

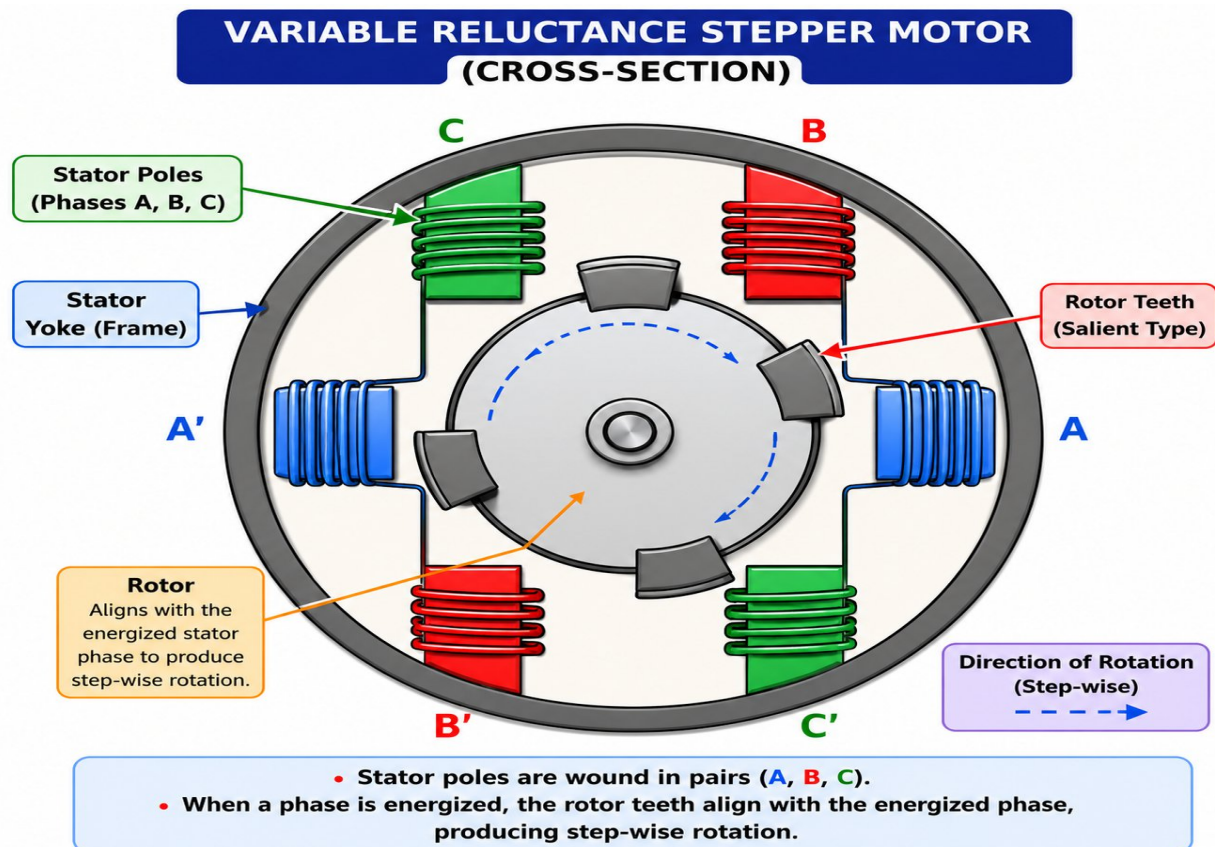
Special Machines

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.

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

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

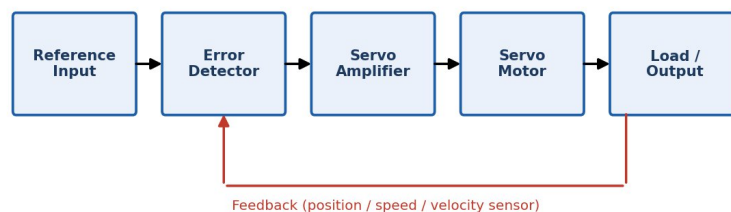
A servo motor is an electromechanical device used in a closed-loop (feedback) control system to achieve precise control of angular (or linear) position, velocity, and acceleration, by continuously comparing the actual output with the desired command signal and correcting any error.

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)

Servo Motor - Closed-Loop Control System



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

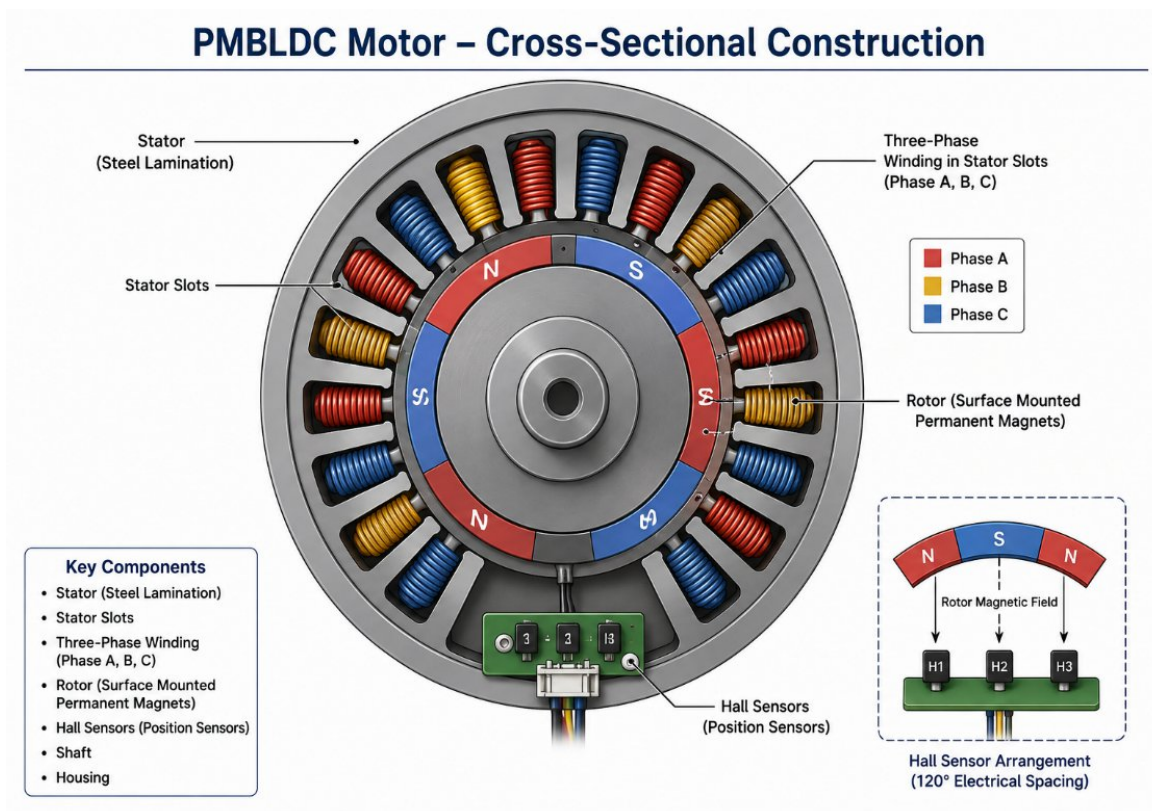
Introduction

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.



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

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

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

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

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

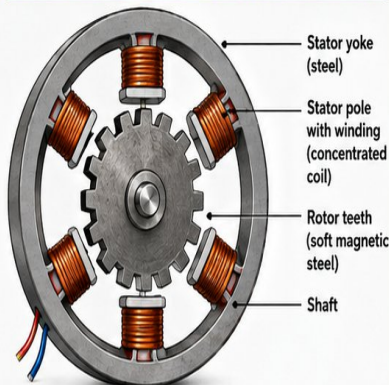
The rotor is a cylindrical permanent magnet with alternate N-S poles. Energizing a stator phase creates a magnetic field that attracts the rotor poles of opposite polarity into alignment. Reversing/switching the stator excitation sequence rotates the rotor. PM motors provide better torque per ampere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

Constructional Comparison of VR, PM and Hybrid Stepper Motor Rotors

1. VARIABLE RELUCTANCE (VR) STEPPER MOTOR

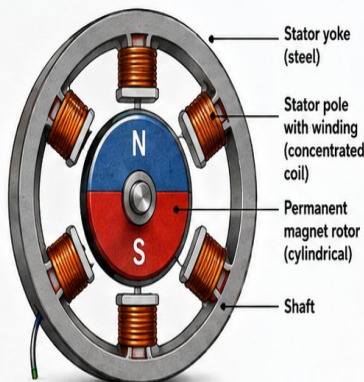


Rotor Construction
Multi-toothed soft-magnetic-steel structure (No windings, No magnets)

WORKING

- Energizing a stator phase pulls the nearest rotor teeth into alignment to minimize reluctance.
- Sequential phase excitation rotates the rotor step-by-step.
- No residual magnetism → No holding torque when unexcited.

2. PERMANENT MAGNET (PM) STEPPER MOTOR

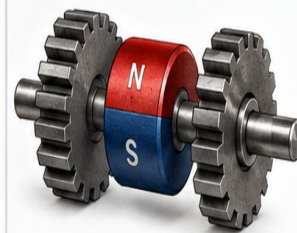
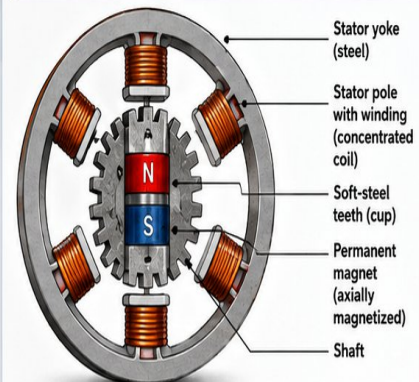


Rotor Construction
Cylindrical permanent magnet with alternate N-S poles

WORKING

- Stator excitation produces a field that attracts the rotor poles of opposite polarity into alignment.
- Switching excitation sequence rotates the rotor.
- Better torque per ampere and detent torque even when unexcited.
- Coarser step angles ($1.8^\circ - 15^\circ$) and lower speed due to higher rotor inertia.

3. HYBRID STEPPER MOTOR



Rotor Construction
Two soft-steel captive cups (with teeth) on either side of an axially magnetized permanent magnet, offset by half tooth pitch

WORKING

- Combines the toothed structure of VR and the magnet of PM.
- Offset (half-tooth pitch) provides fine step resolution.
- Strong torque and detent torque like PM motor.
- Widely used in industrial/CNC applications.
- Typical step angles: 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:

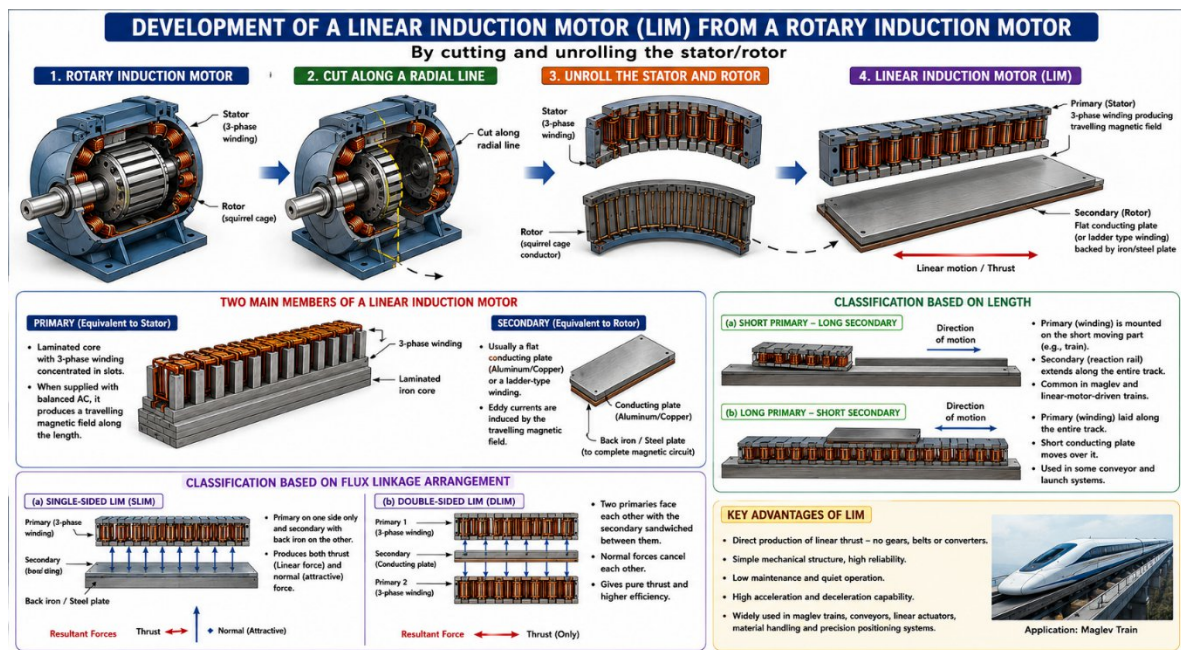
- Primary (equivalent to stator): A laminated core carrying a polyphase winding, producing a traveling magnetic field when supplied with a balanced AC supply.
- Secondary (equivalent to rotor): Usually a flat conducting plate or a ladder-type winding (aluminum/copper sheet, sometimes backed by an iron/steel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

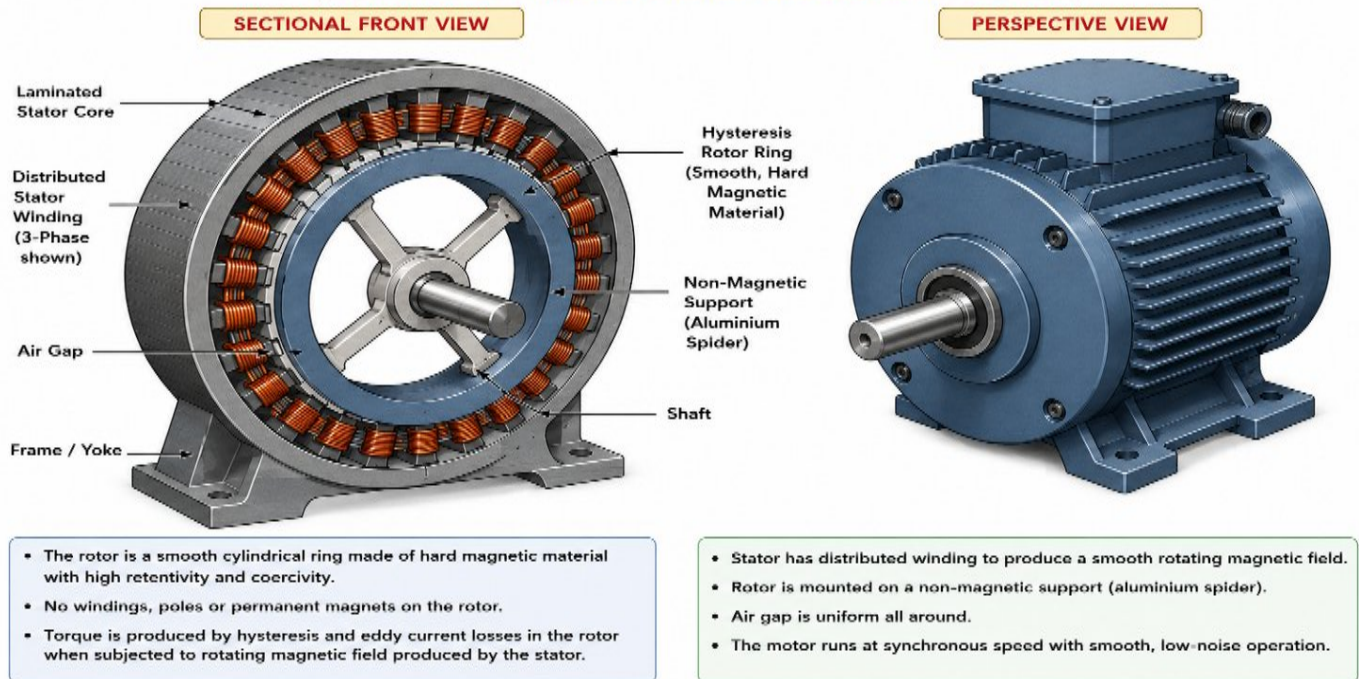
Hysteresis Motor

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.

CONSTRUCTION OF HYSTERESIS MOTOR



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.