Basic Electrical Technology

[ELE 1051]

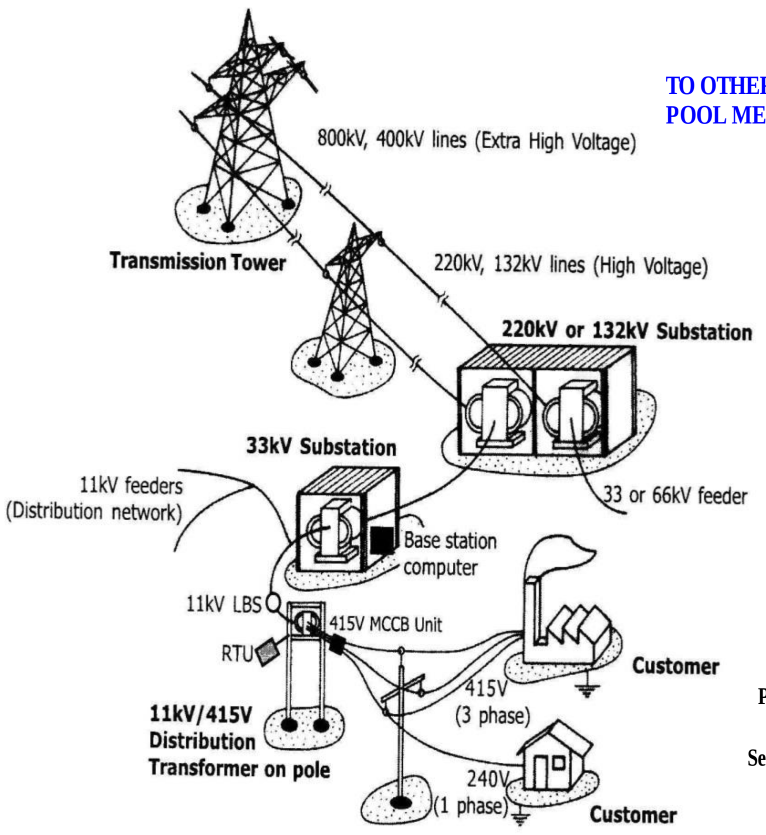
CHAPTER 5 – ELECTRICAL POWER SYSTEM COMPONENTS & MACHINES

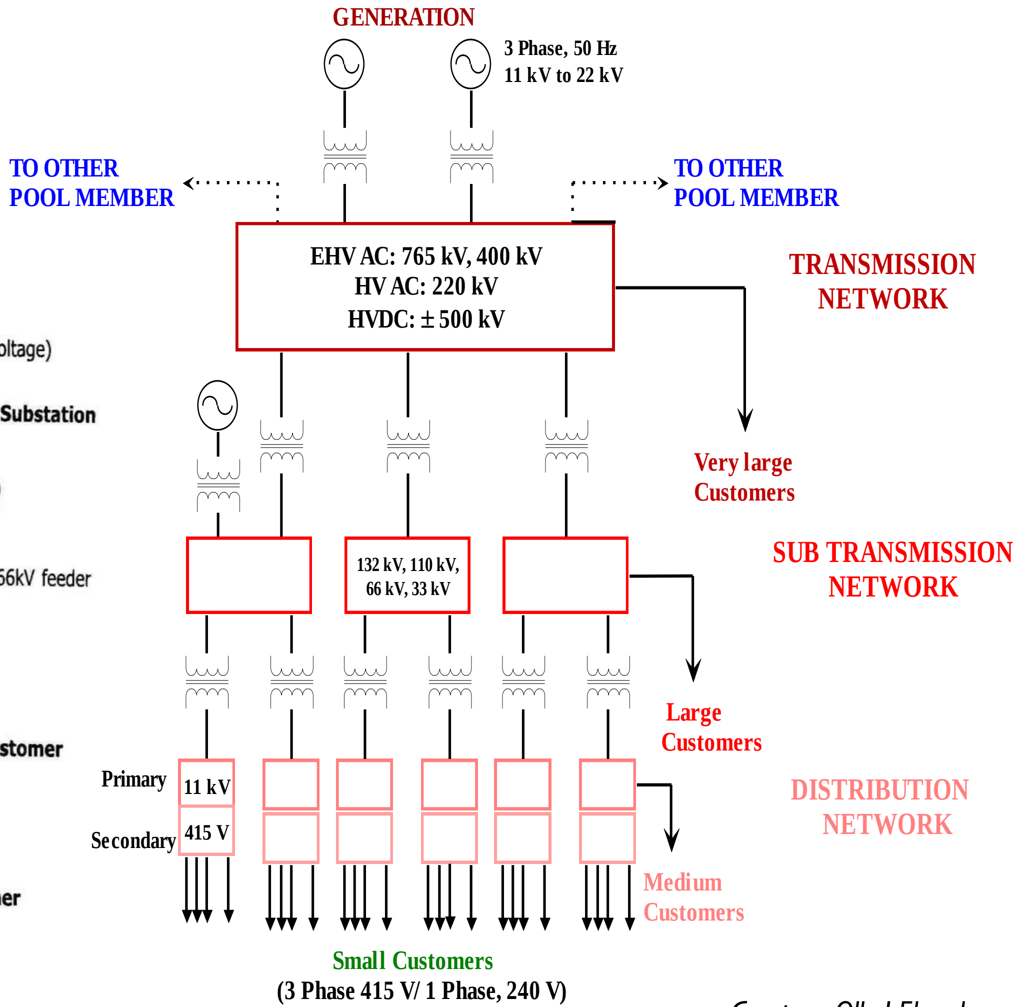
Topics covered…

- Electrical power system
  - An overview
  - Types of generation
  - Loads
  - Digital energy meter
- Electrical machines
  - Transformer
  - DC motor
  - Induction motor
  - Synchronous motor

Electrical Power System

Power system structure





Courtesy: Olle I Elgerd

Power system components

- Generation subsystem
- Transmission subsystem
- Sub-transmission subsystem
- Distribution subsystem
- Protection and Control subsystem

Transmission networks - EHV AC or HVDC

- Operates @765 kV/400 kV/220 kV AC or 500 kV DC.

AC Sub-Transmission networks

- Operates @ 132 kV/110kV/66 kV/ 33 kV

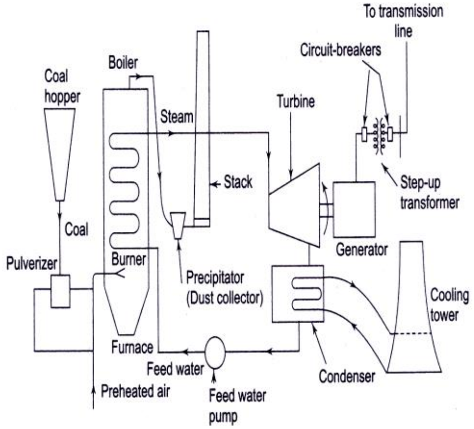
AC Distribution Network

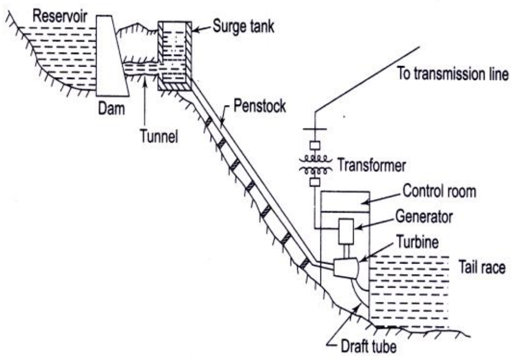
- Primary side: 11 kV
- Secondary side: 415 V, 4 Wire

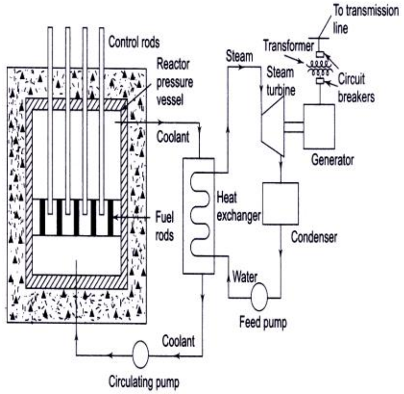
Generation

Primary sources of energy

- Fossil fuel
  - Coal, oil, natural gas
- Renewable energy
  - Water, solar, wind, tidal, geo-thermal etc.
- Nuclear energy







Thermal power stations

- Coal fired
  - Turbo alternators driven by steam turbine
- Oil fired
  - Crude oil or residual oil
- Gas fired
  - Combined cycle- First stage: Gas turbine, Second stage: Steam turbine
- Diesel fired
  - Internal combustion engines as prime mover
  - Standby power plants

Hydroelectric power station

- Salient pole alternators driven by turbines
- Turbines: Impulse turbine & reaction turbine
- Pumped storage plants

Nuclear power plant

- Fissile material
- Moderator
  - D2O, Graphite
  - Control rods
  - Boron OR Cadmium
- Fast breeder reactors
  - Liquid metal (alloy of Na & K) is coolant

Generation

Non-conventional power stations

- Wind power stations
- Solar power stations
- Micro-hydel power stations
- Bio-mass power stations
- Geothermal power stations

Wind Farm in Karnataka

20 MW hydro plant, HP

Bio-mass Plant, Chattisgarh

Solar Park, Charanka Village, Gujarat

Substation

Substation components

- Lightning arrester
- Carrier line communication equipment (Wave trap)
- Instrument transformers (CT, PT)
- Circuit breakers
- Isolators
- Bus bars
- Power transformers
- Control room

Protection & Control Subsystem

- Fail free power is *hypothetical*
- Faults: Open circuit & short circuit
- Faults detection: *Relays*
- Fault Isolation: *Circuit breakers*
- Modern Trend: Supervisory Control And Data Acquisition (SCADA) systems

Types of loads

Industrial Loads

- 3 Phase
- Complex Tariff Structure

Domestic Loads/Commercial Loads

- Single Phase
- Tariff based on energy consumed- kWH

Reduce Electricity bill by minimizing the use of heating / environmental conditioning gadgets

Domestic loads	Typical power rating
Incandescent lamps	5 W to 100 W
Fluorescent lamps	20 W to 40 W
CFL	5 W to 25 W
LED Lamps	1W to 100 W
Air Conditioner (1.5 T)	1800 W
Electric Iron	750 W
Heaters/ Geysers	2000 W
Ceiling Fan	70 W
Washing Machine (with heater)	2500 W
Refrigerator	160 W
Desktop PC	200 W
Office Laptop	65 W

Exercise

Power transmission maps of India

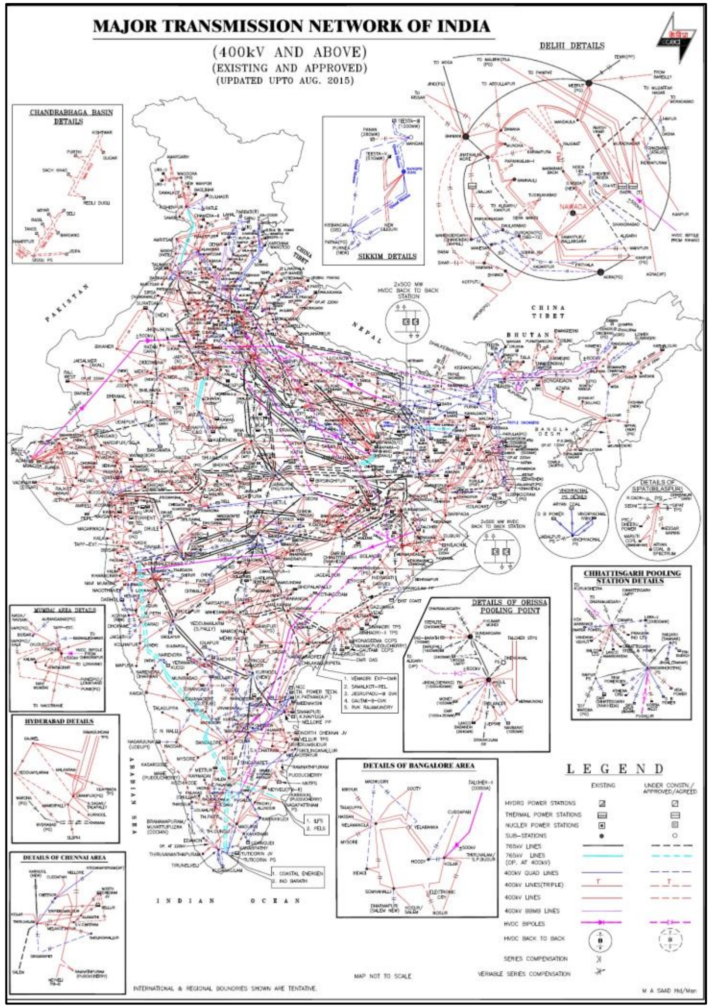
- https://cea.nic.in/old/powermaps.html

Indian Power Sector – A Glance

Sector	MW	%
State		
Central		
Private		
Total		

Fuel	MW	%
Total Thermal		
Coal		
Lignite		
Gas		
Oil		
Hydro (Renewable)		
Nuclear		
RES		
Total		

- https://www.niti.gov.in/edm/
- https://cea.nic.in/dashboard/?lang=en



Energy Meters

Working principle

- Energy is the total power delivered or consumed over a time interval,

Energy = Power x Time

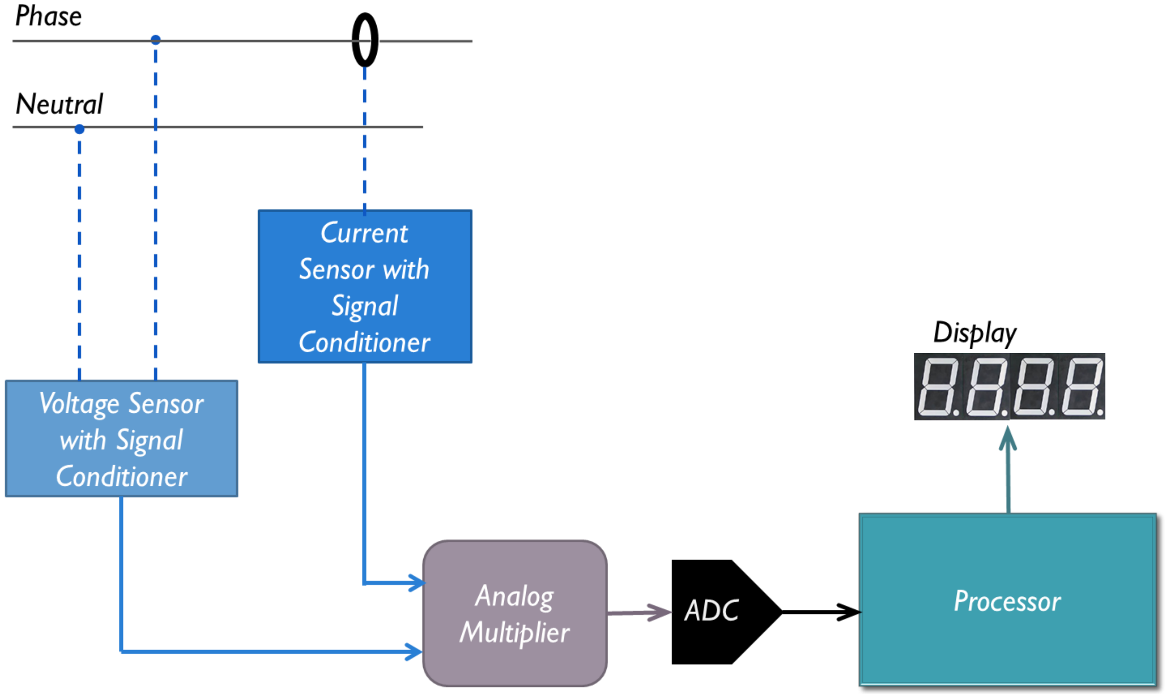
- Electrical energy developed as work or dissipated as heat over an interval of time 't' may be expressed as:

$$Energy = \int_0^t v\, i \;\; dt$$

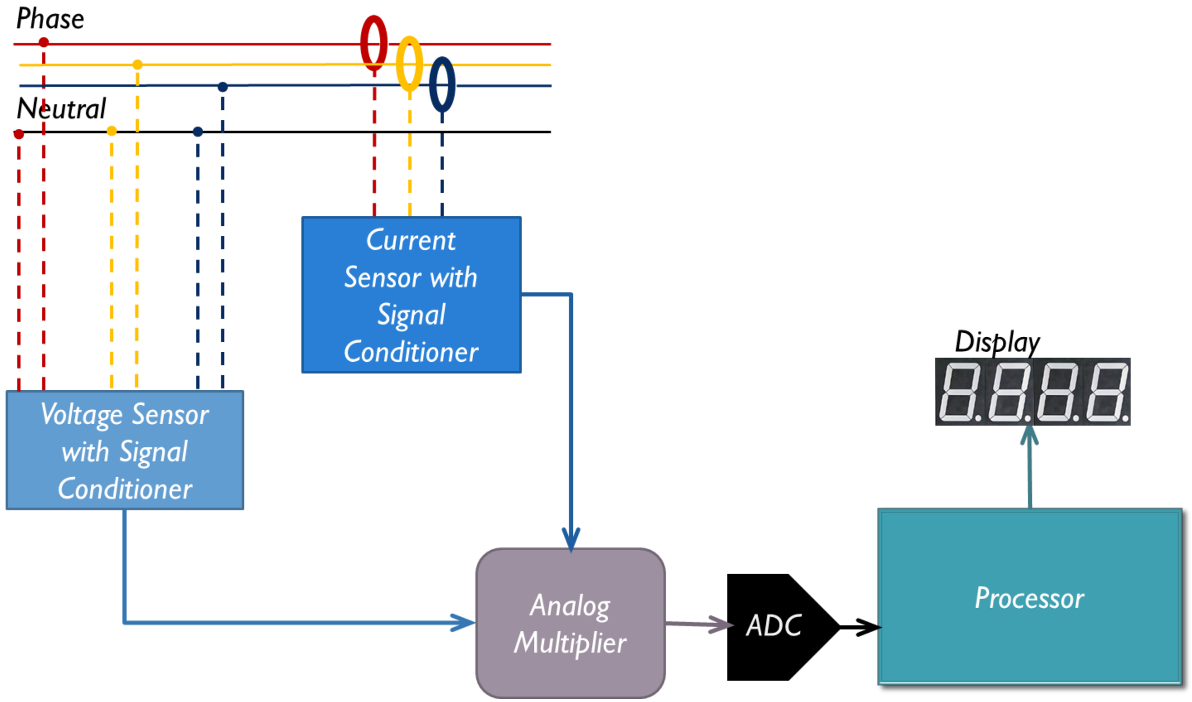
v – Applied voltage in (volts)
i – current (A)
t – time (hr)

- *Unit of Energy:* ***kWh or Units***

Digital energy meter



Single phase digital energy meter schematic



Three phase digital energy meter schematic

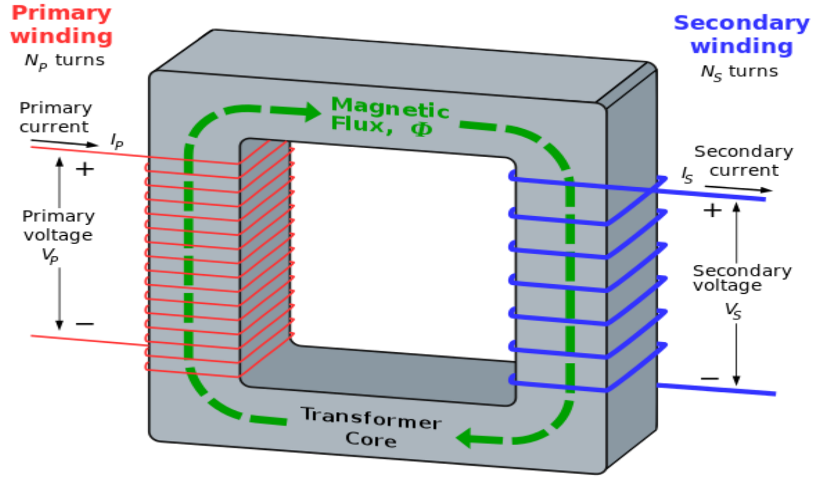
Electricity tariff

Installation	Power supply	Tariff
Industries	11kV and above	Demand Charges (per kVA) Power Factor Surcharge (per unit) Energy Charges (per kWh)
Hotels, Restaurant Cinemas Petrol Bunks Banks Commercial complexes	400V Three Phase 230V Single Phase	Sanctioned Load (per kW) Power Factor Surcharge (per unit) Energy Charges (per kWh)
Residential	400V Three Phase 230V Single Phase	Sanctioned Load (per kW) Energy Charges (per kWh) Rebate for Solar Installations

Transformers

Introduction

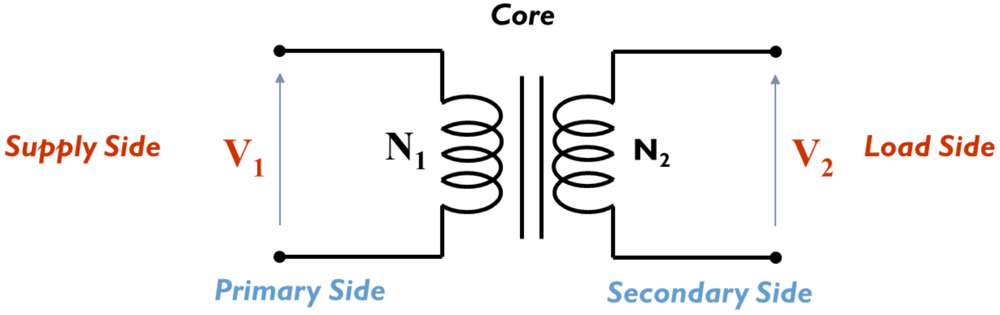
- Static device with AC excitation
- Transfers energy between two or more magnetically coupled circuits without change in frequency
- Principle of operation: Electromagnetic Induction
- Electric circuits are linked by a common ferromagnetic core
- Ferromagnetic core ensures maximum magnetic flux linkage



Types

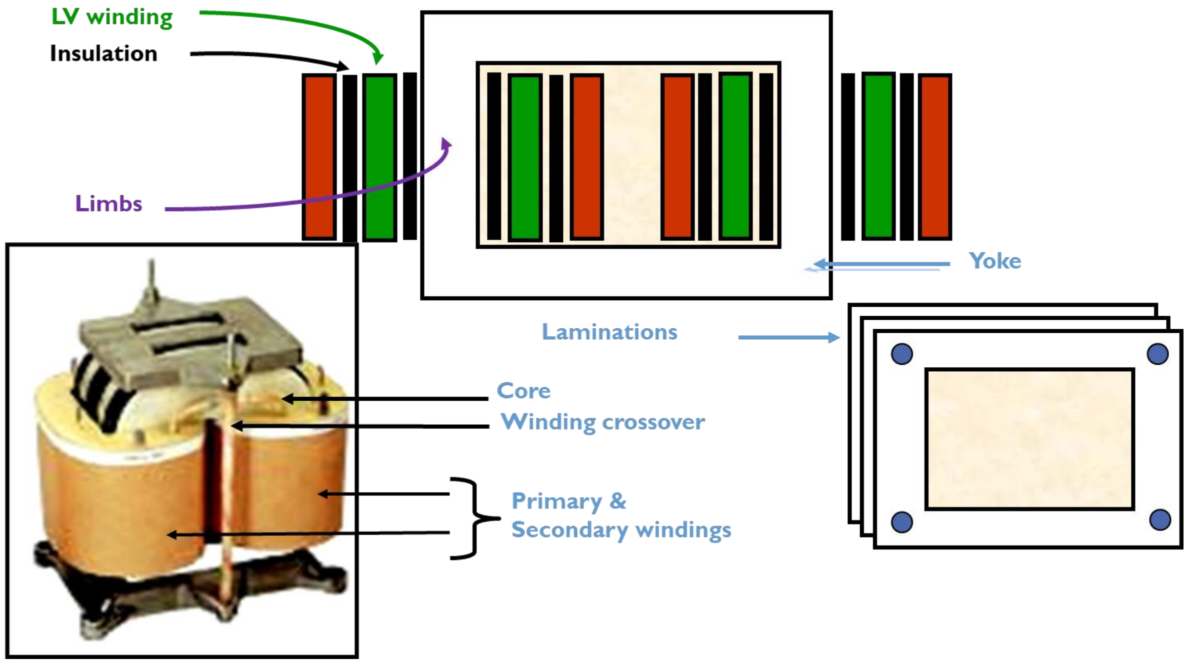
Based on Construction	***Based on Function***	***Based on Windings***
Core Type	Step Up	Single Winding
Shell Type	Step Down	2 or 3 Windings

Representation:

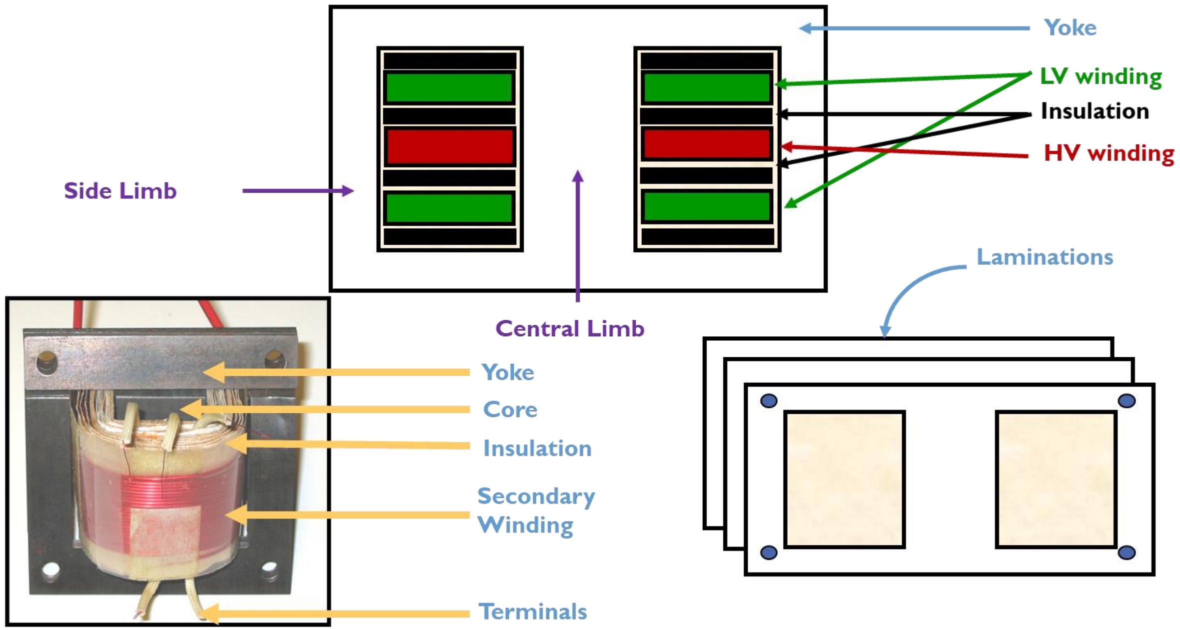


N_1 = Number of turns on primary
N_2 = Number of turns on secondary

Core & shell type

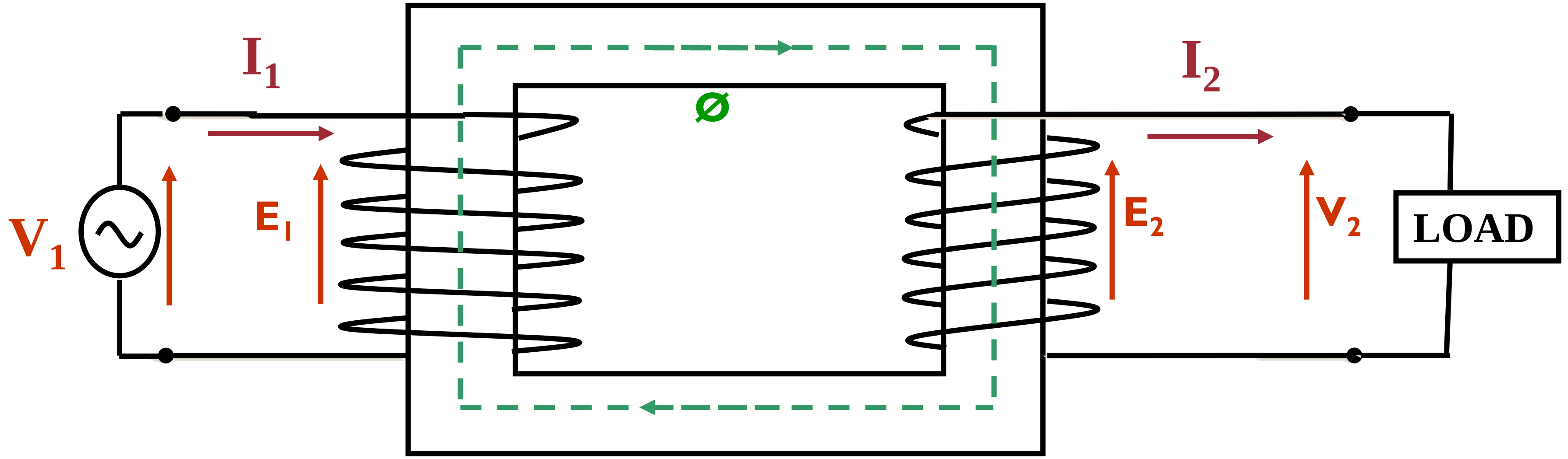


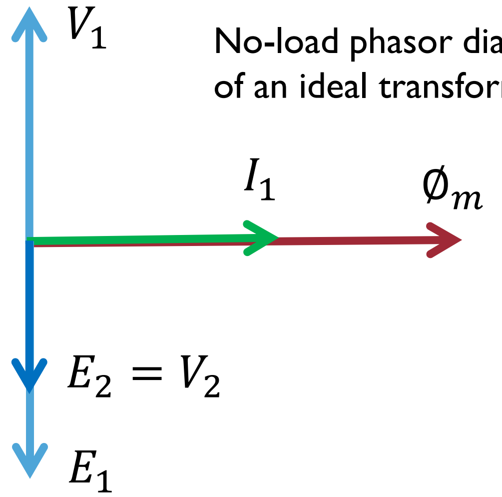
Core type



Shell type

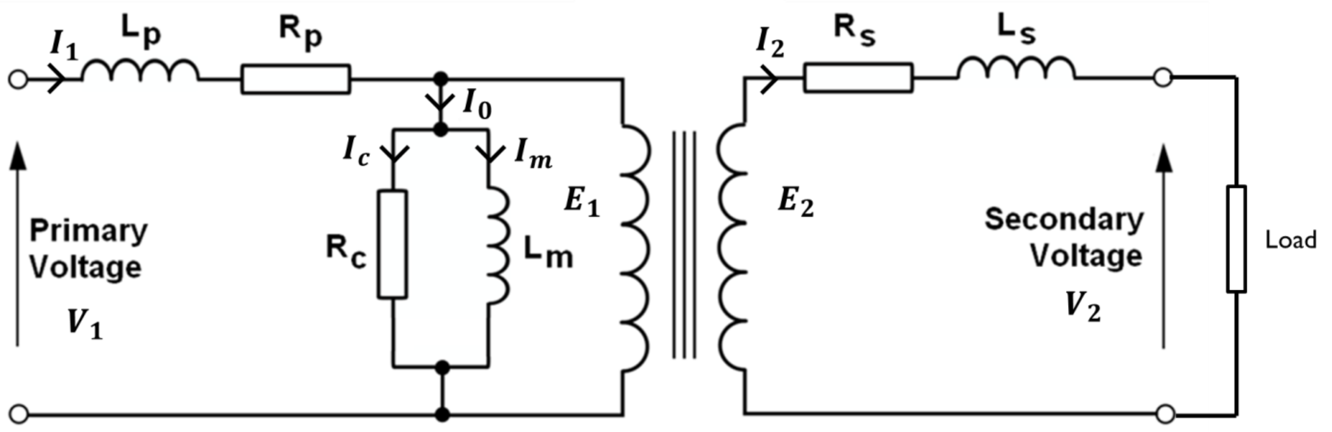
Operation of transformer





No-load phasor diagram of an ideal transformer

- Magnetic core : Flux path
- Flux linkages : Primary & secondary
- Induced Emf :
  - Primary – Self induced emf
  - Secondary – Mutually induced emf



Circuit representation of a practical transformer

EMF equations of transformer

Core flux,

$$\emptyset = \emptyset_m \sin(\omega t)$$

Induced Emf,

$$e = -N\frac{d\emptyset}{dt} = N\omega\emptyset_m sin(\omega t - 90°)$$

$$e = E_m sin(\omega t - 90°), \boldsymbol{where}, E_m = N\omega\emptyset_m$$

RMS value of self induced emf,

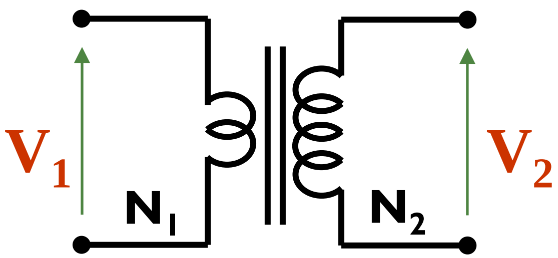
$$E = \frac{E_m}{\sqrt{2}} = \frac{N\omega\emptyset_m}{\sqrt{2}} = \frac{2\pi f N\emptyset_m}{\sqrt{2}}$$

Primary Induced Emf, $E_1 = 4.44\ N_1 f\emptyset_m$
Secondary Induced Emf, $E_2 = 4.44\ N_2 f\emptyset_m$

For an ideal transformer,

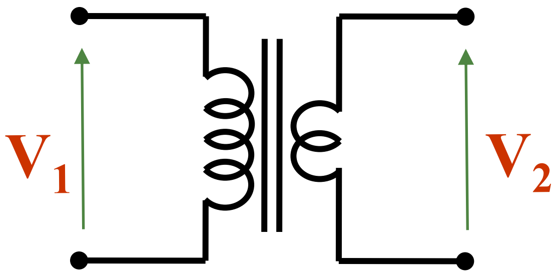
$$\frac{V_1}{V_2} \cong \frac{E_1}{E_2} = \frac{I_2}{I_1} = \frac{N_1}{N_2} = a = \boldsymbol{Turns\ Ratio}$$

$N_2 > N_1$: Step Up



$E_2 > E_1$
$V_2 > V_1$
$I_1 > I_2$

$N_2 < N_1$: Step down



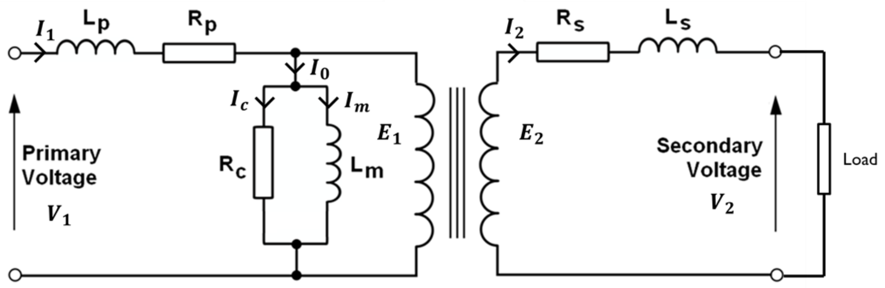
$E_2 < E_1$
$V_2 < V_1$
$I_1 < I_2$

Losses & Efficiency

Total loss = Core loss + copper loss

Core loss (constant)		Copper loss (variable)
Hysteresis loss	Eddy current loss	Winding resistance

- Core loss depends on flux which is constant once core is designed
  - Minimized using high graded core material and lamination
- Copper loss is Current (or load) dependent
- Efficiency: Very high 97% to 99% (since it is a static device)

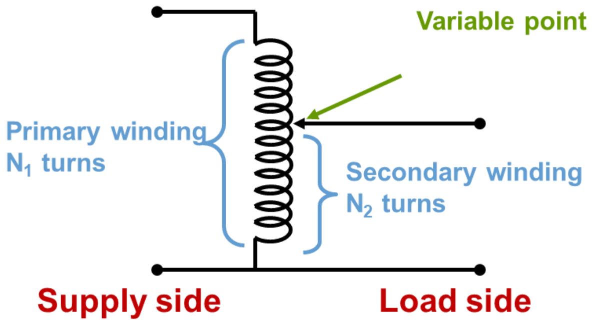


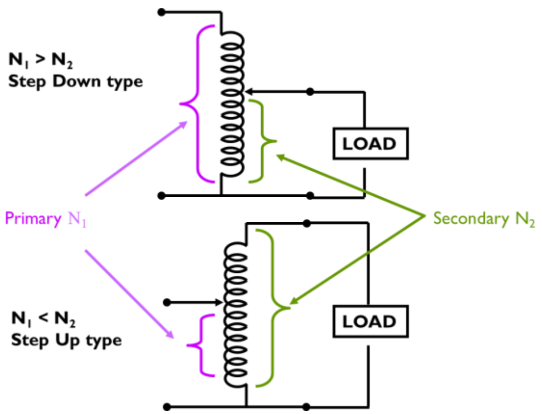
Circuit representation of a practical transformer

Other types

Autotransformer

- One winding transformer
- Secondary winding varied using variable point





Three phase transformer

- Possible connections of primary & secondary windings:
  - star/star
  - star/delta
  - delta/delta
  - delta/star
- 3 single-phase transformers of similar ratings can be connected to form a 3-phase transformer

Power transformer

- Used in electric transmission network

Distribution transformer

- Used in electric distribution networks

Instrument transformers (PT & CT)

- Used for high voltage & current measurement

Isolation transformer

- 1:1 transformers used in circuits to provide electrical isolation.

Constant voltage transformer

- Used as voltage regulators

High frequency transformer

- Transformers designed for operating with high frequency – ferrite core

Problems

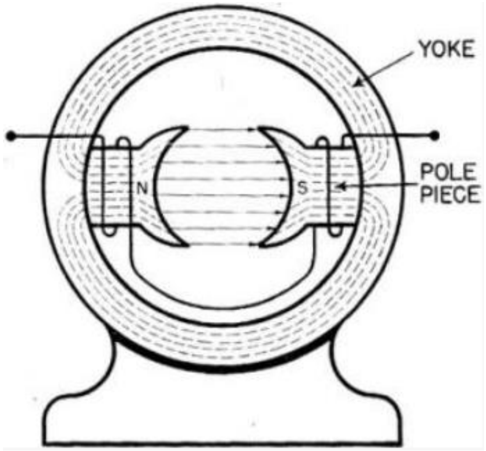
Refer MOOC video

DC Motors

Construction

Stator: Houses the field winding *(consists of the yoke, poles, brushes, brush holders, and end covers)*

Rotor: Carries the armature winding *(armature, commutator)*

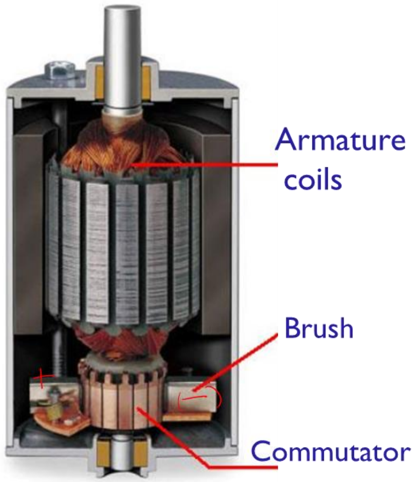


Yoke: Cast steel outer shell housing all the parts

Main poles: Field coils wound when excited with DC produces north and south pole

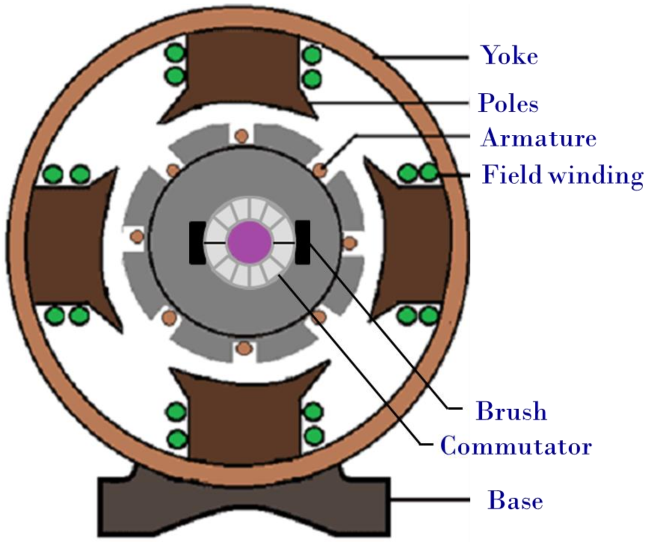
Armature: Rotating part with the armature winding

Commutator: Mechanical rectifier with carbon brushes resting on it



Working principle

- Current carrying armature conductors placed in the magnetic field experience a force that rotates the armature
- Induced emf in armature conductor regulates the current drawn to match with the connected load

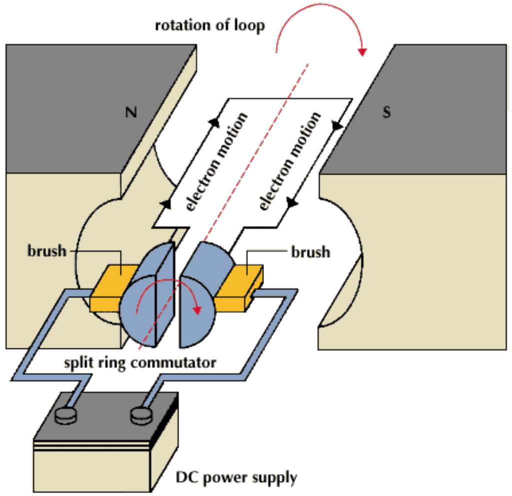


$$V = E_b + I_a R_a$$

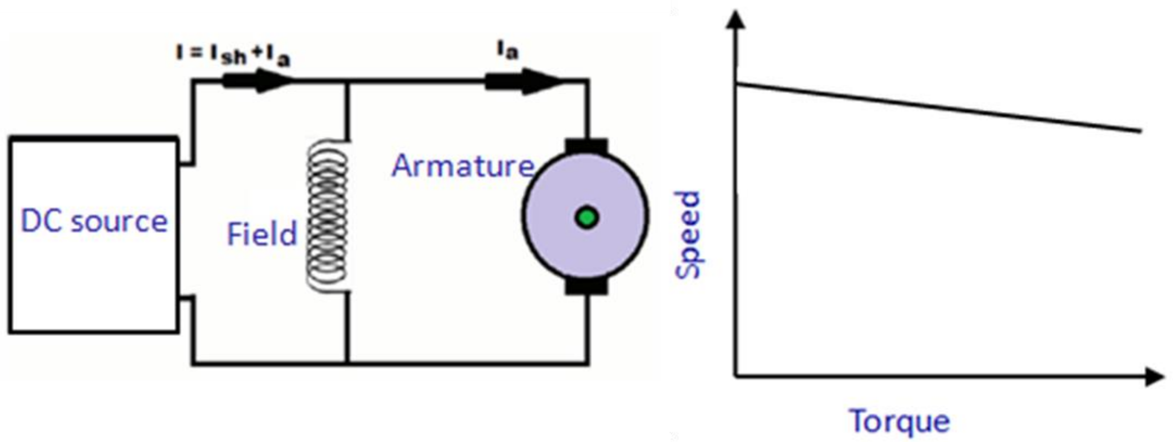
$$N \propto \frac{E_b}{\emptyset}$$

$$T \propto I_a \times \emptyset$$

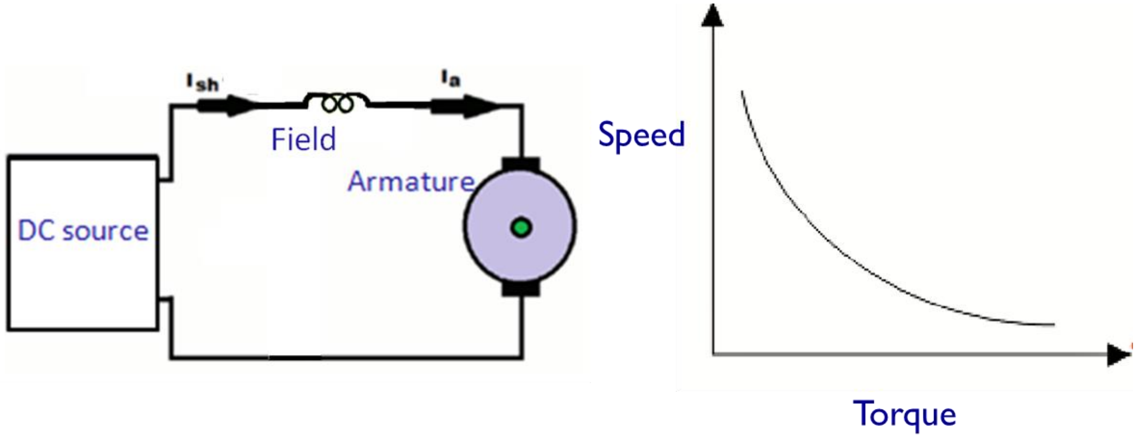
V = Voltage applied(Volts)
Eb = Induced Back e.m.f(Volts)
Ia = Armature current(Amperes)
Ra = Armature resistance(ohms)
N = Speed of the motor(r.p.m)
T = Torque developed(Nm)
Ø = Flux (Webers)



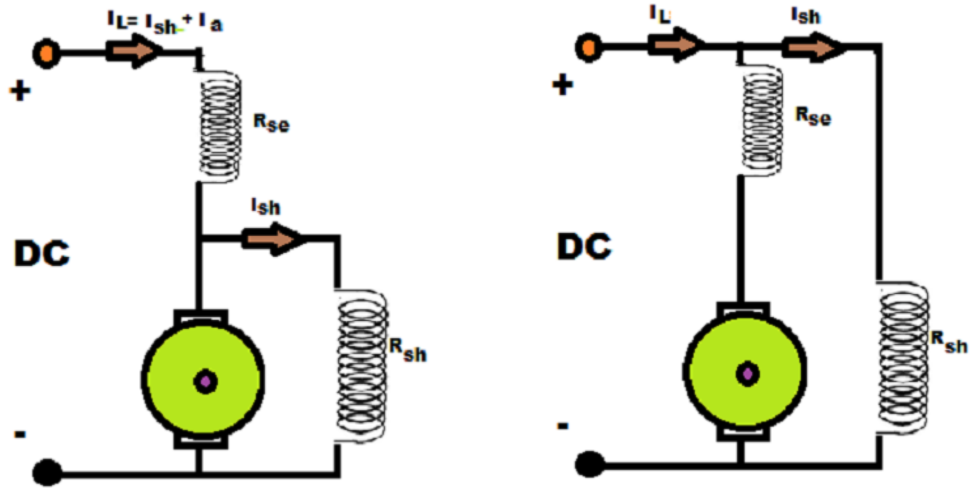
Types of DC motors



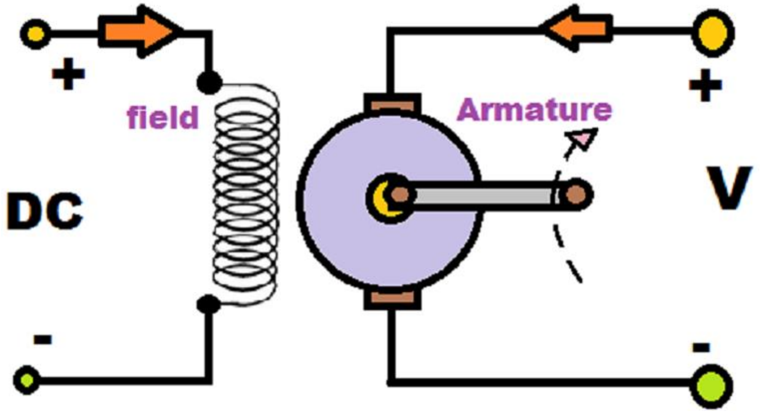
Shunt DC motor



Series DC motor



Compound DC motor

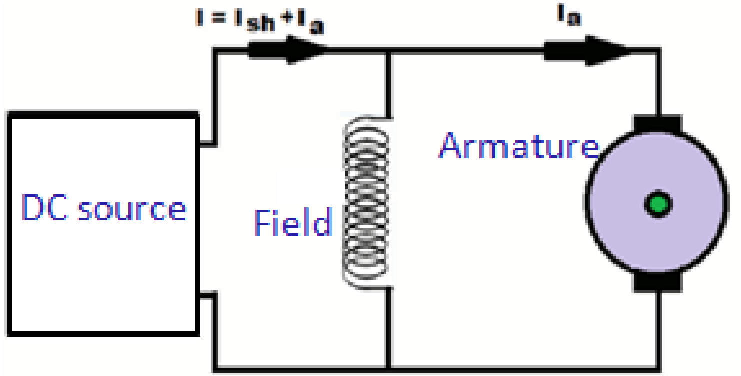


Separately excited DC motor

Types of DC motors

DC shunt motor

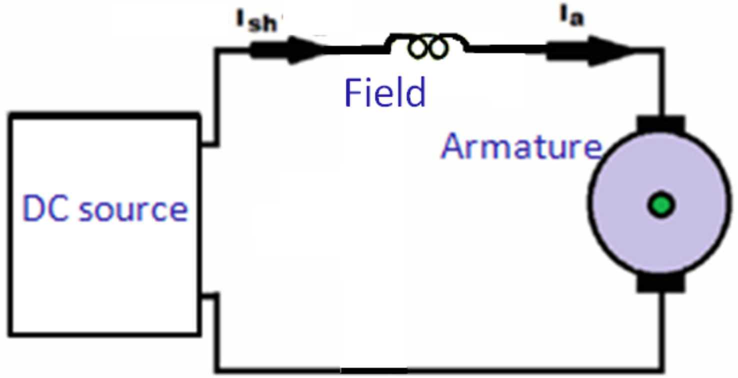
- Field and armature currents are independent of one another
- Torque proportional to armature current
- Excellent speed control



Shunt DC motor

DC series motor

- Field and armature currents are equal
- Torque is proportional to the square of the armature current
- Starting torque is quite high and it gets regulated automatically as speed increases
- Most preferred for traction



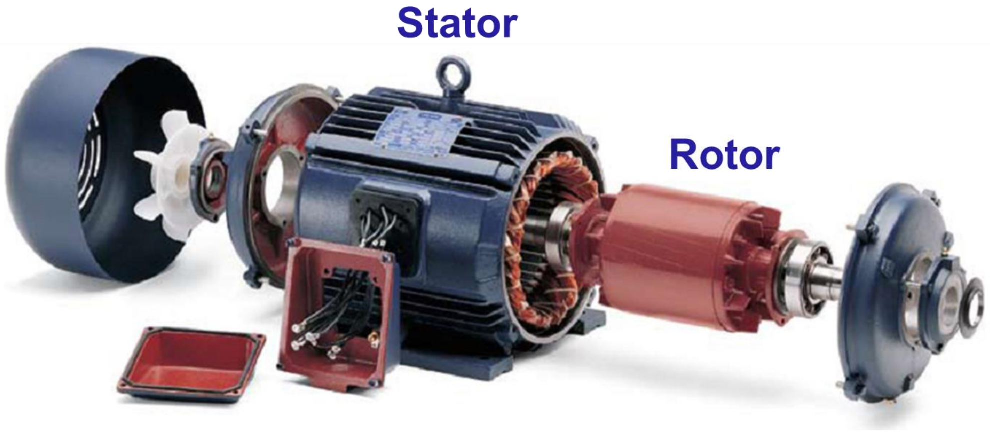
Series DC motor

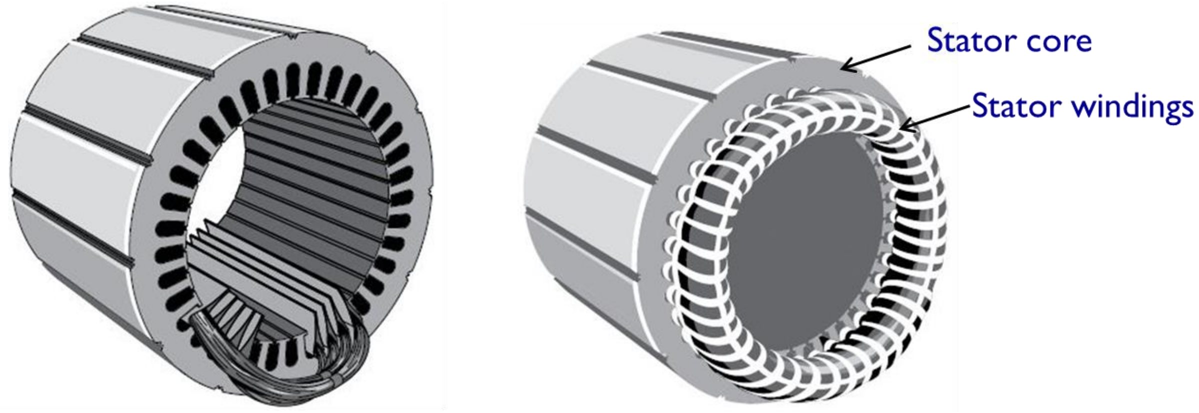
DC compound motor

- Loads that require large momentary torques (e.g. rolling mills)

Three-phase induction motor

Construction

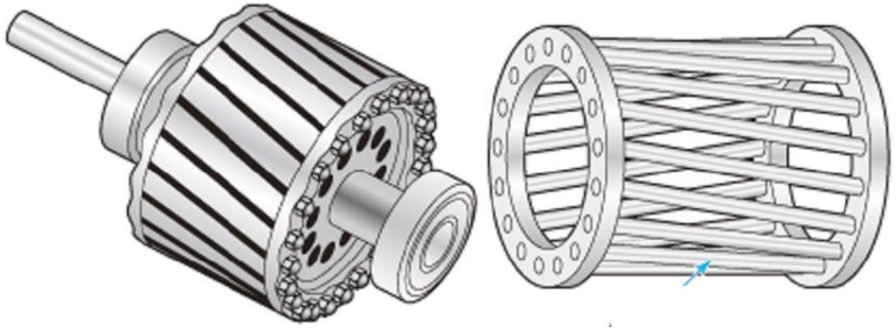




- Stator frame (cast iron) provides mechanical support to the stator core
- Cylindrical stator core laminated and slotted to carry the 3 phase windings
- The balanced windings are displaced in space by 120 degrees electrical
- Slots cut-out on the outer periphery of rotor to place the conductors

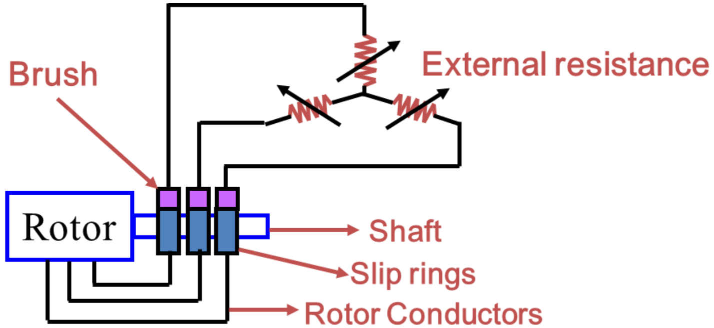
Rotor types

Squirrel cage rotor



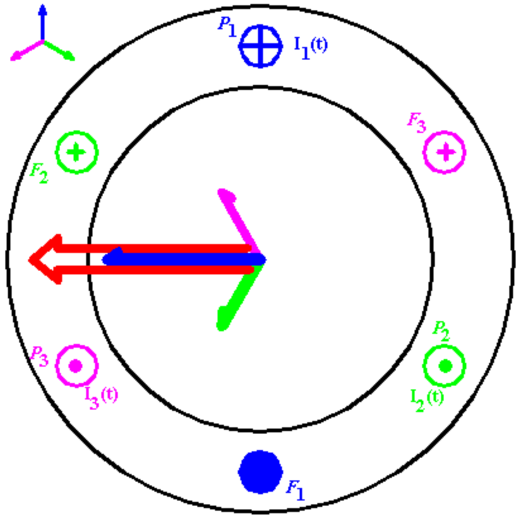
- Skewed arrangement of copper or aluminium bars
- Conductors shorted by end rings – closed rotor circuit
- Cheap, rugged, and needs little or no maintenance

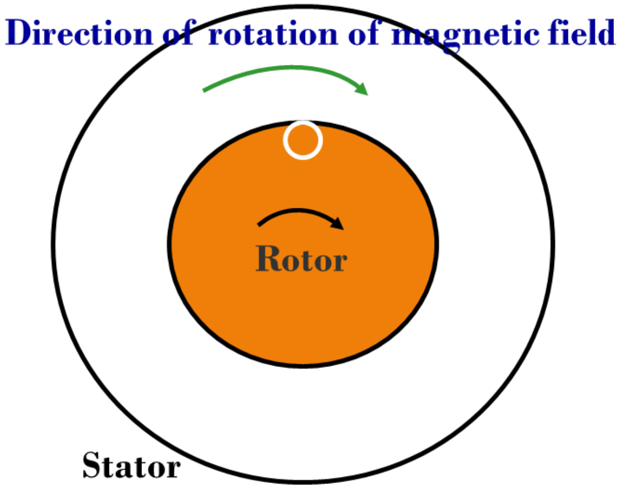
Slip ring rotor



- Rotor winding in star - uniformly distributed
- The terminals of the winding are brought out to three slip rings
- Slip rings in contact with brushes
- Brushes connected to external resistance for higher starting torque

Working principle





- 3-phase currents flowing in the stator winding produce a rotating magnetic field rotating at synchronous speed
- Rotating magnetic field is cut by the rotor conductor
- EMF is induced in rotor conductor
- Current in the rotor conductor sets up a magnetic field which opposes the rotation of the main field
- Main field is independent and hence rotor field tries to catch up the speed of the main field to reduce the relative speed
- Rotor rotates in the same direction as that of rotating magnetic field

Working principle

- Magnetic field rotates at a synchronous speed

$$\boxed{N_S = \frac{120\,f}{P}}$$

N_S = Speed of Rotating magnetic field, rpm
f = Frequency of ac supply, Hz
P = No. of poles

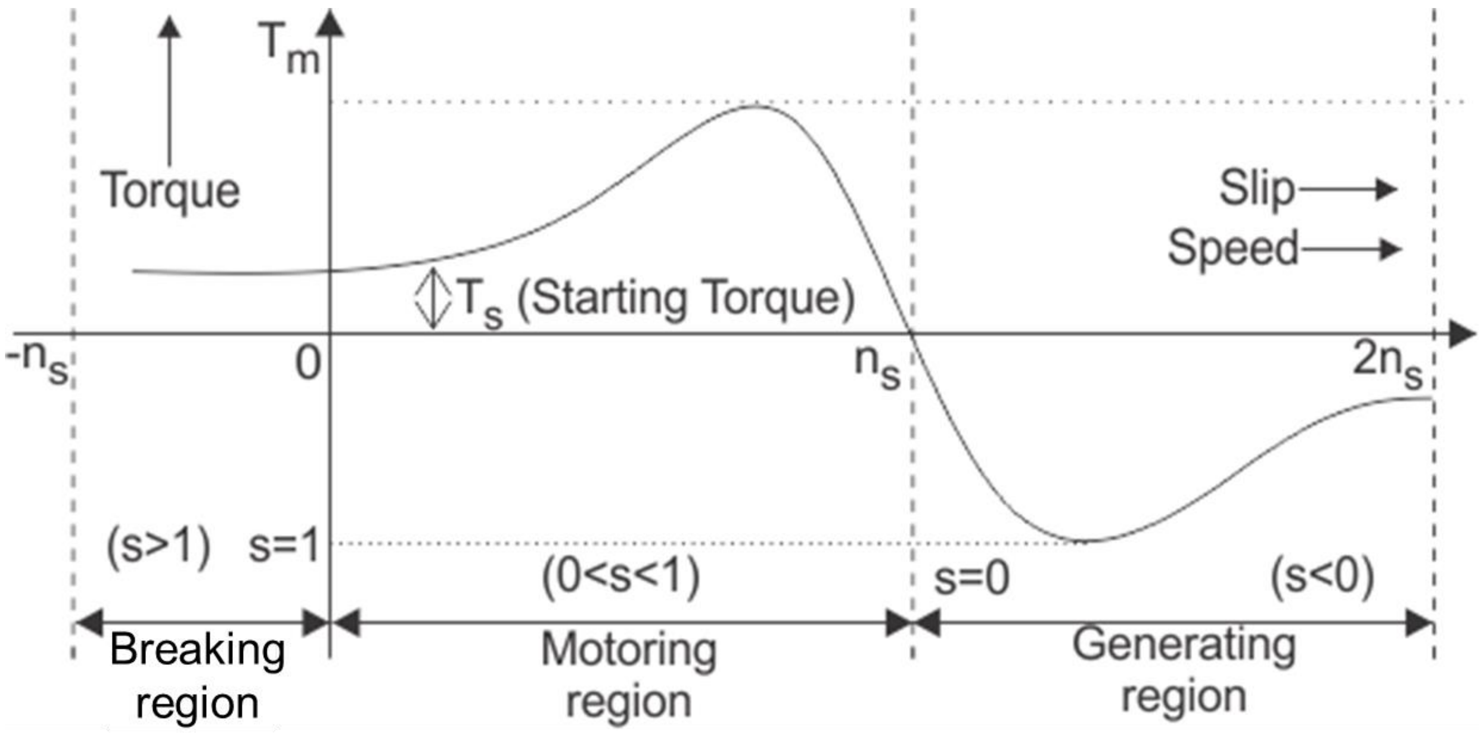
- If rotor speed, $\boldsymbol{N}$ is equal to N_s,
  - No flux cut by rotor conductors
  - No emf induced across rotor conductors
  - No current flow, no torque

- Slip speed, $s = (N_s - N)$, rpm

$$\boxed{\%\,s = \frac{N_S - N}{N_S} \text{ x } 100\,\%}$$

- Rotor frequency, $f_r = \dfrac{P(N_S - N)}{120} = sf$

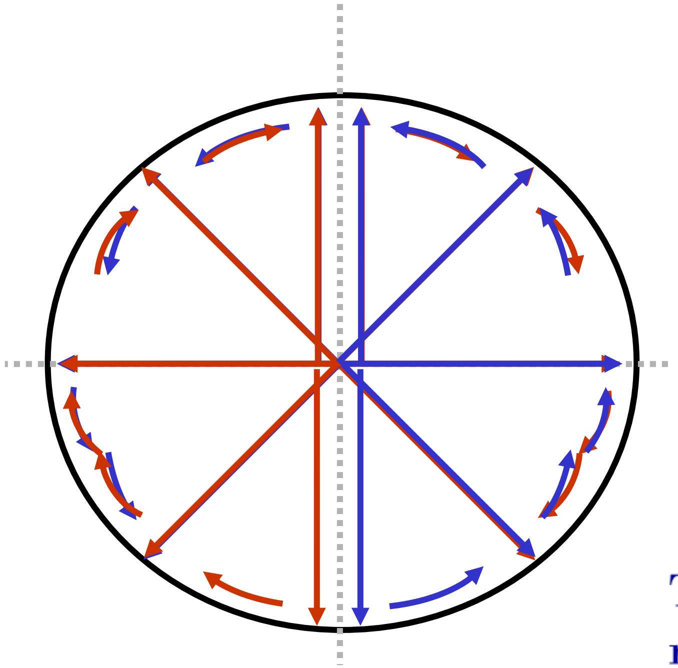
Torque – slip characteristics

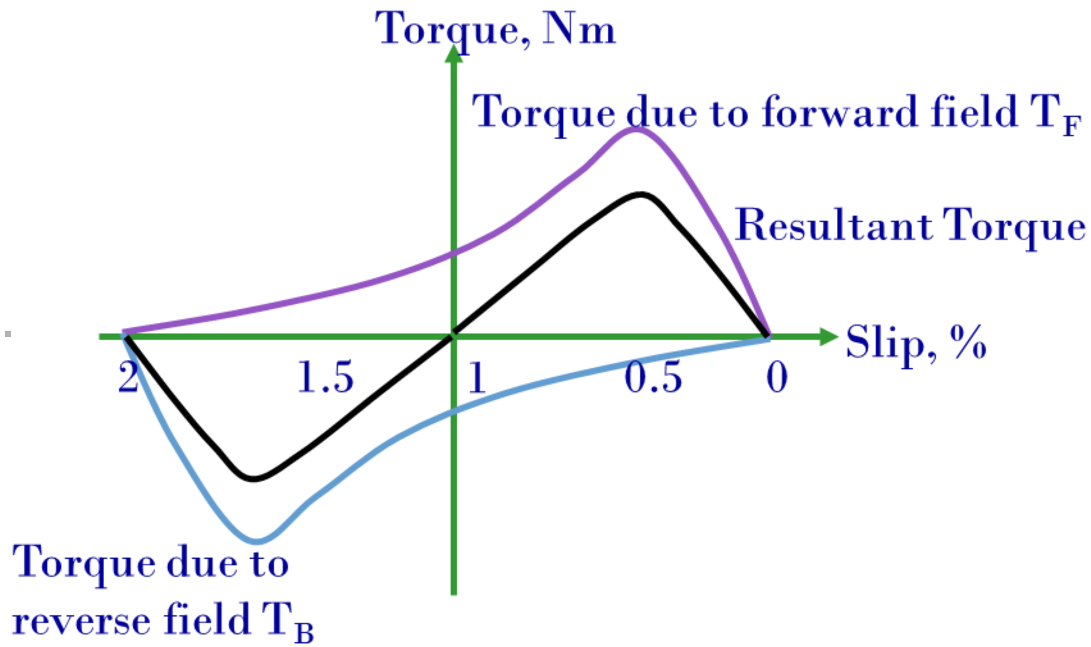


Applications: Pumping systems, refrigeration systems, compressors, fans & blowers, industrial drives

Single-phase induction motor

Double revolving field theory

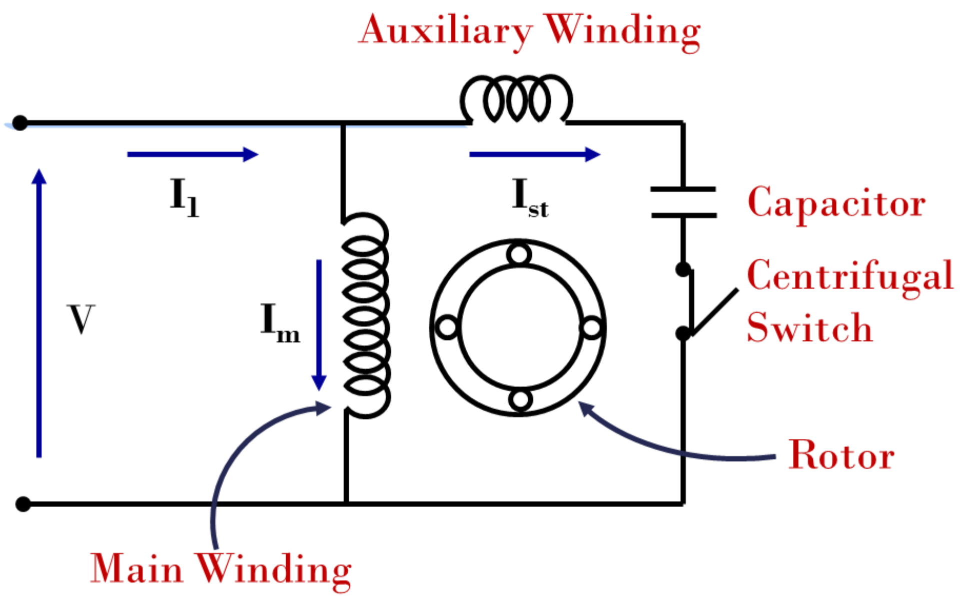


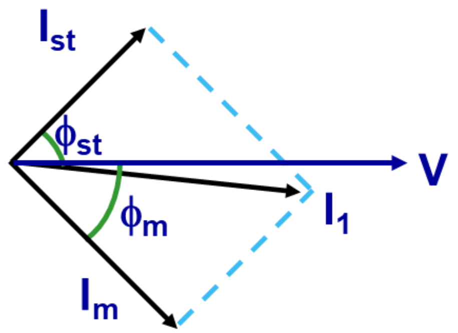


$$\emptyset = \emptyset_m \sin\omega t \cos\alpha = \frac{\emptyset_m}{2}\sin(\omega t + \alpha) + \frac{\emptyset_m}{2}\sin(\omega t - \alpha)$$

Causes T_b Causes T_f

Capacitor start motor





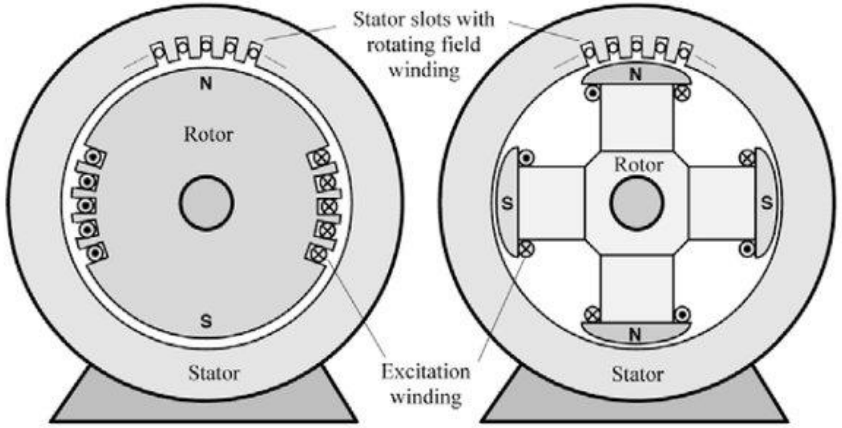
$T_s \propto angle\ between\ I_{st}\ \&\ I_m$

- Auxiliary winding is placed perpendicular to the main winding
- Phase split is achieved by connecting a series capacitor with auxiliary winding
- Centrifugal switch opens the circuit when speed is near about rated speed
- High power factor, high efficiency
- **Application:** High starting torque appliances like compressors, AC, farm tools, lifts, etc.

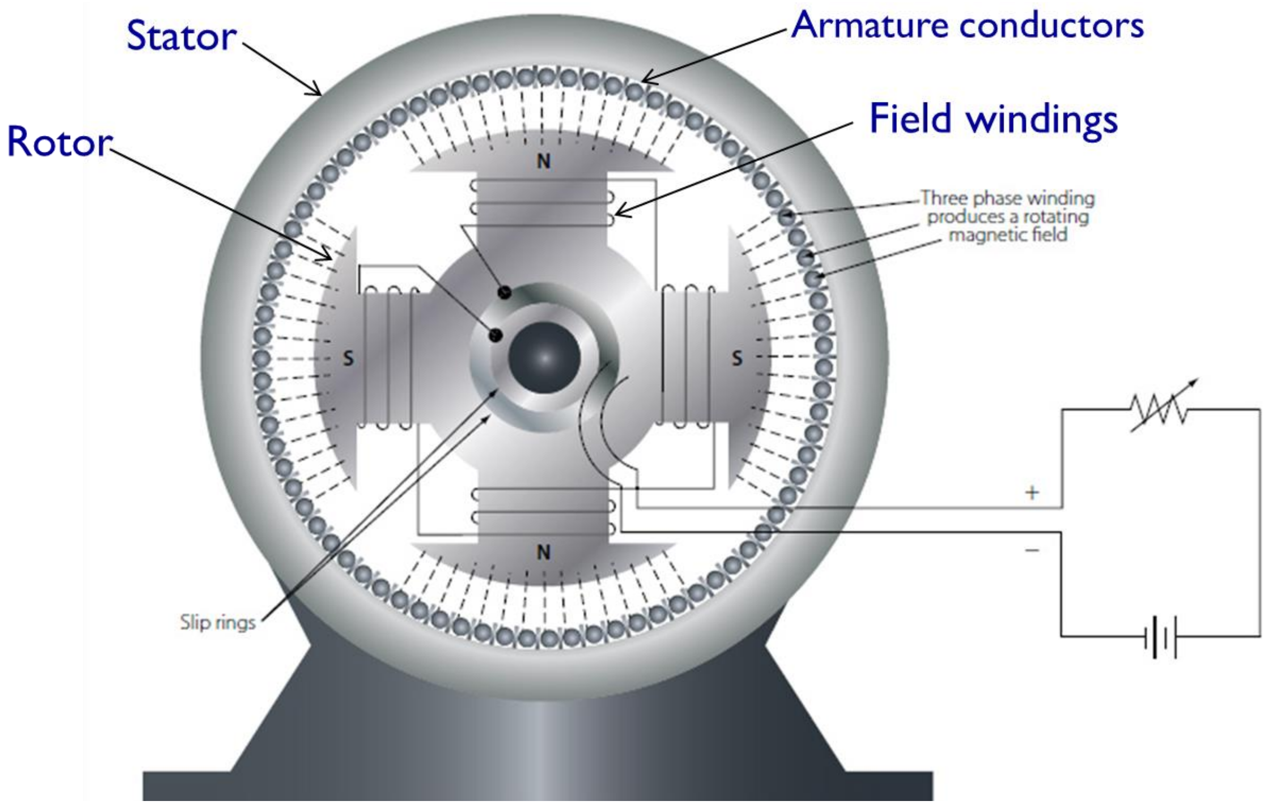
Synchronous motor

Construction

- Stator – accommodates armature windings
- Rotor – carries field windings excited using DC
- Rotor types:
  - Salient-pole: low speed applications
  - Cylindrical: high speed applications



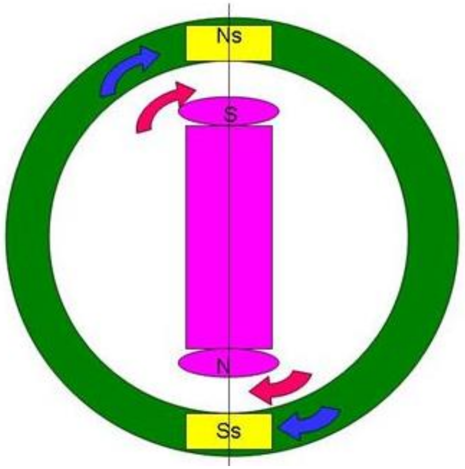
Cylindrical rotor **Salient-pole rotor**



Working principle

- Armature energized from a 3-phase AC source, the machine starts as an induction motor
- After achieving the full speed, the field winding is excited
- Stator and rotor field get magnetically locked

Rotor with damper winding



Magnetic locking near rated speed

Features & applications

- Constant speed AC motor – runs at synchronous speed irrespective of connected load
- Power factor of operation is adjusted by controlling excitation – synchronous condenser

- Used for high power, low-speed applications
  - Lift irrigation
  - Reciprocating pumps
  - Exhaust fans
  - Synchronous condenser