Step-Up Transformer II

- The entire winding AC acts as the secondary winding supplying the load, consisting of N2 turns (N2 ¿ N1).
- The common portion BC carries the phasor difference of primary and secondary currents (I1 - I2).
- Source voltage V1 is applied across the lower section, and the stepped-up output voltage V2 is supplied across the full length AC.

Advantages and Disadvantages I

Operational tradeoffs compared to isolated transformers.

Key Points:

- Advantages: Considerably lower capital cost, improved voltage regulation, smaller footprint, and higher efficiency at equal VA ratings.
- Lower leakage reactance and reduced excitation current due to decreased core material.
- Disadvantages: Complete loss of electrical isolation between the primary high-voltage and secondary low-voltage networks.
- Severe safety hazard: An open-circuit failure in the common winding portion (C-B) forces the full primary voltage V1 directly across the secondary load.

Engineering Applications I

Common use cases in modern electrical engineering.

Key Points:

- Laboratory Testing: Used as continuously variable voltage sources (Variacs) for experimental setups and motor testing.
- Power System Interconnection: Highly economical for interconnecting transmission grids with close voltage levels (e.g., 220kV to 400kV lines).
- Motor Starting: Employed as starting compensators to safely provide reduced starting voltages to large squirrel-cage induction and synchronous motors.
- Distribution Feeder Compensation: Installed as booster transformers along lengthy AC radial feeders to compensate for accumulated voltage drops.

Why Three-Phase Transformers? I

A three-phase system is universally adopted for generation, transmission, and distribution of electrical power due to its economic and operational advantages over single-phase systems.

Key Points:

- Three-phase equipment is smaller and lighter than single-phase equipment of the same kVA rating.
- Three-phase transmission requires less conductor material for a given power and voltage level compared to single-phase.
- Provides a constant power output to loads, reducing vibration in rotating machinery.
- Three-phase transformers are essential for stepping up voltage for transmission and stepping it down for distribution.

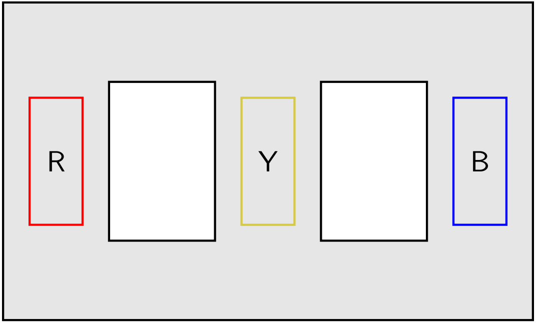
Approaches to Three-Phase Transformation I

Three-phase transformation can be achieved using two distinct methods, each with its own advantages and disadvantages.

Key Points:

- Bank of Three Single-Phase Transformers: Three individual single-phase transformers are interconnected to form a three-phase bank.
- Single Three-Phase Transformer: A single core structure is designed to accommodate the windings of all three phases.
- A single three-phase transformer occupies less space and is lighter and cheaper than a bank of three single-phase transformers.
- However, a bank of single-phase transformers offers higher reliability because if one unit fails, the system can often operate in an open-delta configuration at reduced capacity.

Construction of a Single Three-Phase Transformer I



Three-Phase Core Type Transformer Structure

Key Points:

- Core-Type Construction: The magnetic circuit consists of three vertical limbs or legs and two horizontal yokes.

Construction of a Single Three-Phase Transformer II

- The primary and secondary windings of each phase are concentrically placed on one of the limbs.
- Shell-Type Construction: The magnetic circuit has five limbs. The windings are placed on the three central limbs.
- Core-type is generally preferred due to simplicity in construction, lower weight, and better cooling for high-voltage applications.

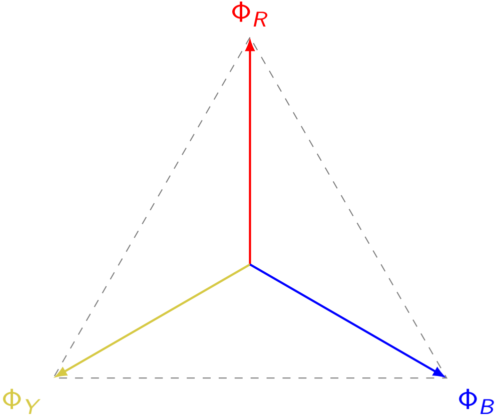
Working Principle: Electromagnetic Induction I

The basic working principle of a three-phase transformer is identical to that of a single-phase transformer: Faraday's Law of Electromagnetic Induction.

Key Points:

- When the three primary windings are connected to a three-phase AC supply, they draw alternating currents.
- These alternating currents set up alternating magnetic fluxes in the core.
- Due to the 120-degree phase shift in the three-phase supply, the fluxes produced in the three limbs are also 120 degrees out of phase with each other.
- The alternating flux links with both primary and secondary windings, inducing EMFs in them according to Faraday's law.

Flux Phasors in a Three-Phase Core I



$$\Phi_R + \Phi_Y + \Phi_B = 0$$

Key Points:

Flux Phasors in a Three-Phase Core II

- In a perfectly balanced three-phase system, the sum of instantaneous currents is zero: i_R + i_Y + i_B = 0.
- Consequently, assuming linear magnetic characteristics, the sum of instantaneous fluxes in the three limbs is zero: $\Phi_R + \Phi_Y + \Phi_B = 0$.
- This implies that at any instant, the flux in any one limb is equal and opposite to the sum of the fluxes in the other two limbs.
- The central return leg required in three single-phase transformers can therefore be eliminated in a balanced core-type construction.

Induced EMF Equations I

The RMS value of the induced electromotive force (EMF) per phase can be calculated using the standard transformer EMF equation.

Key Points:

- Let $\Phi_m bethemaximumfluxinWeberineachlimb.$
- Let f be the supply frequency in Hertz.
- Let N_1 and N_2 be the number of turns per phase in the primary and secondary windings, respectively.
- Induced EMF per phase in primary: $E_1 = 4.44 * f * \Phi_m * N_1$.
- Induced EMF per phase in secondary: $E_2 = 4.44 * f * \Phi_m * N_2$.
- The voltage ratio per phase is E_1/E_2 = N_1/N_2 = a (turns ratio).

Winding Connections: Star and Delta I

The three primary and three secondary windings can be connected in either Star (Y) or Delta (Δ) configurations, leading to different line and phase voltage relationships.

Key Points:

- Star (Y) Connection: One end of each of the three windings are connected together to form a neutral point. Line voltage = 3 * Phase voltage.
- Delta (Δ) Connection: The three windings are connected in series to form a closed mesh. Line voltage = Phase voltage.
- Common configurations include Star-Star (Y-Y), Delta-Delta (Δ-Δ), Star-Delta (Y-Δ), and Delta-Star (Δ-Y).
- The choice of connection depends on factors like required voltage level, availability of neutral, and harmonic suppression.

Single Unit vs. Bank of 3 Single-Phase Transformers I

While both approaches serve the same purpose, the choice between a single three-phase unit and a bank of three single-phase units involves trade-offs.

Key Points:

- Advantages of Single Unit: Occupies less space, 15-20
- Disadvantages of Single Unit: If one phase fails, the entire transformer must be removed from service for repair.
- Advantages of a Bank: High reliability. If one unit fails in a Δ-Δ bank, the remaining two can operate in open-delta (V-V) connection supplying 57.7
- A bank allows for easier transport of individual units to remote locations with weight restrictions.

Summary and Industrial Applications I

Three-phase transformers form the backbone of modern AC electrical grids and industrial power systems.

Key Points:

- Working principle relies on Faraday's law of induction driven by a 120-degree phase-shifted magnetic flux system.
- Core-type structure efficiently utilizes the property that the sum of fluxes is zero in a balanced three-phase system.
- Step-up transformers at generating stations are typically Delta-Star (Δ-Y) to provide high transmission voltages and a solidly grounded neutral.
- Step-down distribution transformers are usually Star-Delta or Delta-Star, serving various industrial loads and commercial networks.

Introduction to Three Phase Systems I

Three-phase power is the predominant method of electrical power generation, transmission, and distribution.

Key Points:

- Three-phase systems offer higher power density and better conductor utilization compared to single-phase systems.
- A three-phase transformer can be constructed as a single unit (core-type or shell-type) or by banking three individual single-phase transformers.
- Using a single three-phase unit is generally more cost-effective, lighter, and requires less floor space than a bank of three single-phase transformers of the same total rating.
- However, a bank of three single-phase units offers better reliability and easier maintenance, as a single failure only requires replacing one unit.

Construction: Core Type vs Shell Type I

Three-phase transformers are primarily built in two physical configurations: core-type and shell-type.

Key Points:

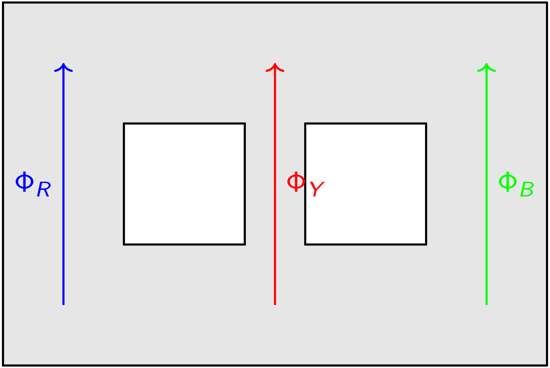
- Core-Type: The windings surround a considerable part of the core. It typically consists of three limbs (legs), with primary and secondary windings placed concentrically on each limb.
- Shell-Type: The core surrounds a considerable portion of the windings. It provides a shorter magnetic path and offers better mechanical protection for the coils.
- In the core-type, the magnetic fluxes of the three phases share the horizontal yokes.
- Shell-type transformers are often preferred for extra-high voltage (EHV) applications due to superior insulation grading capabilities and mechanical robustness against short-circuit forces.

Fundamental Working Principle I

The working principle of a three-phase transformer relies on Faraday's Law of Electromagnetic Induction.

Key Points:

- An alternating voltage applied to the primary winding creates an alternating magnetic flux in the core.
- This alternating flux links with the secondary winding, inducing an electromotive force (EMF) proportional to the rate of change of flux and the number of secondary turns.
- The fundamental relationship is given by the EMF equation: E $= 4.44$ * f * N * $\Phi\_m, *wherefisfrequency*, Nisnumberofturns, and\Phi\_misthepeakmag$
- In a three-phase transformer, this induction process occurs simultaneously across all three phases, driven by excitation currents with a 120-degree electrical phase shift between them.



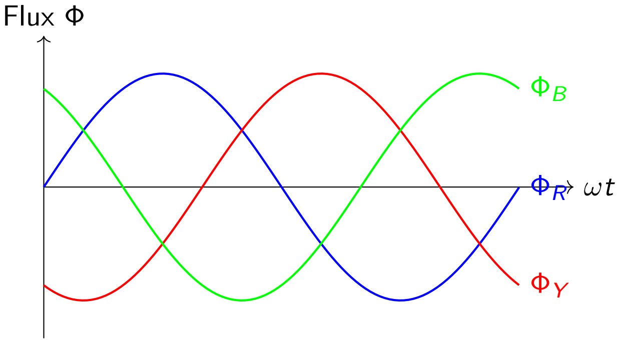
Sum of fluxes $\Phi_R + \Phi_Y + \Phi_B = 0$ at the yokes

Key Points:

Magnetic Flux Distribution in Three-Limb Core II

- In a symmetrical three-limb core, the magnetic fluxes Φ_R, Φ_Y, and Φ_B are established by the respective primary phase currents.
- Under balanced sinusoidal excitation, the phasor sum of the three fluxes is zero at any given instant: $\Phi_R + \Phi_Y + \Phi_B = 0$.
- Because of this property, a central return leg is not strictly required for the fundamental flux, saving material and reducing overall weight.
- During severe unbalanced loads or non-linear operation, zero-sequence fluxes may be forced to return through the transformer tank, potentially causing localized heating.

Time Variation of Phase Fluxes I



Key Points:

- The primary windings are excited by a balanced three-phase voltage source, leading to three-phase exciting currents.

Time Variation of Phase Fluxes II

- These currents produce alternating magnetic fluxes that are displaced from each other by 120 degrees $(2\pi/3 radians) in time phase$.
- The instantaneous value of the total flux at the top or bottom yoke of a three-limb core is the algebraic sum of the instantaneous fluxes in the three individual limbs.
- This continuous, smoothly varying phase sequence is what facilitates the transformation of three-phase power seamlessly across the magnetic core.

Three-Phase Transformer Connections I

The primary and secondary windings can be connected independently in either Star (Y) or Delta (Δ) configurations.

Key Points:

- Star-Star (Y-Y): Economical for high voltage, low current applications due to reduced phase voltage ($V_{line}/\sqrt{3}$). Can suffer from third-harmonic voltage distortion if the neutral is not grounded.
- Delta-Delta (Δ-Δ): Suitable for low voltage, high current applications. Continues to operate in V-V (open delta) capacity if one phase fails, providing 58
- Star-Delta (Y-Δ): Commonly used at the receiving end of a transmission line to step down voltage safely.
- Delta-Star (Δ-Y): Primarily used for step-up transformers at generating stations, and for distribution transformers to provide a neutral line for single-phase loads.

Induced EMF and Voltage Ratios I

The line-to-line voltage ratio of the transformer depends on both the turns ratio of the individual windings and the chosen connection scheme.

Key Points:

- Let N_1/N_2 represent the primary to secondary phase turns ratio.
- For Y-Y and Δ-Δ connections, the line voltage ratio is equal to the phase voltage ratio, which is approximately the turns ratio: $V_{L1}/V_{L2} \approx N_1/N_2$.
- For a Y-Δ connection, the line voltage ratio is $\sqrt{3} * (N_1/N_2)$. The star connection on the primary effectively increases the primary voltage capability.
- For a Δ-Y connection, the line voltage ratio is $(1/\sqrt{3}) * (N_1/N_2)$. The secondary star configuration provides a higher line voltage output relative to the phase voltage.

Advantages of a Single 3-Phase Unit I

Employing a single three-phase transformer provides several mechanical and economic benefits over a bank of three independent single-phase transformers.

Key Points:

- Reduced Core Material: Because the magnetic paths are shared and the sum of balanced fluxes is zero, less iron is required for the core, reducing overall weight.
- Lower Cost: A single unit requires less material for the outer tank, insulating oil, and high-voltage bushings, making it roughly 15-20
- Higher Efficiency: Due to the reduction in core material, the core losses (both hysteresis and eddy current) are comparatively lower, leading to slightly higher overall efficiency.

Advantages of a Single 3-Phase Unit II

- Space Constraints: A single three-phase unit is substantially more compact, occupying less physical footprint in a crowded substation environment.

Summary and Conclusion I

The three-phase transformer is a vital, ubiquitous component in modern alternating current power grids.

Key Points:

- It successfully transforms voltage and current levels of a three-phase system while maintaining the exact same frequency and 120-degree relative phase displacement.
- The transformer core acts as a shared magnetic circuit where the phase shift of the excitation currents naturally balances the magnetic flux across the limbs.
- The engineering choice of core construction (core or shell type) and specific winding connection (Y or Δ) dictates its suitability for applications ranging from generation to distribution.
- Understanding fundamental flux interactions, vector groups, and voltage transformations is essential for analyzing power flow and system stability.

Introduction to Three-Phase Transformers I

A three-phase transformer provides a solution for stepping up or stepping down the voltage of a three-phase power system, forming the backbone of modern AC grids.

Key Points:

- Three-phase systems are universally used for power generation, transmission, and heavy industrial distribution.
- Voltage transformation can be achieved using a single three-phase transformer unit or a combined bank of three distinct single-phase transformers.
- The selection between a single unit and a bank depends on factors like overall cost, required reliability, geographical footprint, and logistical transportation constraints.

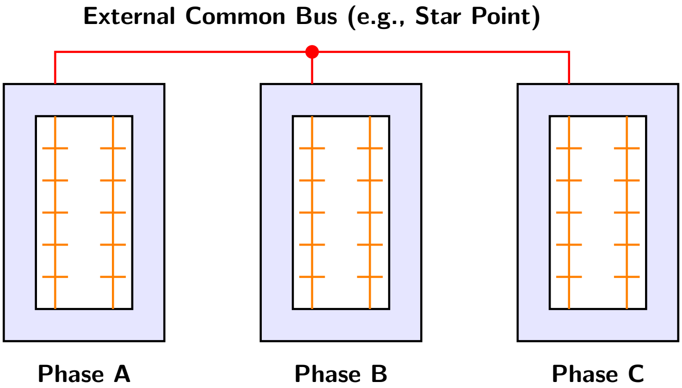
Bank of Three Single-Phase Transformers I

A transformer bank consists of three identical single-phase transformers interconnected externally to handle three-phase power (e.g., Star-Delta, Delta-Delta).

Key Points:

- Provides extreme high reliability: If one transformer fails in a Delta-Delta connection, the remaining two can operate in an open-delta (V-V) configuration, continuously providing 57.7
- Transportation is simplified since individual single-phase units are significantly smaller and lighter than an equivalent single three-phase unit.
- Disadvantages include a requirement for more physical floor space, higher total initial cost, and a highly complex external high-voltage wiring and busbar system.

Schematic Diagram: Bank of Three Single-Phase Transformers I



Key Points:

Schematic Diagram: Bank of Three Single-Phase Transformers II

- Diagram shows three independent single-phase units forming a three-phase bank.
- Individual magnetic circuits are completely decoupled; there is no magnetic interference between phases.
- External connections determine the final vector group and phase shift of the entire bank.

Single Unit Three-Phase Transformer I

A single three-phase transformer consolidates the three phases into a single, unified magnetic core and tank assembly.

Key Points:

- Highly economical to manufacture: It requires approximately 15
- Higher operational efficiency: Due to the reduced volume of core material, the no-load core losses (hysteresis and eddy current losses) are strictly lower.
- It occupies considerably less floor space and is mechanically easier to install, but its massive bulk weight makes transport to remote substations difficult.
- Major drawback: A winding failure in any one phase entirely disables the whole transformer unit, demanding immediate complete replacement or lengthy factory repair.

Construction Topologies: Core-Type vs. Shell-Type I

Single unit three-phase transformers are predominantly constructed in two magnetic and structural topologies: Core-Type and Shell-Type.

Key Points:

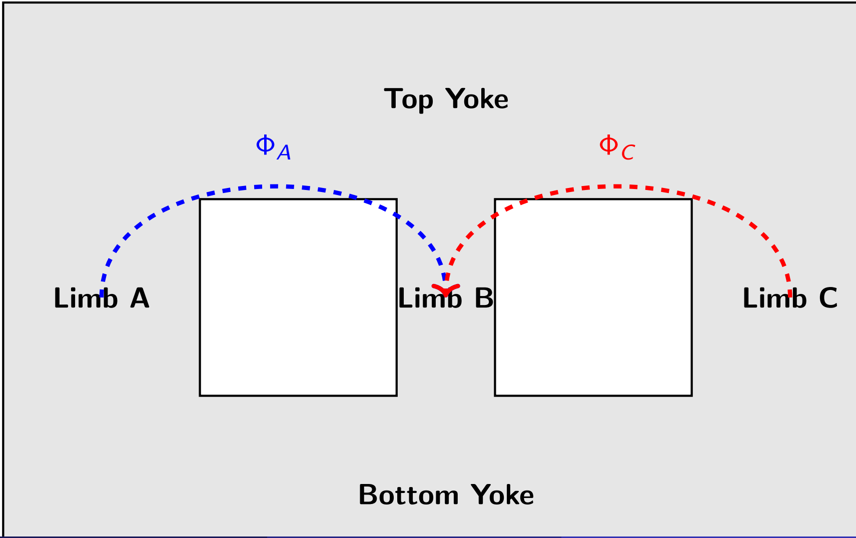
- Core-Type Construction: The magnetic core consists of three vertical limbs connected by top and bottom horizontal yokes. Primary and secondary windings coaxially surround the core limbs.
- In Core-Type, the algebraic sum of the fluxes in the three limbs is naturally zero under balanced load conditions ($\Phi_A + \Phi_B + \Phi_C = 0$), serving as a return path for each other.
- Shell-Type Construction: The iron core physically surrounds and encapsulates the windings, inherently providing multiple parallel return paths for the magnetic flux.

Construction Topologies: Core-Type vs. Shell-Type II

- Shell-type offers vastly superior mechanical bracing against extreme electromechanical short-circuit forces but requires more intricate manual manufacturing processes.

Magnetic Circuit Diagram: Core-Type Three-Phase Transformer I

Magnetic Circuit Diagram: Core-Type Three-Phase Transformer II



Cooling Methods: Thermal Management Fundamentals I

I^2R copper losses and iron core losses constantly generate internal heat, which must be efficiently dissipated to prevent rapid insulation degradation and dielectric failure.

Key Points:

- The absolute life expectancy of a transformer exponentially depends on the operating temperature of its solid cellulose paper insulation (Montsinger's Rule).
- Cooling systems are categorized based strictly on the internal cooling medium (air, mineral oil, ester fluids) and the external circulation technique (natural convection or forced flow).
- Dry-type transformers are primarily cooled by air (common in indoor commercial settings), whereas large utility-scale transformers are completely oil-immersed.

Standard Cooling Classes (ONAN & ONAF) I

Cooling mechanisms adhere to standard IEC 60076 / IEEE nomenclature, strictly specifying the cooling fluid and circulation style.

Key Points:

- AN (Air Natural) / AF (Air Forced): Used universally for dry-type solid cast-resin transformers. AF uses auxiliary fans to boost capacity by up to 33
- ONAN (Oil Natural Air Natural): Thermo-siphon natural convection circulates the heated oil upwards to radiators where ambient air naturally carries away the heat. Standard up to 30 MVA.
- ONAF (Oil Natural Air Forced): Large high-velocity fans are mounted on the exterior radiators to forcefully blow air over the fins, greatly increasing heat dissipation and boosting MVA rating by up to 25-30

Advanced Forced Cooling Methods (OFAF & ODWF) I

For ultra-large transmission power transformers (e.g., ¿100 MVA), natural thermo-siphon oil circulation is thermally insufficient and demands forced mechanical pumping.

Key Points:

- OFAF (Oil Forced Air Forced): Submerged centrifugal pumps rapidly circulate the mineral oil through the internal core and windings, while external fans blast air over massive radiator banks.
- OFWF (Oil Forced Water Forced): Heated oil is pumped directly through a compact tubular heat exchanger where chilled water is simultaneously pumped. Extremely highly efficient, standard in confined hydro-electric generation plants.

Advanced Forced Cooling Methods (OFAF & ODWF) II

- ODWF (Oil Directed Water Forced): The ultimate cooling topology. Oil is not just circulated in the tank but explicitly directed through specific baffled channels inside the winding geometry, eliminating highly localized winding hotspots.

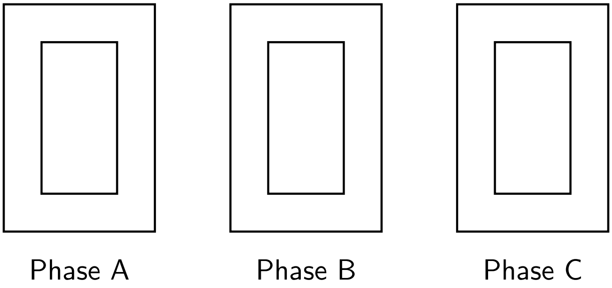
Introduction to Three-Phase Transformers I

Three-phase power is ubiquitous in generation, transmission, and distribution, necessitating three-phase transformation.

Key Points:

- A three-phase transformer can be constructed in two distinct ways.
- Method 1: Connecting three identical single-phase transformers to form a three-phase bank.
- Method 2: Constructing a single three-phase transformer unit with a common magnetic circuit.
- The choice between these two approaches depends on factors like cost, transportation constraints, reliability, and space availability.

Bank of Three Single-Phase Transformers I



Key Points:

- A bank consists of three separate, identical single-phase transformers.
- The primary and secondary windings are connected either in Star (Y) or Delta (Δ).

Bank of Three Single-Phase Transformers II

- The magnetic circuits for each phase are completely independent.
- Each unit handles one-third of the total three-phase apparent power (kVA).

Advantages and Disadvantages of a Transformer Bank I

While taking up more space, a bank of single-phase transformers offers unique operational benefits.

Key Points:

- Advantage: Higher reliability. If one transformer in a delta-delta bank fails, the remaining two can operate in an open-delta (V-V) configuration at 57.7
- Advantage: Easier transportation and installation, as each single-phase unit is smaller and lighter than a single three-phase unit.
- Advantage: Less expensive standby capacity, as only one single-phase transformer needs to be kept as a spare.
- Disadvantage: Requires more installation space, more material overall, and generally has a higher initial cost for the same total kVA rating compared to a single unit.

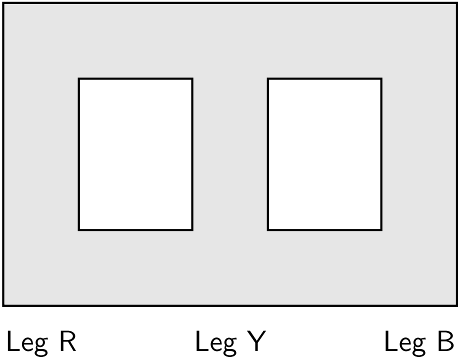
Single Unit Three-Phase Transformer I

A single-unit three-phase transformer combines the magnetic circuits and windings of all three phases into a single physical structure.

Key Points:

- Constructed by placing primary and secondary windings on a common magnetic core.
- Because the sum of the three phase fluxes in a balanced system is zero ($\Phi a + \Phi b + \Phi c = 0$), the central return leg of the core can be eliminated.
- This elimination of the return leg saves core material, making the transformer more compact.
- It is generally cheaper, lighter, and more efficient than a bank of three single-phase transformers of the same total rating.

Core-Type Three-Phase Transformer Construction I



Key Points:

- The core-type three-phase transformer typically uses a three-legged core.

Core-Type Three-Phase Transformer Construction II

- The primary and secondary windings of each phase are concentrically placed on one of the three vertical legs.
- Low voltage (LV) windings are placed adjacent to the core to minimize insulation requirements.
- High voltage (HV) windings are placed outside the LV windings.
- Due to magnetic asymmetry, the magnetizing current for the center phase (Y) is slightly lower than the outer phases (R and B).

Shell-Type Three-Phase Transformer Construction I

The shell-type transformer surrounds the windings with the core material, providing better mechanical protection and bracing.

Key Points:

- Constructed essentially as three independent single-phase shell-type transformers stacked together.
- Provides a separate return path for the flux of each phase.
- The center phase winding is often connected in reverse polarity compared to the outer phases to reduce the flux in the common yoke sections.
- This reversal reduces the required cross-sectional area of the yoke, saving core material.
- Typically used for very high voltage and high power applications where robust mechanical support against short-circuit forces is crucial.

Core Type vs Shell Type Single Unit Transformers I

The choice between core-type and shell-type hinges on voltage rating, mechanical stresses, and maintenance requirements.

Key Points:

- Core-type transformers have a simpler construction and are easier to assemble and dismantle for maintenance.
- Shell-type transformers offer superior mechanical strength to withstand high electro-dynamic forces during short circuits.
- Core-type is generally preferred for high voltage, high power applications, while shell-type is often used for low voltage, high current applications.
- Cooling is more challenging in shell-type transformers because the windings are heavily surrounded by the core.
- Core-type has cylindrical coils which have high mechanical strength under short circuit conditions.

Transformer Cooling Methods: Dry Type I

Cooling is essential to dissipate the heat generated by core losses (iron losses) and copper losses (I^2R losses).

Key Points:

- Dry-type transformers use air as the cooling medium and are typically limited to lower voltage and power ratings (e.g., indoor installations up to 33 kV).
- AN (Air Natural): Relies on natural convection of surrounding ambient air. Used for small distribution transformers.
- AF (Air Forced) or AB (Air Blast): Uses fans or blowers to force air circulation over the core and windings, increasing cooling capacity and allowing a higher rating than AN.
- Dry-type transformers are preferred in locations where fire safety is a critical concern, such as inside residential or commercial buildings, as they contain no flammable oil.

Transformer Cooling Methods: Oil Immersed I

For high power and high voltage transformers, highly refined mineral oil is used for both electrical insulation and heat dissipation.

Key Points:

- ONAN (Oil Natural Air Natural): Relies on natural convection of hot oil to the tank walls and radiators, which are naturally cooled by ambient air. Common up to 30 MVA.
- ONAF (Oil Natural Air Forced): Fans blow air across the radiators while oil circulates naturally. Increases capacity by 25-30
- OFAF (Oil Forced Air Forced): Oil is pumped through the radiators, and fans force air across them. Commonly used for large power transformers.
- OFWF (Oil Forced Water Forced): Oil is pumped through a heat exchanger where cooling water is also pumped. Used in hydro plants where water is abundant.

Transformer Cooling Methods: Oil Immersed II

- The oil serves a dual purpose: it acts as a superior electrical insulator compared to air and is a highly efficient heat transfer medium.

Overview of the Indian Standard Code of Practice for Transformers.

Key Points:

- IS: 10028 is the Indian Standard Code of Practice covering the selection, installation, and maintenance of transformers.
- Part I specifically details the engineering criteria for selecting transformers to ensure safety, reliability, and economic viability.
- The standard applies to power and distribution transformers operating on AC systems with a frequency of 50 Hz.
- It emphasizes the necessity of defining precise technical specifications, including ratings, losses, impedance, and cooling methods, based on intended application and site-specific conditions.

General Site and System Considerations I

Environmental and grid parameters dictating transformer specifications.

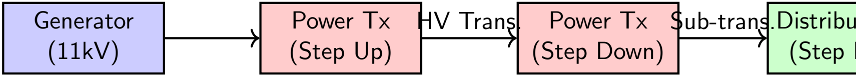
Key Points:

- Altitude: Standard transformers are designed for altitudes up to 1000m. Above 1000m, the cooling efficiency of air decreases, requiring derating of the transformer's continuous capacity or enhanced cooling systems.
- Ambient Temperature: The standard assumes a maximum ambient air temperature of 50°C and a maximum daily average of 40°C. Temperature rise limits for oil and winding must be specified accordingly to prevent accelerated insulation degradation.
- System Fault Level: The anticipated short-circuit MVA at the installation site dictates the mechanical and thermal short-circuit withstand capabilities required by the transformer.

General Site and System Considerations II

- System Variations: Transformers must tolerate standard frequency variations (typically ± 3

Transformer Application in Power Systems I



Key Points:

- Power transformers are utilized at the generating station and transmission substations (step-up and step-down) where voltage levels are very high.
- Distribution transformers are utilized at the distribution network's terminal end to step down voltage to user-utilization levels (e.g., 415V/240V).

Distribution Transformers: Selection Criteria I

Focus on no-load performance and voltage regulation.

Key Points:

- Operating Cycle: Distribution transformers are kept energized 24 hours a day, regardless of whether the consumers are drawing load. Thus, they experience no-load conditions frequently.
- Core Loss Minimization: Because they are continuously energized, core (iron) losses occur constantly. Selection prioritizes designs with extremely low core losses to reduce continuous energy waste.
- Efficiency Optimization: They are engineered to achieve maximum efficiency at approximately 50
- Impedance Constraints: To ensure superior voltage regulation at the consumer end, they are typically designed with low percentage impedance (around 4

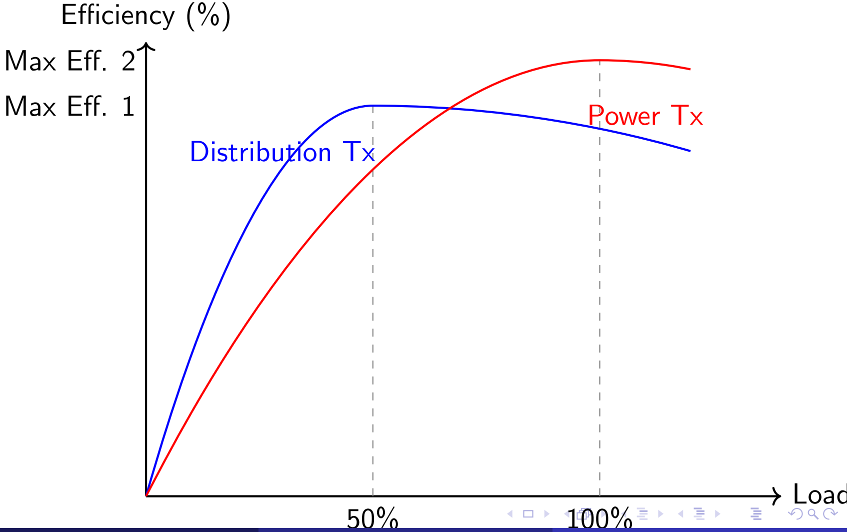
Distribution Transformers: Loading and Sizing I

Capacity planning based on cyclical demand and thermal limits.
Key Points:

- Diversity Factor: Sizing heavily depends on the diversity factor of the connected load (domestic, commercial, or industrial), which determines the actual peak demand versus total connected load.
- Cyclic Loading: IS: 10028 recommends evaluating the cyclic loading capabilities. Short-duration overloads are permissible if the ambient temperature and previous load cycle allow the hot spot temperature to remain within safe limits.
- Spare Capacity: It is standard practice to select a rating such that the continuous operating load is around 70-80

Efficiency Curves: Distribution vs Power Transformers I

Efficiency Curves: Distribution vs Power Transformers II



Focus on full-load performance and fault current limitation.

Key Points:

- Operating Cycle: Power transformers operate near or at full load capacity for the majority of their service time. If load drops, parallel units are often switched off to maintain high loading on active units.
- Copper Loss Minimization: Because they operate near full load, variable I^2R (copper) losses dominate over core losses. Selection prioritizes designs with lower copper losses.
- Efficiency Optimization: Power transformers are designed to achieve maximum efficiency at or very near 100
- Impedance Requirements: They are designed with higher percentage impedance (typically 8

Cooling Methods and Tap Changing Specifications I

Thermal management and voltage regulation mechanisms.

Key Points:

- Cooling Methods: IS: 10028 specifies cooling based on rating. Distribution transformers generally utilize ONAN (Oil Natural Air Natural) cooling due to smaller sizes. Power transformers employ ONAF (Air Forced), OFAF, or ODAF to manage substantial heat dissipation.
- Tap Changers (Distribution): Typically equipped with Off-Circuit Tap Changers (OCTC) with ranges like $+5$
- Tap Changers (Power): Often equipped with On-Load Tap Changers (OLTC) with wider ranges (e.g., $+10$

Economic Evaluation and Capitalization of Losses I

Total Cost of Ownership (TCO) evaluation as per IS recommendations.

Key Points:

- IS 10028 mandates that transformer selection should not be based solely on the lowest initial purchase price. The total lifecycle cost must be evaluated.
- Capitalized Cost of Losses: A mathematical evaluation is performed adding the initial cost to the present value of the cost of no-load (iron) losses and load (copper) losses over the transformer's anticipated lifespan (typically 25-30 years).
- Loss Capitalization Formulae: Utilities assign monetary values (e.g., Rs/kW) to iron and copper losses based on energy generation costs and typical loading cycles to objectively compare bids from different manufacturers.

Economic Evaluation and Capitalization of Losses II

- Conclusion: Proper application of IS: 10028 guidelines ensures the selection of a transformer that balances capital expenditure against long-term operational efficiency, ensuring grid reliability.

Introduction to IS: 10028 (Part I)-1985 I

IS: 10028 Part I provides the code of practice for the selection of power and distribution transformers. It outlines the essential parameters that must be considered to ensure reliability, safety, and economic operation.

Key Points:

- The standard applies to both oil-immersed and dry-type transformers.
- Factors in environmental conditions: ambient temperature, altitude, and humidity.
- Defines service conditions: normal (altitude ¡ 1000m, max ambient 50°C) and abnormal.
- Specifies rating selection based on load cycles and permissible overloads as defined in IS: 6600.

Power vs. Distribution Transformers I

Understanding the fundamental distinction between Power Transformers (PT) and Distribution Transformers (DT) is crucial for correct selection under IS: 10028.

Key Points:

- Power Transformers: Used in transmission networks (¿33 kV), designed for maximum efficiency at or near full load.
- PTs are generally kept in operation only when load is substantial; otherwise switched off to save core losses.
- Distribution Transformers: Step down voltage for consumer use (e.g., 11 kV to 415 V), kept energized 24 hours a day.
- DTs are designed for maximum efficiency at 50-70
- All-day efficiency is the primary performance metric for DTs, while commercial efficiency governs PTs.

Selection Criteria: Rating and Load Sizing I

The kVA rating of a transformer must be selected based on the maximum demand, diversity factor, and expected future load growth as per IS guidelines.

Key Points:

- Calculate maximum demand utilizing load curves and applying appropriate diversity factors.
- For distribution networks, future load growth over 10-15 years is typically factored into the initial capacity.
- Cyclic loading capabilities defined in IS: 6600 should be considered for optimal sizing without accelerated loss of life.
- Parallel operation requirements: percentage impedance must be carefully specified to ensure proportional load sharing.
- Temperature rise limits (e.g., 50°C for oil, 55°C for winding) heavily influence the chosen base kVA rating.

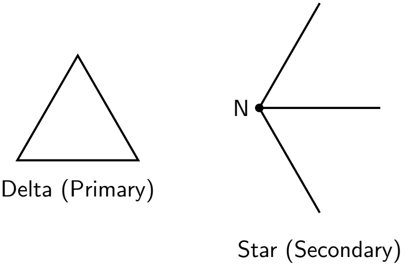
Selection Criteria: Voltage Ratio and Tap Changers I

Voltage regulation is a critical aspect. The choice of primary and secondary voltages along with tap changers determines the network's voltage profile.

Key Points:

- No-load voltage ratio must correspond to the system's nominal voltage levels and expected voltage drops.
- Distribution transformers typically use Off-Circuit Tap Changers (OCTC) with ranges like $+5$
- Power transformers usually employ On-Load Tap Changers (OLTC) with ranges from $+5$
- Consideration of system fault levels is essential when specifying transformer impedance to limit short-circuit currents.
- Vector group selection (e.g., Dyn11 for distribution) is dictated by earthing requirements and harmonic mitigation.

Diagram: Distribution Transformer Connection (Dyn11) I



Key Points:

- Vector group Dyn11 is highly recommended for distribution transformers by IS: 10028.
- Delta connected primary blocks triplen harmonics from entering the high voltage supply.

Diagram: Distribution Transformer Connection (Dyn11) II

- Star connected secondary provides a solidly grounded neutral point for 3-phase, 4-wire consumer systems.
- The neutral allows for single-phase loading (phase-to-neutral) without shifting the neutral point.

Selection Criteria: Cooling Methods I

Transformer heat dissipation directly affects its lifespan and overload capacity. IS: 10028 classifies various cooling methods based on the insulating medium and circulation mechanism.

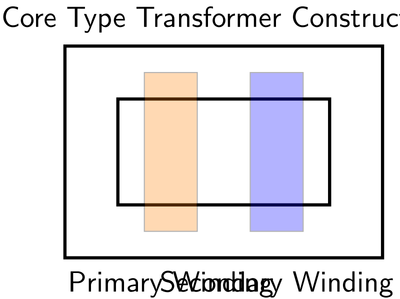
Key Points:

- ONAN (Oil Natural Air Natural): Standard for distribution transformers and small power transformers up to 30 MVA.
- ONAF (Oil Natural Air Forced): Used for larger power transformers to increase capacity by 20-30
- OFAF/ODAF (Oil Forced Air/Water Forced): Applied to very large EHV power transformers requiring high heat dissipation.
- Dry-type transformers (AN/AF) are selected for indoor installations where fire safety and environmental concerns are paramount.

Selection Criteria: Cooling Methods II

- Selection depends heavily on site conditions, space constraints, maintenance capabilities, and continuous overload requirements.

Diagram: Transformer Core and Windings I



Key Points:

- Core type construction is most common for both power and distribution transformers due to ease of repair and good natural cooling.

Diagram: Transformer Core and Windings II

- In core type, the windings surround a considerable part of the magnetic circuit (limbs).
- HV windings are typically wound over LV windings to minimize insulation requirements to the grounded core.
- The IS code dictates specific short-circuit withstand capabilities which are heavily dependent on winding construction and bracing.

Economic Evaluation: Capitalized Cost of Losses I

According to IS: 10028, transformer selection must not be based solely on initial capital cost, but on the Total Owning Cost (TOC) which includes the capitalized cost of losses over its lifetime.

Key Points:

- TOC = Initial Cost + (A × No-Load Loss) + (B × Load Loss).
- 'A' represents the capitalized cost per kW of no-load (iron) loss (active 24/7 regardless of load).
- 'B' represents the capitalized cost per kW of load (copper) loss (dependent on the square of the load factor).
- For distribution transformers, factor 'A' is heavily weighted due to continuous energization at low load factors.
- Purchasers should specify maximum acceptable loss limits or penalize manufacturers for exceeding guaranteed losses.

Conclusion and Final Checklist I

Proper selection of transformers utilizing IS: 10028 ensures system stability, minimizes life-cycle costs, and ensures safety for both operators and the grid.

Key Points:

- Always verify site environmental conditions (temperature, altitude) against standard rating parameters.
- Select the appropriate vector group and matching impedance voltage for parallel operation and fault level containment.
- Factor in the specific load cycle to differentiate between needing a Power or Distribution transformer.
- Evaluate manufacturer bids based on Total Owning Cost (TOC) rather than just the initial purchase price.
- Ensure essential accessories like Buchholz relay, OTI, WTI, and silica gel breathers are specified as per the kVA rating and application.

IS: 2026 (Part IV)-1977 Vector Groups Overview I

Indian Standard 2026 specifies the terminal markings, tappings, and connections for power transformers.

Key Points:

- Vector groups indicate the phase difference between the primary and secondary line voltages.
- Nomenclature consists of letters (HV winding in capital, LV in lowercase) and a clock hour figure.
- Clock hour figure indicates phase shift: 0 (0°), 1 (-30° lagging), 6 (180°), 11 ($+30^\circ$ leading).
- Common groups: Group I (0° phase displacement, e.g., Yy0, Dd0), Group II (180°, e.g., Yy6, Dd6).
- Group III (-30°, e.g., Dy1, Yd1) and Group IV ($+30^\circ$, e.g., Dy11, Yd11).

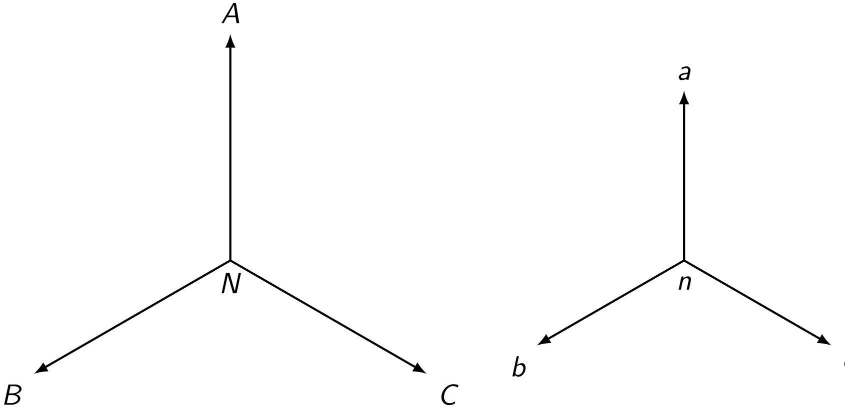
Star-Star (Yy) Connection I

The Star-Star connection is economical for small, high-voltage transformers.

Key Points:

- Phase voltage is $1/3$ times the line voltage, reducing the required insulation per phase.
- Major disadvantage: Absence of a path for third-harmonic currents leads to oscillating neutral and distorted phase voltages.
- Cannot handle unbalanced loads well unless the neutral is solidly grounded.
- Often provided with a tertiary delta winding to allow third harmonic currents to circulate and stabilize the neutral.

Star-Star (Yy0) Phasor Diagram I



Key Points:

Star-Star (Yy0) Phasor Diagram II

- The primary and secondary phasors are perfectly aligned.
- This indicates a 0-degree phase shift (clock hour 0), known as a Yy0 vector group.

Delta-Delta (Dd) Connection I

Suitable for large, low-voltage transformers.

Key Points:

- Phase voltage equals line voltage, meaning more insulation is required per phase compared to Star connection.
- Can operate with unbalanced loads without neutral shift.
- Third-harmonic currents circulate within the closed delta loop, ensuring sinusoidal flux and induced EMFs.
- If one transformer bank fails, the remaining two can operate in Open Delta (V-V) at 57.7

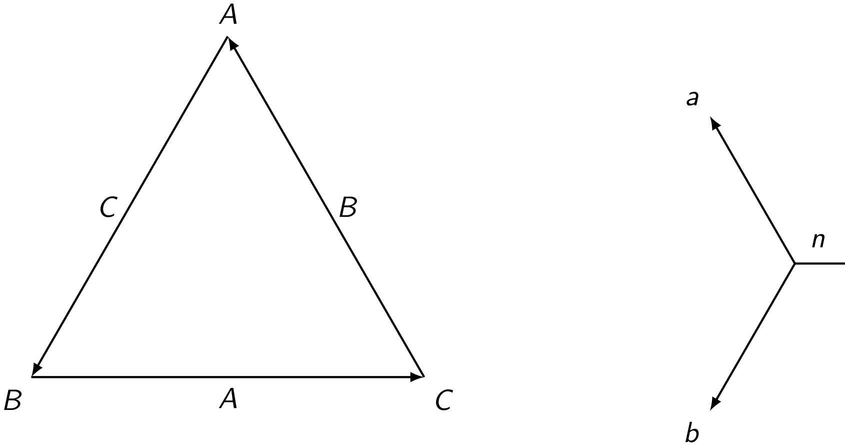
Delta-Star (Dy) and Star-Delta (Yd) Connections I

These connections introduce a phase shift of 30 degrees (either $+30^\circ$ or -30°).

Key Points:

- Delta-Star (Dy): Widely used for step-down distribution transformers. Primary delta allows third harmonics to circulate. Secondary star provides a neutral for mixed loads.
- Star-Delta (Yd): Commonly used for step-up transformers at generating stations.
- Standard vector groups for these are Group III (clock hour 1) and Group IV (clock hour 11).
- Dy11 connection ($+30^\circ$ shift) is the most common for distribution transformers in India.

Delta-Star (Dy11) Phasor Diagram I



Key Points:

Delta-Star (Dy11) Phasor Diagram II

- Primary is connected in Delta forming a closed triangle.
- Secondary is Star connected, with the secondary phase voltage 'a' leading the primary phase voltage 'A' by 30 degrees (the 11 o'clock position on a clock face).

Achieved when one phase of a Delta-Delta bank is removed or disconnected.

Key Points:

- Used temporarily when one single-phase transformer in a 3-phase bank is damaged.
- Also applied to serve small 3-phase loads where a full 3-transformer bank is economically unjustified.
- The total capacity of an open-delta bank is reduced to 57.7
- The utilization factor (ratio of available capacity to installed transformer capacity) is 86.6
- Secondary voltages become slightly unbalanced under heavy load due to unequal internal voltage drops across the two transformers.

Three Phase to Two Phase Conversion (Scott Connection) I

Scott connection utilizes two single-phase transformers to convert a 3-phase supply to a 2-phase supply (or vice versa).

Key Points:

- The 'Main' transformer has a center-tapped primary (50
- The 'Teaser' transformer primary is connected between the third line of the 3-phase supply and the center tap of the main transformer.
- To produce equal voltages on the 2-phase secondary side, the teaser transformer primary requires an 86.6
- It is widely used to supply two-phase electric furnaces and link 3-phase transmission networks with 2-phase systems.

Numerical Example: Scott Connection I

Example calculation demonstrating the voltage and turns ratio relationships in a Scott-connected transformer bank.

Key Points:

- Problem: A Scott connection converts a 400V 3-phase supply to a 200V 2-phase supply. Calculate the turns ratio required for both transformers.
- Main Transformer: Primary voltage = 400V, Secondary voltage = 200V. Main turns ratio (N1/N2) = 400/200 = 2.
- Teaser Transformer: The primary voltage rating required = (3/2) * 400V = 346.41V.
- Teaser Secondary voltage = 200V. Teaser turns ratio (N1_teaser / N2) = 346.41 / 200 = 1.732 (or 3).
- Conclusion: The teaser primary winding requires exactly 86.6

Introduction to IS: 2026 (Part IV)-1977 I

Indian Standard IS: 2026 specifies the conventions for terminal markings, tappings, and connections of power transformers.

Key Points:

- High Voltage (HV) terminals are designated with capital letters (A, B, C) and Low Voltage (LV) terminals with small letters (a, b, c).
- Terminal numbers indicate polarity: 1 and 2 for winding ends, where 1 is the start and 2 is the finish of the winding.
- Phase displacement is defined as the angle by which the LV line-to-neutral voltage vector lags the HV line-to-neutral voltage vector.
- Clock notation is used to indicate phase displacement: Clock hour figure = Phase shift (lagging) in degrees / 30 degrees.

- Common vector groups are Group I (0 degree phase shift), Group II (180 degree phase shift), Group III (minus 30 degree phase shift), and Group IV (plus 30 degree phase shift).

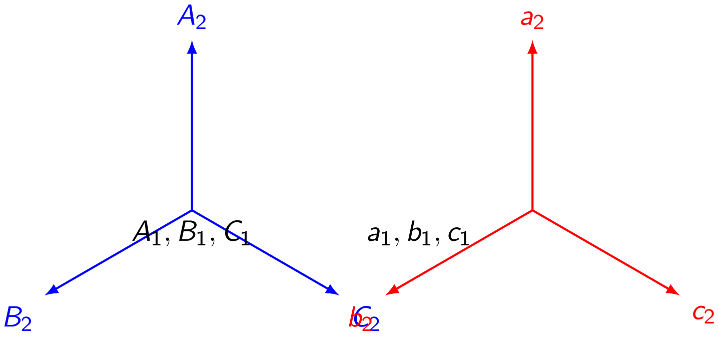
Vector Groups and Clock Notation I

Vector grouping dictates the phase difference between primary and secondary line voltages, crucial for parallel operation.

Key Points:

- The HV voltage phasor is always taken as the reference and set at 12 o'clock (0 degrees).
- Notation examples: 'Yy0' denotes Star HV, Star LV, with 0° phase shift.
- 'Dy11' denotes Delta HV, Star LV, with LV leading HV by 30° (equivalent to lagging by 330° or 11 o'clock).
- Parallel operation of transformers requires identical vector groups to prevent massive circulating currents.
- Transformers with vector groups 0 and 11 cannot be paralleled, but group 11 and 1 (with appropriate phase sequence reversal) sometimes can.

Star-Star (Yy0) Connection Vector Diagram I



Key Points:

- In the Yy0 connection, the primary and secondary phase voltages are strictly in phase.

Star-Star (Yy0) Connection Vector Diagram II

- This connection requires both primary and secondary neutrals to be grounded to avoid floating neutral issues under unbalanced loads.
- It is highly susceptible to third harmonic voltages unless a tertiary delta winding is provided to offer a closed circulating path.
- Typically used for small, high-voltage transformers where the neutral can be solidly grounded, reducing insulation requirements.

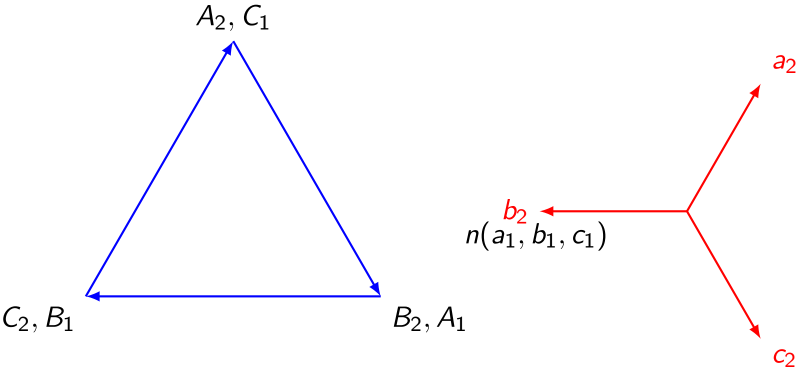
Delta-Delta (Dd0, Dd6) Connections I

The Delta-Delta connection is extensively used for low voltage, high current industrial applications.

Key Points:

- No phase shift exists between primary and secondary line voltages in the Dd0 configuration.
- Advantageous because it provides a path for third harmonic currents in the closed delta loop, preventing third harmonic voltage distortion in the lines.
- If one transformer fails in a bank of three single-phase transformers, the system can continue operating in Open-Delta (V-V) configuration.
- The absence of a neutral point means an artificial neutral (e.g., using a zig-zag grounding transformer) must be created if mixed 3-phase and 1-phase loads are to be supplied.

Delta-Star (Dy11) Connection Vector Diagram I



Key Points:

- Dy11 is the most universally used connection for distribution transformers stepping down to utilization voltages (e.g., 11kV to 400V/230V).

Delta-Star (Dy11) Connection Vector Diagram II

- The secondary line voltage leads the primary line voltage by +30 degrees (hence the '11' clock position).
- The delta-connected primary allows third harmonic currents to circulate, mitigating harmonic distortion and stabilizing the neutral.
- The star-connected secondary provides a solid neutral point, facilitating both 3-phase power (400V) and 1-phase lighting/appliance (230V) loads simultaneously.

Star-Delta (Yd1, Yd11) Connections I

The Star-Delta configuration is typically employed at the generating station end of a transmission line.

Key Points:

- Used extensively as step-up transformers (e.g., generator transformers) from medium generator voltage to high transmission voltages.
- The star connection on the primary (HV side in reverse power flow, or LV side when stepping up) provides a neutral point for solid grounding.
- The delta secondary effectively dampens third-harmonic voltages by providing a closed circulation path for triple-frequency zero-sequence currents.
- Creates a 30-degree phase shift (Yd1 means secondary lags by 30°, Yd11 means secondary leads by 30°), which must be accounted for in system synchronization.

Open Delta or V-V Connection I

The Open Delta connection uses only two single-phase transformers to supply a three-phase load.

Key Points:

- Often used as a temporary emergency measure when one phase of a Delta-Delta transformer bank fails, ensuring continuity of supply.
- The total capacity is heavily reduced to 57.7
- The utilization factor (or V-V capacity over installed capacity of the two remaining transformers) is 0.866, meaning the transformers cannot be fully loaded.
- The secondary voltages become slightly unbalanced under load because the series leakage impedances of the two transformers are not symmetrical with respect to the three phases.

Open Delta or V-V Connection II

- The power factor of the two transformers is always different from the load power factor, operating at cos(30° - ϕ) and cos($30^\circ + \phi$) respectively.

Three-Phase to Two-Phase Conversion (Scott Connection) I

The Scott-T connection is a specialized method of connecting two single-phase transformers to convert 3-phase power to 2-phase power.

Key Points:

- Requires two single-phase transformers: a 'Main' transformer and a 'Teaser' transformer.
- The Main transformer has a 50
- The Teaser transformer's primary is connected between the third phase and the center tap of the Main transformer.
- To achieve balanced 2-phase output voltages, the Teaser primary must have a precise turns ratio of 0.866 (sqrt(3)/2) relative to the Main primary turns.

Three-Phase to Two-Phase Conversion (Scott Connection) II

- Used historically to supply legacy 2-phase induction motors, and currently utilized for electric railway traction systems and electric arc furnaces to balance a massive single-phase load on a 3-phase grid.

Numerical Problem Formulation (Scott Connection) I

A Scott-connected transformer bank converts 3-phase 6600V to 2-phase at 400V. Load on the 2-phase side is 400kW at 0.8 pf lagging on each phase.

Key Points:

- Step 1: Calculate the 2-phase secondary currents. $I_2 = P / (V_2 * pf) = (400{,}000\ W) / (400\ V * 0.8) = 1250$ A.
- Step 2: Calculate the fundamental transformation ratio (K) of the Main transformer. $K = V_2 / V_1 = 400 / 6600 = 0.0606$.
- Step 3: Calculate the required Teaser transformer primary voltage rating. $V_{teaser} = 0.866 * 6600V = 5715.6V$.
- Step 4: Primary current in the teaser transformer is proportional to its turns ratio: $I_{1T} = I_2 * (400 / 5715.6) = 87.48$ A.

Numerical Problem Formulation (Scott Connection) II

- Step 5: Through vector addition, the primary line currents drawn from the 6600V source will be equal in magnitude but differ in phase, maintaining a perfectly balanced 3-phase load on the supply network.

What is Parallel Operation? I

Parallel operation of transformers involves connecting the primary windings of two or more transformers to a common supply busbar and their secondary windings to a common load busbar.

Key Points:

- Primary terminals are connected in parallel to the source.
- Secondary terminals are connected in parallel to the load.
- Facilitates power sharing among multiple transformer units.
- Critical for large-scale power distribution and substation management.

Need for Parallel Operation: Reliability & Maintenance I

One of the primary reasons for operating transformers in parallel is to ensure a continuous and reliable power supply to consumers without interruption.

Key Points:

- System Reliability: If one transformer fails or develops a fault, the remaining transformers can continue to supply the critical load.
- Preventive Maintenance: Transformers can be taken offline one at a time for routine maintenance without completely interrupting power to the load.
- N-1 Security Criterion: Power systems are typically designed so that the loss of a single major component does not compromise system stability.

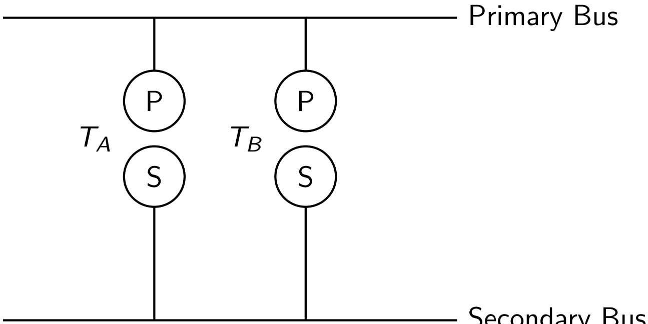
Need for Parallel Operation: Efficiency & Expansion I

Parallel operation allows for better economic management of the power system, especially when dealing with variable load profiles over time.

Key Points:

- Maximized Efficiency: Transformers operate most efficiently near full load. By switching units on/off based on total demand, constant core losses are minimized during light load periods.
- Future Expansion: As power demand grows, new transformers can be added in parallel rather than replacing an existing unit with a larger, more expensive one.
- Transportation Constraints: Extremely large single transformers (e.g., ¿1000 MVA) are difficult to transport due to weight and size limitations. Multiple smaller units are physically more feasible.

Diagram: Parallel Connection of Transformers I



Key Points:

- Primary windings are connected to the same source voltage.
- Secondary windings are connected to the same load bus.
- Any difference in induced EMFs will cause local circulating currents between the transformers.

Conditions for Parallel Operation I

To prevent severe damage and ensure proportional load sharing, several electrical conditions must be met before connecting transformers in parallel. These are categorized as Essential and Desirable conditions.

Key Points:

- Essential Conditions: Must be strictly fulfilled. Failure to do so will result in dead short circuits or dangerously high circulating currents even at no-load.
- Desirable Conditions: Recommended for optimal load sharing and efficiency, but transformers can still operate if they are slightly mismatched.
- Violating essential conditions can lead to winding burnout and catastrophic failure.

Essential Conditions: Polarity and Voltage Ratio I

The fundamental electrical parameters of the transformers must be strictly aligned to avoid creating a phase-to-phase short circuit on the secondary side.

Key Points:

- Same Polarity: Terminals with identical instantaneous polarity must be connected together. Incorrect polarity results in a dead short circuit, drawing massive current.
- Same Voltage Ratio (Turns Ratio): The primary and secondary voltage ratings must be identical. A mismatch creates a voltage difference in the secondary loop.
- Even a small voltage difference drives a large circulating current ($Ic = \Delta V / (Za + Zb)$) because transformer internal impedances are very low.

Essential Conditions: Three-Phase Specifics I

When dealing with three-phase transformers, the spatial orientation of the voltage phasors becomes a critical factor.

Key Points:

- Same Phase Sequence: The sequence in which the phases reach their maximum voltage (e.g., R-Y-B) must be identical. Connecting mismatched sequences will cause a severe short circuit.
- Zero Phase Angle Difference: The phase shift between primary and secondary line voltages must be the same for both transformers.
- Transformers must belong to the same vector group (e.g., a Yd1 transformer with -30° shift cannot be paralleled with a Yy0 transformer with 0° shift).

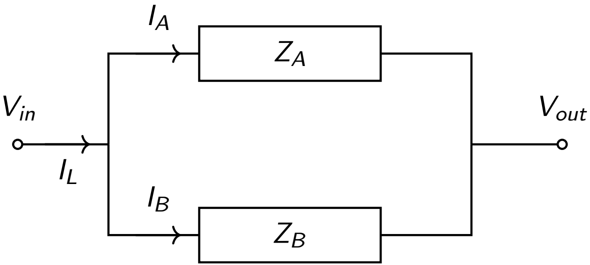
Desirable Conditions: Impedance and X/R Ratio I

For optimal performance, the load should be shared between transformers in exact proportion to their respective kVA ratings.

Key Points:

- Same Percentage Impedance: The per-unit or percentage impedance must be identical so that transformers share the load proportionally to their capacities.
- Same X/R Ratio: The ratio of equivalent leakage reactance to equivalent resistance should be equal. This ensures that the transformers operate at the same power factor as the load.
- If X/R ratios differ, the individual currents will be out of phase, leading to a total kVA demand on the transformers that is greater than the actual load kVA.

Diagram: Equivalent Circuit for Load Sharing I



Key Points:

- The simplified equivalent circuit represents transformers as parallel impedances Z_A and Z_B.
- Load current I_L divides into I_A and I_B inversely proportional to their respective impedances.
- I_A = I_L * [Z_B / (Z_A + Z_B)] and I_B = I_L * [Z_A / (Z_A + Z_B)].