

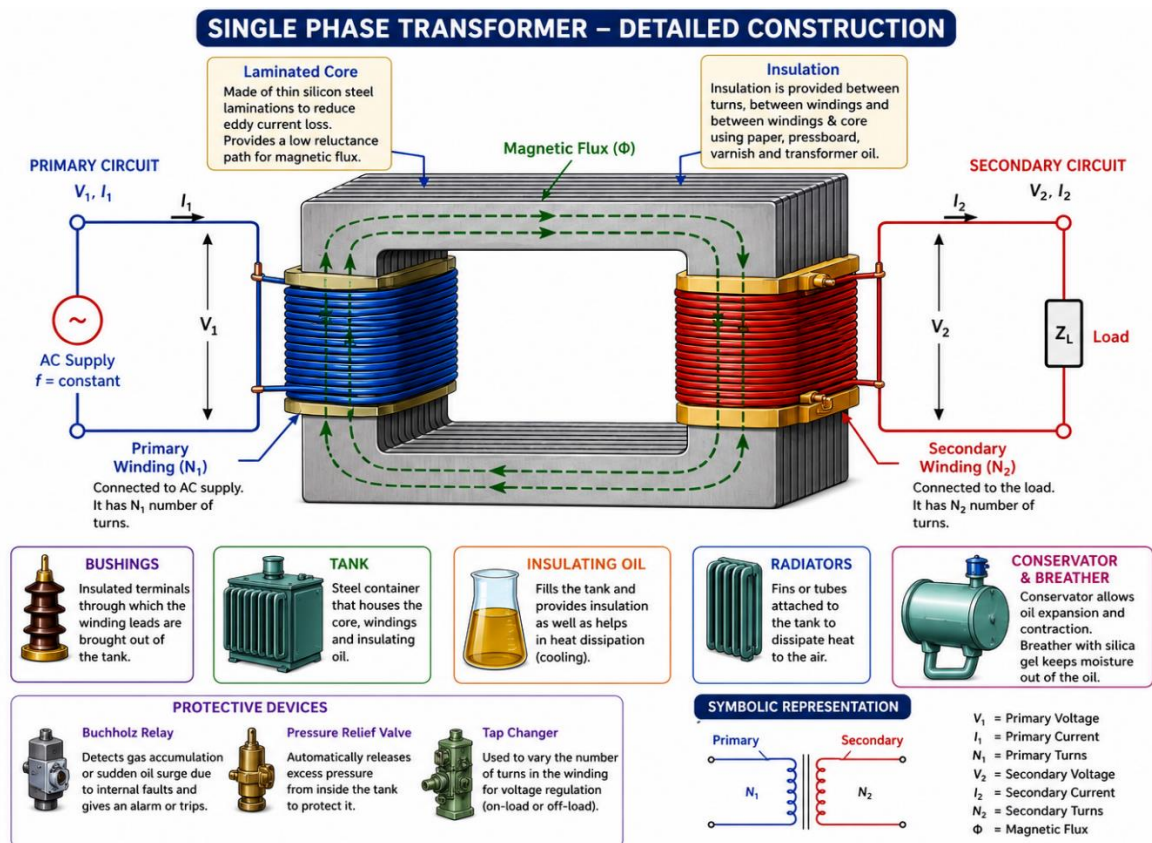
UNIT IV

TRANSFORMERS AND SPECIAL MACHINES

Single Phase Transformer

A transformer is a static electro-magnetic device that transfers electrical energy from one circuit to another through mutual induction, at the same frequency, usually changing the voltage/current level. It has no rotating parts and is one of the most efficient electrical machines (efficiency 95–99%).

Construction



A transformer essentially has two parts – the magnetic circuit (core) and electric circuit (windings):

- **Core:** Built of high-silicon steel laminations (0.35–0.5 mm thick), insulated from each other to reduce eddy current loss; provides a low-reluctance path for flux. Consists of limbs (carry windings) and yokes (connect limbs).
- **Windings:** Primary (connected to supply, N_1 turns) and Secondary (connected to load, N_2 turns), made of insulated copper/aluminium conductor.
- **Insulation:** Between turns, between windings, and between windings & core (paper, press-board, varnish, transformer oil).

- **Tank, conservator & breather:** House the oil-immersed core-coil assembly; accommodate oil expansion; keep moisture out using silica gel.
- **Bushings:** Insulated terminals bringing winding leads out through the tank.
- **Cooling:** ONAN, ONAF, OFAF, OFWF methods depending on rating.
- **Protective devices:** Buchholz relay (detects internal faults), tap changer (voltage regulation), pressure relief valve.

Core Type vs Shell Type

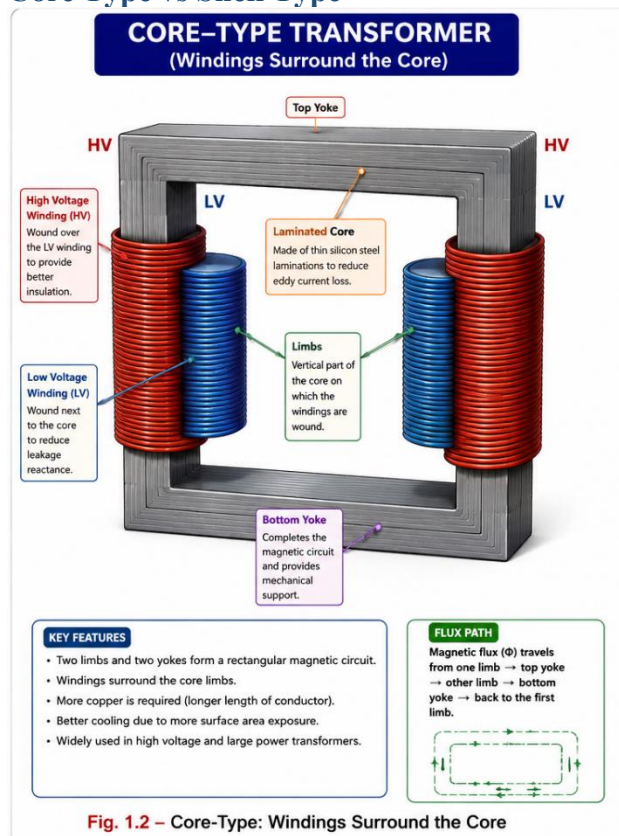


Fig. 1.2 – Core-Type: Windings Surround the Core

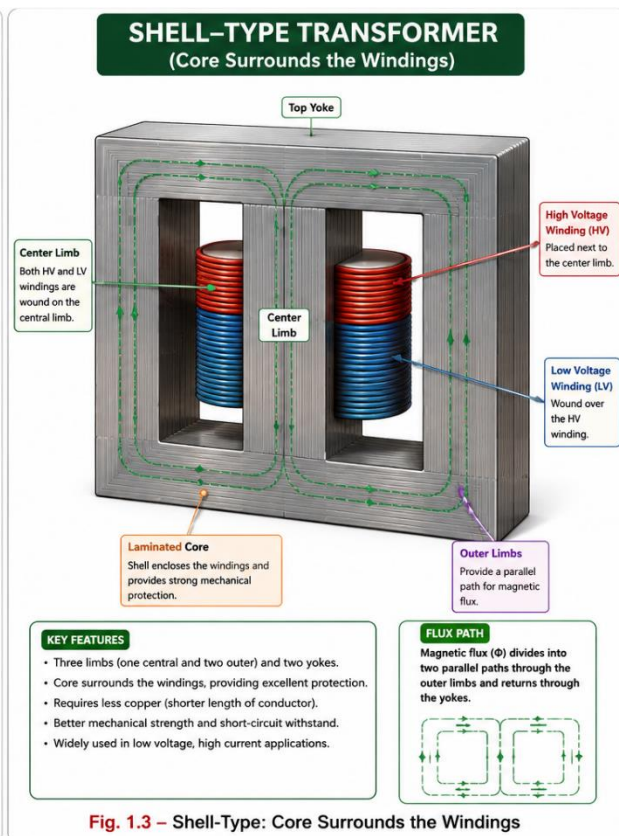


Fig. 1.3 – Shell-Type: Core Surrounds the Windings

Feature	Core Type	Shell Type
Arrangement	Windings surround the core	Core surrounds the windings
Magnetic circuit	Single path	Double/parallel path
Limbs	Two	Three (winding on central limb)
Winding type	Cylindrical (concentric)	Sandwich (disc)
Leakage reactance	Higher	Lower
Preferred use	High voltage, low current	Low voltage, high current

Principle of Operation

A transformer works on the principle of Mutual Electromagnetic Induction. An alternating voltage applied to the primary sets up an alternating current, which produces an alternating flux in the core. This flux links both windings and induces an EMF in each — a self-induced EMF (E_1) in the primary opposing the applied voltage, and a mutually-induced EMF (E_2) in the secondary, at the same frequency as the supply. When the secondary circuit is closed through a load, E_2 drives a current through the load, transferring power without any direct electrical connection between the two circuits.

EMF Equation

Let flux vary sinusoidally: $\Phi = \Phi_m \sin \omega t$. Induced EMF per turn = $-d\Phi/dt$.

$$E_1 = 4.44 f N_1 \Phi_m = 4.44 f N_1 B_m A$$

$$E_2 = 4.44 f N_2 \Phi_m = 4.44 f N_2 B_m A$$

where f = supply frequency (Hz), N_1, N_2 = number of primary/secondary turns, Φ_m = maximum flux (Wb), B_m = maximum flux density (T), A = net core cross-sectional area (m^2).

Transformation Ratio

$$K = E_2/E_1 = N_2/N_1 = V_2/V_1 \text{ (ideal)} \quad \text{and} \quad I_1/I_2 = N_2/N_1 = K$$

- Step-up transformer: $N_2 > N_1 \rightarrow K > 1 \rightarrow V_2 > V_1$
- Step-down transformer: $N_2 < N_1 \rightarrow K < 1 \rightarrow V_2 < V_1$

Losses in a Transformer

Since a transformer has no moving parts, it has no mechanical (friction/windage) losses. Its losses are entirely electrical, and are of two types:

(a) Core / Iron Losses (P_i)

Occur in the core due to the alternating flux, and are practically constant at all loads (since flux is nearly constant from no-load to full-load, being set by the constant supply voltage).

- **Hysteresis Loss (W_h):** Due to reversal of magnetization of the core, $W_h = K_h B_m^{1.6} f V$ watts (K_h = Steinmetz hysteresis constant, V = volume of core). Reduced by using core material with low hysteresis coefficient (silicon steel).
- **Eddy Current Loss (W_e):** Due to circulating currents induced in the core body itself, $W_e = K_e B_m^2 f^2 t^2 V$ watts (t = lamination thickness). Reduced by laminating the core.

$$\text{Core loss, } P_i = W_h + W_e \text{ (found from Open Circuit Test)}$$

(b) Copper Losses (P_{cu})

Occur in the primary and secondary winding resistances due to load current, and vary as the square of the load current (i.e., vary with the square of the load).

$$P_{cu} = I_1^2 R_1 + I_2^2 R_2 = I_2^2 R_{o2} \text{ (found from Short Circuit Test)}$$

where R_{o2} is the total resistance referred to the secondary side.

Efficiency of a Transformer

Efficiency is the ratio of output power to input power:

$$\eta = \text{Output Power} / \text{Input Power} = \text{Output} / (\text{Output} + \text{Losses}) = (V_2 I_2 \cos\Phi) / (V_2 I_2 \cos\Phi + P_i + P_{cu})$$

For a fraction x of full load ($x = I_2/I_{2,\text{full-load}}$), copper loss becomes $x^2 P_{cu}(\text{FL})$, so:

$$\eta = (x \cdot S \cdot \cos\Phi) / (x \cdot S \cdot \cos\Phi + P_i + x^2 P_{cu}(\text{FL}))$$

where S = rated (full-load) VA of the transformer.

Condition for Maximum Efficiency

Differentiating η with respect to x and equating $d\eta/dx = 0$ gives the condition:

$$P_i = x^2 P_{cu}(\text{FL}) \quad \text{i.e.} \quad \text{Iron Loss} = \text{Copper Loss (at that load)}$$

The load at which this occurs:

$$x = \sqrt{(P_i / P_{cu}(\text{FL}))}$$

$$\eta_{\text{max}} = (x S \cos\Phi) / (x S \cos\Phi + 2 P_i)$$

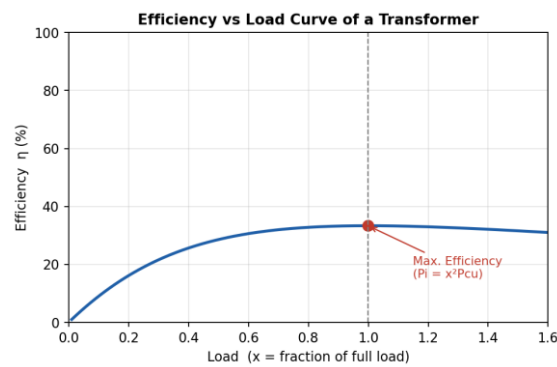


Fig. 1.4 – Efficiency vs Load curve; maximum efficiency occurs where iron loss = copper loss

Note: All-day efficiency (energy efficiency) is defined as the ratio of total energy output to total energy input over a 24-hour period, and is more meaningful than commercial efficiency for distribution transformers that carry varying load throughout the day.

Voltage Regulation

Voltage regulation is the change in secondary terminal voltage from no-load to full-load (at a given power factor), expressed as a percentage of the no-load (or rated) secondary voltage, when the primary voltage is held constant.

$$\% \text{ Regulation} = [(E_2 - V_2) / V_2] \times 100$$

In terms of equivalent circuit parameters referred to secondary (R_{02} = equivalent resistance, X_{02} = equivalent reactance), for a load current I_2 at power factor $\cos\Phi$:

$$\% \text{ Regulation} \approx [I_2 (R_{02} \cos\Phi \pm X_{02} \sin\Phi)] / V_2 \times 100$$

Use '+' sign for lagging power factor loads and '-' sign for leading power factor loads. Voltage regulation indicates how much the output voltage 'sags' (or rises) as load is applied — a smaller regulation value indicates better voltage-holding capability.

Applications of Single Phase Transformer

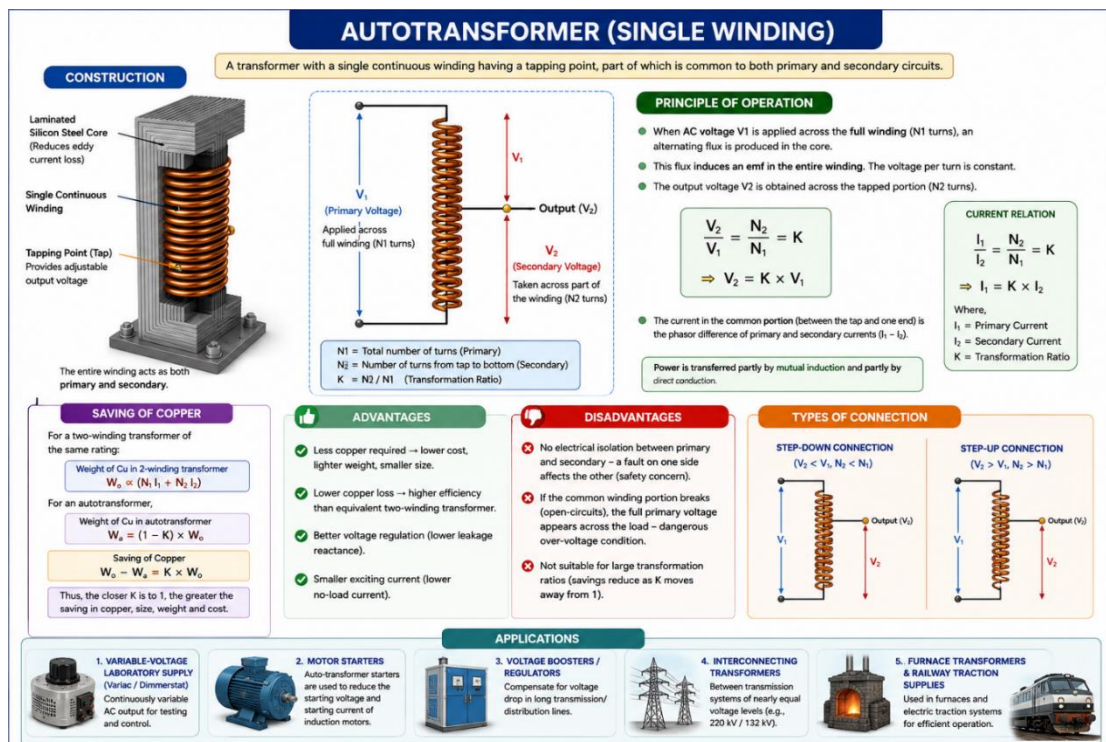
- **Power distribution:** Step-down transformers supplying 230 V AC to homes.
- **Instrument transformers:** CT and PT for metering and protection.
- **Isolation transformers:** Electrical isolation in medical/lab equipment.

- **Control transformers:** Low-voltage supply for relay/PLC control panels.
- **Welding & furnace transformers:** Low-voltage, high-current supply.
- **Audio/impedance matching and rectifier transformers:** Used in electronics and power supplies.

Autotransformer

Construction

An autotransformer is a special type of transformer having only ONE winding, part of which is common to both the primary and secondary circuits. Unlike a two-winding transformer, it transfers power partly by conduction (direct electrical connection) and partly by mutual induction.



The winding is wound on a laminated core just like an ordinary transformer, but only a single continuous winding is used, with a movable or fixed tapping (tap) that divides it into two sections. The input voltage V_1 is applied across the full winding (N_1 turns), and the output V_2 is taken across a part of it (N_2 turns), or vice versa for a step-up connection.

Principle of Operation

When V_1 is applied across the full winding, current flows and produces flux in the core exactly as in a two-winding transformer, inducing a voltage per turn. The output voltage V_2 is simply proportional to the number of turns tapped, $V_2 = (N_2/N_1) V_1$. The portion of the winding common to both circuits carries the (phasor) difference of the primary and secondary currents, which is much smaller than either current — this is the key to the copper saving of an autotransformer.

Saving of Copper

For a two-winding transformer of the same rating, weight of copper required is proportional to $(N_1 I_1 + N_2 I_2)$. For an autotransformer with transformation ratio $K = N_2/N_1 = I_1/I_2$:

Weight of Cu in autotransformer, $W_a = (1 - K) \times$ Weight of Cu in ordinary transformer, W_o

Saving of Copper = $W_o - W_a = K \times W_o$ (i.e., a fraction K of the copper is saved)

Thus, the closer K is to 1 (i.e., primary and secondary voltages are close to each other), the greater the saving in copper, size, weight, and cost. This saving is the biggest advantage of an autotransformer over a two-winding transformer.

Advantages

- Less copper required → lower cost, lighter weight, smaller size for the same rating.
- Lower copper loss → higher efficiency than an equivalent two-winding transformer.
- Better voltage regulation (lower leakage reactance).
- Smaller exciting current (lower no-load current) required.

Disadvantages

- No electrical isolation between primary and secondary — a fault on one side directly affects the other side, which is a safety concern.
- If the common winding portion breaks (open-circuits), the full primary voltage appears across the load — dangerous over-voltage condition.
- Not suitable for large transformation ratios (savings reduce as K moves away from 1).

Applications

- **Variable-voltage laboratory supply (Variac / dimmerstat):** Continuously variable AC output for testing and control.
- **Motor starters:** Auto-transformer starters for reduced-voltage starting of induction motors.
- **Voltage boosters / regulators:** Compensate for voltage drop in long transmission/distribution lines.
- **Interconnecting transformers:** Between transmission systems of nearly equal voltage levels (e.g., 220 kV/132 kV interconnection).
- **Furnace transformers and railway traction supplies.**

Three-Phase Transformer

Necessity

Electric power is generated, transmitted and distributed almost universally as three-phase AC. Three-phase transformation can be achieved either by using a bank of three identical single-phase transformers connected suitably, or by using a single three-phase transformer unit (common core with three sets of windings).

Construction (Brief)

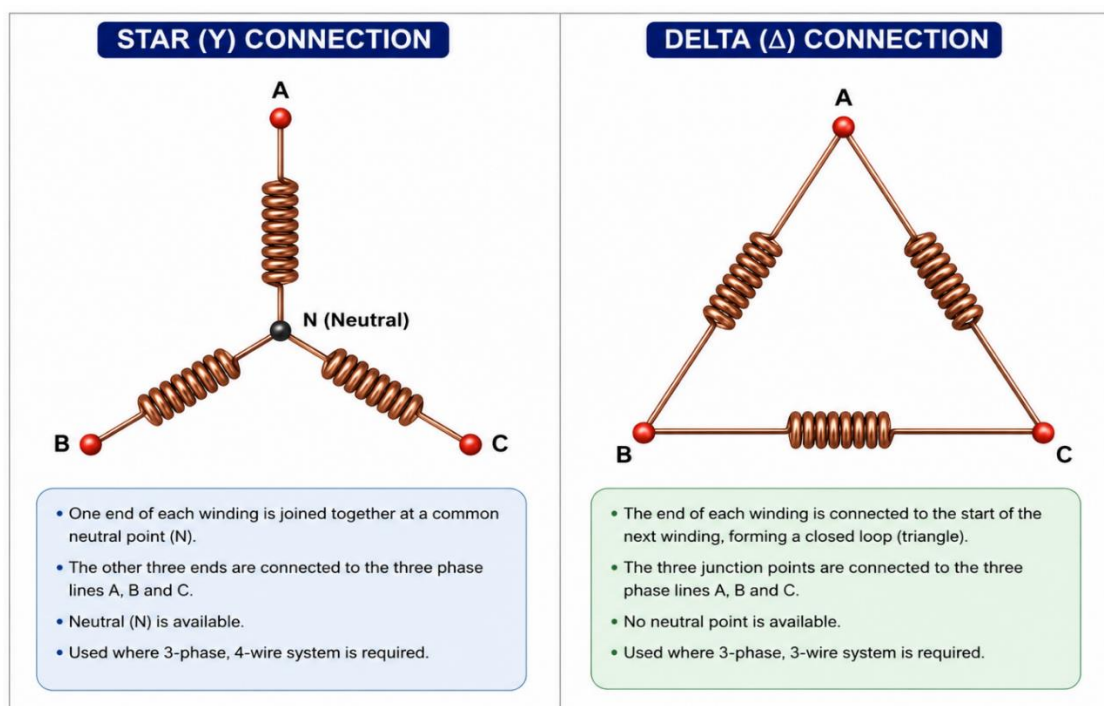
A three-phase transformer core is generally of the core type, with three limbs (one per phase) connected by top and bottom yokes. Each limb carries the LV and HV windings of one phase, similar in principle to a single-phase core-type transformer, but with three limbs instead of two.

Three-Phase Unit vs Bank of Single-Phase Transformers

Feature	Single 3-Phase Unit	Bank of 3 Single-Phase Units
Cost & weight	Lower (shared core & tank)	Higher
Floor space	Less	More
Spare/standby requirement	Entire unit must be spared	Only one single-phase unit needed as spare
Effect of one phase failing	Whole transformer goes out of service	Can run at reduced (open-delta) capacity using remaining two
Transportation (very large ratings)	Difficult (very heavy/bulky)	Easier (smaller individual units)

Three-Phase Transformer Connections

The primary and secondary windings of a three-phase transformer (or bank) can each be connected in Star (Y) or Delta (Δ), giving four common combinations.



Connection	Key Features	Typical Applications
Star – Star (Y–Y)	Provides a neutral on both sides; economical for HV since phase voltage is line/ $\sqrt{3}$; no phase shift; but distorted (non-sinusoidal) flux/voltage due to triplen harmonics unless a tertiary delta winding is added.	Small, low-voltage, high-current transformers where a neutral is required on both sides.
Delta – Delta (Δ – Δ)	No neutral available; no phase shift between primary & secondary; if one transformer of the bank fails, the remaining two can continue supply in open-delta (V-V) at reduced (58%) capacity.	Medium voltage industrial supply; ideal where continuity of supply is critical.
Star – Delta (Y– Δ)	Primary in star (neutral available, good for HV side & grounding); secondary in delta; introduces a 30° phase shift; suppresses triplen harmonics (circulate in delta).	Step-down substations at the receiving end of transmission lines.
Delta – Star (Δ –Y)	Primary in delta, secondary in star (neutral available on LV/output side for 3-phase + neutral distribution); 30° phase shift.	Step-up transformers at generating stations; distribution transformers supplying 3-phase + neutral loads.

Special Machines

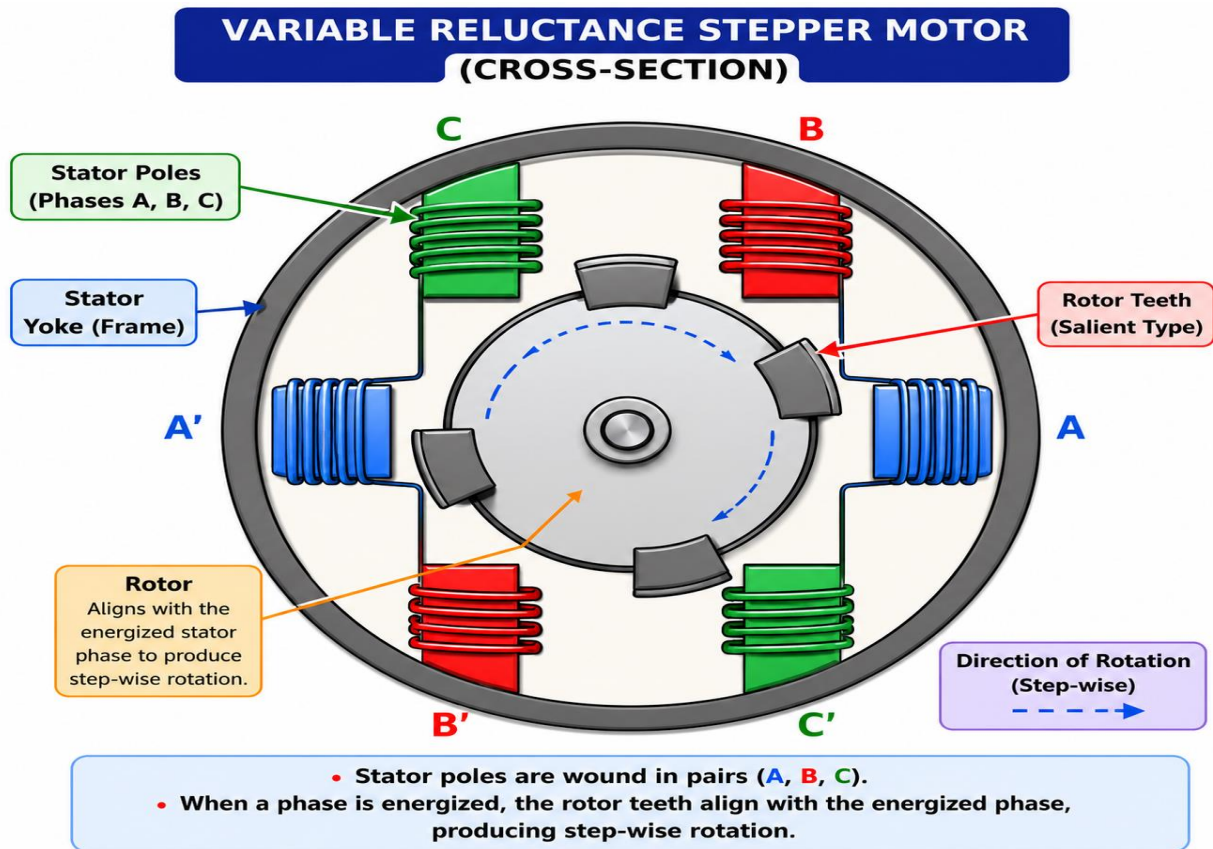
Stepper Motor

A stepper motor is a special electromechanical device that converts a train of input electrical pulses into a corresponding number of precisely defined mechanical steps (discrete angular movements) of its rotor shaft — it does not rotate continuously but moves in fixed, equal angular steps.

Types of Stepper Motors

- **Variable Reluctance (VR) type:** Has a soft-iron toothed rotor (no permanent magnet); rotor teeth align with the energized stator pole pair to minimize reluctance.
- **Permanent Magnet (PM) type:** Rotor is a permanent magnet; rotor poles align with the energized stator poles due to magnetic attraction; gives higher torque than VR type but larger step angle.

- **Hybrid type:** Combines features of VR and PM types (toothed, magnetized rotor); gives small step angle with high torque; most commonly used in industry.



Principle of Operation

The stator has several projecting poles, each wound with a coil; the coils are grouped into phases (A, B, C, ...). When one phase is energized, the nearest rotor teeth align with that stator pole pair (minimum reluctance / magnetic attraction position). By energizing the phases in a proper sequence (switching pattern), the rotor is pulled step-by-step from one aligned position to the next, in the direction of the switching sequence. Reversing the switching sequence reverses the direction of rotation.

$$\text{Step angle } (\theta) = 360^\circ / (\text{Number of rotor teeth} \times \text{Number of phases}) \quad [\text{for VR type}]$$

Characteristics

- Operates in open-loop mode — no feedback sensor is needed to know rotor position, since each pulse produces a known, fixed step.
- Excellent for precise positioning; step angle typically 0.9°, 1.8°, 7.5°, 15° etc.
- Holding torque keeps the rotor firmly in position even when not rotating (with a phase still energized).
- Can suffer from 'missed steps' if driven too fast for the load/torque available.

Applications

- Computer printers, plotters, and scanners

- CNC machines and robotics (precise positioning of tools/arms)
- Floppy/optical disk drives, camera auto-focus and aperture control
- Textile machinery and process control valves

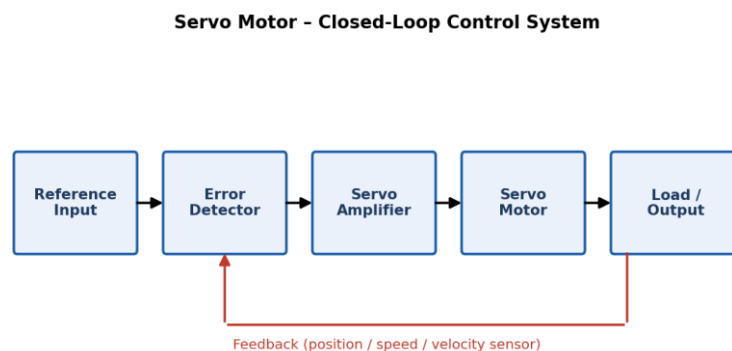
Servo Motor

A servo motor is an electromechanical device used in a closed-loop (feedback) control system to achieve precise control of angular (or linear) position, velocity, and acceleration, by continuously comparing the actual output with the desired command signal and correcting any error.

Types of Servo Motors

- **DC Servo Motor:** A specially designed DC motor (armature-controlled or field-controlled) with low rotor inertia and linear torque-speed characteristics for fast, accurate response.
- **AC Servo Motor:** Usually a 2-phase induction motor (for small servo systems) or a permanent-magnet synchronous/brushless motor (for higher power industrial servo systems); requires no brushes, giving longer life and less maintenance.

Principle of Operation (Closed-Loop Control)



1. A reference (command) input specifies the desired position/speed.
2. The error detector compares this command with the feedback signal from a sensor (encoder, tachogenerator, or potentiometer) mounted on the motor/load shaft, and produces an error signal.
3. The servo amplifier amplifies this (usually small) error signal to a level sufficient to drive the motor.
4. The servo motor rotates the load in the direction that reduces the error.
5. The feedback sensor continuously reports the actual position/speed back to the error detector, and the process repeats until the error becomes (near) zero.

Characteristics

- Closed-loop (feedback) system — always aware of actual output and self-corrects, unlike the open-loop stepper motor.
- High torque-to-inertia ratio → fast acceleration/deceleration, quick response to command changes.
- Linear torque-speed characteristic over the operating range, giving smooth and controllable operation.
- Very high positioning accuracy, since errors are continuously measured and corrected.

Applications

- Industrial robots and robotic arms
- CNC machine tools (precise tool/table positioning)
- Radar and antenna positioning systems
- Automated packaging, conveyor, and process-control systems
- Elevators and precision manufacturing equipment

Stepper Motor vs Servo Motor

Feature	Stepper Motor	Servo Motor
Control loop	Open loop (no feedback)	Closed loop (feedback sensor used)
Positioning accuracy	Good, but can lose steps under overload	Very high — continuously corrected
Torque at low speed	High	Moderate to high
Speed range	Low to moderate	Wide (low to very high)
Cost & complexity	Simple, low cost	More complex, higher cost (needs sensor & controller)
Typical use	Printers, low-cost positioning tasks	Robotics, CNC, high-performance motion control

Permanent Magnet Brushless DC (PMBLDC) Motor

Introduction

A Permanent Magnet Brushless DC (PMBLDC) motor is a synchronous machine in which the field excitation is provided by permanent magnets mounted on the rotor, and the mechanical commutator-brush assembly of a conventional DC motor is replaced by electronic commutation using power semiconductor switches and rotor position sensors. Despite being fundamentally an AC synchronous machine, it is called 'brushless DC' because its external characteristics — linear torque-speed relation and DC supply operation — closely resemble those of a conventional PMDC motor.

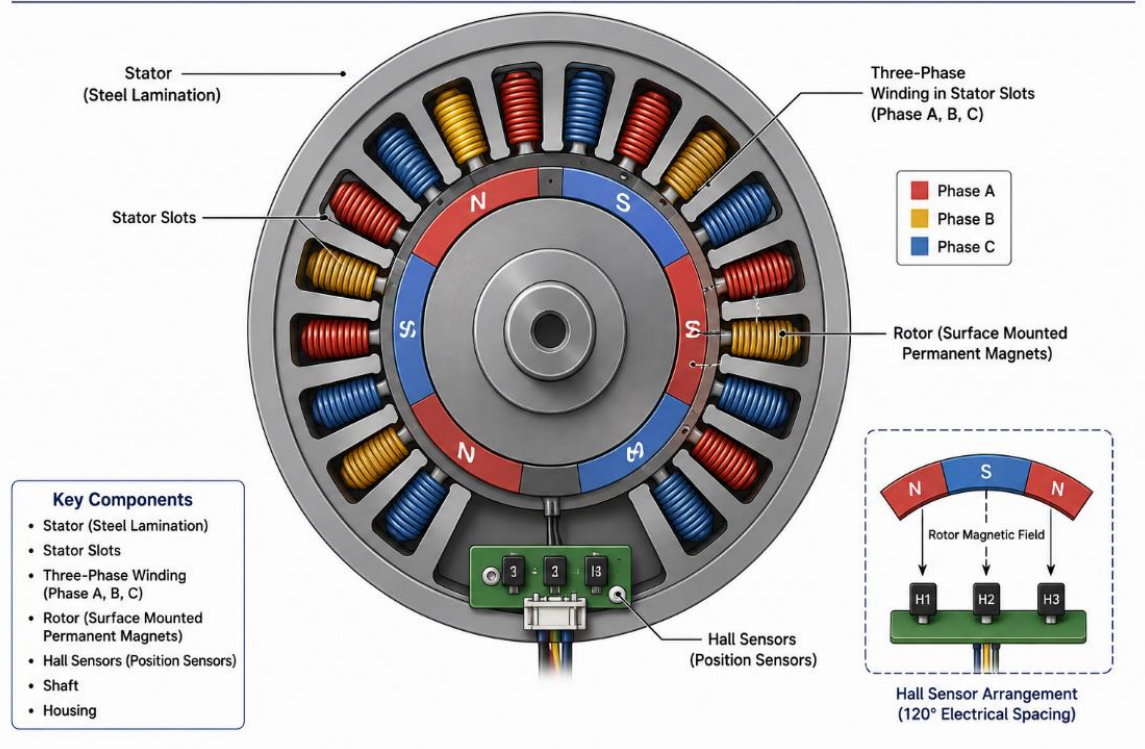
Construction

The PMBLDC motor has two main parts:

- **Stator:** Made of laminated silicon steel with axial slots carrying a three-phase (or occasionally single/two-phase) star or delta connected armature winding, similar to an induction motor stator. The winding is distributed or concentrated to produce a trapezoidal (or quasi-square) MMF/back-EMF waveform.

- Rotor: Consists of permanent magnets (Ferrite, Alnico, or high-energy rare-earth magnets such as Samarium-Cobalt or Neodymium-Iron-Boron) arranged as Surface Mounted (SPM), Inset, or Interior/Buried (IPM) configurations, providing 2, 4, 6 or more poles.
- Position sensors: Typically three Hall-effect sensors placed 120° apart (electrical) on the stator to sense rotor position and provide commutation signals; optical encoders or resolvers may be used in high-precision drives; some modern designs use sensorless back-EMF detection.

PMBLDC Motor – Cross-Sectional Construction



Principle of Operation

Unlike a conventional DC motor where commutation is mechanical (via brushes and commutator segments), in a PMBLDC motor the stator winding currents are electronically switched (commutated) in synchronism with rotor position, sensed by Hall sensors. A three-phase bridge inverter energizes two of the three phases at any instant (120° conduction mode) such that the resultant stator MMF remains approximately 90° electrical degrees ahead of the rotor magnet axis, producing maximum torque. As the rotor rotates, the Hall sensor outputs change state, triggering the switching sequence of the six power devices (Q1–Q6) of the inverter — this process is called electronic commutation.

Drive / Power Converter Circuit

The motor is fed from a DC source through a three-phase voltage source inverter (six-step / 120° conduction inverter) built using MOSFETs or IGBTs. The Hall sensor signals (each 60° apart) are decoded by a commutation logic/microcontroller to generate the correct gating sequence for the six switches, producing a stepped, quasi-square current waveform in each phase synchronized with the trapezoidal back-EMF, which yields ideally ripple-free electromagnetic torque.

EMF and Torque Equations

Back EMF: $e = k_e \cdot \phi \cdot \omega_m$ (trapezoidal waveform, $k_e = \text{EMF constant}$)

Electromagnetic Torque: $T_e = k_t \cdot \phi \cdot I_a$ ($k_t = \text{torque constant}$, ideally $k_t = k_e$)

Power developed: $P = T_e \cdot \omega_m = e_a \cdot i_a + e_b \cdot i_b + e_c \cdot i_c$

Because two phases conduct simultaneously and carry equal, constant current during each 120° interval while flux density under the poles is nearly uniform, the torque produced is essentially constant (ripple-free in the ideal case), unlike the sinusoidal PMSM which needs vector control for smooth torque.

Types of PMBLDC Motors

- Based on Back-EMF waveform: Trapezoidal (BLDC) and Sinusoidal (PMSM/BLAC).
- Based on Rotor construction: Surface mounted magnet (SPM), Inset magnet, Interior/Buried magnet (IPM).
- Based on stator-rotor arrangement: Inner rotor (conventional) and Outer rotor (used in fans, hub motors).
- Based on air-gap flux direction: Radial-flux and Axial-flux (disc-type) BLDC motors.

Torque–Speed Characteristics

The PMBLDC motor exhibits an almost linear torque–speed characteristic similar to a shunt DC motor: speed decreases marginally with increase in load torque up to the rated torque, beyond which it enters an intermittent/peak-torque region limited by winding current and demagnetization limits of the magnets.

Advantages

- No brushes or commutator — eliminates sparking, brush wear, and maintenance.
- Higher efficiency (no field/rotor copper loss, no brush friction loss).
- Better speed–torque characteristics, higher torque-to-inertia and torque-to-weight ratio.
- Longer life, quieter operation, higher speed capability, and reduced electromagnetic interference (EMI) from arcing.
- Good heat dissipation as the winding is on the stator (easier to cool).

Disadvantages

- Higher initial cost due to permanent magnets (especially rare-earth) and electronic controller.
- Requires a dedicated inverter and position sensor/estimation, increasing control complexity.
- Possible demagnetization of magnets at high temperature or heavy overload.
- Limited constant-power (field-weakening) speed range compared with wound-field machines.

Applications

- Computer hard-disk drives, CD/DVD drives, cooling fans.
- Electric vehicles and hybrid vehicles (traction motor), e-bikes, e-scooters.
- Industrial servo drives, robotics, CNC machine spindles.
- Aerospace actuators, medical equipment, home appliances (washing machines, mixers, air conditioners — inverter ACs).

Comparison: PMBLDC vs Conventional DC Motor

Parameter	Conventional DC Motor	PMBLDC Motor
Commutation	Mechanical (brush + commutator)	Electronic (inverter + position sensor)
Maintenance	High (brush wear)	Low / negligible
Field source	Field winding or PM (stator)	Permanent magnet (rotor)
Armature location	Rotor	Stator
Efficiency	Moderate	High
Speed range	Limited by commutator sparking	Very high speeds possible
Cost	Lower	Higher (magnets + electronics)

Stepper Motor

A stepper (stepping) motor is a special electromechanical device that converts a train of electrical input pulses into precise, discrete mechanical shaft rotations called 'steps.' Each pulse applied to the stator winding advances the rotor by a fixed angle (the step angle); hence the shaft position and speed can be controlled accurately in open loop without feedback, making stepper motors ideal for digital and computer-controlled positioning systems.

Classification / Types

Stepper motors are broadly classified into three types based on rotor construction:

1. Variable Reluctance (VR) Stepper Motor — soft-iron toothed rotor with no magnets; rotor aligns to minimize reluctance of the magnetic path.
2. Permanent Magnet (PM) Stepper Motor — rotor is a permanent magnet (often multi-pole, 'can-stack' construction); rotor aligns with the stator pole of opposite polarity.
3. Hybrid Stepper Motor — combines VR and PM principles; toothed rotor magnetized axially, giving fine step angles (typically 1.8°) with high torque and holding power. Most widely used commercially.

Construction and Working

Variable Reluctance (VR) Stepper Motor

The stator has salient poles wound with concentrated coils; the rotor is a multi-toothed soft-magnetic-steel structure with no windings or magnets. When a stator phase is energized, the nearest rotor teeth are pulled into alignment with the energized stator poles to minimize the reluctance of the magnetic circuit. Sequentially energizing the phases in a fixed order rotates the rotor step-by-step. Since there is no residual magnetism, the rotor has no holding torque when unexcited.

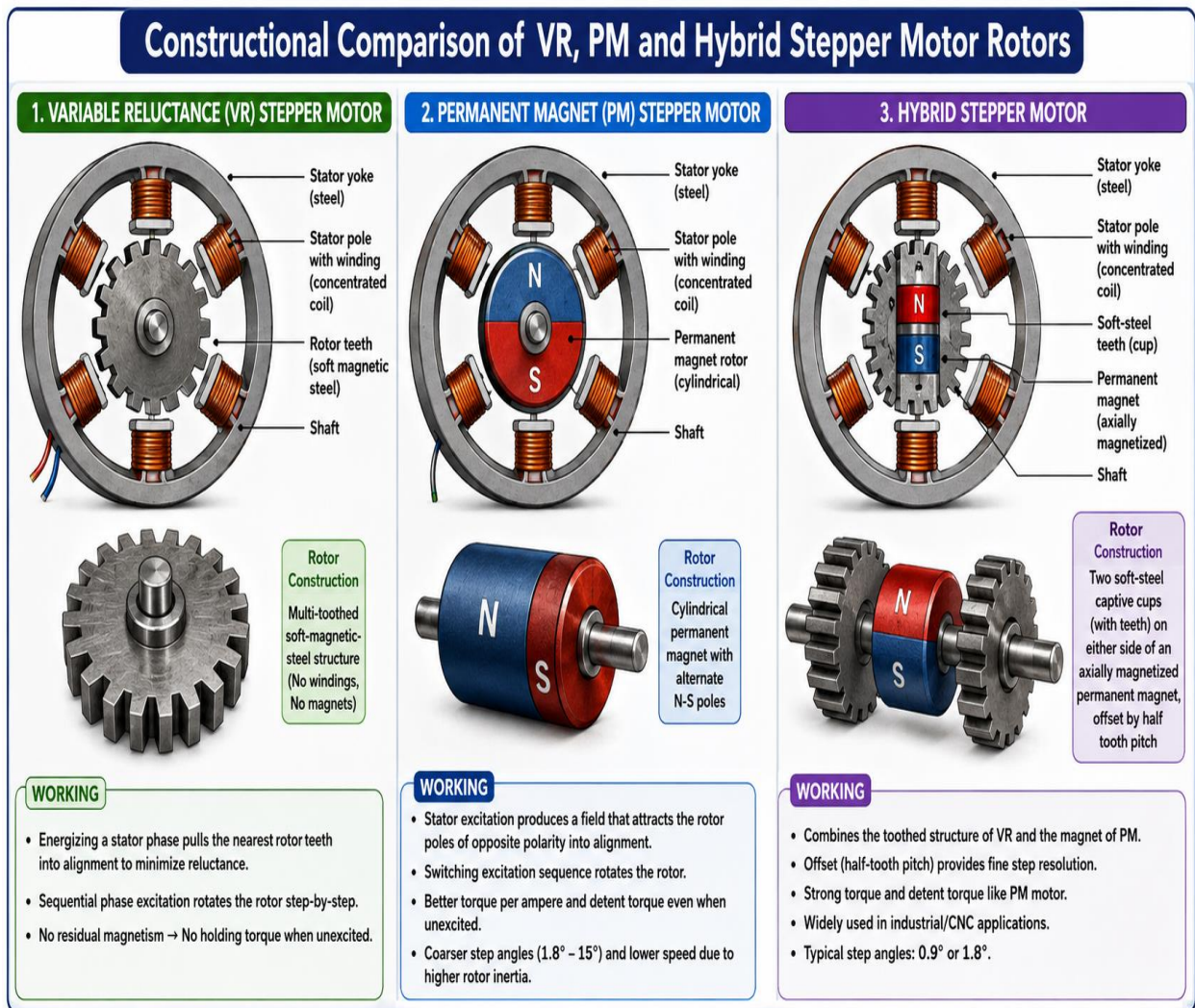
Permanent Magnet (PM) Stepper Motor

The rotor is a cylindrical permanent magnet with alternate N-S poles. Energizing a stator phase creates a magnetic field that attracts the rotor poles of opposite polarity into alignment. Reversing/switching the stator excitation sequence rotates the rotor. PM motors provide better torque per ampere and detent (holding)

torque even when unexcited, but coarser step angles (typically 1.8° – 15°) and lower speed compared to VR motors owing to rotor inertia.

Hybrid Stepper Motor

The rotor consists of two soft-steel cups (with teeth) mounted on either side of an axially magnetized permanent magnet, offset by half a tooth pitch. This combines the fine step resolution of the VR motor's toothed structure with the strong torque and detent torque of the PM motor. Hybrid motors dominate industrial/CNC applications with typical step angles of 0.9° or 1.8° .



Step Angle Calculation

$$\text{Step angle, } \beta = 360^\circ / (m \times N_r)$$

where m = number of stator phases and N_r = number of rotor teeth (poles).

$$\text{Number of steps per revolution} = 360^\circ / \beta = m \times N_r$$

$$\text{Resolution (steps/rev) with half-stepping} = 2 \times m \times N_r$$

Modes of Excitation

- Single-phase (Wave) excitation — only one phase energized at a time; simple but low torque and poor damping.

- Two-phase-ON excitation — two adjacent phases energized simultaneously; gives higher torque (≈ 1.4 times) and better stability, same step angle as single-phase mode.
- Half-step excitation — alternately switching between one-phase-ON and two-phase-ON states; doubles the resolution (halves the effective step angle) at the cost of slightly non-uniform torque.
- Microstepping — proportioning current between adjacent phases using PWM to achieve very fine, smooth sub-step positioning and reduced resonance/vibration.

Torque Equation and Characteristics

The instantaneous torque of a stepper motor is derived from the rate of change of co-energy with rotor position:

$$T = (i^2 / 2) \cdot (dL/d\theta)$$

Static torque–displacement characteristic is approximately sinusoidal, given by $T = T_{\max} \sin(N_r \cdot \theta)$, where θ is the rotor displacement from equilibrium. Key characteristic curves used in analysis are: (a) Static torque vs rotor displacement curve, (b) Pull-in torque–speed curve (motor can start, stop, reverse without losing steps), and (c) Pull-out torque–speed curve (maximum torque motor can sustain at a given stepping rate without losing synchronism).

Advantages

- Precise open-loop positioning without feedback sensors — compatible directly with digital pulses.
- Excellent low-speed torque and instant start/stop/reverse capability.
- No cumulative positioning error; robust and low maintenance (brushless).
- Compatible with microprocessor/microcontroller control.

Disadvantages

- Resonance and vibration problems at certain stepping rates.
- Can lose synchronism ('step loss') under sudden overload with no feedback to detect it.
- Efficiency and torque fall off rapidly at high speeds.
- Produces audible noise at some stepping frequencies.

Applications

- Computer peripherals — printers, plotters, scanners, disk drives.
- CNC machine tools, 3-D printers, robotics, camera auto-focus/aperture control.
- Textile machinery, process control valves, X-Y positioning tables, ATMs, and instrumentation.

Linear Induction Motor (LIM)

A Linear Induction Motor (LIM) is obtained conceptually by cutting a conventional rotary induction motor along a radius and unrolling it flat, converting the rotating air-gap magnetic field into a magnetic field that travels linearly along a straight path. Instead of producing rotary torque, the LIM produces a linear thrust (force) directly, eliminating the need for mechanical gears, belts, or rotary-to-linear converters (rack-and-pinion, screw, etc.).

Construction

A LIM has two main members, analogous to the stator and rotor of a rotary induction motor:

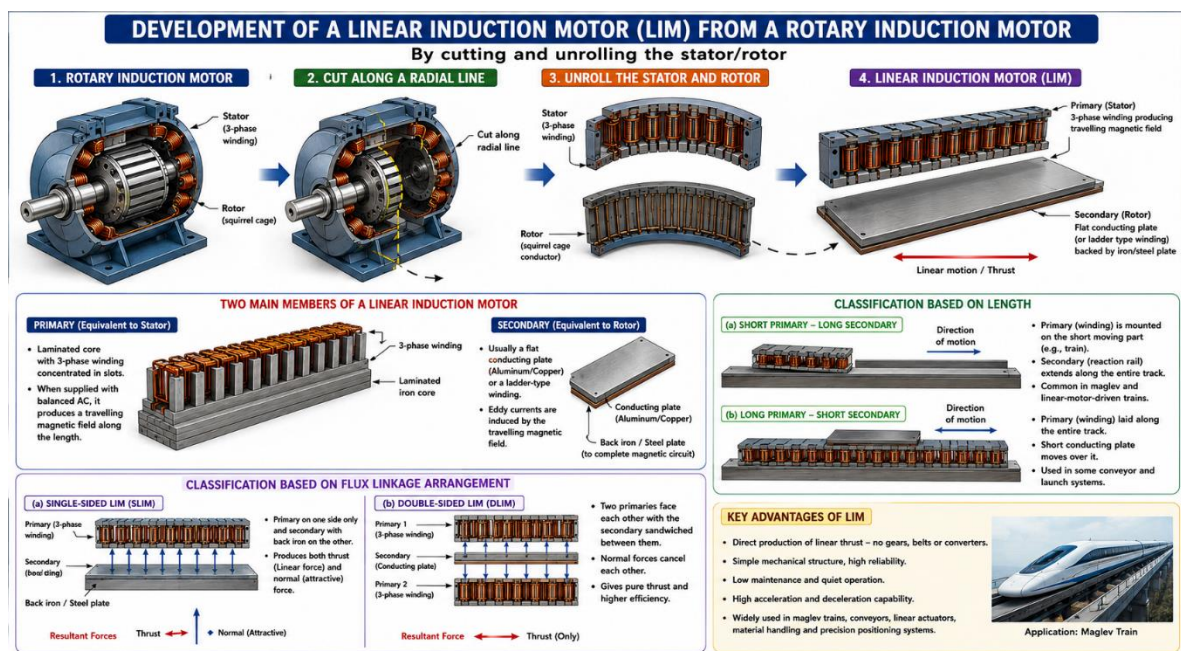
- Primary (equivalent to stator): A laminated core carrying a polyphase winding, producing a traveling magnetic field when supplied with a balanced AC supply.
- Secondary (equivalent to rotor): Usually a flat conducting plate or a ladder-type winding (aluminum/copper sheet, sometimes backed by an iron/steel plate to complete the magnetic circuit), in which eddy currents are induced by the traveling field.

Based on relative lengths of primary and secondary, LIMs are classified as:

- Short Primary, Long Secondary — primary (winding) is mounted on the short moving part (e.g., train), secondary (reaction rail) extends along the entire track. Common in maglev and linear-motor-driven trains.
- Long Primary, Short Secondary — winding laid along the entire track while a short conducting plate moves; used in some conveyor and launch systems.

Based on flux linkage arrangement, LIMs are also classified as:

- Single-sided LIM (SLIM) — primary on one side only, secondary (reaction plate with back iron) on the other; produces both thrust and a normal (attractive) force.
- Double-sided LIM (DLIM) — two primaries face each other with the secondary sandwiched between them; normal forces cancel, giving pure thrust and higher efficiency.



Principle of Operation

When the polyphase primary winding is energized from a balanced AC supply, it produces a magnetic field that travels linearly along the primary at synchronous linear speed instead of rotating. This traveling field cuts the conductors of the secondary (reaction plate), inducing eddy currents in it (Faraday's law). By Lenz's law, these induced currents interact with the traveling field to produce a force that drags the secondary along in the direction of the traveling field (or drags the primary if the secondary is fixed, as in linear-motor propelled vehicles), exactly analogous to the rotor being dragged by the rotating field in a normal induction motor.

Synchronous Linear Speed and Slip

$$\text{Synchronous linear speed: } V_s = 2 \cdot \tau \cdot f$$

where τ = pole pitch (m), f = supply frequency (Hz).

$$\text{Slip: } s = (V_s - V) / V_s$$

where V = actual linear velocity of the secondary (or vehicle).

End Effects (Special Feature of LIM)

Because the primary has a finite length (unlike the closed magnetic path of a rotary machine), the LIM suffers from 'end effects': as the secondary enters and leaves the primary field region, entry and exit transients distort the air-gap flux distribution, reduce useful thrust, increase losses, and lower efficiency and power factor, especially at high speeds and small pole numbers. This is a phenomenon unique to linear machines and does not occur in rotary induction motors.

Equivalent Circuit and Thrust Equation

The per-phase equivalent circuit of a LIM is similar to that of a rotary induction motor (primary resistance R_1 , primary leakage reactance X_1 , magnetizing branch, secondary resistance R_2'/s , and secondary leakage reactance X_2' referred to primary), modified to include end-effect correction factors.

$$\text{Thrust, } F = P_{ag} / V_s \quad (P_{ag} = \text{air-gap power, } V_s = \text{synchronous linear speed})$$

$$F = (3 \cdot I_2'^2 \cdot R_2'/s) / V_s$$

Advantages

- Direct linear thrust — no gearbox, crank, or rotary-to-linear converter needed; frictionless (non-contact) propulsion possible.
- High acceleration/deceleration, silent operation, low maintenance (no mechanical wear between primary and secondary).
- Suitable for high-speed transportation with magnetic levitation (maglev), removing wheel-rail friction limitations.

Disadvantages

- Lower efficiency and power factor than rotary induction motors due to large effective air gap and end effects.
- Higher cost of installation for long-track applications (long secondary/reaction rail).
- Requires sophisticated power-electronic variable-frequency drives for speed control.

Applications

- Maglev (magnetic levitation) trains and other linear-motor-propelled transit systems.
- Conveyor systems, sliding door actuators, baggage handling systems at airports.
- Electromagnetic launch systems, actuators for automation and material handling, pumping of liquid metals (electromagnetic pumps).

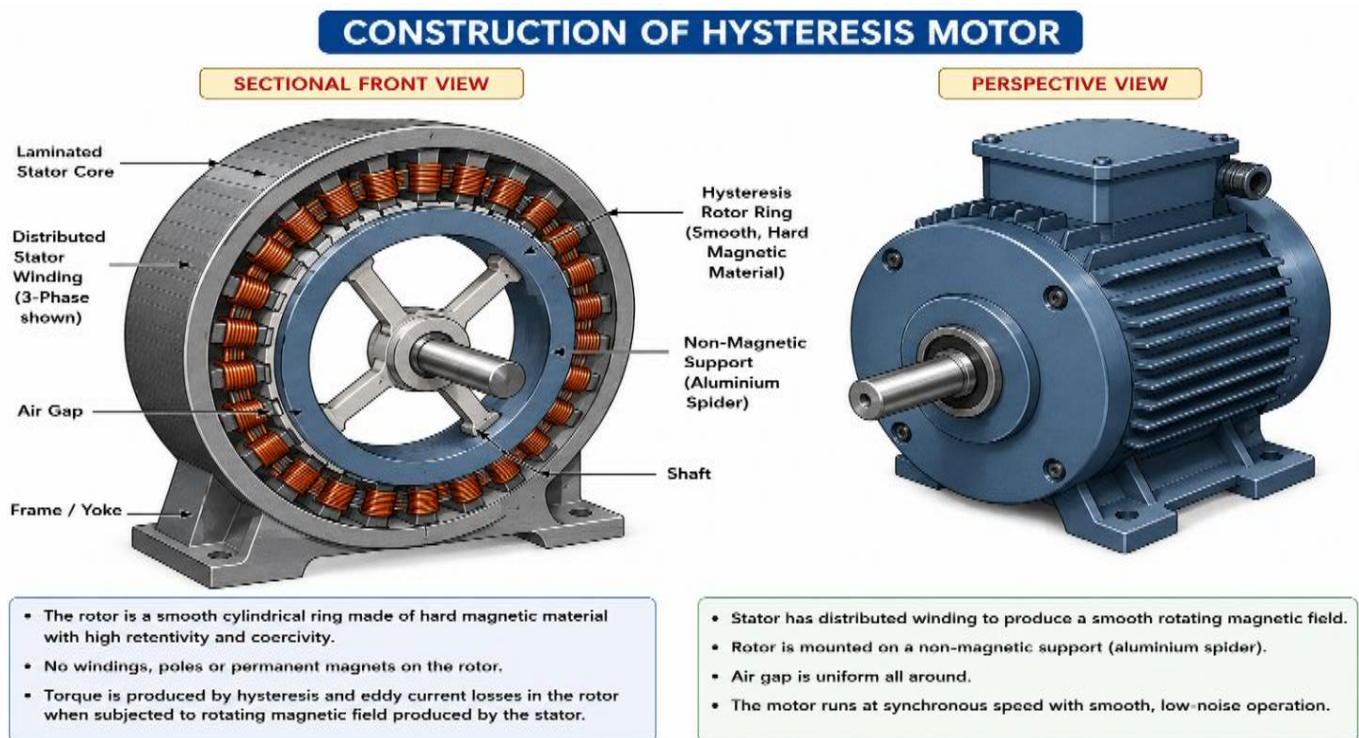
Hysteresis Motor

A hysteresis motor is a single/two-phase synchronous motor which develops its torque purely from the hysteresis and eddy-current losses induced in a rotor made of hard magnetic material (high retentivity/high coercivity), without any winding, salient poles, or permanent magnets on the rotor. It is unique in being able

to start as an induction-type (asynchronous) motor and run at exact synchronous speed with a perfectly smooth, low-noise, and low-vibration output — hence its use in precision timing and instrumentation applications.

Construction

- **Stator:** Consists of a laminated core with a distributed (or shaded-pole) winding designed to produce a smooth rotating magnetic field. For single-phase supply, an auxiliary winding with a capacitor is used to obtain a rotating field, similar to a capacitor-run induction motor.
- **Rotor:** A smooth, cylindrical, unslotted ring made of a magnetically hard material with a wide hysteresis loop (high retentivity and coercivity), such as chrome steel, cobalt steel, or Alnico, mounted on a non-magnetic (e.g., aluminum) spider/shaft. There is no squirrel-cage winding.



Principle of Operation

The rotating stator field magnetizes the hard-magnetic rotor material cyclically. Because the material has a wide hysteresis loop, the induced magnetization (B) lags behind the applied rotating field (H) by a hysteresis lag angle δ_h . This lag angle causes the rotor's magnetic axis to always trail the stator's rotating field axis by δ_h , producing a continuous unidirectional torque, called hysteresis torque, that is independent of rotor speed/slip — it remains constant from standstill right up to synchronous speed.

In addition, eddy currents induced in the solid rotor material produce an eddy-current torque component, which — like an induction motor — is maximum at standstill and decreases as speed rises, becoming zero at synchronous speed. The sum of these two torque components (hysteresis torque, constant, plus eddy-current torque, speed-dependent) is what accelerates the rotor from standstill; once the rotor reaches synchronous speed, only the constant hysteresis torque continues to act (locking the rotor magnetically in synchronism with the rotating field), while eddy-current torque vanishes.

Torque–Speed Characteristics

The distinctive torque-speed curve of the hysteresis motor shows: (a) constant torque (equal to the hysteresis torque component) from standstill ($N = 0$) up to synchronous speed ($N = N_s$) — a straight horizontal line, unlike the induction motor's characteristic which peaks and dips; and (b) an additional eddy-current torque component superimposed at lower speeds that decays to zero at N_s . Because starting torque equals full-load (running) torque, the hysteresis motor can smoothly accelerate any load it can run, including high-inertia loads, without hunting or oscillation, and it locks into synchronism automatically without any additional starting/pull-in mechanism, unlike reluctance synchronous motors.

$$\text{Hysteresis torque, } T_h = k_h \cdot \phi^2 \cdot \sin \delta_h \text{ (approximately constant, independent of slip)}$$

Phasor / Working Explanation

The lag angle δ_h between the rotor's induced magnetization and the stator's rotating MMF wave is determined by the hysteresis-loop area (coercivity) of the rotor material and is essentially independent of rotor speed, which explains why the developed torque remains constant across the entire speed range from zero to synchronous speed.

Advantages

- Smooth, vibration-free, quiet acceleration and truly synchronous running speed with no hunting.
- Starting torque equal to running (pull-out) torque — can start and synchronize any load within its rating, including high-inertia loads.
- Simple, rugged rotor construction (no windings, no permanent magnets, no squirrel cage) — inherently very reliable and requires negligible maintenance.
- Self-starting without special starting arrangements.

Disadvantages

- Low efficiency and low power factor compared with other synchronous motors.
- Low output torque/power for a given frame size (used only for small fractional and sub-fractional horsepower ratings).
- Higher cost of special hard magnetic rotor material.

Applications

- Electric clocks, timers, record players/turntables, tape recorders, and other precision timing devices requiring constant synchronous speed.
- Sound-recording/reproducing equipment, gyroscopes, and other instruments needing smooth, hunting-free rotation.
- Small servo and control applications where synchronism with silent, low-vibration operation is essential.

Introduction to Electric Vehicle (EV)

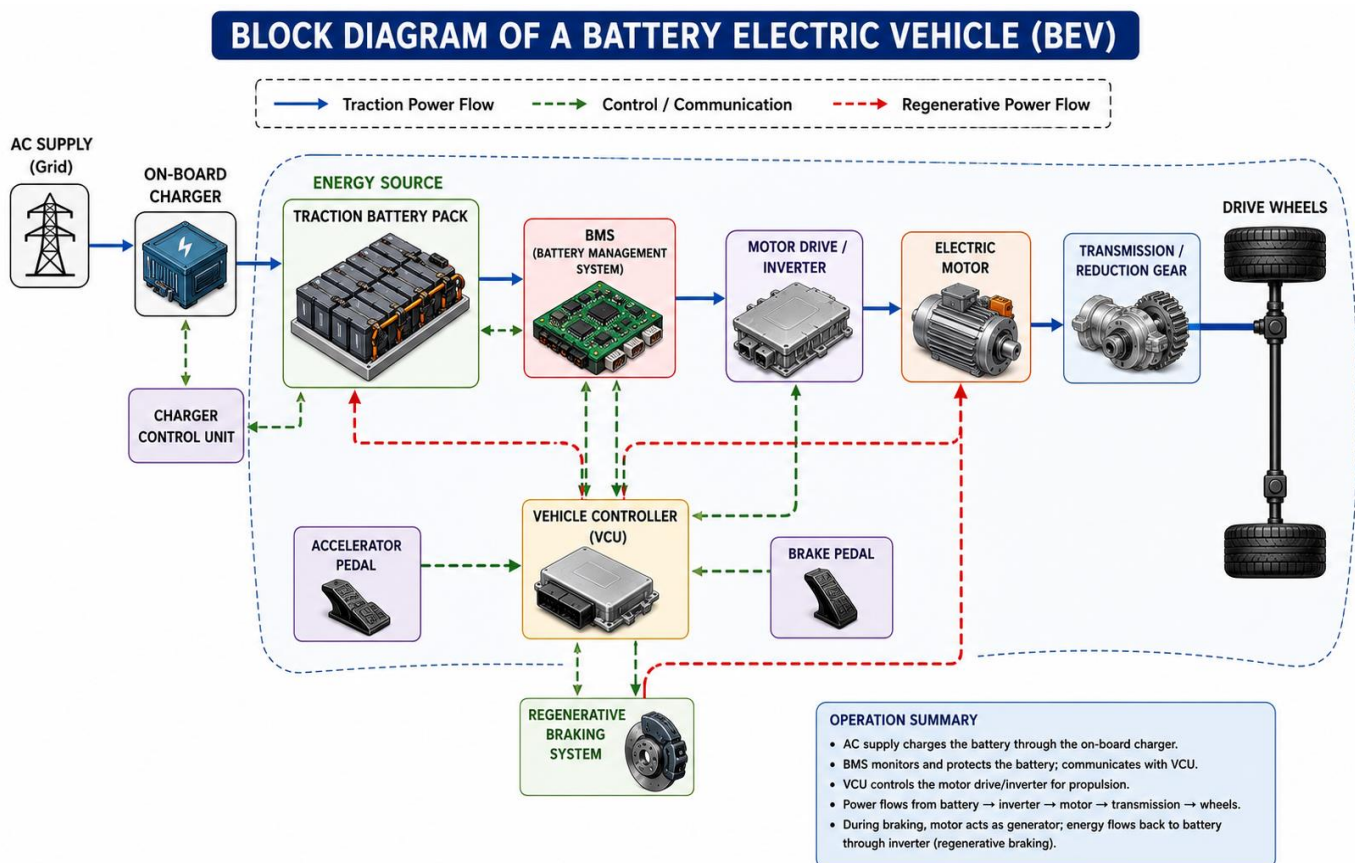
An Electric Vehicle (EV) is a vehicle that uses one or more electric motors, powered from an on-board rechargeable energy source (battery, fuel cell, or ultracapacitor), for propulsion, either partially or wholly replacing the internal combustion engine (ICE). The push toward EVs is driven by depleting fossil-fuel reserves, rising crude-oil prices, the need to curb greenhouse-gas emissions and urban air pollution, the higher efficiency of electric drivetrains compared to ICEs, and rapid advances in battery and power-electronics technology that have improved range and reduced cost.

Classification of Electric Vehicles

- Battery Electric Vehicle (BEV) — fully electric; propulsion entirely from a battery pack charged from the electric grid; zero tailpipe emission (e.g., pure EV cars).
- Hybrid Electric Vehicle (HEV) — combines an ICE and an electric motor/battery; battery is charged by the ICE and regenerative braking, not from an external plug. Configurations: Series, Parallel, and Series-Parallel (combined) hybrid.
- Plug-in Hybrid Electric Vehicle (PHEV) — similar to HEV but the battery can additionally be charged from an external electrical outlet, giving a limited all-electric range before the ICE engages.
- Fuel Cell Electric Vehicle (FCEV) — uses a hydrogen fuel cell stack to generate electricity on-board (through an electrochemical reaction with oxygen) to power the electric motor, emitting only water vapor.

Basic Configuration / Block Diagram of an EV

The essential subsystems of a typical BEV drivetrain are arranged as: Energy Source (battery pack) → Battery Management System (BMS) → Power Converter/Controller (bidirectional DC-DC and DC-AC inverter) → Electric Motor (traction motor, often PMBLDC/PMSM or induction motor) → Transmission/Differential → Wheels. A separate on-board/off-board Charger interfaces the battery with the electric grid, and an auxiliary energy source (or supercapacitor) may support peak power demand and regenerative braking energy recovery.



Major Components

- Energy Source: Batteries (Lead-acid, Nickel-Metal Hydride, Lithium-ion, Lithium-polymer), fuel cells, or ultracapacitors — chosen based on specific energy, specific power, cycle life, and cost.
- Battery Management System (BMS): Monitors state of charge (SOC), state of health (SOH), cell balancing, temperature, and protects against overcharge/over-discharge.

- **Power Electronic Converter/Controller:** Regulates power flow between battery and motor (inverter for AC motors, chopper for DC motors); enables variable-speed operation and regenerative braking.
- **Electric Traction Motor:** Converts electrical energy to mechanical propulsion; commonly PMSM, induction motor, or switched reluctance motor, selected for high torque density, efficiency, and wide speed range.
- **Transmission System:** Often a single-speed fixed-ratio gear/differential (due to the wide constant-torque and constant-power speed range of electric motors), unlike the multi-speed gearbox needed for ICE vehicles.
- **Charging System:** On-board/off-board chargers (AC slow charging, DC fast charging) that convert grid AC power to the DC required to charge the battery.
- **Regenerative Braking System:** Recovers kinetic energy during braking/deceleration by operating the traction motor as a generator, feeding energy back to the battery, thereby improving overall efficiency and range.

Advantages of Electric Vehicles

- Zero (BEV) or significantly reduced (HEV/PHEV) tailpipe emissions, improving urban air quality.
- Higher overall drivetrain (well-to-wheel) efficiency compared to ICE vehicles.
- Lower running cost per kilometer, fewer moving parts, and reduced maintenance (no engine oil, exhaust system, or clutch).
- Quiet operation and instant torque availability from zero speed, giving good low-speed acceleration.
- Compatible with renewable electricity generation, further reducing net carbon footprint.

Challenges / Limitations

- Limited driving range per charge (range anxiety) compared to refueling an ICE vehicle.
- Long battery charging time compared to conventional refueling, and inadequate public charging infrastructure in many regions.
- High initial cost, primarily due to the battery pack.
- Battery degradation over charge–discharge cycles, limited life, and end-of-life recycling/disposal concerns.
- Added weight of the battery pack, and dependency on availability of critical materials (lithium, cobalt, rare-earth magnets).

Comparison of EV Types

Feature	BEV	HEV	PHEV	FCEV
Energy source	Battery only	ICE + Battery	ICE + Battery (plug-in)	Hydrogen fuel cell
External charging	Yes	No	Yes	No (H2 refuelling)
Tailpipe emission	Zero	Reduced	Reduced	Water vapour only
All-electric range	Full range	Very limited/none	Limited (20–80 km)	Full range
Typical use	City/highway EVs	Fuel-efficient hybrids	Flexible hybrids	Emerging/long-range

Future Scope

The future of EV technology is oriented toward higher energy-density solid-state batteries, ultra-fast charging infrastructure, wireless/inductive charging, vehicle-to-grid (V2G) energy exchange, increased use of wide-bandgap (SiC/GaN) power electronics for higher efficiency converters, and greater integration of renewable