Professional Diploma in Railway Engineering

(EG524401P)

ELE4907 Intermittent and Hidden Fault Finding in Train (Temp)

ELE4909 Drives and Traction & Electromagnetic Compatibility (Temp)

Objectives

Module Title	Drives and Traction & Electromagnetic Compatibility (Temp)	
Module Code	ELE4909	
Credit Value	15	
QF Level	4	
Curriculum Hours	30	Lecture: 30 hours
		Tutorial: 0 hours
		Laboratory / Workshop: 0 hours
		Others: Nil
Pre-requisite(s)	Nil	
Co-requisite(s)	Nil	
Award Title	Module Certificate in Drives and Traction & Electromagnetic Compatibility (Level 4)	
Award Title (in Chinese)	驅動牽引與電磁兼容性單元證書 (四級)	

Intended Learning Outcomes

On completion of the module, students are expected to be able to:

1. Identify hidden faults in train control circuit within a reasonable period of time;
2. Use fault finding techniques to identify intermittent faults in the train system and equipment;
3. Design, use of special tools and tailor-made testers for fault finding.

Learning Contents and Indicative Curriculum Hours

	Learning Contents		Indicative Curriculum Hours	UoC Reference Code
A	Tractive Effort • Train resistance • Mechanics of train movement • Calculation of speed time curves • Performance of regenerative braking		6 hours	
B	**Drives** • DC Drives • DC motor drive • Performance characteristics • Operating modes • Chopper drives • Various speed control methods	• AC Drives • Induction motor drives • Performance characteristics • Various speed control methods	18 hours	EMRAMA401A EMELDE412A
C	Electromagnetic Compatibility • Introduction and principles of EMC • EMC regulations, requirement and standards in different countries • Measurement and test facilities • Problem solving skills		6 hours	

Mapping of Learning Contents with Module Intended Learning Outcomes

	Learning Contents	Module Intended Learning Outcomes		
		1	2	3
A	Tractive Effort	✓		
B	Drives	✓	✓	
C	Electromagnetic Compatibility			✓

Assessment

Continuous Assessment (CA)	50%
Final Examination (FE)	50%
Total	100%

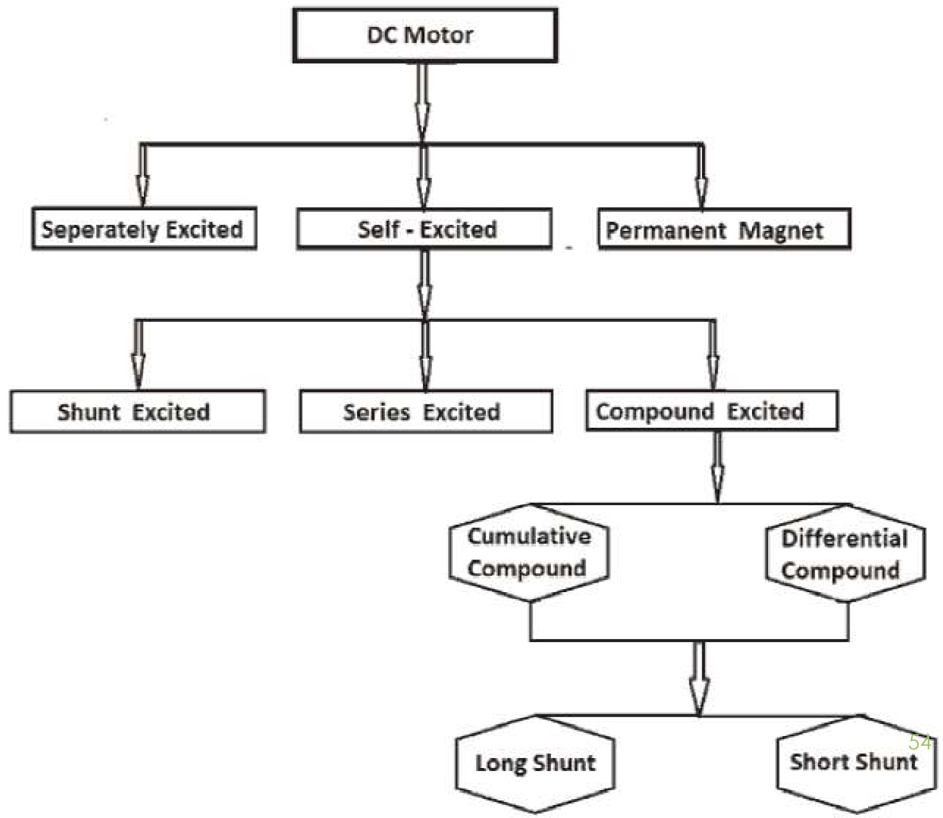
CHAPTER B

Drives

- DC Drives

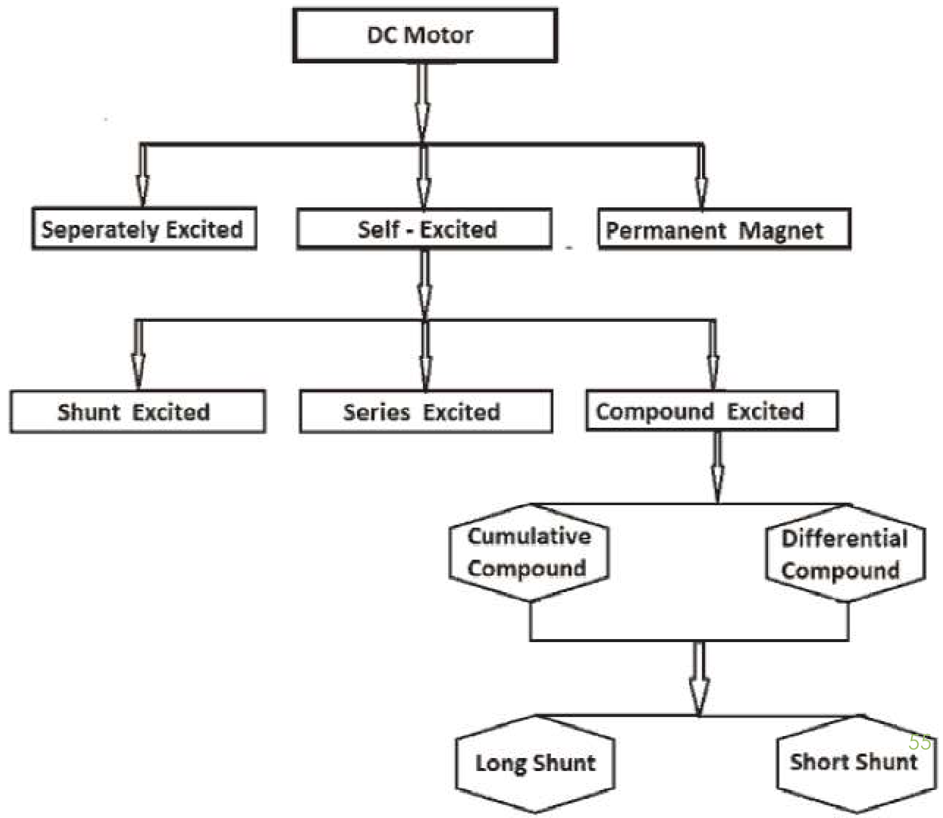
DC Drives

- Permanent Magnet
- Separately Excited
- Self Excited

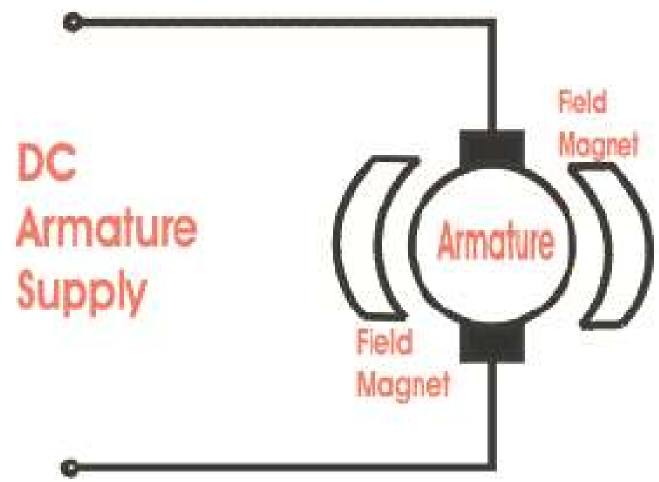


Permanent DC machine

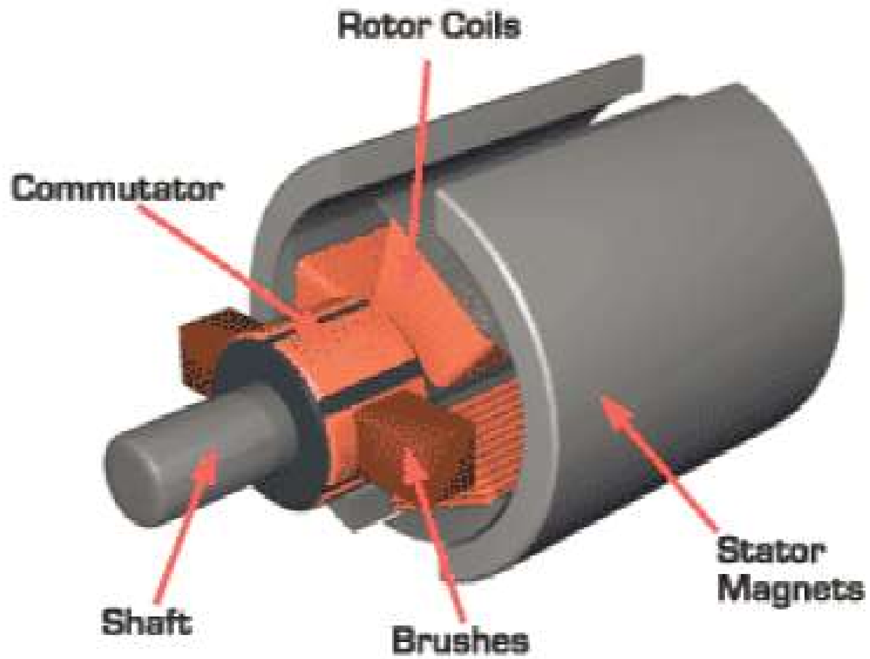
- Permanent Magnet
- Separately Excited
- Self Excited



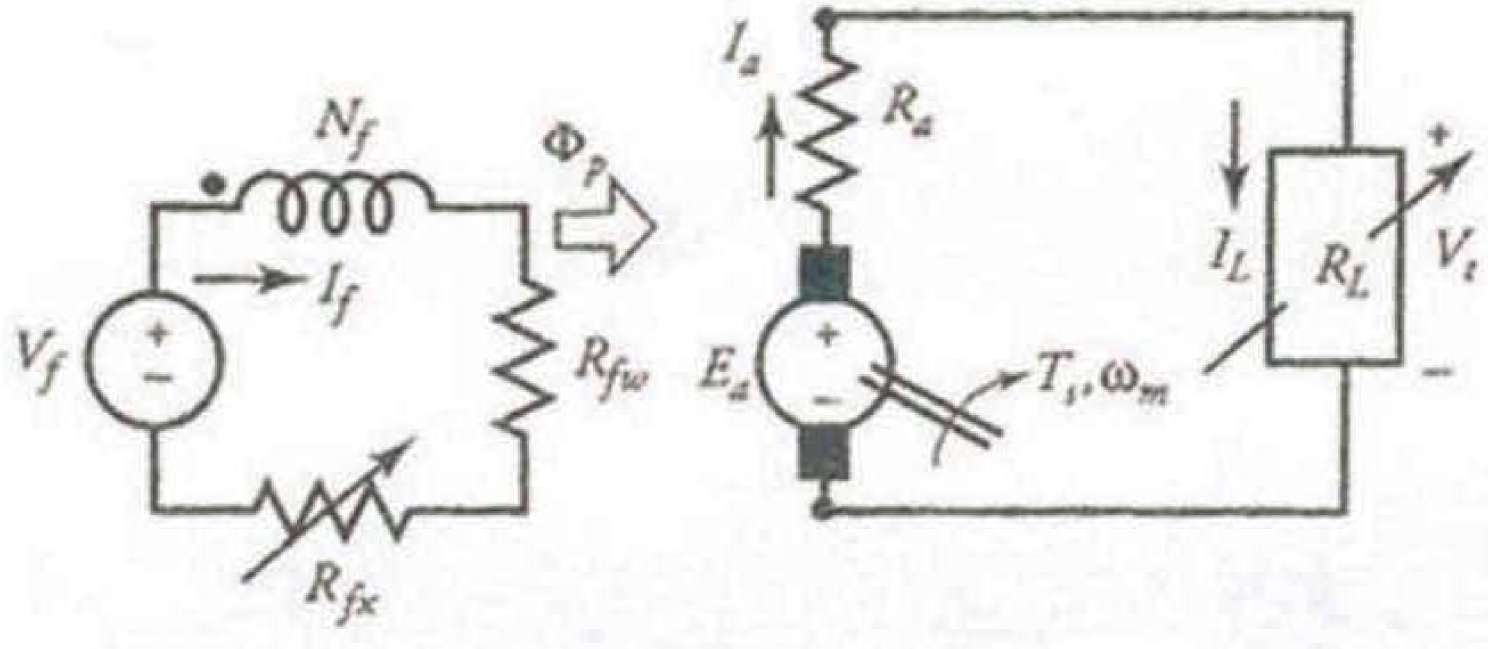
Permanent DC machine



Permanent Magnet DC Motor



Separately Excited DC machine



Self Excited DC machines

Shunt Excited	Series Excited	Compound
		By Connection - Long Shunt - Short Shunt **By Excitation** - Differential Compound - Cumulative Compound

Family of AC Machines

- Asynchronous Machine
- Synchronous Machine

Asynchronous Machine

- 3-phase Induction Motor
- Single phase Induction Motor

3-phase Induction Motor

Slip Ring Wound Rotor

Squirrel Cage Rotor

Single Phase Induction Motor

- Split phase motor
- Capacitor motor
  - Capacitor Start
  - Capacitor Run
  - Capacitor Start
  - Capacitor Run
- Shaded-pole motor
- Universal motor
- Miscellaneous

Synchronous Machine

- Three-phase synchronous
- Single-phase synchronous

Special Machines

- Stepping motor
- Brushless dc motor (BDCM)
- Direct Drive (DD) motor
- Linear motor
- Ultrasonic motor
- Others

DC Machines

Two types of DC machines:

DC Generator

- Converts mechanical energy into electrical energy
- Follows Fleming's right hand rule

DC Machines

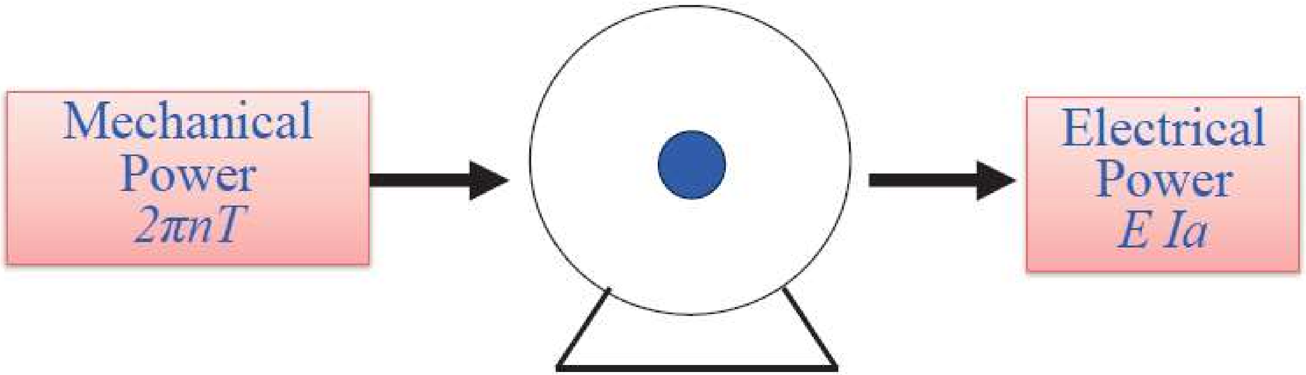
DC Motor

http://www.youtube.com/watch?v=lC-PWxtcirl

- Converts electrical energy into mechanical energy
- Follows Fleming's left hand rule

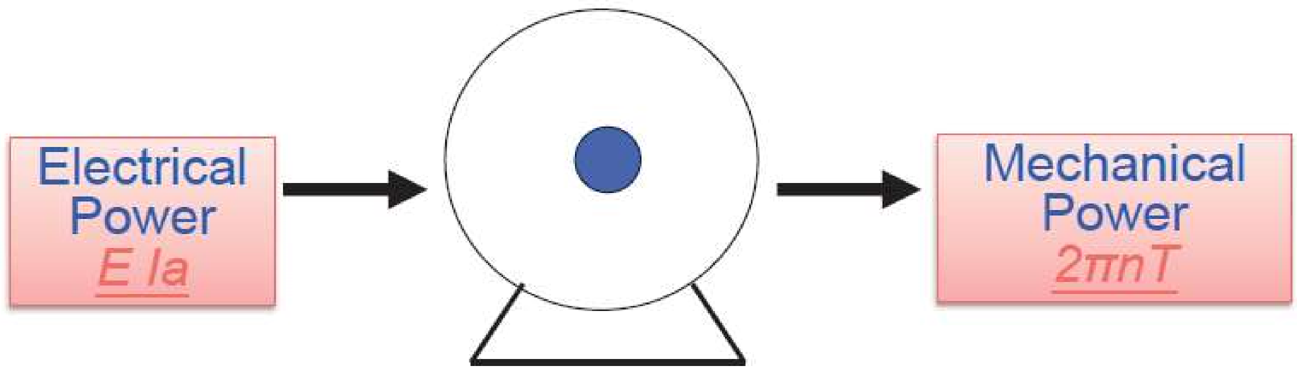
Generator

- The electromechanical energy conversion is from **mechanical to electrical**



Motor

- The electromechanical energy conversion is from **electrical to mechanical**



DC Machines

- Versatile and extensively used in industry
- Wide variety of VA or torque-speed characteristics can be obtained from various connection of field windings.
- Can be operated both as generator or motor.
- **Extensively used as motor in industry**.
- Speed can be controlled.

Application of DC machines

Large power DC motors are used:

- In machine tools, printing presses, conveyors, fans, pumps, hoists, cranes, paper mills, textile mills rolling mills.
- Dominates as traction motors used in transit cars and locomotives.

Small dc machines are used:

- As control devices such as tacho-generators for speed sensing
- As servomotors for positioning and tracking.

Operating Principles of DC Machine

- Field winding is placed on the stator
- Armature winding is placed on the rotor
- DC current is passed through the field winding to produce flux in the machine.

Operating Principles of DC Machine

- Voltage is induced in the armature winding and is alternating.

- A mechanical commutator and a brush assembly function as a rectifier or inverter, making the armature terminal voltage unidirectional.

- DC Motor principle:

http://www.youtube.com/watch?v=Ue6S8L4On-Y&feature=related

Principles parts of DC Machine

- Magnetic field system
- Armature
- Commutator and brushgear

Basic Construction of DC Machines

Stator (Field Pole)

- This part of the machine does not move and normally is the outer frame of the machine.

Rotor (Armature)

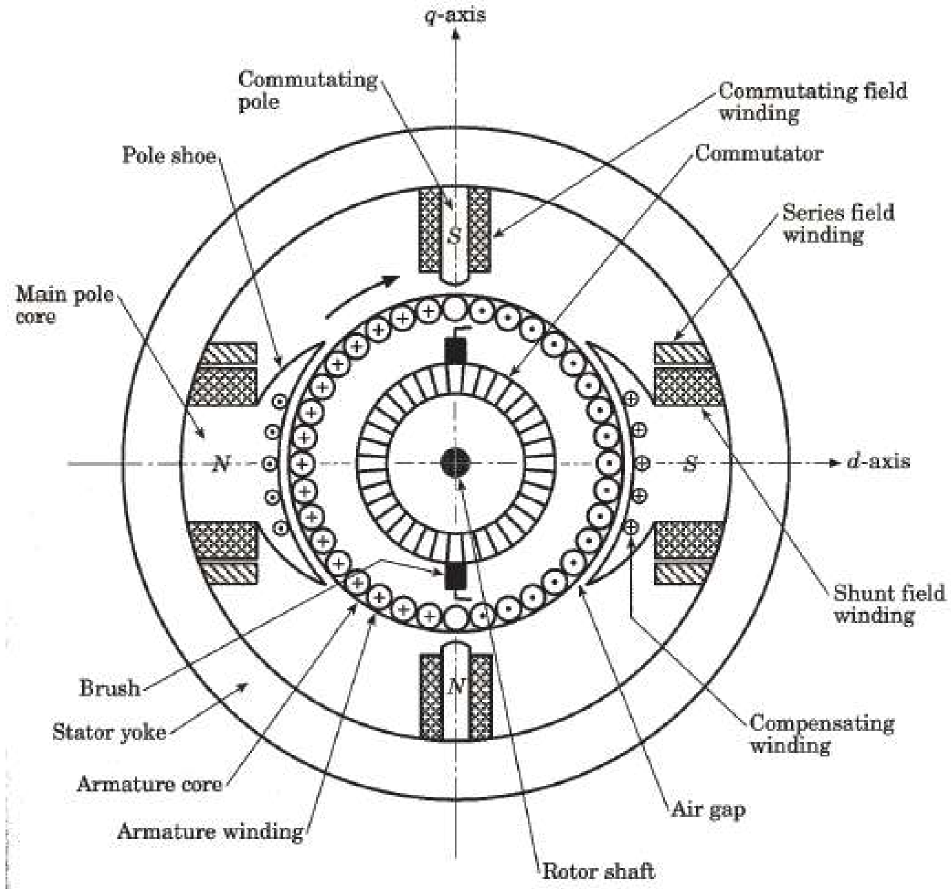
- This part of the machine is free to move and normally is the inner part of the machine.

Basic Construction of DC Machines

Commutator-brush Gear

- Used as a mechanical rectifier to make the armature terminal voltage unidirectional and also to make the mmfwave due to armature current fixed in space.

Detailed Construction Parts



Direct Current Machines Construction

- The stator of the DC motor has poles, which are excited by DC current to produce magnetic fields.

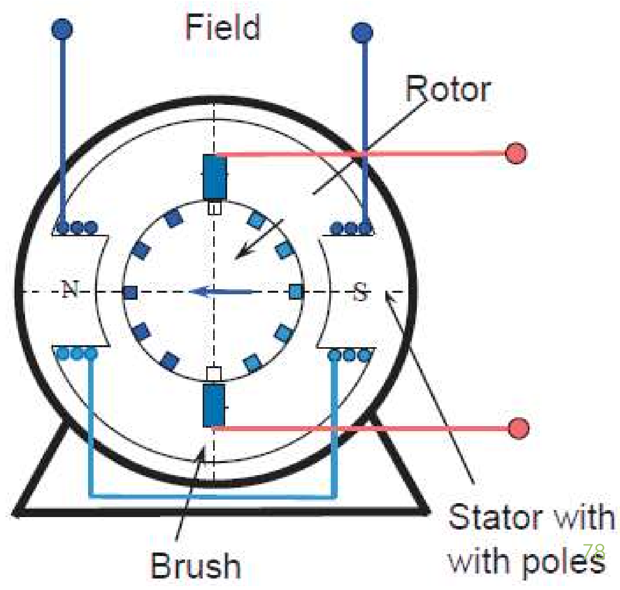
- The rotor has a ring-shaped laminated iron-core with slots.

Direct Current Machines Construction

- Coils with several turns are placed in the slots.

- The distance between the two legs of the coil is about 180 electric degrees.

Dc motor construction



Direct Current Machines

DC machine Construction

- The picture shows the stator of a large DC machine with several poles.

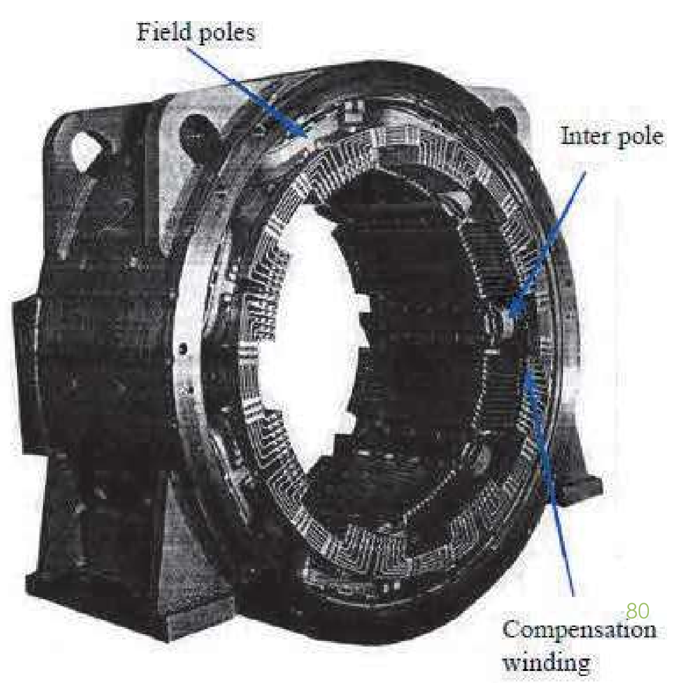
- Note the interpoles between the mainpoles. These poles reduce the field in the neutral zone and eliminate arcing of the commutator.

Direct Current Machines

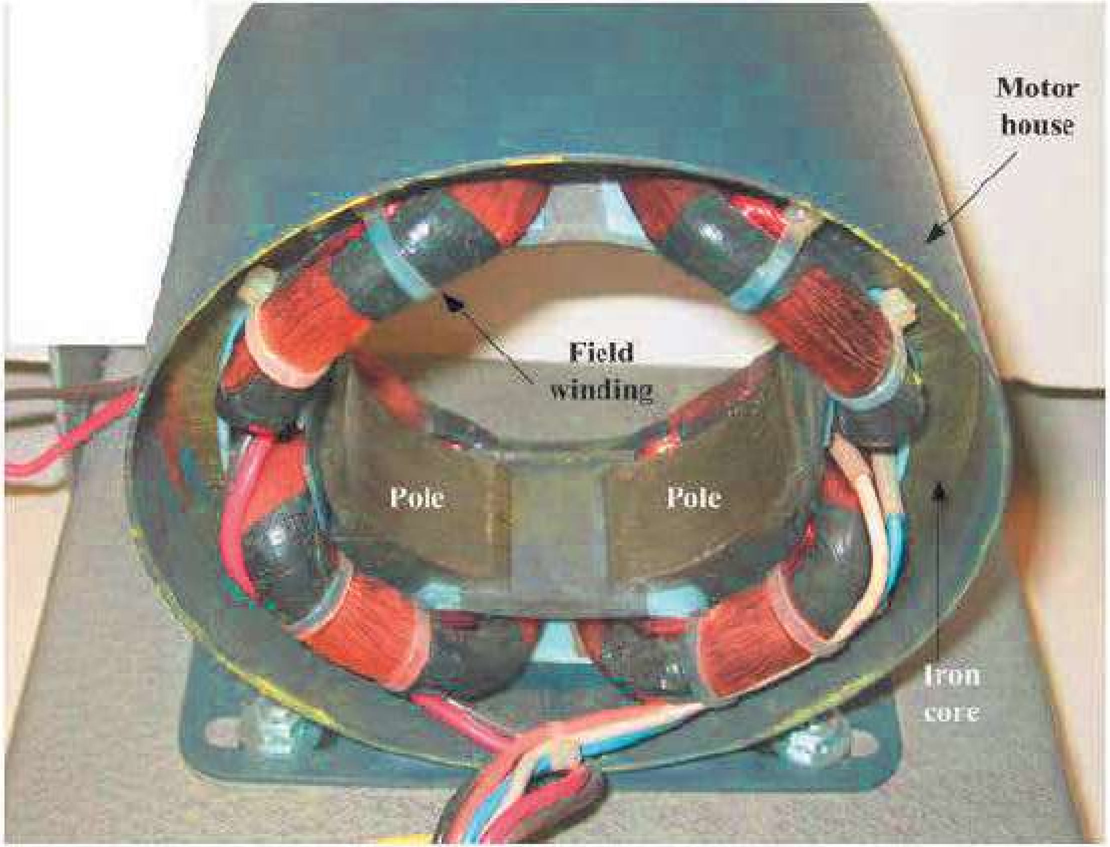
DC machine Construction

- A compensation winding is placed on the main poles to increase field during high load.
- The iron core is supported by a cast iron frame.

Dc motor stator construction



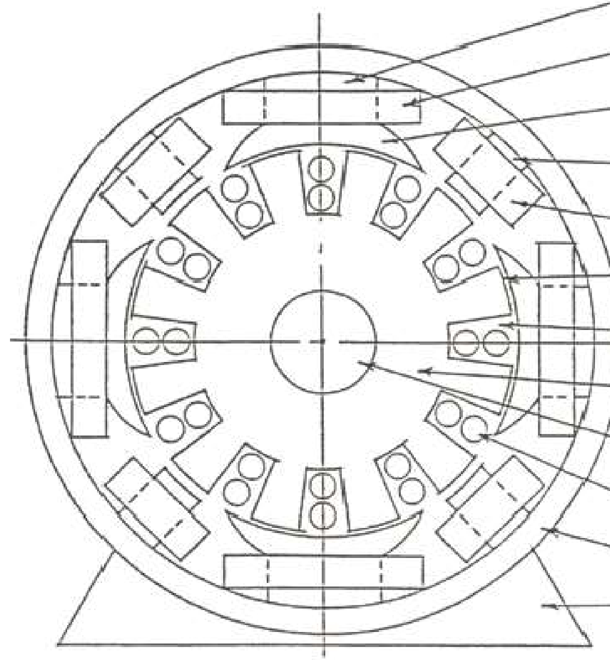
DC motor stator with poles



DC Machine Construction

Stator has salient poles that are excited by one or two field windings:

- Shunt field winding
- Series field winding



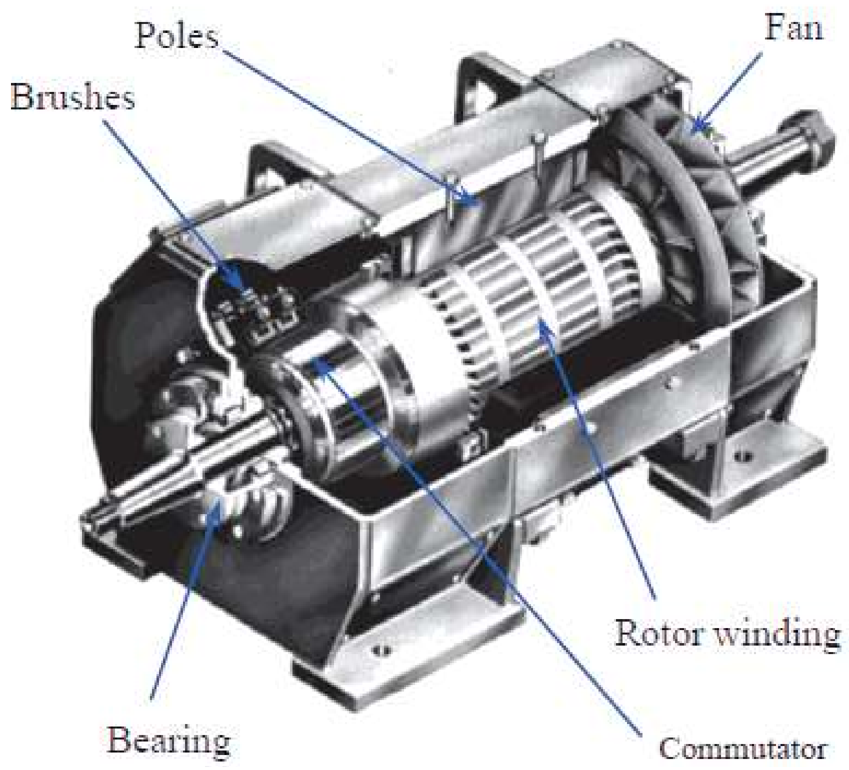
Direct Current Machines

DC machine Construction

- The adjoining picture shows the rotor of a DC machine.
- The rotor iron core is mounted on the shaft.
- Coils are placed in the slots.
- The end of the coils are bent and tied together to assure mechanical strength.
- Note the commutator mounted on the shaft. It consists of several copper segments, separated by insulation.

Direct Current Machines

DC motor armature (rotor) construction



Direct Current Machines

DC machine Construction

- The coils are connected in series.
- The junction points of the coils are connected to a commutator.

Direct Current Machines

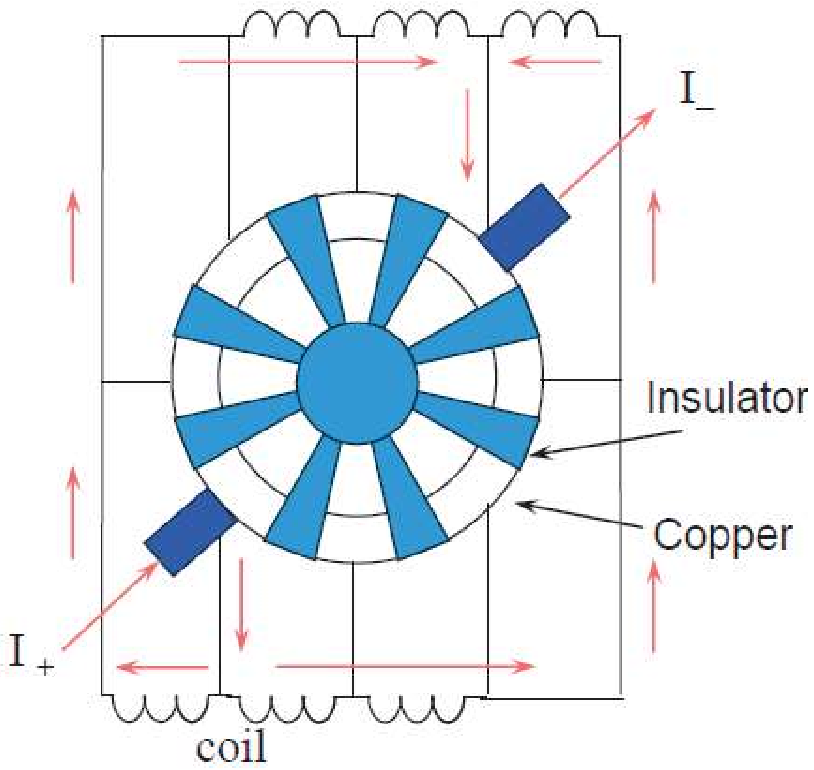
- The commutator consists of insulated copper segments mounted in a cylinder.

- Two brushes are pressed to the commutator to permit current flow.

- The brushes are placed in the neutral zone(magnetic field is close to zero)to reduce arcing.

Direct Current Machines

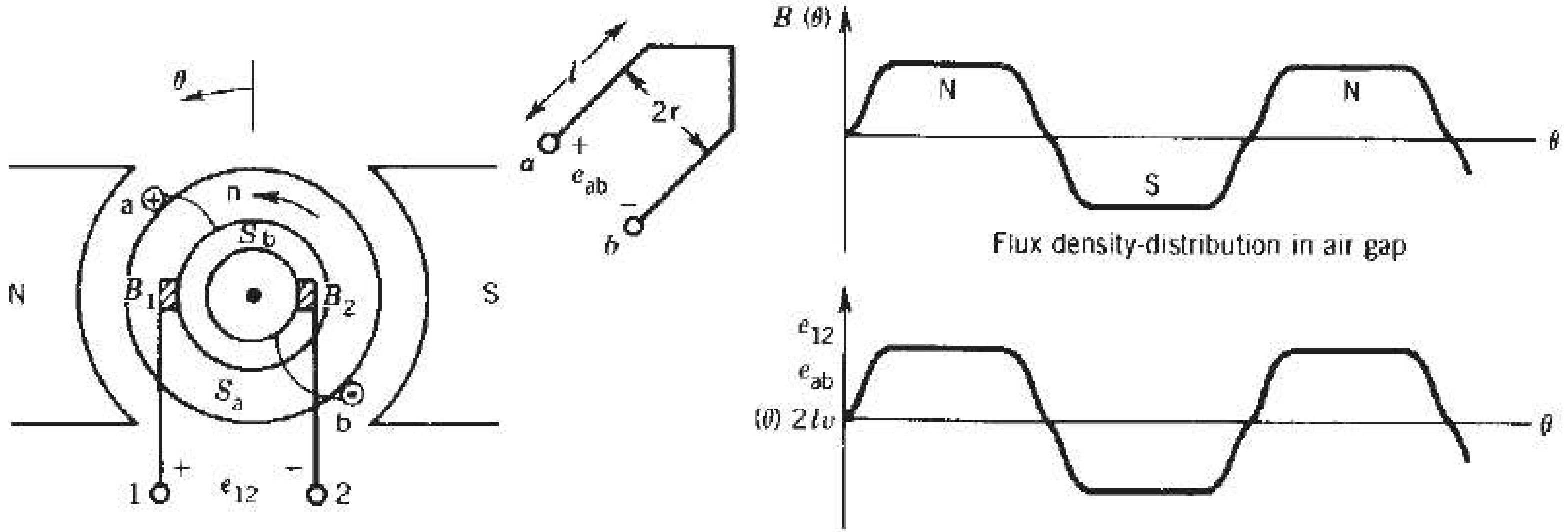
Concept of the commutator



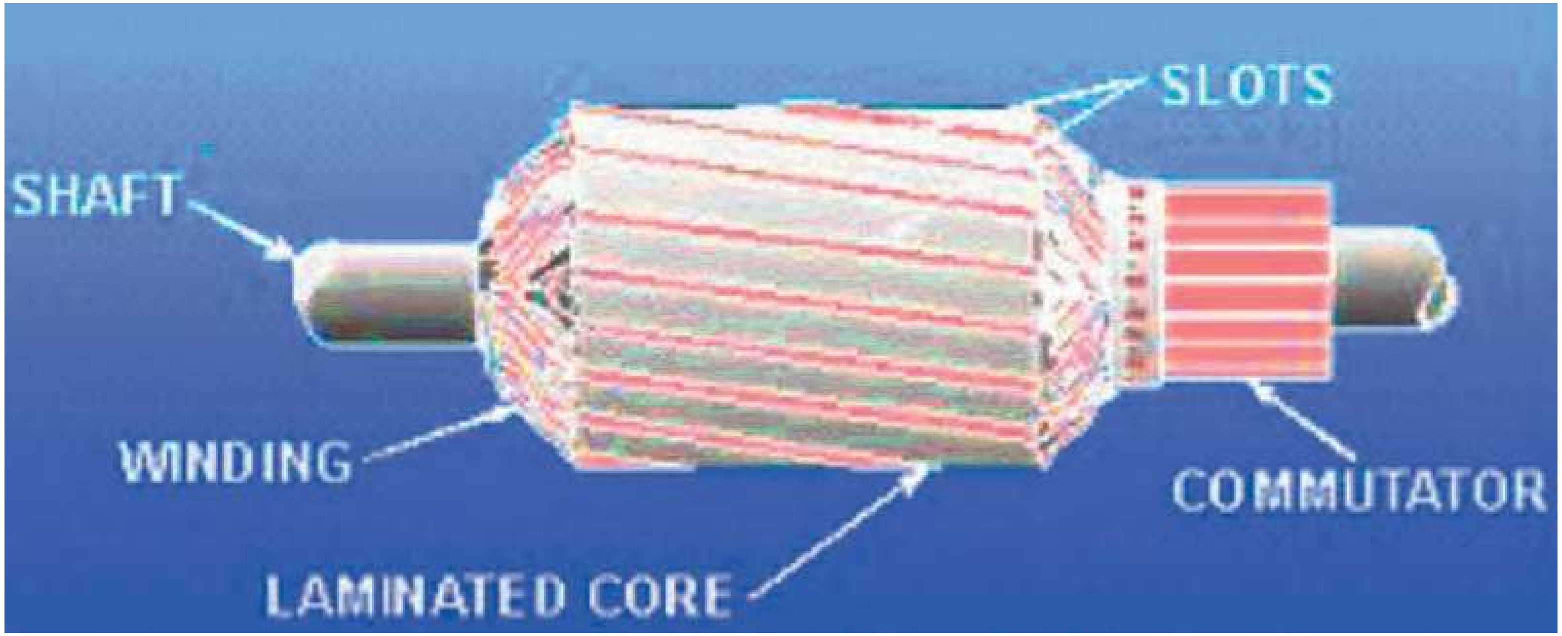
DC Machine Construction

- Armature winding is placed on the rotor

- Voltage induced in armature winding is alternating



Armature

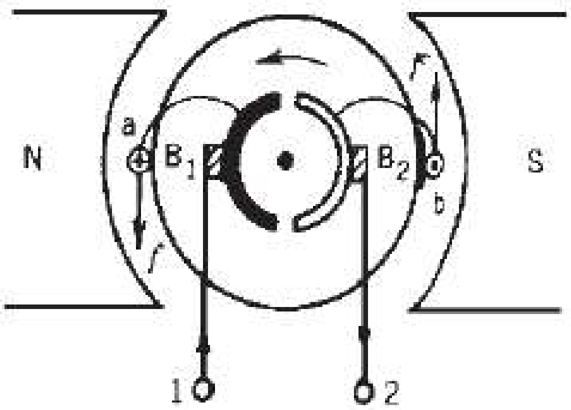


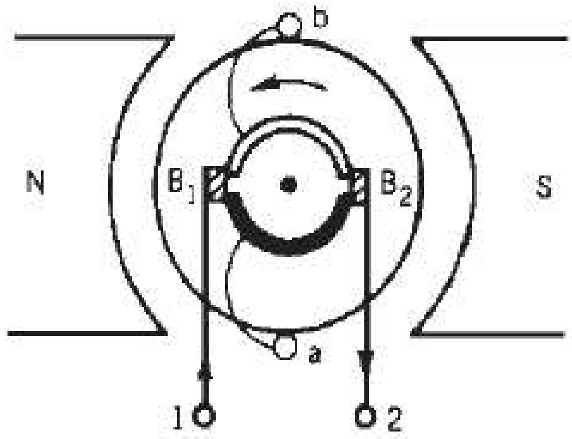
DC Machine Construction

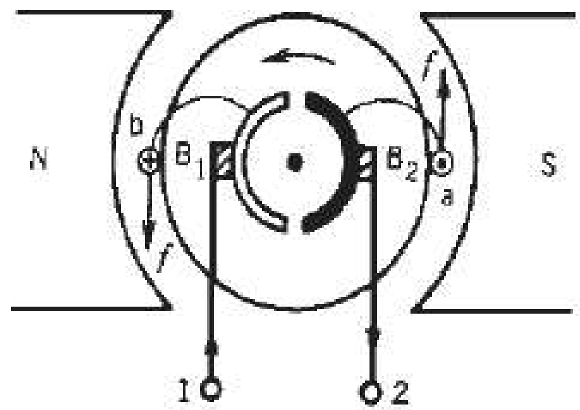
Commutator-brush combination is used as a *mechanical rectifier to:*

- Make the armature terminal voltage unidirectional
- Make the mmf wave due to armature current fixed in space

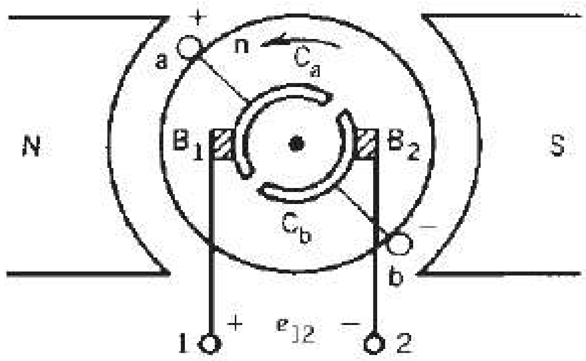
DC Machine Construction





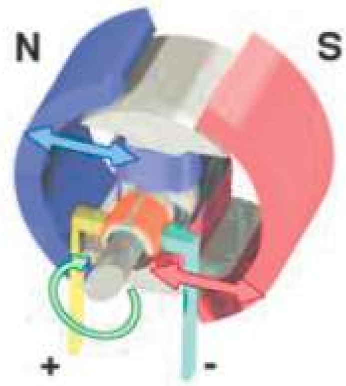


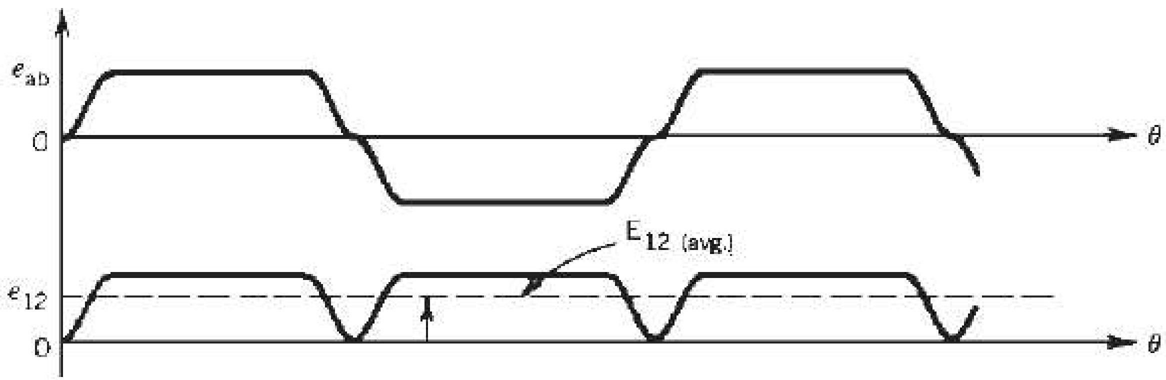
Voltage Rectification by Commutators



(a)

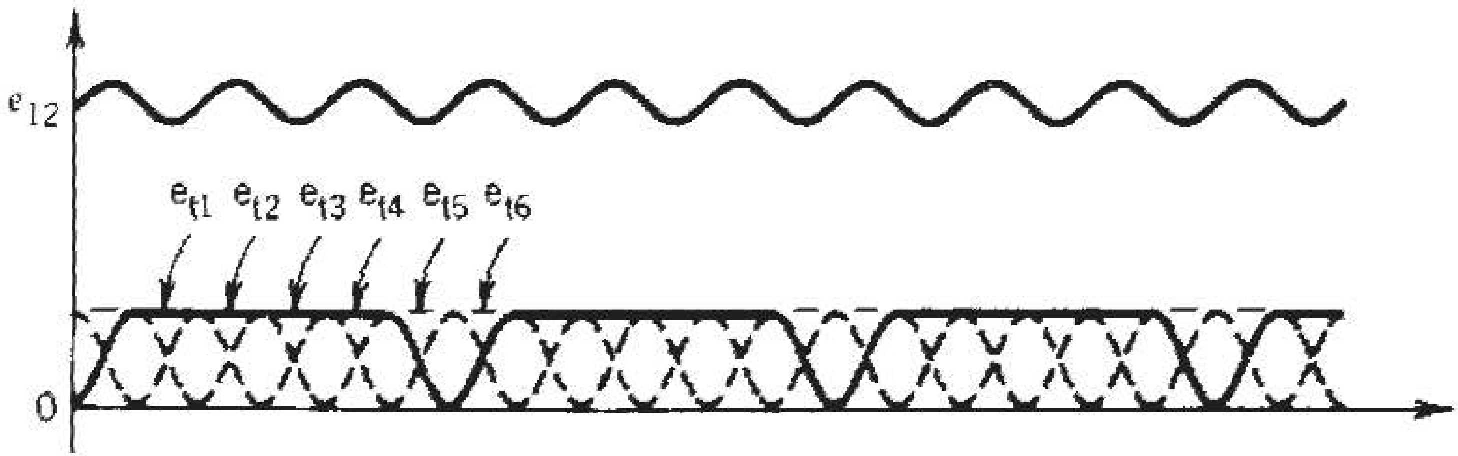
C_a, C_b-commutator segment





DC Machine Construction

- In an actual machine a large number of turns are placed in several slots around the periphery of the rotor to reduce the ripple.



DC Machine -Commutator

Commutator Construction

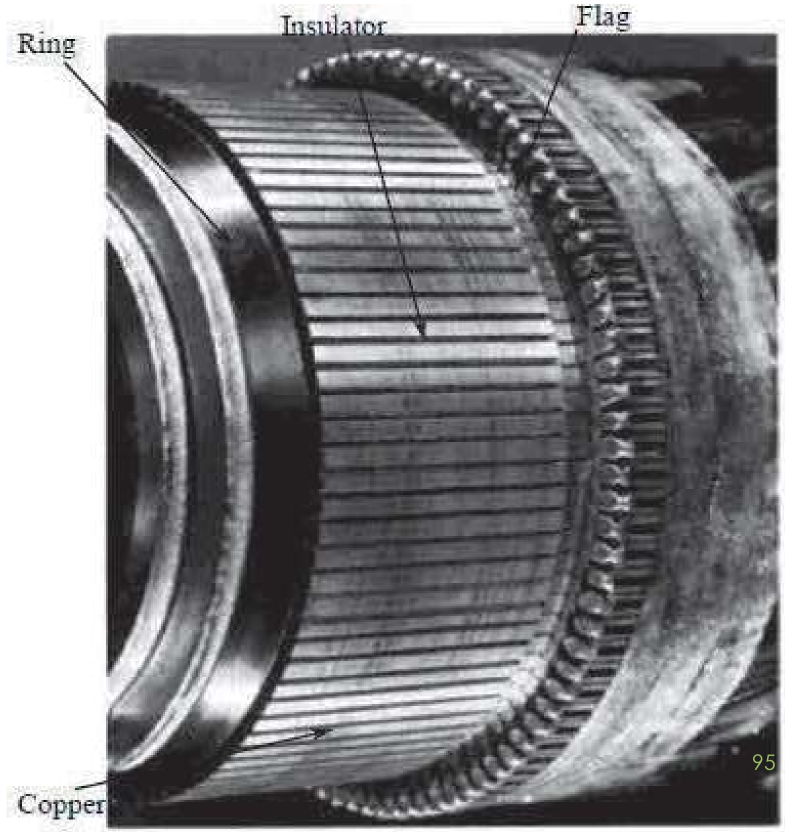
- The adjoining picture shows the commutator of a large DC machine.

- The segments are made out of copper and mica insulation is placed between the segments.

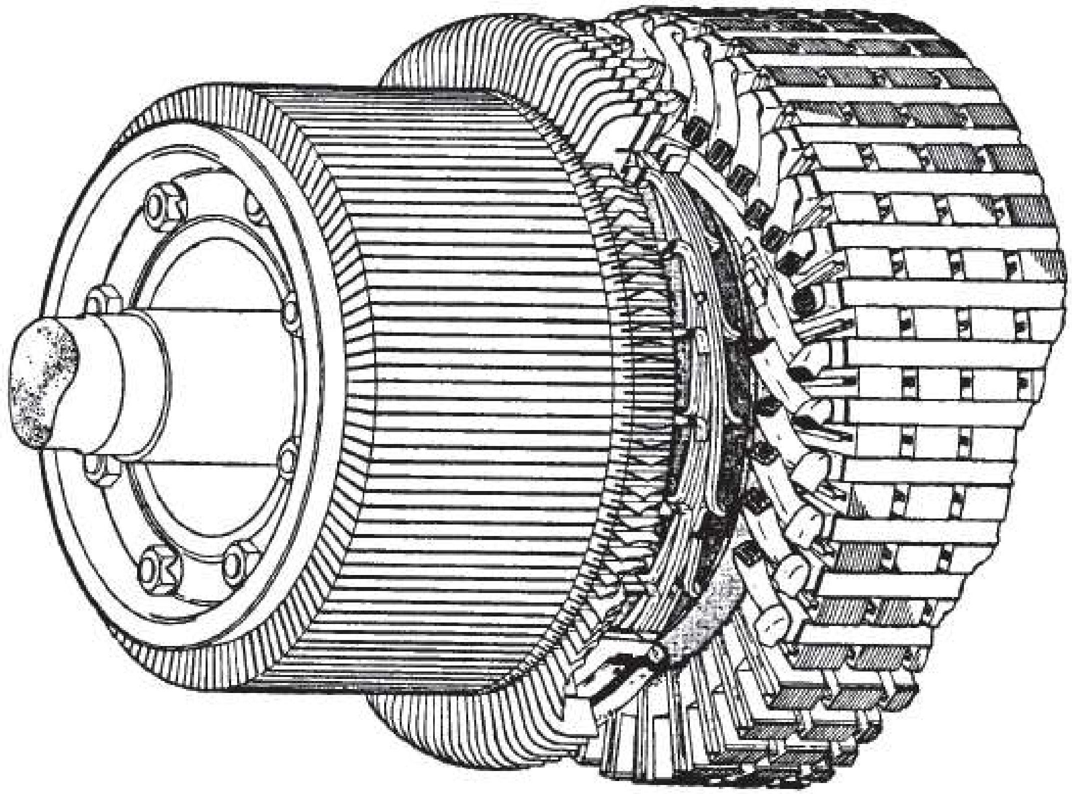
DC Machine -Commutator

Commutator Construction

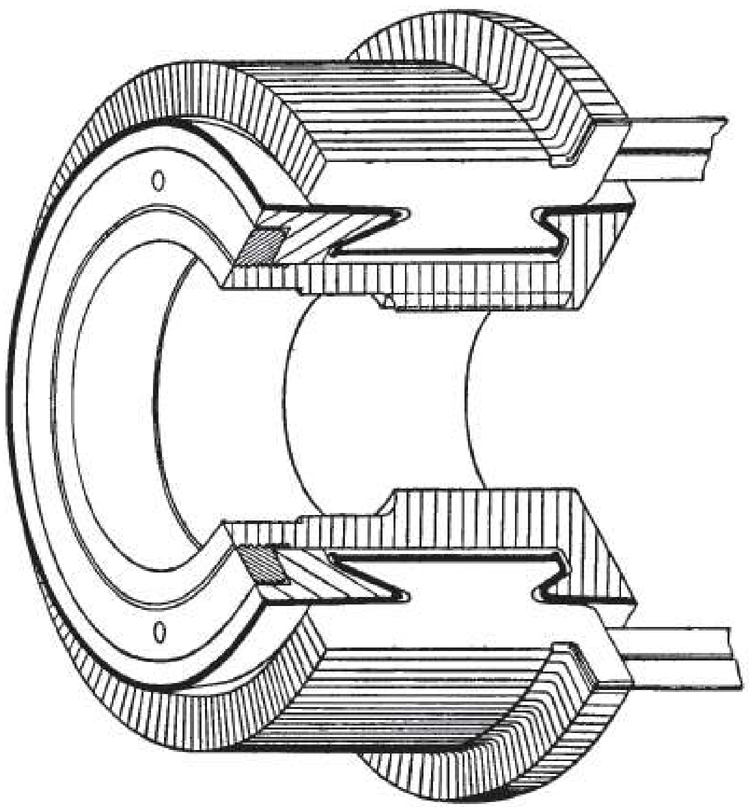
- The end of each segment has a flag attached. The coil endings are welded to these flags.
- An insulated ring is placed on the coil ends to assure proper mechanical strength.

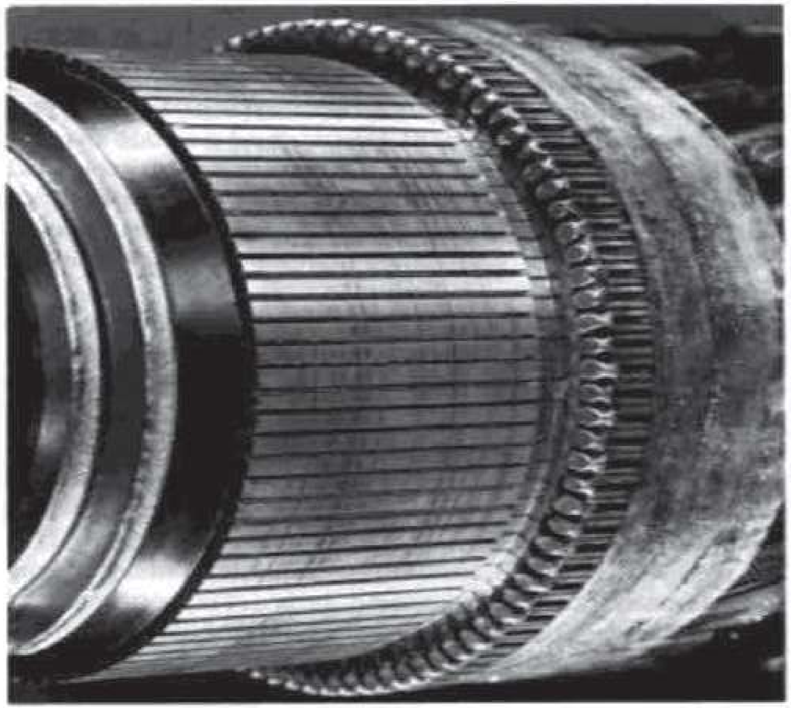


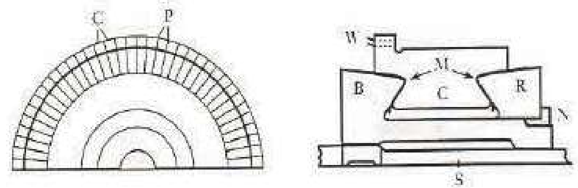
Close-up of Commutator



Close-up of Commutator



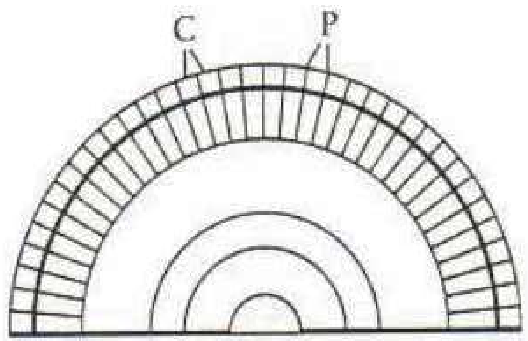


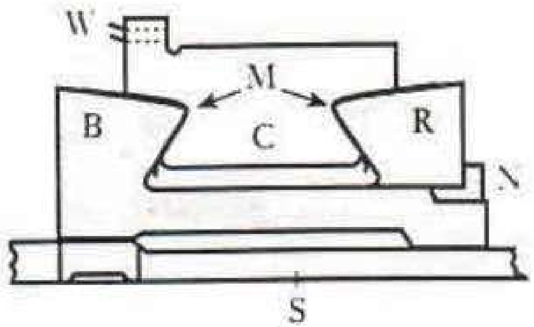


Commutator

Commutator Construction

C: wedge shaped copper segments





P: mica sheets

B: V –ring

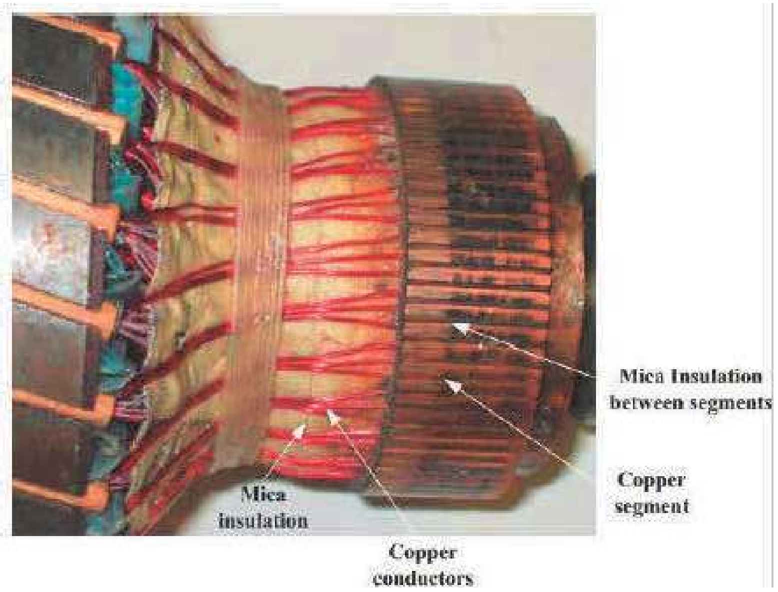
N: nut to tighten and keep in place V-ring B

W: armature wires which are soldered to the segment.

Armature Connection to Commutator

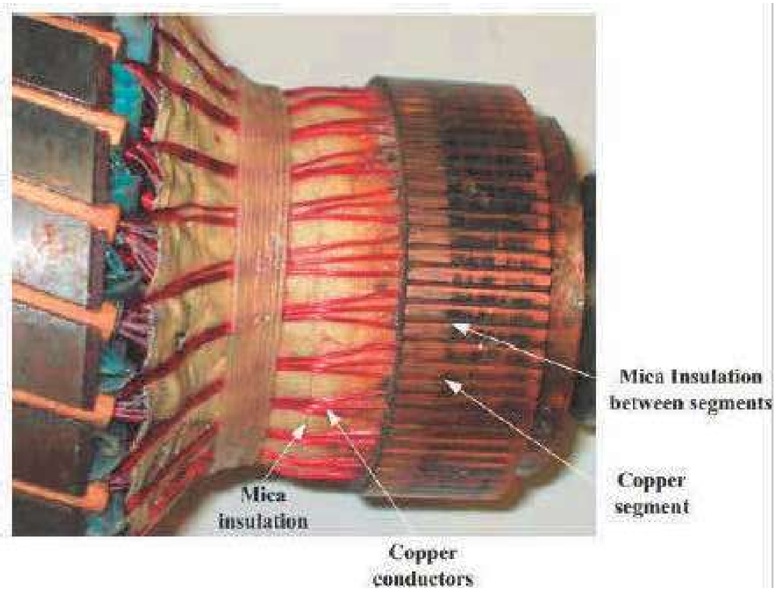
- The rotor has a ring-shaped laminated iron core with slots.

- The commutator consists of insulated copper segments mounted on an insulated tube.



Armature Connection to Commutator

- Two brushes are pressed to the commutator to permit current flow.
- The brushes are placed in the neutral zone, where the magnetic field is close to zero, to reduce arcing.



Armature Connection to Commutator

- The commutator switches the current from one rotor coil to the adjacent coil

- The switching requires the interruption of the coil current.

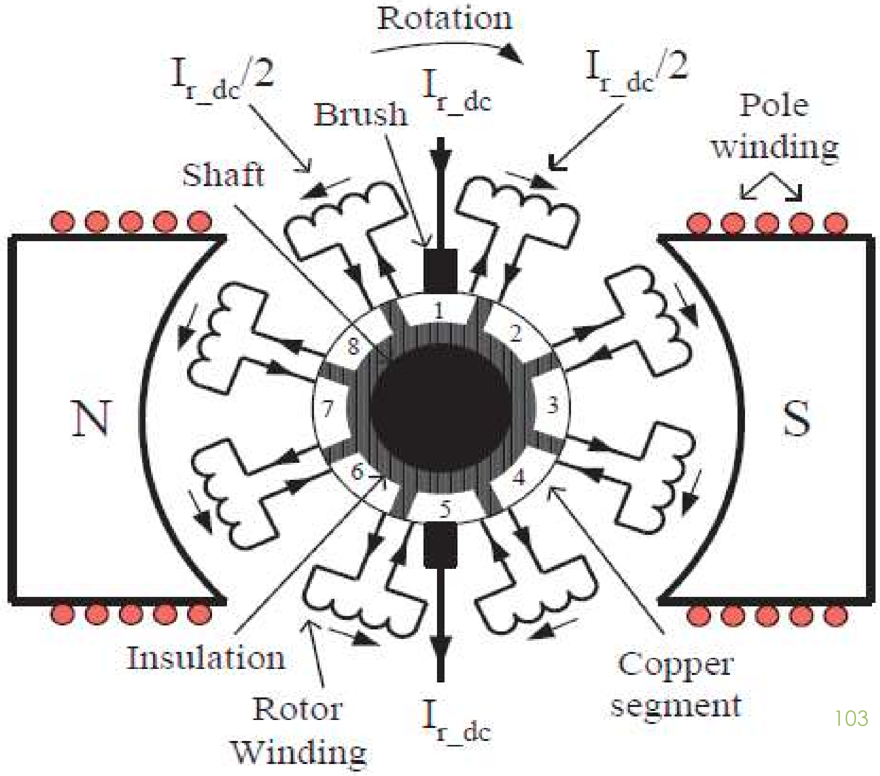
Armature Connection to Commutator

- The sudden interruption of an inductive current generates high voltages .

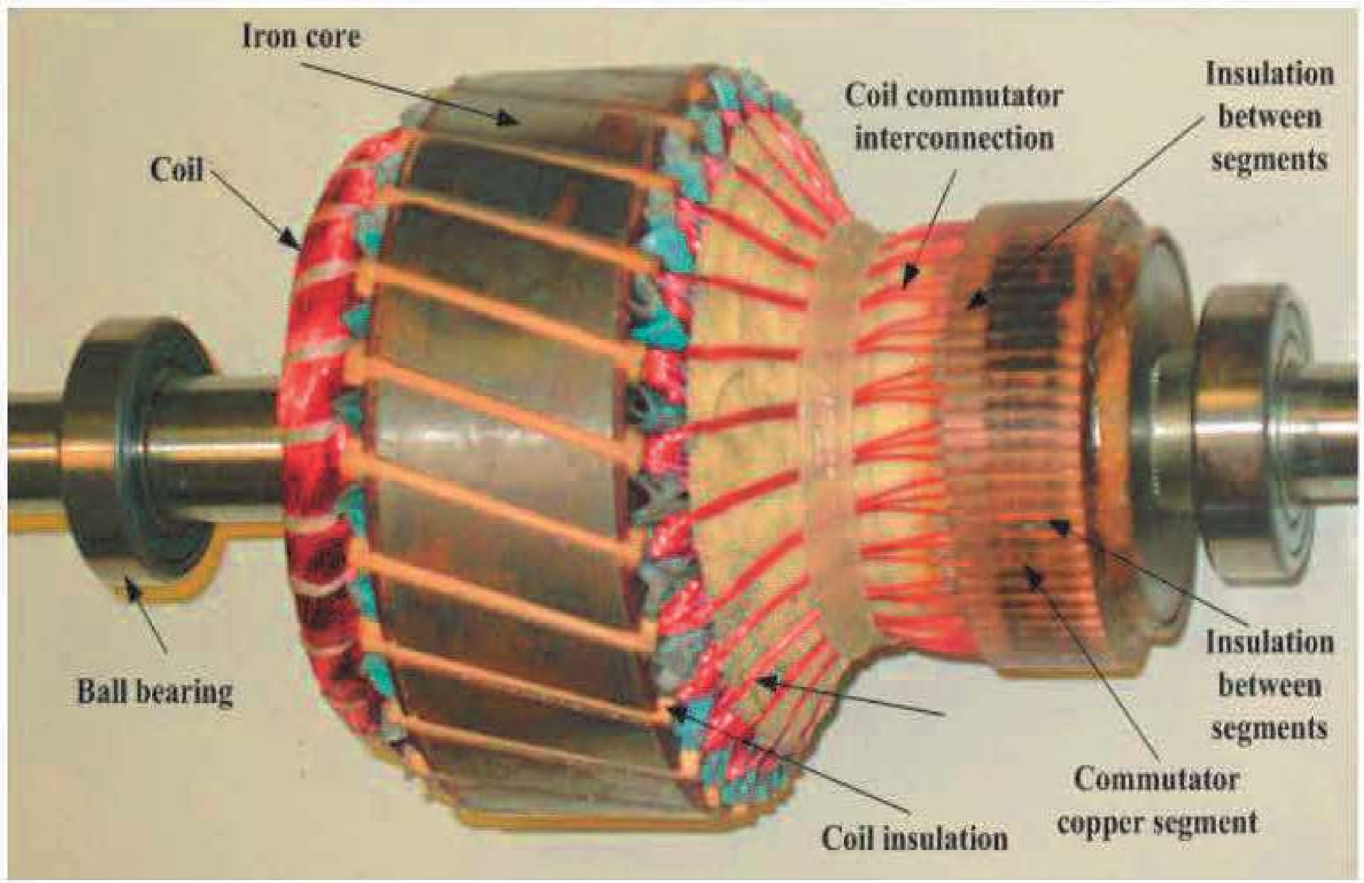
- The high voltage produces flashover and arcing between the commutator segment and the brush.

Armature Connection

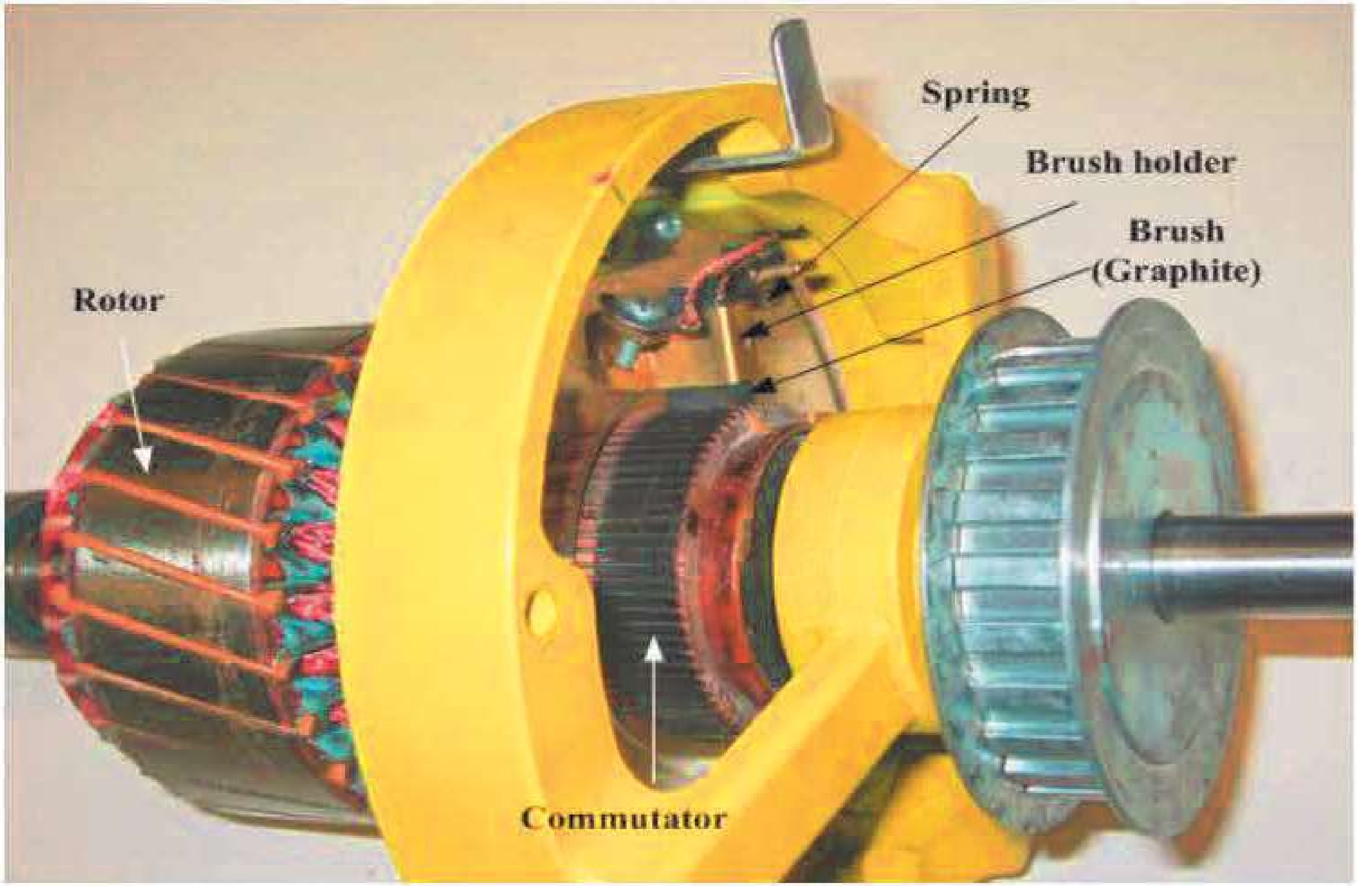
- Commutator with the rotor coils connections.



Armature (Rotor) of a DC motor

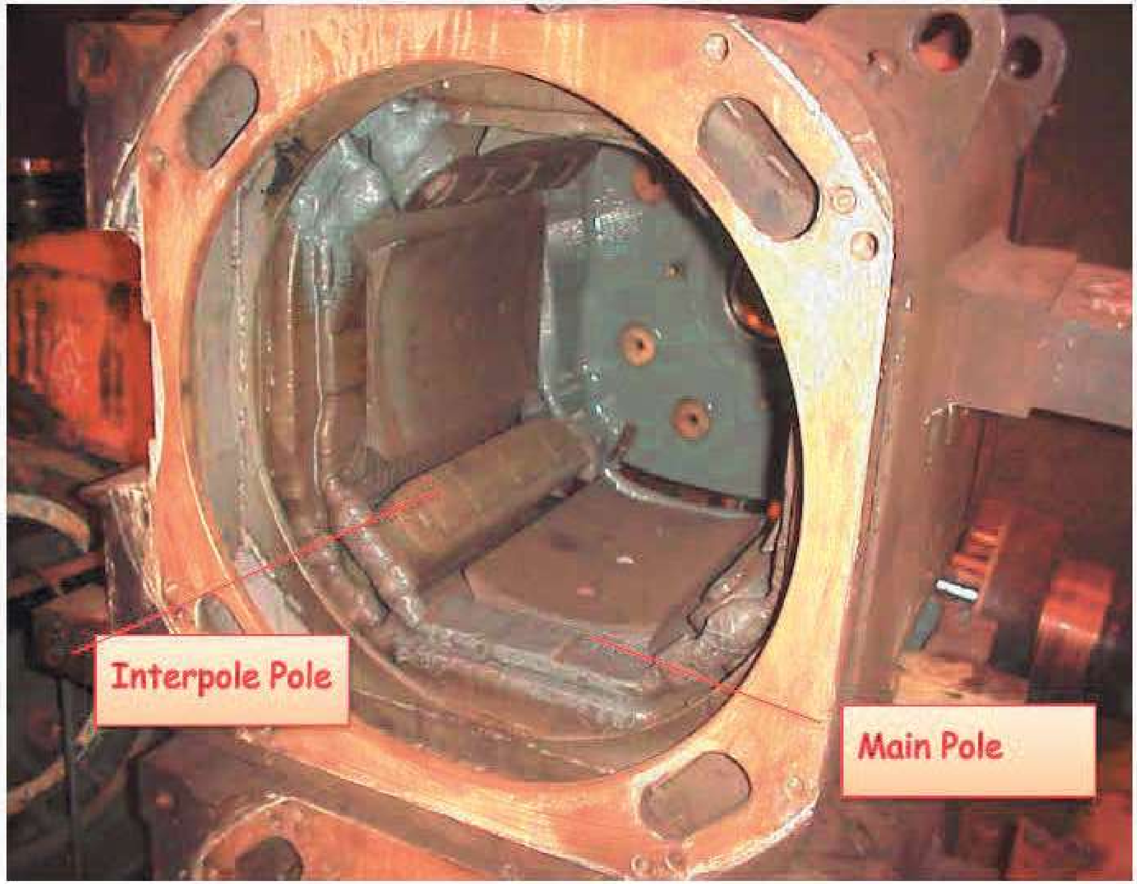


Cutaway View of a DC Motor



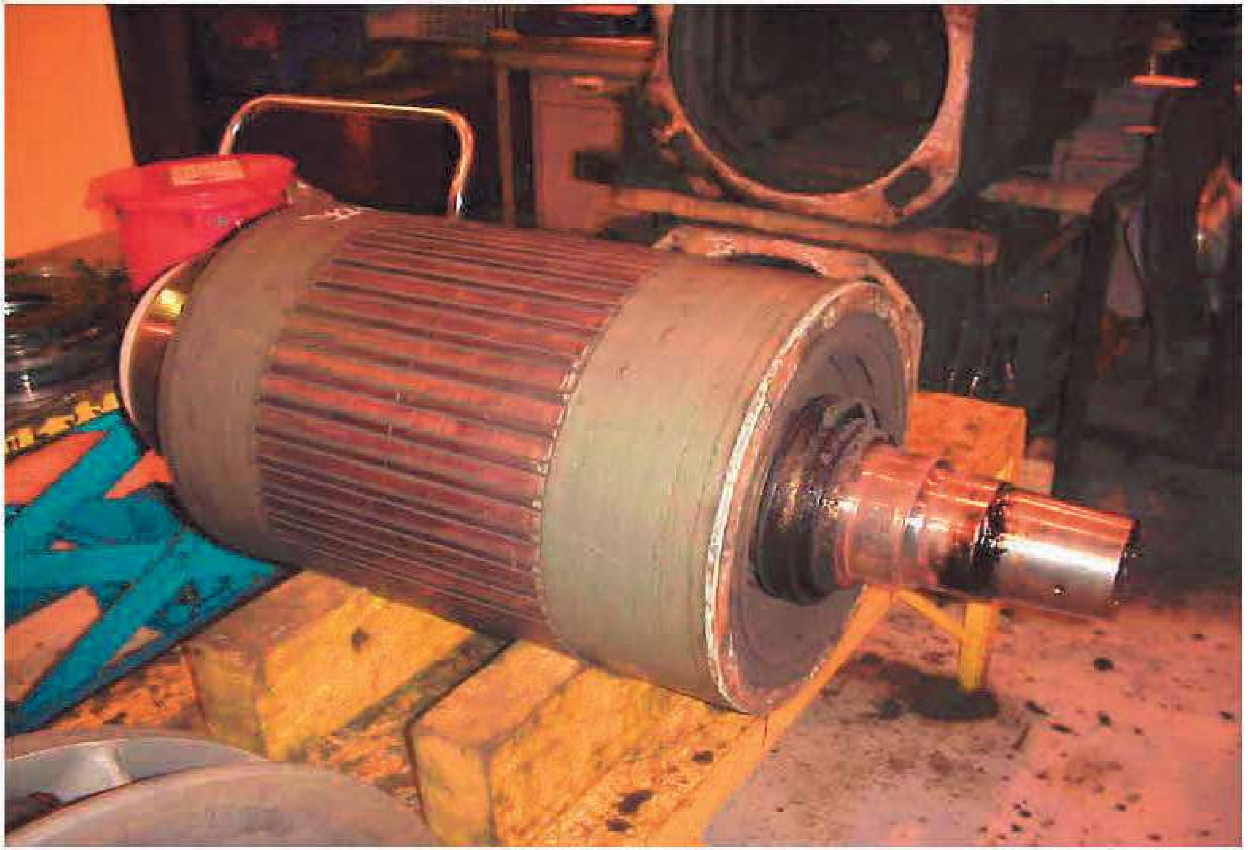
DC Machine Construction

DC Machine Construction

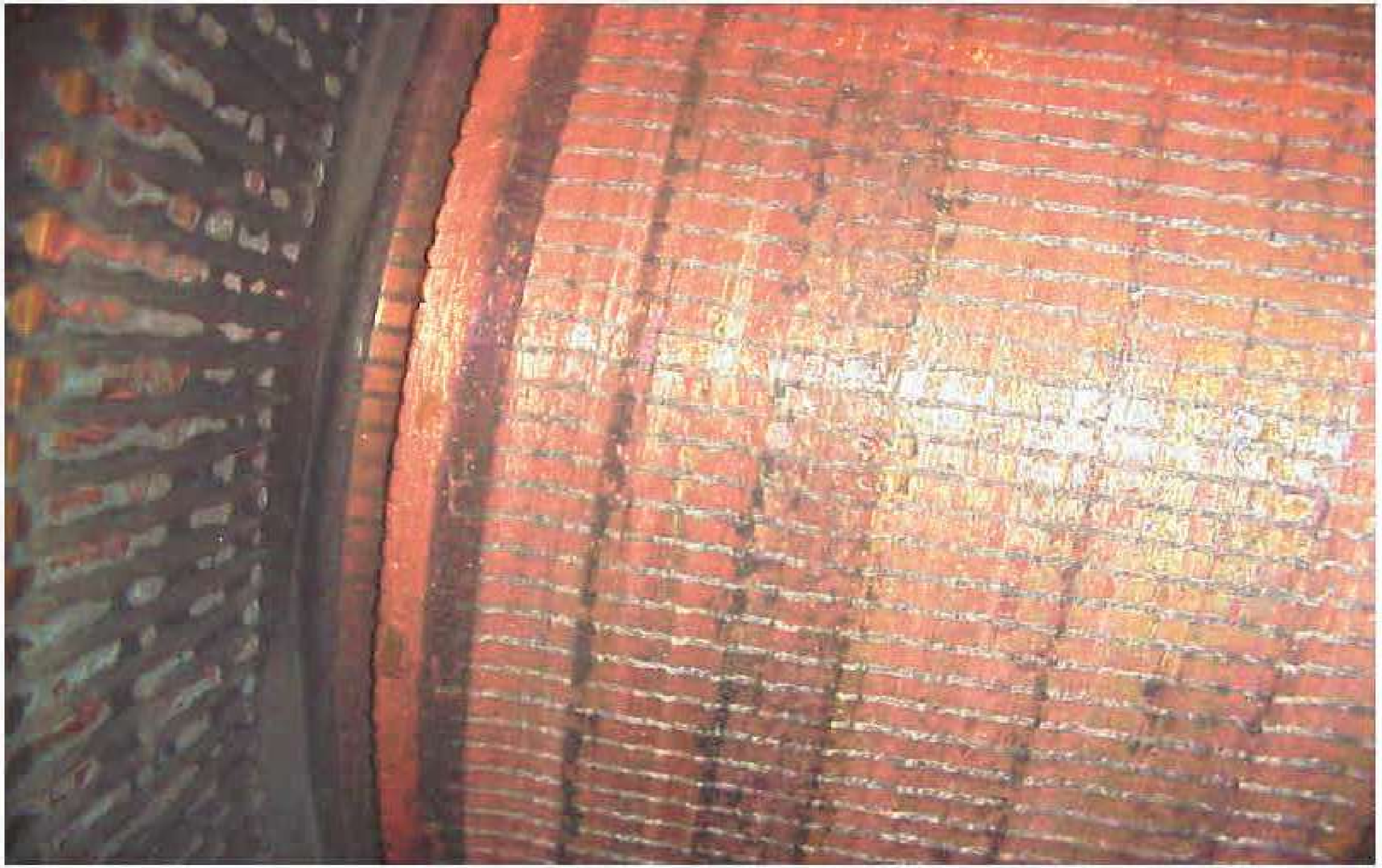


DC Machine Construction

Armature of a DC Machine



Commutator Close up



220kW Exciter Armature for Generator

220kW Exciter Armature for Generator

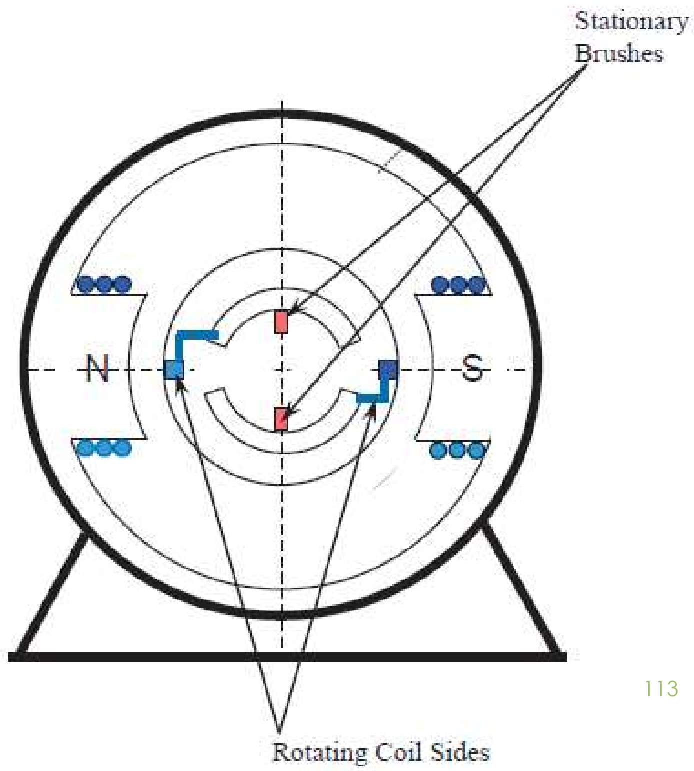
220 KW Exciter Armature for an Electric Utility generator

Operating Principles of Generator

Operation Principles

- The poles are supplied by DC current producing a DC magnetic field.
- The poles are shaped in such away the field distribution along the pole is more or less sinusoidal.

DC Generator operation concept

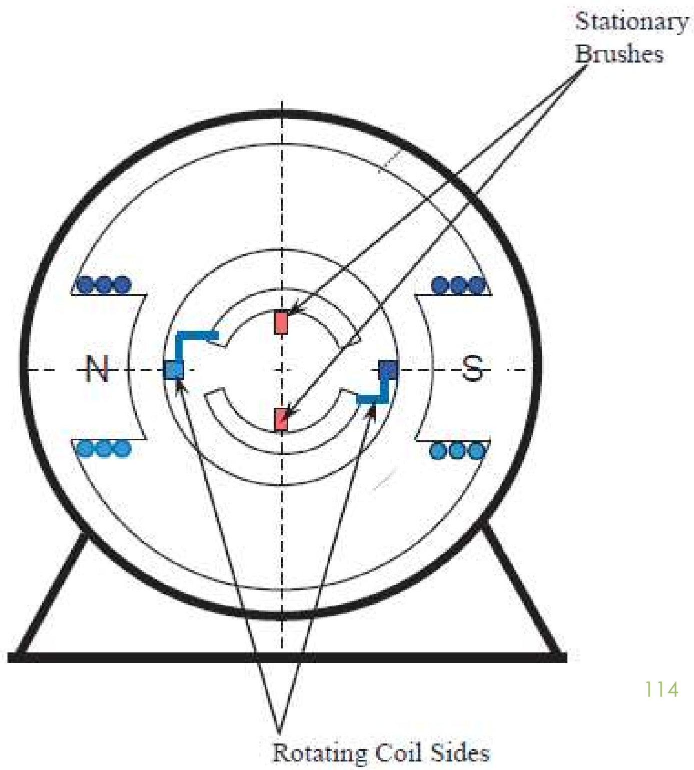


Operating Principles of Generator

Operation Principles

- When the rotor coil is rotated, the flux linkage changes during the rotation.
- It is maximum when the coil is in vertical position and zero when it is in horizontal position.

DC Generator operation concept



Classification of DC Machines

DC machines may be classified according to the connection of their

- Field
- Armature windings

Types of Excitations in DC Machine

- Separate excitation
- Self-excitation

Separate Excitation

- The separately excited field windings consists of several hundred turns of fine wire and is connected to a separate or external dc source.

Separate Excitation

- The voltage of the external dc source has no relation with the armature voltage.

- Field winding energized from a separate source can be designed for any suitable voltage.

Self Excitation

- When the field winding is excited by its own armature the machine is called a self-excited DC machine.

- The field poles of these machines must have residual magnetism.

Self Excitation

A self-excited dc machine can be classified as follows:

- Shunt excitation
- Series excitation
- Compound excitation

Compound Excitation

Depending upon the number of turns of the series field three types of compound generators can be obtained:

Over Compounded Generator:

- the generated voltage increases as the load increases

Compound Excitation

Level or Flat Compounded Generator:

- The no load voltage is same as that of the full load voltage

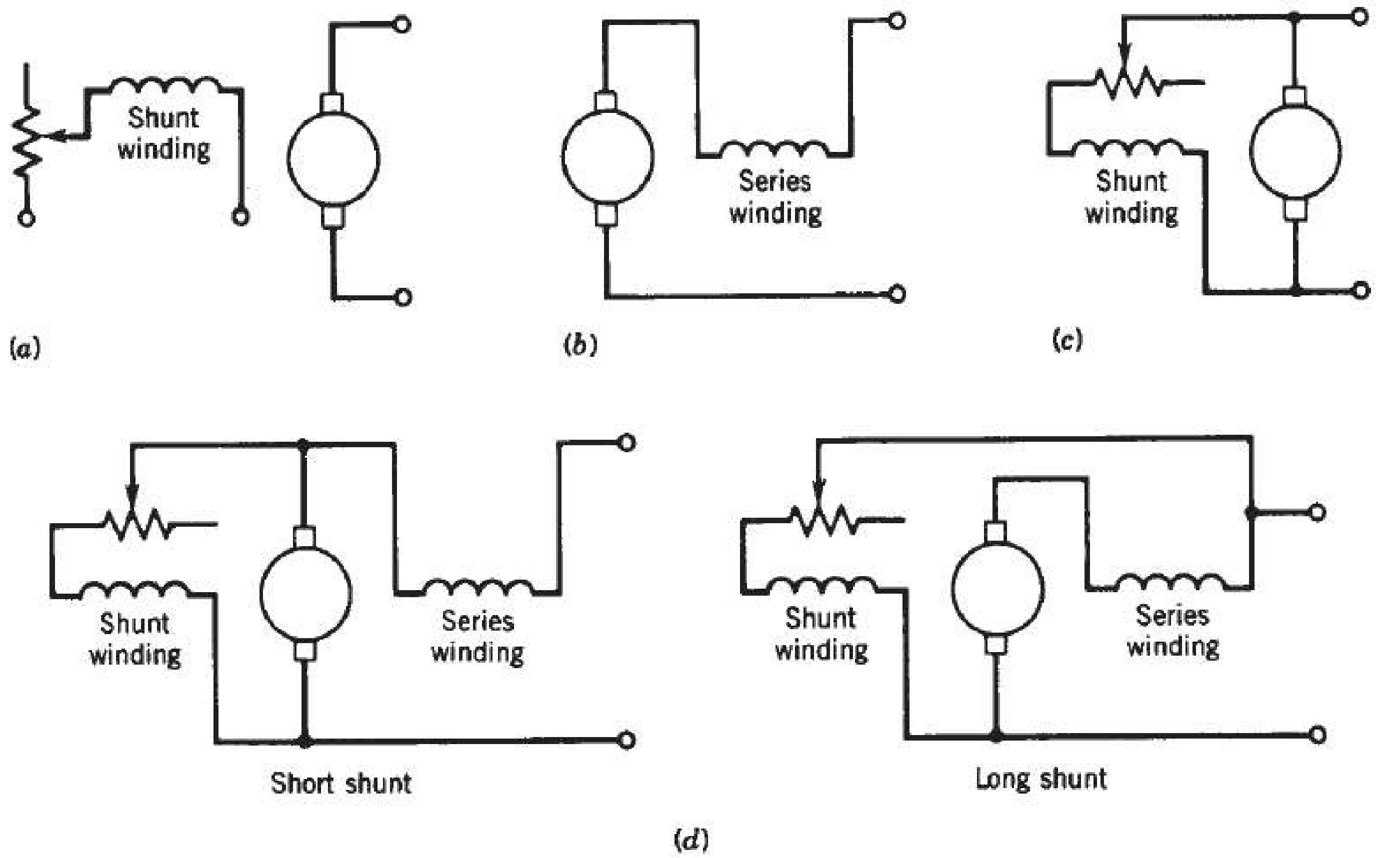
Under Compounded Generator:

- the generated voltage decreases as the load increases

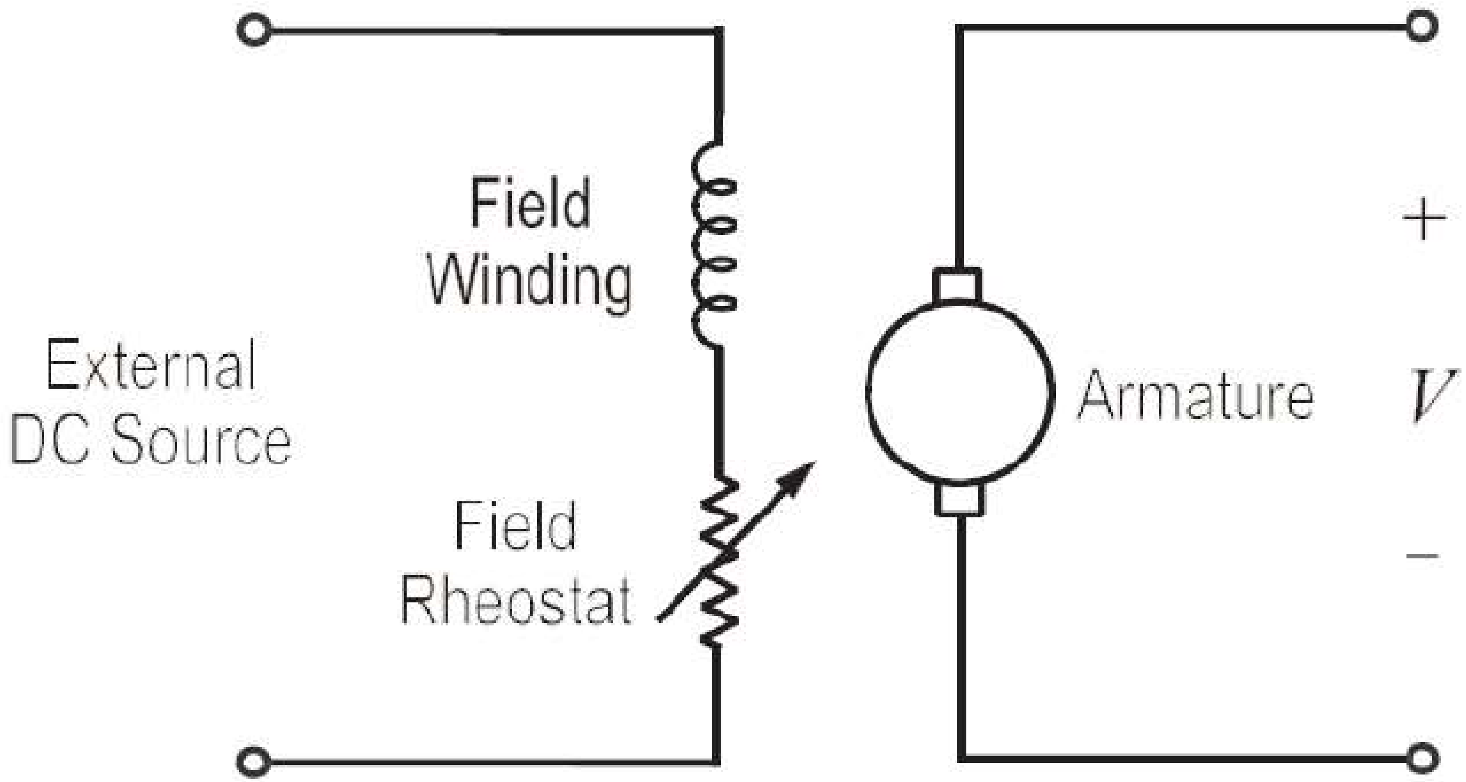
Classification of DC Machines

- Separately excited DC machine
- Series DC machine
- Shunt DC machine
- Compound DC machine
  - Long Shunt
  - Short Shunt

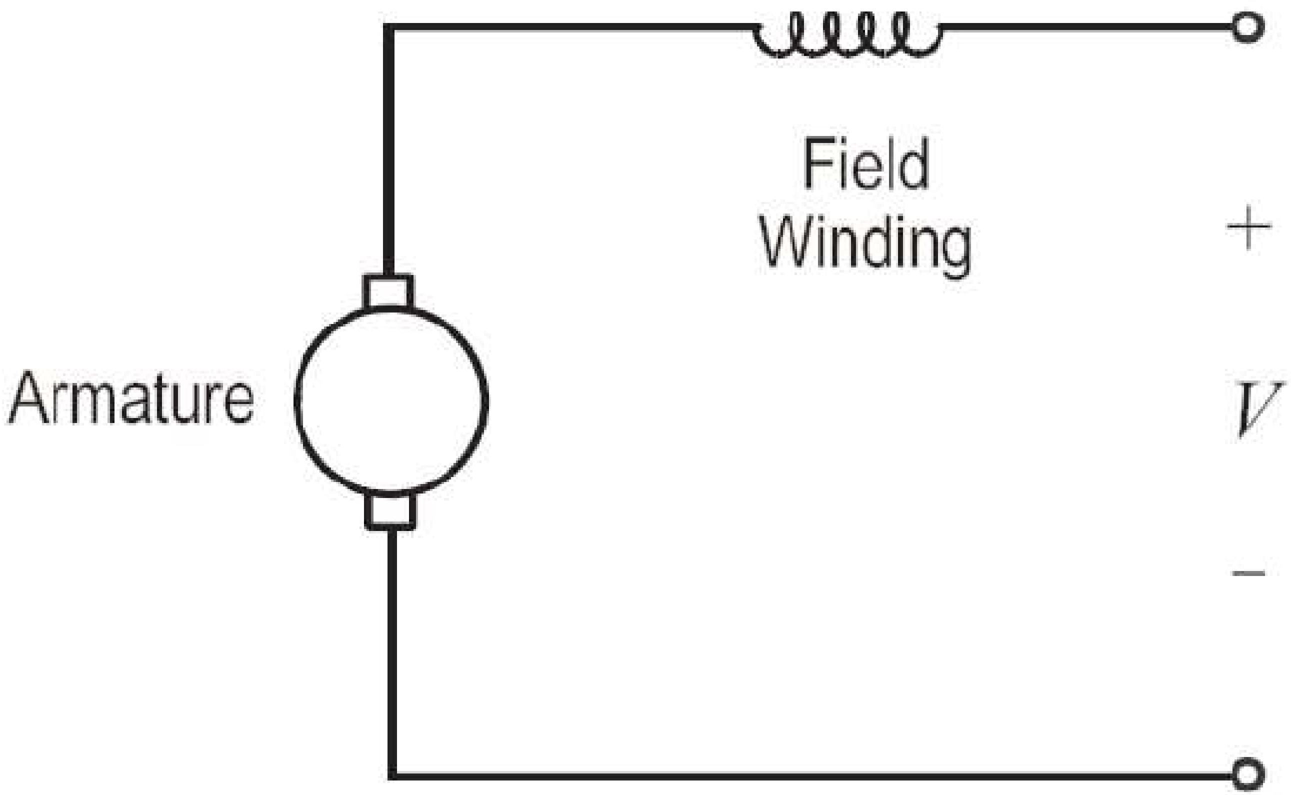
Classification of DC Machines



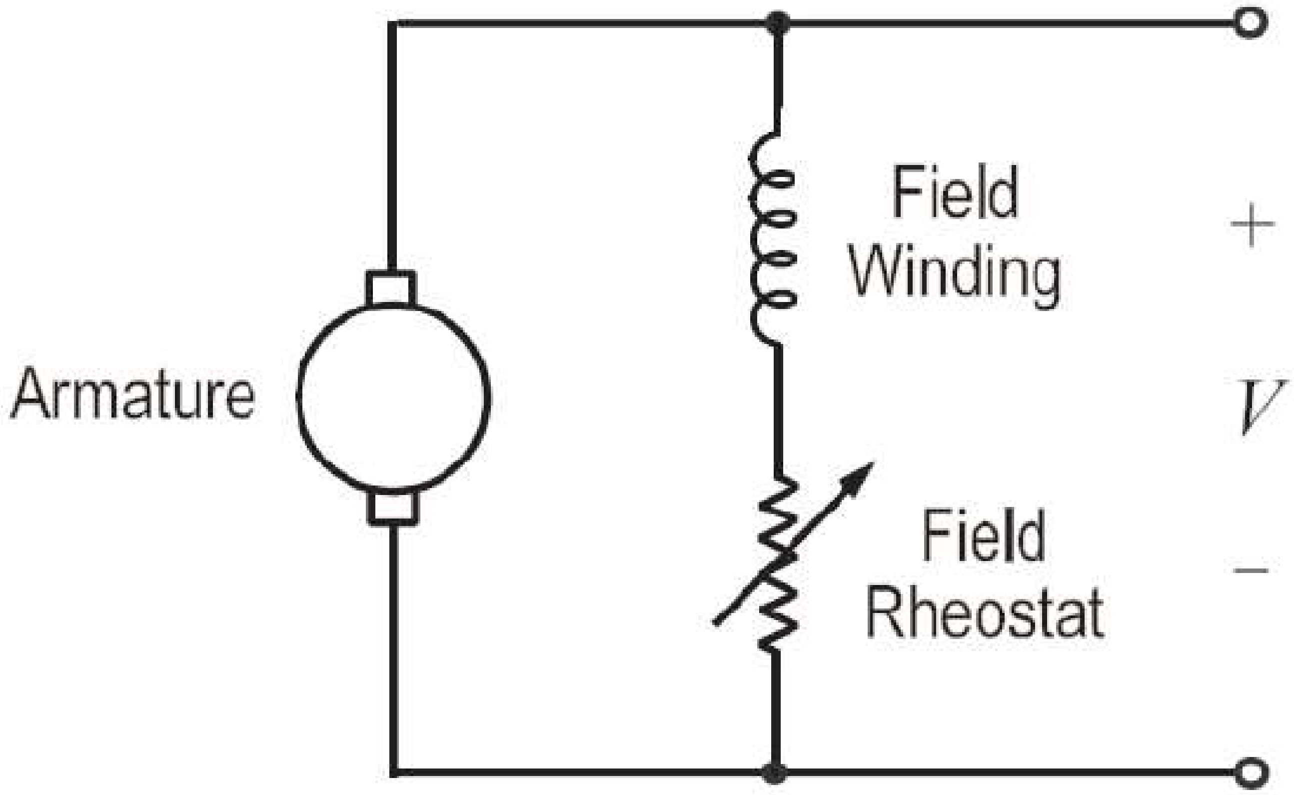
Separately Excited



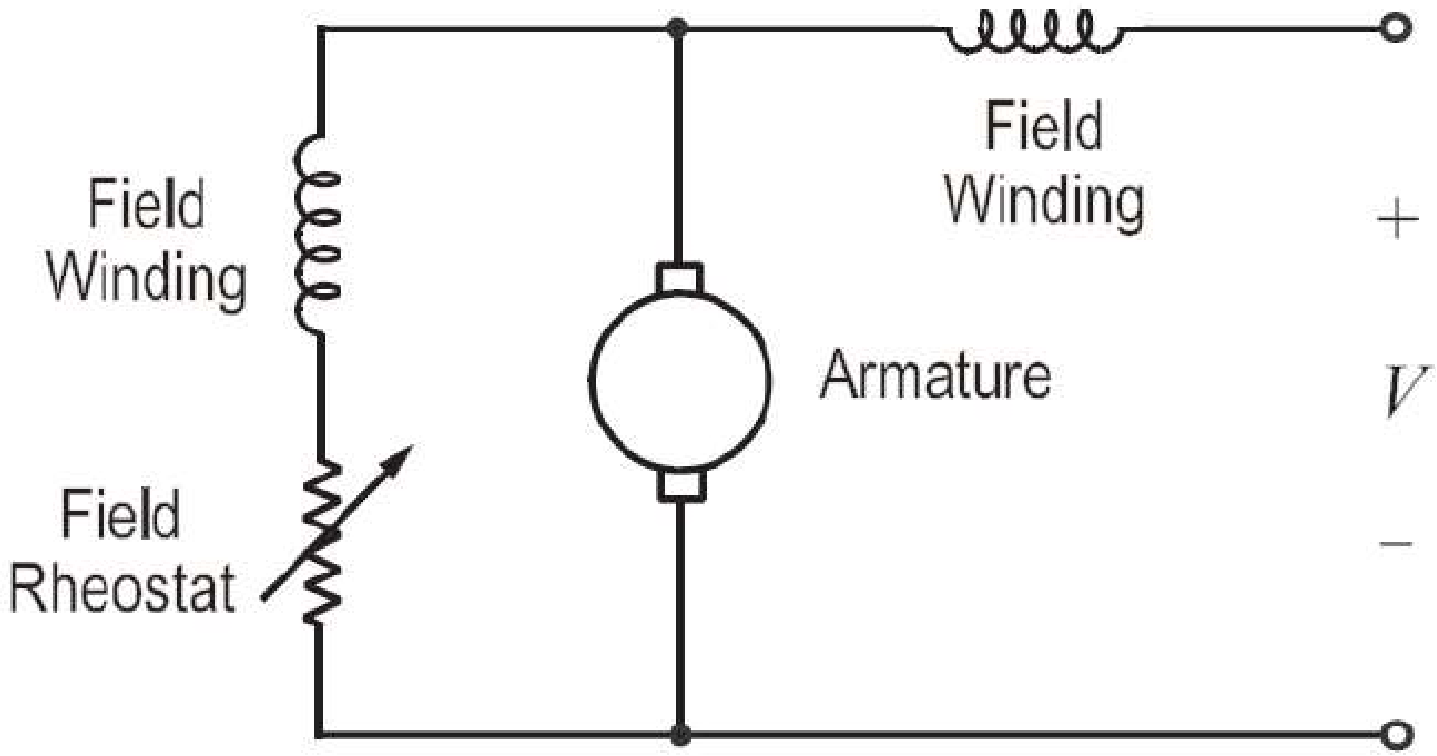
Self-excited Series DC Machine



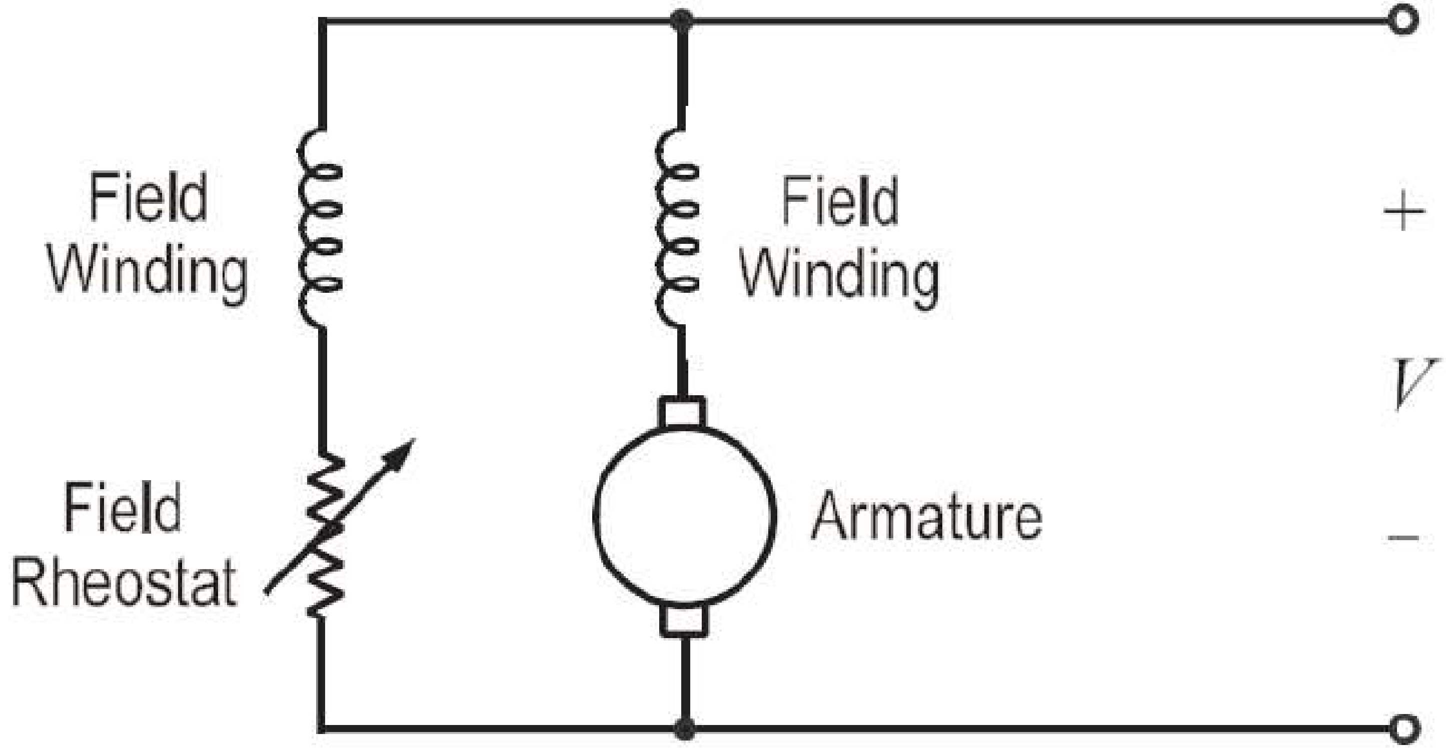
Self-excited Shunt DC Machine



Self-excited Compound DC machine (Short Shunt)



Self-excited Compound DC machine (Long Shunt)



EMF Equation of a DC Machine

As the armature of a dc machine rotates, a voltage is generated in its coils.

- **DC generator:** the emf of rotation Eris called the generated emf Eg(or armature emf)

EMF Equation of a DC Machine

As the armature of a dc machine rotates, a voltage is generated in its coils.

- **DC motor:** the emf of rotation Eris known as back emf Eb(or counter emf)

Armature Emf Equation

Total number of poles = 2p

A particular conductor pass one revolution/sec (n)=2pn poles/sec

Time taken to pass one pole = $\frac{1}{2pn}$ sec

Emf induced per conductor = $\frac{d\phi}{dt} = \frac{\phi}{\frac{1}{2pn}} = 2pn\phi$ Volts

On the armature, there are Z/c conductors in series

$\therefore$ Total induced emf, $E = 2pn\phi x \frac{Z}{c}$ V

$$= 2\frac{Z}{C}\frac{N\Phi P}{60} \quad V$$

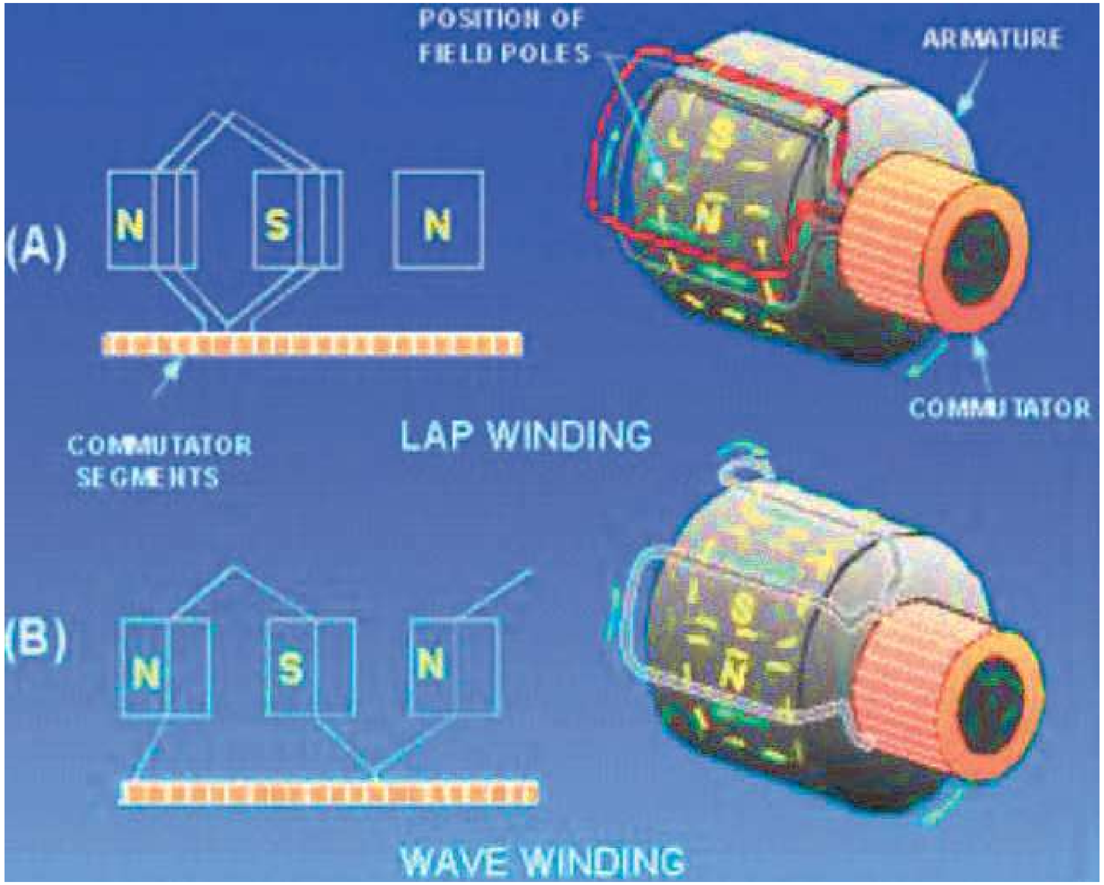
Armature Voltage

As the armature rotates in the magnetic field produced by the stator poles, voltage is induced in the armature winding:

- **Eg** = generated voltage (Generator)
- **Eb** = back emf (Motor)

$$E = 2\frac{Z}{C}\frac{N\phi P}{60}V$$

Types of Armature Winding



Lap Winding

- This type of winding is used in dc generators designed for high current applications.
- The windings are connected to provide several parallel paths for current in the armature.
- The 2 ends of a coil are connected to adjacent commutator segments.

Lap Winding

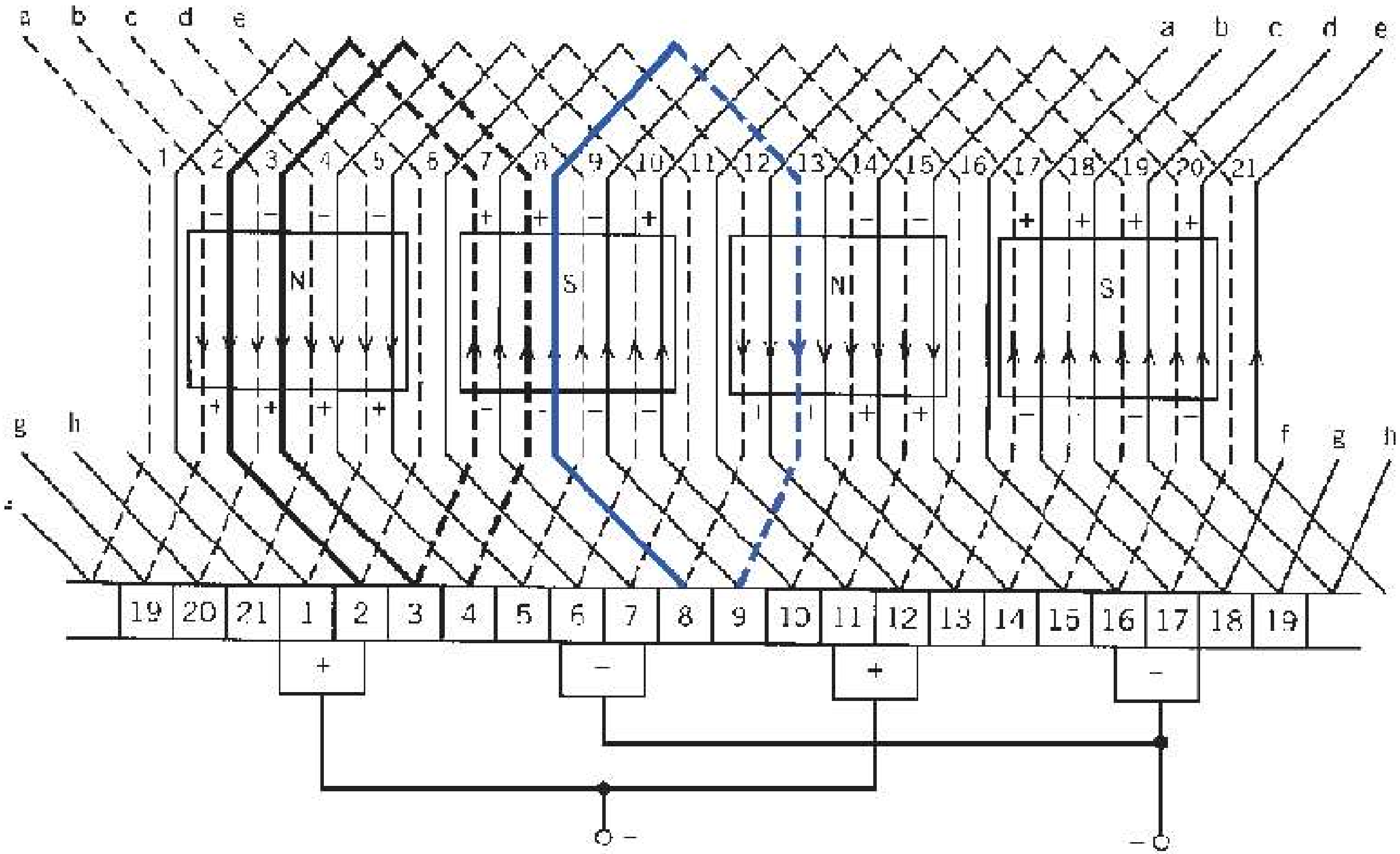
- The number of brushes is equals to the number of poles.

- The number of parallel paths C is equals to the number of poles ($C = 2p$).

- Each path takes $1/2p$ times the load current

  (p = no. of pole-pair)

Lap Winding



Wave Winding

- This type of winding is used in dc generators employed in high-voltage applications.
- The two ends of each coil are connected to commutator segments separated by the distance between poles.
- This configuration allows the series addition of the voltages in all the windings between brushes and requires one pair of brushes.

Wave Winding

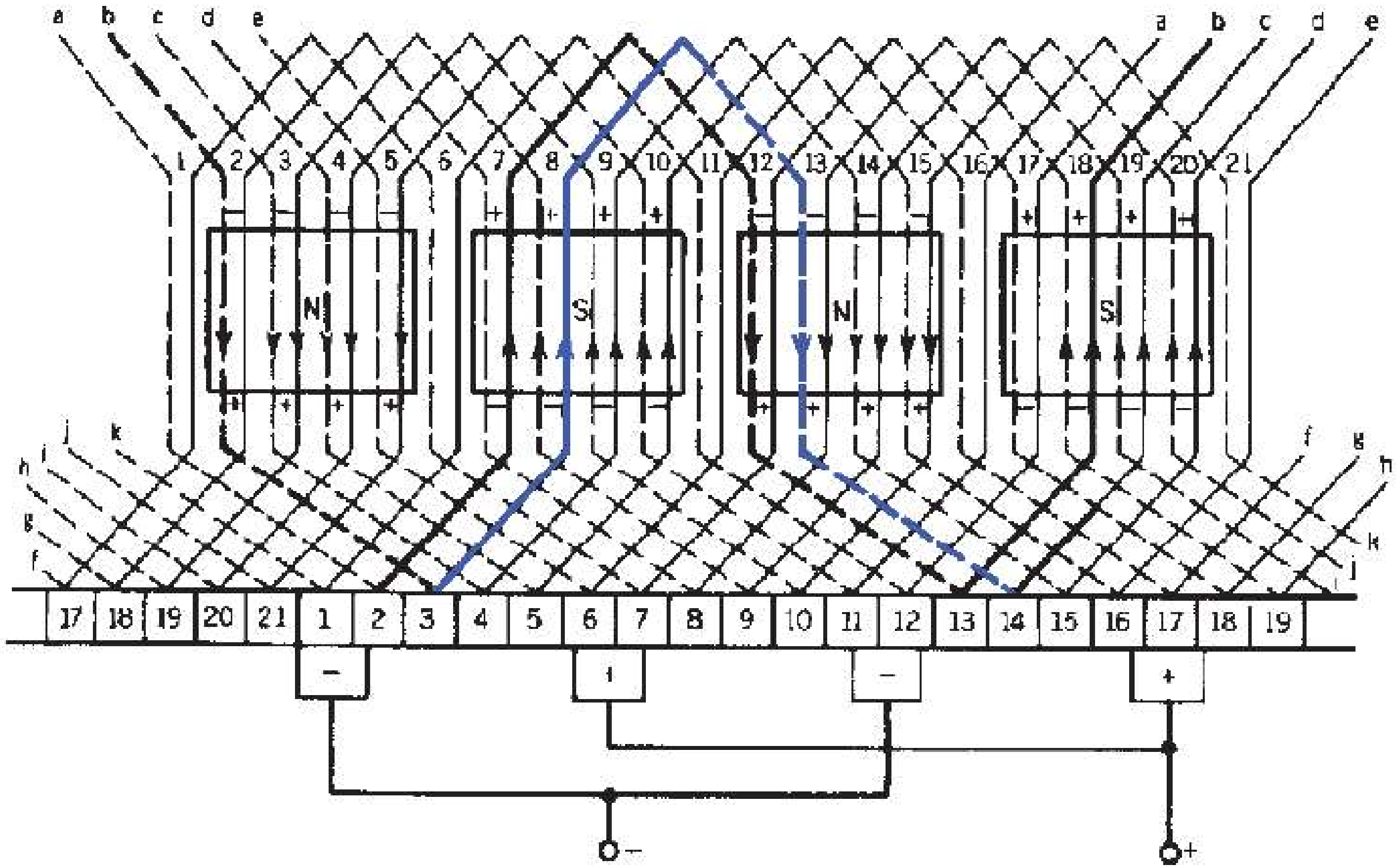
- The 2 ends of a coil are connected to commutator segments which separated by twice the pole-pitch.

- Only 2 brushes are necessary, irrespective of the number of poles, but 4 or more may be used for mechanical balance.

- The number of parallel paths C is always 2. (C=2)

- Each path takes 1/2 of the load current.

Wave Winding



Example 1

- A 6-pole armature is wound with 498 conductors. The flux and the speed are such that the average emf generated in each conductor is 2V. The current in each conductor is 120A. Find the total current and the generated emf of the armature if the winding is connected (a) wave, (b) lap. Also find the total power generated in each case.

Example 1

(i) For Wave Wound :

$$\text{Total Generated Emf} \quad E = \frac{498 \times 2}{2} = 498\ \text{V}$$

Current output $= 120 \text{ x } 2 = 240$ A

Power delievered $= E \text{ x } Ia = 498 \text{ x } 240 = 11.952$kW

(ii) For Lap Wound

$$\text{Total Generated Emf} \quad E = \frac{498 \times 2}{2 \times 3} = 166\ \text{V}$$

Current output $= 120 \text{ x } 2 \text{ x } 3 = 720$ A

Power delievered $= E \text{ x } Ia = 166 \text{ x } 720 = 11.952$kW

Example 2 (EMF generation of a given armature)

- A 4-pole wave wound armature has 51 slots with 12 conductors per slot and is rotated at 900 RPM. If the useful flux per pole is 25mWb, calculate the value of the generated e.m.f.

Example 2 (EMF generation of a given armature)

$$E = 2\frac{Z}{c} \times \frac{N_r p}{60}\phi$$

Z = 51 x 12 = 612; c=2; p=2; N =900rpm; Φ =0.025 Wb

$$E = 2 \times \frac{612}{2} \times \frac{900 \times 2}{60} \times 0.025 = 459\ V$$

Example 3 (EMF generation of a given armature)

- A 8-pole lap wound armature rotated at 350 rpm is required to generated 260V. The useful flux per pole is 0.05 Wb. If the armature has 120 slots, calculate a suitable number of conductors per slot.

Example 3 (EMF generation of a given armature)

For a 8-pole lap winding, C = 2P = 2 x 4 = 8

$$E = 2\frac{Z}{c} \times \frac{N_r p}{60} \phi$$

$$260 = 2\frac{Z}{8} \times \frac{350 \times 4}{60} \times 0.05$$

$$\therefore Z = 890$$

$$and\ no.\ of\ conductors\ per\ slot = \frac{890}{120} = 7.4 \cong 8$$

Example 4

- An 8-pole lap wound dc generator has 1000 armture conductors, flux of 20 mWb per pole and emf generated is 400V. What is the speed of the machine?

Example 4

Number of poles (P)=8 , pole pair (p) =4

Number of parallel path c=2p

Number of armature conductors (Z) = 1000;

Flux per pole (φ)= 20 mWb = 0.02 Wb

EMF generated (E)=400V

Therefore N the speed of the machine in rpm is:

$$\frac{Ex60xC}{2xZx\phi xP} = N = \frac{400x60x2x4}{2x1000x0.02x4}$$

$$= \underline{\underline{1200rpm}}$$

Armature Reaction

- When the current flows in the armature conductors. It produces a magnetic field surrounding the conductors.

- This armature flux reacts with the main flux. The effect of armature flux on the main field flux is called armature reaction.

Method of improving armature reaction
(Compensating winding)

- The demagnetizing effect of armature reaction has a detrimental effect on the operation of dc motors whenever there is a sudden change in load.

- This causes a sudden change in flux/pole resulting in induction of large static emf which can short-circuit the complete commutator.

Method of improving armature reaction
(Compensating winding)

- Armature reaction AT (ampere-turns) in dc machines can be compensated by placing a compensating winding in the pole faces with its axis along the brush axis and excited by the armature current in series connection so that it causes cancellation of armature reaction AT at all values of armature current.

Commutation

- Commutation is the process of producing a unidirectional or direct current from the alternating current generated in the armature coils.

Methods of Improving Commutation

The main cause of sparking at the commutator being the reactance voltage, it can be minimized by the following methods:

- **Use of High Resistance Carbon Brushes**

It increases the circuit resistance of coils undergoing commutation to reduce the reactance voltage

- **Use of Interpoles**

Use of Interpoles

- To reduce sparking at the commutator, small auxiliary poles called interpoles are provided in the machine.

- These are narrow cross-section poles with small cross-sectional area placed in between the main poles.

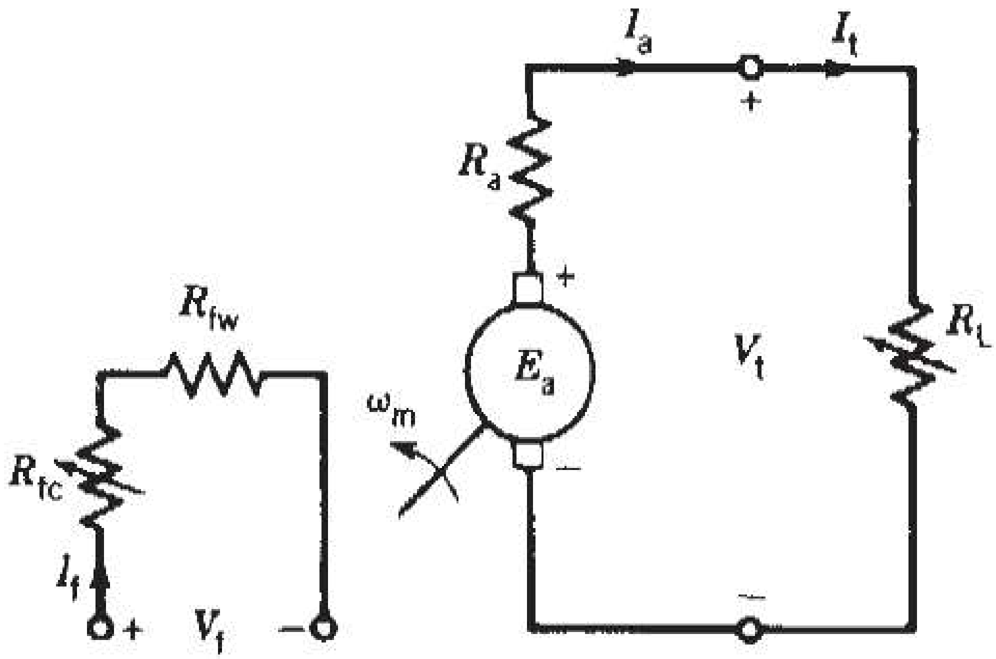
- Flux is produced in these poles only when current flows in the armature circuit.

Use of Interpoles

- The flow of current in the interpole winding is such that the polarity of an interpole in a dc generator is the same as that of the next pole ahead, in the direction of rotation.

- In a dc motor, the polarity of an interpole is opposite to that of the next main pole in the direction of rotation.

DC machine - Voltage Drop Equation



From Fig. $Vt = Ea \pm RaIa$

(where (+) for Motor and (−) for Generator)

DC Machine

Armature Voltage: Ea

In general, the induced voltage is:

$$
\begin{aligned}
E_a &= K F_f N \\
&= K K_f I_f N \\
&= K_2 I_f N
\end{aligned}
$$

Where F_f field flux, I_f is field current, N in rpm

DC Generators

- The speed of a DC machine operated as a generator is fixed by the prime mover.

- For general-purpose operation, the prime mover is equipped with a speed governor so that the speed of the generator is practically constant.

DC Generators

For general-purpose operation, the prime mover is equipped with a speed governor so that the speed of the generator is practically constant.

- Under such condition, the generator performance deals primarily with the relation between **excitation**, **terminal voltage** and **load**.
- These relations can be best exhibited graphically by means of curves known as **generator characteristics**.

DC Generators

For general-purpose operation, the prime mover is equipped with a speed governor so that the speed of the generator is practically constant.

- Knowledge of the variation of the terminal voltage with load current, known as the **external (terminal) characteristic** is essential.

DC Generators

Two types of ARMATURE WINDINGS :

Lap Winding and Wave Winding

Total emf. between brushes $E = 2x\frac{Z}{c}x\frac{N\phi p}{60}$ *(Volts)*

N	=	Speed of armature in rev/min.
∅	=	Useful flux per pole in Wb.
P	=	No. of pairs of poles.
Z	=	total no. of armature conductors.
c	=	no. of parallel paths between positive and negative brushes. (c = 2 for a wave winding) (c = 2p for a lap winding)

Example 1

- The armature of a 6-pole DC generator has 30 slots and in each slot there are 8 conductors. The flux per pole is 0.0174Wb. When the speed of the armature is 1200 rev/min. Calculate the value of the emf generated if the armature is:

Example 1

(i) Wave wound and (ii) Lap Wound.

(i) For Wave Wound :

$$E = 2\frac{Z}{C} \times \frac{N\Phi P}{60} \ V$$

$$= 2\frac{30 \times 8}{2} \times \frac{1200 \times 0.0174 \times 3}{60} = \underline{\underline{250.56 \ V}}$$

(ii) For Lap Wound

$$E = 2\frac{Z}{C} \times \frac{N\Phi P}{60} \ V$$

$$= 2\frac{30 \times 8}{2 \times 3} \times \frac{1200 \times 0.0174 \times 3}{60} = \underline{\underline{83.52 \ V}}$$

D.C. Generator Characteristics

The following are the three most important characteristics of a DC generator:

- Open Circuit Characteristic (O.C.C.)
- Internal or Total Characteristic (E/Ia)
- External Characteristic (V/IL)

1. Open Circuit Characteristic (O.C.C.)

This curve shows the relation between the generated e.m.f. at no-load (E0) and the field current (If) at constant speed.

- It is also known as magnetic characteristic or no-load saturation curve.

1. Open Circuit Characteristic (O.C.C.)

- Its shape is practically the same for all generators whether separately or self-excited.

- The data for O.C.C. curve are obtained experimentally by operating the generator at no load and constant speed and recording the change in terminal voltage as the field current is varied.

2. Internal or Total characteristic (E/Ia)

This curve shows the relation between the generated e.m.f. on load (E) and the armature current (Ia).

- The e.m.f. E is less than E0 due to the demagnetizing effect of armature reaction.
- Therefore, this curve will lie below the open circuit characteristic (O.C.C.).

2. Internal or Total characteristic (E/Ia)

- The internal characteristic is of interest chiefly to the designer.
- It cannot be obtained directly by experiment.
- It is because a voltmeter cannot read the e.m.f. generated on load due to the voltage drop in armature resistance.

2. Internal or Total characteristic (E/Ia)

- The internal characteristic can be obtained from external characteristic if winding resistances are known because armature reaction effect is included in both characteristics.

3. External (Load) characteristic (V/IL)

This curve shows the relation between the terminal voltage (V) and load current (IL). The terminal voltage V will be less than E due to voltage drop in the armature circuit.

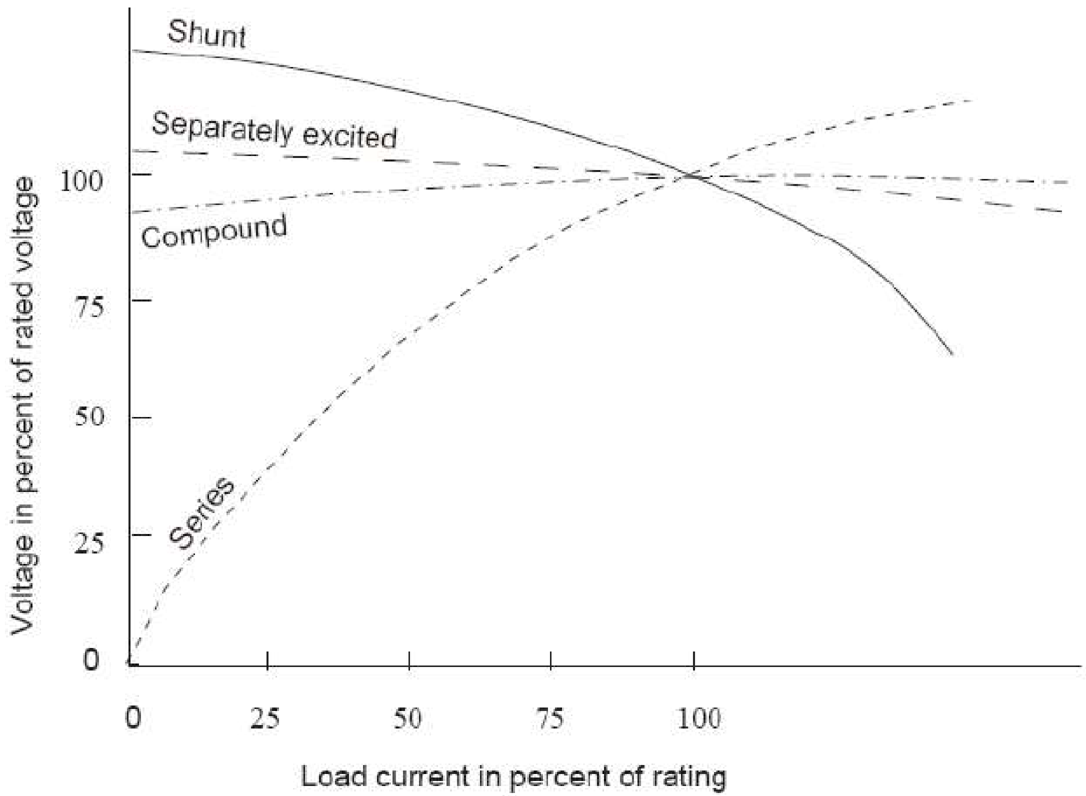
Therefore, this curve will lie below the internal characteristic.

3. External (Load) characteristic (V/IL)

- This characteristic is very important in determining the suitability of a generator for a given purpose.

- It can be obtained by making simultaneous measurements of **terminal voltage and load current** (with voltmeter and ammeter) of a loaded generator.

3. External (Load) characteristic (V/IL)



Volt-ampere characteristics of dc generators

Characteristics of DC generators

- OCC(Open Circuit Characteristic) of a DC Shunt Generator

- Load Characteristics of a DC Shunt Generators

OCC (Open Circuit Characteristics) of dc shunt generator

- The DC generator on an open circuit being run at speed n rpm by means of a prime mover.
- The field excitation is varied by regulating the resistance placed in the field circuit.

OCC (Open Circuit Characteristics) of dc shunt generator

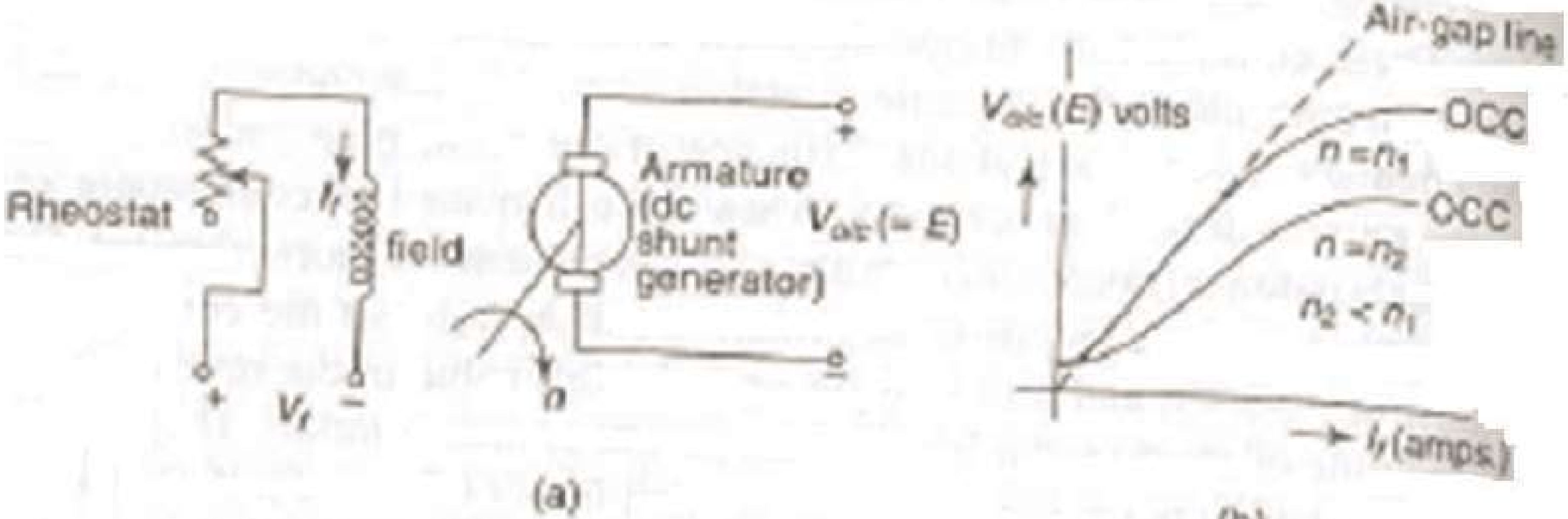


Fig. 9.8 *Open circuit characteristic of a dc generator*

Internal characteristics of DC shunt generator

- The terminal voltage V versus armature current In characteristic is called the internal characteristic of a dc shunt generator as shown.

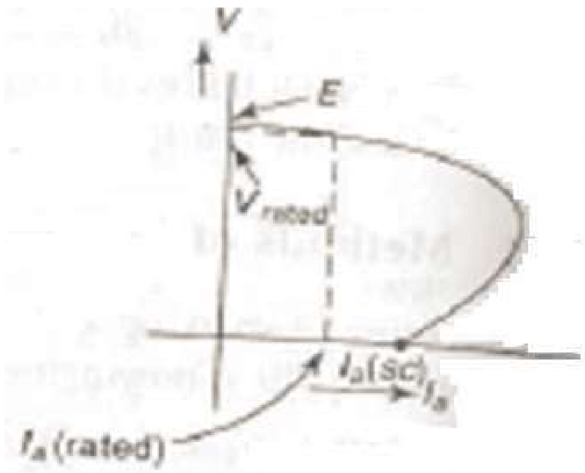


Fig. 9.9 *Internal characterstic of dc shunt generator [terminal voltage V = Induced voltage E - drop within the armature]*

Internal characteristics of DC shunt generator

- The load characteristic of a dc generator is called *the external characteristic*.

- It will only be slightly shifted from the internal characteristic as

$$I_L = I_a - I_f$$

$$I_f(field\ current)\ usually\ very\ small$$

Load (External) characteristic of a series DC generator

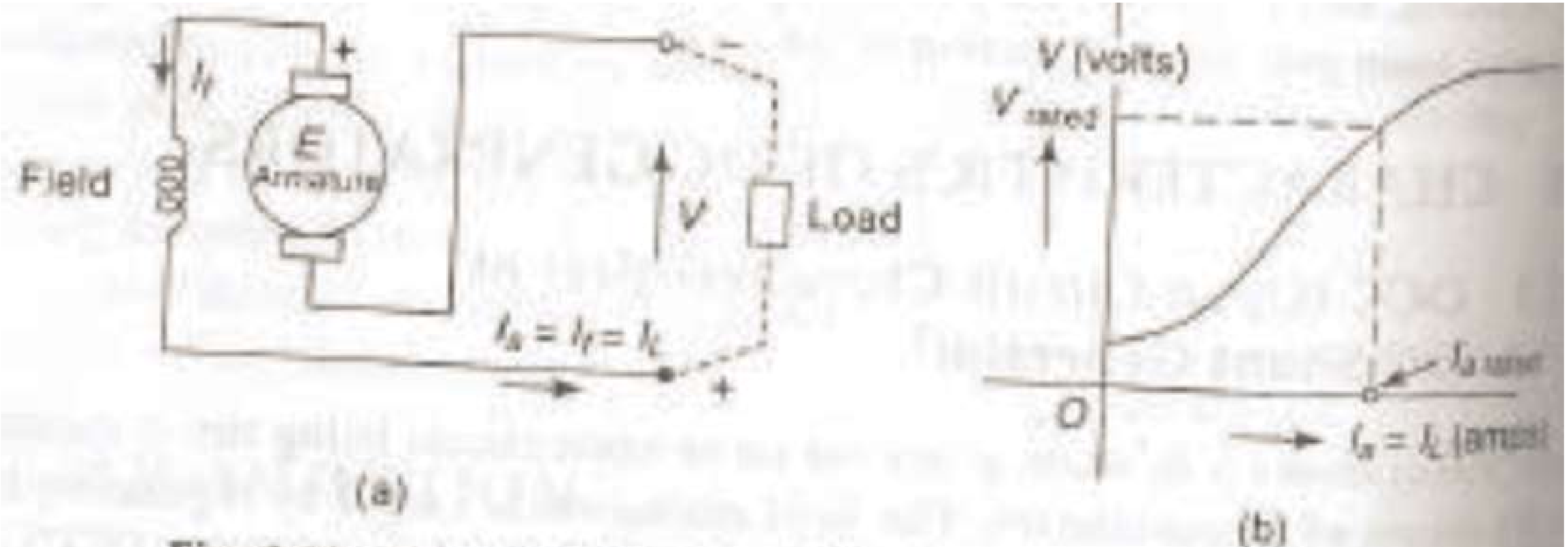


Fig. 9.10 External characteristic of a dc generator (series)

Load (External) characteristic of a series DC generator

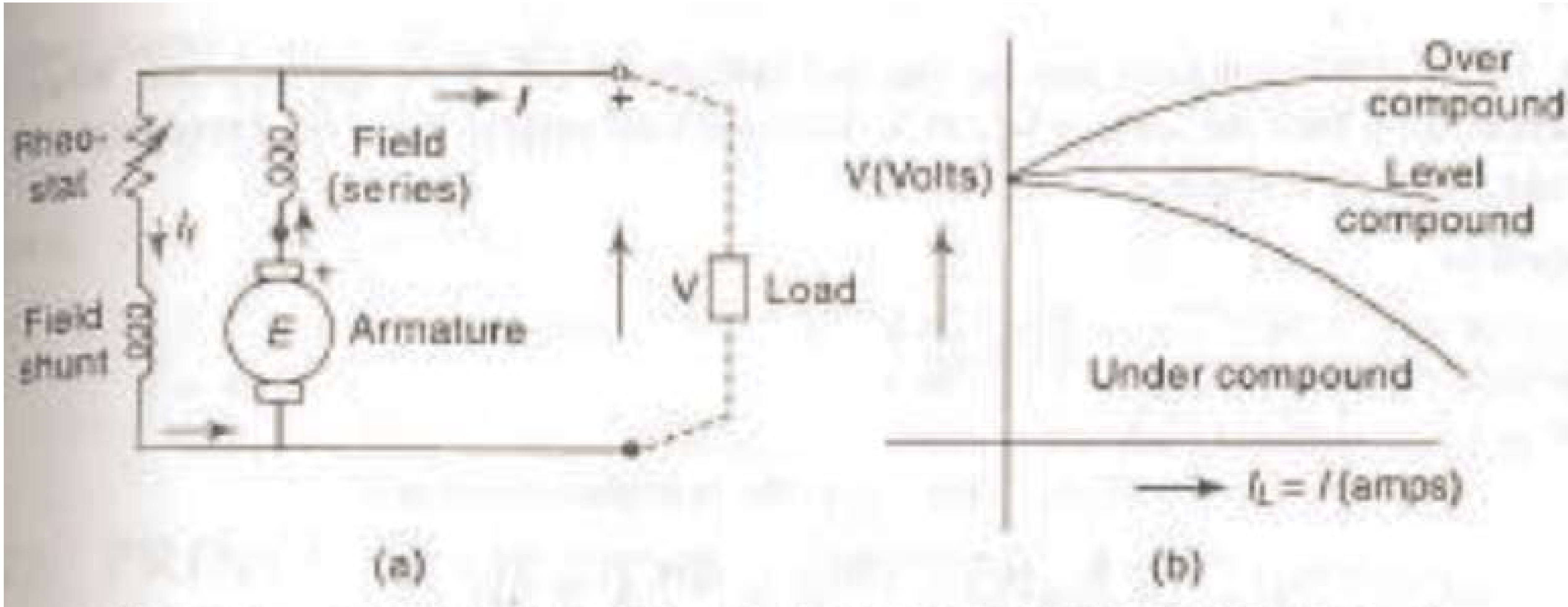
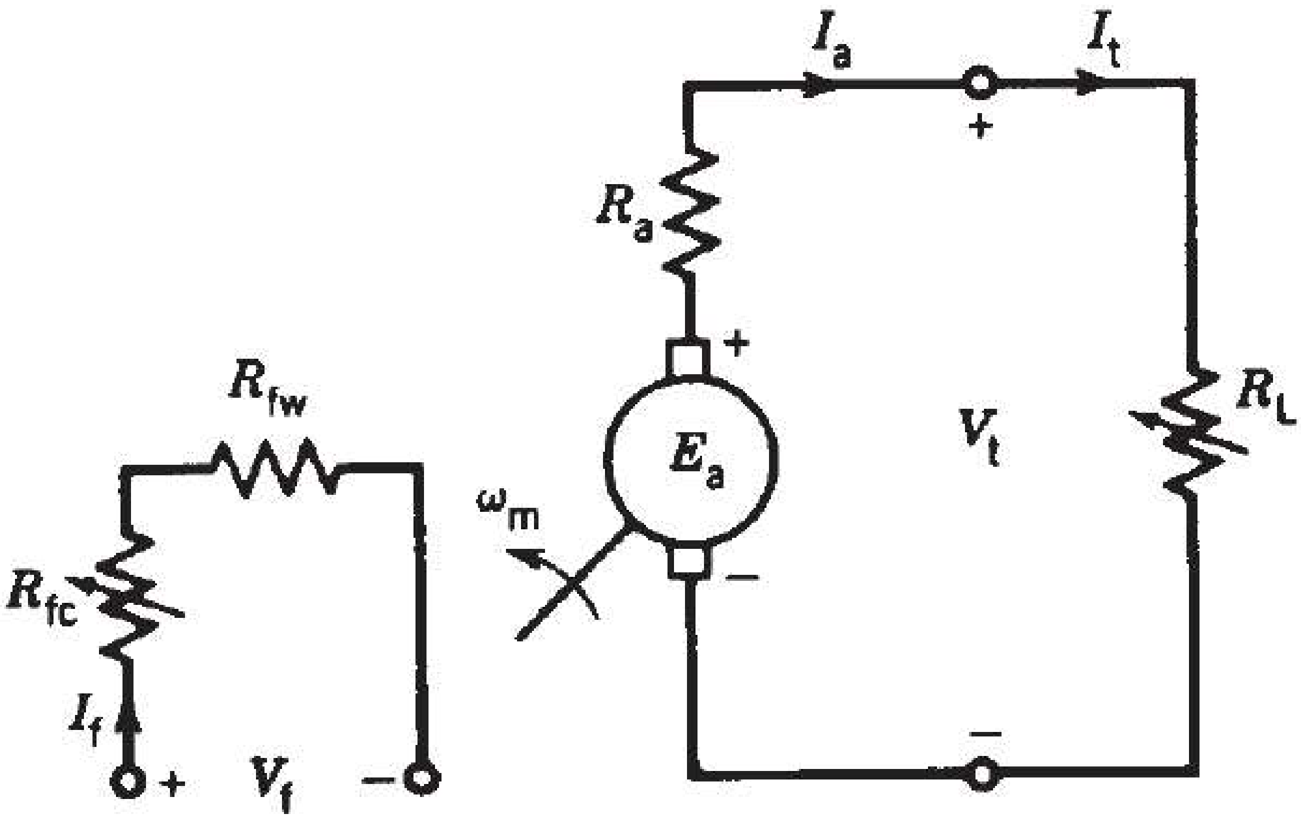


Fig. 9.11 *External characteristic of a dc generator (compound)*

Types of DC Generators

- Separately Excited Generator
- Shunt (Self Excited) Generator
- Series Generator
- Compound Generator
  - Long Shunt
  - Short Shunt

Separately Excited Generator



Separately Excited Generator

- $\boldsymbol{R_{fw}}$ is the resistance of the field winding
- $\boldsymbol{R_{fc}}$ is the resistance of the control rheostat used in the field circuit
- $\boldsymbol{R_f = R_{fw} + R_{fc}}$ is the total field circuit resistance

Separately Excited Generator

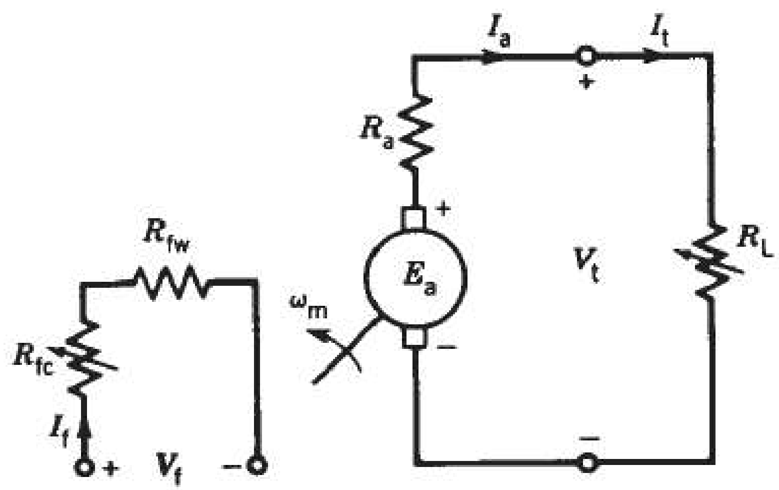
- R_a is the resistance of the armature circuit, including the effects of the brushes. Sometimes Ra is shown as the resistance of the armature winding alone; the brush-contact voltage drop is considered separately and is usually assumed to be about 2 V.

- RL is the resistance of the load

Separately Excited Generator

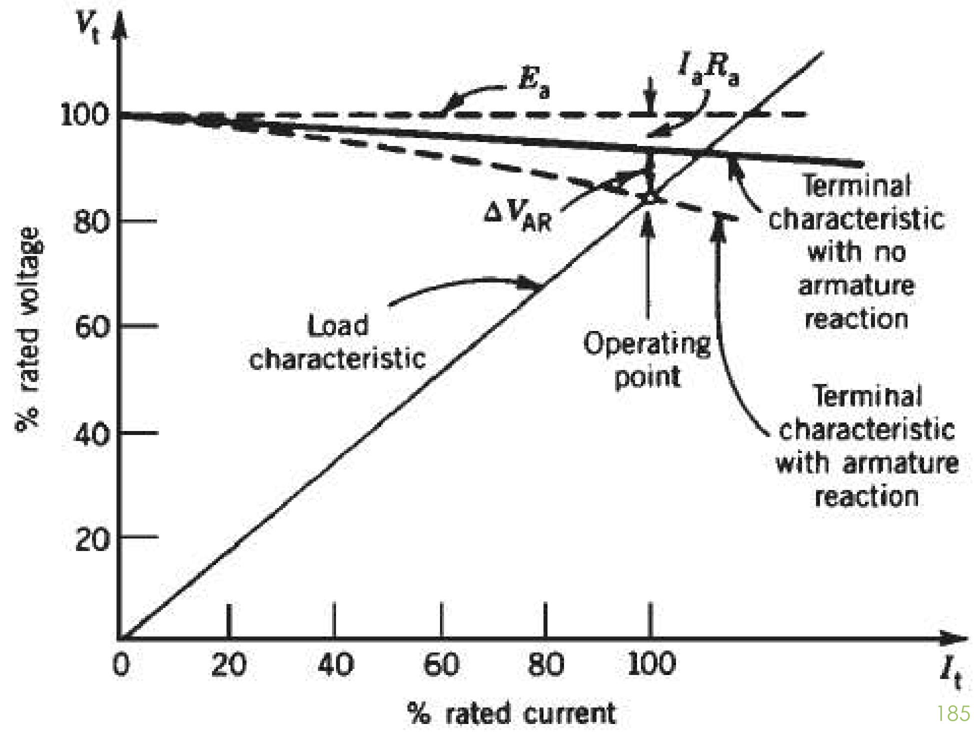
Useful equations:

- $V_f = R_f I_f$
- $E_a = V_t + IaRa$
- or $Vt = Ea - I_a R_a$
- $E_a = K_a \Phi \omega_m = KN\Phi$
- $V_t = I_t R_L$
- $I_a = I_t$



Separately Excited Generator

- External Characteristic of a Separately excited DC Generator:



Separately Excited Generator

- Open Circuit Characteristics (OCC)

- Terminal Characteristic (On-load Characteristic or VI Characteristic) Dropping of terminal voltage:
  - $I_a R_a$ drop
  - reduction of flux due to Armature Reaction

Example 2 (Separately excited)

- A 12 kW, 100 V, 1000 rpm dc shunt generator has armature resistance $R_a=0.1\Omega$, shunt field winding resistance $R_{fw}=80\Omega$, and $N_f=1200$ turns per pole. The rated field current is 1 ampere. The magnetization characteristic at 1000 rpm is shown in fig.4.24.

- The machine is operated as a **separately excited dc generator** at 1000 rpm with rated field current.

Example 2 (Separately excited)

- Neglect the armature reaction effect. Determine the terminal voltage at full load.

- Consider that armature reaction at full load is equivalent to 0.06 field amperes.

i. Determine the full-load terminal voltage.

ii. Determine the field current required to make the terminal voltage at $V_t=100V$ at full load condition.

Magnetization Curve

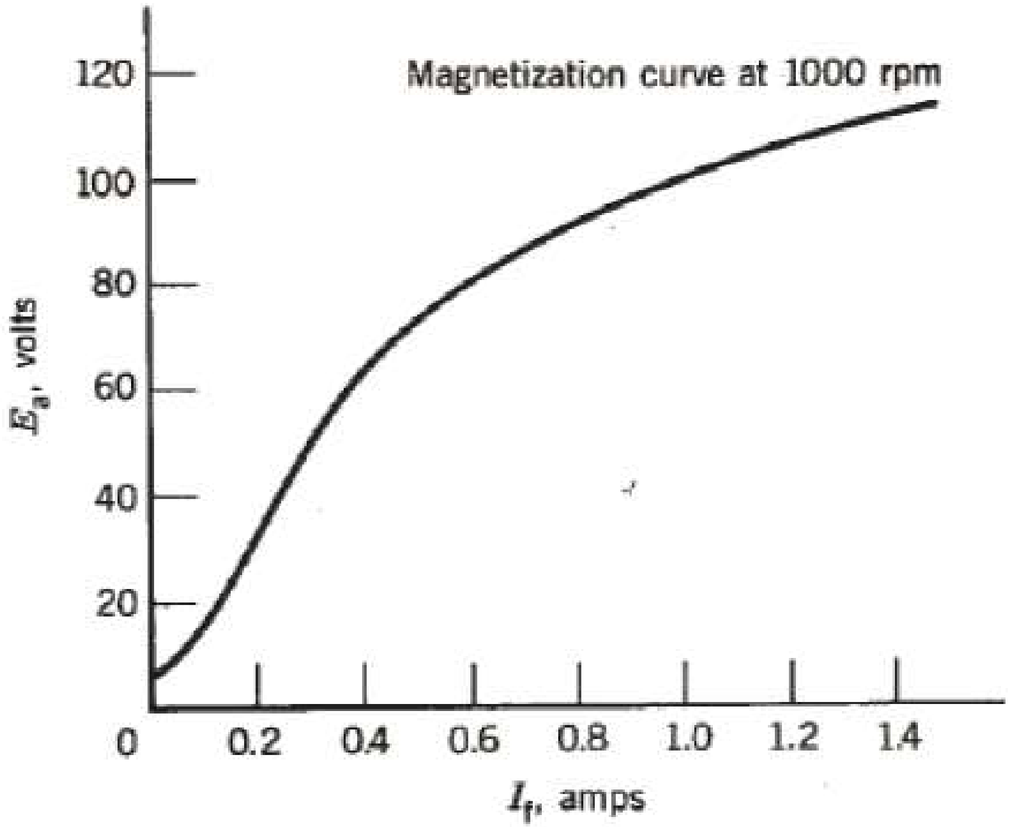


FIGURE 4.24 Test result: magnetization curve.

Solution

In a dc shunt generator, the main field winding is the shunt field winding. Also, from the data on the machine,

- Rated armature voltage Ea/rated = 100V
- Rated armature (or full load) = 12 kW

Solution

- Rated armature current (or full load)

  = Ia/rated = 12000/100 = 120A

- Rated speed = 1000 rpm

- Rated field current If/rated = 1A

Solution

(a) $Vt = Ea - IaRa = 100 - 120 \times 0.1 = 88V$

(b) (i)

$If(eff) = If(actual) - If(AR) = 1 - 0.06 = 0.94A$

From Fig. 4.24, at this field current

$Ea = 98V \qquad Vt = Ea - IaRa$

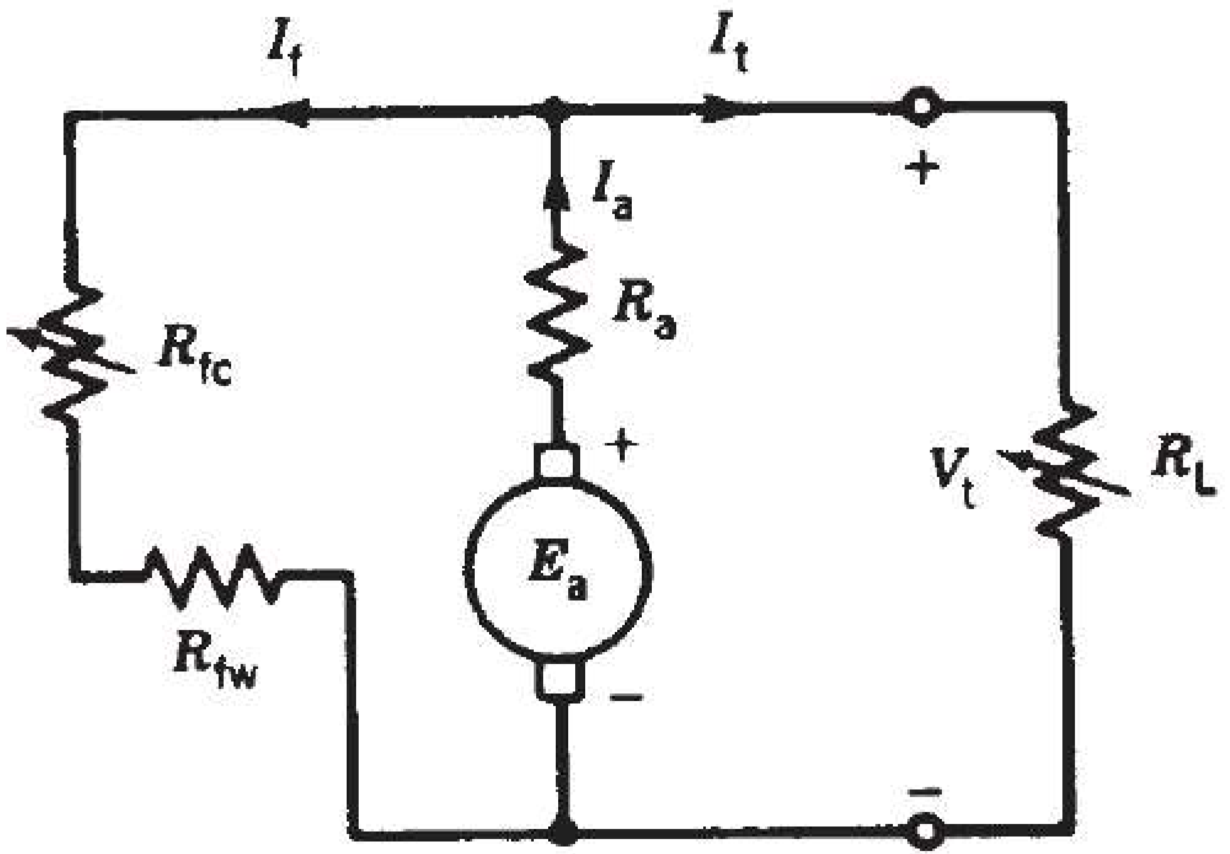
$= 98 - 120 \times 0.1 = 86V$

(ii) $Ea = Vt + IaRa = 100 + 120 \times 0.1 = 112V$

From Fig. 4.24, the effective field current required is $If(eff) = 1.4A$

From b(i) $If(actual) = If(eff) + If(AR) = 1.4 + 0.06 = 1.46A$

Shunt (Self-excited) Excited Generator

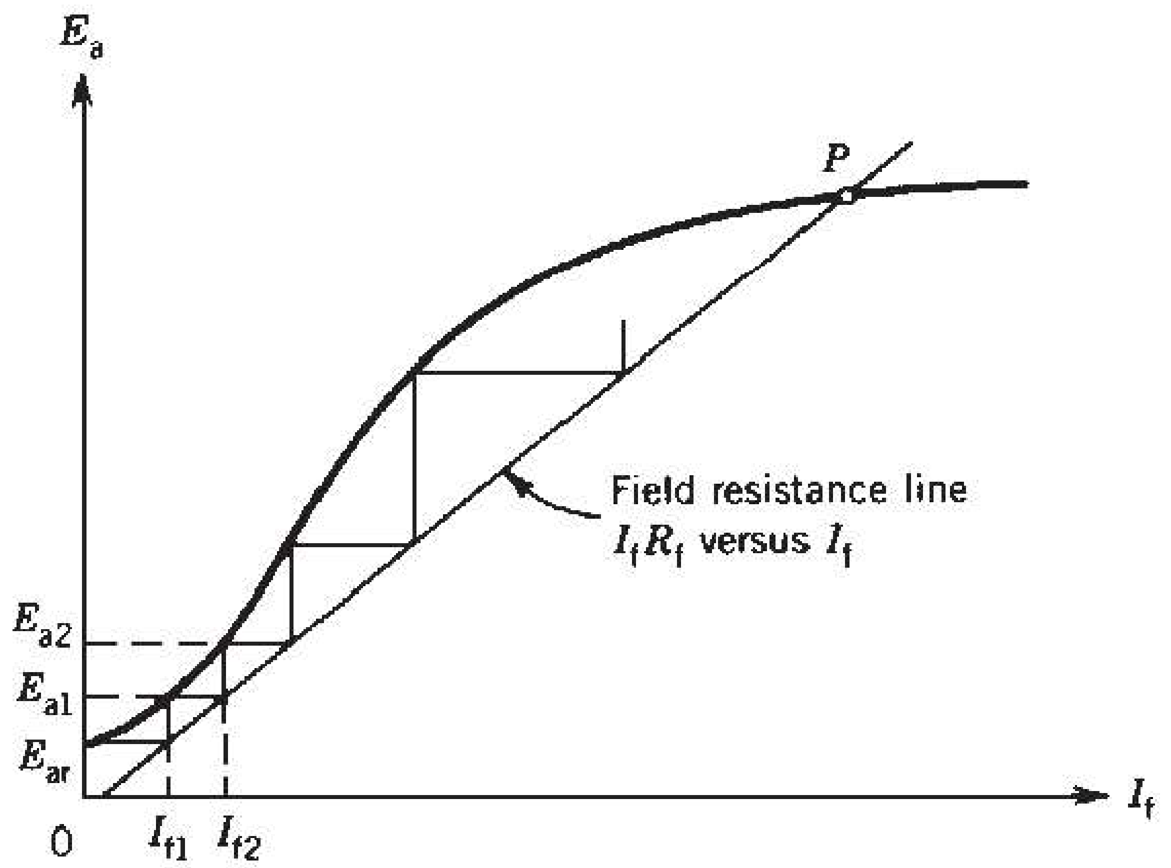


Shunt (Self-excited) Excited Generator

3 conditions for building-up of voltage:

1. Residual magnetism must be present in the magnetic system
2. Field winding mmf should aid the residual magnetism
3. Field circuit resistance should be less than the critical field circuit resistance

Open Circuit Characteristics (Building-up of emf)



Voltage build up (1)

- The line OP has a slope equal to the shunt field resistance Rf

- The armature of the machine is rotated, a small voltage Ear is generated due to the residual magnetism in the field poles.

- The voltage causes field current $If1$ to flow.

Voltage build up (1)

- This current $If1$ increases the field flux and generates voltage $Ea1$ which in turn results in field current $If2$ which will generate a still higher voltage.

- This process goes on and the generated voltage continues to increase.

Voltage build up (1)

- This process continues till point P is reached where the generated voltage is equal to $IfRf$. If being the shunt field current.

Voltage build up (2)

- If the resistance of shunt field be such that Rf is equal to the slope of the line OA, the value of the generated voltage would remain at value , *so no voltage would build up.*

Voltage build up (2)

- This value is known as ***Critical field resistance*** Rf.
- The voltage build up is possible if Rf is less than the critical value.

Conditions for voltage build up in self-excited generators

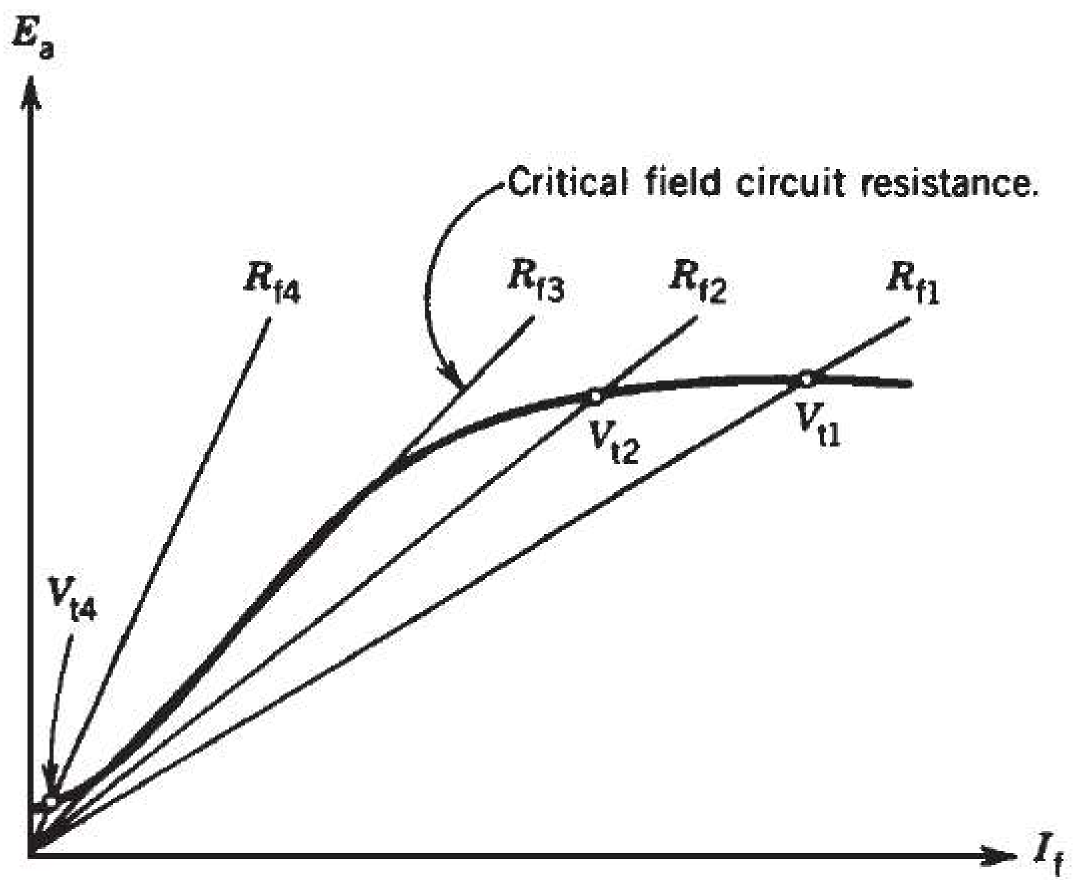
- Residual magnetism must be present
- Field winding should be properly connected so that field current strengthens the residual magnetism
- The resistance of the field should be less than the critical resistance

Conditions for voltage build up in self-excited generators

- The speed of the machine should be higher than the critical speed.

- For series generator load should be connected and resistance of load should be less than critical resistance.

Effect of Field Resistance



Example 3

- A shunt wound dc generator has an induced voltage of 200V. The terminal voltage is 180V. Find the load current if the field and armature resistances are 100 Ωand 0.1 Ωrespectively.

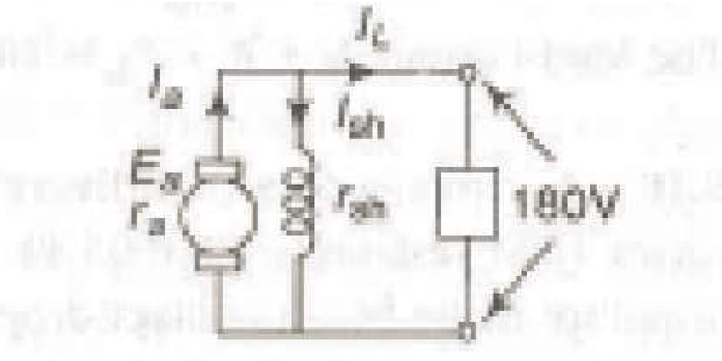


Fig. 9.12 *A shunt wound a dc generator (Ex. 9.7)*

Example 3

Induced emf Ea = 200V

Terminal voltage Vt = 180V

Shunt field resistance rsh = 100 Ω

Armature resistance ra = 0.1Ω

$$Field\ current\ (I_{sh}) = \frac{V_t}{r_{sh}} = \frac{180}{100} = 1.8A$$

$$E_a = V_t + I_a r_a$$

$$I_a = \frac{E_a - V_t}{r_a} = \frac{200-180}{0.1} = 200A$$

$$Load\ current\ I_L = I_a - I_{sh} = 200 - 1.8A = \underline{\underline{198.2A}}$$

Example 4 (shunt excited)

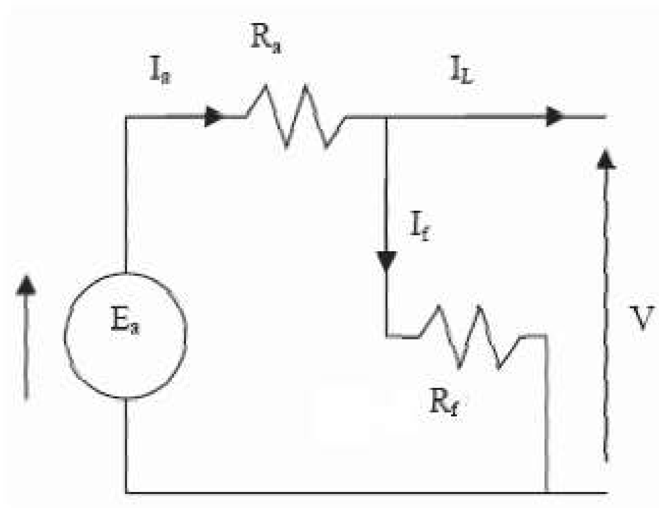
The figure shows a 20 kW, shunt excited dc machine function as a generator having a field resistance of 80Ω. When the generator is delivering at rated output power, the generated emf is 630V, and the terminal voltage is 600V. Find:

(a) The full load current I_L;

(b) The field current I_f;

(c) The armature current Ia;

(d) The armature resistance of this generator.



Example 4 (shunt excited)

For 20kW shunt with 600V output:

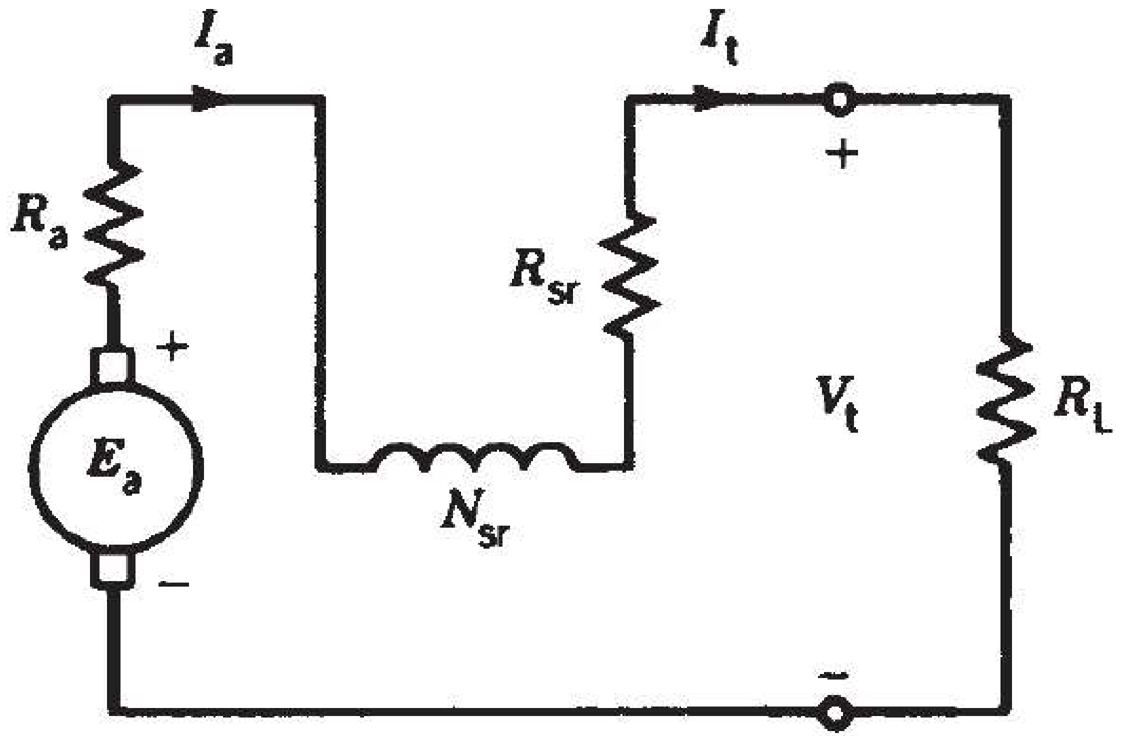
(a) $I_L = 20kW/600V = 33.3A$

(b) $I_f = V_L/R_f = 600V/80\Omega = 7.5A$

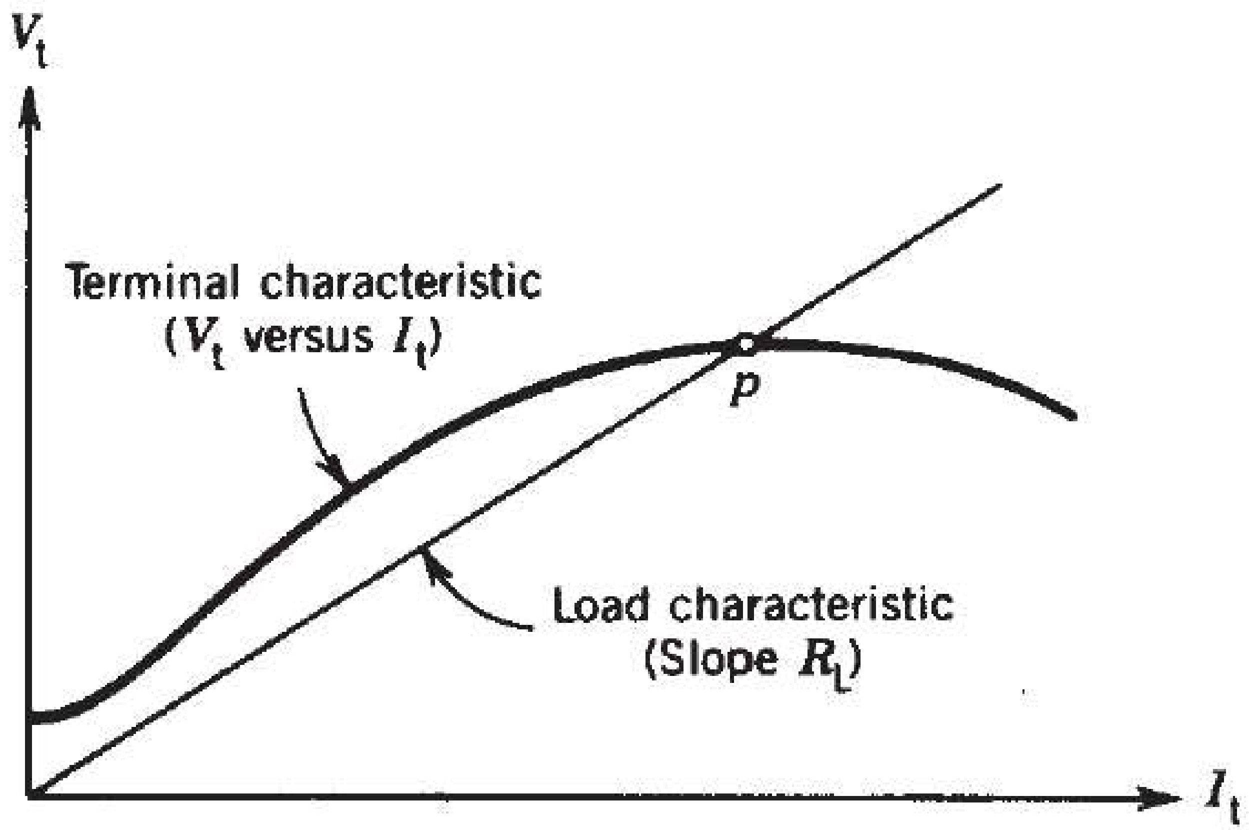
(c) $I_a = I_f + I_L = 33.3 + 7.5 = 40.8A$

(d) $R_a = (E_a - V_L)/I_a = (630-600)V/40.8A = 0.735\Omega$

Series Generator



External Characteristic of Series Generator



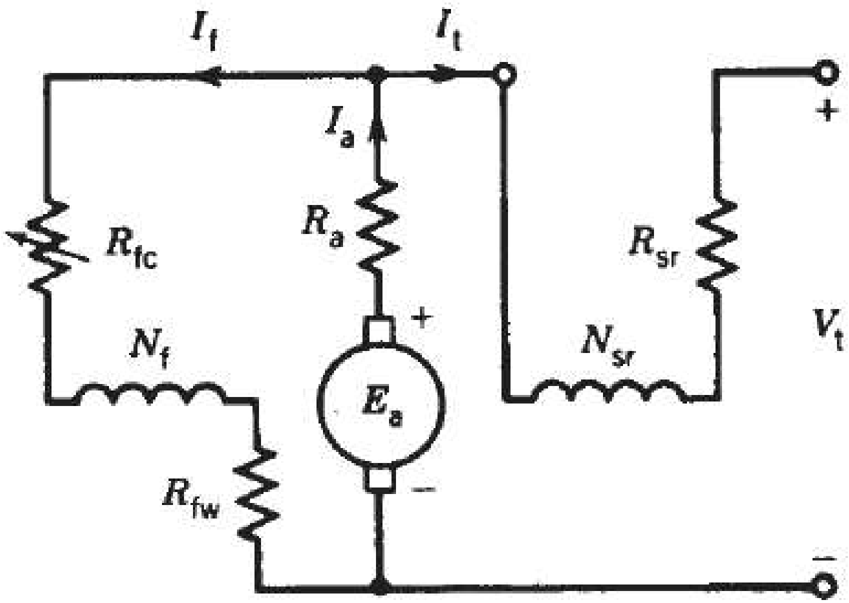
Example 5

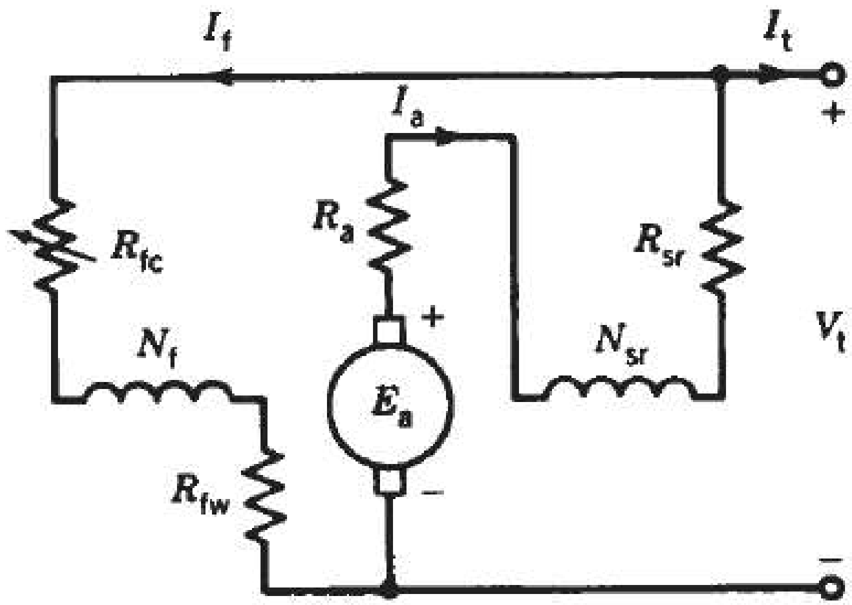
A series generator delivers a load current of 50A at 400V and has armature and series field resistance of 0.05 Ω and 0.04 Ω respectively. Find the induced emf in the armature if the brush contact drop is 1V per drop.

- In a series generator,

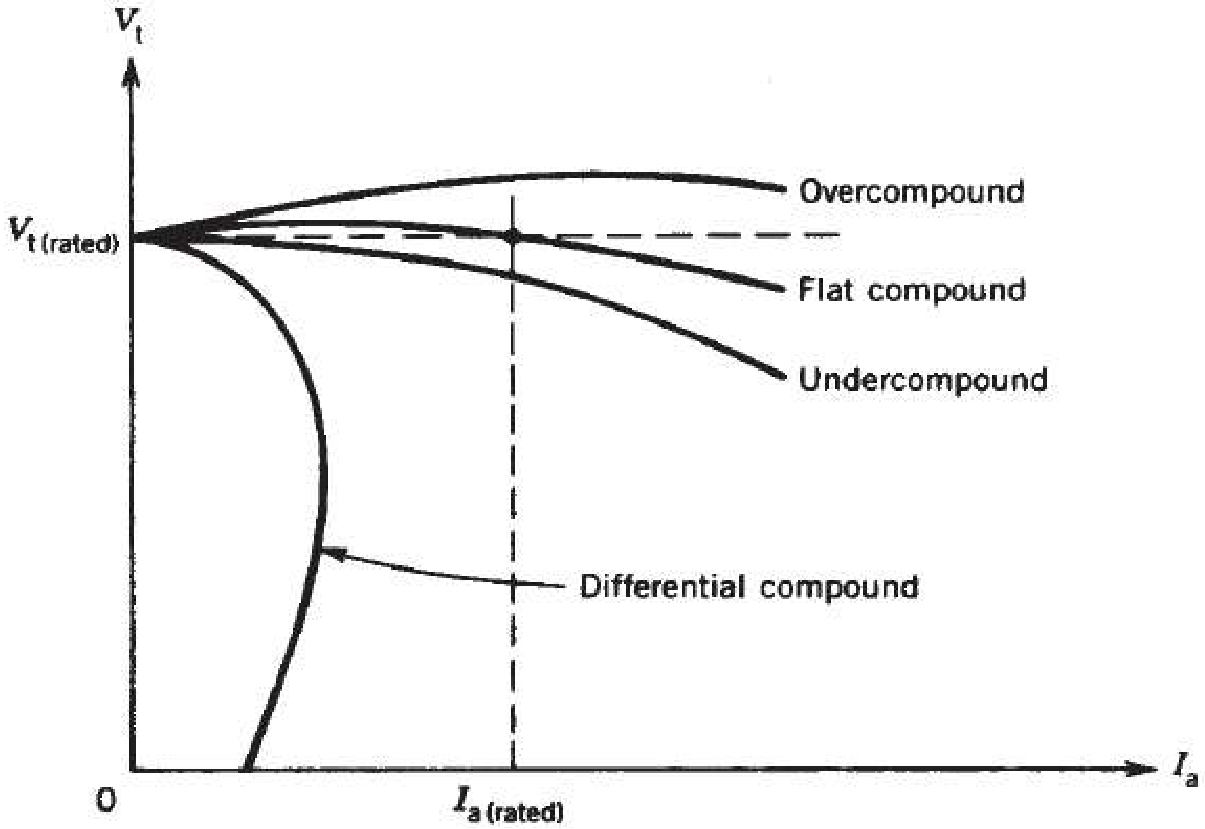
  load current = armature current
- $I_a=50A$, $V=400V$, $R_a=0.05$ and $R_{sr}=0.04$
- $Emf=V+I_aR_a+I_aR_{sr}+\text{Brush drop}$
- $= 400+50\times0.05+50\times0.04+2\times1$
- $= 406.5V$

Compound Generator





V-Ia Characteristic of Compound Generator



Example 6 (Long shunt compound)

- A **long shunt compound** wound dc generator delivers a load current of 100A at 400V. The armature, series and shunt field resistances are 0.04 Ω, 0.02 Ωand 200 Ωrespectively. Find the armature current and the generated emf.

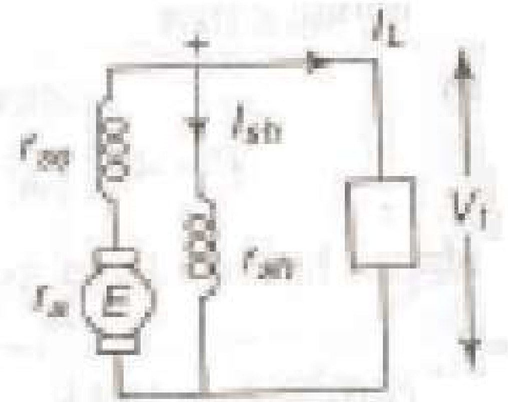


Fig. 9.14 A long shunt compound generator

Example 6 (Long shunt compound)

$$I_L = 100A, V = 400V, r_a = 0.04\Omega, r_{se} = 0.02\Omega, \text{and } r_{sh} = 200\Omega$$

$$\therefore I_{sh} = \frac{400}{200} = 2A$$

$$\text{and} \quad I_a = I_L + I_{sh} = 100 + 2 = 102A$$

$$\text{Generated emf } E = V + Ia(ra + rse)$$

$$= 400 + 102(0.04 + 0.02)$$

$$= \underline{\underline{406.12V}}$$

Example 7 (Short shunt compound)

- A **short shunt compound** wound dc generator delivers a load current of 100A at 400V. The armature, series and shunt field resistances are 0.04 Ω, 0.02 Ωand 200 Ωrespectively. Find the armature current and the generated emf.

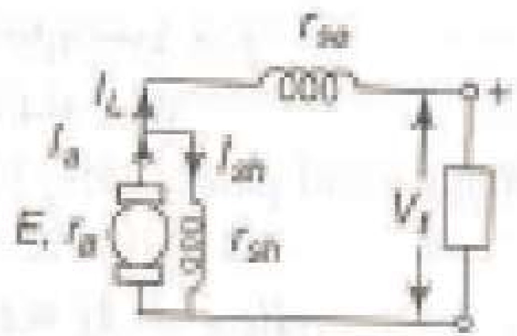
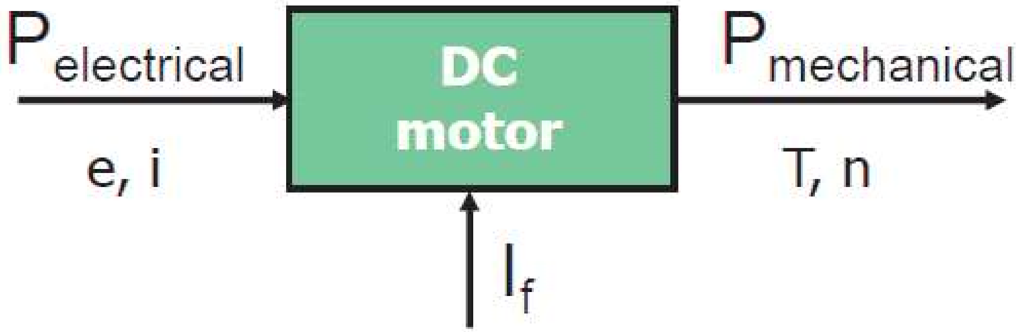


Fig. 9.15 A short shunt compound generator

DC Motor



Developed Torque:

- The output power if the losses are neglected is:

$$P_{out} = I_a E_a = 2\pi n T_m = \omega T_m.$$

- The torque is:

$$T_m = I_a E_a / 2\pi n = K \Phi_f I_a = K_m I_f I_a$$

Speed Equation

Since $E_a = 2z/c \times N\Phi P/60 = K_a\Phi\omega_m = V_t - I_aR_a$

$c = 2$ for Wave Winding,

$= 2p$ for Lap Winding

then re-arrange:

$$N = \frac{E_a x 60 x c}{2 x Z x P x \phi} = \frac{E_a}{K\phi} = \frac{V - I_a R_a}{K_a \phi}$$

$$where\ K = \frac{2ZP}{60xc} \qquad n = \frac{KV}{\phi}$$

Speed Equation

The equation shows that the speed of a dc machine is directly proportional to the emf of rotation E and inversely proportional to flux per pole ϕ.

If the suffixes 1 and 2 denotes the initial and final values,

we can write : $N_1 = \frac{E_1}{k\phi_1}$ *and* $N_2 = \frac{E_2}{k\phi_2}$

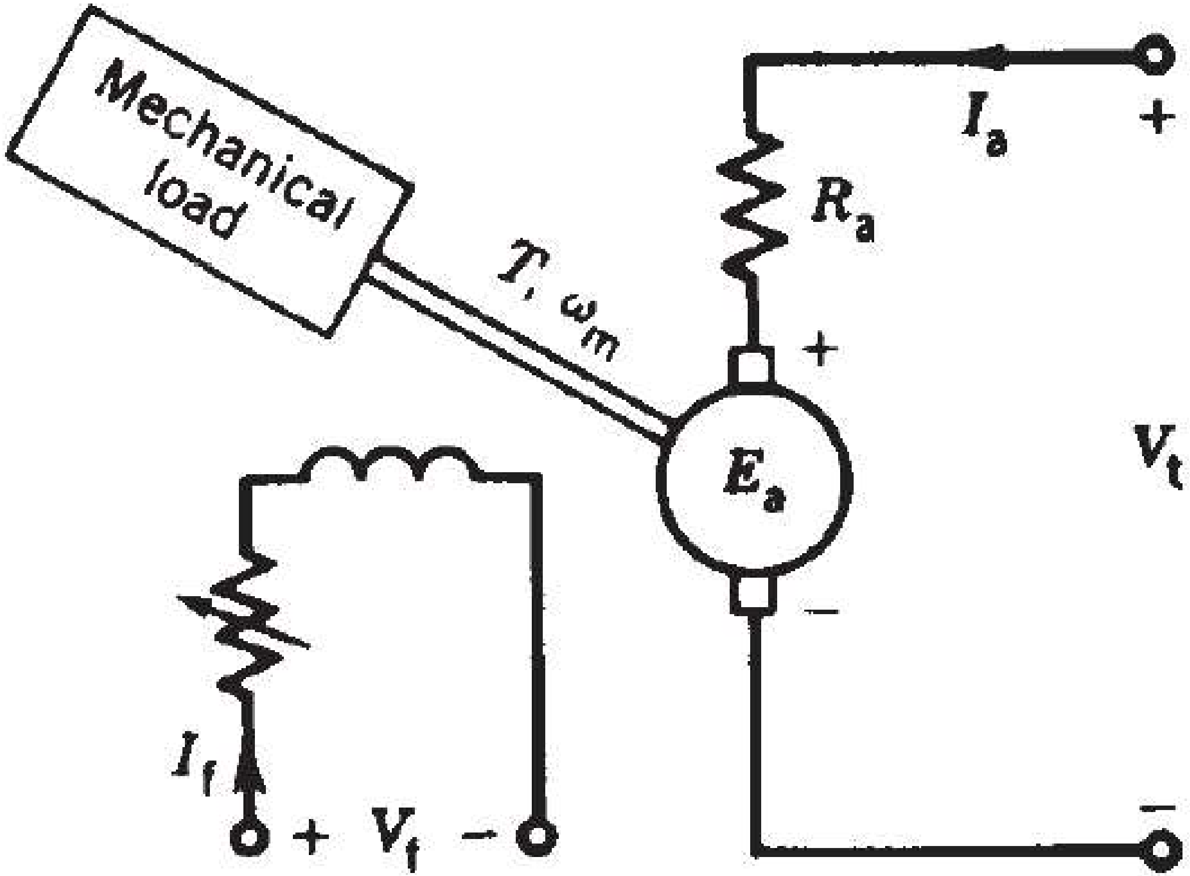
$$\therefore \frac{N_1}{N_2} = \frac{E_2}{E_1} x \frac{\phi_1}{\phi_2}$$

For dc shunt motor, $\phi 1 = \phi 2$ *for rated conditions,*

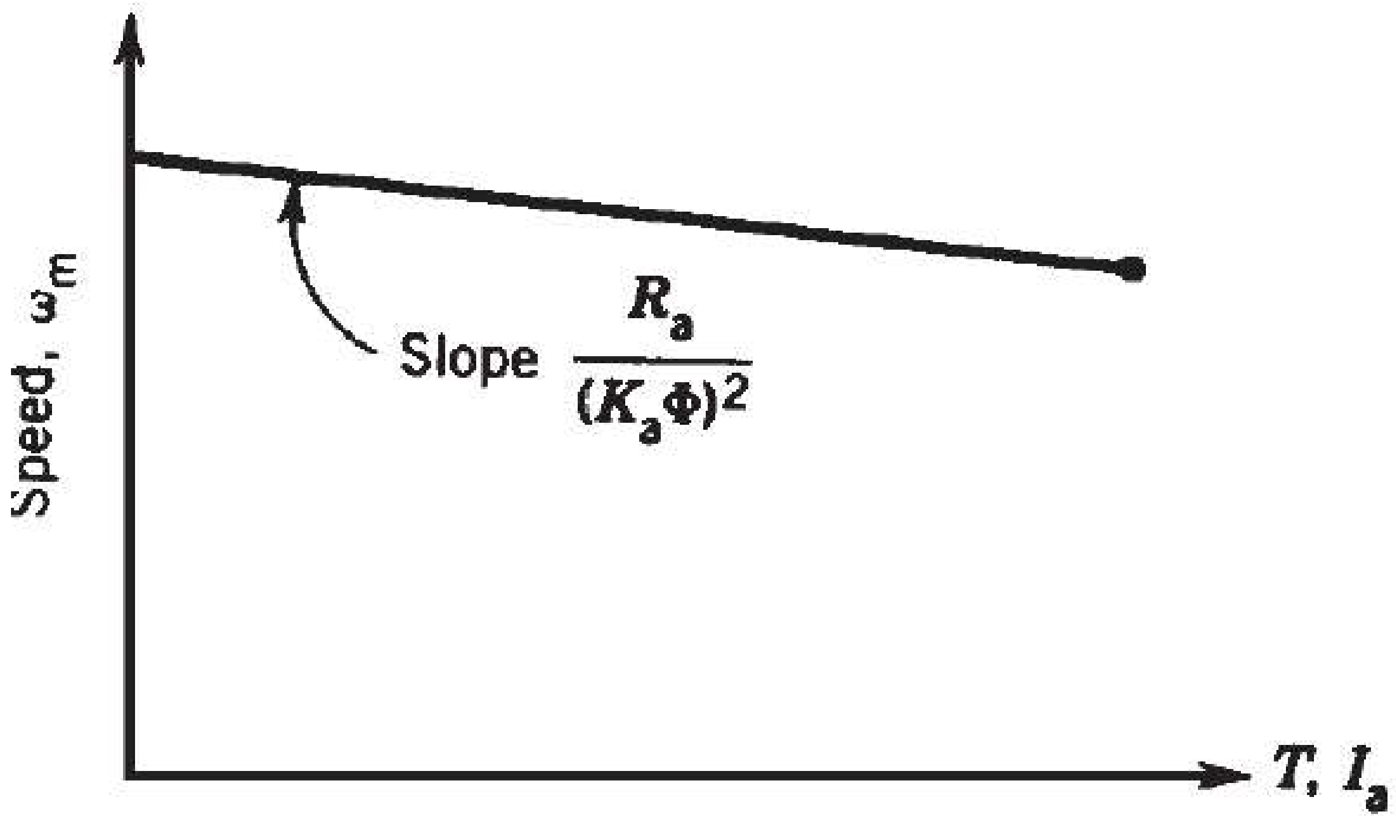
Thus for such a motor we can write :

$$\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}}$$

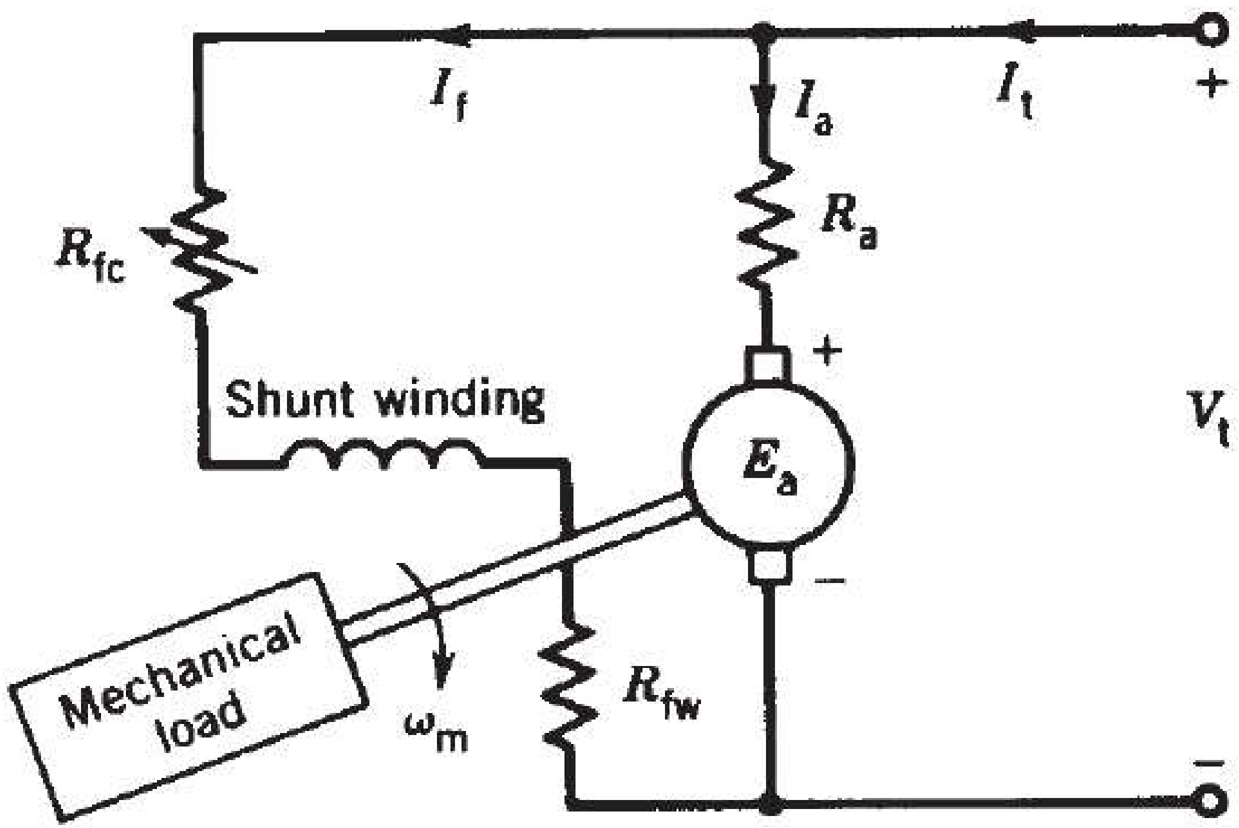
Separately Excited Motor



Torque-speed Characteristic of Separately Excited Motor



Shunt Motor



I_f
I_a
I_t
+
R_a
R_{fc}
+
Shunt winding
V_t
E_a
−
Mechanical load
ω_m
R_{fw}
−

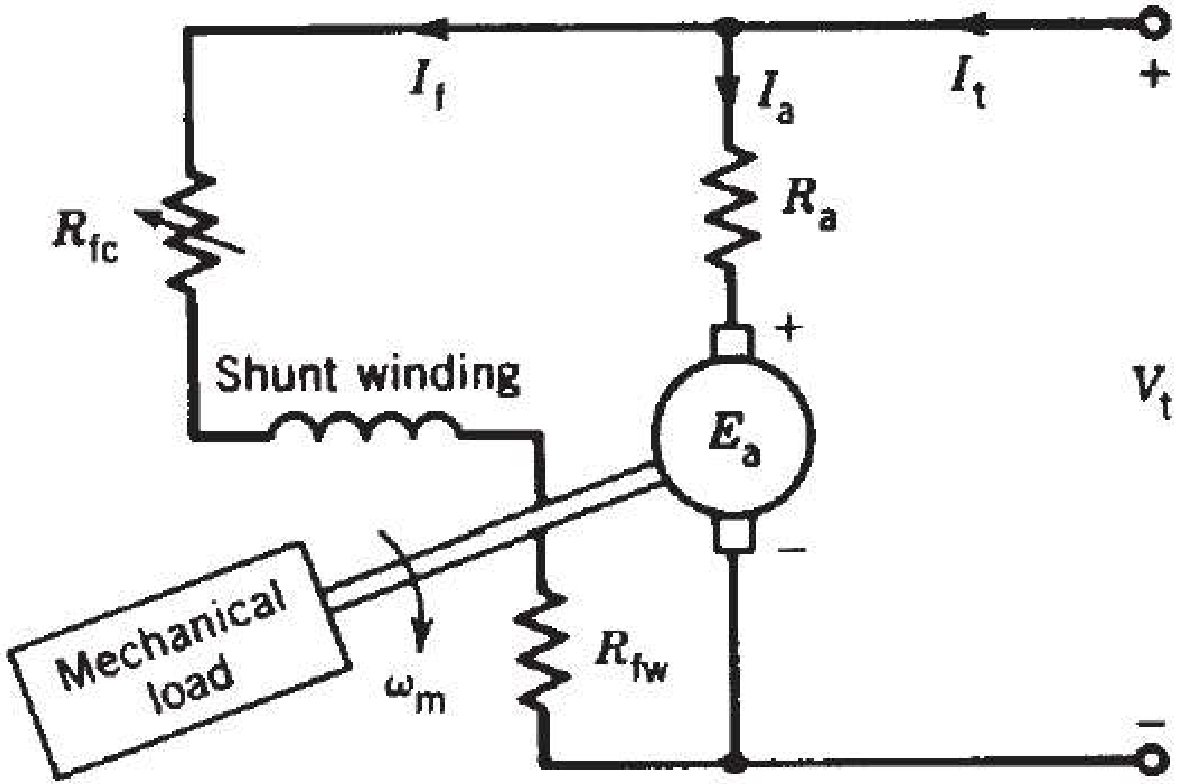
Example 1

A shunt motor is running off a 220V supply taking an armature current of 15A, the resistance of the armature circuit being 0.8Ω.

a) Calculate the value of the generated emf, if the flux were suddenly reduced by 10 per cent;

b) To what value would the armature current increase momentarily?

Example 1



Example 1

(a) $E_{b1} = V - I_a R_a = 220 - 15 \times 0.8 = 208V$

When magnetic field Φ reduced by 10%,

$E_{b2} = 0.9 \times E_{b1} = 0.9 \times 208 = 187.2V$,

(b) $I_a = (220 - 187.2)/0.8 = 41A$

Example 2 (DC shunt motor)

- An 8-pole, 400V shunt motor has 960 wave connected armature conductors. The full load armature current is 40A and the flux per pole is 0.02 Wb. The armature resistance is 0.1Ω and the contact drop is 1V per brush. Calculate the full load speed of the motor.

Example 2 (DC shunt motor)

$$Given : P = 8, V = 400V, Z = 960, Ia = 40A, \phi = 0.02Wb$$

$$ra = 0.1\Omega \ and \ c = 2, brush \ drop = 2x1 = 2V$$

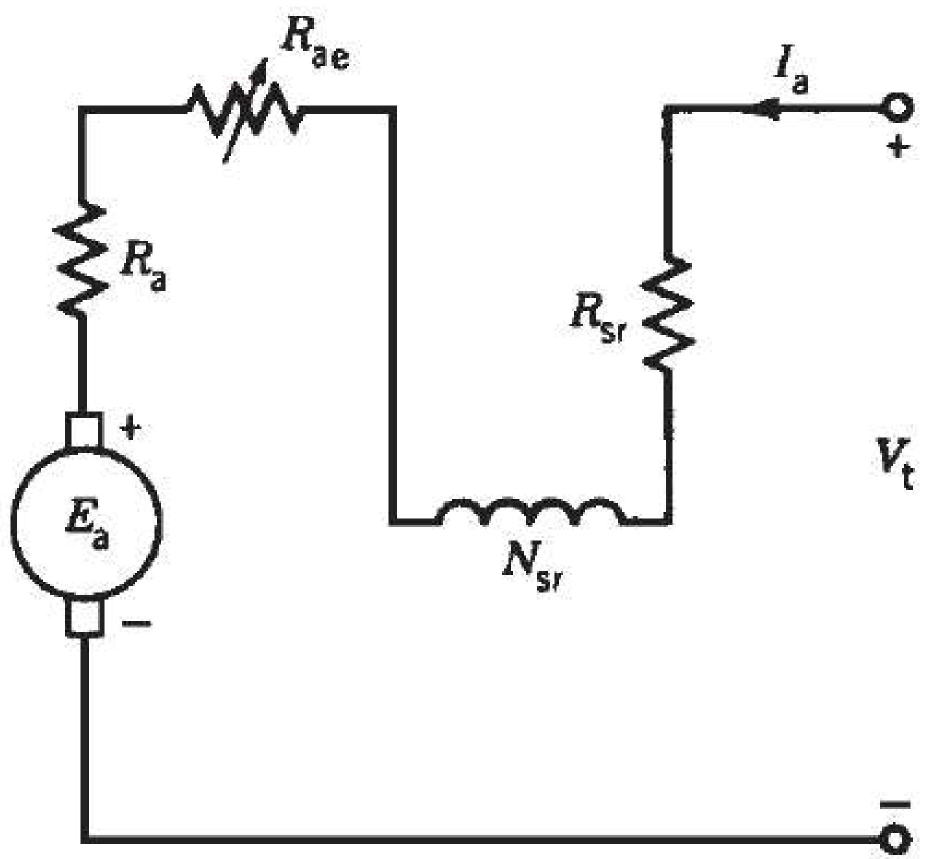
$$Back \ emf \ \ Eb = V - Iara - brush \ drop$$

$$= 400 - 40x0.1 - 2 = 394V$$

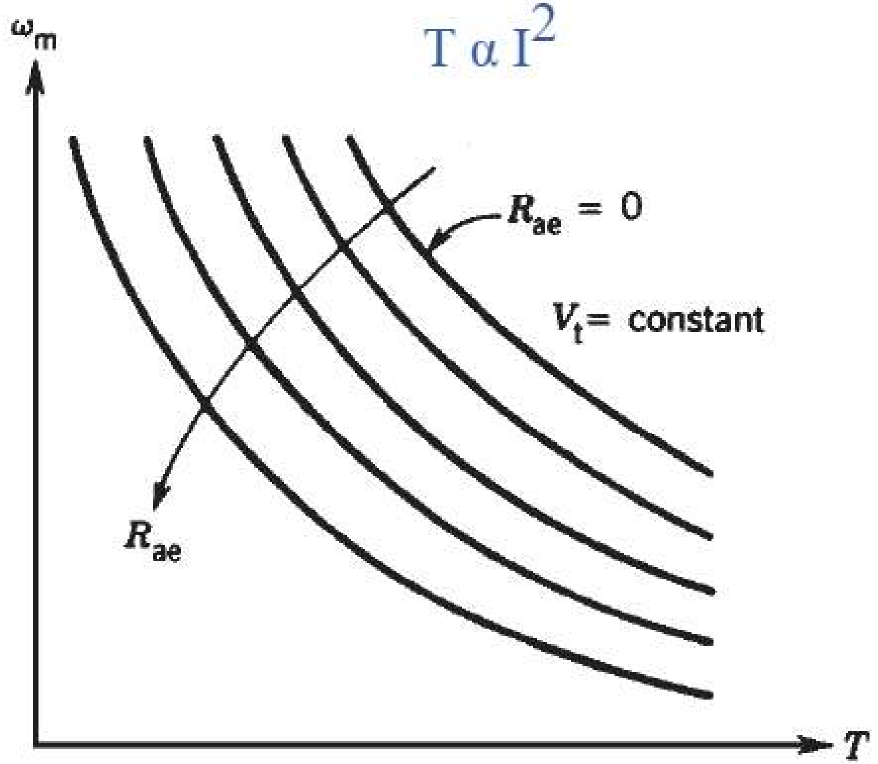
$$Eb = \frac{2xZxPxNx\phi}{60xc}$$

$$\therefore N = \frac{60cEb}{p\phi Z} = \frac{60x2x394}{2x4x0.02x960} rpm = \underline{\underline{308rpm}}$$

Series Motor



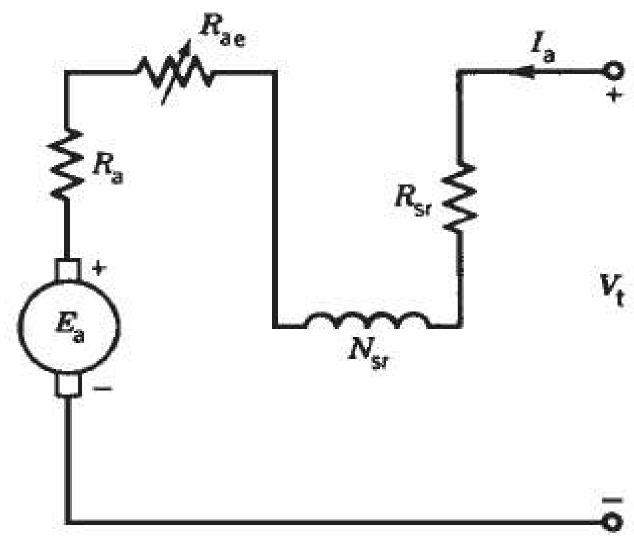
Torque-speed Characteristic of Series Motor



$T \alpha I^2$

$$\omega_m = 2\pi n = \frac{V_t - I_a R_a}{K_a \Phi}$$

$$n = \frac{KV_t}{\Phi}$$



Example 3: Series motor

- A 400V, 10 kW series motor drives a fan when running at 800 rpm. The motor draws 50A from the supply. The resistance of the armature and series field are 0.2Ω and 0.1Ω respectively. Determine the electromagnetic torque developed by the motor.

Example 3: Series motor

Terminal voltage V = 400V

Armature current Ia = 50A

Armature resistance Ra = 0.2 Ω

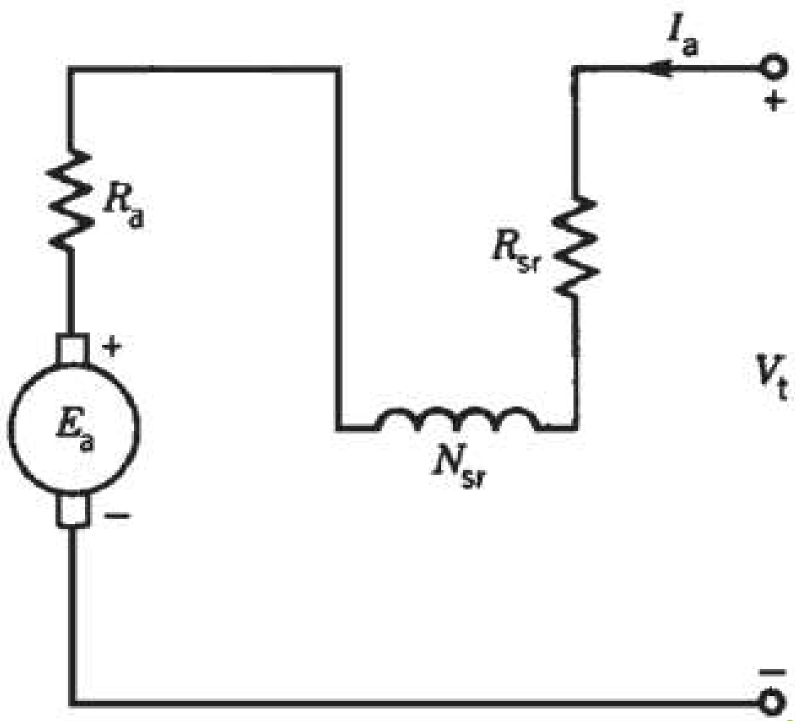
Series field resistance Rsf=0.1 Ω

Back emf Eb=Ea=V-Ia(Ra+Rsf)

= 400-50(0.2+0.1)=385V

Now speed = 800 rpm

$$T = \frac{EbIa}{\frac{2\pi N}{60}} = \frac{385x50}{2x3.1416x800}x60 = \underline{\underline{230Nm}}$$



1. Adjustment of field current

Speed control can be done by

- Adjustment of armature current by field controller

- Adjustment of input voltage

  - i.e. M-G set and Electronic Inverter

1. Adjustment of field current

field diverter and field regulator

- The field current control mode is used **to obtain speed above the base speed.**

- In this mode, the armature voltage **Vt remains constant** and the motor field current **Im is decreased** (field weakening) to obtain higher speeds.

1. Adjustment of field current

field diverter and field regulator

- The **armature current can be kept constant**, thereby operating the motor in a constant-horsepower mode.

- The Torque obviously decreases as speed increases.

2. Adjustment of armature current

- Adjustment of armature current by **field controller**

3. Adjustment of input voltage

M-G set and Electronic Inverter

- by varying the generator field current *Ifg*, the generator voltage Vt is changed, which in turn changes the speed of the dc drive motor.

CHAPTER C

Power Losses in a DC Machine

Types of Losses in a DC Machine

1. Copper Losses:

– Armature copper loss $P_{CU(armature)} = I_a^{\ 2} R_a (W)$

where Ia = armature current;

Ra = armature resistance;

- Field copper loss (Series or Shunt)

$$P_{CU(field)} = I_f^{\ 2} R_f (W)$$

i.e. shunt field copper loss or series field copper loss,

Types of Losses in a DC Machine

2. Iron Losses (Core or Magnetic Losses)

These losses occur in the armature and field core. They are of two types – hysteresis loss and eddy current loss.

Hysteresis loss = $KhBm^{1.6}f$

Eddy current loss = $KbBm^{2}f$

Bm=maximum flux density

f = frequency of magnetic reversal and

Kh and Kb = constant

Types of Losses in a DC Machine

3. Mechanical Losses –

These losses consist of bearing frictional and windage loss.

No Load rotational losses (P_o)= Pi+Pw

=Iron losses + mechanical losses

and are constant for a particular machine.

Total Power loss (P_L)=$P_o + I_a^2 R_a + I_f^2 R_f$

Efficiency of a DC Machine

DC Generator

$$Efficiency(\eta_g) = \frac{P_{OUT}}{P_{OUT} + P_L} = \frac{V(I_a - I_f)}{V(I_a - I_f) + P_L}$$

DC Motor

$$Efficiency(\eta_m) = \frac{P_{in} - P_L}{P_{in}} = \frac{V(I_a + I_f) - P_L}{V(I_a + I_f)}$$

Example 4 (Generator Efficiency)

- A 10kW 125V long shunt compound generator has rotational losses amounting to 580W. The shunt field resistance is 62.5Ω , the armature resistance 0.12Ω , and the series field resistance 0.022Ω . Calculate the full-load efficiency.

Example 4 (Generator Efficiency)

The full-load current is I_L = 10,000 / 125 = 80 A

Assuming a long-shunt connection,

the field currents is I_F = 125/62.5 = 2 A

Then $I_A = 80 + 2 = 82$ A, which is the current through the series winding.

The $I^2 R$ losses can now be determined:

Armature loss = $82^2 \times 0.12$ = 807 W

Series field loss = $82^2 \times 0.022$ = 148 W

Shunt field loss = $2^2 \times 62.5$ = 250 W

Rotational loss = 580 W

Total loss = 1,785 W

Hence η = P out / (Pout + P loss) = 10,000 x100/ 11,785 = 84.9 %

Example 5 (Motor Efficiency)

- A 400V DC shunt motor runs at no load at 1500 rpm with input 1000W. The shunt field current is 1A and the armature resistance is 0.2Ω. Find the line current at which maximum efficiency occurs and the value of maximum efficiency.

Example 5 (Motor Efficiency)

$$Given: V = 400V; N = 1500\,rpm; Input\ Power = 1000W;$$

$$I_{sh} = 1\,A; r_a = 0.2\,\Omega$$

$$Line\ current\ at\ no\ load = \frac{1000}{400} = 2.5\,A$$

$$Armature\ current\ at\ no\ load = 2.5 - 1 = 1.5A;$$

$$Armature\ copper\ loss\ at\ no\ load\ (Ia^2 r_a) = (1.5)^2 x 0.2 = 0.45W;$$

Example 5 (Motor Efficiency)

$$Constant\ loss = 1000 - 0.45 = 999.55W$$

$$For\ maximum\ efficiency,\ constant\ loss = variable\ loss$$

$$If\ I'a\ be\ the\ armature\ current\ at\ maximum\ efficiency\ condition\ then$$

$$I'a^2 x 0.2 = 999.55\ or\ I'a = 70.69A$$

$$\therefore Line\ current = 70.69 + 1 = 71.69A$$

$$Also\ at\ maximum\ efficiency,\ total\ loss = 2x\,999.55 = 1999.1W$$

$$Input = 400x71.69 = 28676W$$

$$\therefore Maximum\ efficiency = \frac{28676 - 1999.1}{28676} = 0.93 = \underline{\underline{93\%}}$$

Application of DC motors

Types of motor	Applications
SeriesMotor	▪ For traction work, i.eelectric locomotives, Rapid transit system, trolley cars etc ▪ Cranes and hoists ▪ Conveyors
Shunt motor	▪ For Driving constant speed line shafting lathes ▪ Centrifugal pumps Machine tools Blowers & Fans ▪ Reciprocating pumps

Application of DC motors

Types of motor	Applications
Cumulative Compound	▪ For intermittent high torque loads ▪ For shears and punches ▪ Elevators Conveyors Heavy planers ▪ Rolling mills: Ice machine: ▪ Printing Presses: ▪ Air Compressors

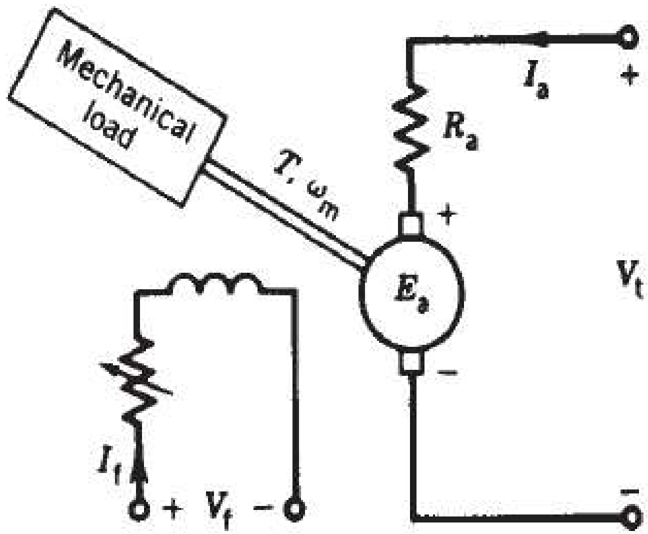
DC Motor Starter

From Fig, the starting armature current is:

$$I_a = \frac{V_t - E_a}{R_a} \qquad I_a\big|_{start} = \frac{V_t}{R_a}$$

When a d.c motor is stationary, the back emf, Ea=0, and the armature current is then:

Since R_a is small, the starting current is very large.



DC Motor Starter

The in-rush current on starting a DC machine must be limited to:

- About 1 to 2 times the full load current,
- Prevent excessive temperature rise and mechanical vibration.

Starting current can be limited to a safe value by

- Use a low DC applied voltage at starting, and hence requires a variable-voltage supply.

- The variable voltage is gradually increased from zero to the machine normal voltage.

Starting current can be limited to a safe value by

- As the back emf builds up, the current will come down to its normal level even with an increase of input voltage.

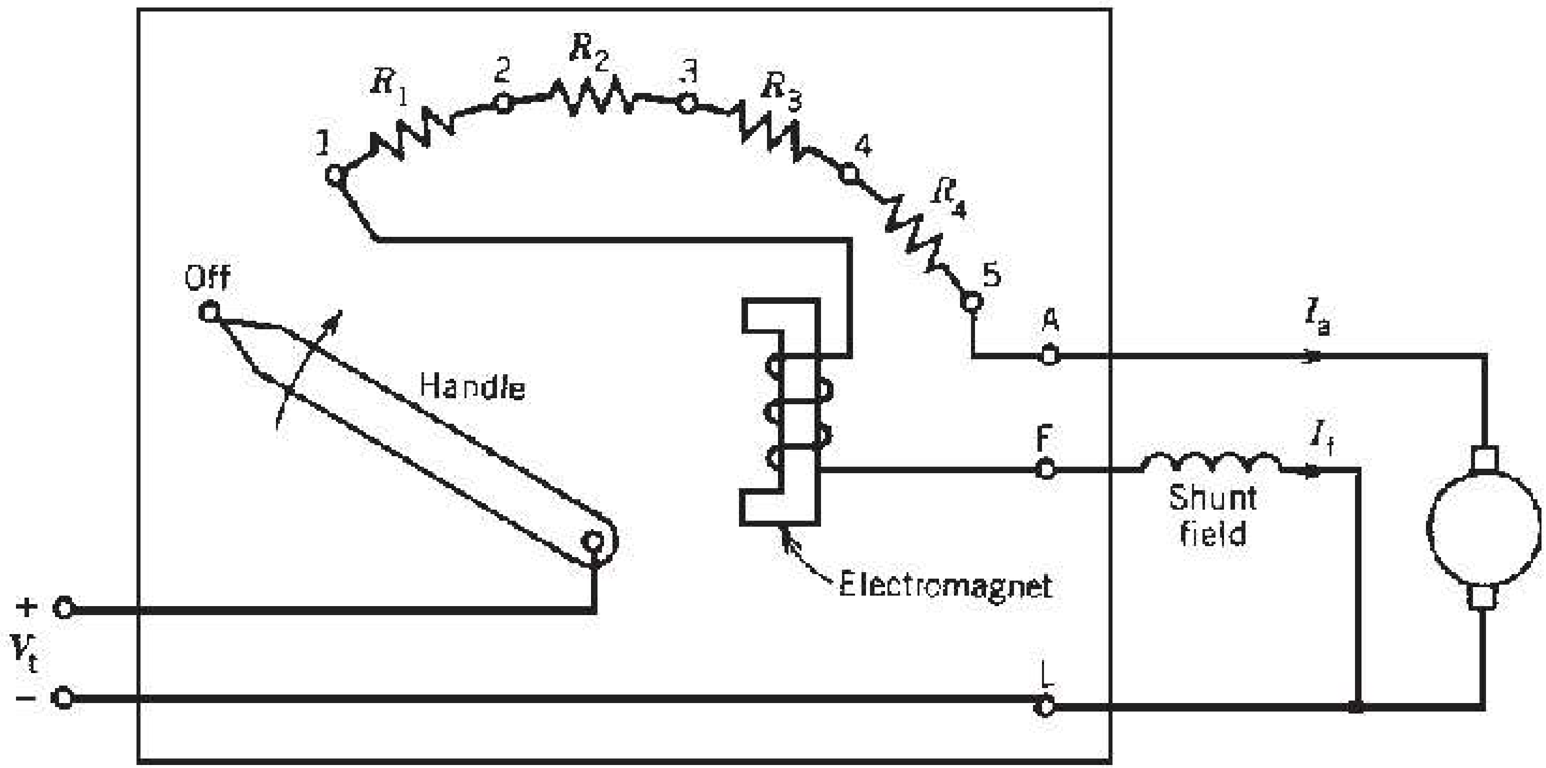
2. Inserting external resistance

Insert an external resistance, Rae, in series with the armature at starting Fig.1.

The resistance is then gradually cut down when the back emf builds up.

$$I_a = \frac{V_t - E_a}{R_a + R_{ae}}$$

DC Motor Starter (insertion of external resistors)



Example 6

A 10 kW, 100V, 1000 rpm dc machine has $R_a = 0.1\Omega$ and is connected to a 100V dc supply.

a) Determine the starting current if no starting resistance is used in the armature circuit.

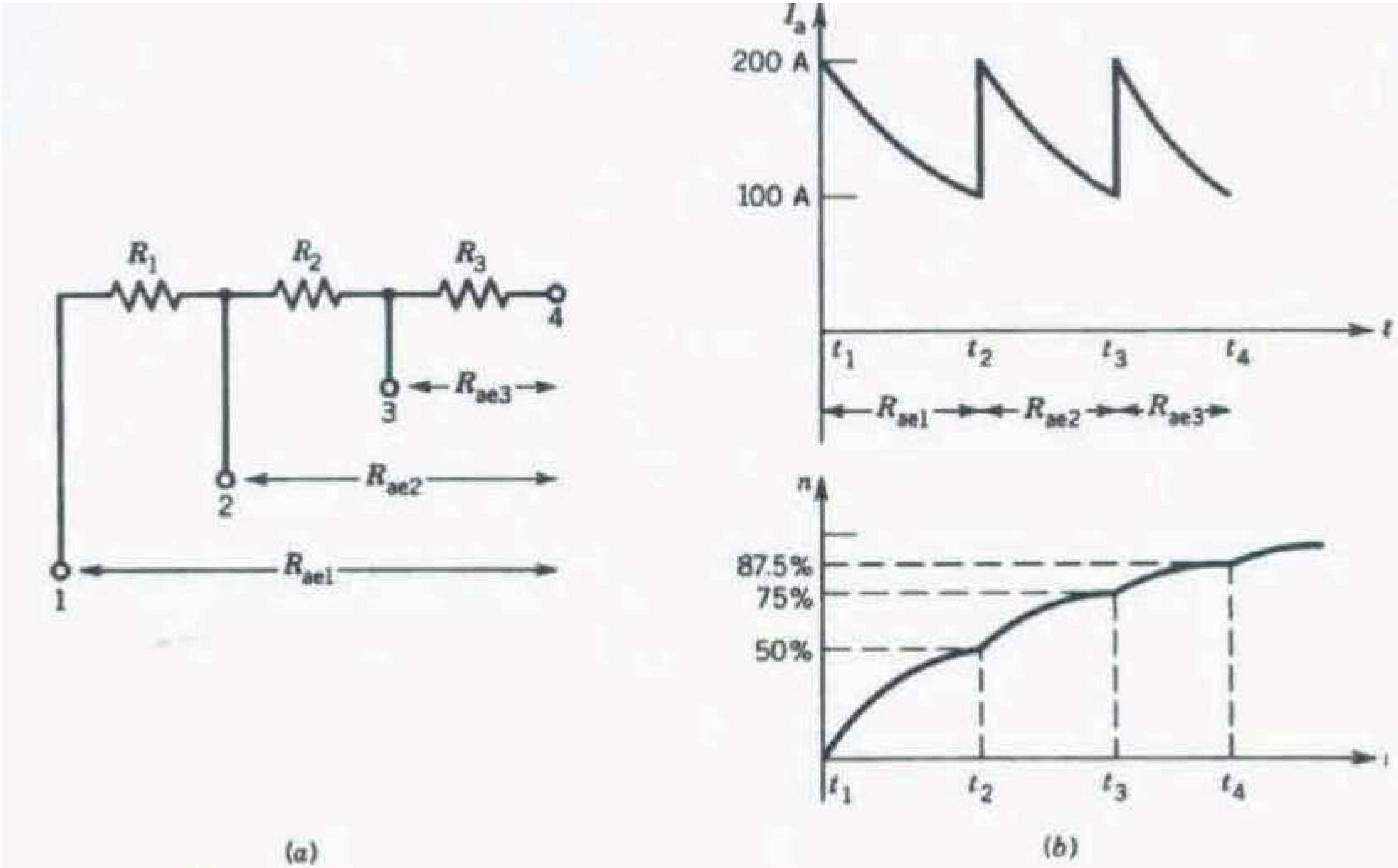
Example 6

b) Determine the value of the starting resistance if the starting current is limited to twice the rated current. This dc machine is to be run as a motor, using a starter box.

Example 6

c) Determine the values of resistances required in the starter box such that the armature current I_a is constrained within 100 to 200% of its rated value (i.e. 1 to 2 pu) during start-up.

Example 6



R_1
R_2
R_3
1
2
3
4
R_{ae1}
R_{ae2}
R_{ae3}
(a)
I_a
200 A
100 A
t
t_1
t_2
t_3
t_4
R_{ae1}
R_{ae2}
R_{ae3}
n
87.5%
75%
50%
t_1
t_2
t_3
t_4
(b)

Example 6

(c) An arrangement of the resistances in the starter box is shown in Fig. E4.10*a*, where R_{ae1}, R_{ae2}, …represent total resistances of the box for positions 1, 2,…, respectively. The handle will be moved to a new position when I_a decreases to 100 A (rated armature current). The variation of current I_a and speed n with time is shown in Fig. E4.10*b*.

R_{ae1} . From part (b)

$$R_{ae1} = 0.4\,\Omega$$

= total resistance in starter box

R_{ae2} . At any speed,

$$\underset{\substack{\uparrow \\ \text{fixed}}}{V_t} = \underset{\substack{\uparrow \\ \text{increases} \\ \text{with} \\ \text{speed}}}{E_a} + I_a\,(\underset{\substack{\uparrow \\ \text{decreases} \\ \text{with} \\ \text{speed}}}{R_a} + R_{ae})$$

Example 6

At $t = t_2^-$ (i.e., before the handle is moved to position 2),

$$I_a = 100\text{A}$$

and

$$\begin{aligned} E_{a2} &= V_t - I_a(R_a + R_{ae1}) \\ &= 100 - 100(0.1 + 0.4) \\ &= 50\text{ V} \end{aligned}$$

At $t = t_2^+$ (i.e., before the handle is moved to position 2),

$$I_a = 200\text{A} = \frac{V_t - E_{a2}}{R_a + R_{ae2}}$$

or

$$200 = \frac{100 - 50}{0.1 + R_{ae2}}$$

$$R_{ae2} = 0.15\,\Omega$$

Example 6

R_{ae3}. At $t = t_3^-$, $I_a = 100$ A.

$$E_{a3} = 100 - 100(0.1 + 0.15)$$
$$= 100 - 25$$
$$= 75V$$

At $t = t_3^+$,

$$I_a = 200A = \frac{100 - 75}{0.1 + R_{ae3}}$$
$$R_{ae3} = 0.025\,\Omega$$

R_{ae4}. At $t = t_4^-$, $I_a = 100$ A.

$$E_{a4} = 100 - 100(0.1 + 0.025)$$
$$= 87.5\ V$$

At $t = t_4^+$,

$$I_a = 200 = \frac{100 - 87.5}{0.1 + R_{ae4}}$$
$$R_{ae4} = -0.0375\,\Omega$$

Example 6

The negative value of R_{ae4} indicates that it is not required, that is, $R_{ae4} = 0$. At $T = t_4^+$ (i.e., after the handle is moved to position 4), the armature current without any resistance in the box will not exceed 200 A. In fact, the value of I_a when the handle is moved to position 4 at $t = t_4$ is

$$I_a = \frac{100 - 87.5}{0.1} = 125 \text{ A}$$

Therefore, three resistances in the starter box are required. Their values are

$$R_1 = R_{ae1} - R_{ae2} = 0.4 - 0.15 = 0.25\,\Omega$$
$$R_2 = R_{ae2} - R_{ae3} = 0.15 - 0.025 = 0.125\,\Omega$$
$$R_3 = R_{ae3} - R_{ae4} = 0.025 - 0 = 0.025\,\Omega$$

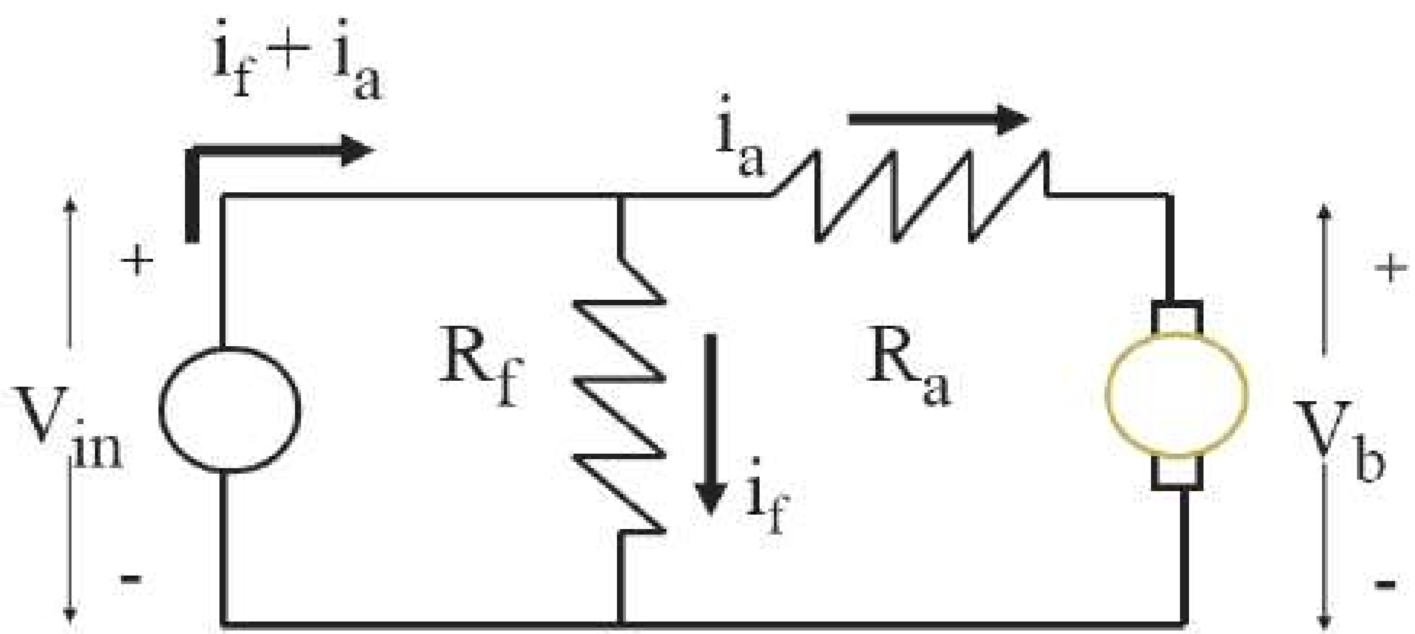
Example 7

A 250V DC machine has an armature resistance (including interpoles) of 0.5Ωand a shunt field resistance of 125 Ω. When it is running as a motor on no load, the current taken from the supply is 5 A. Calculate the efficiency of the machine when it is

a) Delivering a current of 35A as a generator;

b) Taking a current of 52A from the supply as a motor.

Example 7



Example 7

(a)On no-load, $I_f = V/R_f = 250/125 = 2$ A

- $\therefore I_a = I - I_f = 5\text{-}2 = 3$ A
- $P_a = VI_a = 250 \times 3 = 750$ W
- Constant field copper loss $I_f^2 R_f = 2^2 \times 125 = 500$ W

Example 7

When delivering a current of 35 A as a generator:

Power output $P_{out} = VI = 250 \times 35 = 8750$ W

- For generator operation, $I_a = I + I_f = 35+2 = 37$ A
- Armature copper loss, $I_a^2 + R_a = 37^2 \times 0.5 = 685$ W
- Total loss, $P_L = P_o + I_f^2 R_f + I_a^2 R_a = 750+500+685 = 1935$ W
- $\therefore$ Efficiency, $\eta = P_{out}/(P_{out}+P_L) = 8750/(8750+1935) = 0.819$

Example 7

(b) When taking a current of 52 A from the supply as a motor:

Power input, $P_m = VI = 250 \times 52 = 13000$ W

For motor operation, $I_a = I - I_f = 52\text{-}2 = 50$ A

$\therefore$ armature copper loss, $I_a{}^2R_a = 50^2 \times 0.5 = 1250$ W

Total loss, P_L

$= P_o + I_f{}^2R_f + I_a{}^2R_a = 750 + 500 + 1250 = 2500$ W

$\therefore$ Efficiency, η

$= (P_{in} - P_L)/P_{in} = (13000 - 2500)/13000$

$= 0.808$ pu or 80.8%

CHAPTER D1

AC Electric Machines

AC Electric Machines

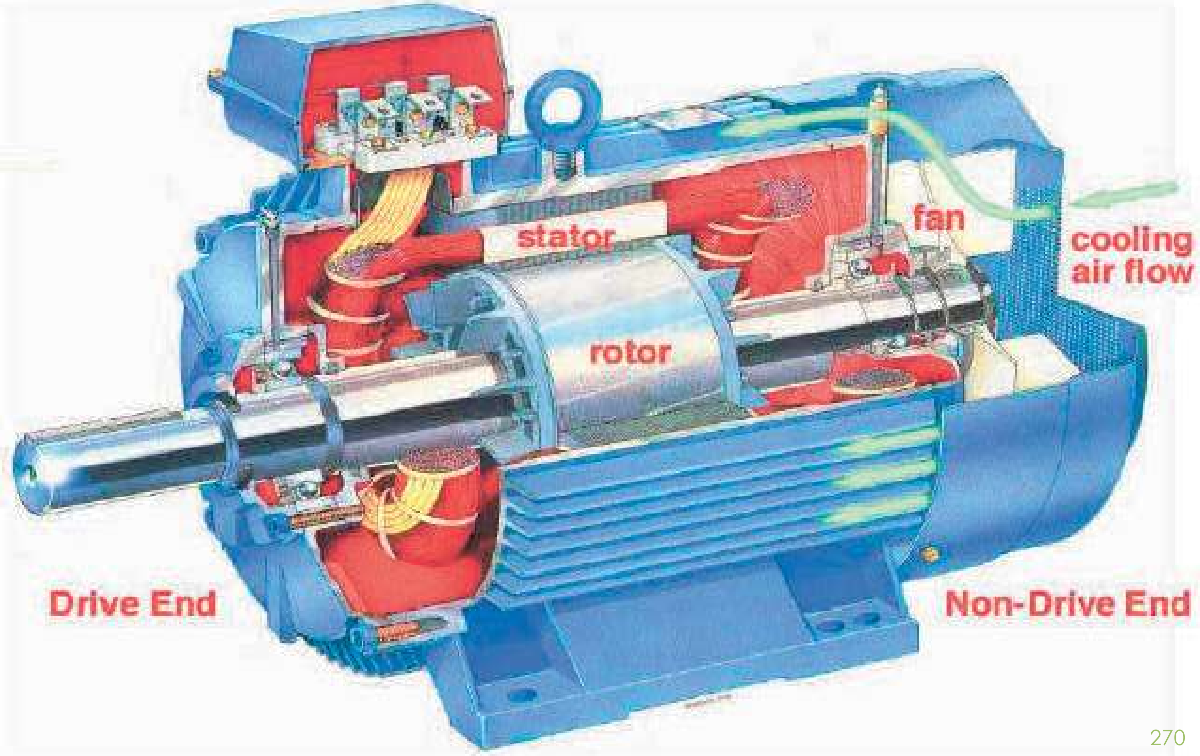
1. Construction and Operating Principles
2. Advantages and disadvantages of 3-phase induction motor
3. Production of rotating magnetic field

3-Ø Induction Motor

Constructions and Operating Principles

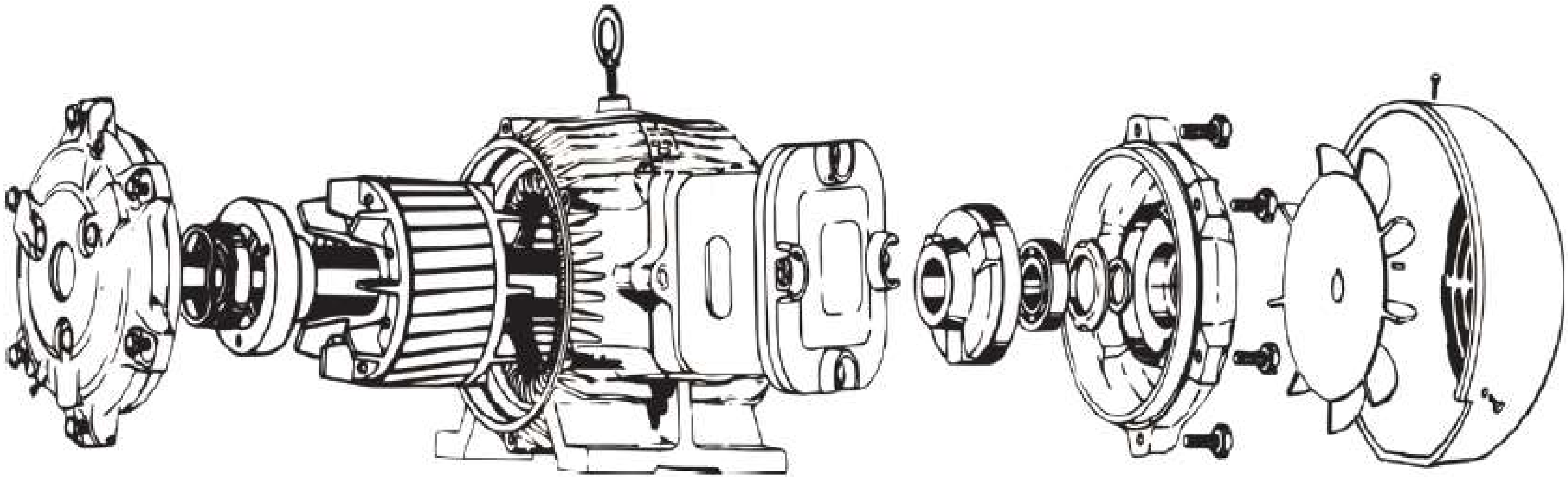
3-Ø Induction Motor Assembly

http://www.youtube.com/watch?v=7tEsJ-AoEQ&feature=related



P4-1 Induction Motor v1.0

Construction of Induction Motor



Induction Machine

Also called Asynchronous Machines

- Most widely used machine in industry
- Most rugged

Induction Machine

Consists of:

- **A stator**
- **A rotor** mounted on bearing separated from the stator by an air gap.
- Both stator winding and rotor winding carry **alternating currents**.
- Induction motor basic principles video:
- http://www.youtube.com/watch?v=N8LUOTQKXlk

Operating Principles

- AC is supplied ***directly to*** the stator winding
- AC current flowing in the ***rotor winding*** by ***induction***

Induction Machine

- Stator windings serve as both armature windings and field windings.

- AC supply is connected to the stator windings and produce flux in the air gap and revolves at a fixed speed known as synchronous speed.

Revolving Flux/Speed

- The revolving flux induces voltage in the stator windings as well as in the rotor windings.

Revolving Flux/Speed

- **If the rotor circuit is closed**, current flows in the rotor winding and reacts with the revolving flux to produce torque.

- The steady state speed of the rotor is very close to the ***synchronous*** *speed*.

Rotor Windings

The rotor can have a winding similar to:

- The stator ***(wire-wound rotor)***, or
- a ***cage-type winding***

Rotor Winding Construction

Wire-wound Type:

- Similar to the stator windings

Cage Type:

- Formed by placing aluminum or copper bars in the rotor slots and shorting them at the ends by means of rings.

3-Ø Induction Motor

Advantages and Disadvantages

Advantages 3-Ø Induction Motor

- Induction motor is cheap and robust
- The motor is driven by the rotational magnetic field produced by 3 phase currents, hence NO commutator or brush is required
- Maintenance is relatively easy and at low cost

Disadvantages 3-Ø Induction Motor

- Low inherent starting torque

- Difficult to control the speed of induction motor unless modern power electronic drive is used.

Types of 3-Ø Induction Motor

- Squirrel Cage Type
  - **Induction Motor**
    - http://www.youtube.com/watch?v=3MbP4t920Is&feature=related
- Slip-ring (wound) Rotor Type
  - **Induction Motor**

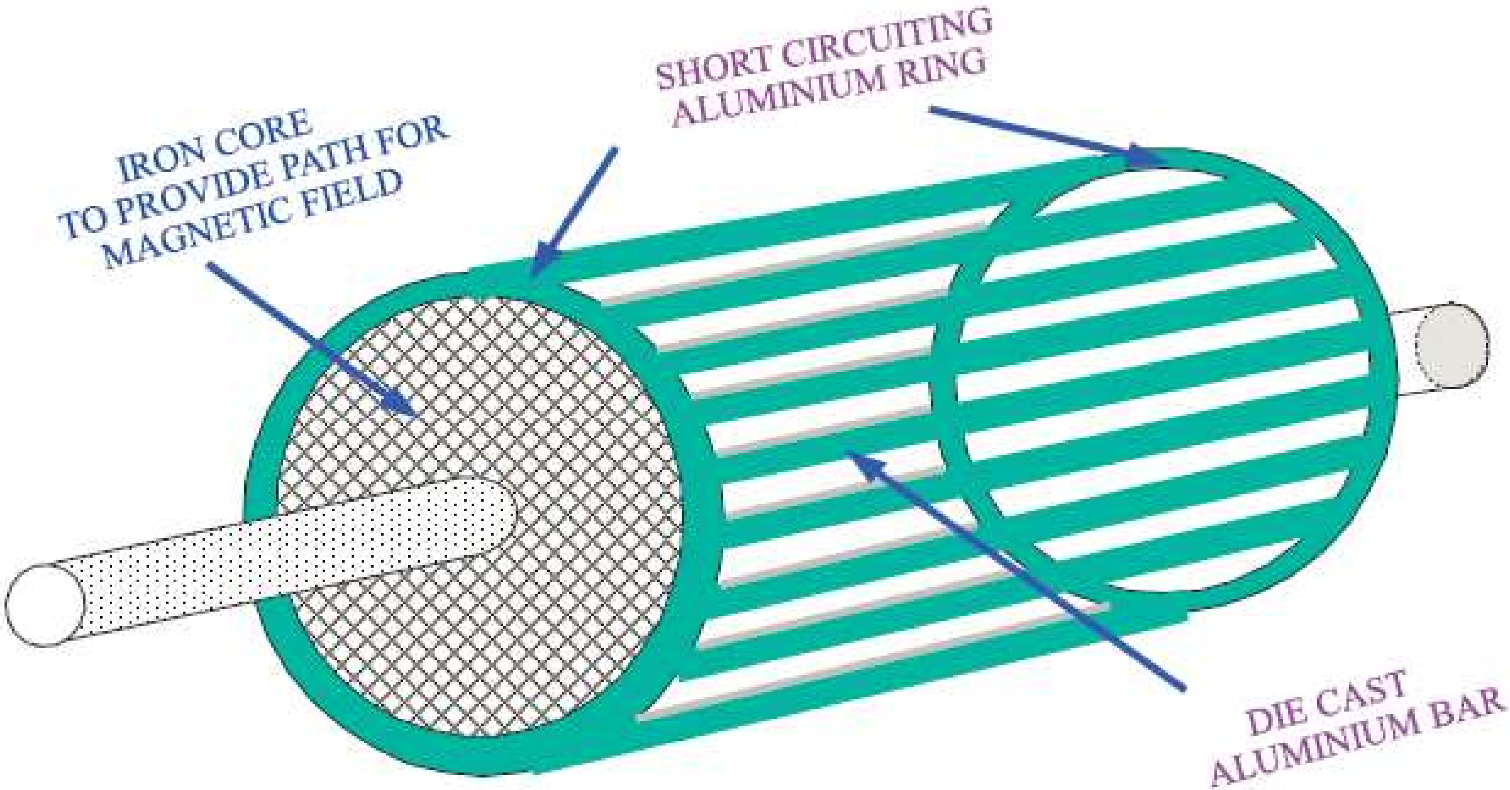
3-Ø Squirrel Cage Induction Motor

- The cage rotor is easy to manufacture, hence it is cheap and robust.

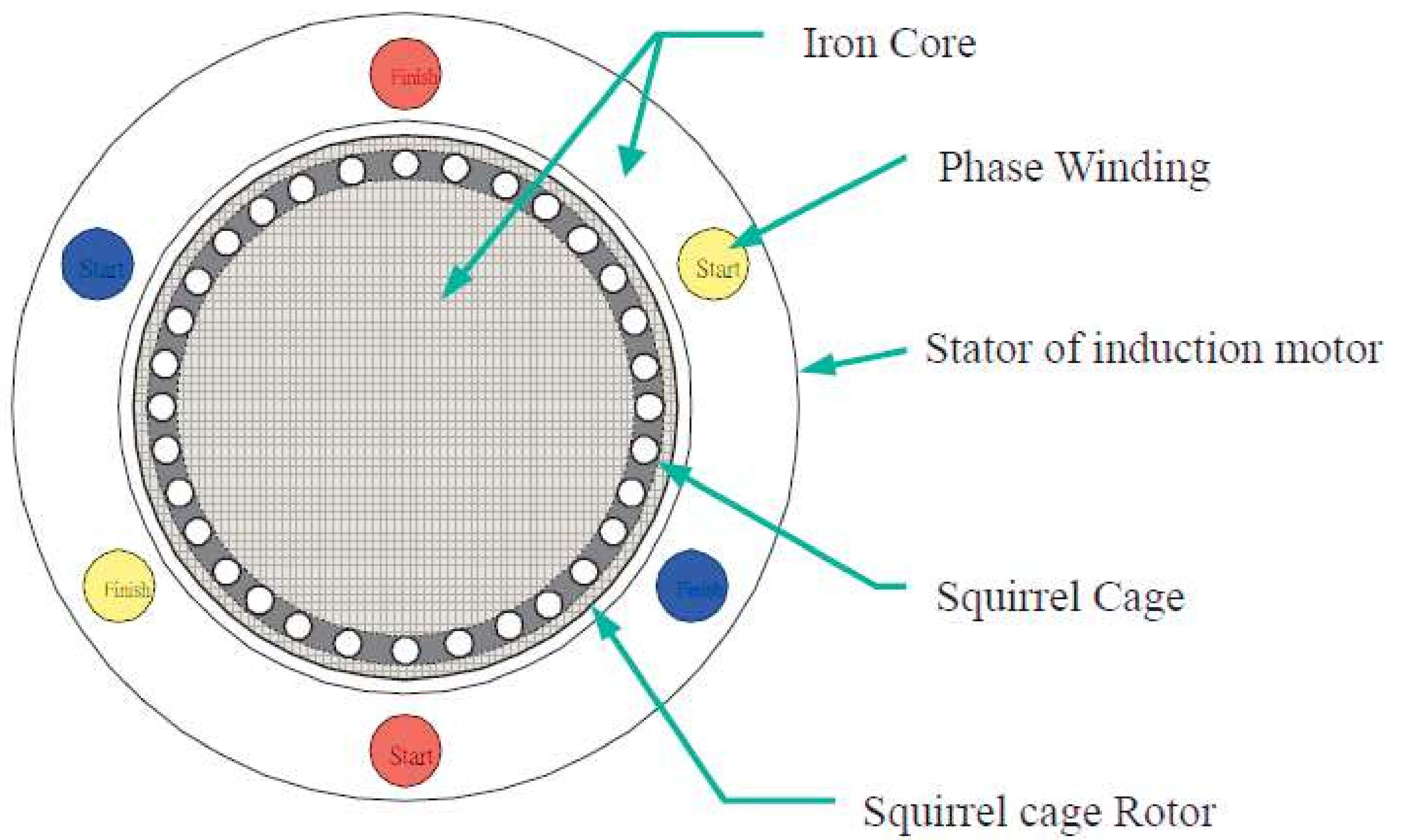
But

- we ***cannot*** control ***the speed or starting torque*** of a cage rotor.

Squirrel Cage Rotor



Squirrel Cage Induction Motor (cross sectional view)



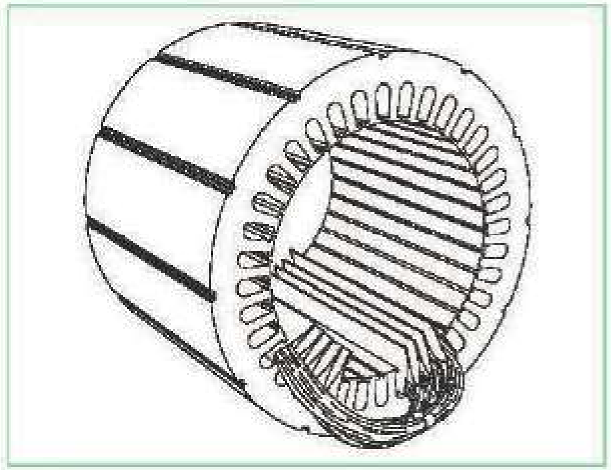
3-Ø Slip-ring Induction Motor

http://www.youtube.com/watch?v=onSectN11Dw

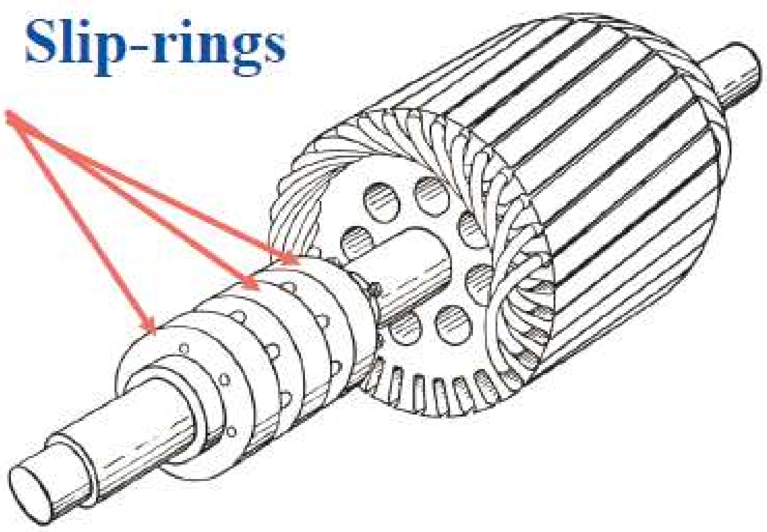
3-Ø Slip-ring Induction Motor

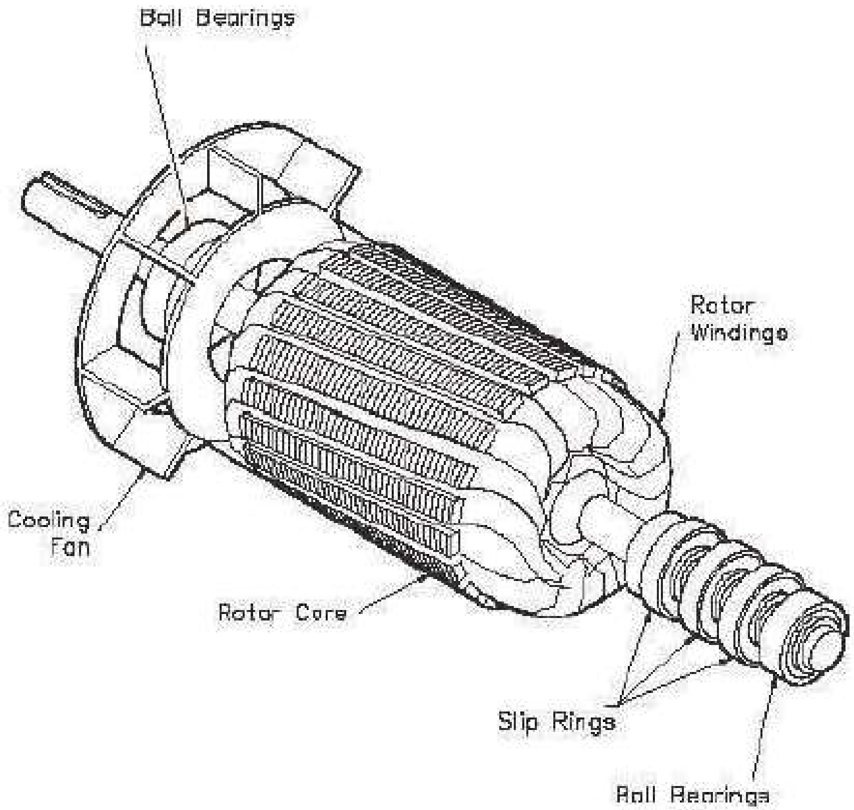
(Construction of Stator)

- The stator construction is same for both squirrel cage and slip ring induction motor.
- The main difference in slip ring induction motor is on the rotor construction and usage.

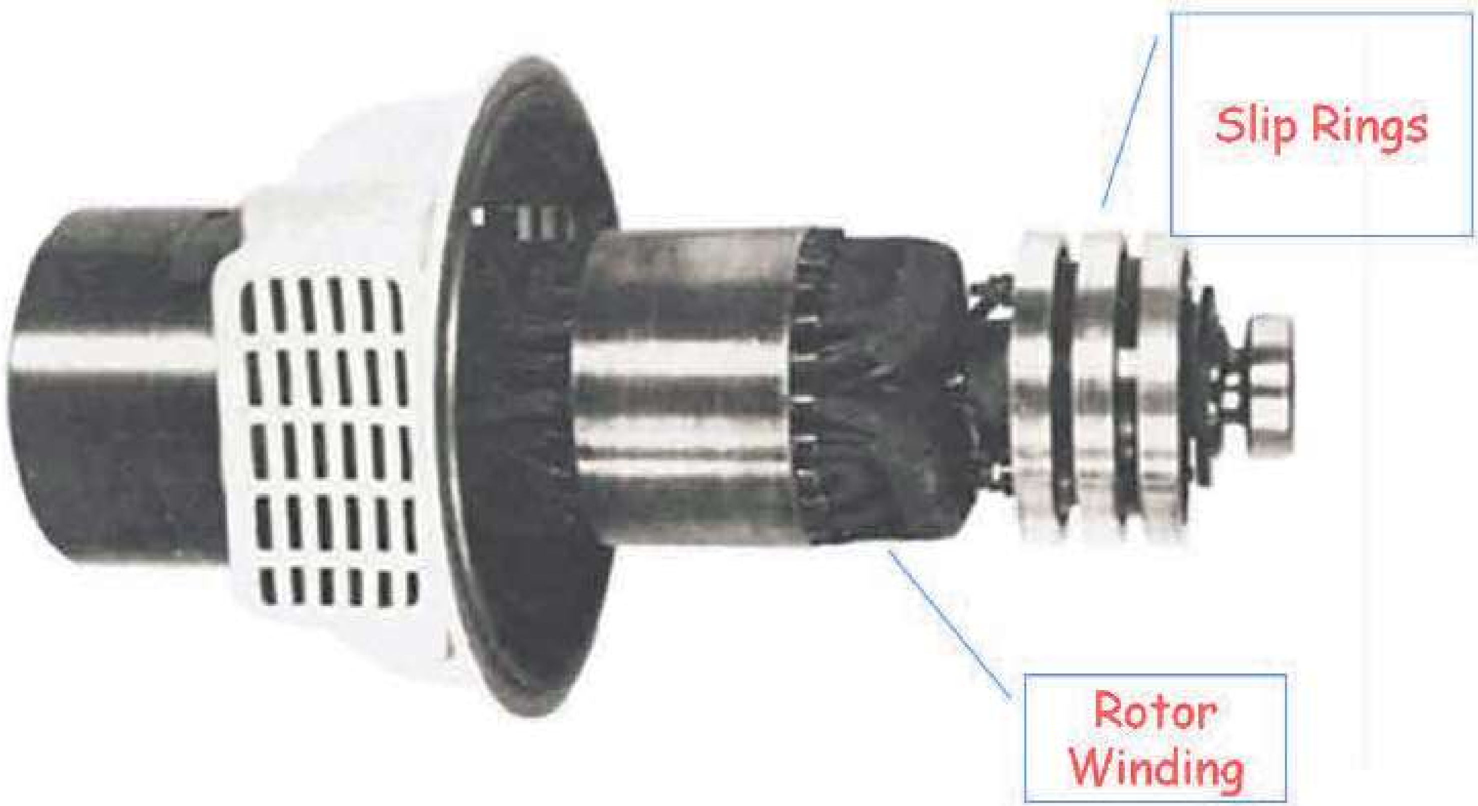


3-Ø Slip-ring Induction Motor





Slip-ring Rotor



3-Ø Slip-ring Induction Motor

- A slip ring rotor is wound with star connected three phase windings, the winding ends are brought out and connected to the exterior through ***three slip rings***.

3-Ø Slip-ring Induction Motor

- A slip ring rotor is expensive to manufacture and it is vulnerable to overheat, but we can ***connect suitable external resistance through the slip rings to the rotor circuit***.

- As a result, **we *can* control the starting torque and running characteristic of the slip ring motor**.

Slip ring Induction Motor (rotor)

- The slip ring induction motors usually have "Phase-Wound" rotor.

- This type of rotor is provided with a 3-phase, double-layer, distributed winding consisting of coils used in alternators.

Slip ring Induction Motor (rotor)

- The rotor core is made up of steel laminations which has slots to accommodate formed 3-single phase windings.

- These windings are placed 120 degrees electrically apart.

Slip ring Induction Motor (rotor)

- The rotor is wound for as many poles as the number of poles in the stator and is always 3-phase, even though the stator is wound for 2-phase.

Slip ring Induction Motor (rotor)

- These three windings are "starred" internally and other end of these three windings are brought out and connected to three insulated slip-rings mounted on the rotor shaft itself.

Slip ring Induction Motor (rotor)

- The three terminal ends touch these three slip rings with the help of carbon brushes which are held against the rings with the help of spring assembly.

Slip ring Induction Motor (rotor)

- These three carbon brushes are further connected externally to a 3-phase start connected rheostat.

- These slip ring and external rheostat makes the slip ring induction motors possible to add external resistance to the rotor circuit, thus enabling them to have a higher resistance during starting and thus higher starting torque.

Slip ring Induction Motor (rotor)

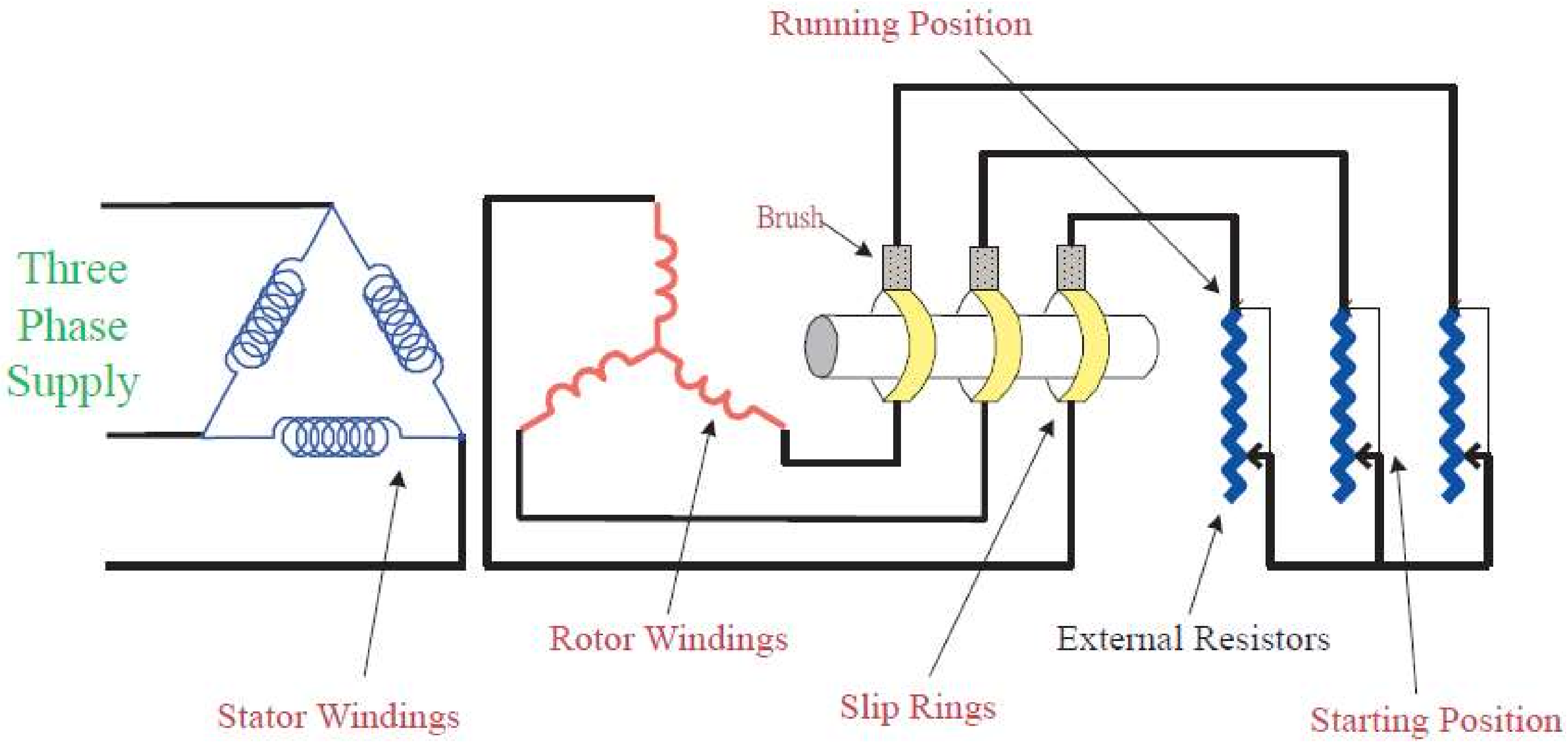
- When running during normal condition, the slip rings are automatically short-circuited by means of a metal collar, which is pushed along the shaft, thus making the three rings touching each other.

Slip ring Induction Motor (rotor)

- The brushes are automatically lifted from the slip-rings to avoid frictional losses, wear and tear.

- Hence, under normal running conditions, the wound rotor is acting as same as the squirrel cage rotor.

3-Ø Slip-ring Induction Motor



(Also called Wound Rotor Induction Motor)

3-Ø Slip-ring Induction Motor

Motor Production of Rotating Magnetic Field

Production of Rotating Magnetic Field

- *Rotating Magnetic Field* is very important to the operation of induction motor and it is produced by three-phase voltages

- Three phase voltages has a phase displacement of $120°$, hence at any instant of time there is a different voltage values in the three phases

Production of Rotating Magnetic Field

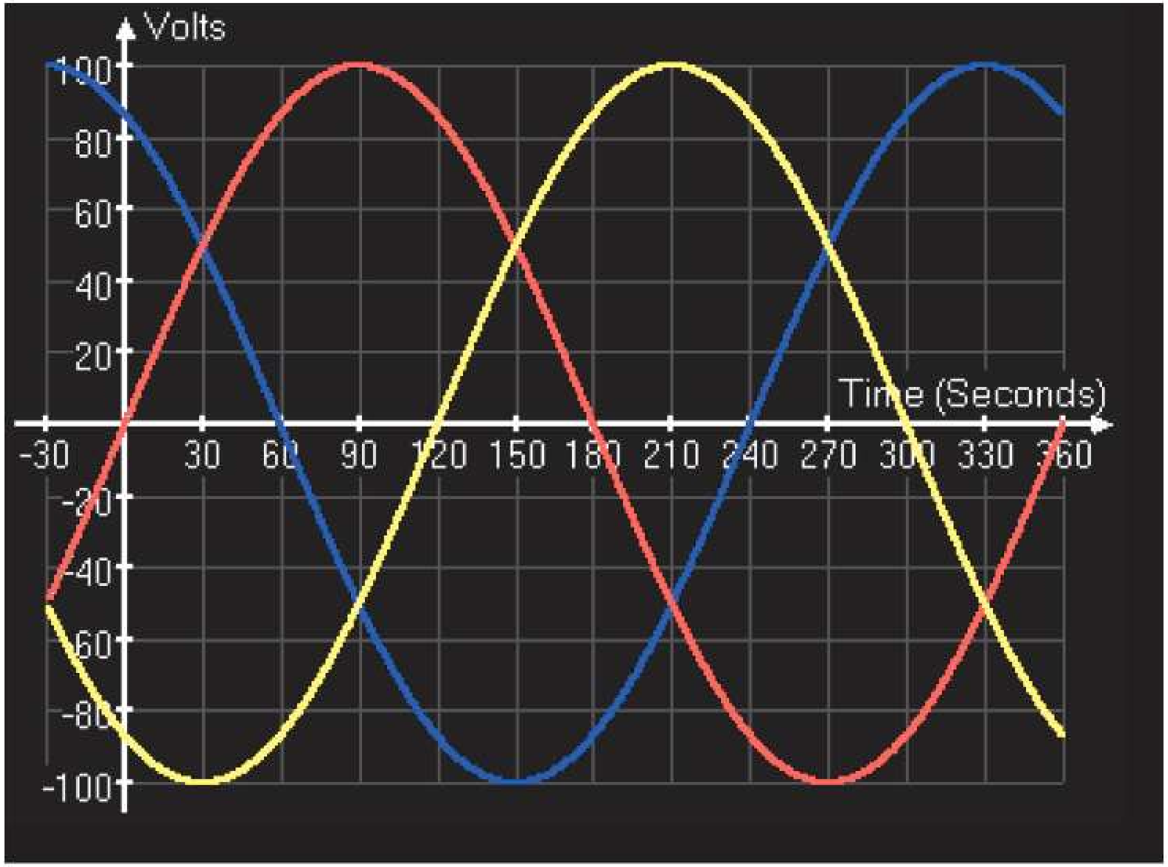
- The three phase voltage is sinusoidal in waveform

- One complete cycle of a very low frequency three phase voltage (period T = 360 seconds), at an interval of 30° electrical degrees, and the three phase voltages:

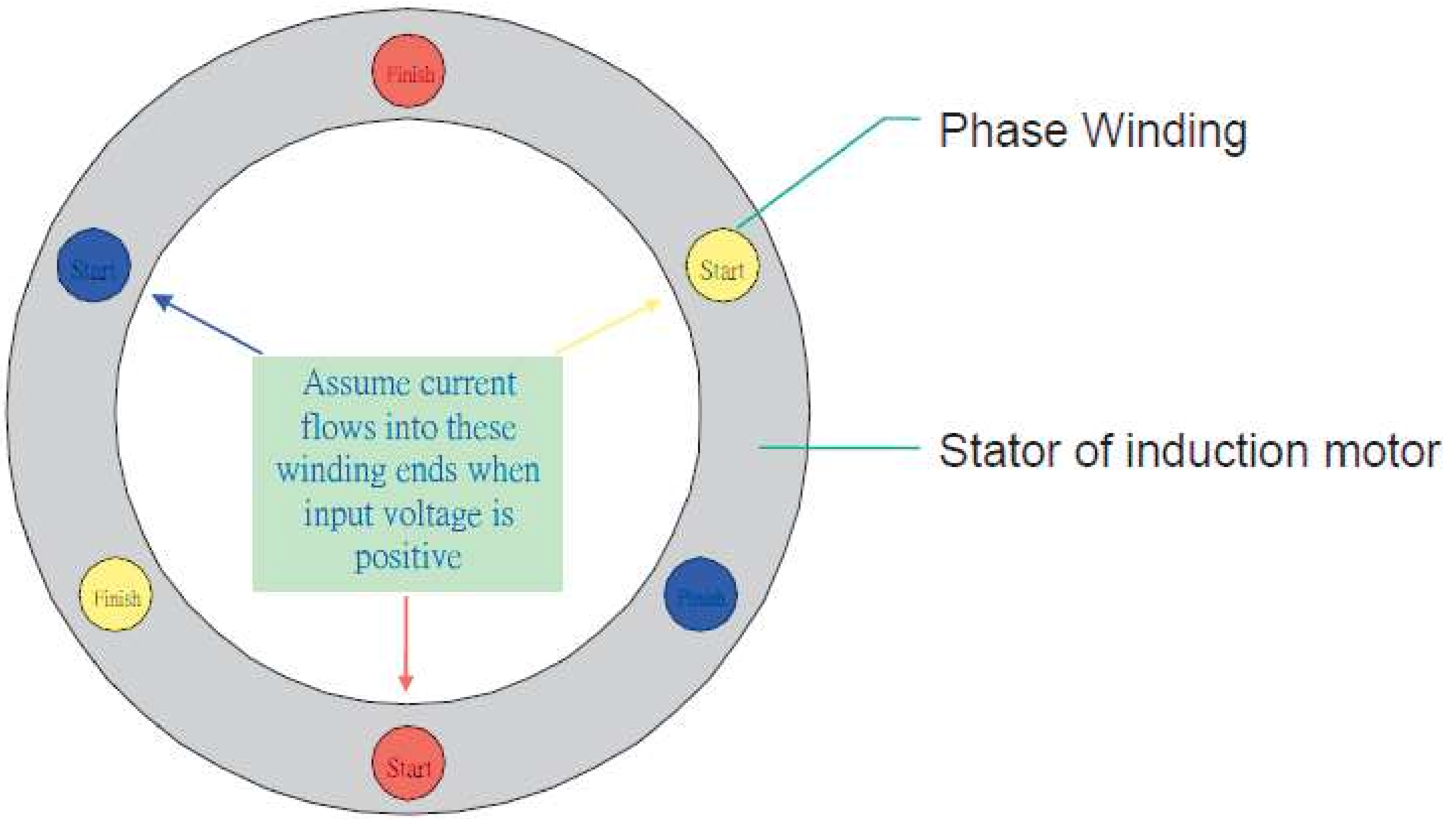
Instantaneous Values of 3-Ø Voltages

		3 Phase Voltage (Volts)		
Time	**angle**	Red Phase	Yellow phase	Blue Phase
0	0	0	-86.6	86.6
1	30	50	-100	50
2	60	86.6	-86.6	0
3	90	100	-50	-50
4	120	86.6	0	-86.6
5	150	50	50	-100
6	180	0	86.6	-86.6
7	210	-50	100	-50
8	240	-86.6	86.6	0
9	270	-100	50	50
10	300	-86.6	0	86.6
11	330	-50	-50	100
12	360	0	-86.6	86.6

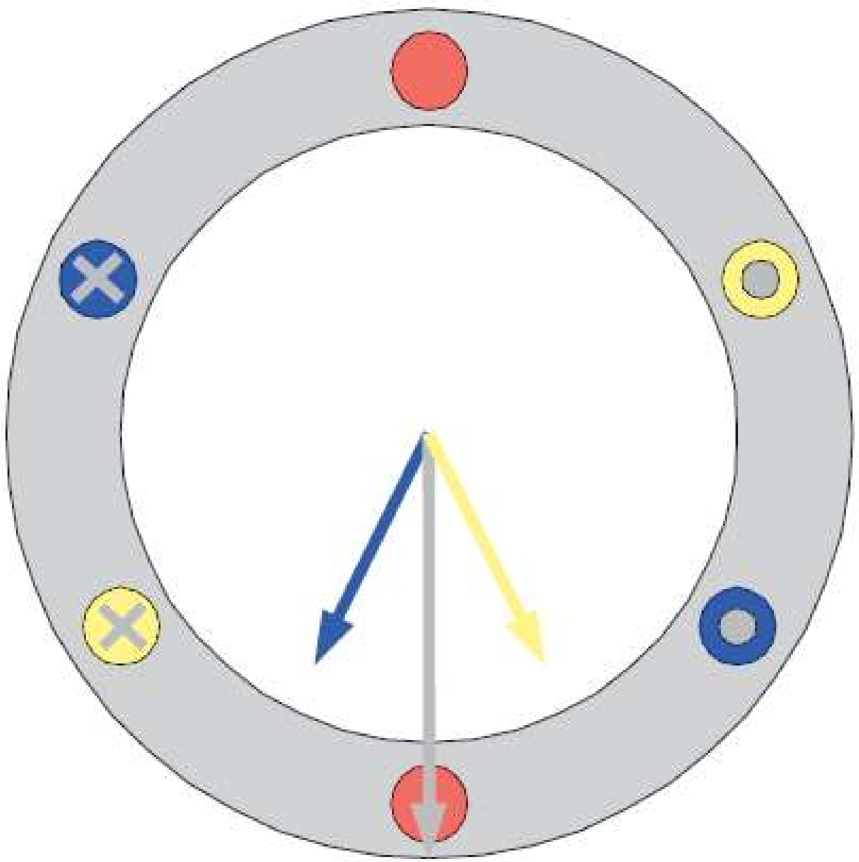
Instantaneous Values of 3-Ø Voltages

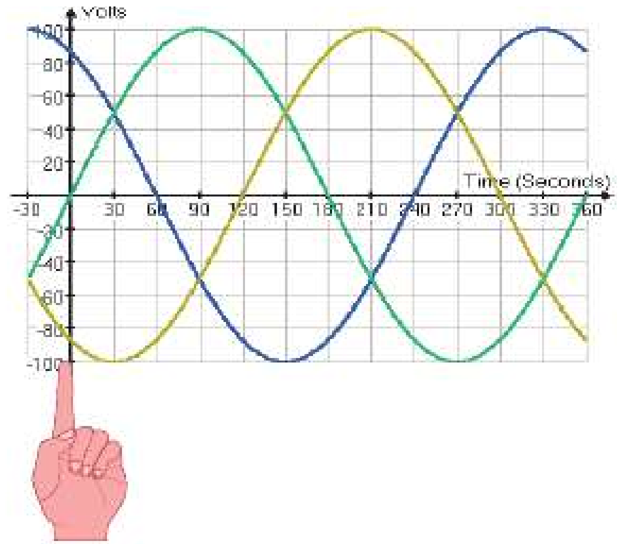


Magnetic Field produced by three phase currents when 3 phase voltage is applied to the stator of a 2-pole induction motor



Magnetic Field produced in a 2-pole induction motor





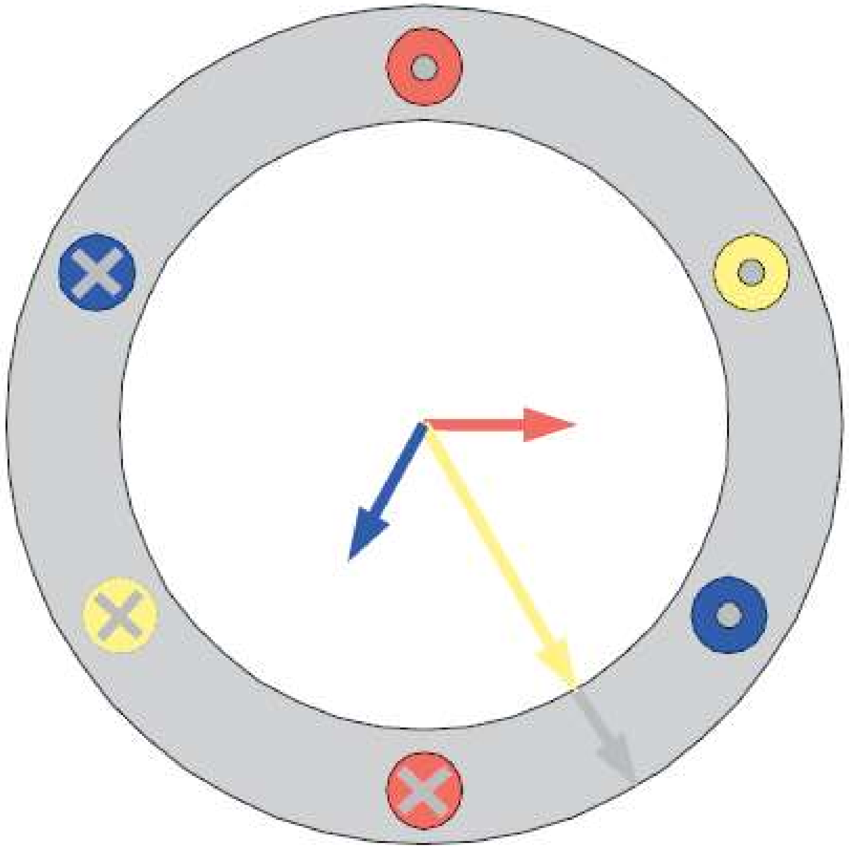
Time : t = 0

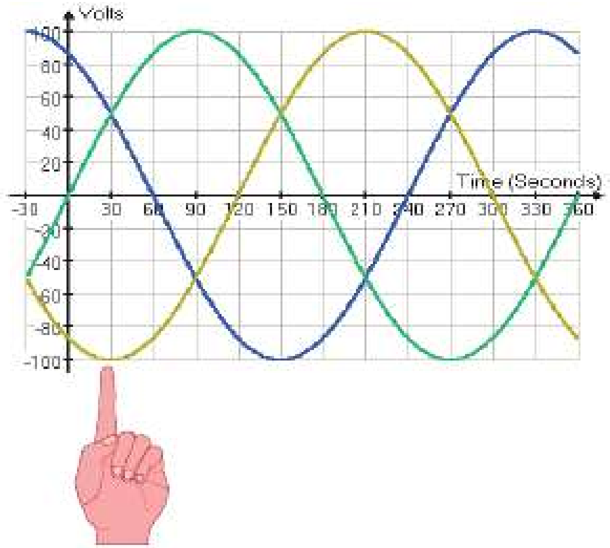
Red phase = 0 V

Yellow Phase = -86.6 V

Blue Phase = +86.6 V

Magnetic Field produced in a 2-pole induction motor





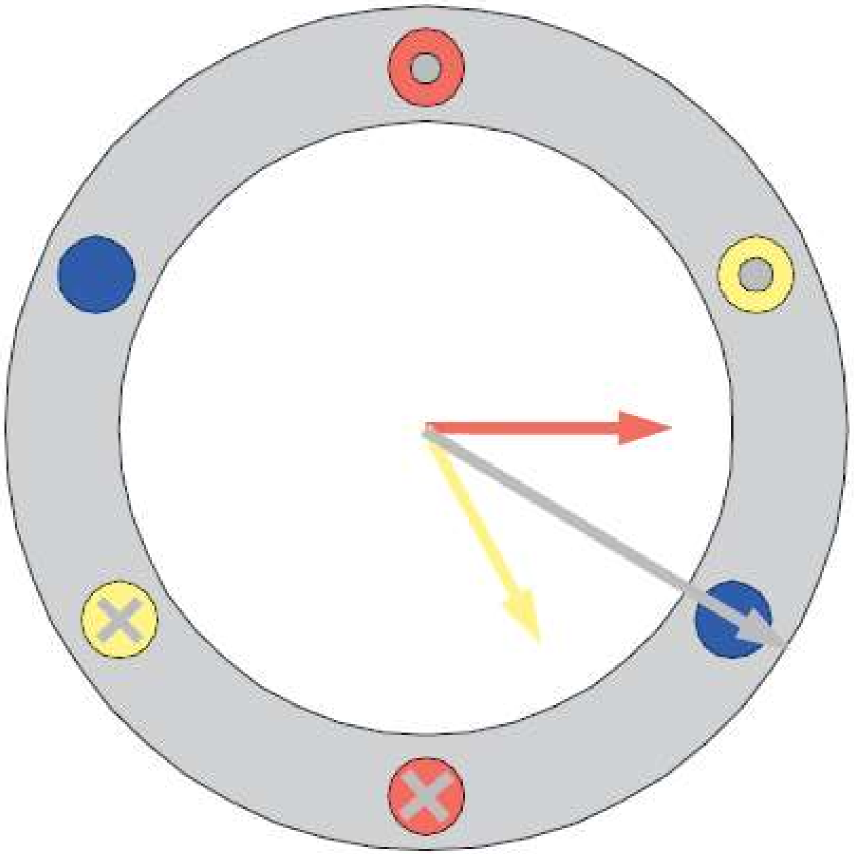
Time : t = 30 Sec

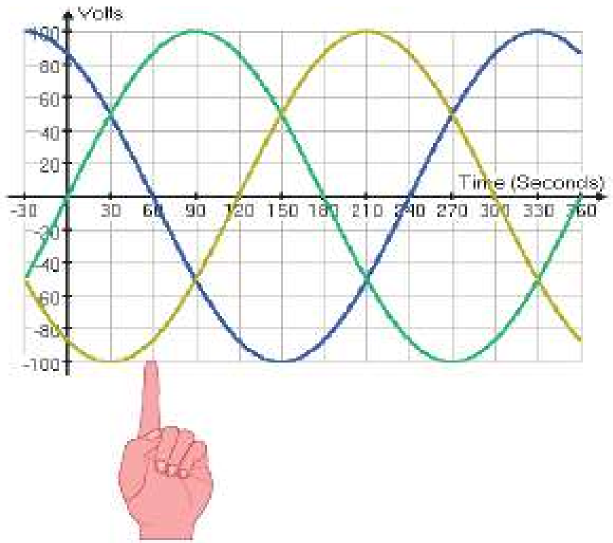
Red phase = 50 V

Yellow Phase = - 100 V

Blue Phase = + 50 V

Magnetic Field produced in a 2-pole induction motor

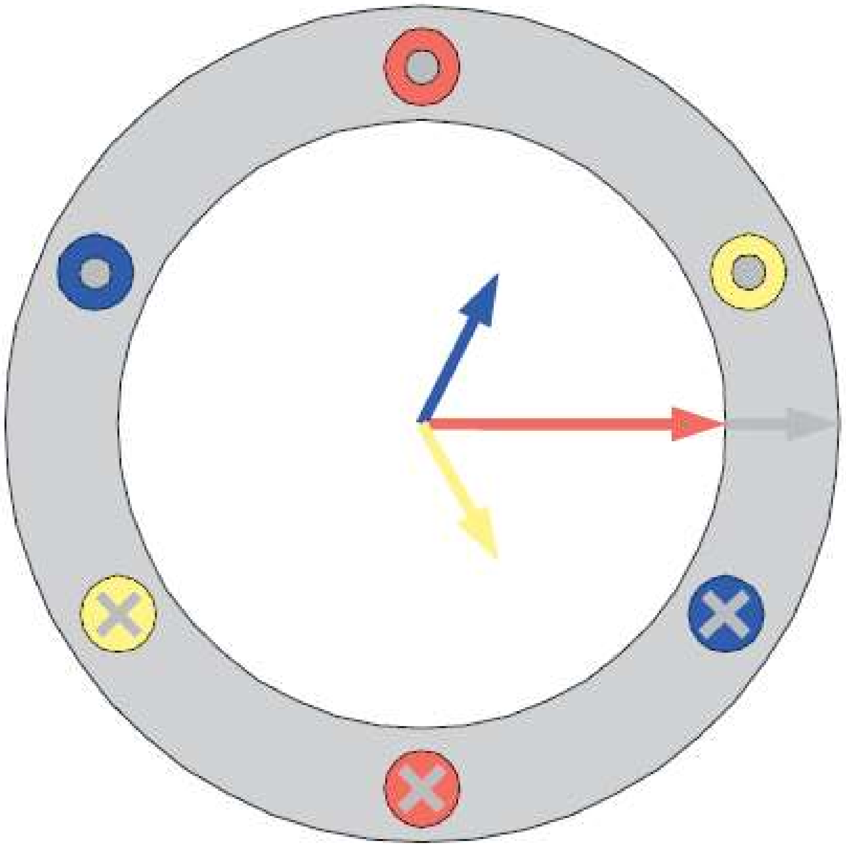


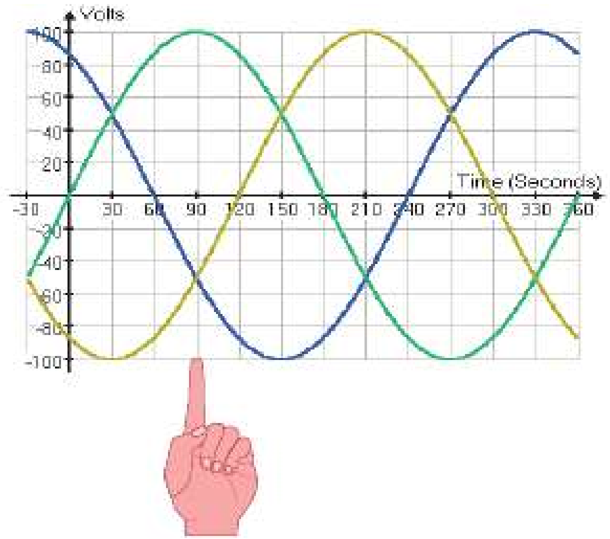


Time : t = 60 sec

Red phase = +86.6 V
Yellow Phase = -86.6 V
Blue Phase = 0 V

Magnetic Field produced in a 2-pole induction motor

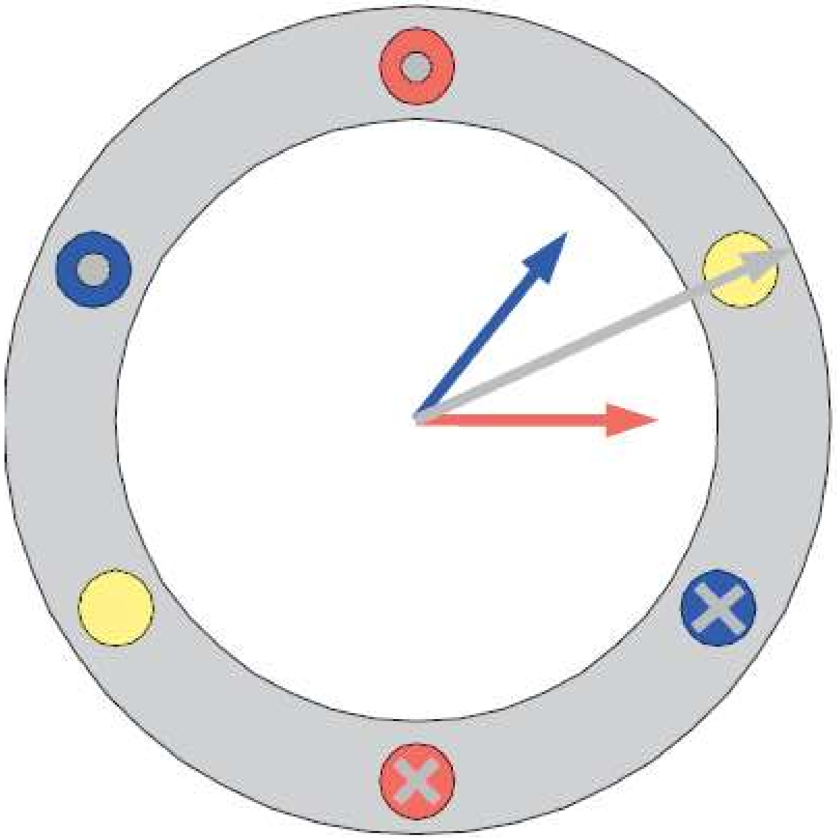


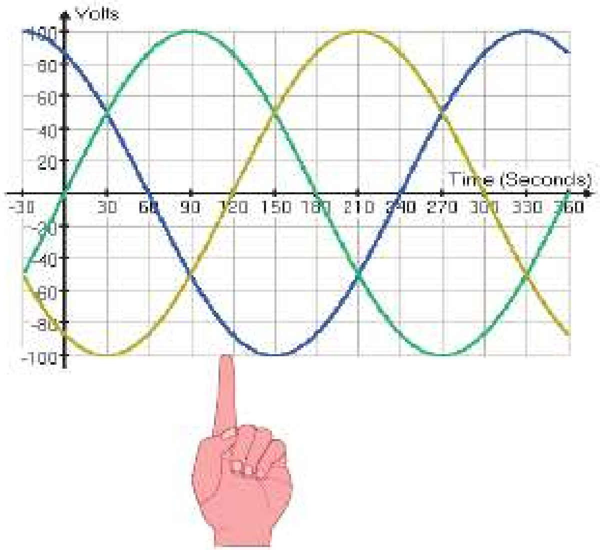


Time : t = 90 sec

Red phase = +100 V
Yellow Phase = - 50 V
Blue Phase = - 50 V

Magnetic Field produced in a 2-pole induction motor





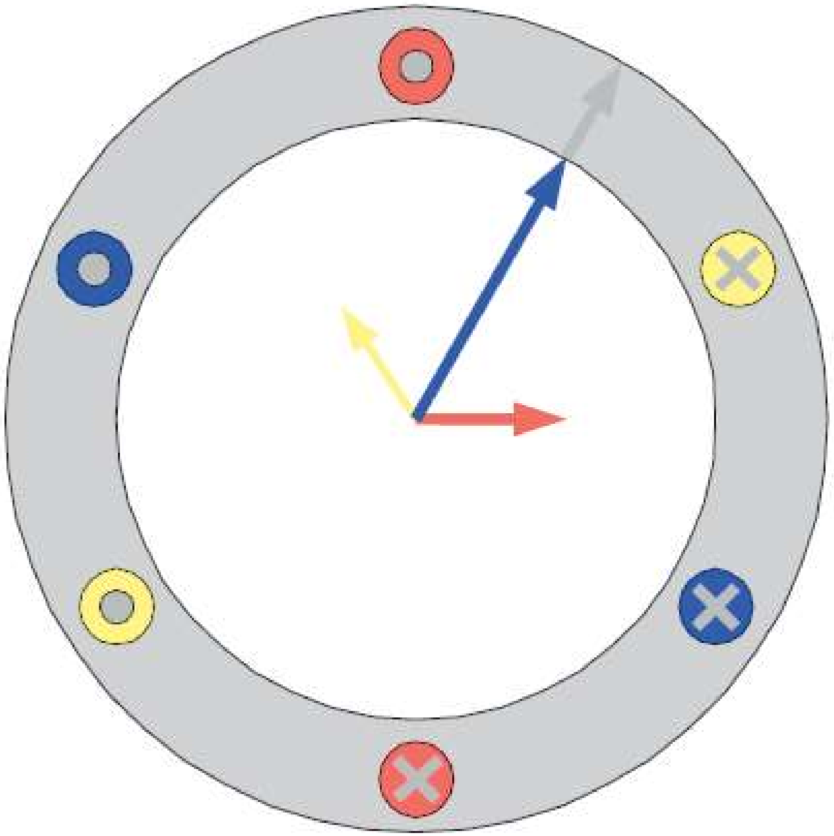
Time : t = 120 sec

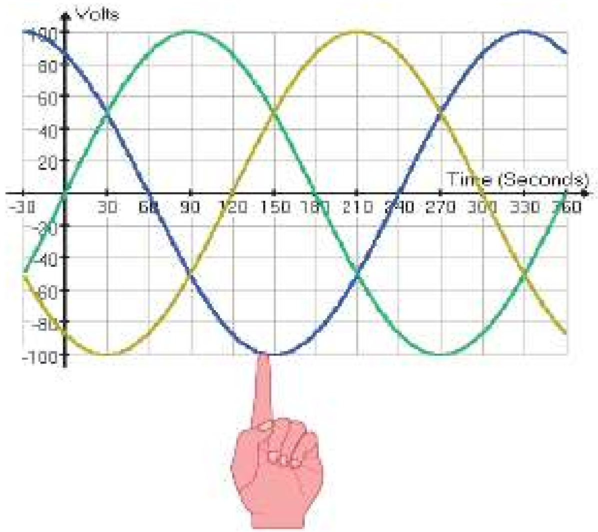
Red phase = +86.6 V

Yellow Phase = 0 V

Blue Phase = -86.6 V

Magnetic Field produced in a 2-pole induction motor

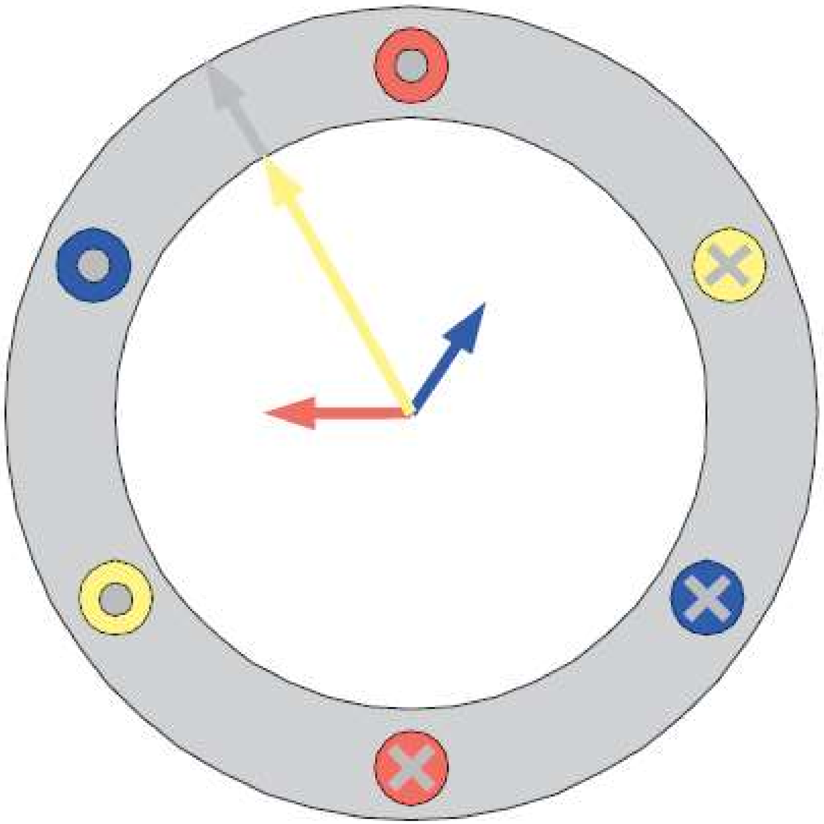


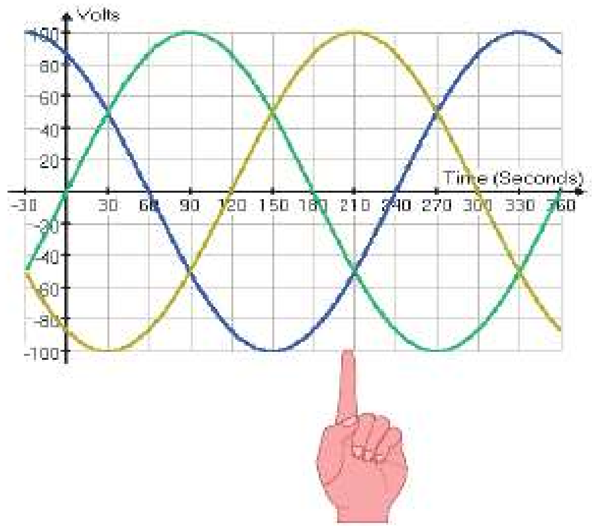


Time : t = 150 sec

Red phase = +50 V
Yellow Phase = +50 V
Blue Phase = -100 V

Magnetic Field produced in a 2-pole induction motor

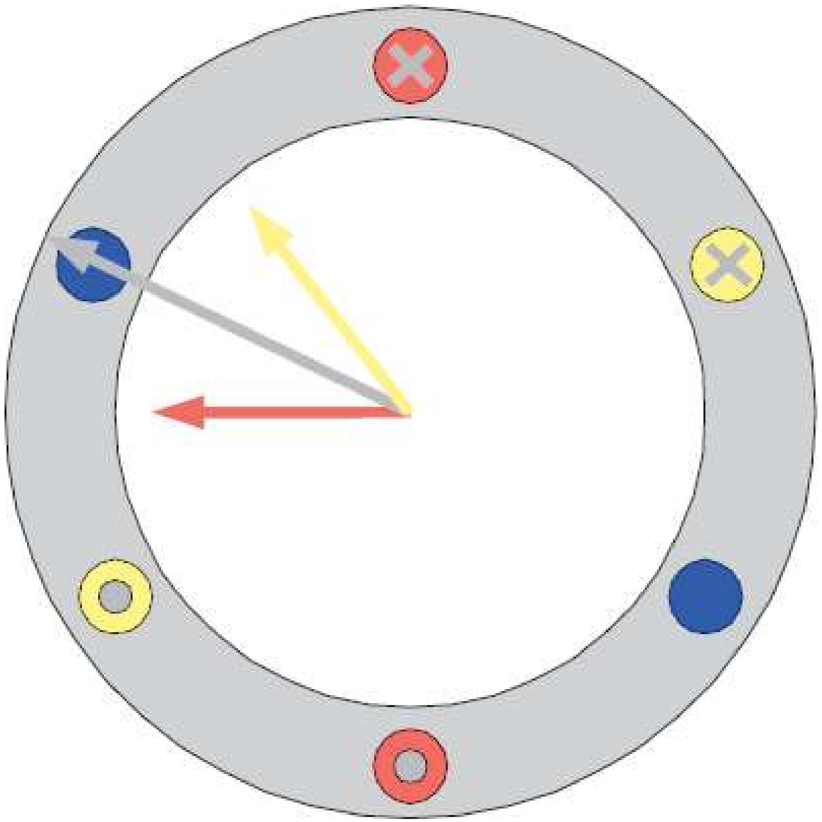


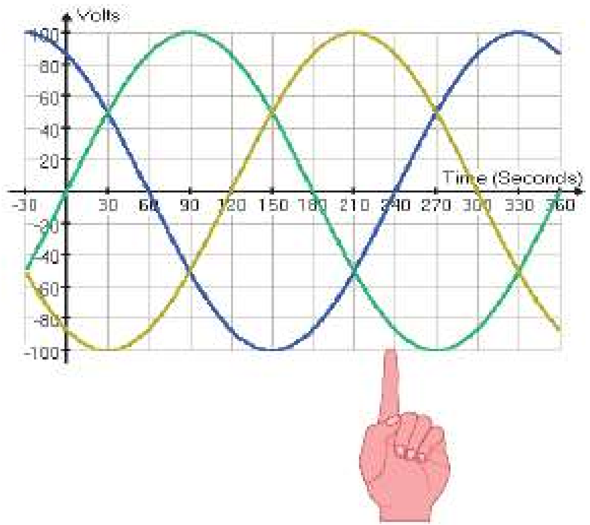


Time : t = 210 sec

Red phase = -50 V
Yellow Phase = +100 V
Blue Phase = -50 V

Magnetic Field produced in a 2-pole induction motor





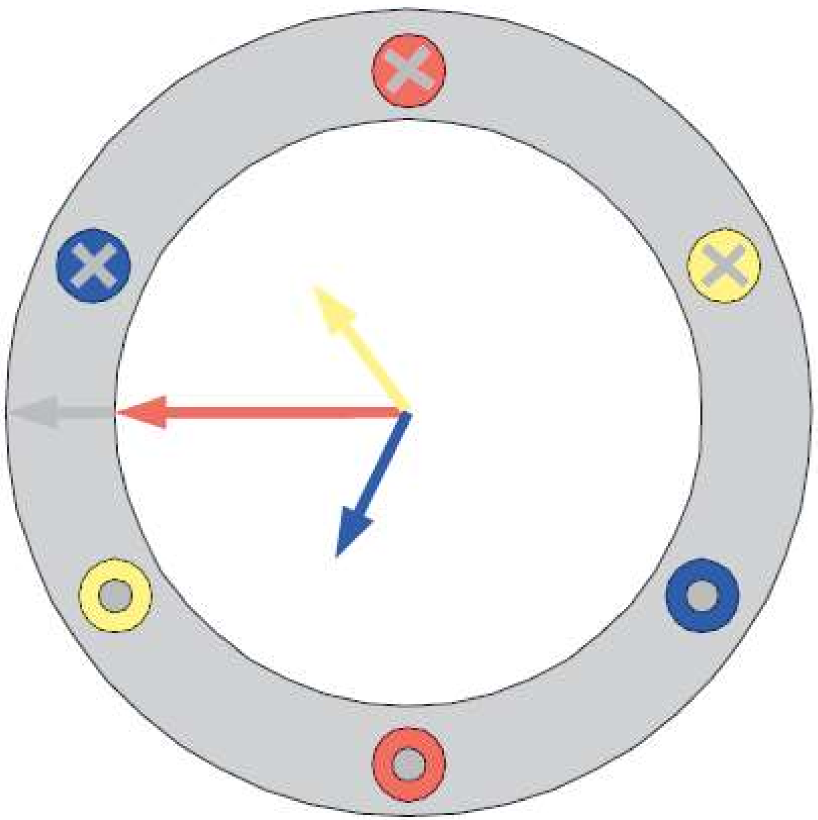
Time : t = 240 sec

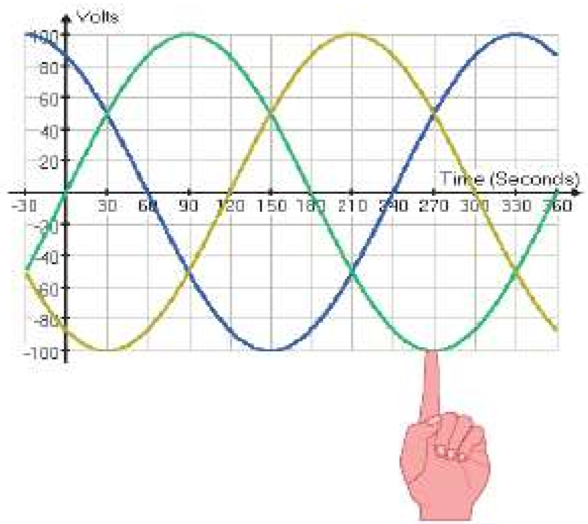
Red phase = -86.6 V

Yellow Phase = +86.6 V

Blue Phase = 0 V

Magnetic Field produced in a 2-pole induction motor

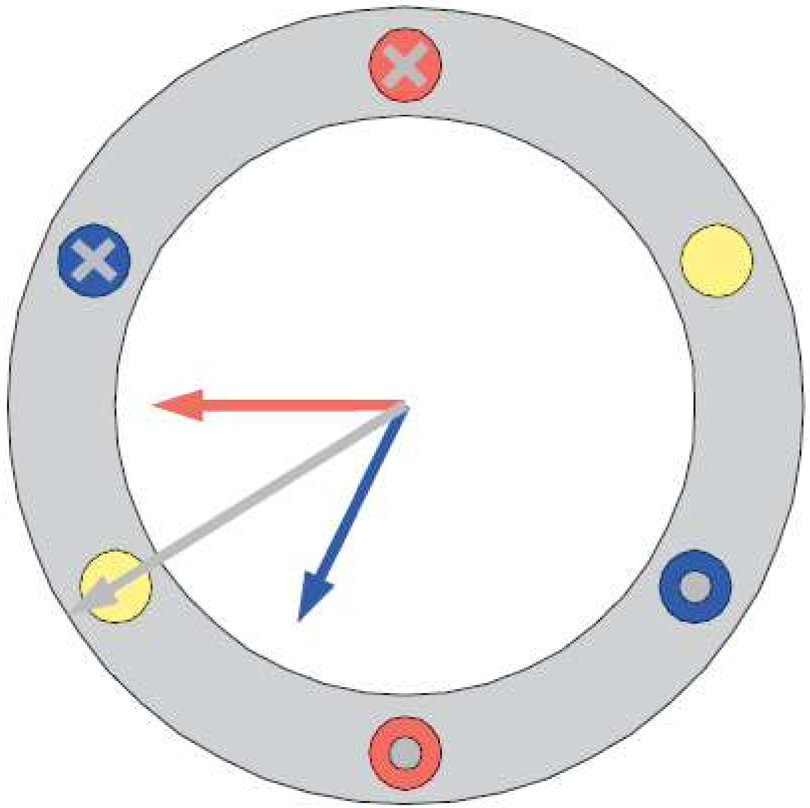


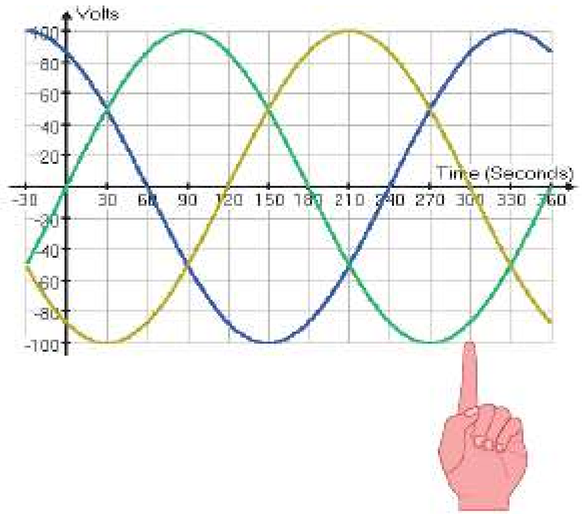


Time : t = 270 sec

Red phase = -100 V
Yellow Phase = +50 V
Blue Phase = +50 V

Magnetic Field produced in a 2-pole induction motor

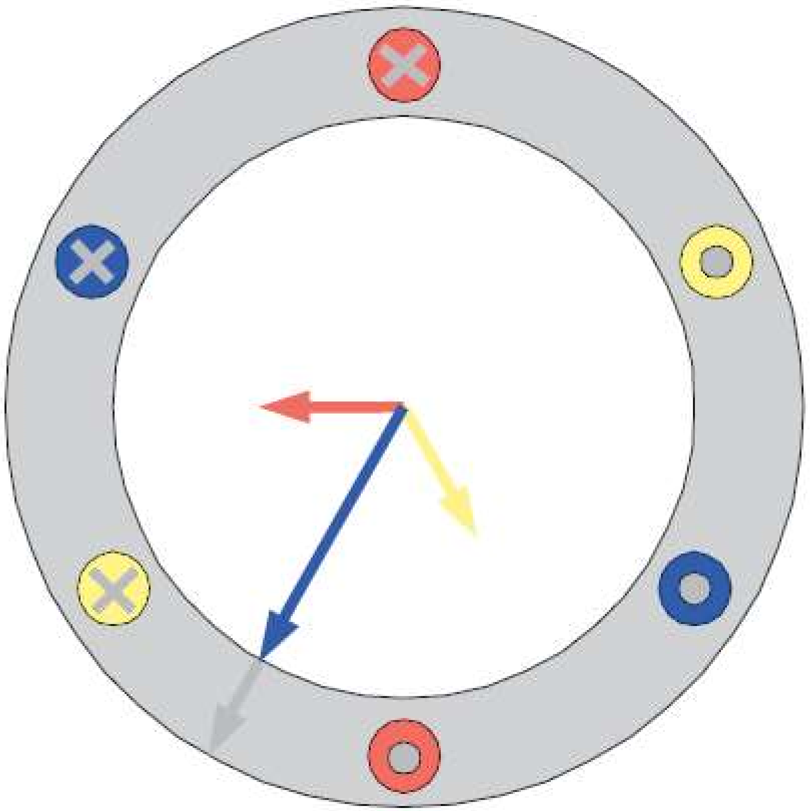


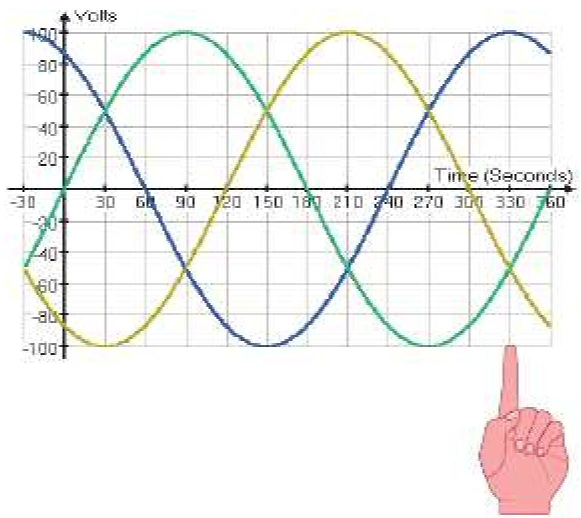


Time : t = 300 sec

Red phase = -86.6 V
Yellow Phase = 0 V
Blue Phase = +86.6 V

Magnetic Field produced in a 2-pole induction motor

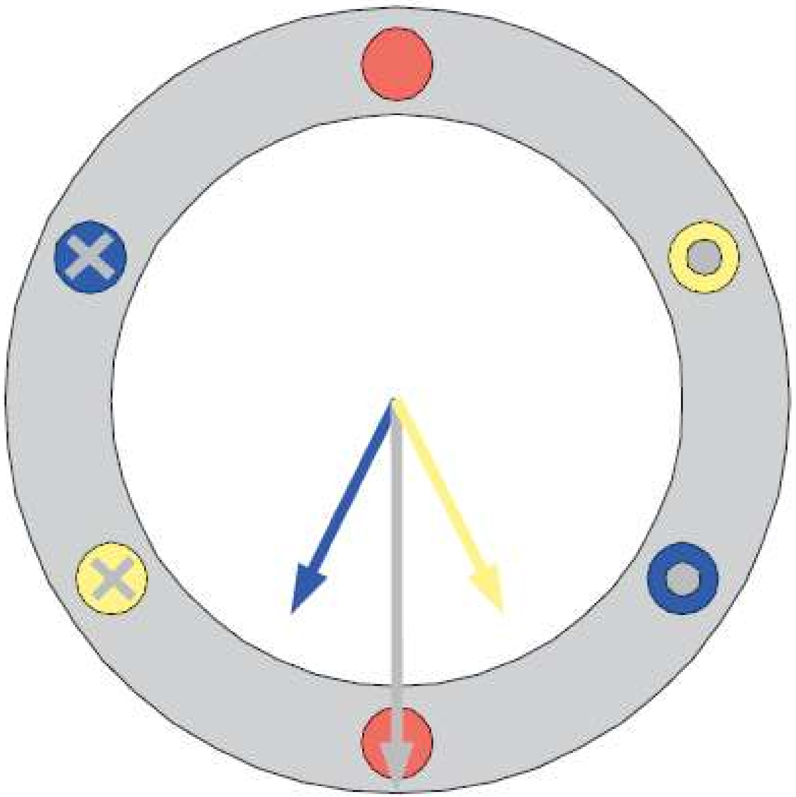


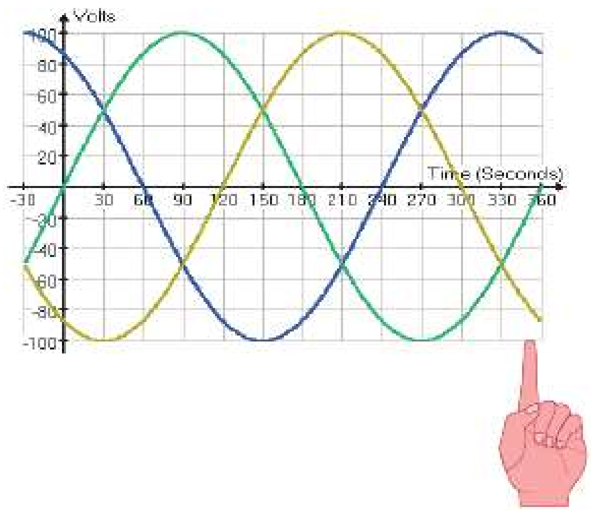


Time : t = 330 sec

Red phase = -50 V
Yellow Phase = -50 V
Blue Phase = +100 V

Magnetic Field produced in a 2-pole induction motor





Time : t = 360 sec

Red phase = 0 V
Yellow Phase = -86.6 V
Blue Phase = +86.6 V

SPEED of Rotating Field

Synchronous Speed $[N_S(rpm) or\ n_s\ (rps)]$

- A complete sinusoidal cycle will cause the magnetic field produced to rotate a complete 360° in a two pole3-phase induction motor.

- Since there are 60 second sin one minute, the speed of the rotating field is equal to:

- **60 x frequency**

SPEED of Rotating Field

A basic **2-pole** induction motor:

- has a set of three winding groups installed in the stator (**Red** start & finish, **Yellow** start & finish and **Blue** start & finish).

$$\frac{f}{p}(rps)\ OR\ \frac{60f}{p}(rpm)$$

- f = supply frequency and **p** = No. of pole-pairs

SPEED of Rotating Field

- For an induction motor with **4 poles**, there are two sets of three winding groups installed in the stator, as a result, the magnetic field only rotates 180° for every complete cycle of the sinusoidal waveform.

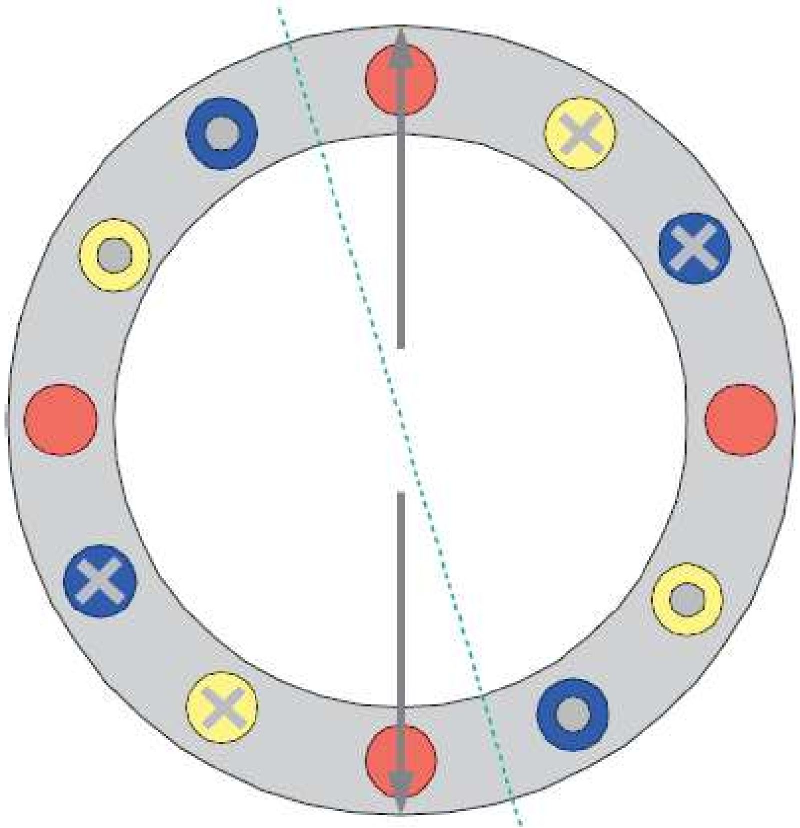
SPEED of Rotating Field

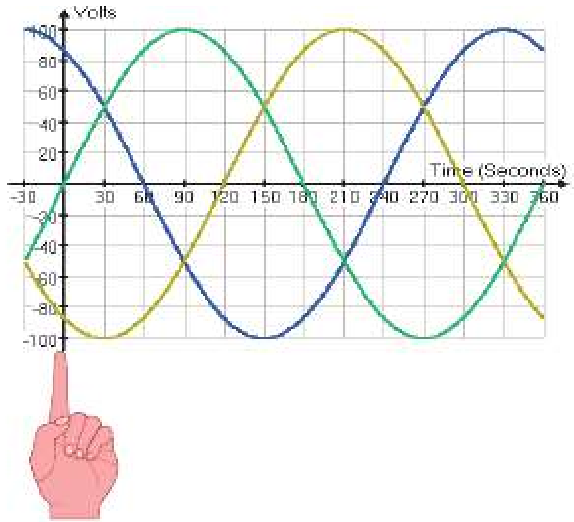
- Therefore, for an induction motor with $\boldsymbol{p}$ pole-pairs, the speed of the rotating field is given by:

$$\frac{f}{p}(rps)\ OR\ \frac{60f}{p}(rpm)$$

- $\boldsymbol{f}$ = supply frequency and **p** = No. of pole-pairs

Magnetic Field produced in a 4-pole induction motor

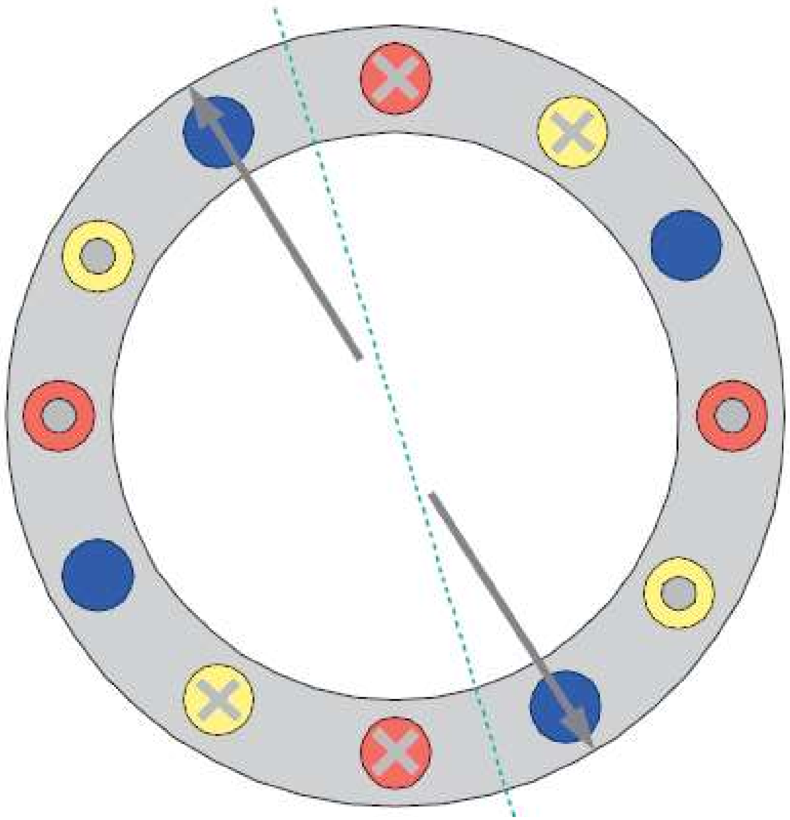


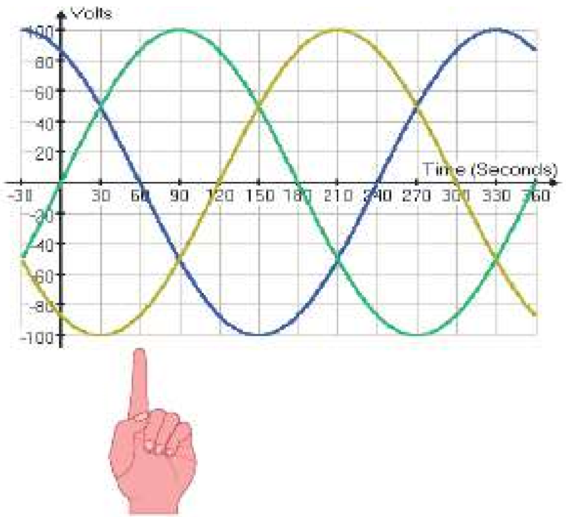


Time : t = 0

Red phase = 0 V
Yellow Phase = –86.6 V
Blue Phase = +86.6 V

Magnetic Field produced in a 4-pole induction motor

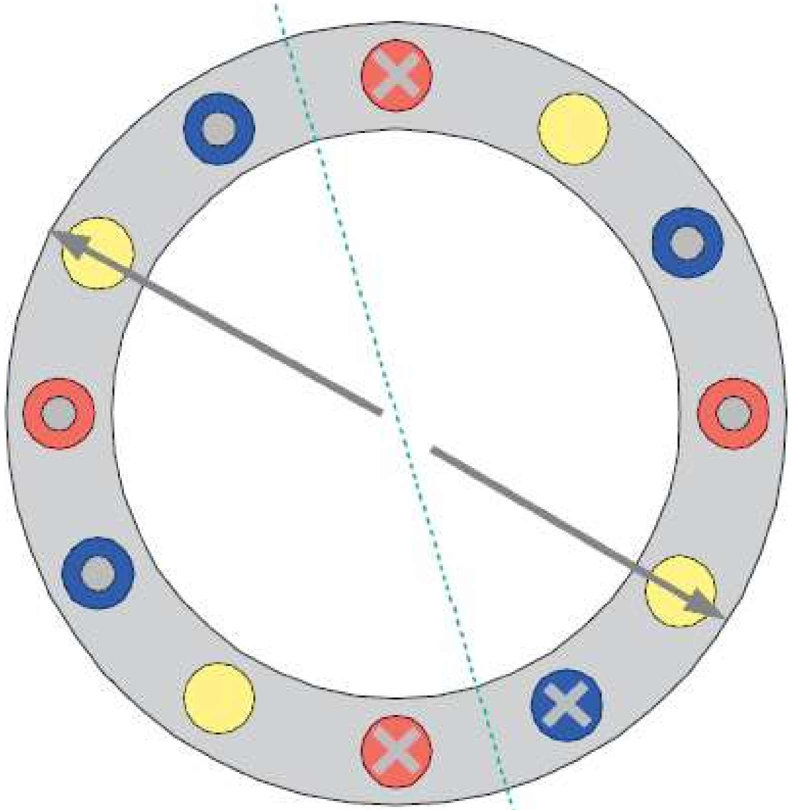


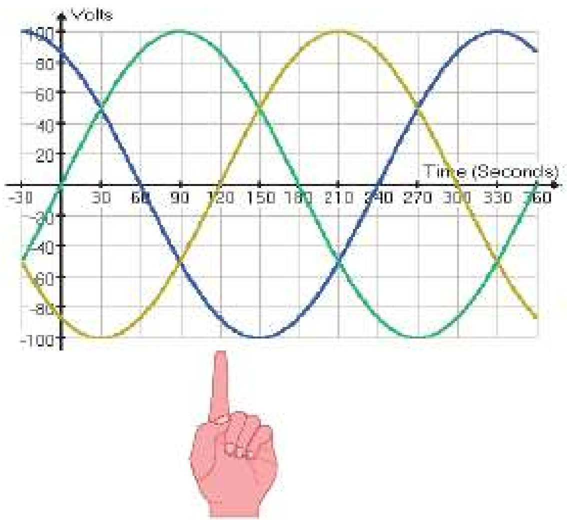


Time : t = 60

Red phase = +86.6 V
Yellow Phase = –86.6 V
Blue Phase = 0 V

Magnetic Field produced in a 4-pole induction motor

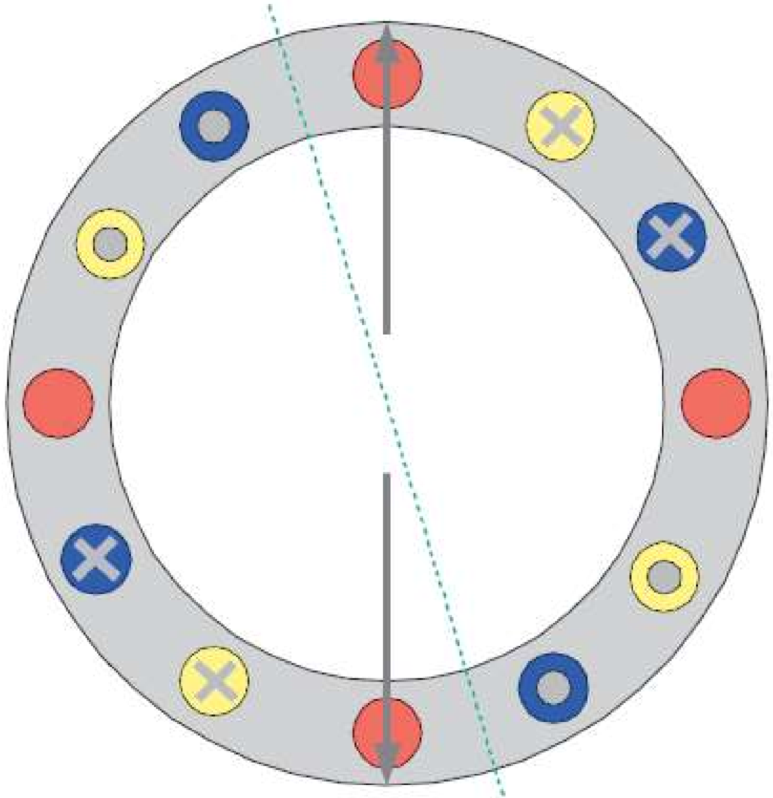


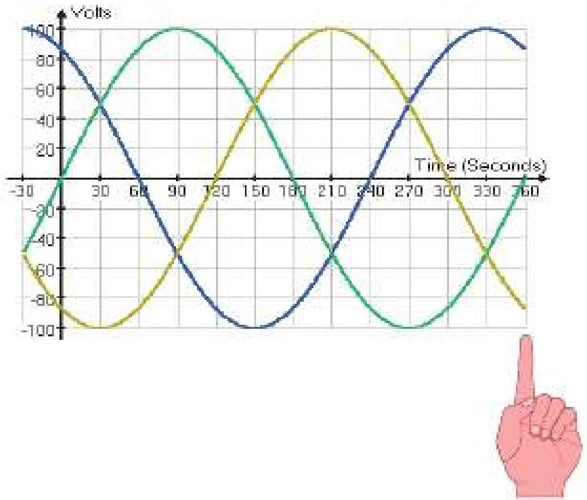


Time : t = 120

Red phase = +86.6 V
Yellow Phase = 0 V
Blue Phase = –86.6 V

Magnetic Field produced in a 4-pole induction motor

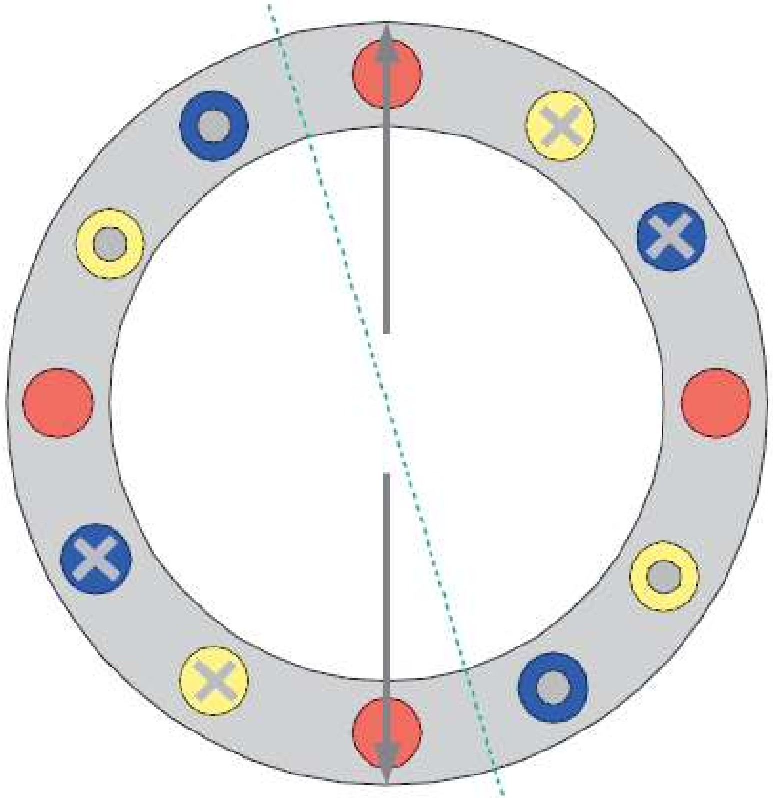


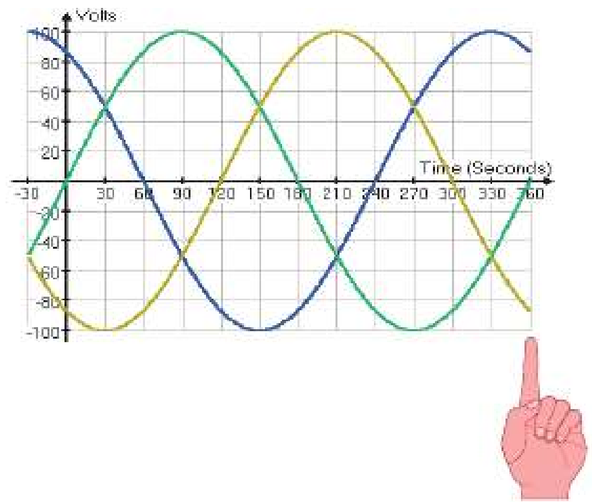


Time : t = 360

Red phase = 0 V
Yellow Phase = –86.6
Blue Phase = +86.6 V

TORQUE produced in 3-□induction motor





Time : t = 360

Red phase = 0 V
Yellow Phase = –86.6
Blue Phase = +86.6 V

TORQUE produced in 3 – Ø induction motor

- A ***rotating magnetic field*** is produced when a three phase voltage is fed to the stator of a three phase induction motor

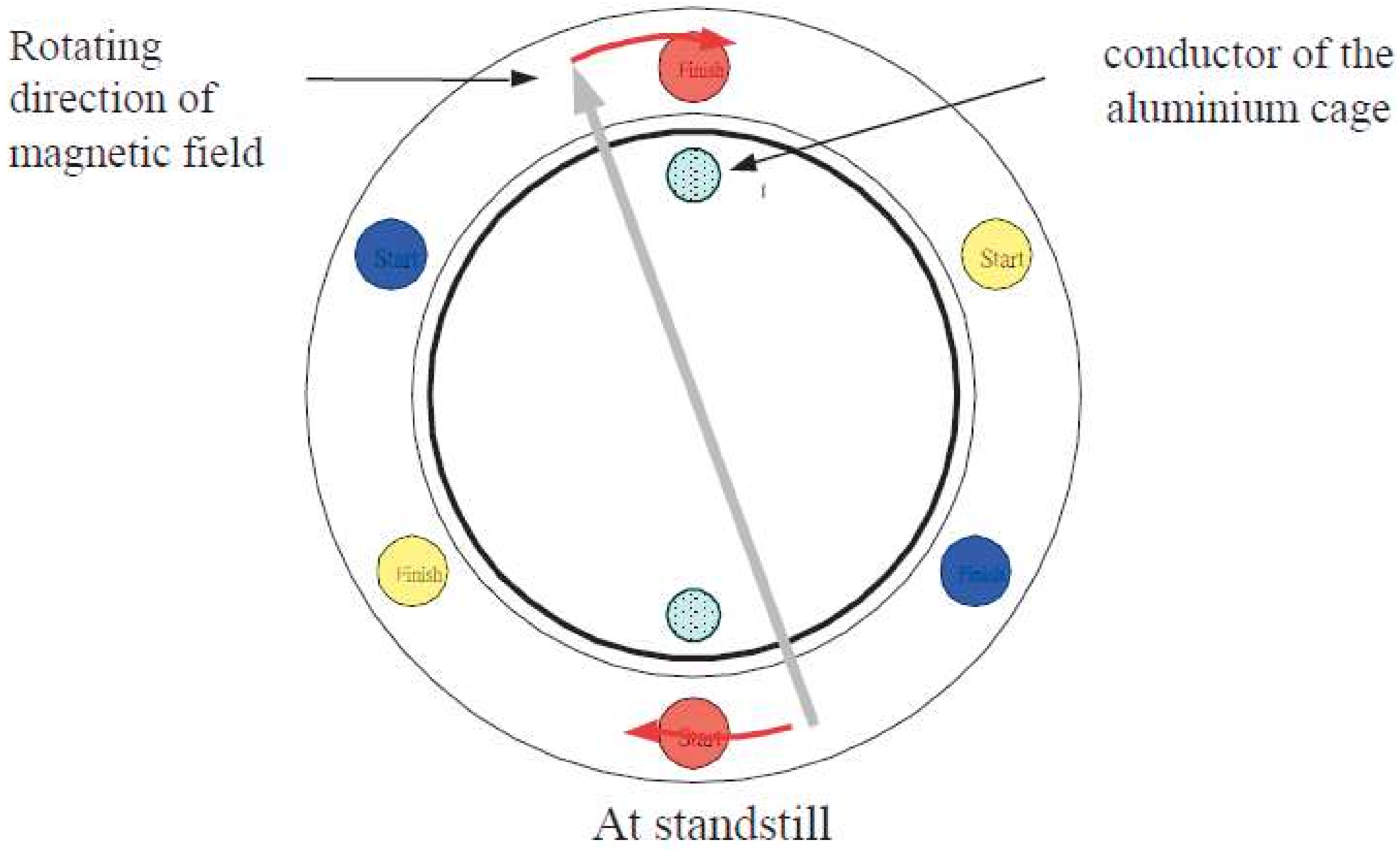
- This rotating field will traverse the a luminium conductors of the squirrel cage rotor

TORQUE produced in 3 – ø induction motor

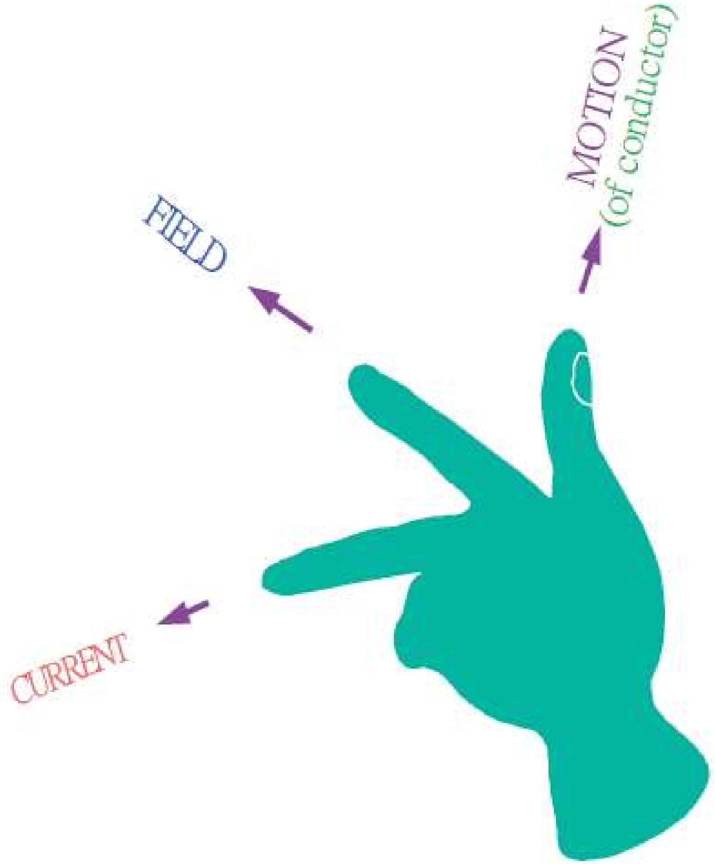
- According to ***Fleming's Right hand rule*** for generator, emf is induced in the a luminium bars of the squirrel cage

- According to ***Fleming's Left hand rule*** for motor, a torque is produced which will drive ***the rotor rotating in the same direction as the magnetic field***

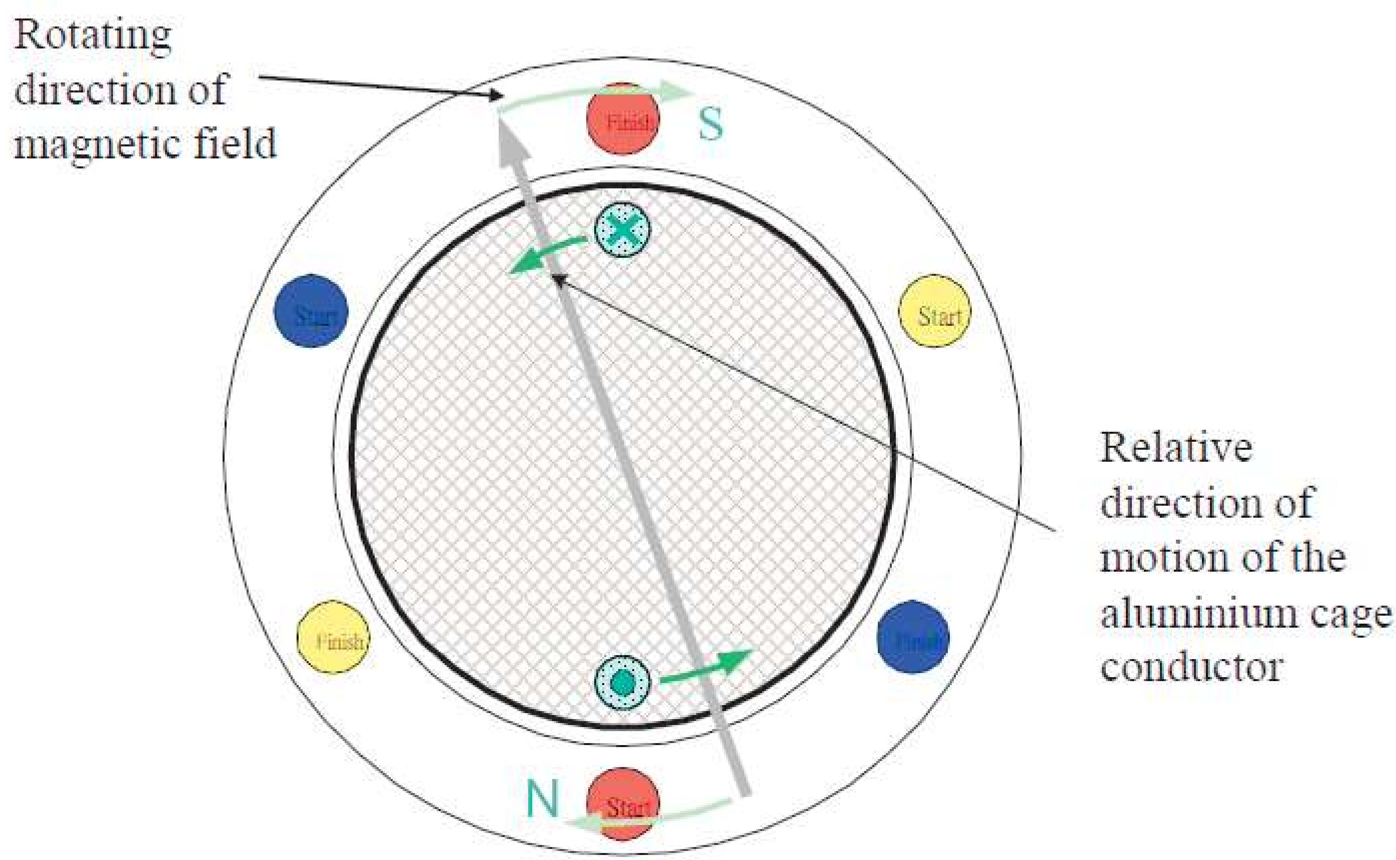
Rotor Conductor "cutting" by the Rotating Magnetic Field



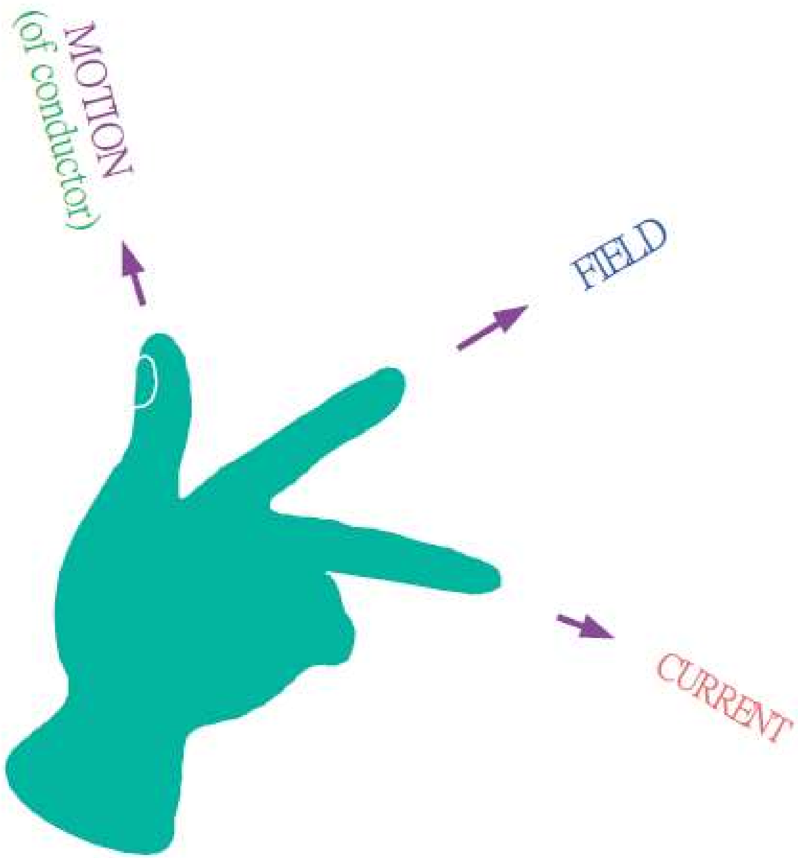
Fleming’s Right Hand Rule (Gen)



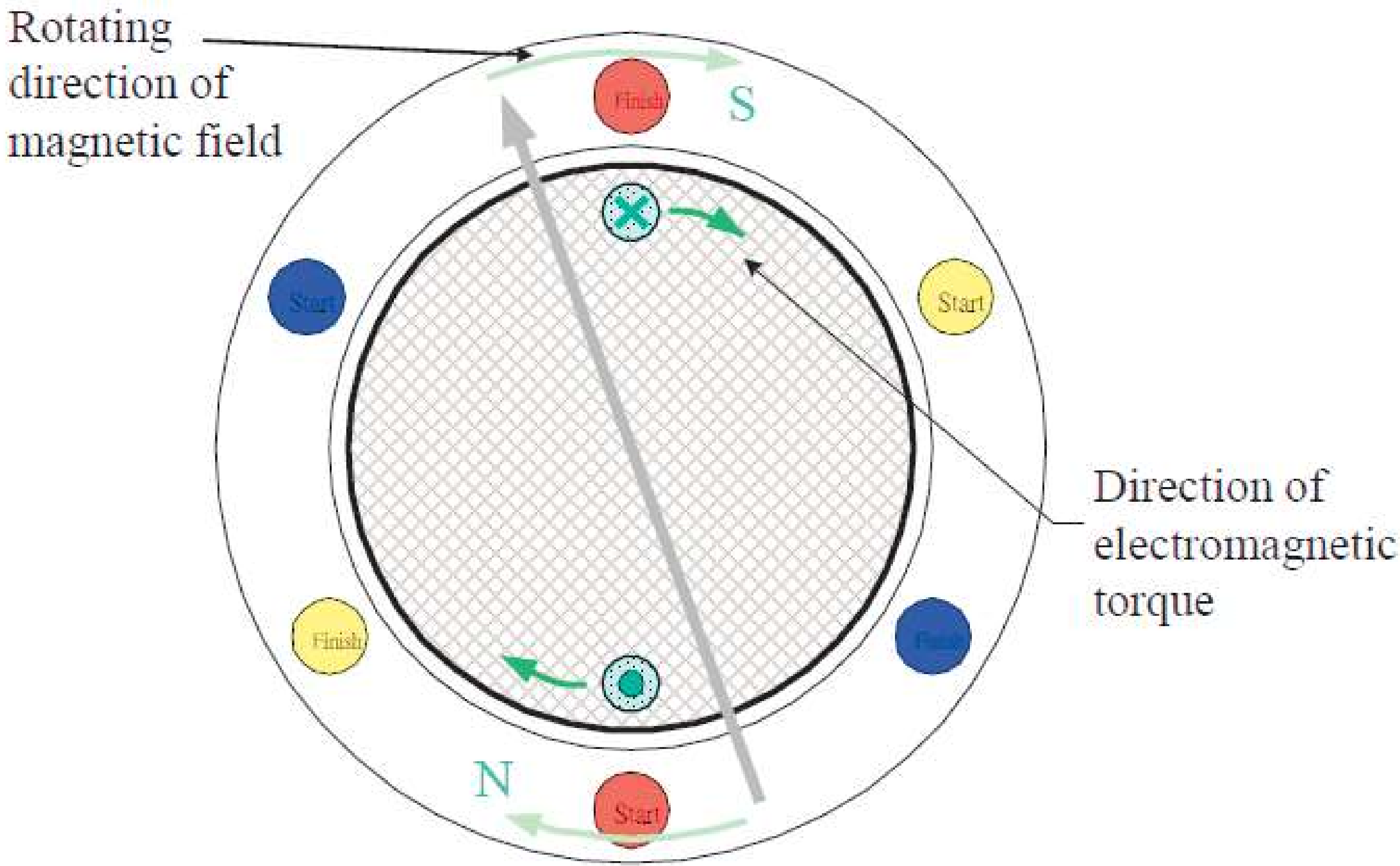
The Induced Current Direction



Fleming's Left Hand Rule (Motor)



The Rotor Torque Direction



CHAPTER D2

AC Electric Machines

Induction Machine

Induction Machine

1. Definition of Slip
2. Single phase equivalent circuit
3. Power flow diagram
4. Torque equation-
5. Slip at maximum torque
6. Effect of external rotor resistance
7. Starting Methods & Speed Control

Definition of Slip

Slip (滑率)

- The magnetic field of an induction motor rotates at a ***synchronous speed (Ns)*** which is equal to $\frac{60f}{p}$

- This magnetic field will induce current in the rotor circuit, causing the **rotor to run in the same direction as the field**

Slip (滑率)

- However, the ***speed of the rotor (Nr)*** is always slower than the speed of the field. Since **if the speed of the rotor is equal to that of the field there will be no induced e.m.f. and there will be no driving torque to keep the rotor running**

- Slip (**s**) is defined as $\frac{Ns-Nr}{Ns}$

Example of Slip Calculation

Calculate the slip of an 8-pole, 3-phase induction motor running at 720 rpm. The frequency of the three phase supply is 50 Hz.

$$\text{Now Synchronous speed } N_s = \frac{60 \times \text{frequency}}{\text{pole} - \text{pairs}}$$

$$= \frac{60 \times 50}{4} = 750 \ \textbf{rpm}$$

$$\text{Rotor speed } N_r = 720 \text{ rpm}$$

$$\text{Therefore Slip } s = \frac{N_s - N_r}{N_s}$$

$$= \frac{750 - 720}{750} = \frac{30}{750} = 0.04$$

Slip Equation Revisit

$$s = \frac{N_s - N_r}{N_s}$$

$$sN_s = N_s - N_r$$

Slip Speed
(Speed of the rotating magnetic field cutting across the rotor conductors)

sf frequency

Synchronous Speed
(Speed of the rotating magnetic field)

Rotor Speed
(Speed of the rotor)

3-Ø Induction Motor

1. Rotor Circuit Impedance
2. Equivalent Circuit

Induced Rotor Current Frequency

- E.m.f. and current are induced in the rotor circuit when the rotor conductor is cut by the rotating magnetic field at a rate which is equal to the **difference** in speed of the magnetic field and the rotor

Induced Rotor Current Frequency

- When the rotor is at standstill**(s=1)** or **Nr=0**, we can treat the induction motor as a 3-phase transformer, the frequency of the induced e.m.f.= supply frequency f

Induced Rotor Current Frequency

When the slip of the motor is '**s**', the rotor is running at a speed **Nr = (1 – s)Ns**, e.m.f. is induced in the rotor conductor at a rate which is equal to the difference between the rotating field and the rotor speed

This rate is equal to Ns – Nr

$$= Ns - (1 - s)Ns$$

$$= sNs$$

$$= \boxed{\frac{60 \times sf}{p} \quad \text{(rpm)}}$$

- In other words, the frequency of the induced e.m.f. in the rotor circuit is equal to ***sf*** frequency (***slip frequency***)

Rotor Circuit Impedance

- The rotor circuit consists of conductor resistance and reactance.

- The resistance of the rotor circuit is independent upon the frequency of the rotor current, it always has a value equal to R_2 (the suffix 2 represent rotor)

Rotor Circuit Impedance

The reactance (**X2**) of the rotor circuit, however depends on the frequency of the rotor induced current:

- When the rotor is at stationary, the rotor current is at supply frequency, the rotor reactance is equal to: $X_2 = 2\pi f L_2$

Rotor Circuit Impedance

- When the rotor is running at slip $\boldsymbol{s}$, the frequency of the rotor current is equal to $\boldsymbol{sf}$ (slip frequency), the rotor reactance is equal to:

$$\boldsymbol{sX_2 = 2\pi s f L_2}$$

Rotor Induced Emf

When the rotor is at stationary:

- The e.m.f. induced in the rotor circuit has a value which is equal to $\boldsymbol{E_2 = 4.44 f \emptyset N_2}$ where N_2 is the effective number of turns of the rotor circuit

Rotor Induced Emf

When the rotor is running at slip ‘s’ :

- The e.m.f. induced in the rotor circuit has a value which is equal to $\boldsymbol{sE_2 = 4.44sf\emptyset N_2}$

- Since a 3-phase induction motor is a balanced load, we can simply use 1-phase transformer circuit to represent the 3-phase induction motor

Summary of Rotor Parameters at Standstill and Running

Parameter	Symbol at stator side	Rotor parameter at standstill, S=1	Rotor parameter at slip S
Frequency of current (Hz)	f_1	$f_2=f_1$	$f_r=Sf_2$
Speed of rotation (rpm)	Synchronous speed of rotating magnetic field $= N_s=60f_1/p$	$N_r = 0$	$N_r=N_s(1-S)$
Reactance (ohm)	X_1	$X_2=2\pi f_1 L_2$	$X_r=sX_2$
Induced emf (V)	$E_1=4.44N_1f_1\psi$	$E_2=4.44N_2f_1\psi$	$E_r=SE_2$
Current (A)	I_1	$I_2=E_2/Z_2$	$I_r=E_r/Z_r$

Example 1

A 3-phase 460V, 100 hp, 60 Hz, 4-pole induction machine delivers rated output power at a slip of 0.05. Determine the

a) Synchronous speed and motor speed.
b) Speed of the rotating air gap field.
c) Frequency of the rotor circuit.

Example 1

d) Slip rpm.

e) Speed of the rotor field relative to the

   i. Rotor structure.

   ii. Stator structure.

   iii. Stator rotating field.

Example 1

(a) $n_S = \frac{60x60}{2} = 1800 \quad rpm$

$n = (1 - s)n_S = (1 - 0.05)1800 = 1710\, rpm$

(b) $1800\, rpm(same$ as synchronous speed)

(c) $f_2 = sf_1 = 0.05x60 = 3Hz$

(d) $slip - rpm = sn_s = 0.05x1900 = 90\, rpm$

(e) (i) $90\, rpm$

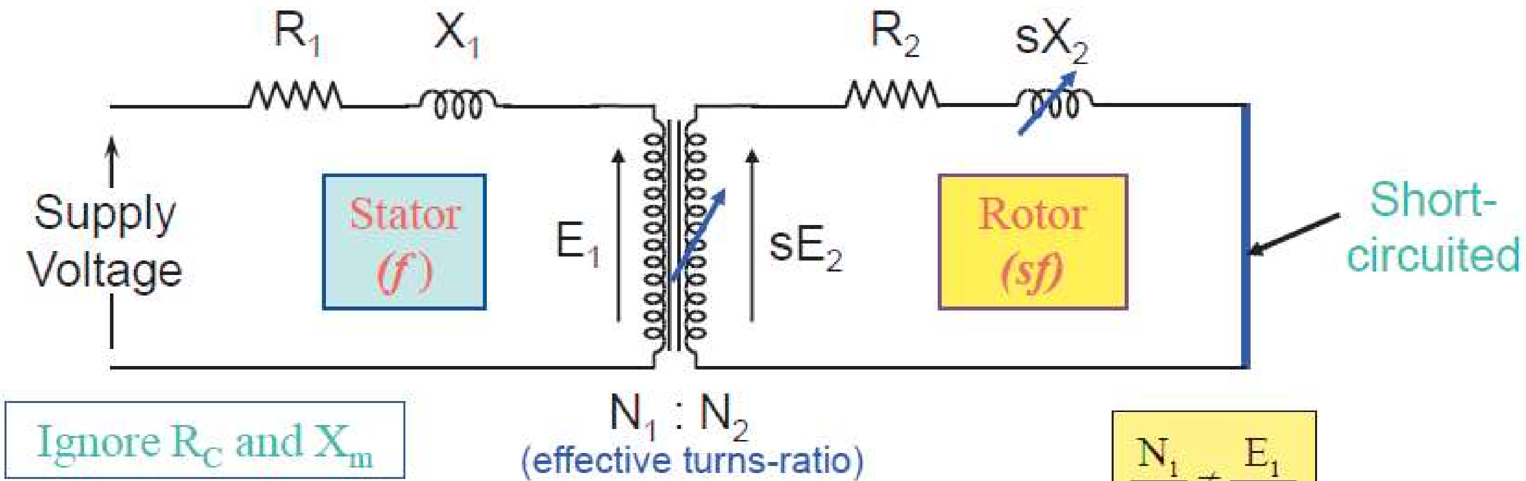
(ii) $1800\, rpm$

(iii) $0\, rpm$

3-Ø Induction Motor

Rotor Equivalent Circuit

Equivalent Circuit of 3-Ø Induction Motor
(only one phase is shown)



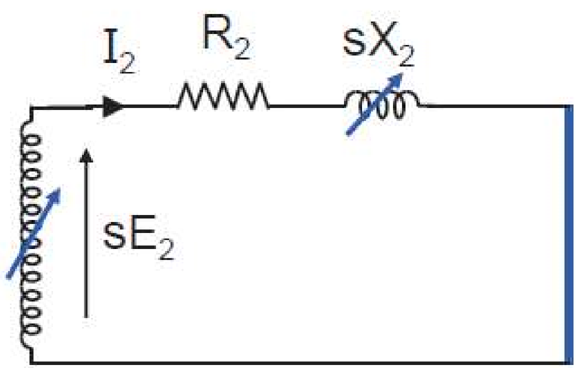
Ignore R_C and X_m

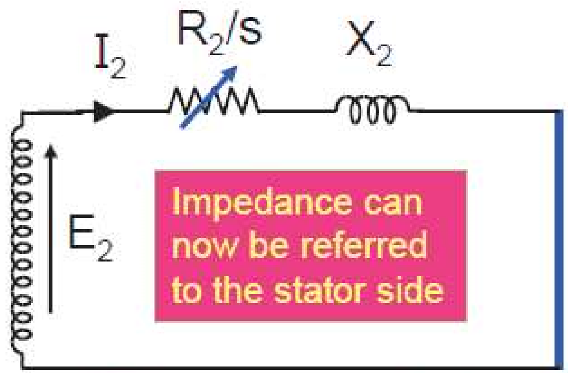
$$\frac{N_1}{N_2} \neq \frac{E_1}{sE_2}$$

R_1 = Stator winding resistance
R_2 = Rotor winding resistance
X_1 = Stator leakage reactance
X_2 = Rotor leakage reactance at standstill
E_1 = Stator induced emf
E_2 = Rotor induced emf at standstill

Hence, impedance cannot be referred to stator side as in transformer

Alternation of Rotor Circuit



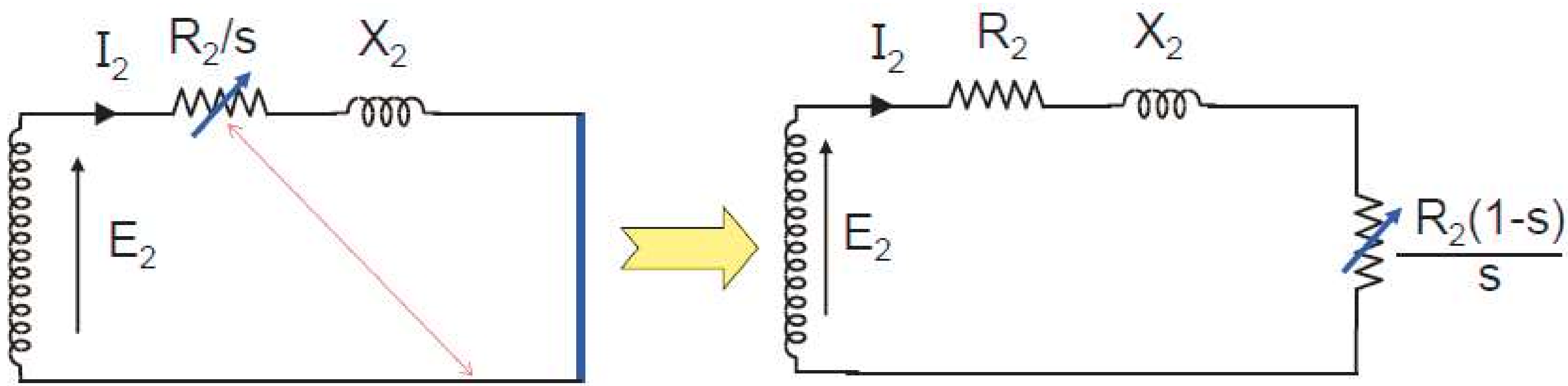


E2 is now constant

$$I_2 = \frac{sE_2}{\sqrt{R_2^2 + sX_2^2}}$$

$$I_2 = \frac{\frac{sE_2}{s}}{\sqrt{\left(\frac{R_2}{s}\right)^2 + \left(\frac{sX_2}{s}\right)^2}}$$

Further Alternation of Rotor Circuit



$$\frac{R_2}{s} = R_2 + R_2\frac{(1-s)}{s}$$

$3I_2^2R_2/s$	= *Total power transfer from stator to rotor*
$3I_2^2R_2$	= *Rotor copper loss*
$3I_2^2R_2(1-s)/s$	= *Gross mechanical power output*

Power Ratio

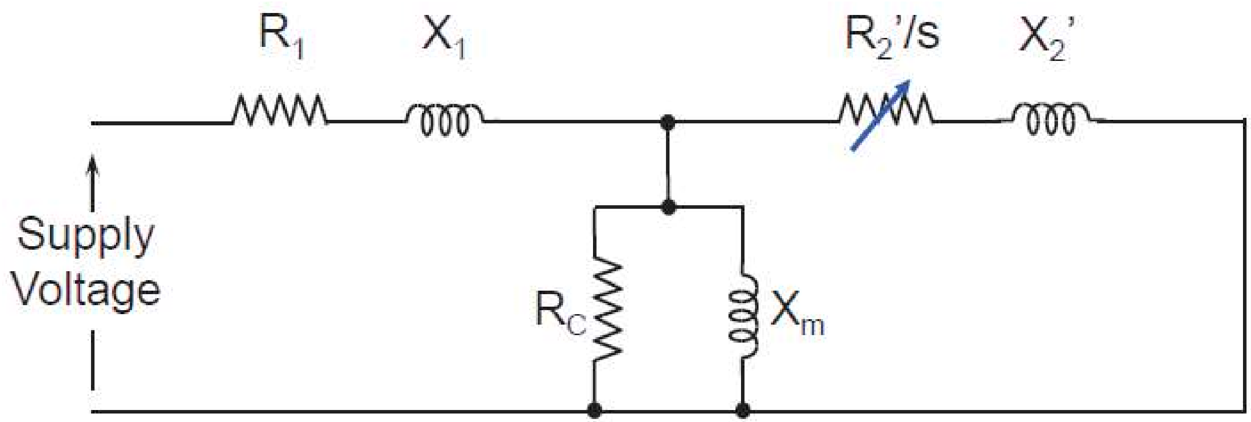
- $\frac{3I_2^2R_2}{s} = P_{ag}$
- $3I_2^2R_2 = P_{cu2}$
- $\frac{3I_2^2R_2(1-s)}{s} = P_m$

$$P_{ag} = P_m + P_{cu2}$$

$$P_{ag} : P_{cu2} : P_m = 1/s : 1 : (1-s)/s$$

$$\mathbf{P_{ag} : P_{cu2} : P_m = 1 : s : (1-s)}$$

Rotor Impedance Referred to Stator

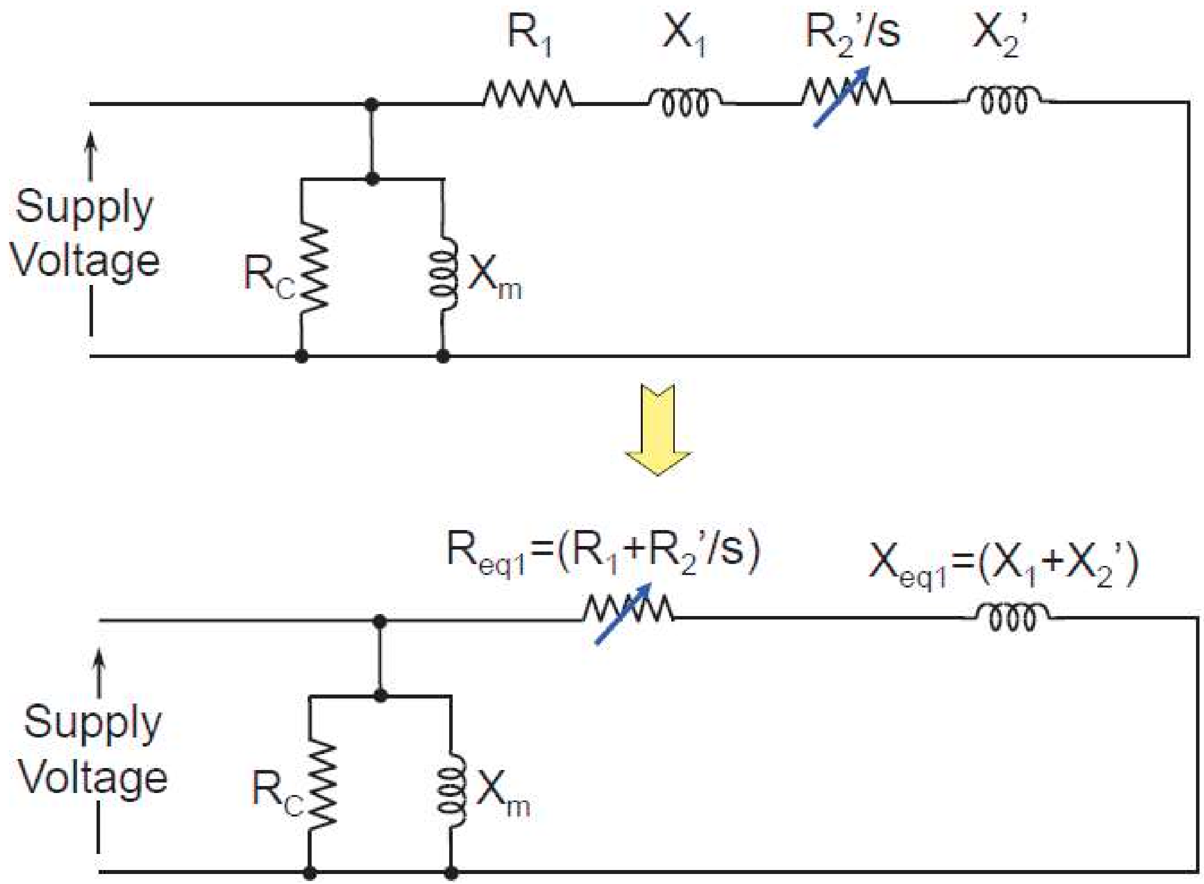


$$\frac{R_2'}{s} = \left(\frac{N_1}{N_2}\right)^2 \frac{R_2}{s}$$

$$X_2' = \left(\frac{N_1}{N_2}\right)^2 X_2$$

R_C = Core loss resistance
X_m = Magnetising reactance

Approximate Equivalent Circuit



Example 2

A 3Φ, 11.19kW, 460V, four-pole, 60Hz, 1728rpm induction motor delivers full output power to a load connected to its shaft. The windage and friction loss of the motor is 750W. Determine the:

a) Mechanical power developed.
b) Air gap power.
c) Rotor copper loss.

Example 2

(a) $$\begin{aligned} &\textit{Mechanical power developed} \\ &= \textit{shaft power} + \textit{windage and friction loss} \\ &= 11190 + 750 = \underline{\underline{11940W}} \end{aligned}$$

(b) $$n_S = \frac{60x60}{2} = 1800 \quad rpm$$

$$Slip \quad s = \frac{1800-1728}{1800} = 0.04$$

$$Air\ gap\ power\ Pag = \frac{11940}{1-0.04} = \underline{\underline{12437.5W}}$$

(c) $$\begin{aligned} &Rotor\ copper\ loss\ P_2 = 0.04x12437.5 \\ &= \underline{\underline{497.5W}} \end{aligned}$$

3-Ø Induction Motor

No-load Test (OC Test)
and
Locked-rotor Test (SC Test)

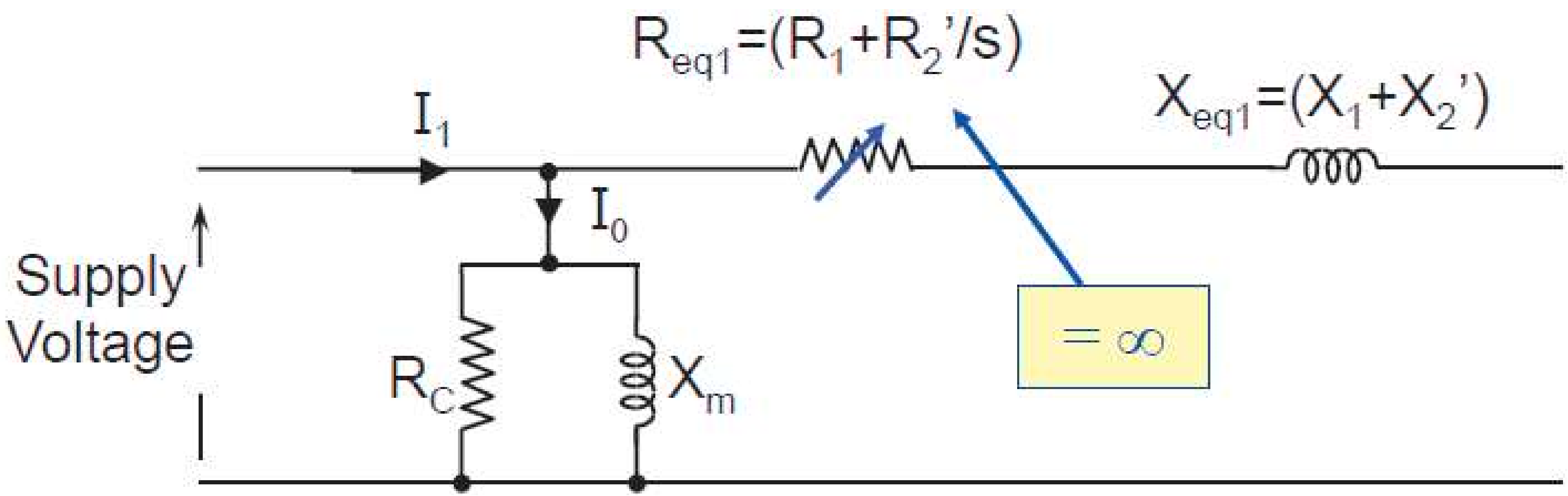
No-load Test (OC Test)

- Similar to the transformer equivalent circuit, we can use '**open-circuit test**' to find out the no-load components, R_C and X_m

No-load Test (OC Test)

- When an induction motor is **running no-load**, $s \approx 0, R_{eq1} = \infty$, the secondary circuit is open-circuited. All the current taken from the supply is the no load current I_0

No-load Test (OC Test)



Locked-rotor Test (SC Test)

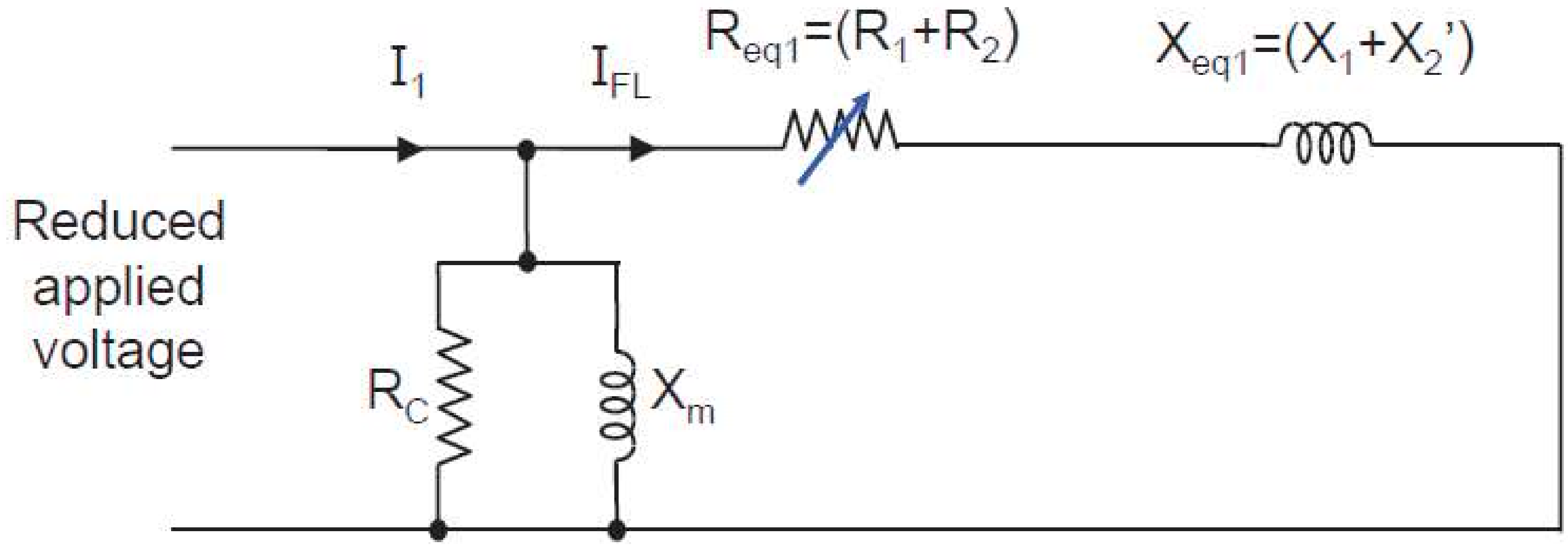
- We can use "**short-circuit test**" to find out the series components, R_{eq1} $(R_1 + R_2')$ and X_{eq1} $(X_1 + X_2')$
- When the rotor of an induction motor is locked,

$$s = 1, R_2'/s = R_2'$$

- Since the secondary circuit is short circuited, we cannot apply full line voltage to the stator, only reduced voltage (about 1/7) is applied to the stator until full load current flows into the stator.
- Since no-load current is only about 1/20 full load current, reduction of the applied voltage will cause this current to reduce to 1/140 full load current, hence I_0 may be neglected.

Locked-rotor Test

- Locked-rotor test is also called blocked-rotor test or clamp rotor test

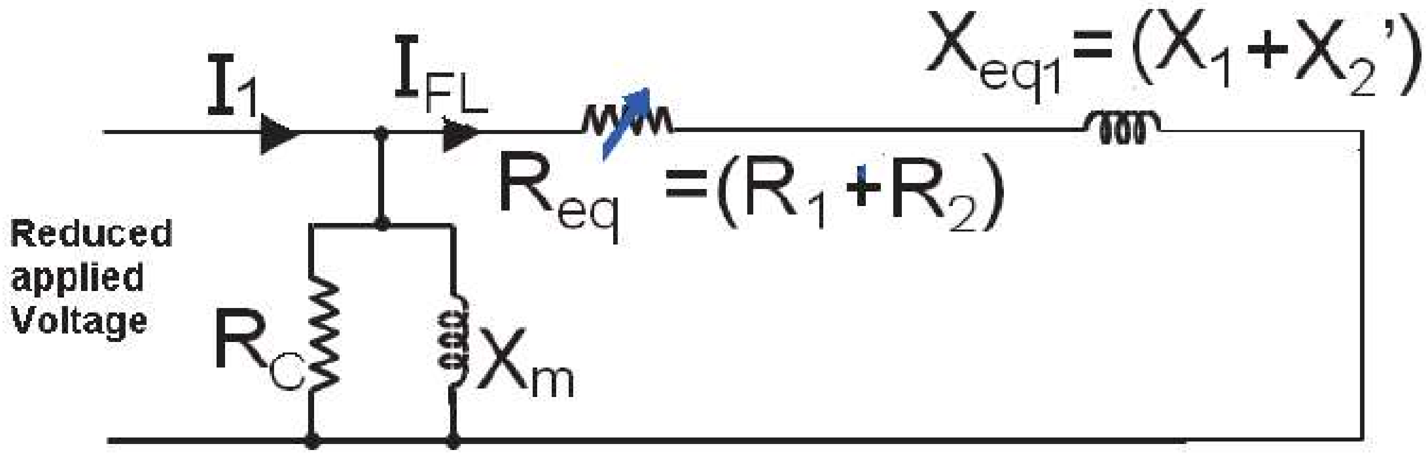


Example 3

- The result of no-load and locked-rotor tests on a 3-phase, Y-connected induction motor are as follows.

- Determine the parameters of the approximate equivalent circuit.

Example 3



No-load Test:
Line-to-line voltage = 400V

Input power = 1770W

Input current = 18.5A
Friction and windage losses = 600W

Locked-rotor Test :
Line-to-line voltage = 45V

Input power = 2700W

Input current = 63A

Example 3

From no-load test:

$$V_0 = \frac{400}{\sqrt{3}} = 231\,V,\; P_0 = \frac{1}{3}(1770 - 600) = 390\text{ W}$$

$$I_0 = 18.5A$$

$$R_c = \frac{V_0^2}{P_0} = \frac{(231)^2}{390} = 136.8\,\Omega$$

$$X_m = \frac{V_0^2}{\sqrt{\underbrace{V_0^2 I_0^2 - P_0^2}_{Q}}} = \frac{(231)^2}{\sqrt{(231)^2(18.5)^2 - (390)^2}} = 12.5\,\Omega$$

Example 3

From locked-rotor test:

$$V_s = \frac{45}{\sqrt{3}} = 25.98\,V,\ I_s = 63\,A$$

$$P_s = \frac{2700}{3} = 900\ \text{W}$$

$$R_{eq1} = R_1 + R_2' = \frac{P_s}{I_s^2} = \frac{900}{(63)^2} = 0.23\,\Omega$$

$$X_{eq1} = X_1 + X_2' = \frac{\sqrt{V_s^2 I_s^2 - P_s^2}}{I_s^2} = \frac{\sqrt{(25.98)^2(63)^2 - (900)^2}}{(63)^2} = 0.34\,\Omega$$

$Qs = I_s^2 X_{eq1}$

Power Flow Diagram
and
Efficiency

Power Losses

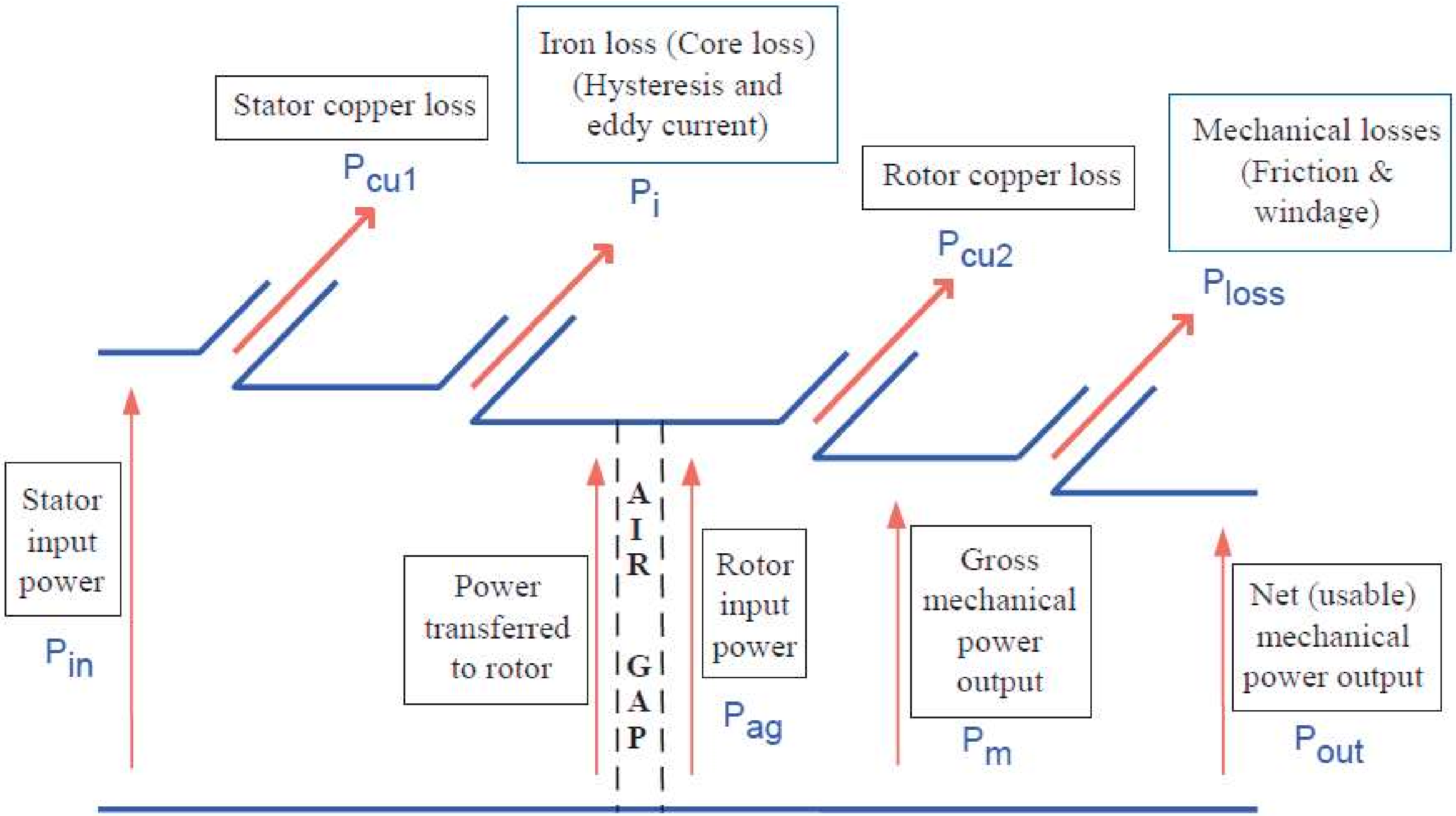
- When the induction motor is connected to a 3-phase supply, current flows in the primary circuit, heat is produced in the stator conductor as copper loss(Pcu1)

- No load current also flows and further power is lost as iron losses(Pi)

Power Losses

- Power then flow through the air gap as magnetic field energy, there will be no loss in the air gap
- Further energy is lost in the rotor winding as rotor copper loss(Pcu2)
- Now the electrical energy is converted to mechanical energy, but before this energy can be fully utilized, further energy is lost as friction and windage losses(Pw)

Induction Motor (Power Flow Diagram)



Power Losses in Equivalent Circuit

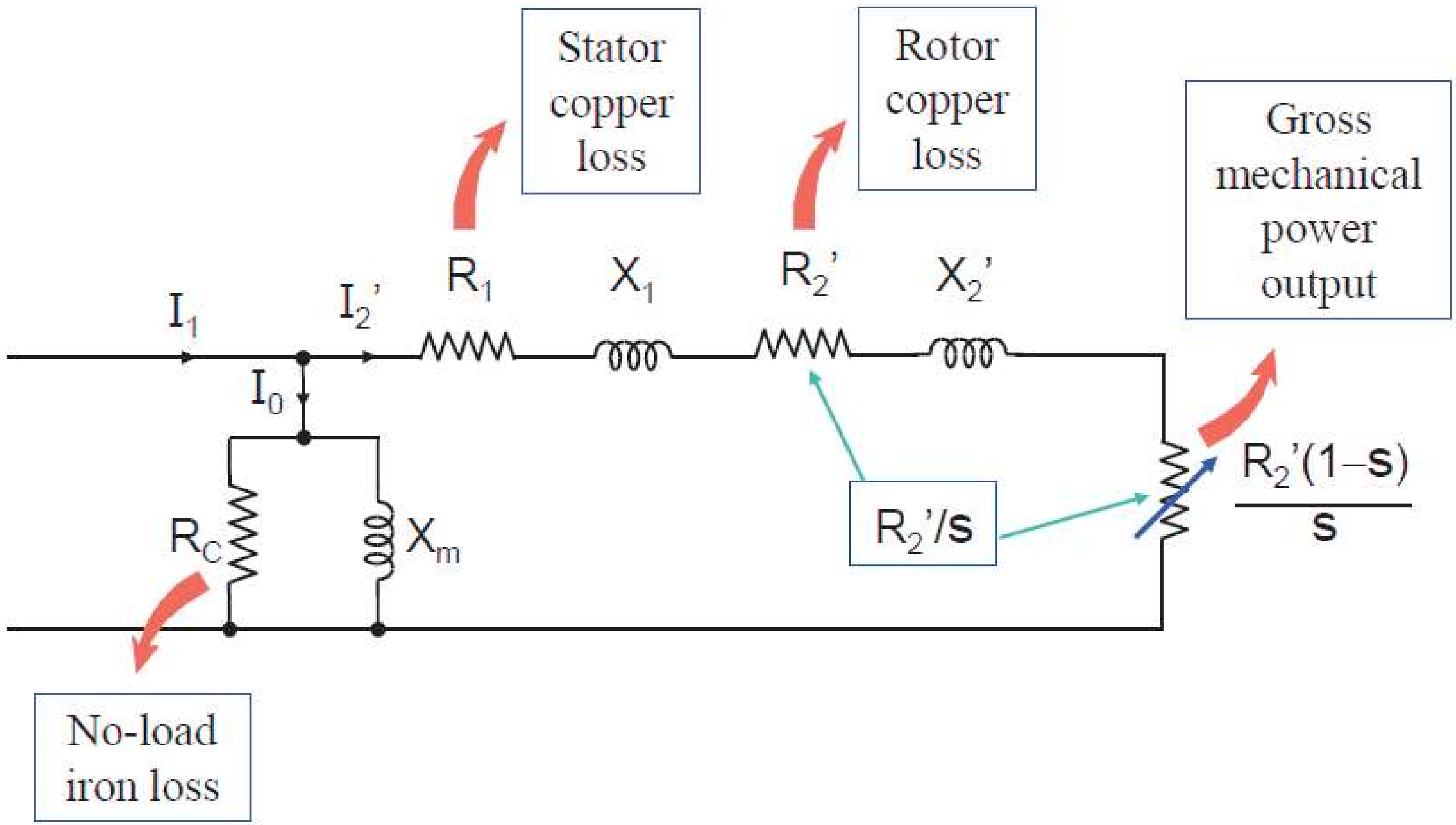
- We can relate the power flow diagram and the equivalent circuit 's' parameters

- Since only resistors will dissipate power, therefore in the induction motor equivalent circuit **only resistive components will represent power**

Power Losses in Equivalent Circuit

- We must multiply the power in the single-phase equivalent circuit by 3 in order to calculate the actual 3-phase power

Power Losses in Equivalent Circuit



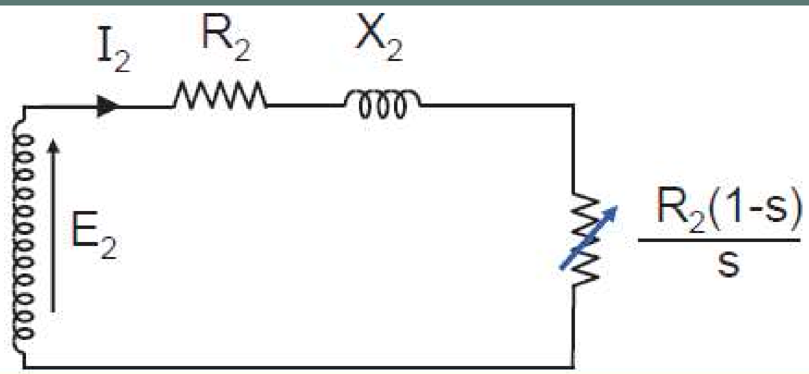
3-Ø Induction Motor

Torque Equation

Electrical Power = Mechanical Power

$$P(W) = 2\pi \frac{N_R}{60} T(Nm)$$

Torque Equation from Rotor Circuit

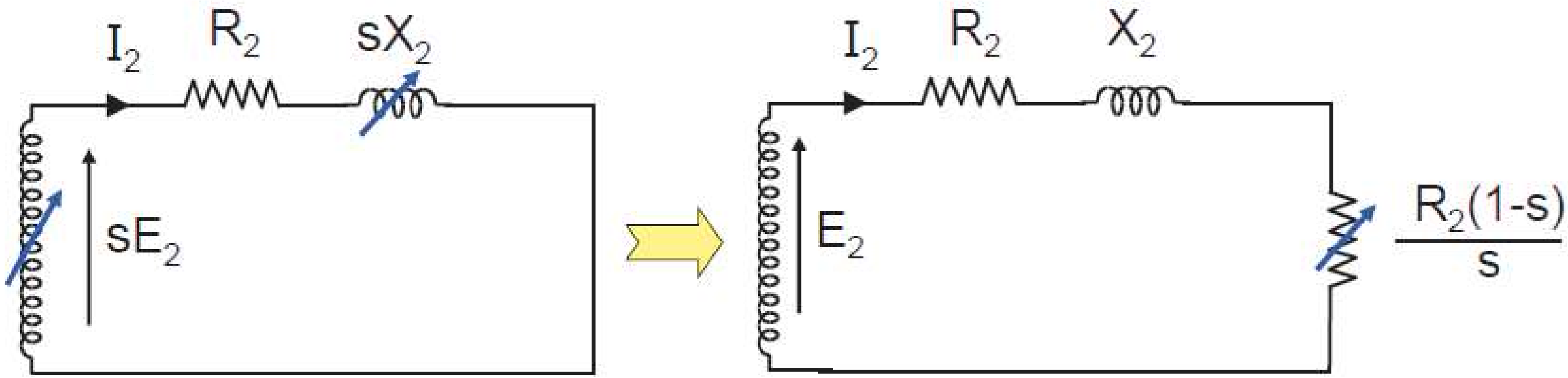


Motor converts **electrical energy** into **mechanical energy**

Electrical Energy → Mechanical Energy

$$3I_2^{\,2}\left[R_2\frac{(1-s)}{s}\right] = 2\pi n_r T$$

Torque Equation from Rotor Circuit



$$I_2 = \frac{sE_2}{\sqrt{R_2^2 + (s\,X_2)^2}}$$

$$I_2^2 = \frac{s^2 E_2^2}{R_2^2 + s^2 X_2^2}$$

$$2\pi n_r T = 3I^2 R_2 \frac{(1-s)}{s}$$

$$2\pi n_r T = 3\left(\frac{3s^2 E_2^2}{R_2^2 + s^2 X_2^2}\right) \times \frac{R_2(1-s)}{s}$$

Torque Equation from Rotor Circuit

$$2\pi n_r T = 3x\frac{s^2 E_2^{\ 2}}{R_2^{\ 2} + s^2 X_2^{\ 2}} \times \frac{R_2(1-s)}{s}$$

$$2\pi(1-s)n_s T = 3x\frac{s^2 E_2^{\ 2}}{R_2^{\ 2} + s^2 X_2^{\ 2}} \times \frac{R_2(1-s)}{s}$$

$$T = 3x\frac{s^2 E_2^{\ 2}}{R_2^{\ 2} + s^2 X_2^{\ 2}} \times \frac{R_2(1-s)}{s} \times \frac{1}{2\pi(1-s)n_S}$$

$$T = 3x\frac{E_2^{\ 2}}{2\pi n_S} \times \frac{sR_2}{R_2^{\ 2} + s^2 X_2^{\ 2}}$$

Motor torque is dependent on slip **s**

Typical Torque / Slip Curve

$$T = \frac{3E_2^2}{2\pi n_s} \times \frac{sR_2}{R_2^2 + s^2X_2^2}$$

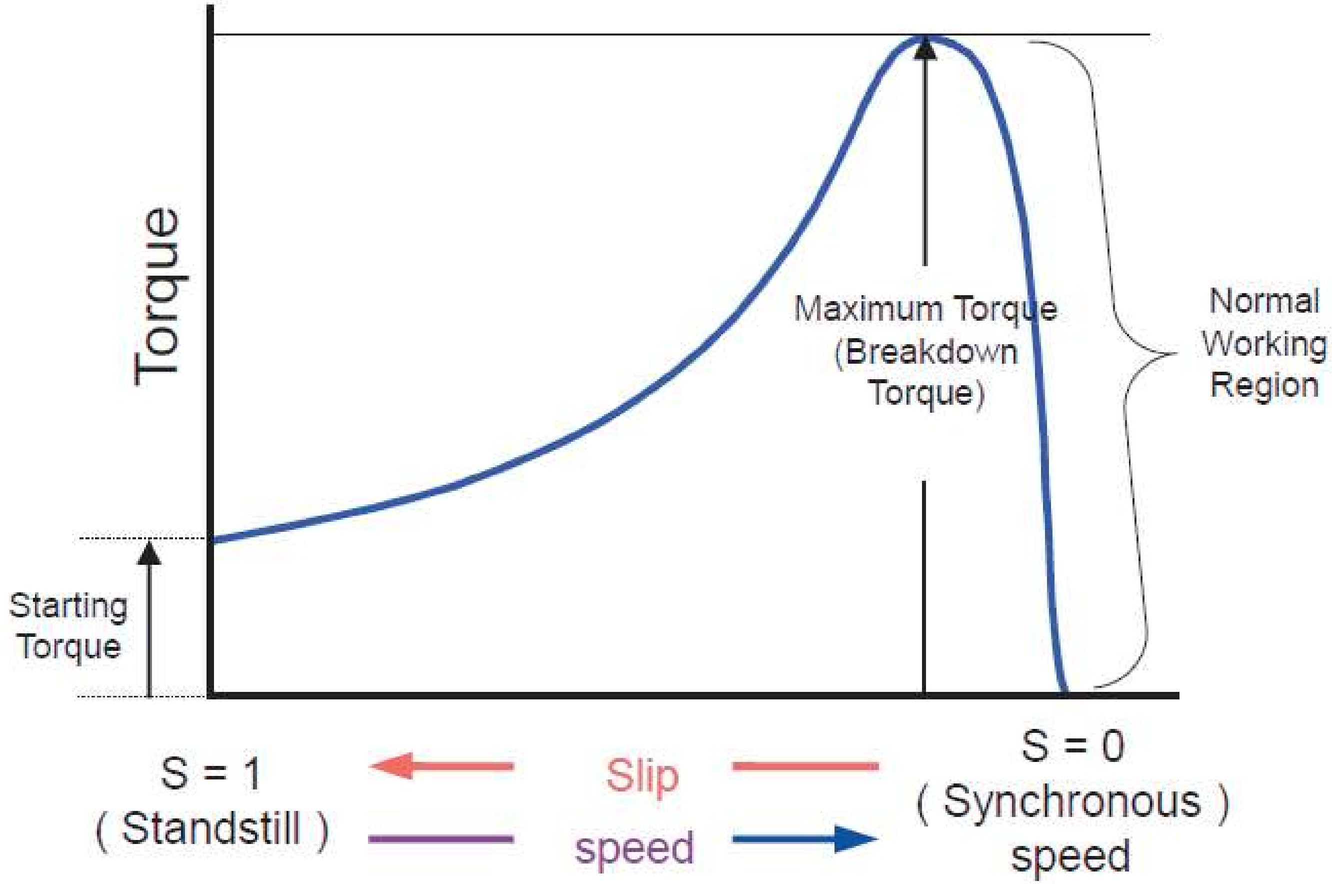
For s is small, i.e. less than 0.1

$$T \alpha \frac{sR_2}{R_2^2} \alpha \frac{s}{R_2}$$

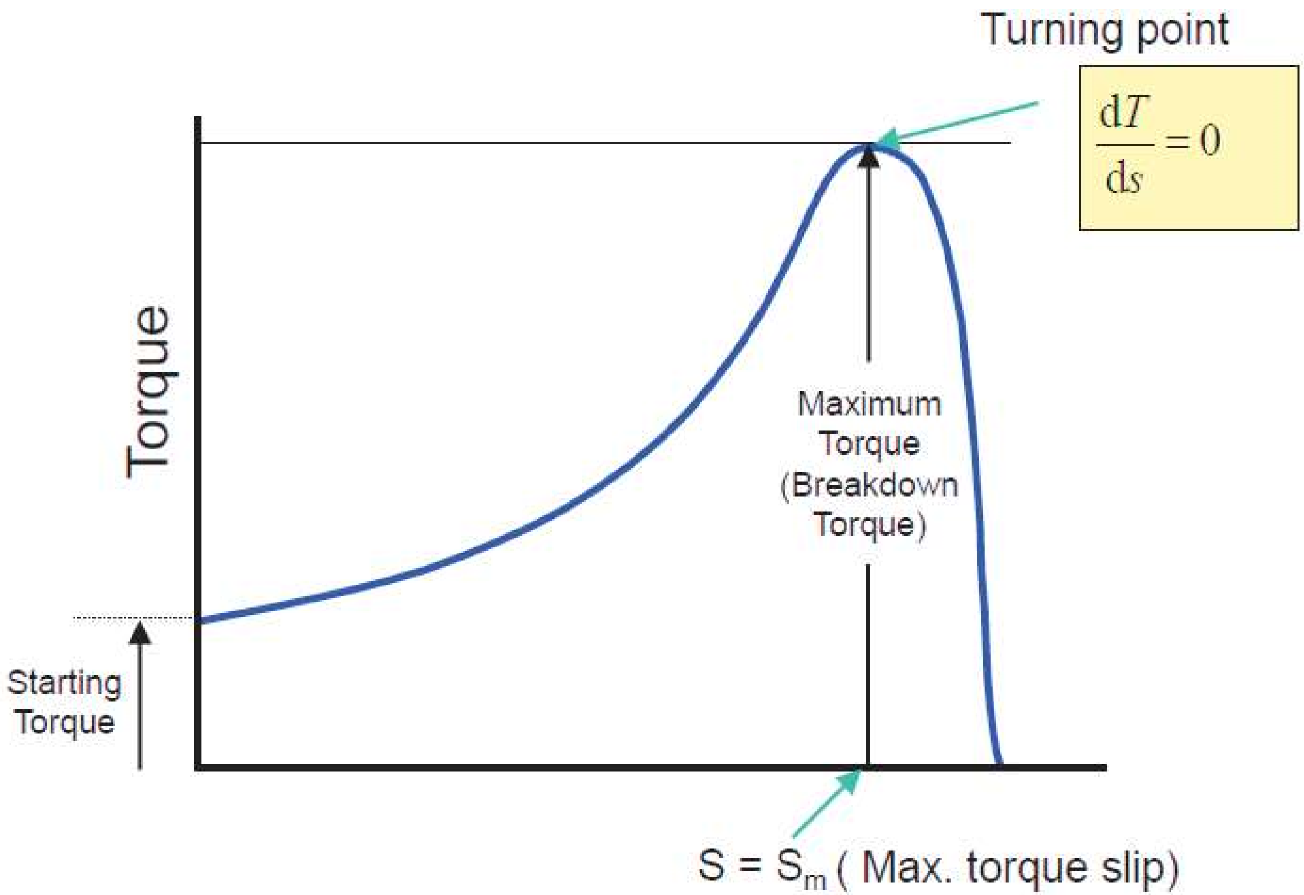
For s is large, i.e. 0.2 and 1

$$T \alpha \frac{sR_2}{s^2X_2^2} \alpha \frac{R_2}{s}$$

Typical Torque / Slip Curve



Maximum Torque Slip (S_m)



Maximum Torque Slip (S_m)

$$\frac{dT}{ds} \Rightarrow \frac{d}{ds}\left(\frac{3E_2^{\,2}}{2\pi n_s} \times \frac{sR_2}{R_2^{\,2} + s^2X_2^{\,2}}\right) = 0$$

$$\Rightarrow \frac{(R_2^{\,2} + s^2X_2^{\,2})R_2 - (sR_2)(2sX_2^{\,2})}{\left(R_2^{\,2} + s^2X_2^{\,2}\right)^2} = 0$$

$$\Rightarrow (R_2^{\,3} + s^2R_2X_2^{\,2}) - 2s^2R_2X_2^{\,2} = 0$$

$$\Rightarrow R_2^{\,3} = s^2R_2X_2^{\,2}$$

$$\Rightarrow R_2^{\,2} = s^2X_2^{\,2}$$

$$s^2 = \frac{R_2^{\,2}}{X_2^{\,2}}$$

$$S_m = \sqrt{\frac{R_2^{\,2}}{X_2^{\,2}}} = \frac{R_2}{X_2}$$

$$s_{Tmax} = \frac{R_2'}{\sqrt{R_2^{\,2} + X_{eq}^{\,2}}}$$

Maximum Torque and its characteristics

Note:

- Maximum torque do not depend on the value of the rotor resistance, but
- The value of the rotor resistance will affect at what slip (speed) the maximum torque will occur.

Maximum Torque Equation

Maximum torque occurs when slip = $\mathbf{s_m}$

$$T_m = \frac{3E_2^2}{2\pi n_S} \times \frac{s_m R_2}{R_2^2 + s_m^2 X_2^2}$$

Substitute $R_2 = s_m X_2$ into torque equation

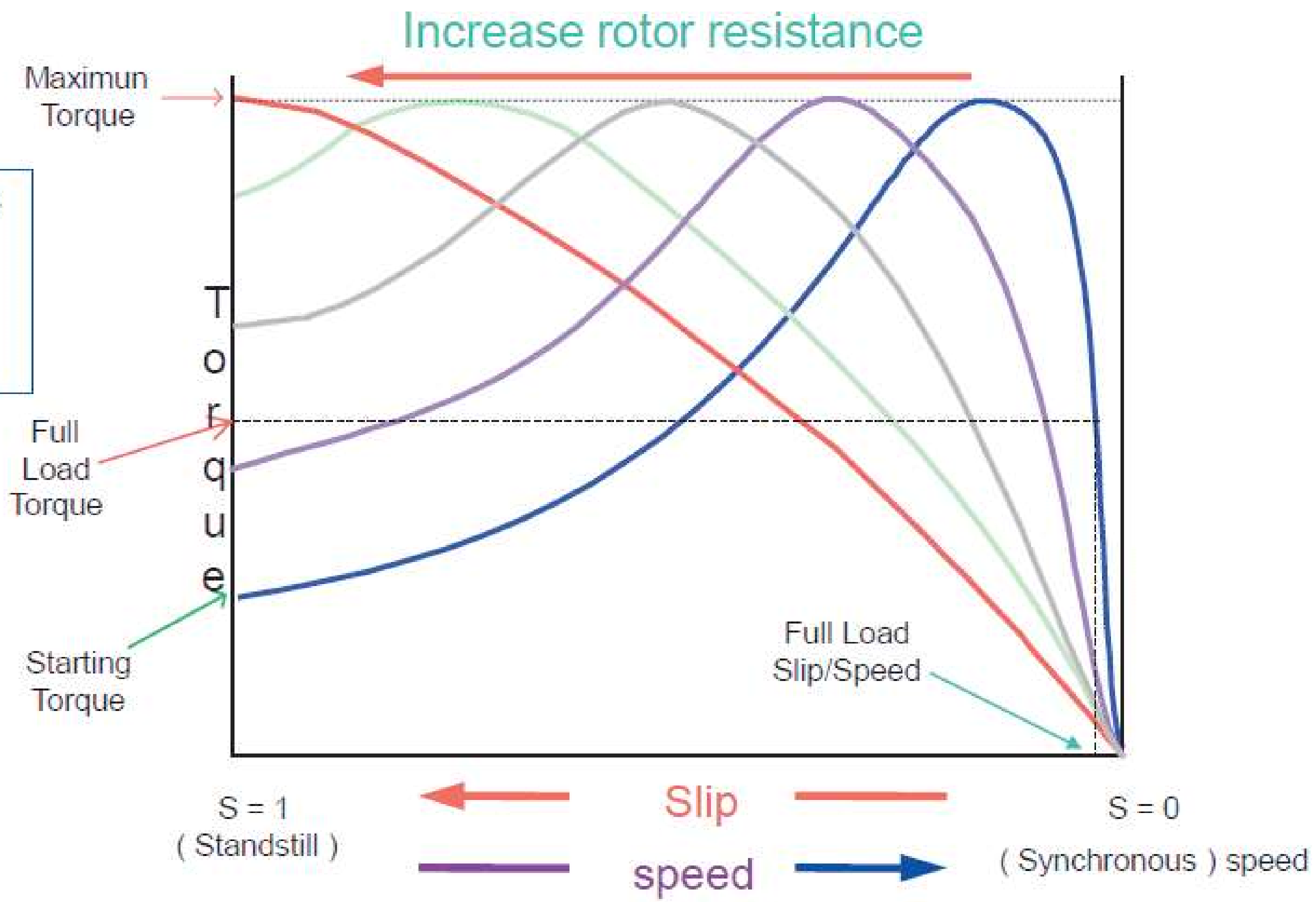
$$T_m = \frac{3E_2^2}{2\pi n_S} \times \frac{s_m^2 X_2}{s_m^2 X_2^2 + s_m^2 X_2^2}$$

$$T_m = \frac{3E_2^2}{2\pi n_S} \times \frac{1}{2X_2}$$

T_m is independent of R_2

Effect of additional Rotor Resistance on Torque/Slip Curve

Only possible in slip-ring induction motor



Torque Ratio Equation

$$T_m = 3x \frac{E_2^2}{2\pi n_S} \times \frac{1}{2X_2}$$

Max torque

$$T_S = 3x \frac{E_2^2}{2\pi n_S} \times \frac{sR_2}{R_2^2 + s^2 X_2^2}$$

Torque at slip s

$$\frac{T_m}{T_S} = \frac{1}{2X_2} \times \frac{R_2^2 + s^2 X_2^2}{sR_2}$$

Substitute $R_2 = s_m X_2$ into the above torque equation

$$\frac{T_m}{T_S} = \frac{1}{2X_2} \times \frac{s_m^2 X_2^2 + s^2 X_2^2}{s s_m X_2}$$

Torque Ratio Equation

$$\frac{T_m}{T_S} = \frac{1}{2X_2} \times \frac{s_m^2 X_2^2 + s^2 X_2^2}{s s_m X_2}$$

$$\frac{T_m}{T_S} = \frac{1}{2}\left(\frac{s_m^2 + s^2}{s s_m}\right)$$

$$\frac{T_m}{T_S} = \frac{1}{2}\left(\frac{s_m}{s} + \frac{s}{s_m}\right)$$

Typical specification of induction motor

Toshiba

0.4 KW		Type:	IK
4 poles		Volts:	346V
E class		Hz:	50
		Amp:	1.4A
		RPM:	1410
		Code:	K

Example 4

- The rating plate of a 3-phase induction motor is as follows:

Frequency	**50 Hz**
Power	20 kW
Connection	Delta
Current	44.6 A
Voltage	380 V
Power factor	0.8
Speed	960 rev/min
Insulation	Class E (Class E is a European spec, 120 C or 248 F maximum temp

Example 4

Determine

a) The stator input power

b) The efficiency on full-load

c) The full-load torque

Example 4

Determine

d) The rotor copper loss on full-load if the mechanical loss is 250 Watts

e) The stator copper loss if the stator resistance is 0.4 ohm per phase

f) The core loss

Example 4

$$(a)\ Pin = \sqrt{3} V_L I_L \cos\phi = 23.49kW$$

b) Efficiency = $\dfrac{20 \times 10^3}{\sqrt{3} \times 380 \times 44.6 \times 0.8} = \underline{\underline{85.16\%}}$

c) Full-load torque = $\dfrac{20 \times 10^3}{2\pi \times \dfrac{960}{60}} = \underline{\underline{199Nm}}$

d) Slip = $\dfrac{Ns - Nr}{Ns} = \dfrac{1000 - 960}{1000} = 0.04$

Gross mechanical power output, P_m

$= 20000 + 250 = 20250$ W

$$\frac{P_{cu}}{P_m} = \frac{s}{1-s} \Rightarrow P_{cu} = 20250 \times \frac{0.04}{1-0.04} = 884W$$

Example 4

(e) Stator copper loss $Pcu1 = 3xI_1{}^2R_1 = 3xI_p{}^2R_1$

$$= 3x\left(\frac{44.6}{\sqrt{3}}\right)^2 x0.4 = 796W$$

f) Core loss $P_i = P_{in} - P_{out} - P_{cu1} - P_{cu2} - P_{loss}$

$= 23.49 - 20 - 0.796 - 0.844 - 0.25$

$= \mathbf{1.6\ kW}$

3-Ø Induction Motor

Starting Methods

1. Direct on Line (DOL)

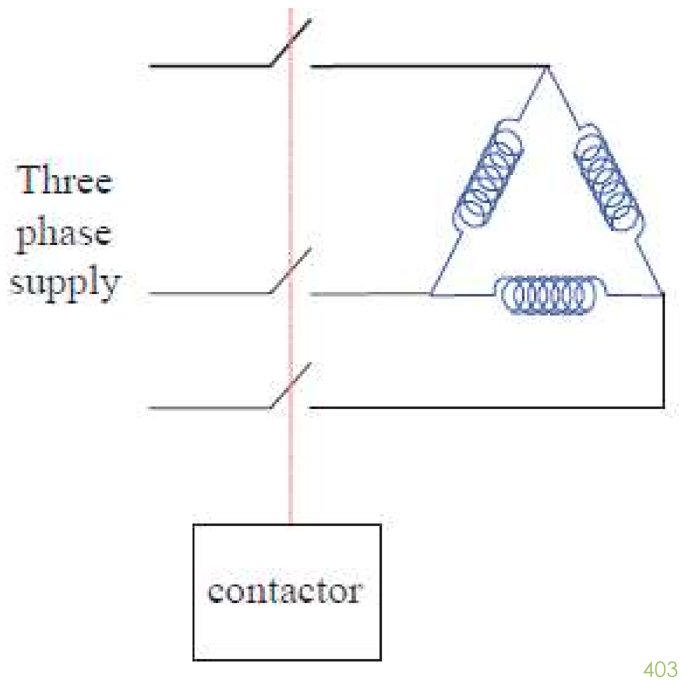
- A squirrel cage motor is at stationary before it is started, there is no back e.m.f. to oppose the current.

- Therefore, if this motor is connected directly to the supply, it will take an initial starting current which is about 5 to 10 times the full load value.

1. Direct on Line (DOL)

- Though this current decreases rapidly as the motor accelerates, it will cause harm to the motor and will affect the voltage regulation of the power supply

- Small motors up to the size of 5hp are allowed to be started with direct on line (DOL) starter



2. Star-Delta Starter

- When the rating of the motor **exceed 5hp**, **a star/delta starter** is normally used to start the motor because it is the simplest and cheapest type of starter.

- During starting, the stator winding is temporarily connected in star, therefore only phase voltage is applied to the stator.

2. Star-Delta Starter

- The starting current is reduced to 1/3 of the Direct on line starting current.
- The starting torque, which is proportional to the starting current, reduces also to 1/3 of the value at direct on line starting.

2. Star-Delta Starter

- After a period of **about 5 seconds**, the motor have accelerated to nearly full load speed.

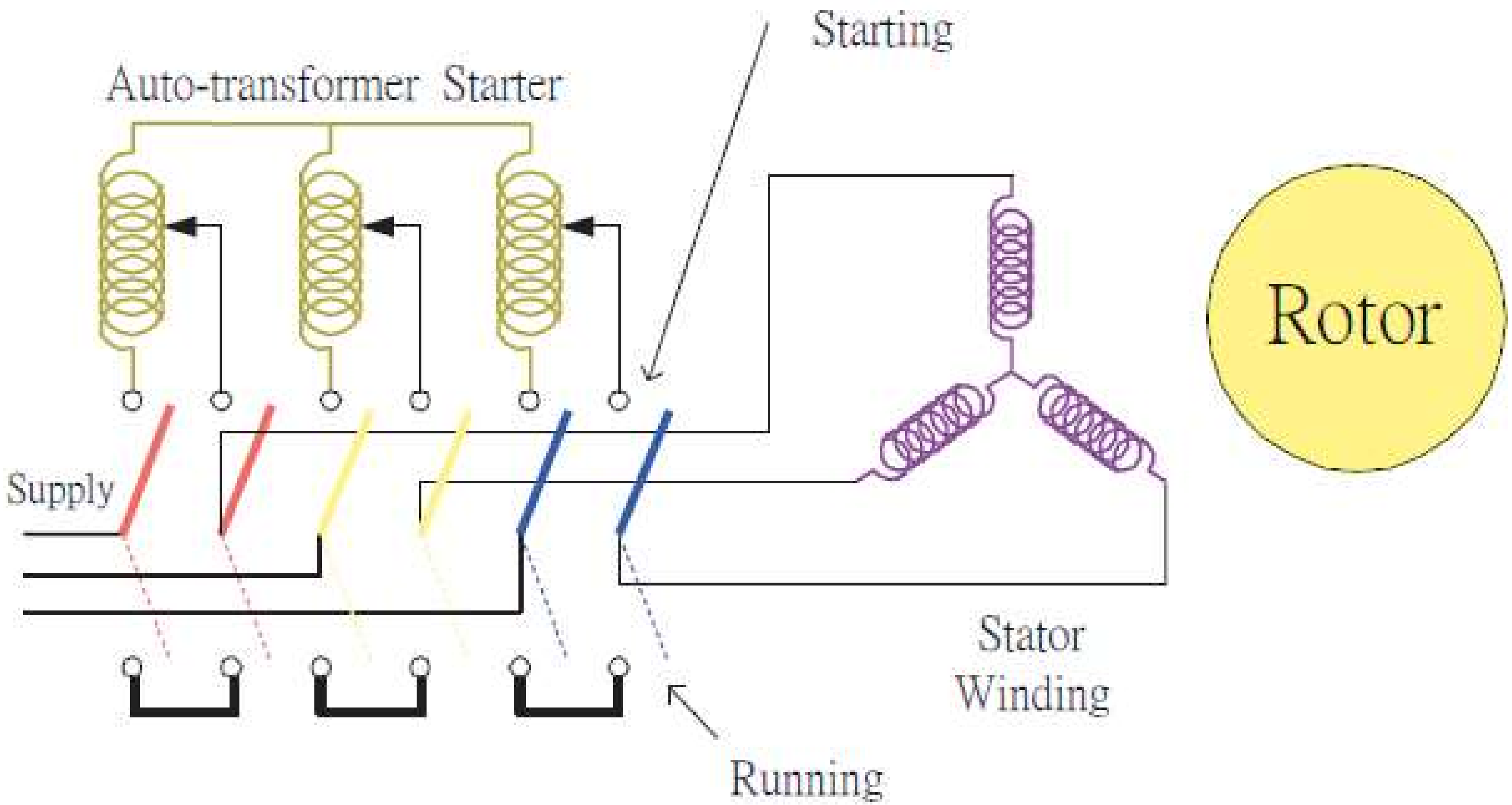
- The stator winding is now reconnected as delta, and full line voltage is applied each phase of the stator.

3. Auto-transformer Starter

- Some loads are very heavy and it will take a few minutes before it can run to full speed, these motors have to be started by means of transformer starter.

- The reduced voltage during starting is obtained from the different tappings (40%,60%,75%) of an auto-transformer. In the running condition, full voltage is applied to the stator and the transformer is cut out of the circuit.

3. Auto-transformer Starter

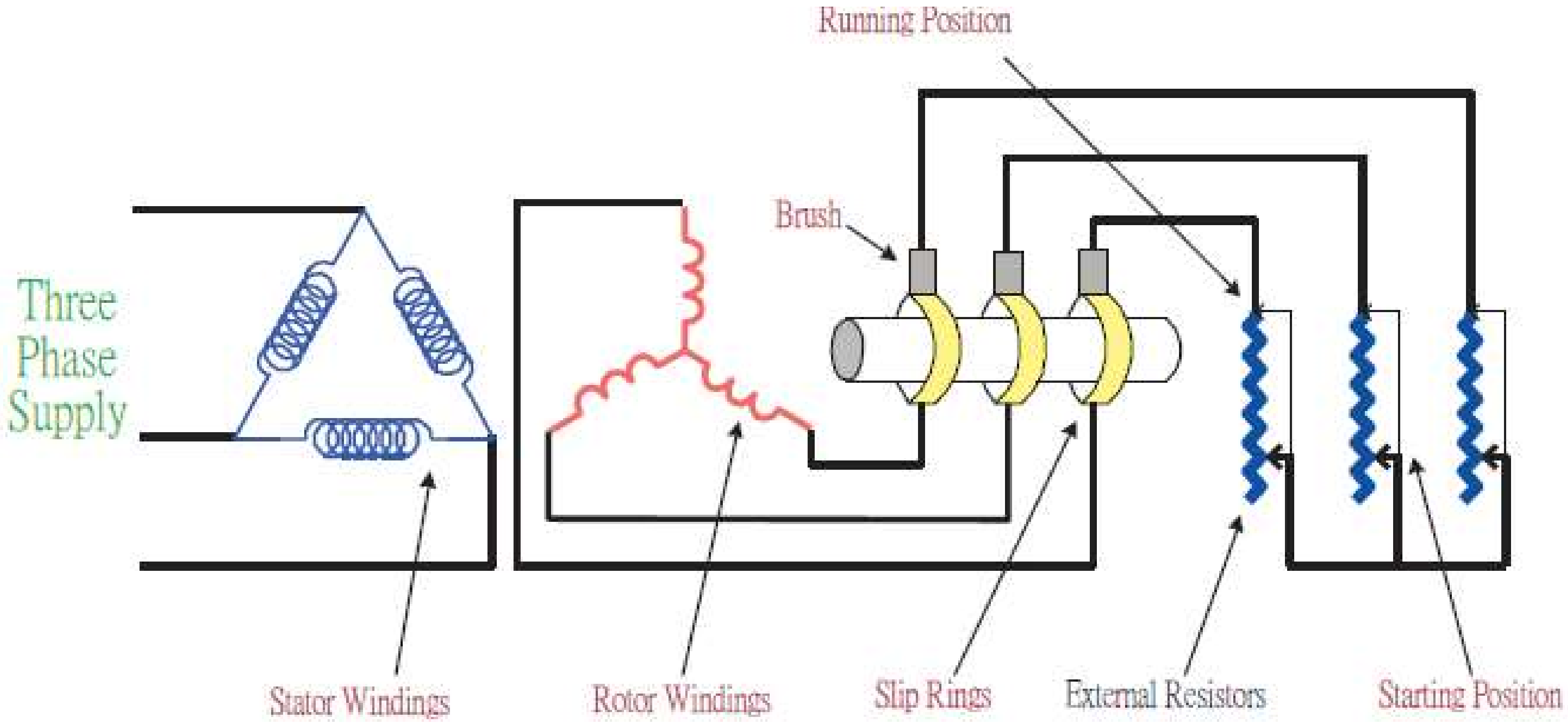


Starting of Wound Rotor Induction Motor

- The wound rotor (slip ring) induction motor can be started by inserting additional resistance in series with the rotor winding through the slip rings.

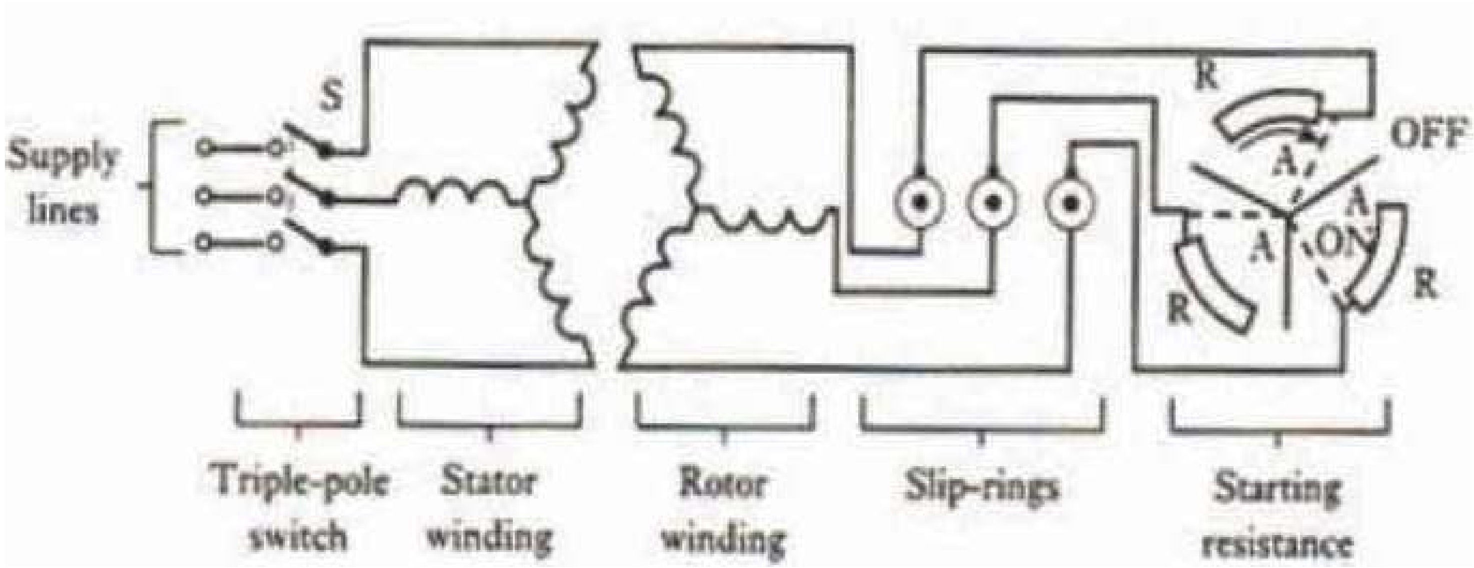
- In this way, maximun torque is obtained during starting. The additional resistance is cut off from the circuit as soon as the motor is started to avoid excessive power loss in the resistance.

Starting of Wound Rotor Induction Motor



Starting Torque

- For a large induction motor, the starting torque can be increased by inserting resistances during the starting phase.



Starting Methods

- In order to reduce the starting current which can be 4-7 times the full load current, it is usual to use one of the following methods to start the induction motor:

Starting Methods

(a) Star-delta starter

- At starting the stator windings are connected as star and at running position, the windings are back to delta connected.

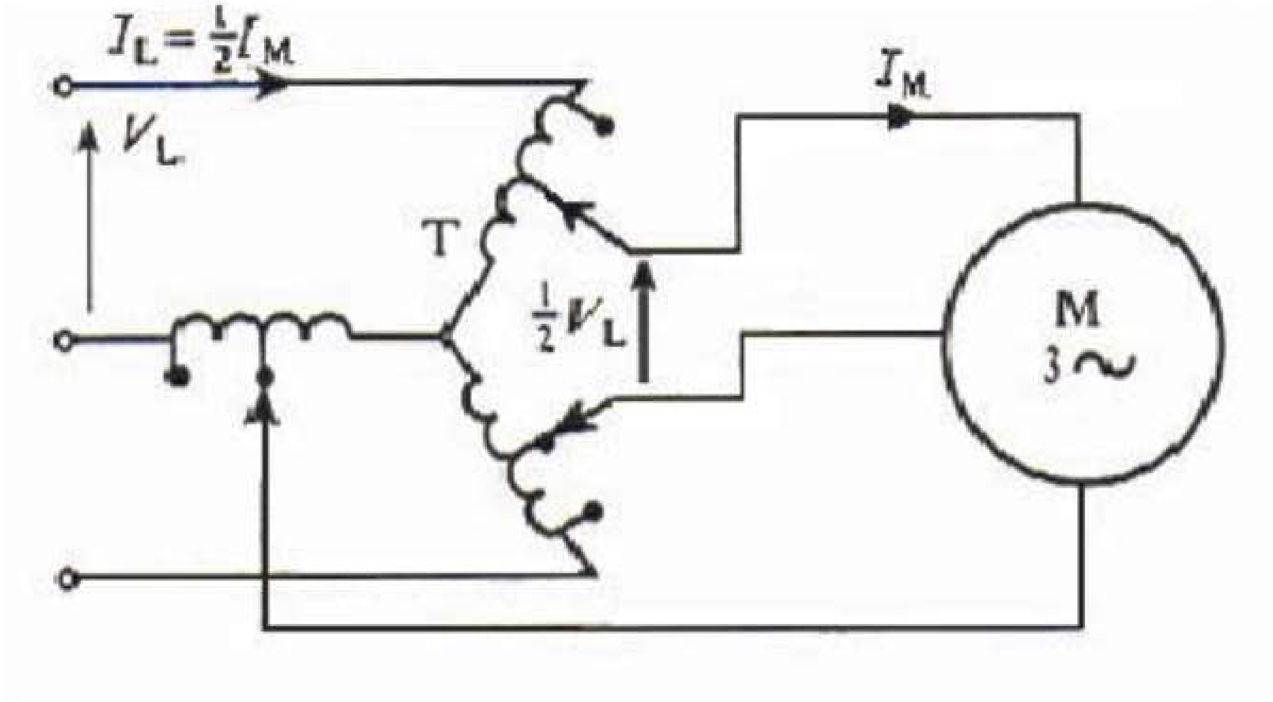
- Thus the starting voltage is reduced by $1/\sqrt{3}$, Starting current and torque is reduced by 1/3.

Starting Methods

(b) Auto-transformer starter

- To step down the voltage across the motor during the starting.
- The current and torque are reduced by n2, where n is the tapping ratio.

Auto – Transformer Starting



$$\frac{\text{Starting Torque with Auto Transformer}}{\text{Starting Torque with direct switching}} = \left(\frac{\text{Output Voltage}}{\text{Input Voltage}}\right)^2 = n^2$$

Solid State Soft Starter

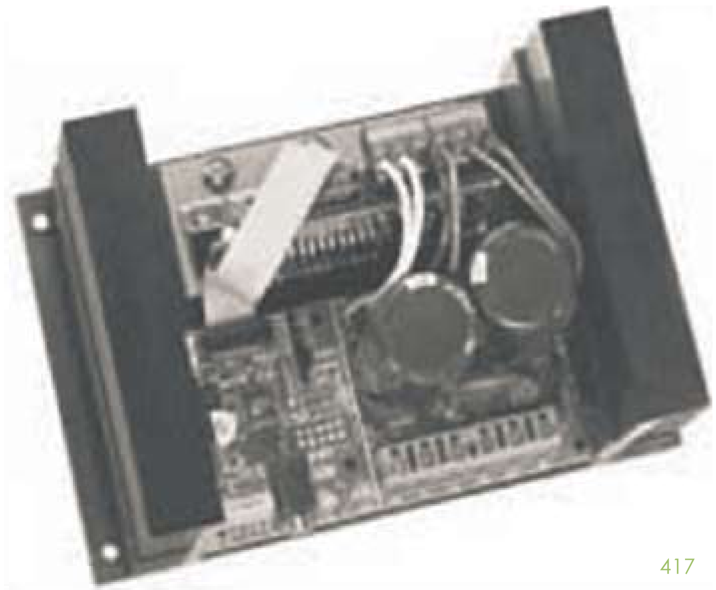
(c) Solid state soft starter

- To use an adjustable time ramp circuit that gradually increases power to the motor.
- As voltage is applies, current is gradually increased as needed by the motor, until full voltage and current bring the motor to its operating RPM.

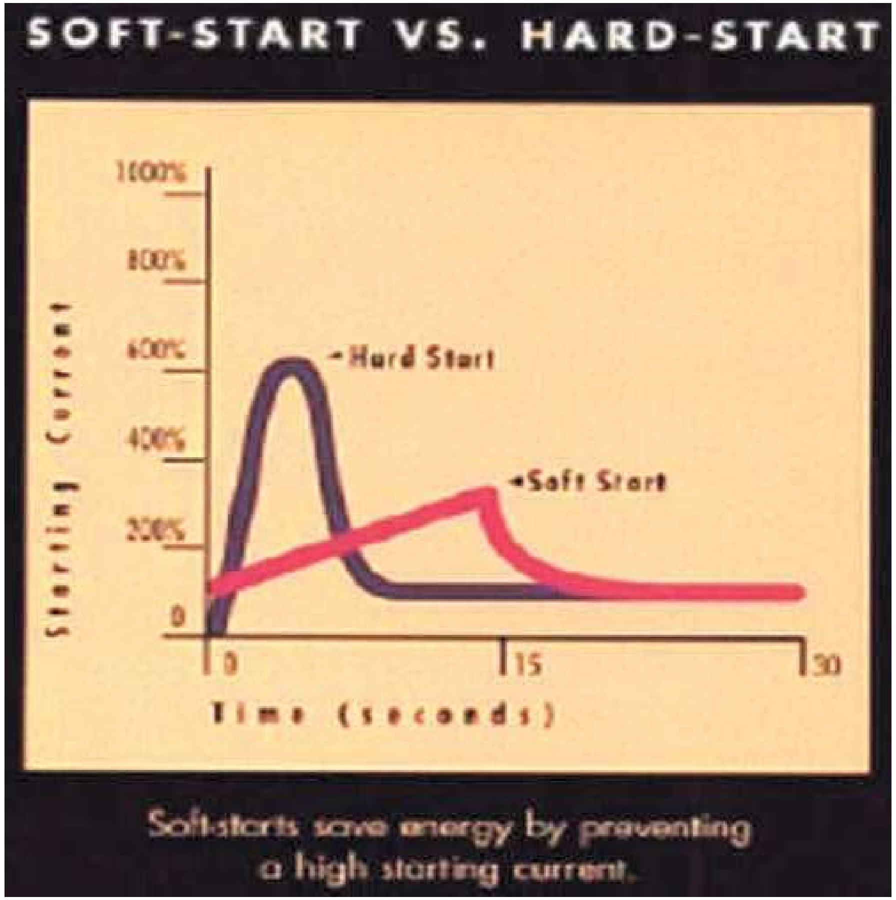
Solid State Soft Starter

(c) Solid state soft starter

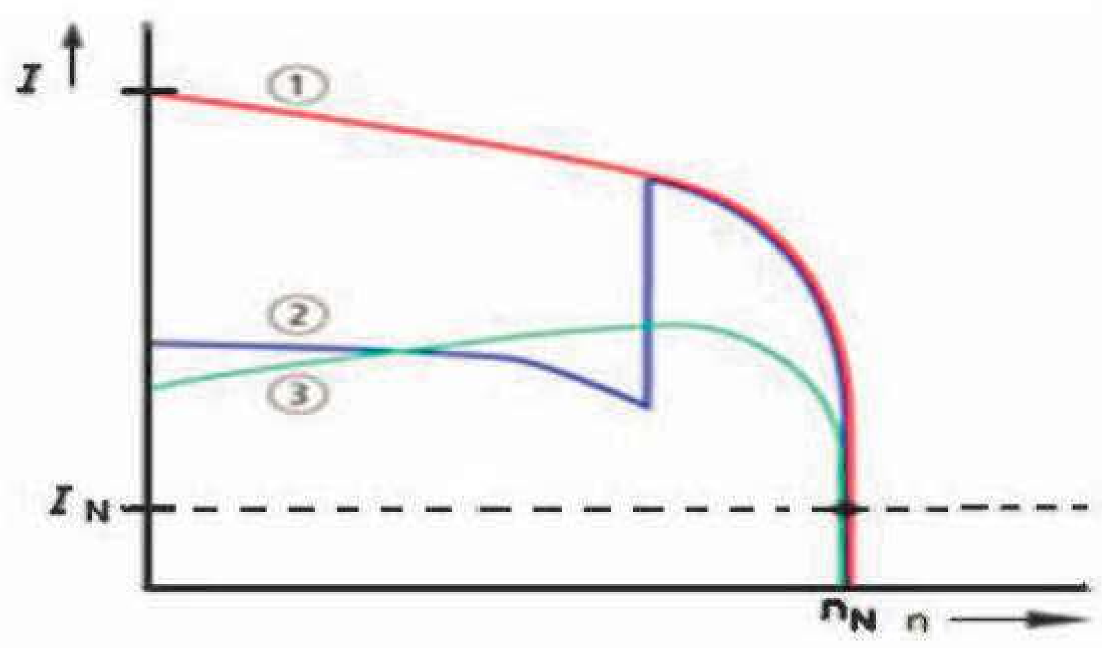
- At that point, the soft-start circuit turns off and the energy saving circuits (economic mode) take control of the motor.



Solid State Soft Starter



Comparison of Starting Current



1. Direct-on-line starting
2. Star-delta starting
3. Soft starting

Example 5

To install a 3-phase cage induction motor restricting the maximum line current drawn from a 380 V 3-phase supply to 120 A. if the starting current is 5 times full load current, Find the maximum permissible full load kVA of the motor when

Example 5

a) It is directly connected to the mains;

b) It is connected through an auto-transformer with a tapping of 60%;

c) It is designed for used with star-delta starter.

Example 5 (a)

Direct-on-line

$$Starting\ maximum\ line\ current = I_L = 120A$$

$$Starting\ current\ \ I_{ST} = 5 \times full\ load\ current = 5I_{FL}$$

$$5I_{ST} = 120\ A, then\ I = \frac{120}{5} = 24A$$

$$Maximum\ permissible\ rating\ of\ the\ motor$$

$$= \sqrt{3}V_L I_{ft} = \sqrt{3}x24x380 = \underline{\underline{15796VA}}$$

Example 5 (b)

Auto Transformer Starting :

$$\text{Starting current } I_{ST} = x^2 \times ISC = 0.6^2 x 5 I_{FL}$$

$$I_{FL} = \frac{120}{5 \times (0.6)^2} = 66.67\,A$$

Maximum permissible rating of the motor

$$= \sqrt{3} V_L I_{ft} = \sqrt{3} x 66.67 x 380 = \underline{\underline{43879VA}}$$

Example 5 (c)

Star - delta Starting :

$$\text{Starting current } I_{ST} = \frac{1}{3}(5I_{FL})$$

$$I_{FL} = \frac{120}{1.67} = 71.8\,A$$

Maximum permissible rating of the motor

$$= \sqrt{3}V_L I_{ft} = \sqrt{3}x71.8x380 = \underline{\underline{47255A = 47.25kVA}}$$

3-Ø Induction Motor

Speed Control Methods

Speed Control Methods

Methods of speed control for induction motor are:

(a) **Pole changing:**

$$N_R = (1 - s)\frac{60f}{P}$$

- The more the no. of poles, the slower will be the speed. However, it cannot give a stepless speed control of the motor.

Speed Control Methods

(b) Variable frequency:

- The frequency is changed by an electronic converter from 10Hz to 150Hz to achieve a stepless speed control. of the motor.
- The speed of the motor is directly proportional to the supply frequency from the inverter.

Speed Control Methods

(c) Change of slip:

- By varying the operating voltage of the motor hence its torque in order to lower the speed of the motor under a constant load.

- This method can only apply to speed control with constant load and can only give down-speed control.