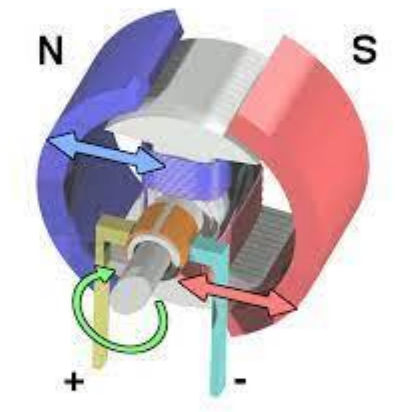
- 26742_DC Machine
- 4th Semester
- Electrical Technology



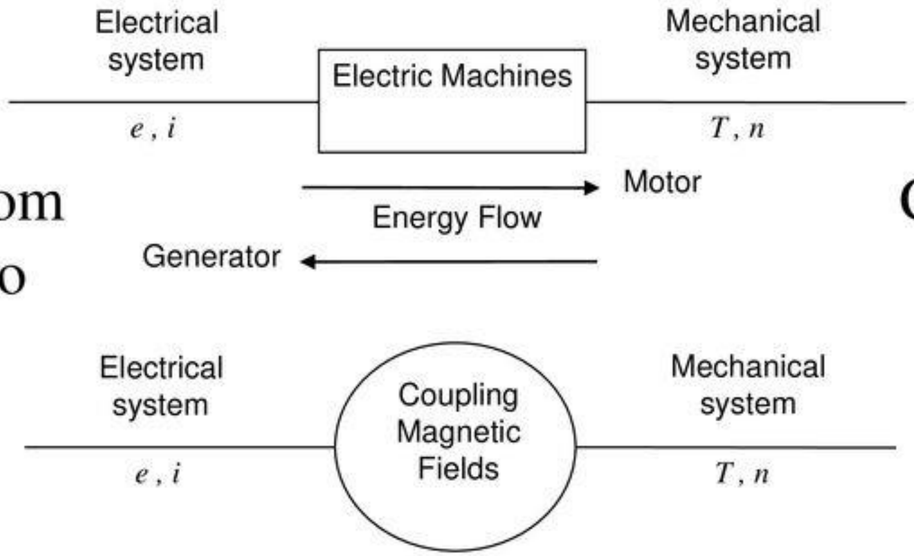
- Engr. Md Sadekul Islam
- Chief Instructor (Electrical)
- Dinajpur Polytechnic Institute

Electromagnetic Conversion

Energy is needed in different forms:

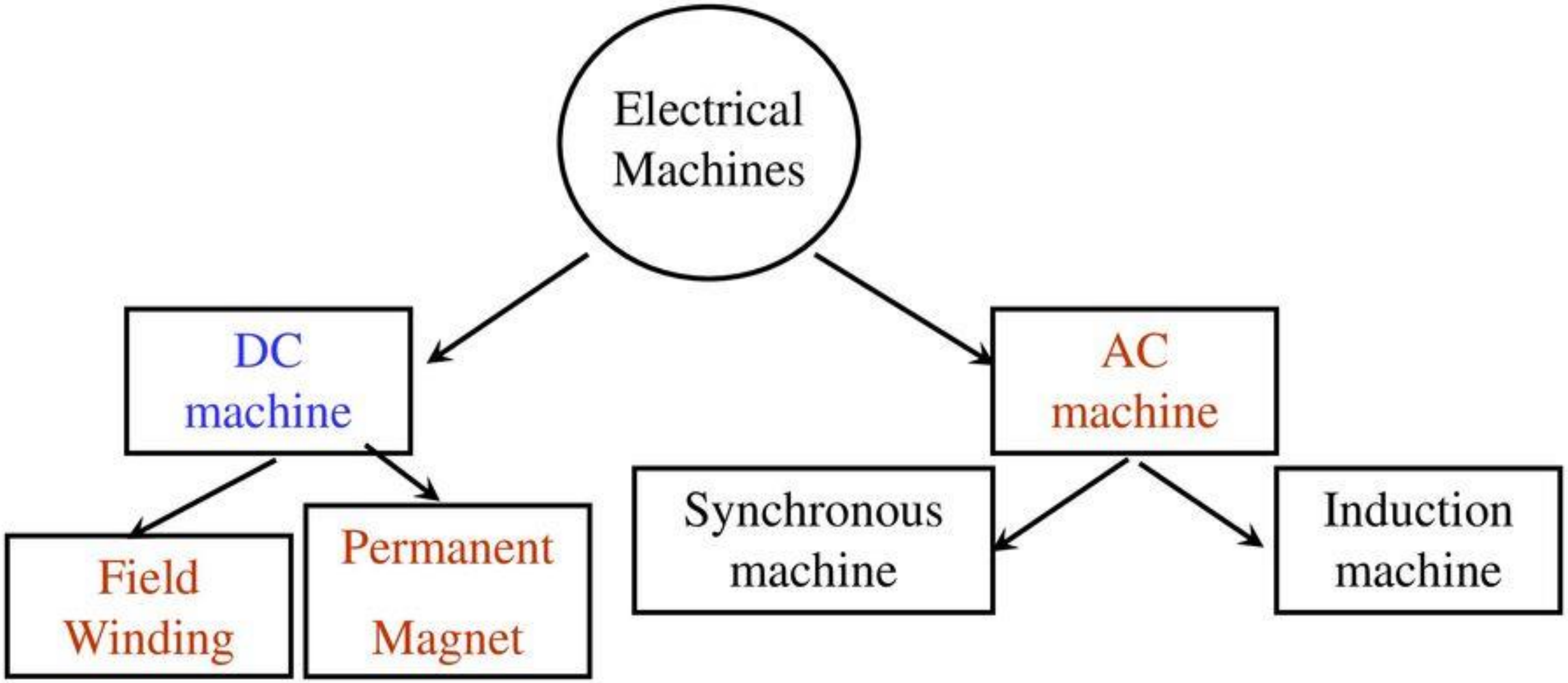
- Light bulbs and heater → electrical energy
- Fans and rolling mills → mechanical energy

Conversion from mechanical to electrical: generator



Conversion from electrical to mechanical: motor

- Continuous energy converter are called electrical machines
- AC electric supply → AC machines (synchronous and asynchronous)
- DC electric supply → DC machines



- Machines are called AC machines (generators or motors) if the electrical system is AC.
- DC machines (generators or motors) if the electrical system is DC.

Two electromagnetic phenomena in the electric machines:

- 1. Conductor moving in magnetic field

  - Motional voltage

$$e = Blv$$

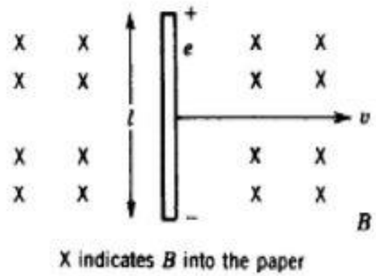
- Current carrying conductor in magnetic field

  - Electromagnetic force (Lorentz Force)

$$f = Bli$$

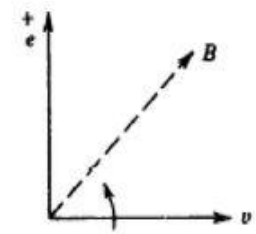
- Both phenomena occur simultaneously in energy conversion process.

Mutually perpendicular vectors



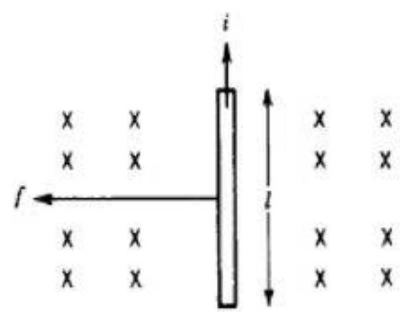
(a)

Conductor moving in magnetic field



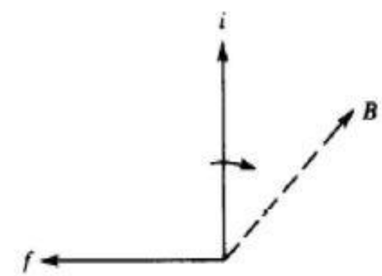
(b)

Right-hand screw rule



(a)

Current -carrying conductor moving in magnetic field

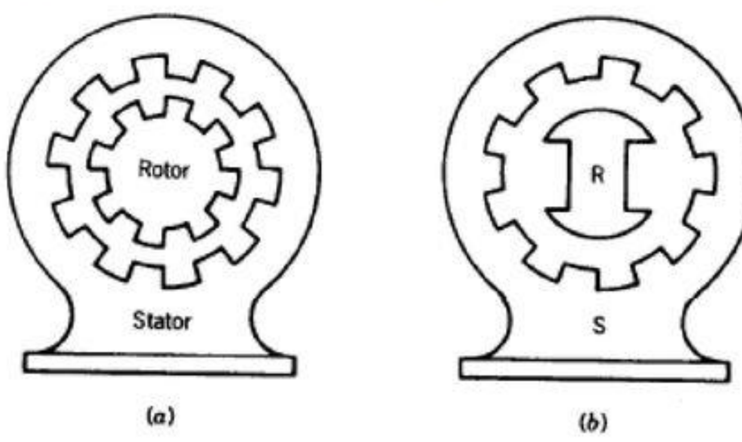


(b)

Force direction

Electric Machines Construction

- Stator and rotor (ferromagnetic materials)
- Slots with conductor
- Cylindrical machine (a) →uniform air gap
- Salient pole machine (b) → non uniform air gap
- Iron core → maximize flux density
- Laminations → reduce eddy current
- Conductors interconnected to form windings
- Armature winding → in which voltage is induced
- Field winding → the one that produces the primary flux



Structure of electrical machines

DC Machine Fundamentals

- **Generator action:** An emf (voltage) is induced in a conductor if it moves through a magnetic field.

- **Motor action:** A force is induced in a conductor that has a current going through it and placed in a magnetic field

- Any DC machine can act either as a generator or as a motor.

DC Machine Fundamentals

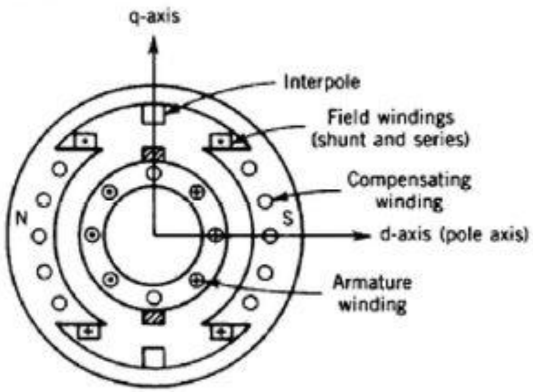
- DC Machine is most often used for a motor.
- The major advantages of dc machines are the easy speed and torque regulation.
- However, their application is limited to mills, mines and trains. As examples, trolleys and underground subway cars may use dc motors.
- In the past, automobiles were equipped with dc dynamos to charge their batteries.

DC Machine Fundamentals

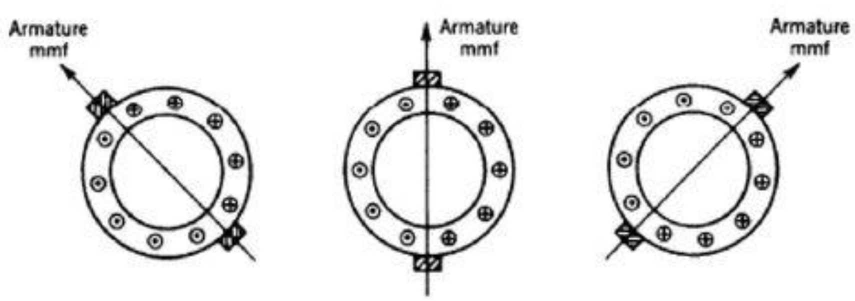
- Even today the starter is a series dc motor
- However, the recent development of power electronics has reduced the use of dc motors and generators.
- The electronically controlled ac drives are gradually replacing the dc motor drives in factories.
- Nevertheless, a large number of dc motors are still used by industry and several thousand are sold annually.

DC Machine

- Variable speed, large and small power range
- Field winding carrying DC-current in stator produces flux symmetrically distributed about pole axis = direct (d) axis
- Armature winding in rotor → Alternating voltage is induced
- Mechanical commutator and brush assembly rectify the voltage to become DC.
- Commutator-brush combination makes armature current distribution fixed in space
- mmf of armature winding along quadratic (q) axis → maximum torque , i.e at θ = 90 degree, Max. Torque produced at any time.



2-pole DC machine

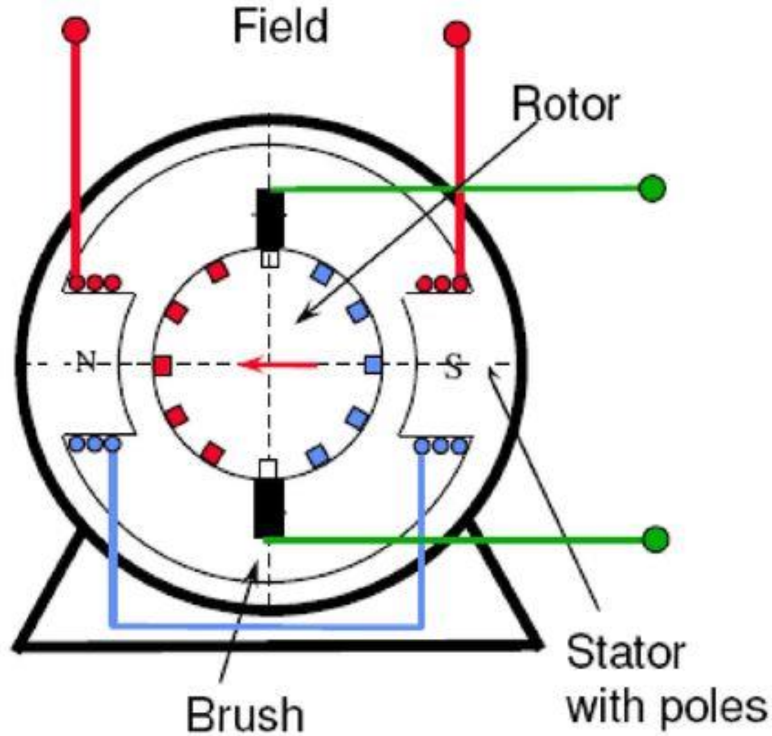


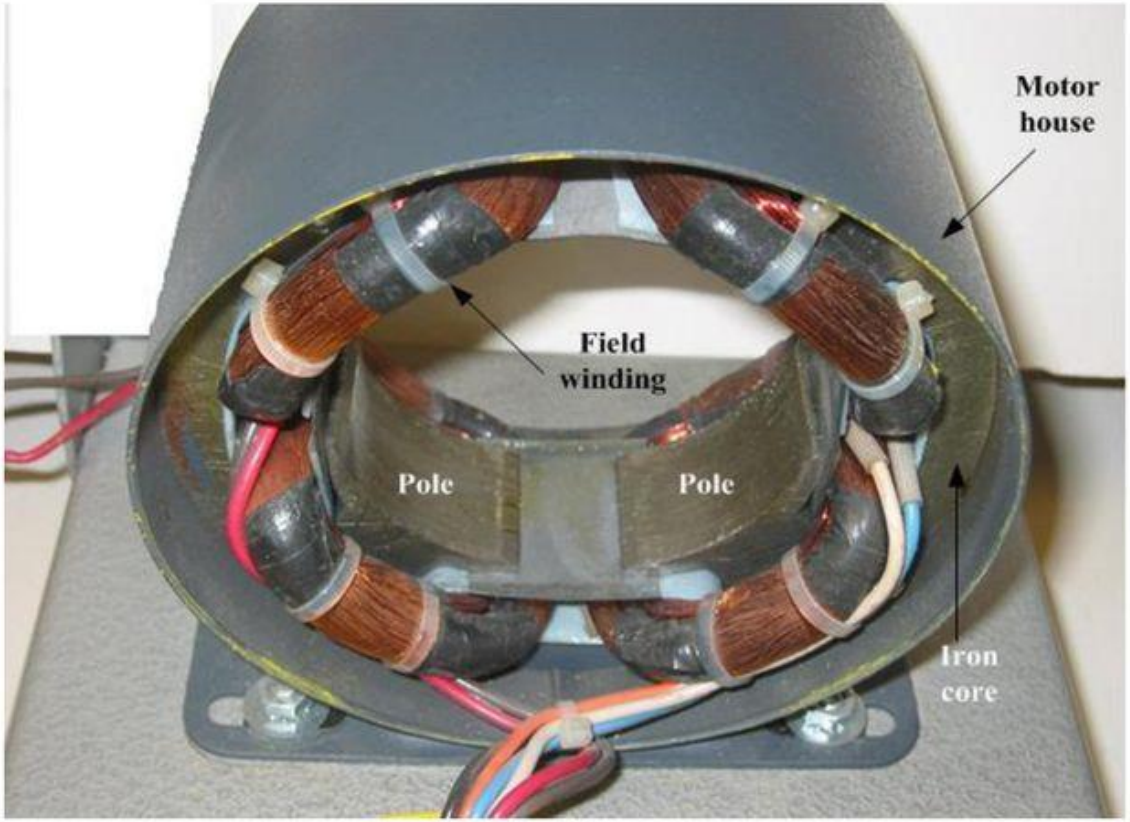
Shift of brush position to change armature mmf

DC Machines Construction

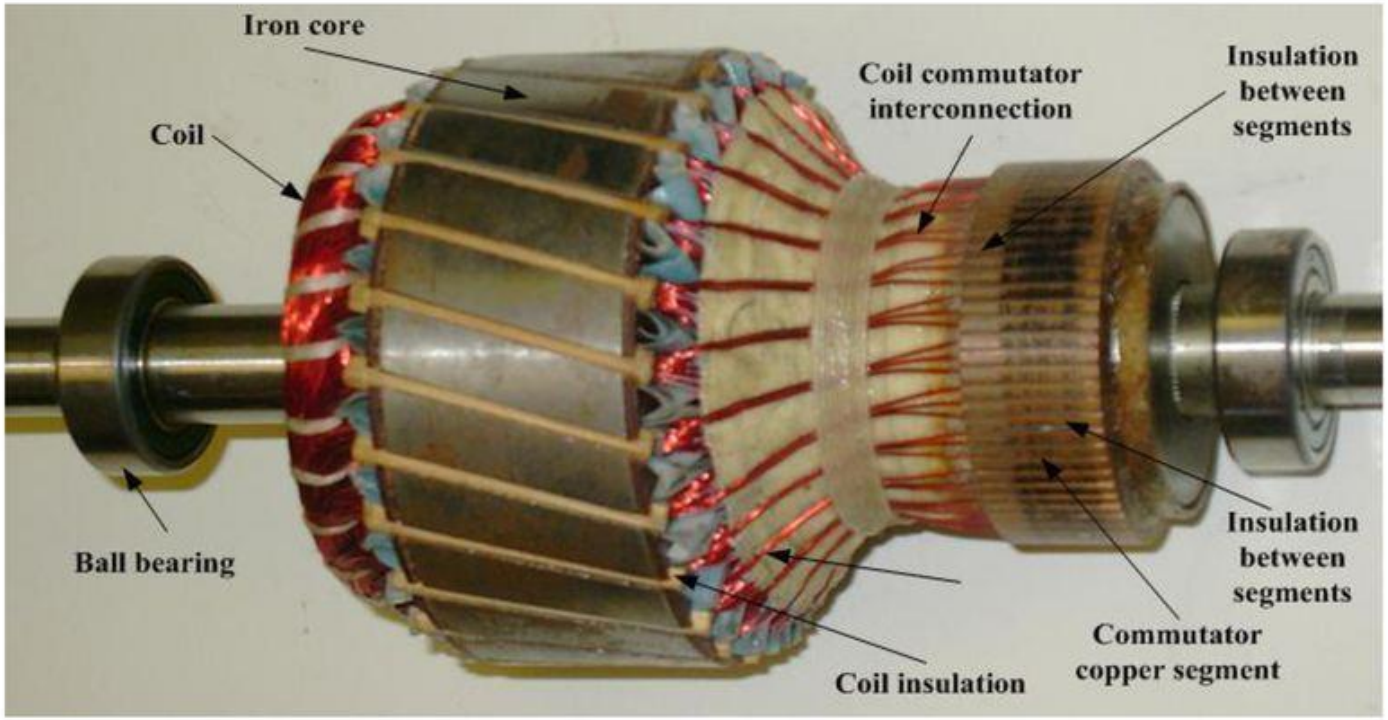
- **Stator:** Stationary part of the machine. The stator carries a field winding that is used to produce the required magnetic field by DC excitation. Often know as the field.

- **Rotor:** The rotor is the rotating part of the machine. The rotor carries a distributed winding, and is the winding where the emf is induced. Also known as the armature.

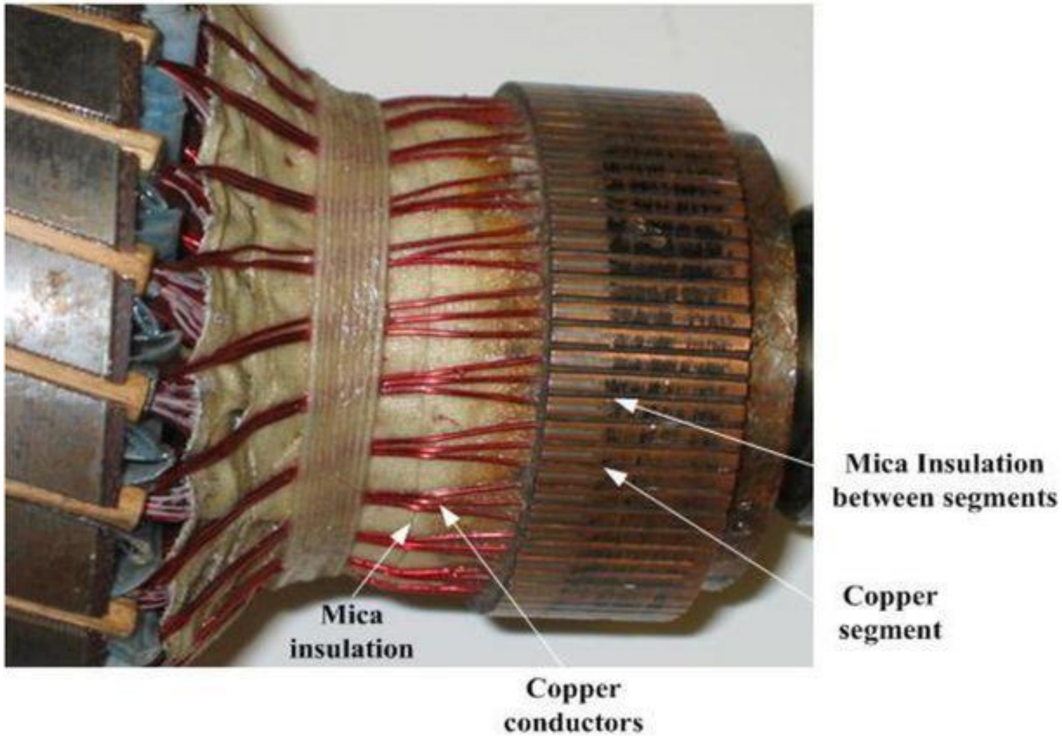




DC motor stator with poles



Rotor of a dc motor.

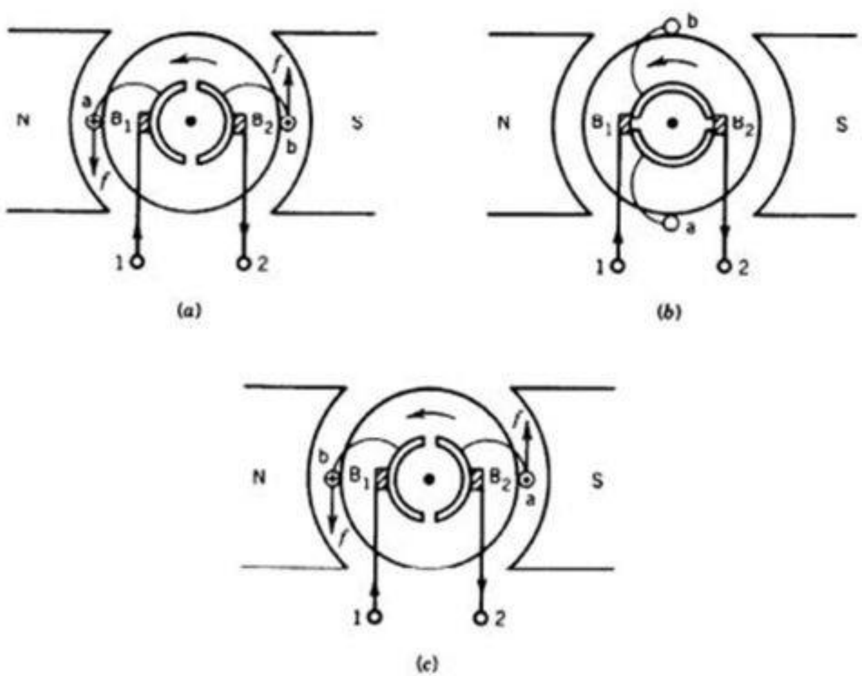


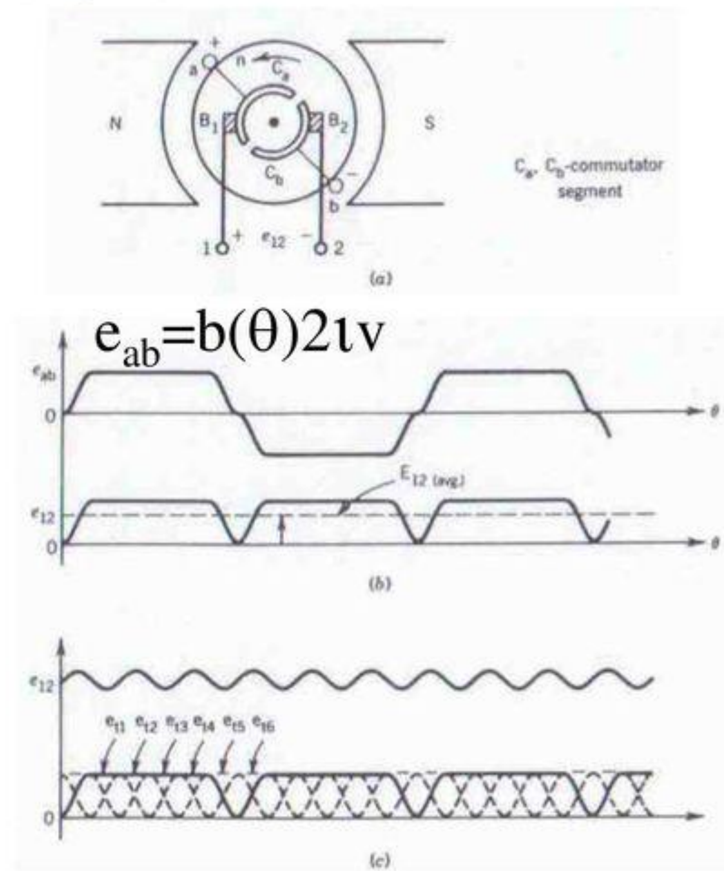
Details of the commutator of a dc motor.

Commutator & Brushes Operation

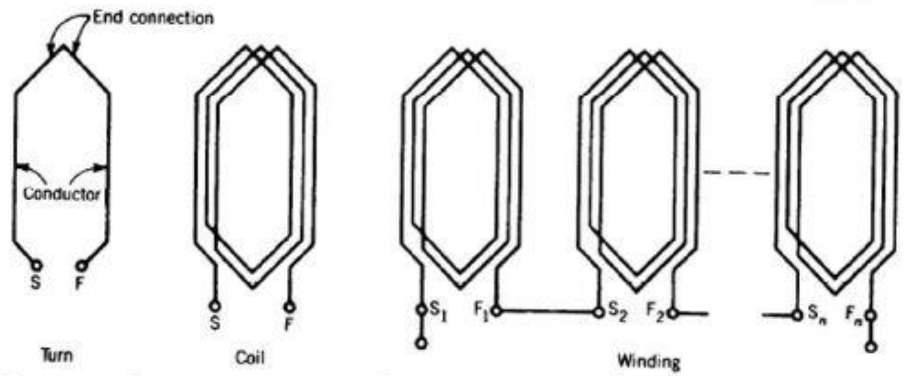
When the turn passes the interpolar region

- End touch brush B1, current flows from a to b (fig. a)
- The turn is short-circuited (fig. b), voltage e_{12}=0V
- The current in the turn will reverse (fig. c) i.e. from b to a

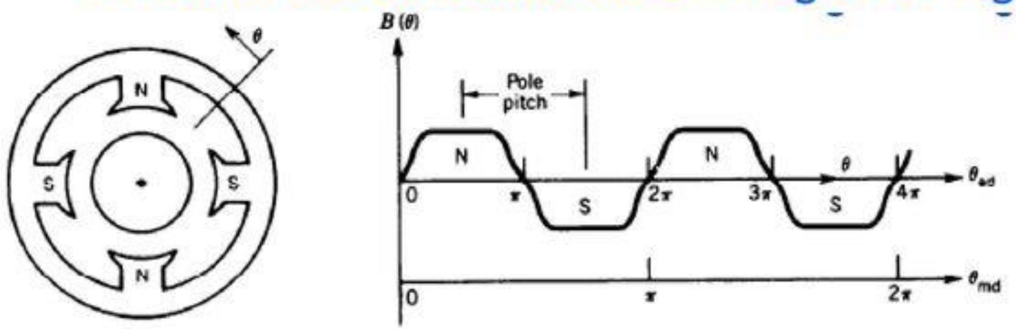




Armature Windings



- Large machines have more than two poles
  →most of the conductors are in region of high flux density



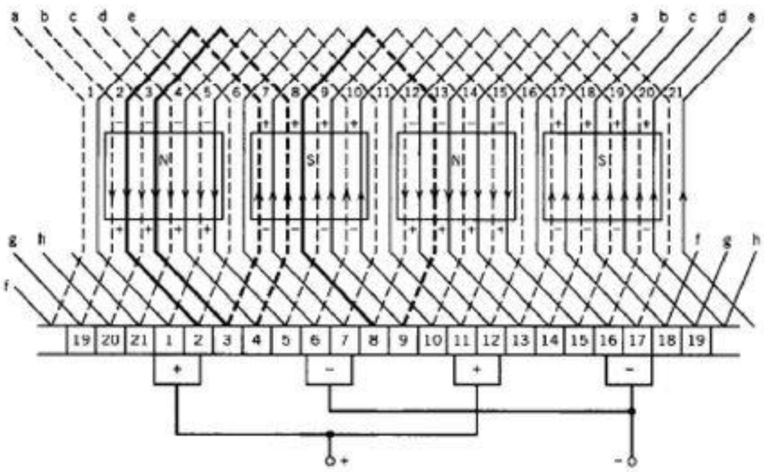
(a) (b)

- electrical degrees θ_{ed}
- mechanical degrees θ_{md}
- p number of poles

$$\theta_{ed} = \frac{p}{2}\theta_{md}$$

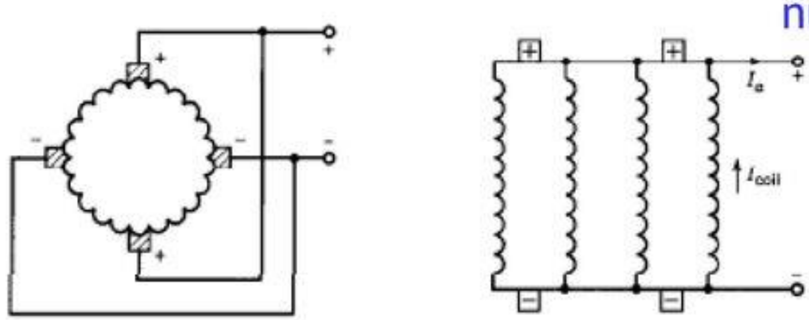
- pole pitch = distance between centers of two adjacent poles =180^{o}_{ed}
- coil pitch = distance between two sides of a coil
- full-pitch: coil pitch = pole pitch
- short-pitch: coil pitch < pole pitch (mainly in ac-machines)

Armature Windings - Lap winding



(a)

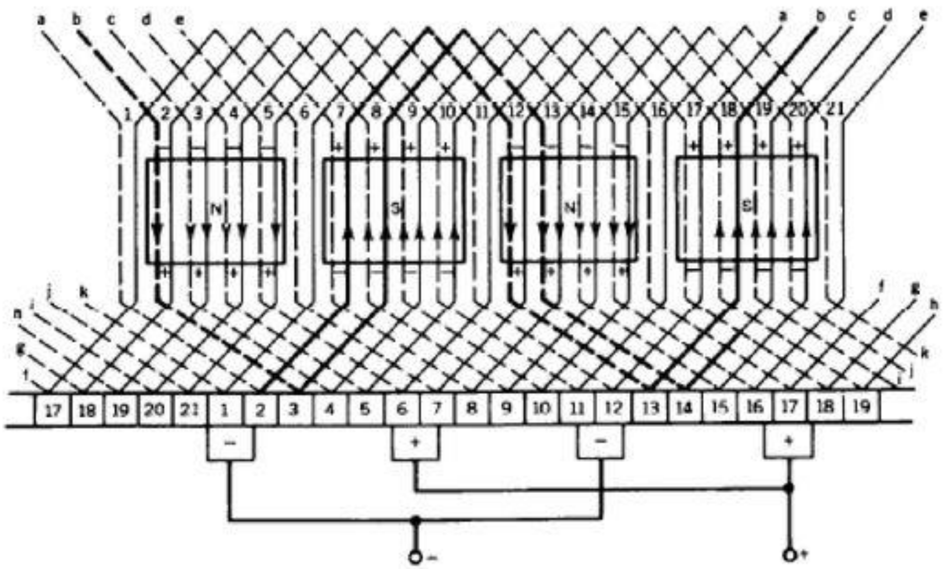
- one coil between two adjacent commutator bars
- 1/p of the total coils are connected in series
- suitable for high-current low voltage



(b)

number of parallel paths = a=number of poles
= number of brushes

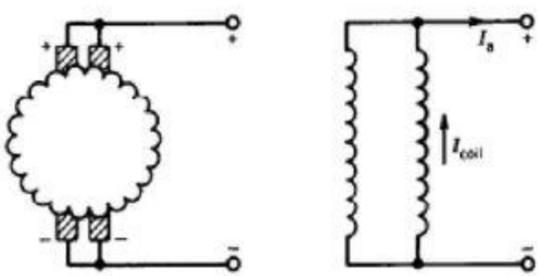
Armature Windings - Wave winding



(a)

- p/2 coil connected in series between two adjacent commutator bars
- suitable for high voltage low current

(a)

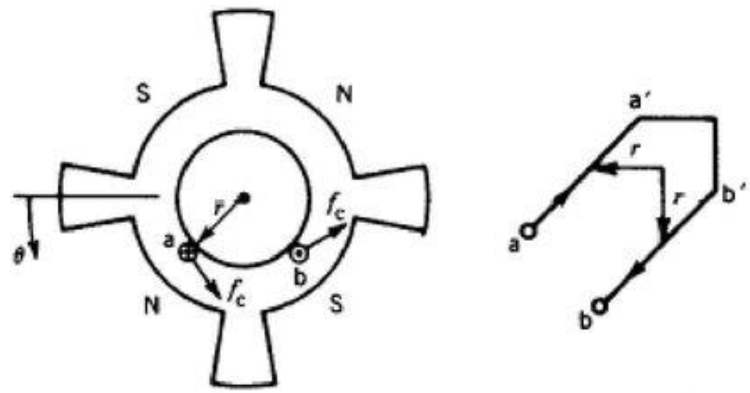


(b)

- number of parallel paths = 2
- number of brushes positions = 2 or more
- number of brushes is increased in large machines to minimize the current density In brushes.

Armature Windings - Voltage

- the voltage induced in a turn
  $$e_t = Blv = 2B(\theta)l\omega_m r$$
- average value of the voltage induced in a turn
  $$\bar{e}_t = 2\overline{B(\theta)}l\omega_m r = \frac{\Phi p}{\pi}\omega_m$$
- flux per pole Φ
  $$B(\theta) = \frac{\Phi}{A} = \frac{\Phi}{2\pi rl/p}$$
- induced voltage in the armature winding/parallel path
  $$E_a = \frac{N}{a}\bar{e}_t = \frac{Np}{\pi a}\Phi\omega_m = K_a\Phi\omega_m$$
- *Ea* independent of operation mode
  - in generator: generated voltage
  - in motor *back emf*



N number of turns in the armature winding
a number of parallel paths
Z total number of armature conductors = 2N

- machine constant, Ka

$$K_a = \frac{Np}{\pi a} \qquad K_a = \frac{Zp}{2\pi a}$$

Armature Windings - Torque

- the force on a conductor

$$f_c = Bli = B(\theta)li_c = B(\theta)l\frac{I_a}{a}$$

- the torque on a conductor

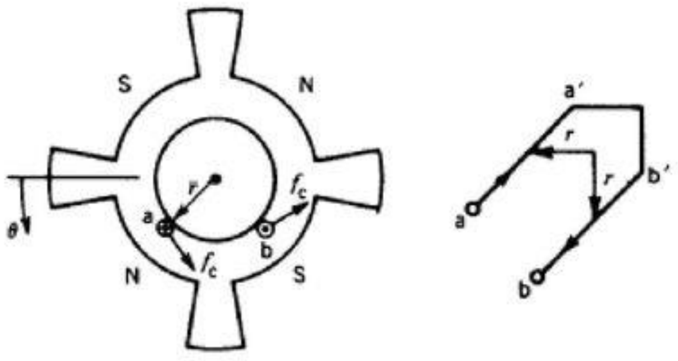
$$T_c = f_c r$$

- the average torque on a conductor

$$\bar{T}_c = \overline{B(\theta)}l\frac{I_a}{a}r = \frac{\Phi p I_a}{2\pi a}$$

- the total torque developed

$$T = 2N\bar{T}_c = \frac{N\Phi p}{\pi a}I_a = K_a\Phi I_a$$



- machine constant

$$K_a = \frac{Np}{\pi a}$$

- power balance

$$T = K_a\Phi I_a$$
$$E_a = K_a\Phi\omega_m$$
$$\Rightarrow \quad E_a I_a = K_a\Phi\omega_m I_a = T\omega_m = P$$

Example 1

Q. A four pole dc machine has an armature of radius 15 cm and an effective length of 30 cm. The poles cover 75% of the armature periphery. The armature winding consists of 35 coils, each coil having seven turns. The coils are accommodated in 35 slots. The average flux density under each pole is 0.85 T.

If the armature is lap-wound,

N(rpm)(2π/60) $rads^{-1}$

(a) Determine the armature constant K_a.

(b) Determine the induced armature voltage when the armature rotates at 1000 rpm.

(c) Determine the current in the coil and electromagnetic torque developed when the armature current is 400 A.

(d) Determine the power developed by the armature.

r=15cm, l=30cm, N=35, slot=35, B=0.85. , p=4, w=1000

Sol_pg20

Sen Pg. 139

Example 2

If the dc machine armature in example 1 is wave-wound, repeat parts (a)-(d).

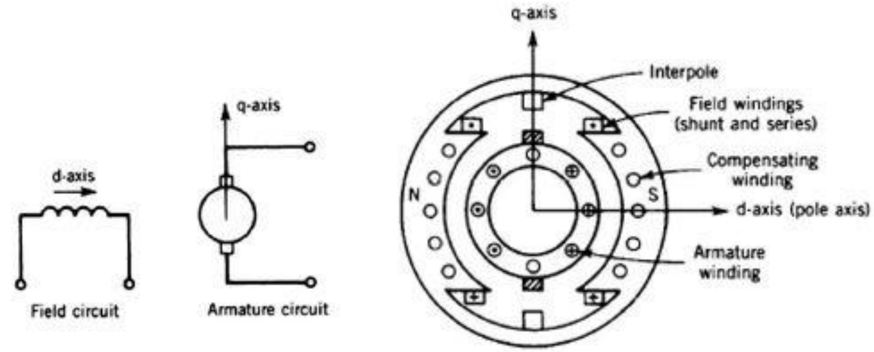
$$K_a = \frac{Zp}{2\pi(a)} = \frac{2x35x7x4}{2\pi(2)} = 156.1$$

$$\Phi = 0.0374$$

$$E_a = K_a \Phi.\omega = 156.1x0.0374x1000x\frac{2\pi}{60} = 611.1V$$

Magnetization

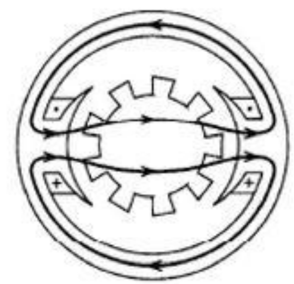
- field mmf on d-axis
  - armature mmf on q-axis
  - no coupling (quadrature/decoupled mmf)



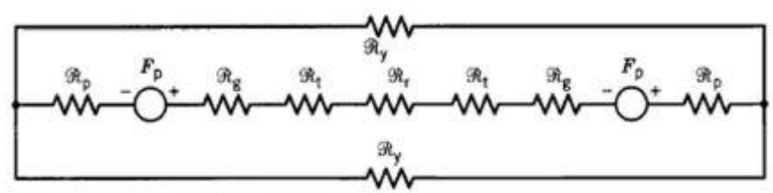
- Magnetic core with infinite permeability at low values of flux (ampere-turns)
- Assume material U_r infinite permeability, reluctance in airgap only.

Magnetic flux/pole Φ given as

$$\Phi = \frac{2F_p}{2\Re_g} = \frac{F_p}{\Re_g}$$



(a) Cross-section view



(b)

Equivalent circuit

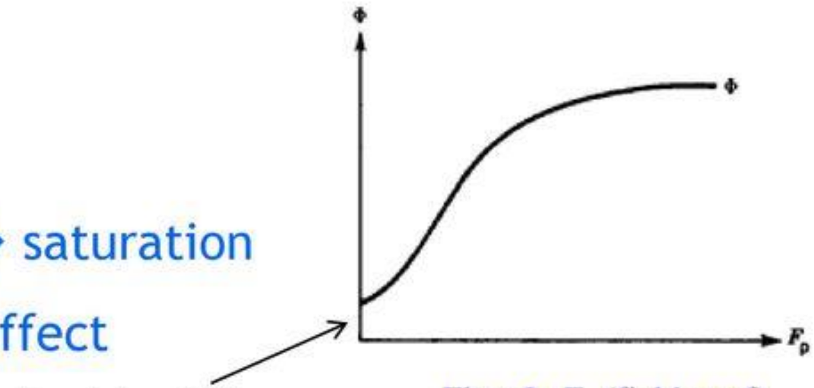
Magnetization Curve

- It is more convenient if the magnetization curve is expressed in terms of armature induce voltage E_a at a particular speed (Fig. a).
- The magnetization curve obtained experimentally by rotating the dc machine at 1000 rpm and measuring the open-circuit armature terminal voltage as the current in the field winding is changed (Fig b). Represents the saturation level in the magnetic system of the dc machine for various values of the excitation mmf.

Magnetization Curve

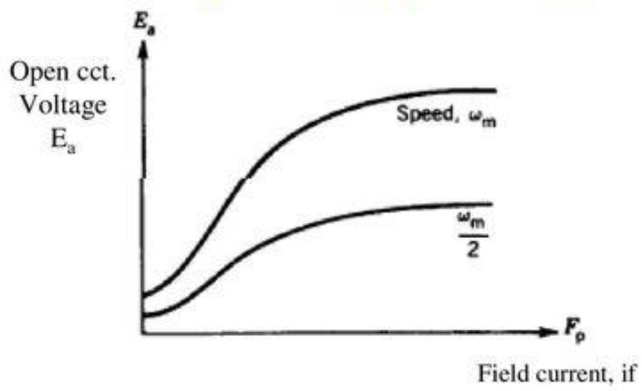
$$\Phi = \frac{2F_p}{2\Re_g} = \frac{F_p}{\Re_g}$$

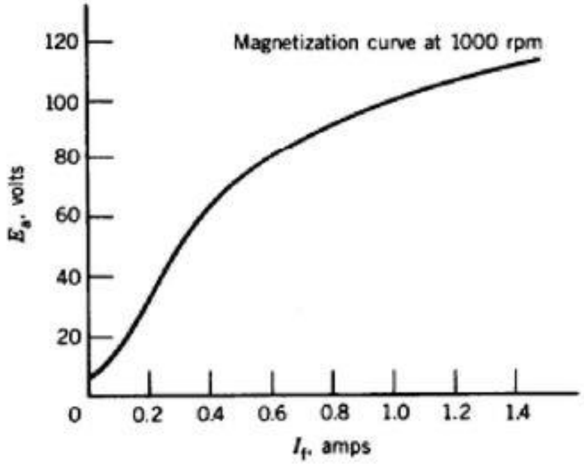
- increased F_p → Φ increased √→ saturation
- Assume armature mmf has no effect



Flux Φ- F_p (field mmf) relationship

- induced voltage in armature proportional to flux times speed ($E_a \propto \Phi\omega_m$)

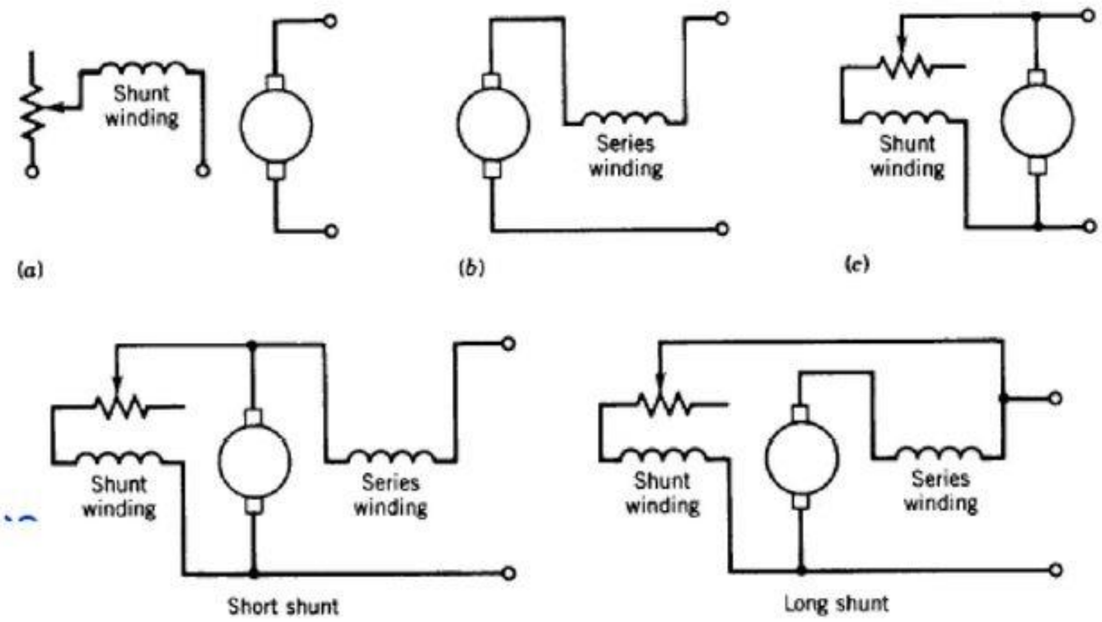




Classification of DC Machines

- The field circuit and armature circuit can be interconnected in various ways to provide a wide variety of performance characteristics-an out standing advantage of dc machines.
- The field poles can be excited by two field windings, a shunt filed winding and a series field winding.
- The shunt winding has a large number of turns and takes only a small current (< 5% rated armature current).
- The series winding has fewer turns but carries a large current.
- If both windings are used, the series winding is wound on top of the shunt winding.

Classification of DC Machine



(a) Separately excited machine

(b) Series machine

(c) Shunt machine

(d) Compound machine

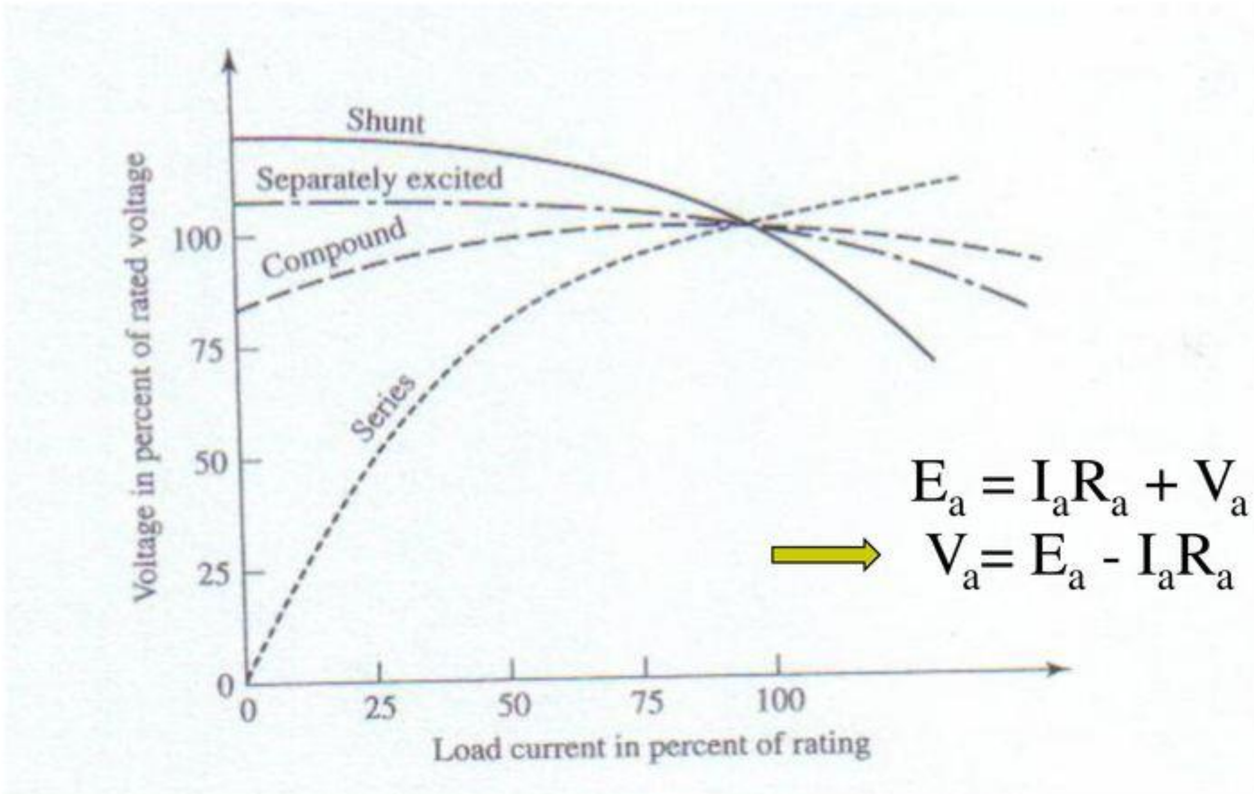
Self-excited generator – need residual flux in machine iron (applies to b–d)

* Permanent magnet can be considered as separately excited m/c., but constant excitation

Classification of DC Machines

- Both shunt and series windings may be used , resulting in a compound machine.
- If the shunt winding is connected across the armature, it is known as short-shunt machine.
- In an alternative connection, the shunt winding is connected across the series connection of armature and series winding, and the machine is known as long-shunt machine.
- A rheostat is inserted in field winding to control the field excitation (vary mmf field)

Generators v-i characteristics



$$E_a = I_a R_a + V_a$$

$$V_a = E_a - I_a R_a$$

V-I characteristics of DC generators

Example 3

- A lap-wound armature is used in a six-pole dc machine. There are 72 coils on the armature, each containing 12 turns. The flux per pole in the machine is 0.039 W_b and the machine spins at 400 rpm.

  Determine the induced voltage E_a.

$$Z = 2N = 2x72x12 = 1728;$$

$$K_a = Zp/(2a\pi)$$

$$a = p = 6$$

$$\text{flux/pole} = 0.039$$

$$\omega = 400\ \text{rpm} = 400(2\pi)/60$$

$$E_a = K_a.\omega.\Phi = 449.28$$

Example 4

- A 12 pole dc generator a wave wound armature containing 144 coils of 10 turns each. The resistance of each turn is 0.011 ohm. Flux per pole is 0.05 W_b and it is running at a speed 200 rpm.

  $E_a = ?$

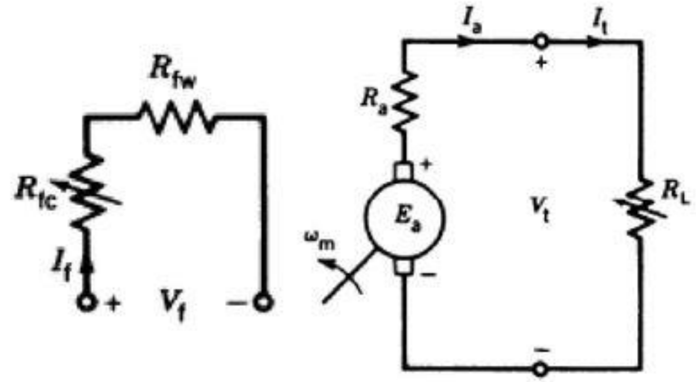
  $T = ?$

DC Generator

- The dc machine operating as a generator is driven by a prime mover at a constant speed and the armature terminals are connected to a load.
- In many applications of dc generators, knowledge of the variation of the terminal voltage with load current is essential.

Separately Excited DC Generator

- The field winding is connected to a separate source of dc power, i.e. another dc generator, a controlled rectifier, a diode rectifier, or a battery.
- The steady-state defining equations are



• field winding

$$V_f = R_f I_f$$

• armature winding

$$E_a = V_t + I_a R_a$$

External Characteristic

$$E_a = K_a \Phi \omega_m$$

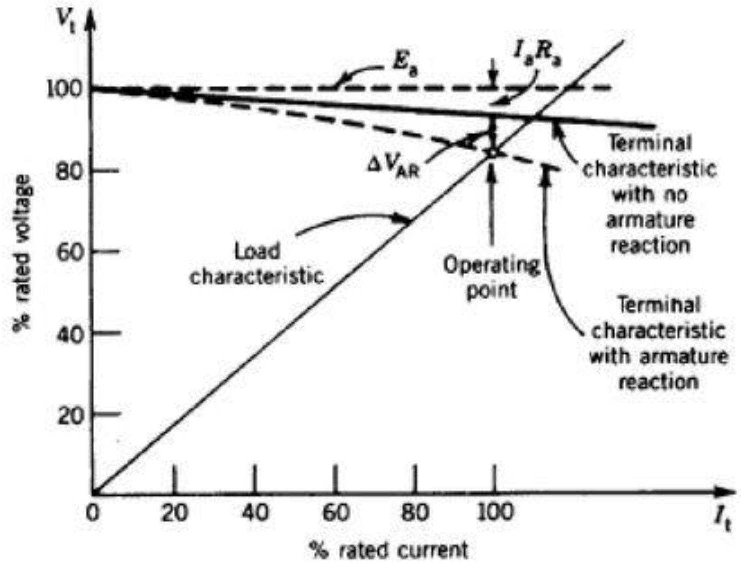
• operating point

$$V_t = I_t R_L$$

$$I_a = I_t$$

$$V_t = E_a - R_a I_a$$

Separately Excited DC Generator



ΔV_{AR} voltage drop due to armature reaction (see later)

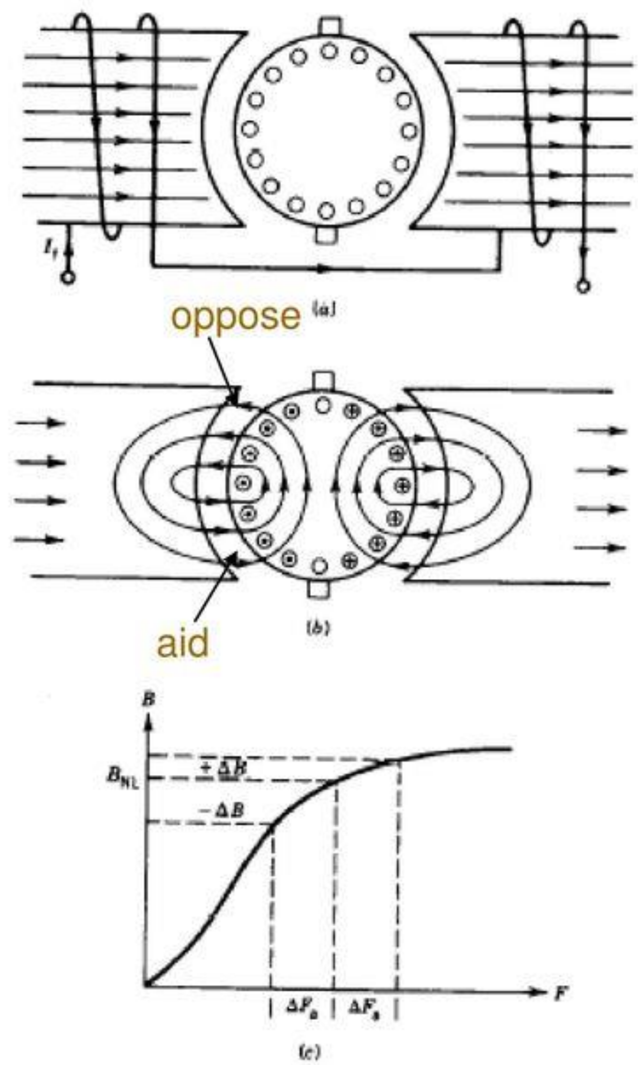
$V_t = E_a - (I_aR_a + \Delta VAR)$

Load charac. $V_t = I_t.R_L$

- The terminal and load characteristic is shown in the Fig.
- The point of intersection between the generator external characteristic and the load characteristic determines the operating point, that is, the operating values of the terminal voltage V_t and the terminal current I_t

Armature Reaction

- With no current flowing in the armature, flux in the machine is established by the mmf produced by the field current (a).
- However, if the current flows in the armature circuit it produces its own mmf (hence flux) acting along the q axis (b). Hence the original flux from field is disturbed.
- Saturation (flux density under one pole increased-> reduction flux per pole



Armature Reaction

$$E_a = V_t + I_a R_a$$

- armature reaction in equivalent field current

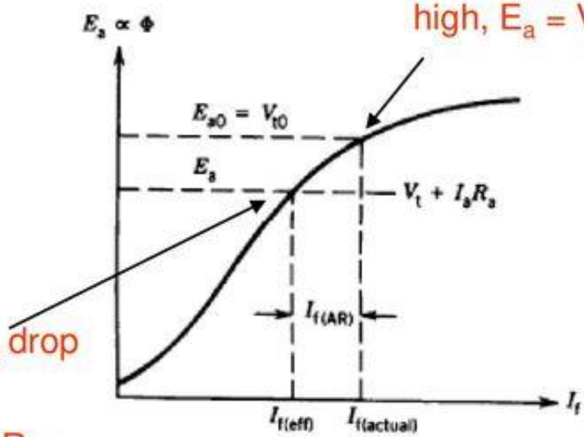
$$I_{f(eff)} = I_{f(actual)} - I_{f(AR)}$$

- terminal characteristic

$$V_t = E_a - R_a I_a$$

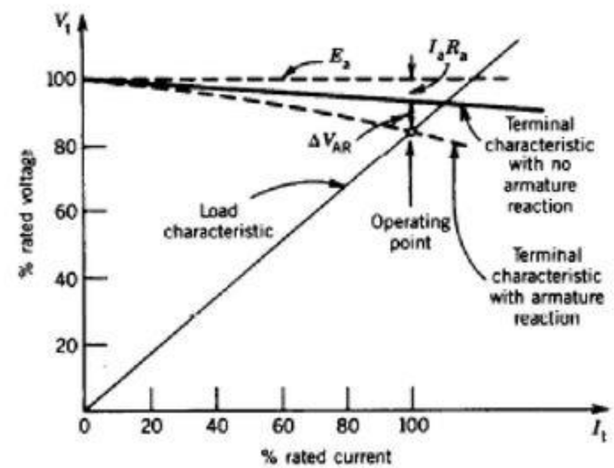
$$E_a = K_a \Phi \omega_m$$

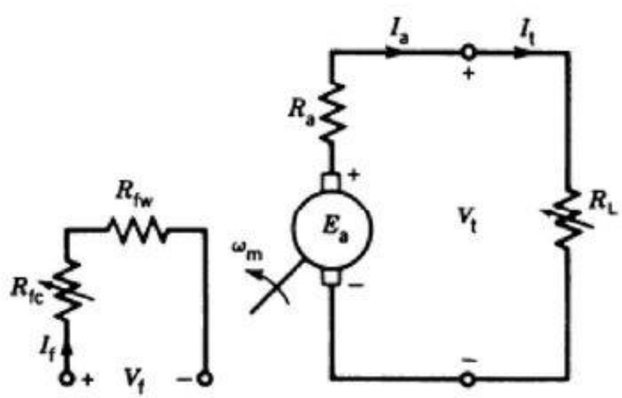
At no load, I_a=0, E_a high, $E_a = V_t$



Loaded, E_a drop due AR'

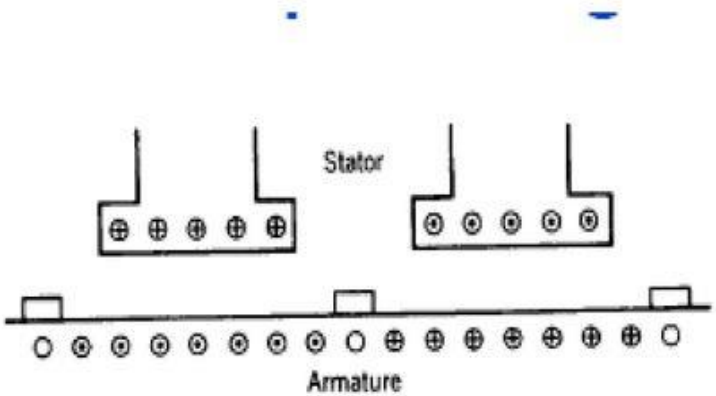
$E_a = V_t + I_aR_a$

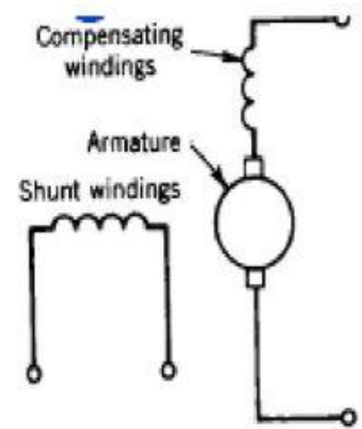




Armature Reaction – Compensating Winding

- The armature mmf distorts the flux density distribution and also produces the demagnetizing effect known as armature reaction.
- Much of the rotor mmf can be neutralized by using a compensating winding, which is fitted in slots cut on the main pole faces.
- These pole face windings are so arranged that the mmf produced by currents flowing in these windings are proportional of armature mmf but opposes the armature mmf.





Remedies for field distortion

- By increasing the length of air gap – make reluctance high and strong mmf requires to force flux in air gap.
- By providing machine with a compensating winding – produce mmf to neutralise mmf armature
- By using interpole – small auxiliary pole
- By reducing cross-section of pole pieces

Example 5

Q. A 12 kW, 100 V, 1000 rpm dc shunt generator has armature resistance R_a= 0.2 ohm, shunt field winding resistance R_{fw}= 80 ohm, and N_f= 1200 turns per pole. The rated field current is 1.0 ampere. The magnetization characteristic at 1000 rpm is shown in the next figure.

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

a. Neglect the armature reaction effect. Determine the terminal voltage, Vt, at full load (rated load).

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

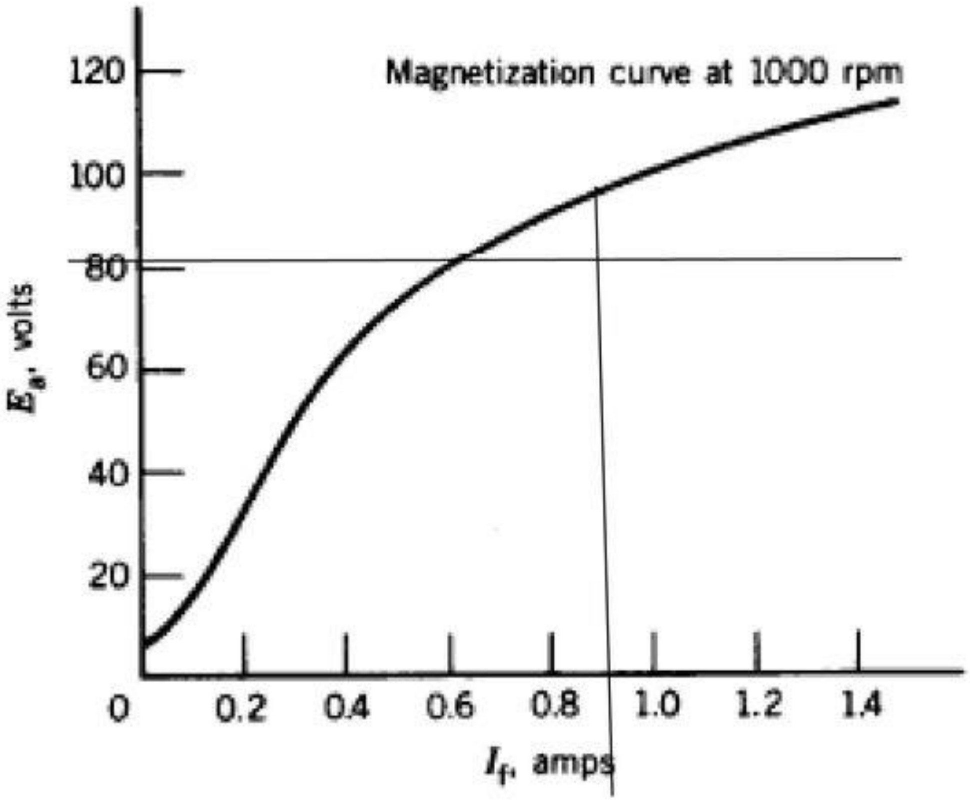
(i) Determine the full load terminal voltage.

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

Sen pg. 151

Sol_pg10

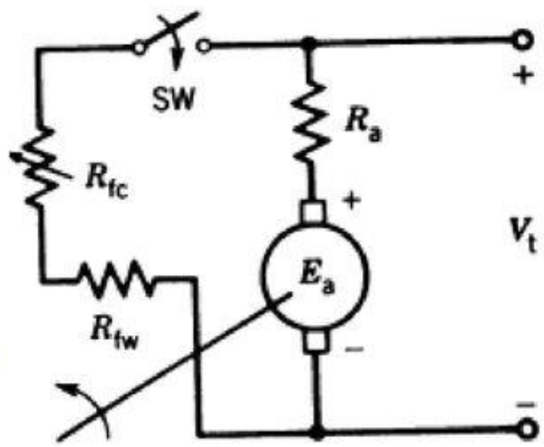
Cont. Example 5



Shunt (Self-Excited) Generator

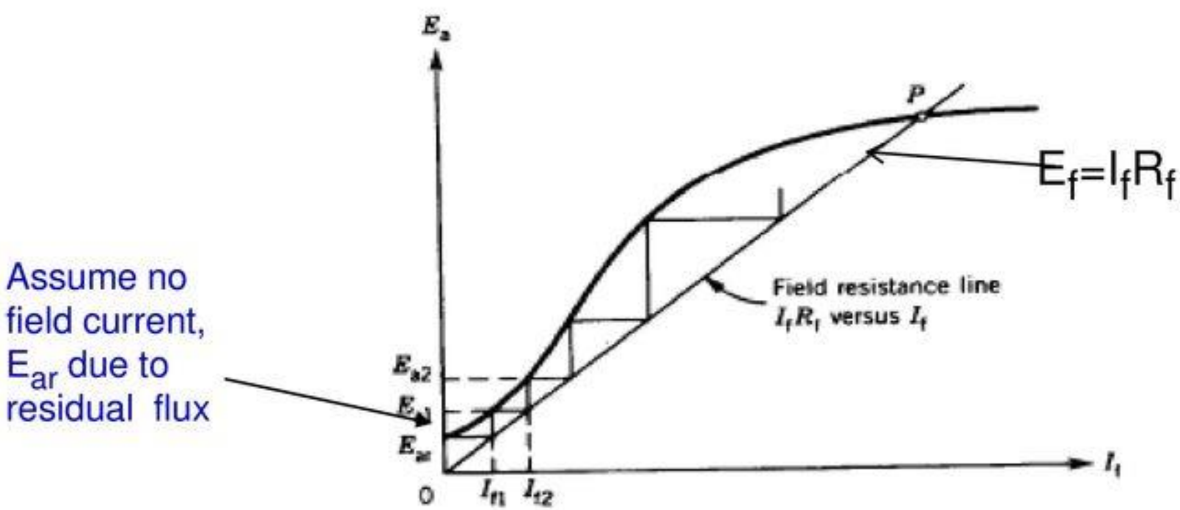
- In the shunt or self-excited generator the field is connected across the armature so that the armature voltage can supply the field current (5% of I_a rated).
- Under certain conditions, this generator will build up a desired terminal voltage.
- The circuit for the shunt generator under no-load conditions is shown below.

$$R_f = R_{fc} + R_{fw}$$



Shunt Generator

- If the machine is to operate as a self-excited generator, some residual magnetism must exist in the magnetic circuit of the generator.
- Magnetization curve of the dc machine (Fig)
- Also shown the field resistance line, which is a plot of $R_f I_f$ versus I_f
- A simplistic explanation of the voltage buildup process in the self-excited dc generator.
- Assume field initially disconnected and armature is driven at certain speed. Small voltage E_{ar} appears due to the residual flux.
- Then switch closed. If flows in the field . If this if add to previous flux, then if increase. This increase E_{ar} to E_{a1} then it will build up.

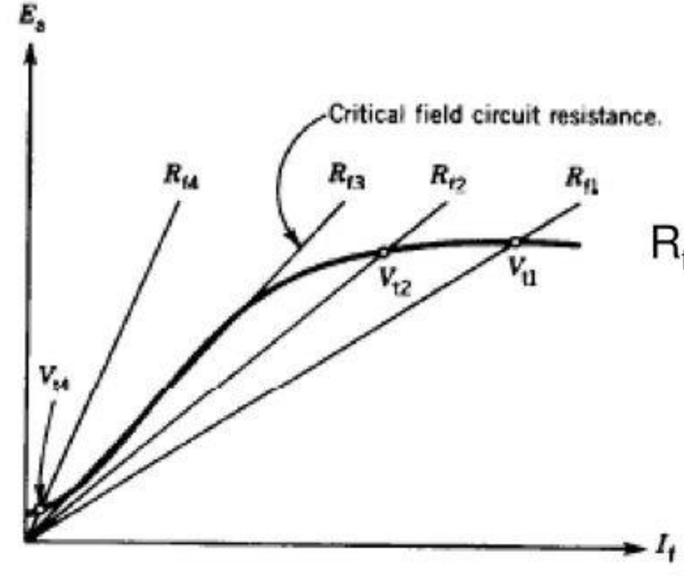


Shunt Generator

- Voltage buildup in the self excited dc generator for various field circuit resistances (Fig)
- At some resistance value R_{f3}, the resistance line is almost coincident with the linear portion of the magnetization curve, is known as the critical field circuit resistance., $R_{f3} = Ef_3/if_3$
- If the resistance is smaller than this value, such as R_{f1} or R_{f2}, the generator will buildup higher voltages.

Three conditions for voltage build up:

1. Residual magnetism must be present.
2. Field winding mmf aids residual magnetism.
3. $R_f < R_{fc}$



$R_{f1}<R_{f2}<R_{f3}$

Example 6

- The dc machine in Example 5 is operated as a self-excited (shunt) generator at no load.

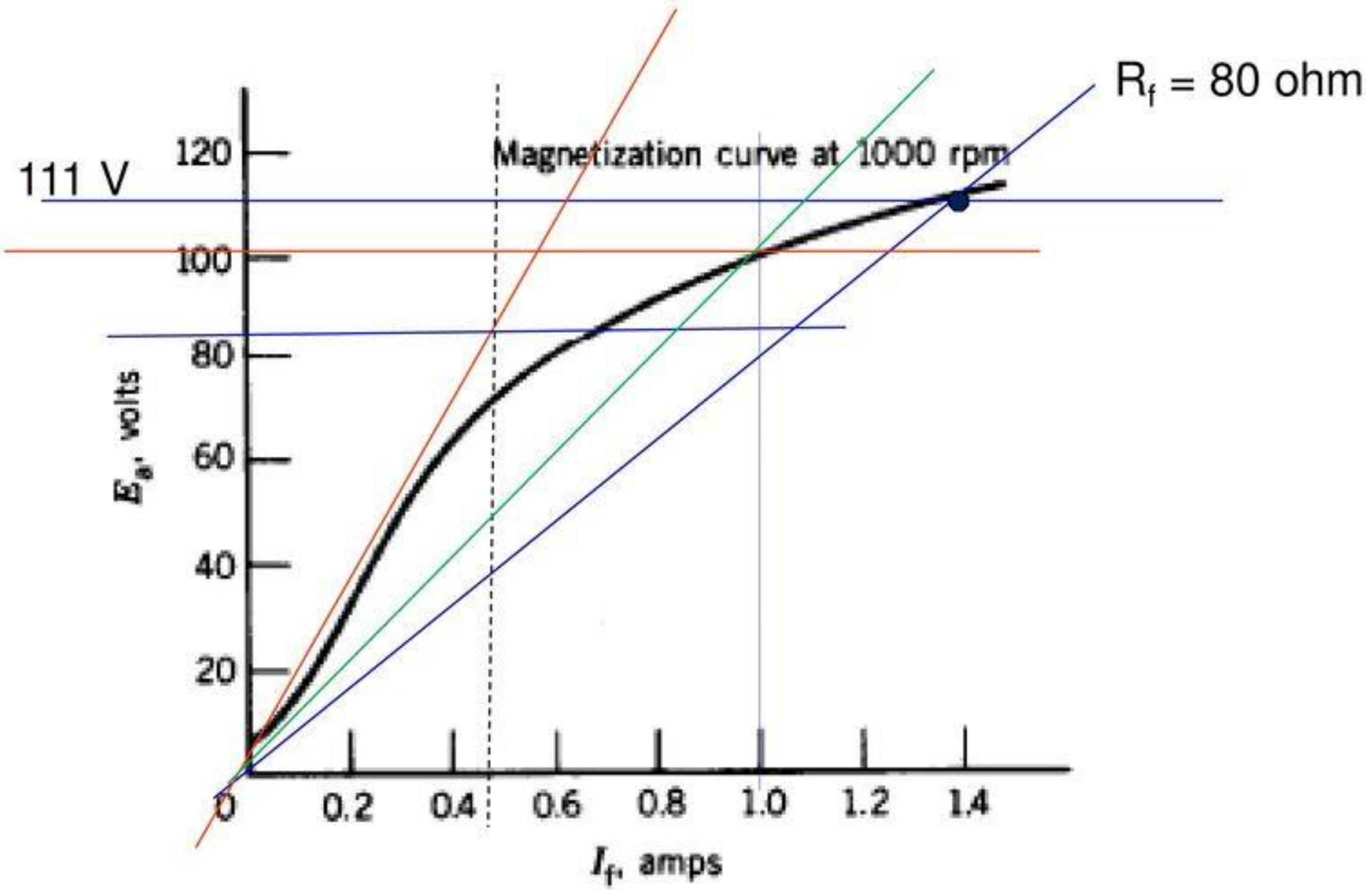
a. Determine the maximum value of the generated voltage.
b. Determine the value of the field circuit control resistance (R_{fc}) required to generate rated terminal voltage.
c. Determine the value of the critical field circuit resistance.

Sol_pg15

Sen pg. 154

i. Step --Maximum E_a at min R_f, i.e .$R_f = R_{fw}$ = 80 0hm– Draw line $80i_f$ --- Ea = 111 V

ii. At rated, Ia = 12k/100= 120 A. ; Vt= 111-120(0.1) = 100V



Shunt Generator – Voltage (V_t)–Current (I_a) Characteristics/ External Characteristic

- steady-state equations

function of I_f

$$E_a = V_t + I_a R_a \qquad E_a = K_a \Phi \omega_m$$

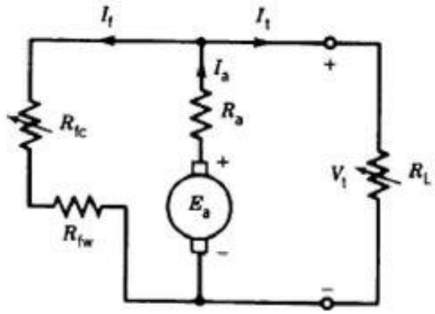
$$V_t = I_f R_f = I_f (R_{fw} + R_{fc})$$

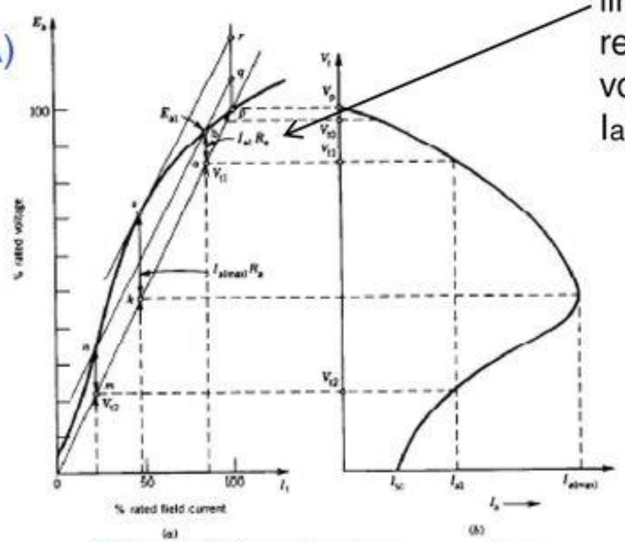
$$V_t = I_L R_L \qquad I_a = I_f + I_L$$

- procedure to get the terminal characteristic (no RA)
  - magnetization curve + field resistance line

$$V_t = I_f R_f \qquad I_a = \frac{E_a - V_t}{R_a}$$

- for a given I_f we get V_t and I_a
- plot V_t vs. I_a
- if I_t=0, I_a= I_f → $V_{t0} \neq V_p$
- voltage drops faster with armature current because voltage drop → field current drop





Magnetising curve

V-I curve

Voltage – Current Characteristics

Terminal voltage drop if armature reaction take into account . i.e $V_{ta} < V_{t1}$. Slide down the triangular pqr, until it suites one complete area under OCC and field line, op., then find V_{ta}.

- *pq* is proportional to I_aR_a

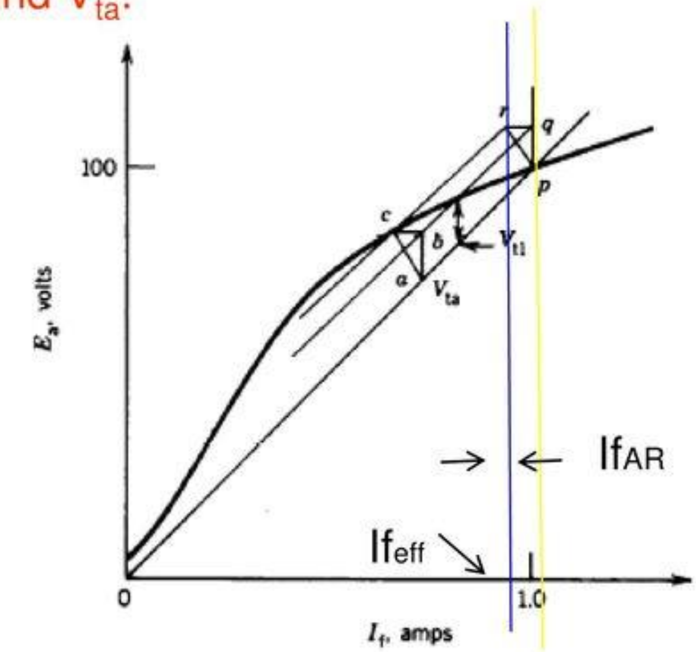
$$I_a = \frac{E_a - V_t}{R_a}$$

- *qr* represent armature reaction in equivalent field current

$$I_{f(eff)} = I_{f(actual)} - I_{f(AR)}$$

$= I_{f\,(actual)} - qr$

qr =bc



Vt_1 – No armature reaction

Vt_a – with armature reaction

Example 7

- The dc machine in Example 5 is operated as a self-excited (shunt) generator.

a. The no load terminal voltage is adjusted to 100V. Determine the full load terminal voltage. Neglect armature reaction.

b. Repeat (a), assuming that the effect of armature reaction at full load is equivalent to 0.06 A field ampere, that is $I_f(AR) = 0.06$ A.

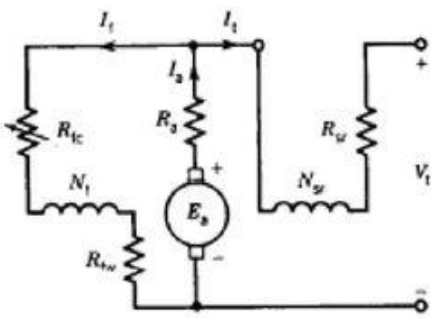
c. Determine the maximum value of the armature current and corresponding value of the terminal voltage. Assume $I_f(AR)$ proportional to I_a.

d. Determine the generator short-circuit current.

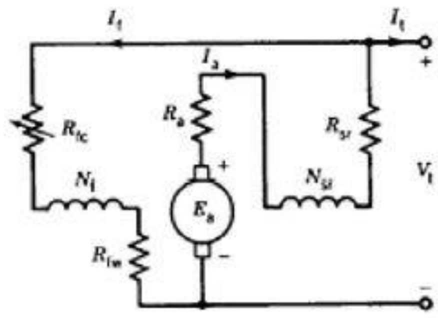
Sen pg. 159

Compound DC Machines

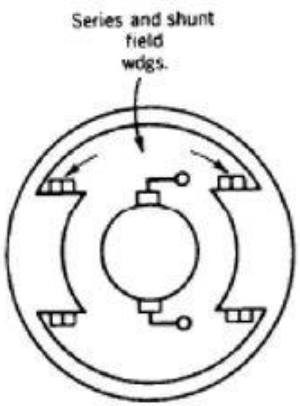
To overcome the I_aR_a drop and decrease of pole flux due to armature reaction, the additional winding (series winding) is mounted on the field poles along with shunt winding. It provides additional mmf to increase or decrease pole flux.



(a)



(b)



- short-shunt

$$V_t = E_a - I_aR_a - I_tR_{sr}$$

$$I_t = I_a - I_f$$

- long-shunt

$$V_t = E_a - I_a(R_a + R_{sr})$$

$$I_t = I_a - I_f$$

$$I_f = \frac{V_t}{R_{fw} + R_{fc}}$$

Compound DC Machines

- generated voltage for both connection

$$E_a = K_a(\Phi_{sh} \pm \Phi_{sr})\omega_m$$

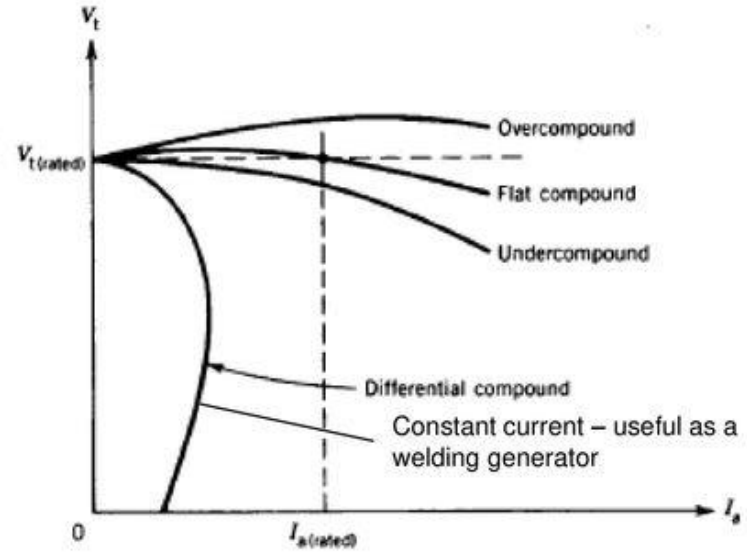
- shunt and series mmf act on the same circuit

$$F_{eff} = F_{sh} \pm F_{sr} - F_{AR}$$

$$N_f I_{f(eff)} = N_f I_f \pm N_{sr} I_{sr} - N_f I_{f(AR)}$$

$$I_{f(eff)} = I_f \pm \frac{N_{sr}}{N_f} I_{sr} - I_{f(AR)}$$

- Φ_{sh} – flux/per pole in shunt field winding
- Φ_{sr} – flux/per pole in series field winding
- Commulative compound machine – flux aid each other
- Differential compound machine – flux oppose each other



V-I characteristics of compound DC generators

Example 9

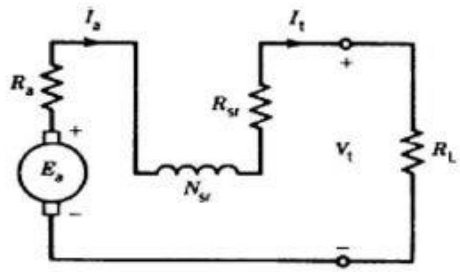
- The dc machine in Example 5 is provided with a series winding so that it can operate as a compound dc machine. The machine is required to provide a terminal voltage of 100 V at no load as well as at full load. (i.e. zero voltage regulation) by cumulatively compounding the generator. If the shunt field winding has 1200 turns per pole, how many series turns per pole are required to obtain zero voltage regulation. Assume a short-shunt connection and that the series winding has a resistance R_{sr} = 0.01 ohm.

PC Sen pg 163

Sol_pg24

Series Generator

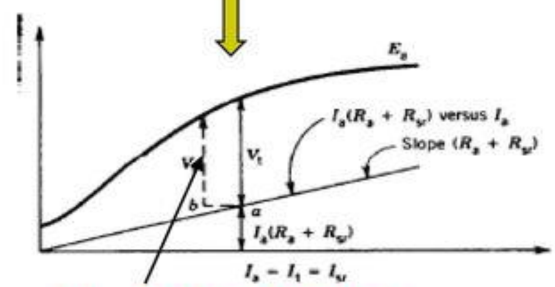
Field winding provides flux as the armature current flows through it. A load RL must be connected



$$E_a = V_t + I_a(R_a + R_{sr})$$

$$I_t = I_a$$

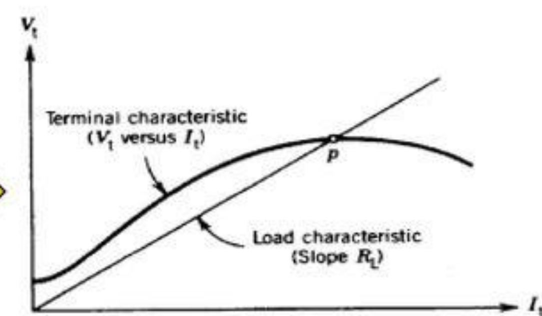
Graf :Magnetization curve, (E_a vs. I_a) and I_a(Ra+Rsr) vs. I_a



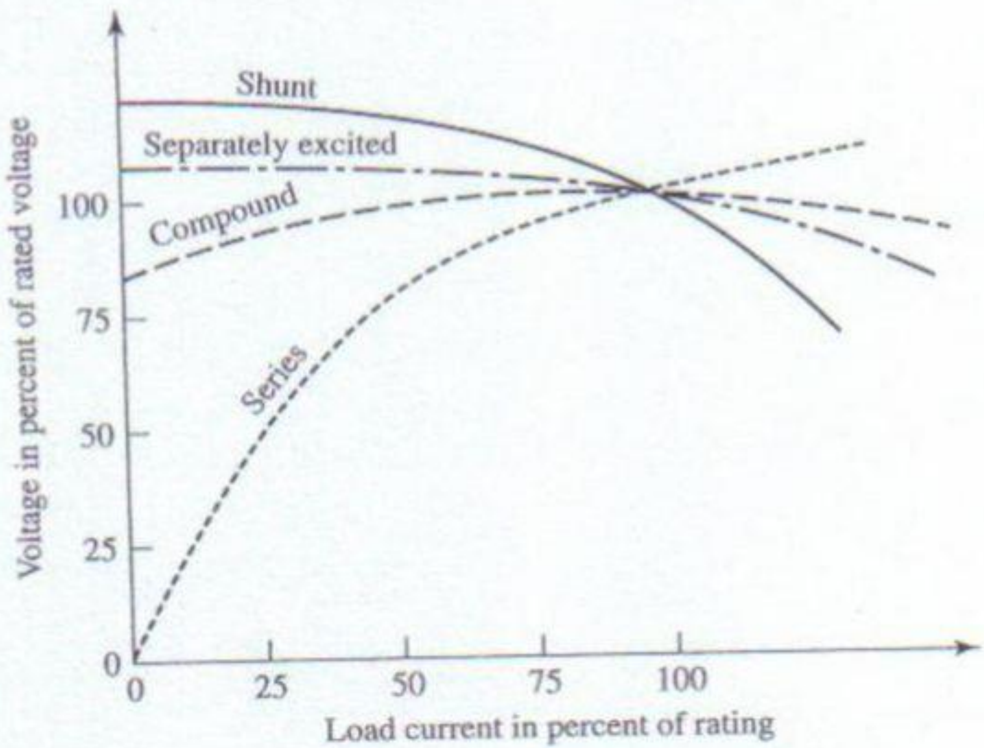
Vt'- effect of armature reaction

- terminal characteristic

Terminal characteristic (V_t Vs. I_a) can be plotted at varios Ia . Data V_t obtained from magnetising curve.



V-I Characteristics

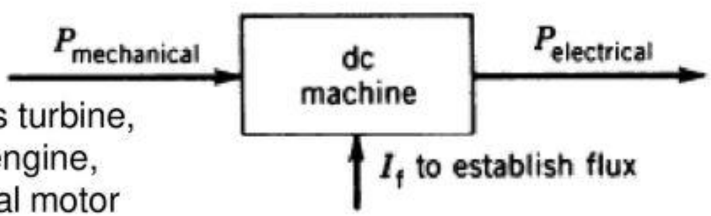


V-I characteristics of DC generators

DC Motors

- Construction very similar to a DC generator
- The dc machine can operate bath as a generator and a motor.
- When the dc machine operates as a motor, the input to the machine is electrical power and the output is mechanical power.
- In fact, the dc machine is used more as a motor.
- DC motors can provide a wide range of accurate speed and torque control.
- Principle of operation – when a current-carrying conductor is placed in magnetic field, it experiences a mechanical force., F = Bli

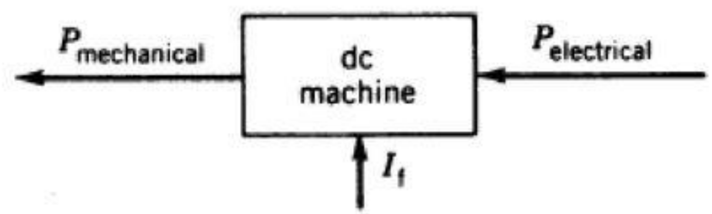
- generator



Eg. Gas turbine,
diesel engine,
electrical motor

(a)

- motor



(b)

DC Motors

- **Separately Excited Motors**

Field and armature windings are either connected separately.

- **Shunt Motors**

Field and armature windings are connected in parallel.

- **Series Motors**

Field and armature windings are connected in series.

- **Compound Motors**

Has both shunt and series field so it combines features of series and shunt motors.

Comparisons of DC Motors

Shunt Motors: "Constant speed" motor (speed regulation is very good). Adjustable speed, medium starting torque.
Applications: centrifugal pump, machine tools, blowers fans, reciprocating pumps, etc.

Series Motors: Variable speed motor which changes speed drastically from one load condition to another. It has a high starting torque.
Applications: hoists, electric trains, conveyors, elevators, electric cars.

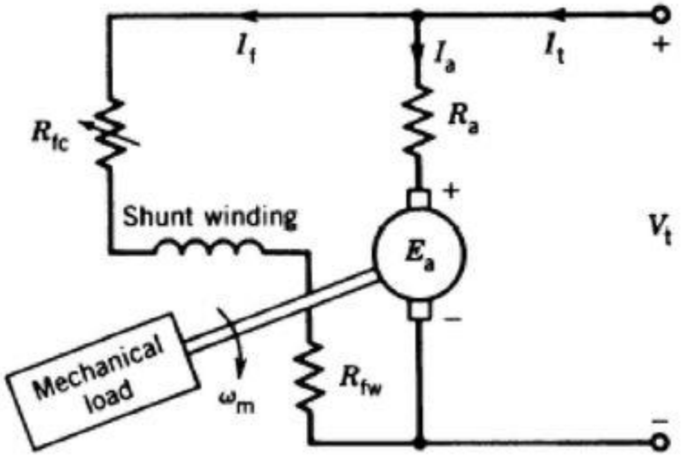
Compound motors: Variable speed motors. It has a high starting torque and the no-load speed is controllable unlike in series motors.
Applications: Rolling mills, sudden temporary loads, heavy machine tools, punches, etc

Shunt Motor

- The armature circuit and the shunt field circuit are connected across a dc source of fixed voltage V_t

R_{fc} in the field circuit is used to control the motor speed by varying i_f.

- the field circuit is independent of the armature circuit because both circuit are fed from voltage source



$$V_t = I_a R_a + E_a = I_f(R_{fc} + R_{fw})$$

$$I_t = I_a + I_f$$

$$E_a = K_a \Phi \omega_m = V_t - I_a R_a$$

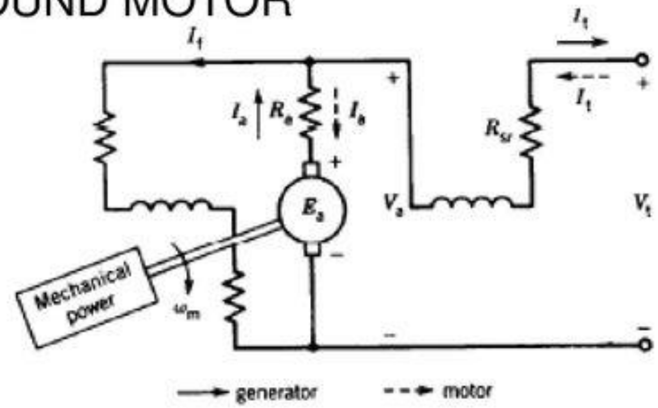
- Armature current and speed depend on the mechanical load

Power Flow and Efficiency

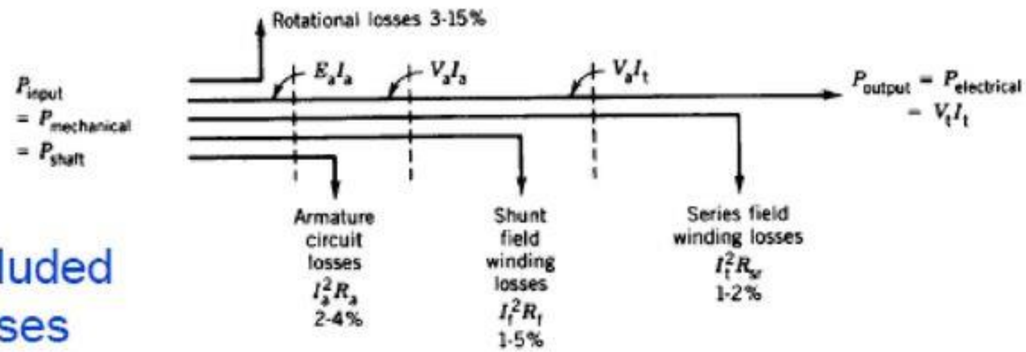
SHORT SHUNT COMPOUND MOTOR

- efficiency

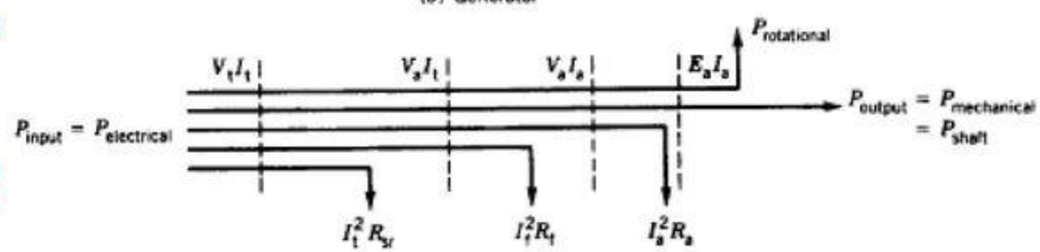
$$\eta = \frac{P_{output}}{P_{input}}$$



(a)

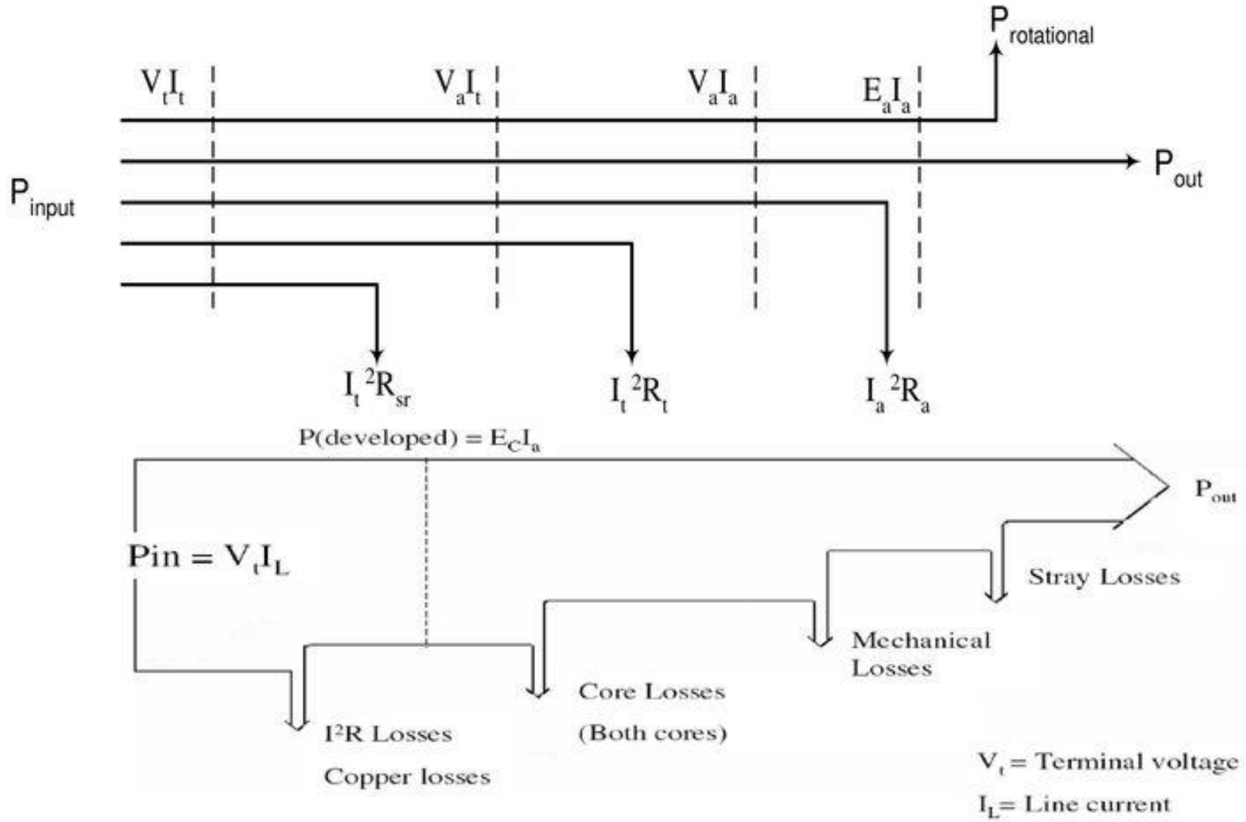


(b) Generator

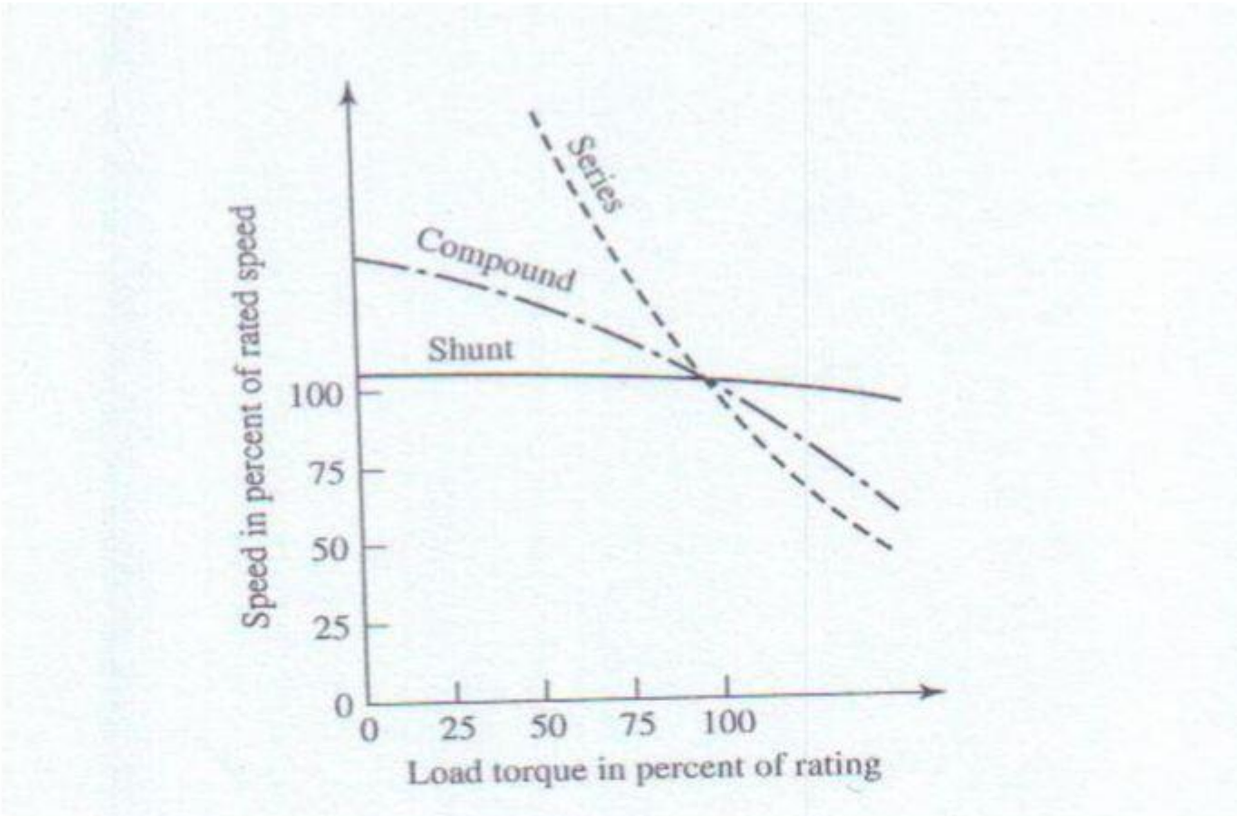

(c) Motor

- core losses are included in the rotational losses
- depend on machine size
- Range shown for machine 1 to 100 kW

Power Flow and Losses in DC Motors



ω– T characteristics



Speed- torque characteristics of DC motors

Example 11

Q. A DC machine (12 kW, 100 V, 1000 rpm) is connected to a 100 V DC supply and is operated as a DC shunt motor. At no-load condition, the motor runs at 1000 rpm and the armature current takes 6 A. Given armature resistance $R_a = 0.1\ \Omega$, shunt field winding resistance $R_{fw} = 80\ \Omega$, and $N_f = 1200$ turns per pole. The magnetization characteristic at 1000 rpm is shown in the next figure.

a. Find the value of shunt field control R_{fc}

b. Find the rotational losses at 1000 rpm

c. Find the speed, torque, and efficiency when the rated current flows.

   i) Consider the air gap flux remains the same (no armature reaction) at that at no load

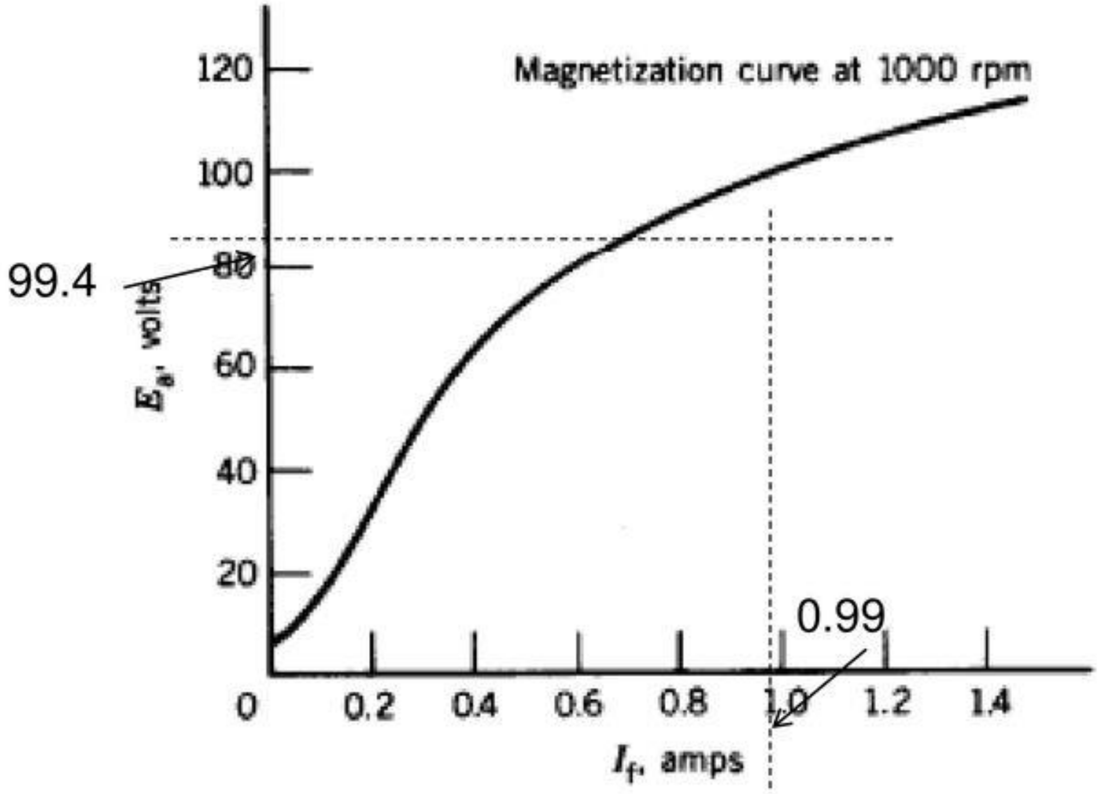
   ii) Consider the air gap flux reduces by 5 % when the rated current flow in the armature due to the armature reaction

d. Find the starting torque is the starting current is limited to 150 % of its rated current i) Neglect armature reaction ii) Consider armature reaction, $I_{fAR} = 0.16$ A

Sen pg. 170

Sol_pg8

Cont. Example

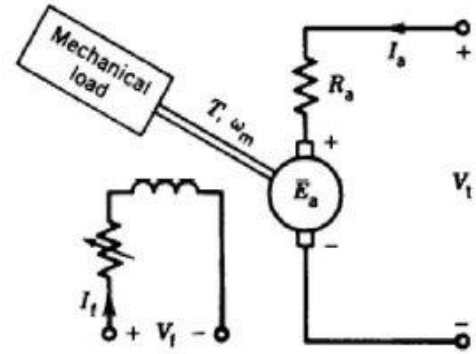


Separately Excited DC Motor – Torque speed characteristic

$$E_a = K_a \Phi \omega_m = V_t - I_a R_a$$

$$T = K_a \Phi I_a$$

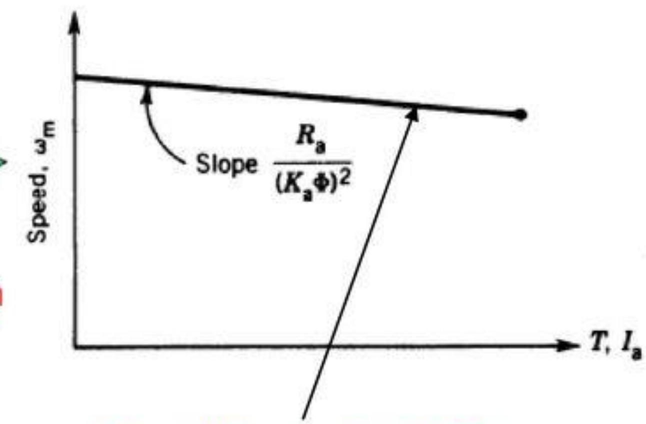
$$\omega_m = \frac{V_t - I_a R_a}{K_a \Phi} = \frac{V_t}{K_a \Phi} - \frac{R_a}{(K_a \Phi)^2} T$$



- for constant flux and voltage good speed regulation
- armature reaction decreases the flux → less speed drop

AR- Improve speed regulation

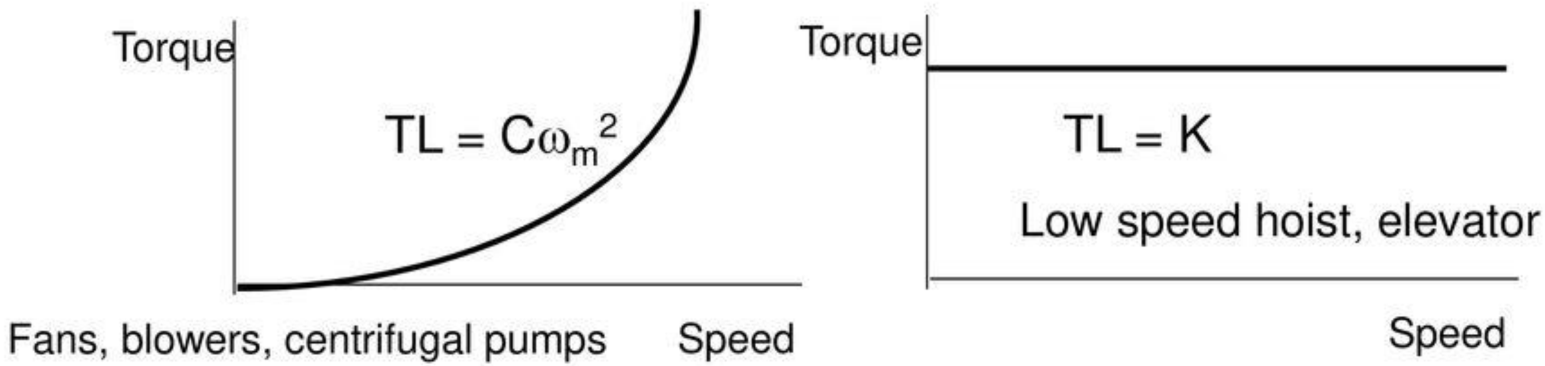
- speed control by
  - armature voltage control
  - field control
  - armature resistance control



Vt and flux constant - Drop in speed as torque increase is small – good speed regulation

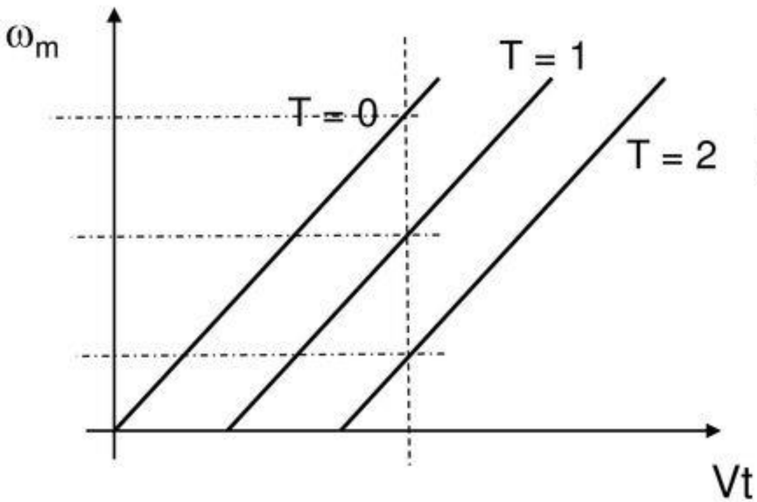
DC Speed Control

- Can be achieved by
  - Armature Voltage Control, V_t
  - Field resistance control, Φ
  - Armature resistance Control, R_a
  - Speed increases as V_t increases, R_a increases and field flux Φ decreases



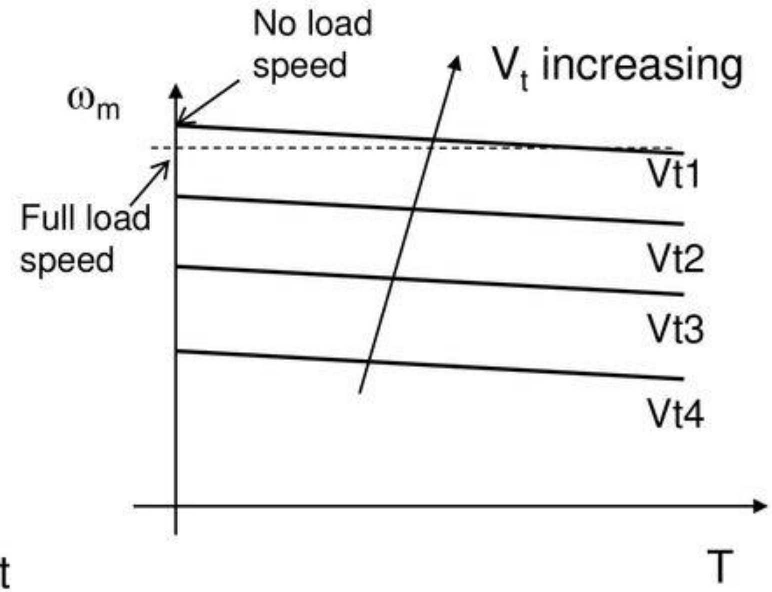
Load Torque profile

Armature Voltage Control



Armature Voltage control-

Constant load torque – speed varies linearly as V_t changes

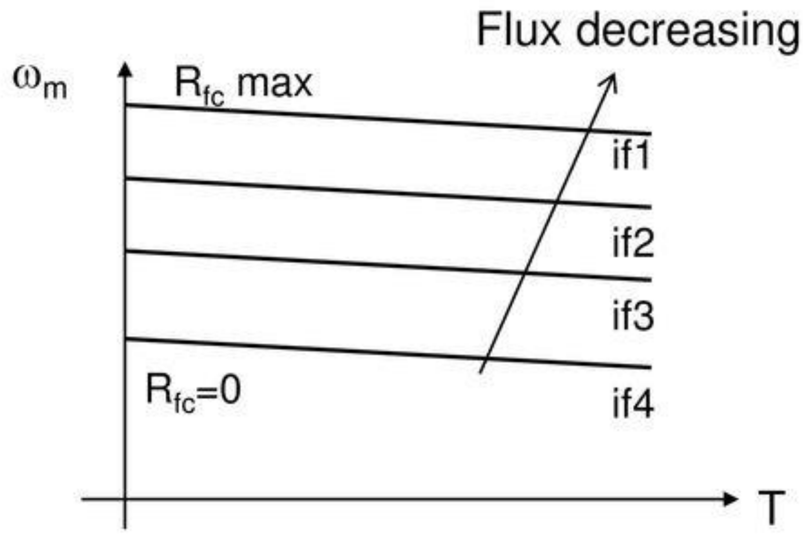


Armature Voltage control-

Terminal voltage (Vt) varies- speed adjusted by varying V_t

The speed of DC motor can simply be set by applying the correct voltage (fixed flux and R_a). Good speed regulation. Maintain maximum torque capability. Expensive control.

Field Control



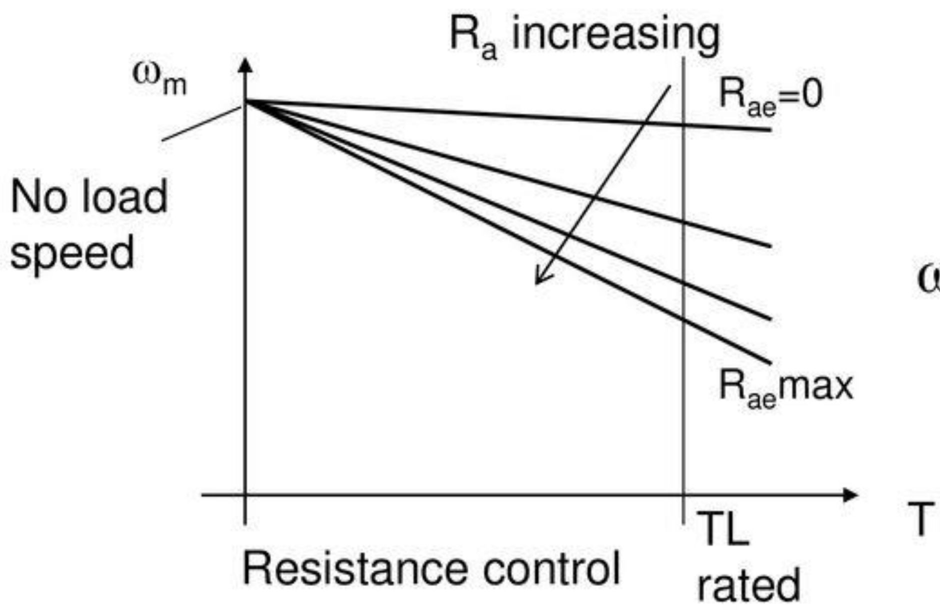
Field Control

$$\omega = \frac{V_t}{K_a\Phi} - \frac{(R_a + R_{ae})}{(K_a\Phi)^2}T$$

where $\Phi \, \alpha \; i_f$

The speed of DC motor can simply be set by applying the correct field resistance (R_{fext}) (fixed V_a and R_a). Slow/sluggish transient respond. Unable to maintain maximum torque capability. Simple and cheap control.

Armature Resistance Control



$$\omega = \frac{V_t}{K_a\Phi} - \frac{(R_a + R_{ae})}{(K_a\Phi)^2}T$$

The speed of DC motor can simply be set by applying the correct armature resistance (R_{aext}) (fixed V_a and R_f). Poor speed regulation. High Losses. Unable to maintain maximum torque capability (TL rated). Simple and cheap control.

Example 12

- A variable speed drive system uses a dc motor which is supplied from a variable-voltage source. The drive speed is varied from 0 to 1500 rpm (base speed) by varying the terminal voltage from 0 to 500 V with the field current maintained constant.

  (a) Determine the motor armature current if the torque is held constant at 300 N-m up to the base speed.

  (b) Determine the torque available a speed of 3000 rpm if the armature current is held constant at the value obtained in part (a).

  Neglect all losses.

Sen pg 180

Sol_pg15_motor

Series Motor

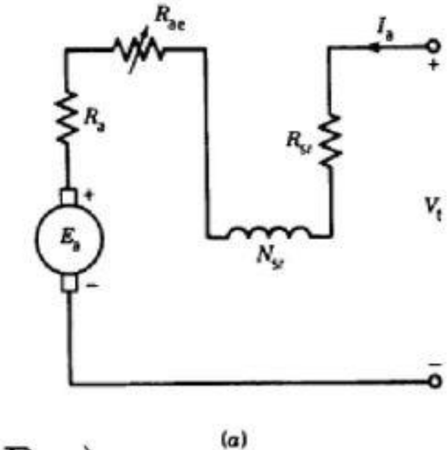
- magnetic linearity

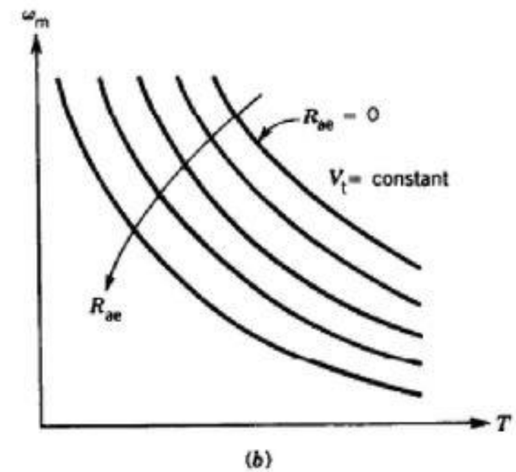
$$K_a \Phi = K_{sr} I_a$$

$$E_a = K_{sr} I_a \omega_m$$

$$T = K_{sr} I_a^2$$

$$E_a = V_t - I_a (R_a + R_{ae} + R_{sr})$$

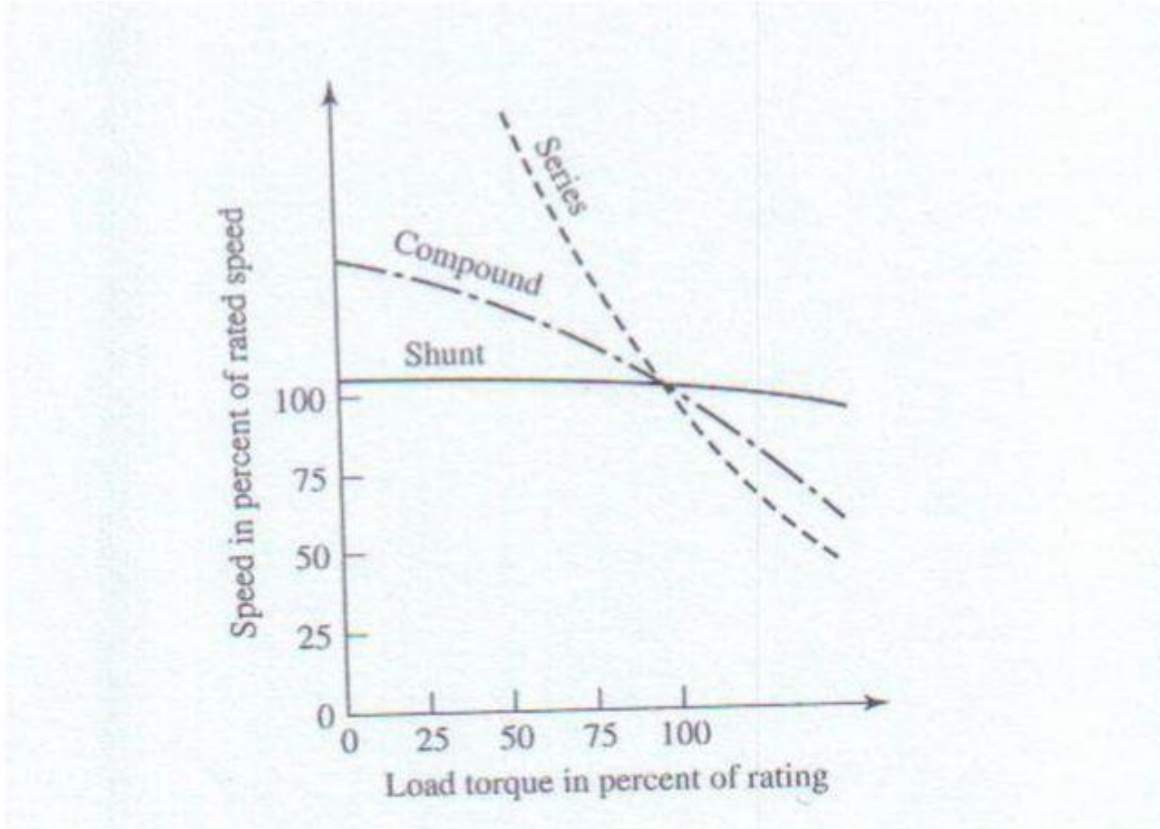




$$\omega_m = \frac{V_t}{K_{sr} I_a} - \frac{R_a + R_{sr} + R_{ea}}{K_{sr}} = \frac{V_t}{\sqrt{K_{sr}}\sqrt{T}} - \frac{R_a + R_{sr} + R_{ea}}{K_{sr}}$$

- large starting torque – subway car, automobile starter, hoist, crane, blender
- speed control over a wide range

T – ω characteristics



Speed- torque characteristics of DC motors

Example 13

- A 220 V, 7 hp series motor is mechanically coupled to a fan and draws 25 amps and runs at 300 rpm when connected to a 220 V supply with no external resistance connected to the armature circuit ($R_{ae} = 0\ \Omega$). The torque required by the fan is proportional to the square of the speed. $R_a = 0.6\ \Omega$ and $R_{sr} = 0.4\ \Omega$. Neglect armature reaction and rotational loss.

  (a) Determine the power delivered to the fan and the torque developed by the machine.

  (b) The speed is to be reduced to 200 rpm by inserting a resistance R_{ae} in the armature circuit. Determine the value of this resistance and the power delivered to the fan.

PC Sen pg 182

Sol_pg18

Motor Starter

- If a DC motor directly connected to a DC supply, the starting current will be dangerously high

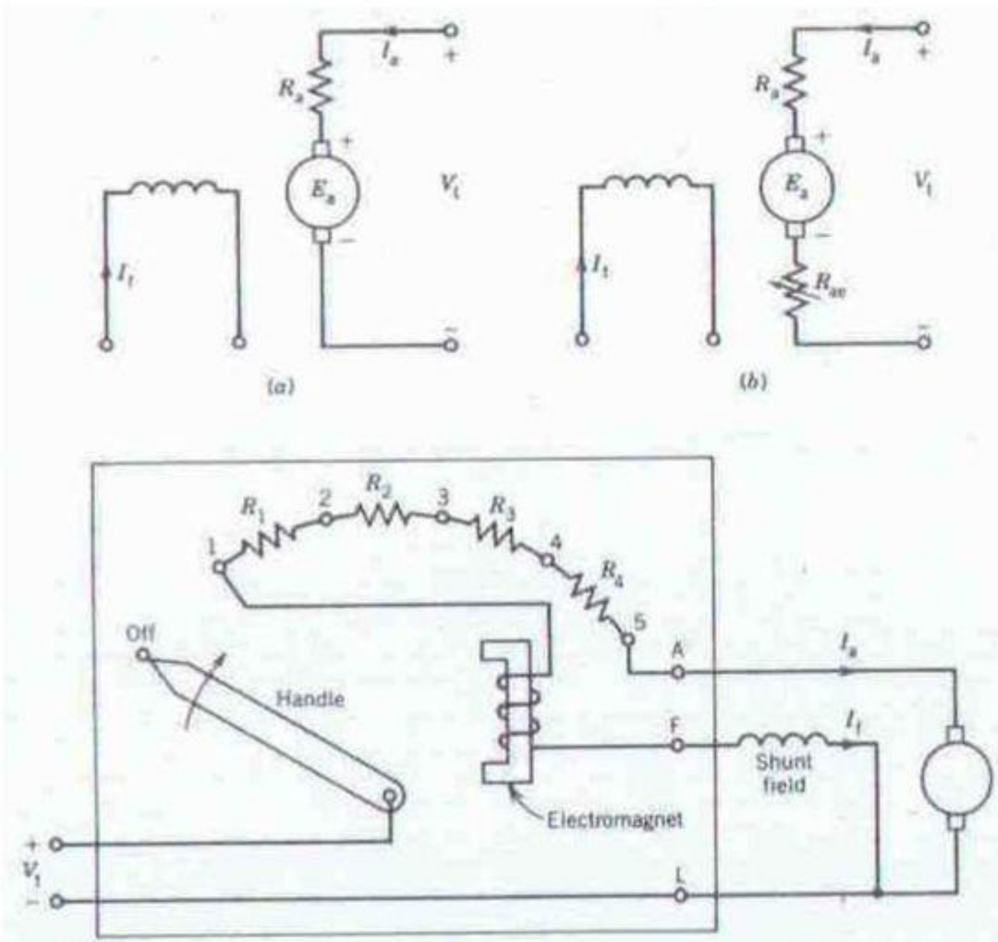
$$I_a = \frac{V_t - E_a}{R_a}$$

$$E_a = K_a \Phi \omega = 0 \text{ at start}; I_a = \frac{V_t}{R_a}$$

- R_a small, I_a large. I_a can be limited to a safe value by:
  - Insert an external resistance, R_{ae}
  - Use a low dc voltage (Vt) at starts, which require a variable-voltage supply
  - With external resistance,

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

Motor Starter



Development of a DC motor starter

E_a α speed (ω). As speed increases R_{ae} can be gradually taken out without the current exceed a limit (starter box). Initially at position 1, as the speed increases, the starter move to position 2,3,4and 5,


Thank you