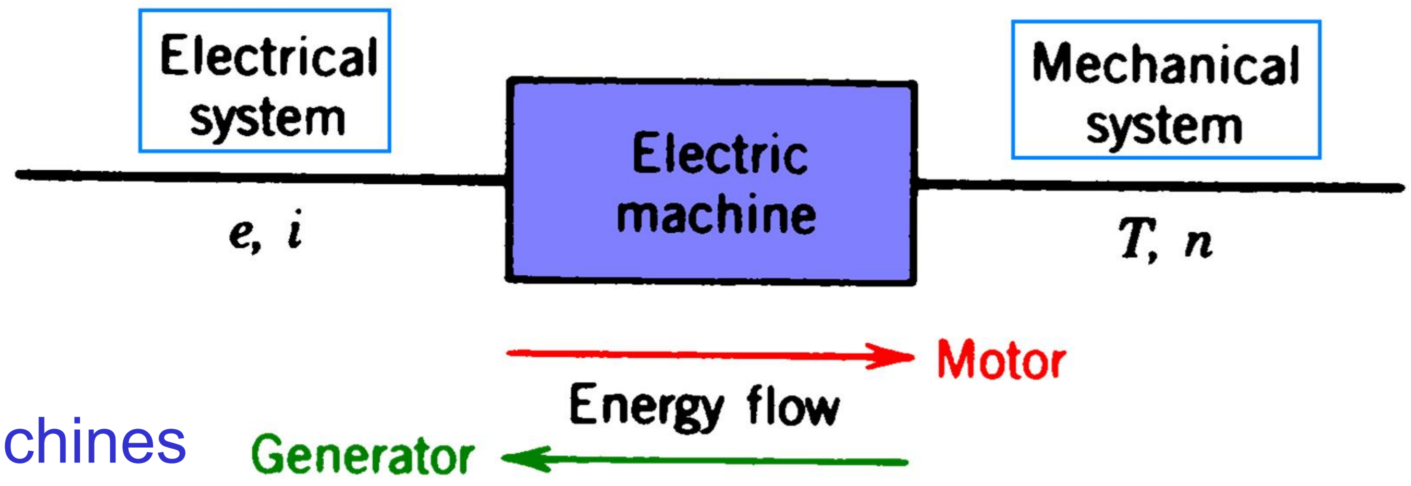
Introduction

What does AC and DC stand for?

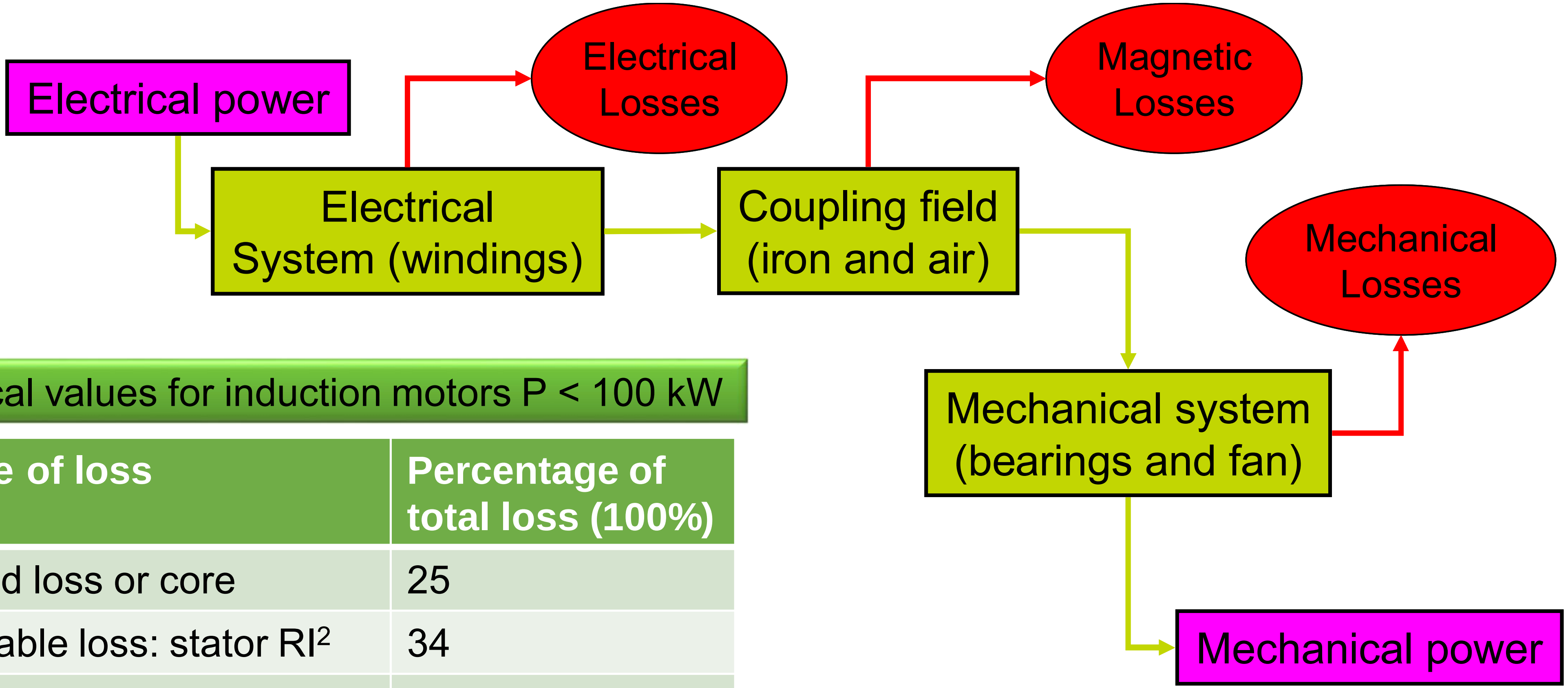
- Energy is needed in different forms:
  - Light bulbs and heaters need electrical energy
  - Fans and rolling miles need mechanical energy



- Electrical machines
  - Motors and generators
  - Operate in both modes
  - AC or DC machines

http://www.youtube.com/watch?NR=1&v=JFSTHTE5VZE&feature=endscreen

Energy conversion process and losses



Typical values for induction motors P < 100 kW

Type of loss	Percentage of total loss (100%)
Fixed loss or core	25
Variable loss: stator RI^2	34
Variable loss: rotor RI^2	21
Friction & rewinding loss	15
Stray load loss	5

Motoring operation mode of electrical machines and related losses

Outcome of this lecture

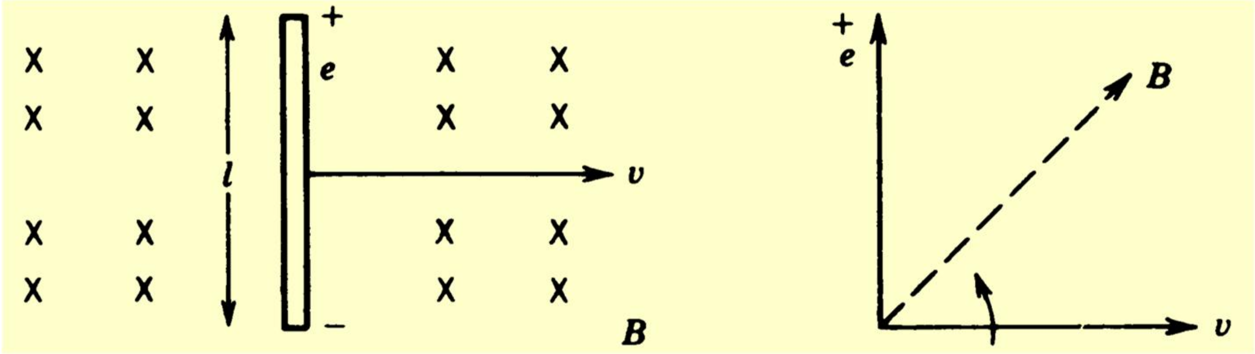
- At the end of this lecture you will be able to:
- describe different parts of a dc machine and their functions
- calculate the operation point of a dc machine at steady-state
- describe different kinds of dc machines
- describe the control methods of dc machine
  - you will understand the principle of operation of a dc machine
  - you will familiarize with some magnetic phenomena related to the operation of dc machine

Basics of electromagnetic energy conversion

Conductor moving in magnetic field

Motional voltage

$$e = Blv$$

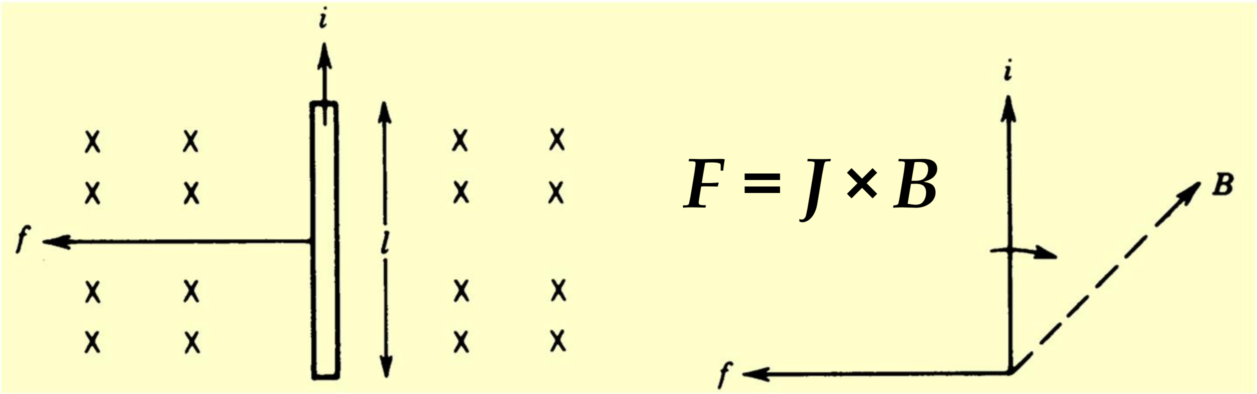


$$E = v \times B$$

Current carrying conductor in magnetic field

Electromagnetic force

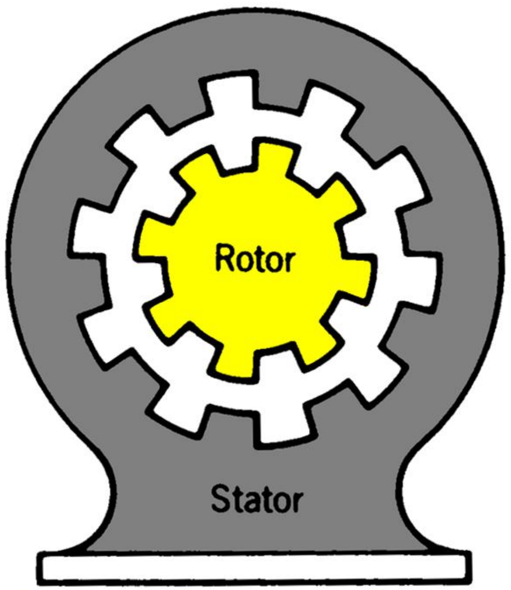
$$f = Bli$$



$$F = J \times B$$

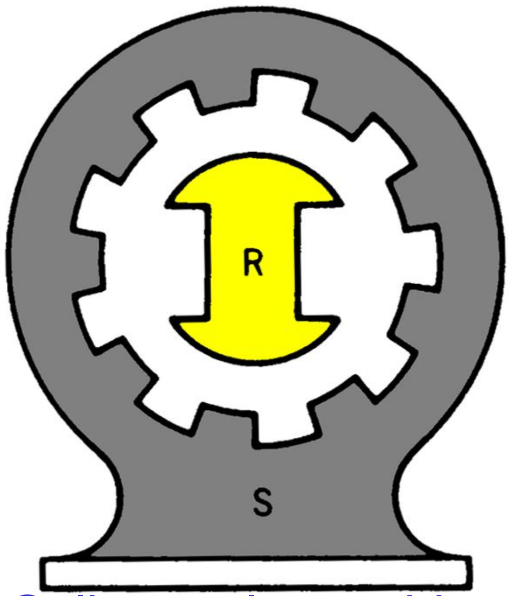
Both phenomena occur simultaneously in energy conversion process

Basic structure of electric machine



Cylindrical machine
Uniform air gap

Why do we need iron core ?

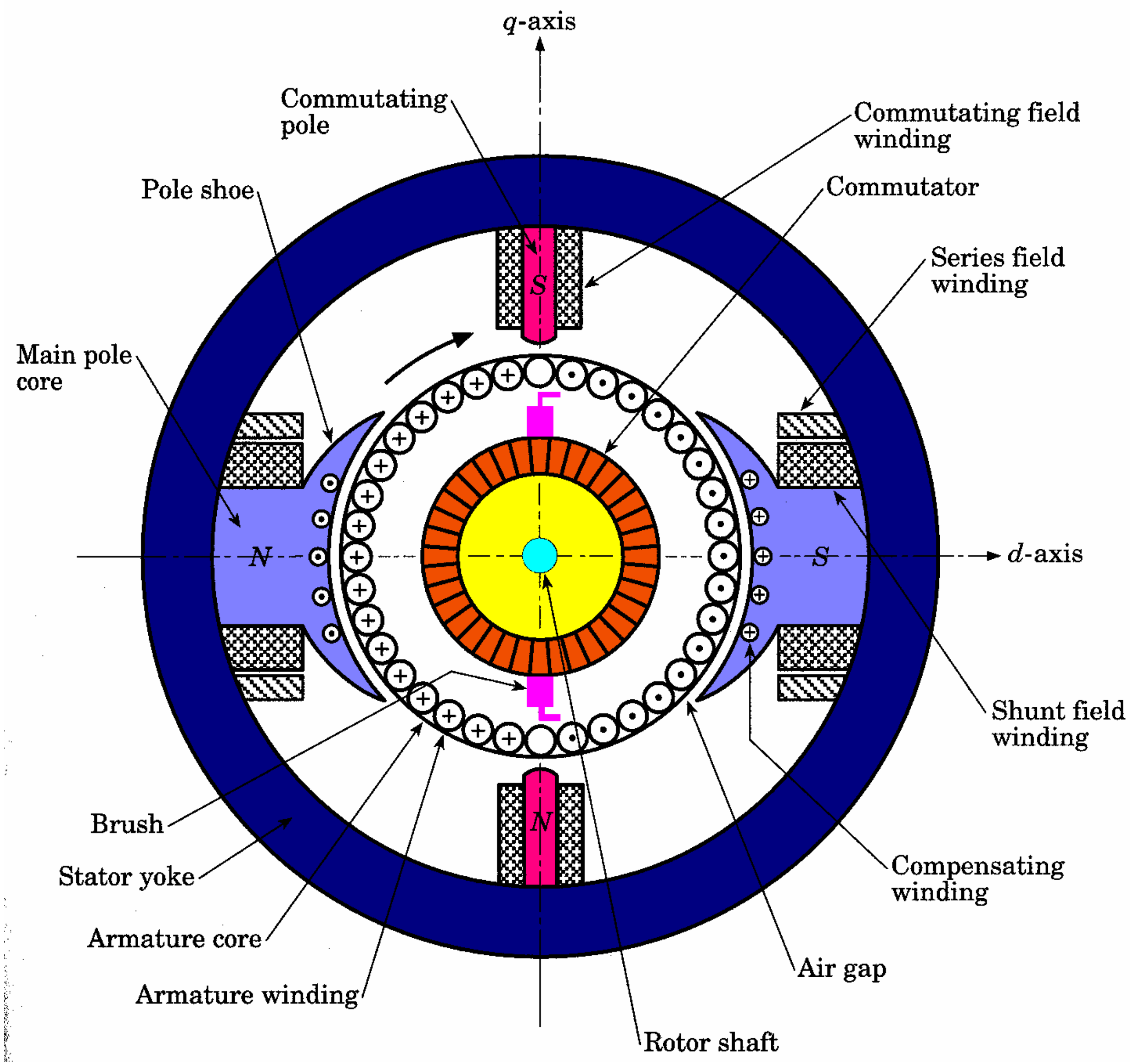


Salient pole machine
Non-uniform air gap

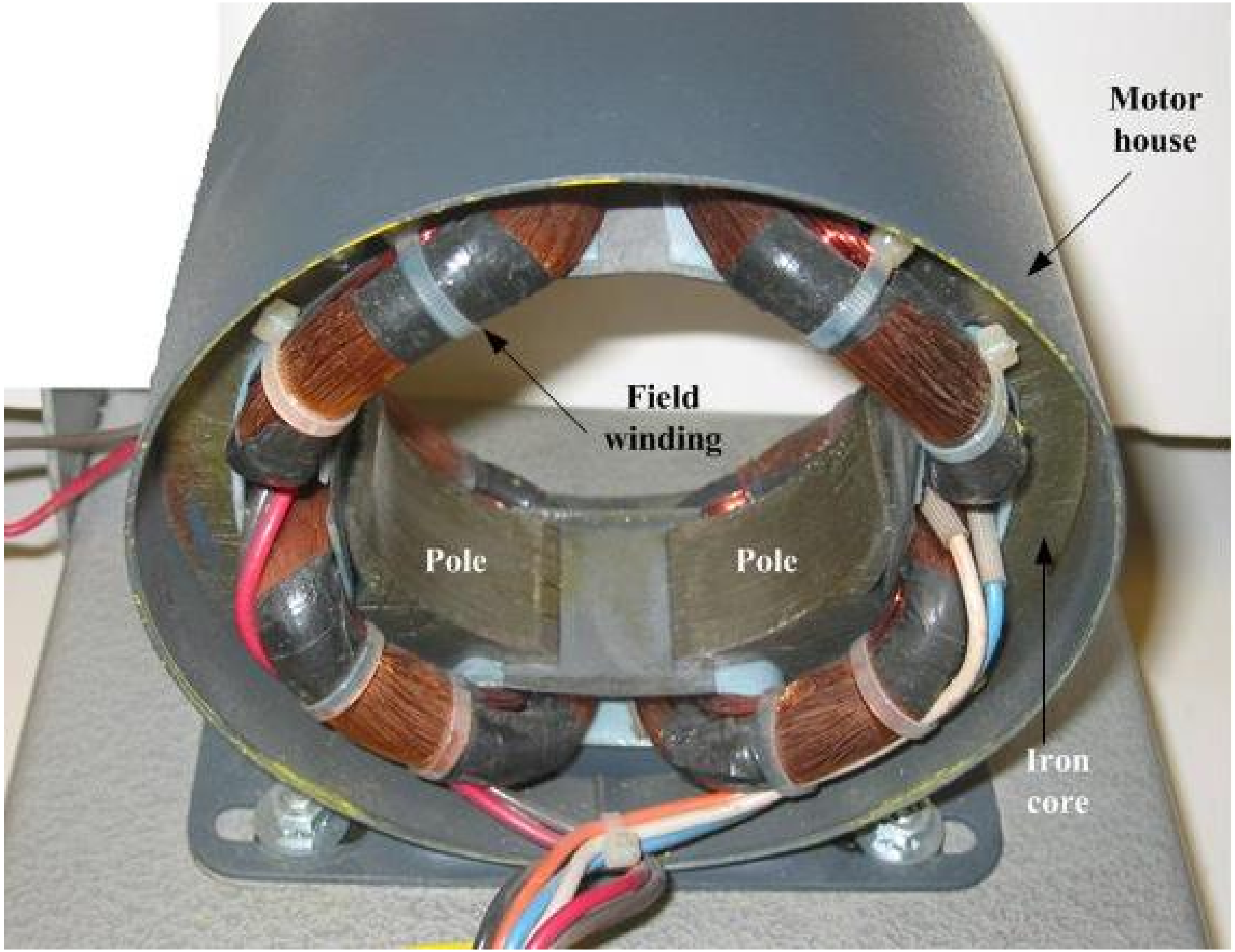
- Slots with conductors
- Iron core
- Laminations

What this could be?

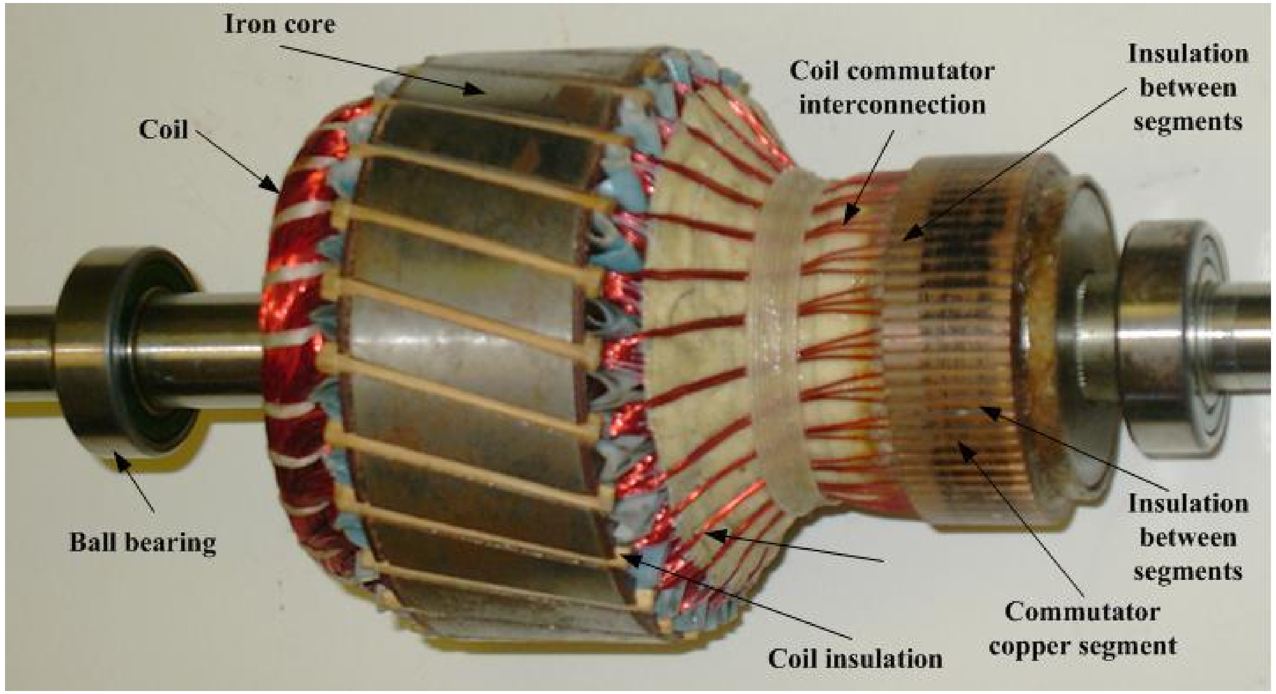
Cross section view of dc machine



Structure of the stator of dc machine



Structure of the rotor of dc machine



- Conductors interconnected to form windings
- Armature winding = in which voltage is induced
- Field winding = the one that produces the primary flux
- Permanent magnet can be used to produce the flux

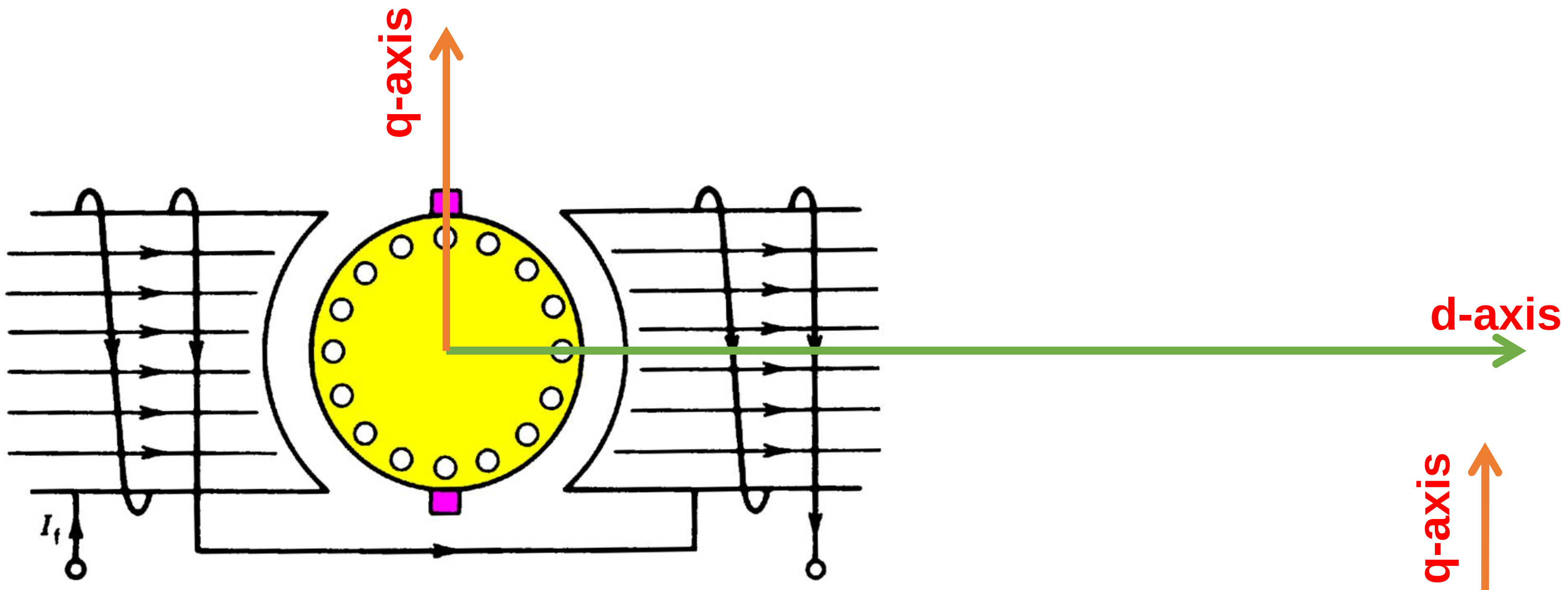
Operation of DC Machines

- Operates as motor and generator, mainly used as motor
- Variable speed, large and small power range

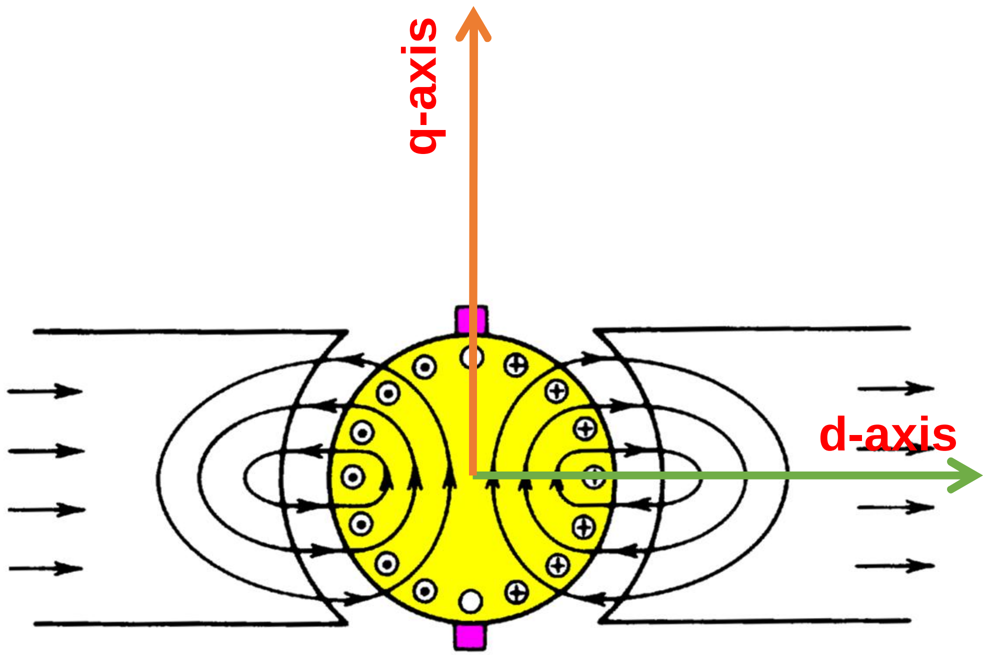
- Field winding currying DC-current in stator

  → flux symmetrically distributed about pole axis
- Armature winding in rotor → induced alternating voltage
- Mechanical Commutator and brush assembly rectify the voltage
- Armature current distribution fixed in space
- MMF of armature winding along quadratic axis ← What is it?

Definition of direct and quadratic axis



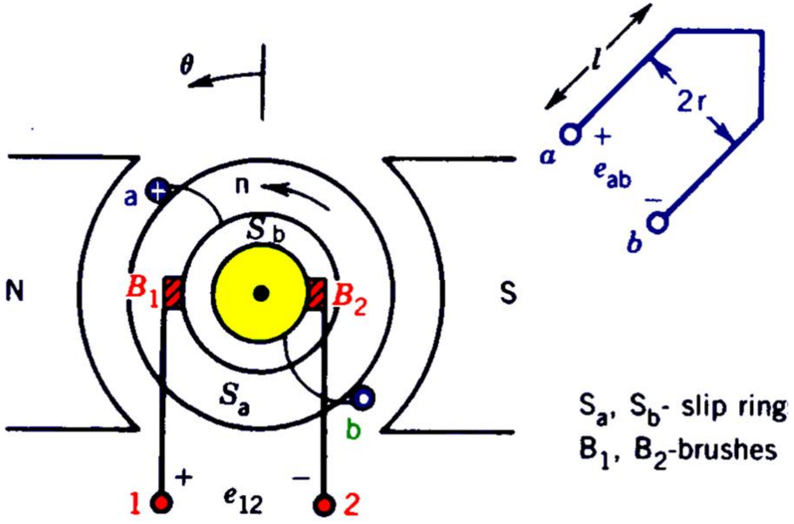
Magnetizing filed

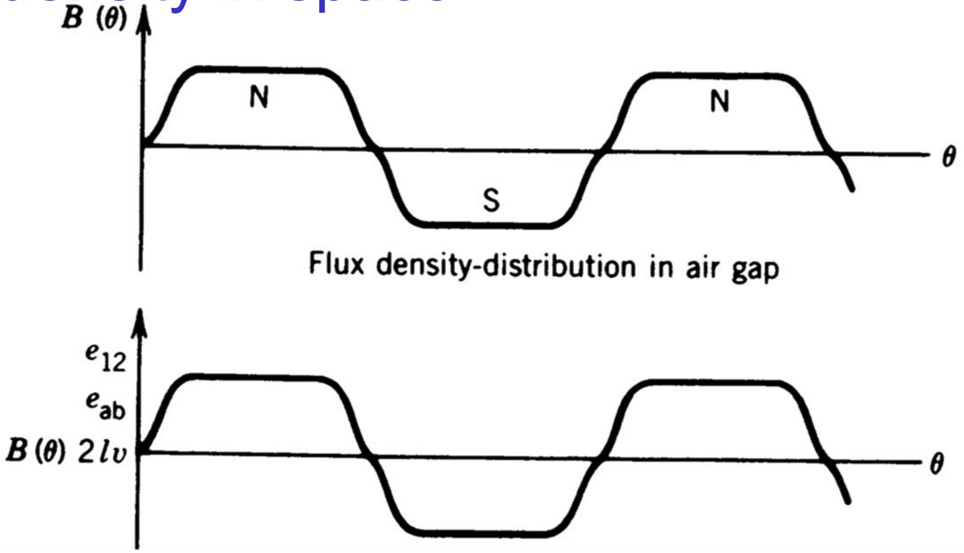


Armature field

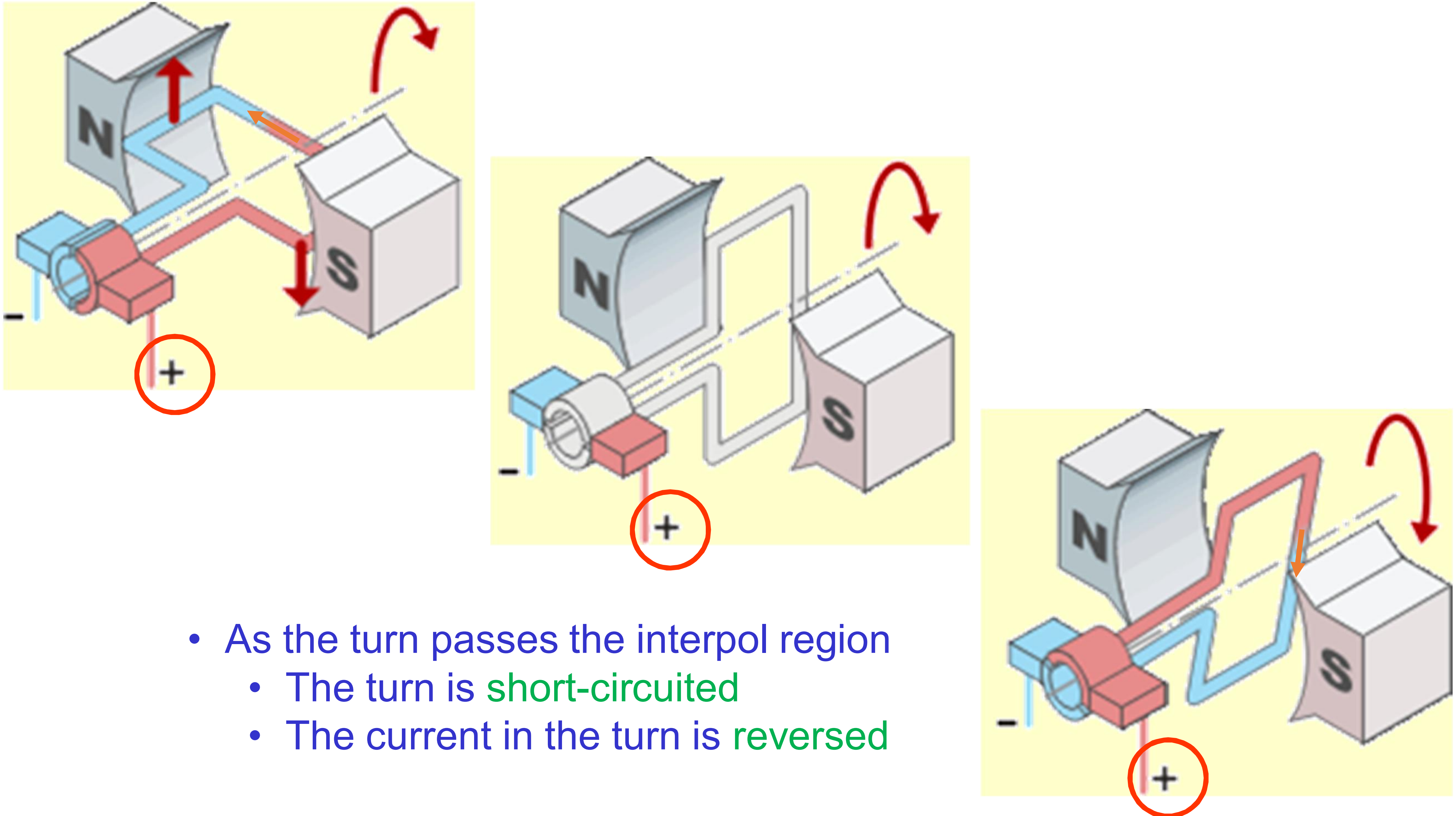
Induced voltage

- Turn a-b
  - Sides placed on diametrically opposite slots
  - Terminals connected to slip rings
  - Brushes provide access to revolving turn a-b
- Induced voltages on each side of the turn are in series
- Induced voltage in the turn is alternating
- Its waveform is the same as that of flux density in space





Commutator and Brushes- Principle



- As the turn passes the interpol region
  - The turn is short-circuited
  - The current in the turn is reversed

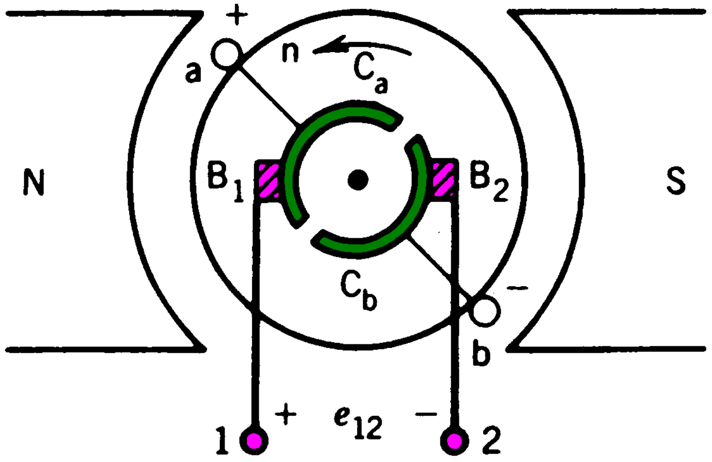
Rectification of the induced voltage

- Slip rings replaced with commutator segments

  ⮡ Voltage rectified

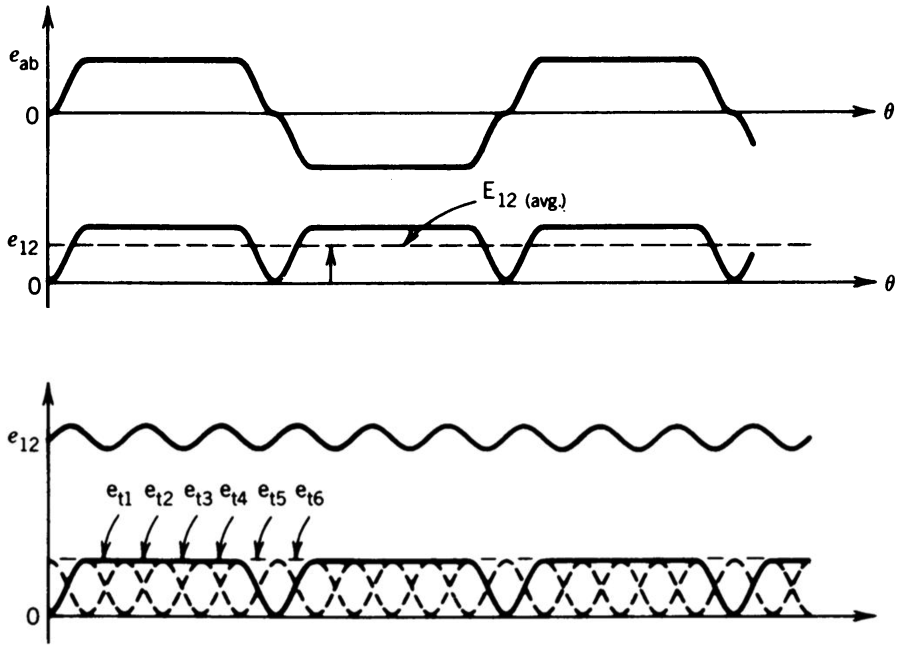
- Large number of turns in several slots connected in series through commutator segments

  ⮡ Voltage with less ripple.

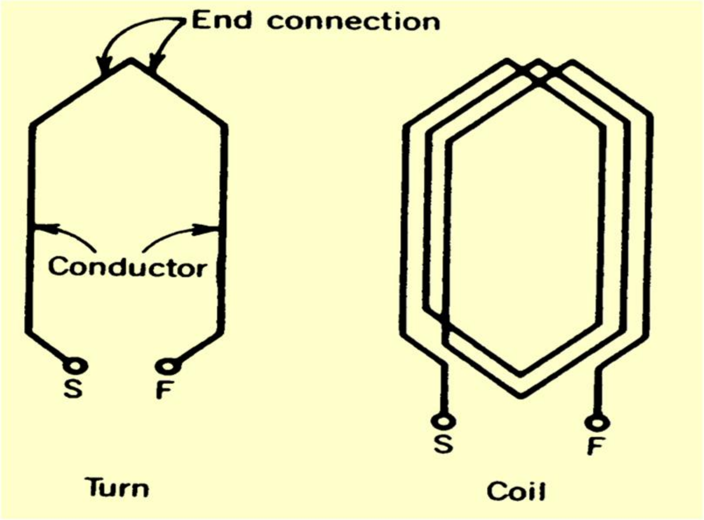


C_a, C_b-commutator segment

(a)



Windings- some definitions

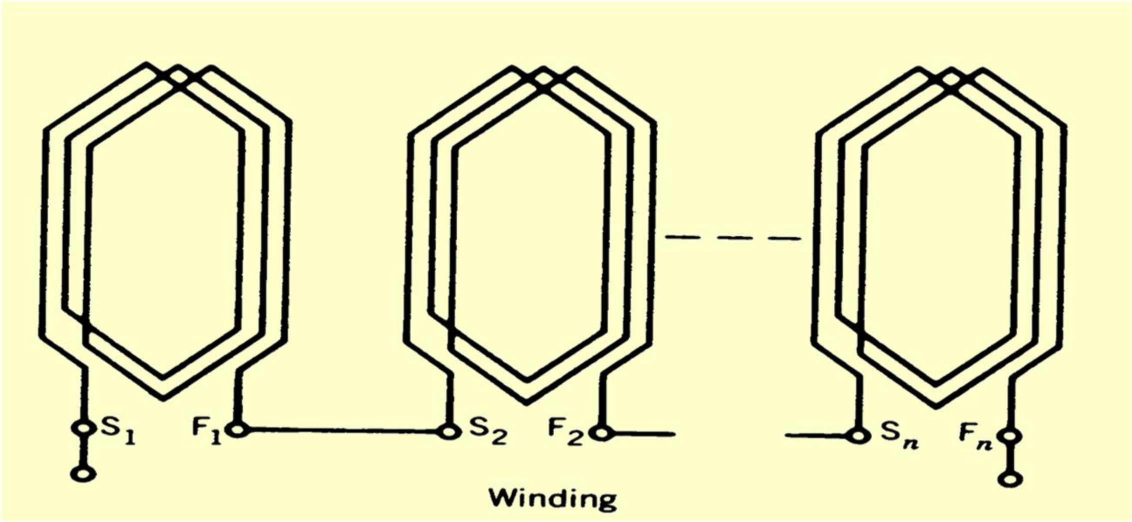


Conductors conneceted → turn

Turns connected → coil

Connected coils

↳ winding



Large machines have more than two poles

↳ most conductors in region of high flux density

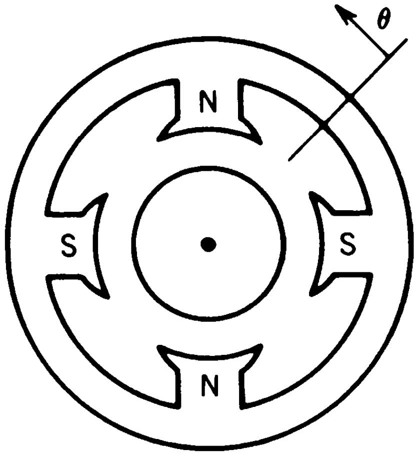
Windings- some definitions

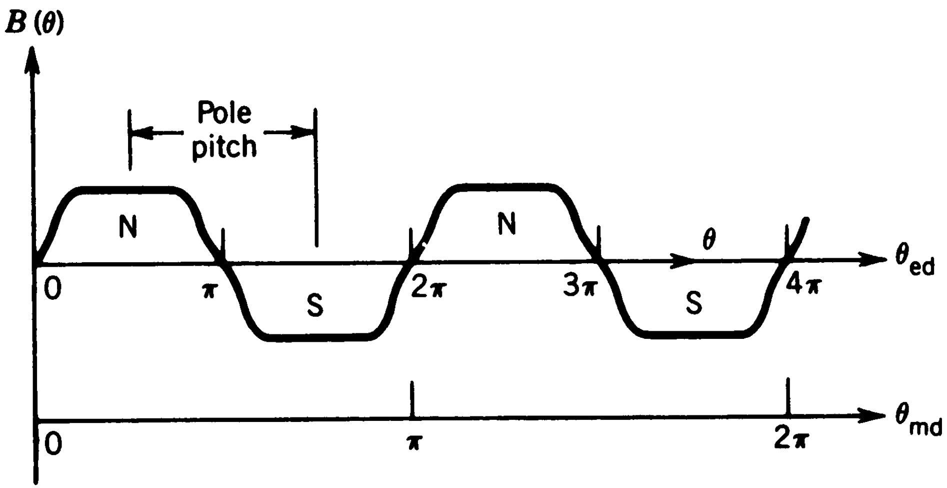
- Pole pitch = distance between centers of two adjacent poles
- Coil pitch = distance between two sides of a coil
- Full-pitch → coil pitch = pole pitch
- Short-pitch → coil pitch < pole pitch

The electrical angle describes a two pole machine whatever is the number of poles. The electrical angle varies between 0 and 360 deg.

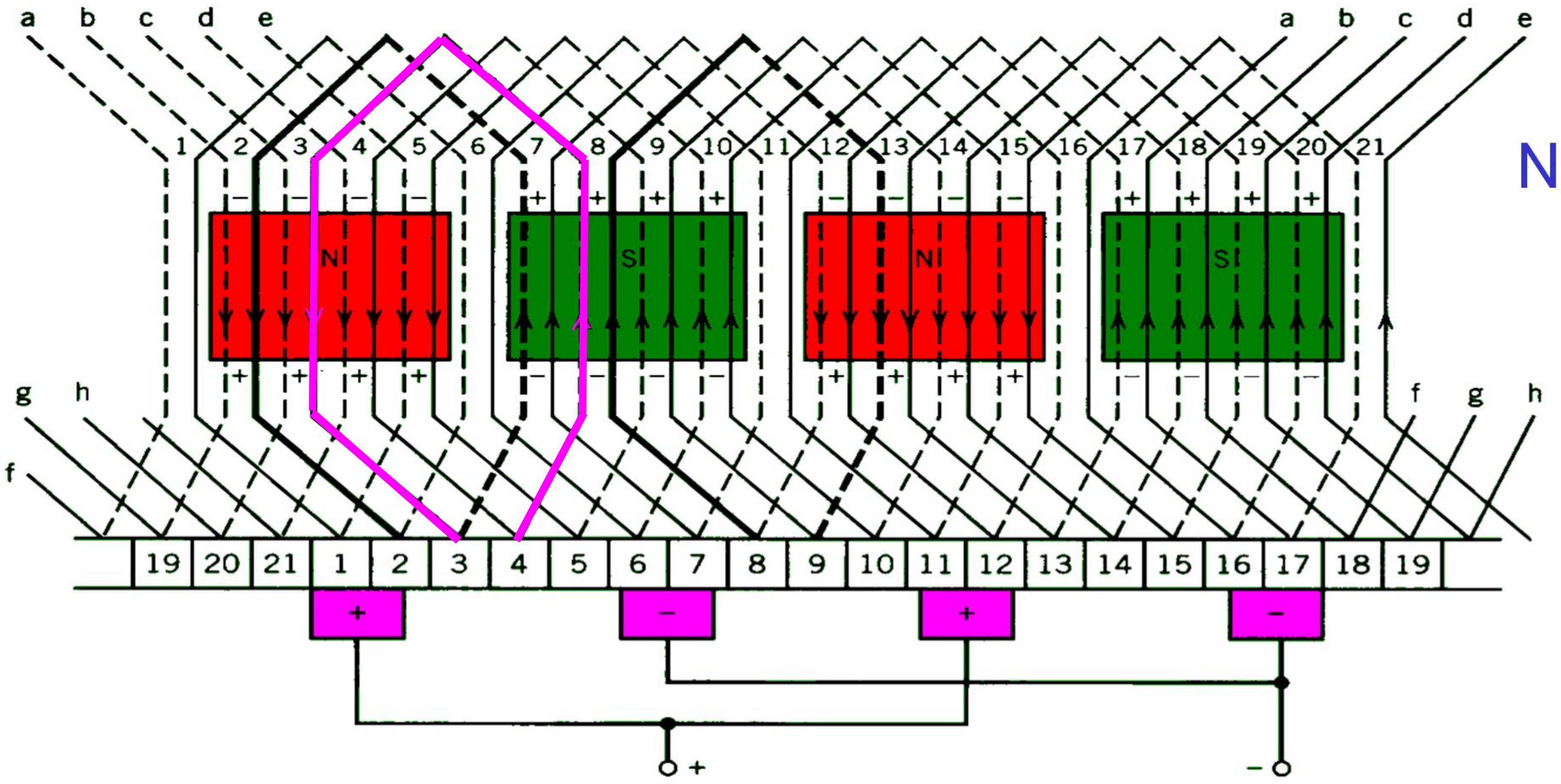
- Electrical angle θe
- Mechanical angle θm
- p : number of poles

$$\theta_e = \frac{p}{2}\theta_m$$

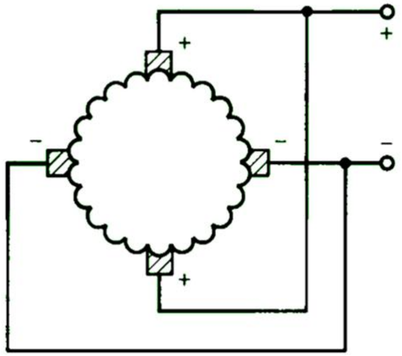


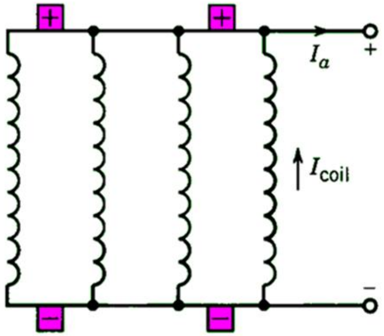


Lap Winding



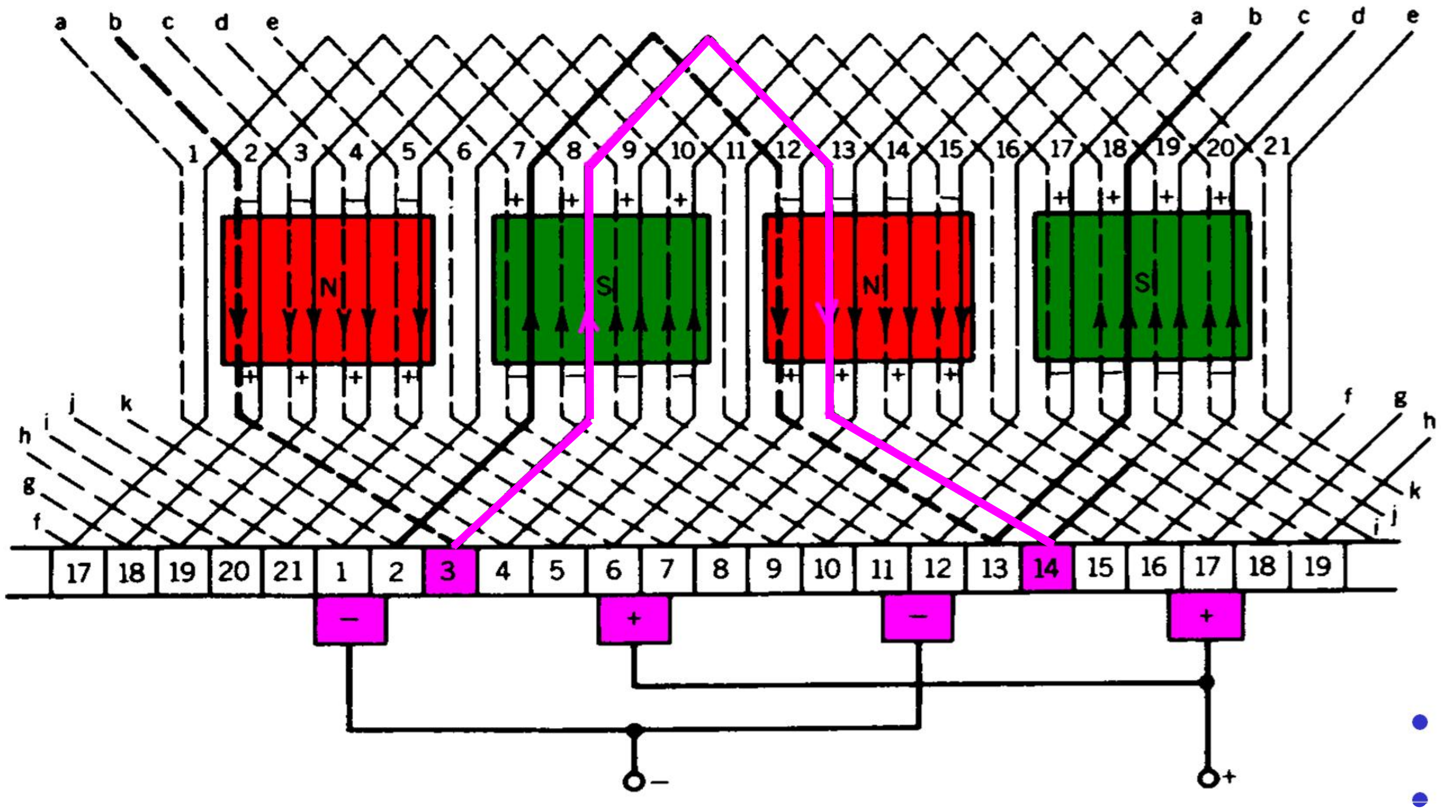
Number of parallel paths
= number of poles
= number of brushes

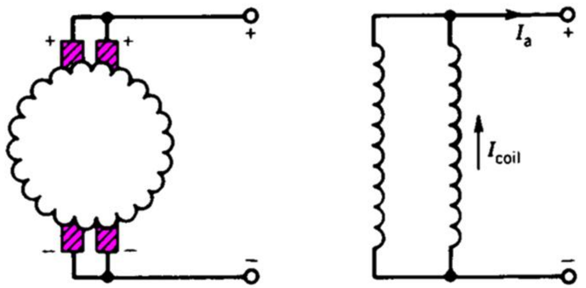




- one coil between two adjacent commutator bars
- 1/p of the total coils are connected in series
- suitable for high-current low voltage

Wave Winding



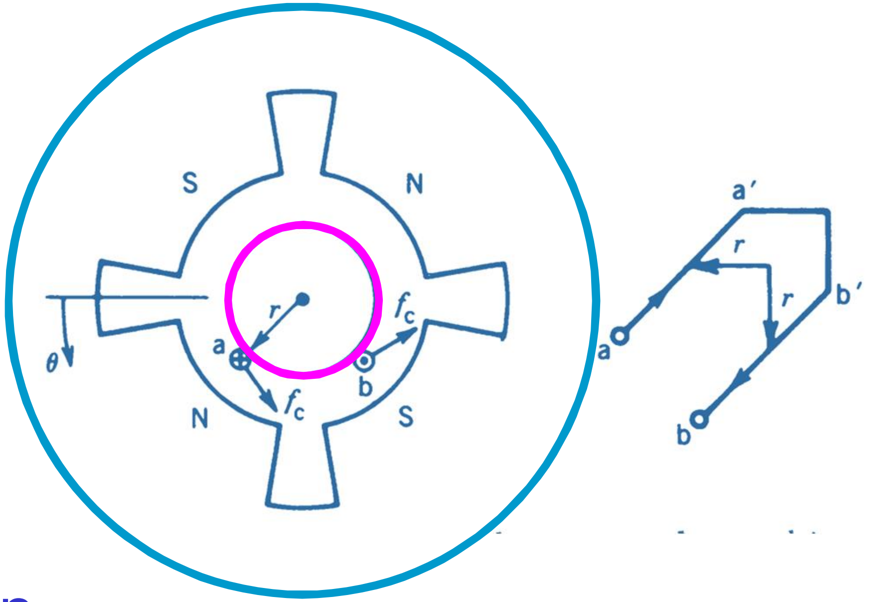


p/2 coil connected in series between two adjacent commutator bars

Suitable for high voltage low current

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

Induced voltage



- The voltage induced in a turn

$$e_{\mathrm{t}} = 2B(\theta)\, l \omega_{\mathrm{m}} r$$

- Average value of the voltage induced in a turn

$$\overline{e}_{\mathrm{t}} = 2\overline{B(\theta)}\, l \omega_{\mathrm{m}} r = \frac{\Phi p}{\pi} \omega_{\mathrm{m}}$$

- Flux per pole Φ

$$\overline{B(\theta)} = \frac{\Phi}{A} = \frac{\Phi}{2\pi r l / p}$$

Induced voltage

- Induced voltage in the armature winding

$$E_a = \frac{N}{a}\overline{e}_t = \frac{Np}{\pi a}\Phi\,\omega_m = K_a\Phi\,\omega_m$$

  - *N* number of turns in the armature winding
  - *a* number of parallel paths
  - *Z* total number of conductors =2N
  - E_a independent of operation mode

Machine construction-dependent constant

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

- In generator: generated voltage
- In motor *back emf*

Torque

- The force on a conductor

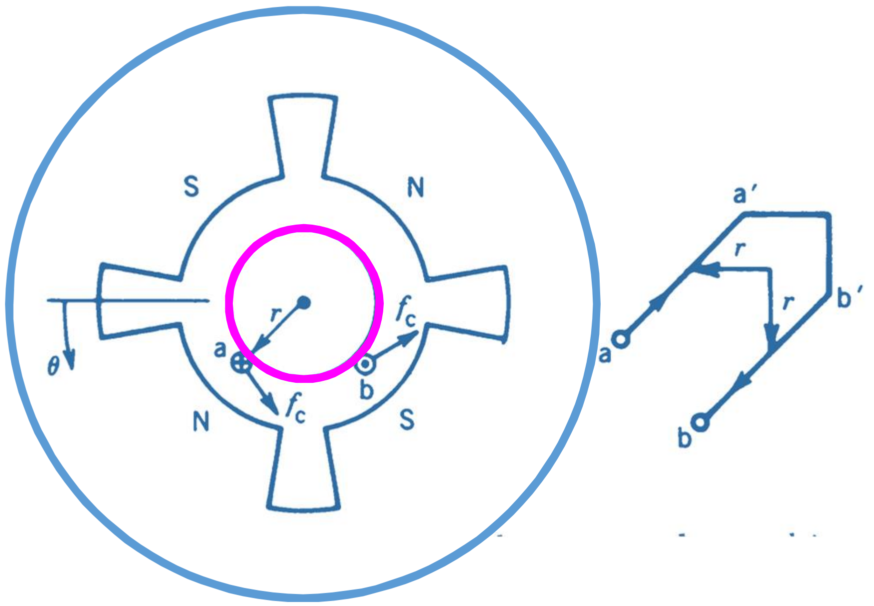
$$f_c = B(\theta) l i_c = B(\theta) l \frac{I_a}{a}$$

- The torque on a conductor

$$T_c = f_c r$$

- The average torque on a conductor

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



Torque

- The total torque developed

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

Machine construction-dependent constant

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

- Power balance

$$T = K_a \Phi I_a$$

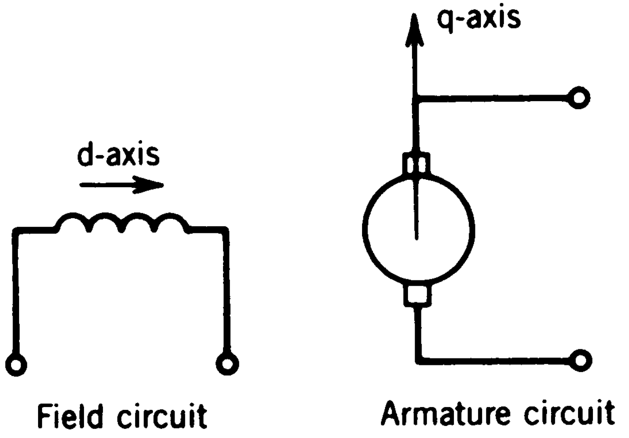
$$E_a = K_a \Phi \omega_m$$

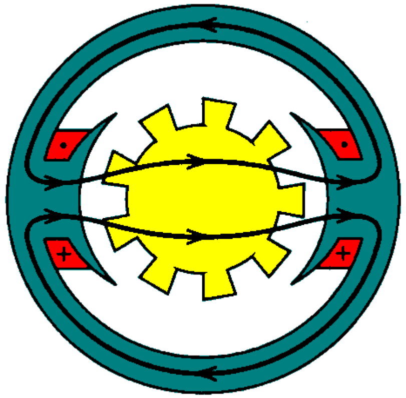
$$E_a I_a = K_a \Phi \omega_m I_a = T\omega_m$$

What is missing?

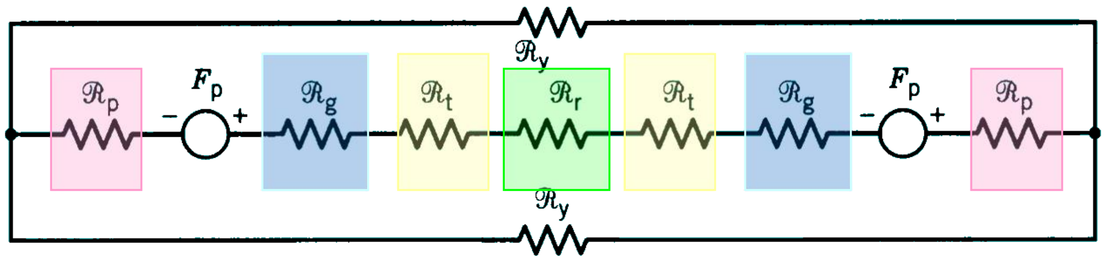
Magnetization

- Field mmf on d-axis
- Armature mmf on q-axis
- No coupling (see later)





(a)



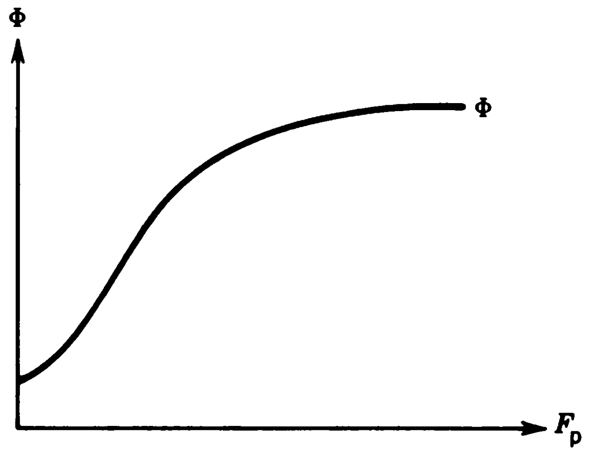
(b)

Magnetic core with infinite permeability at low values of flux (ampere-turns)

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

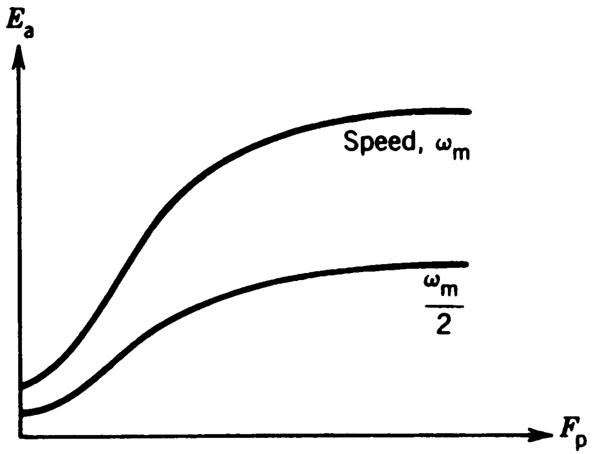
Magnetization curve

$$\Phi = \frac{F_p}{R_g}$$

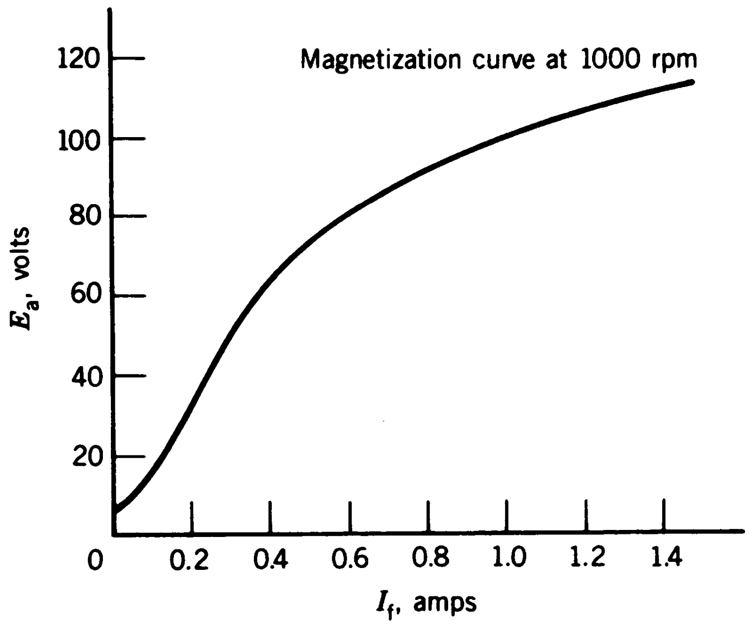


Increased F_p ➡ increased Φ ➡ saturation

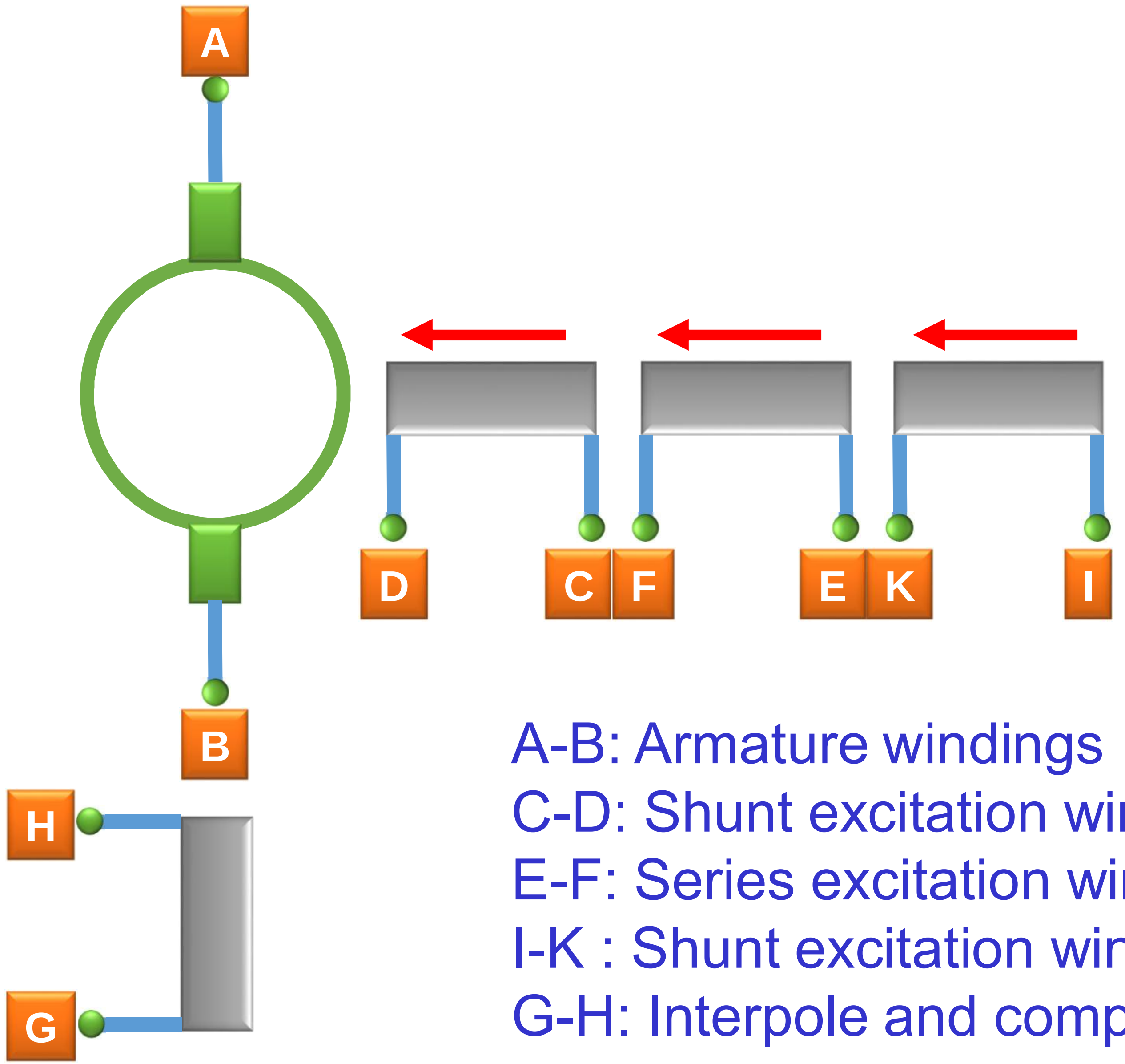
Induced voltage proportional to flux times speed



➡



Terminals marking



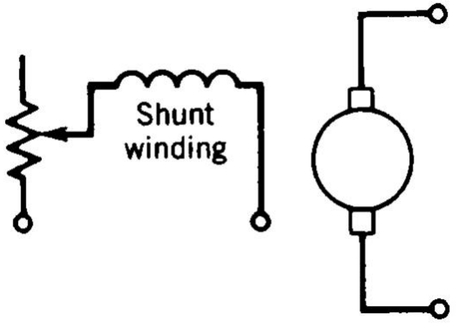
A-B: Armature windings
C-D: Shunt excitation winding (for self-excitation)
E-F: Series excitation winding
I-K : Shunt excitation winding (for external excitation)
G-H: Interpole and compensation windings in series

Classification of DC Machines

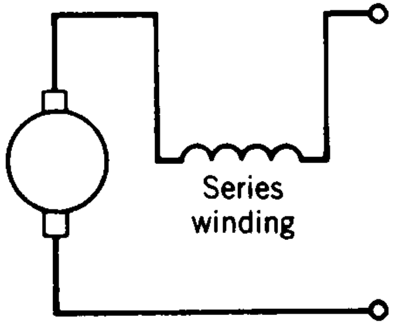
- Field and armature circuits can be connected in various ways

  → different performance characteristic

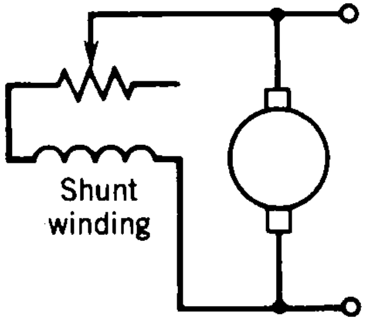
- Field pole can be exited by series and shunt windings



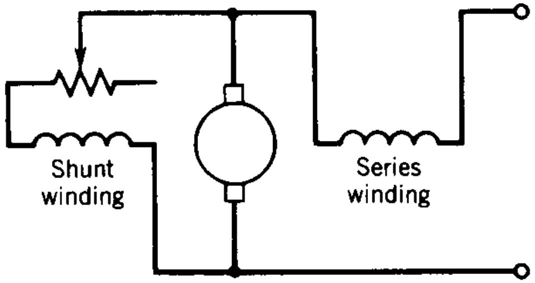
separately excited machine



series machine

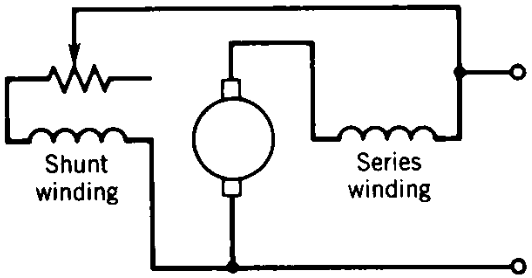


shunt machine



Short shunt

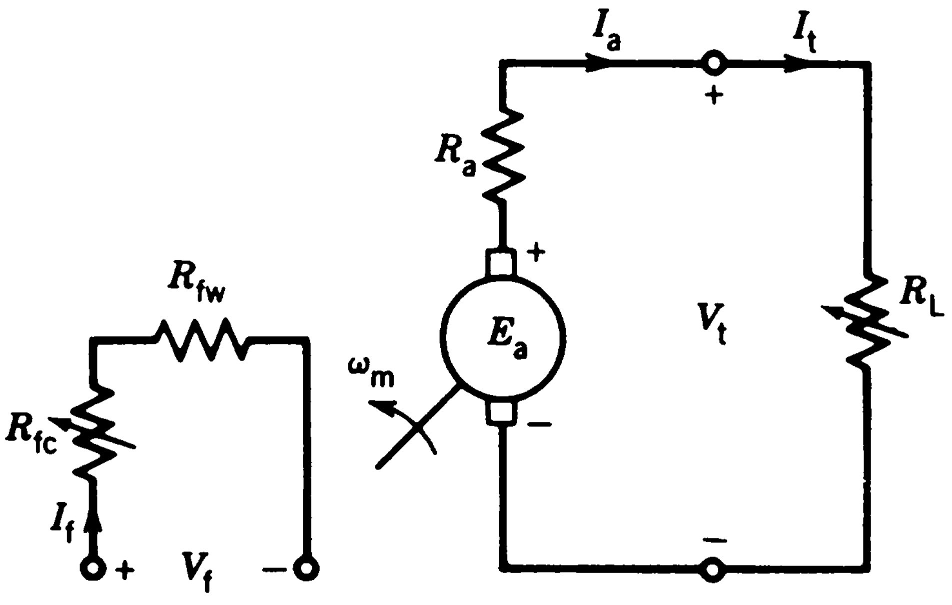
compound machine



Long shunt

Separately Excited DC generator

- Prime mover with constant speed
- Armature connected to electrical load
- Steady-state (inductances ignored)



- Field winding $V_f = R_f I_f$

- Armature winding $E_a = V_t + I_a R_a$

$$E_a = K_a \Phi \omega_m$$

- Operating point

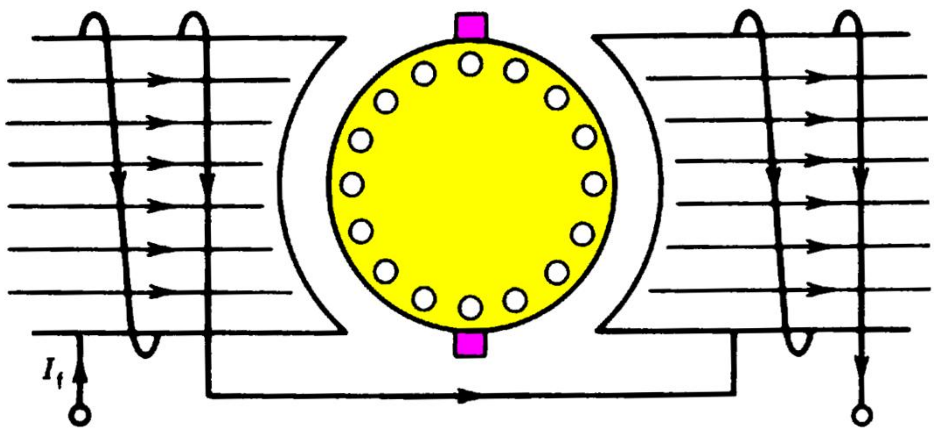
$$V_t = I_t R_L$$

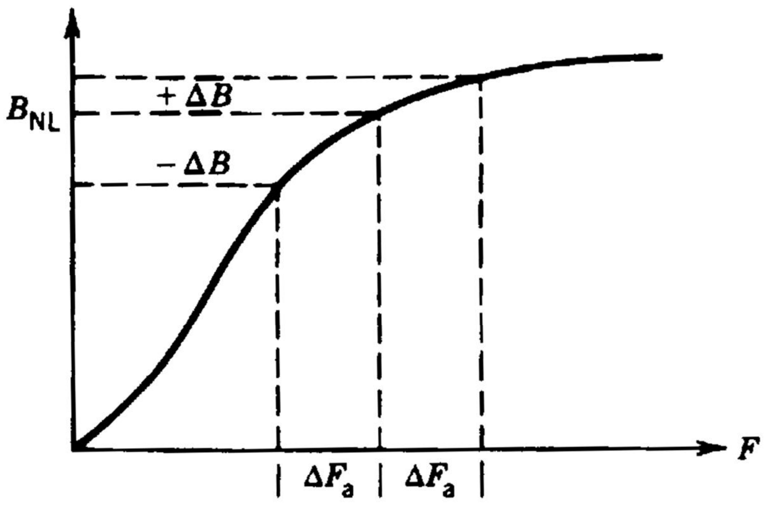
$$V_t = E_a - R_a I_a$$

Plot it in the VI-plan

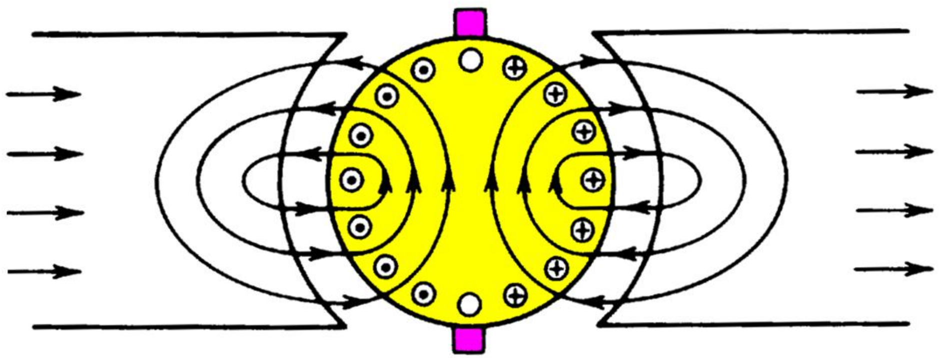
Armature Reaction

- Magnetizing filed





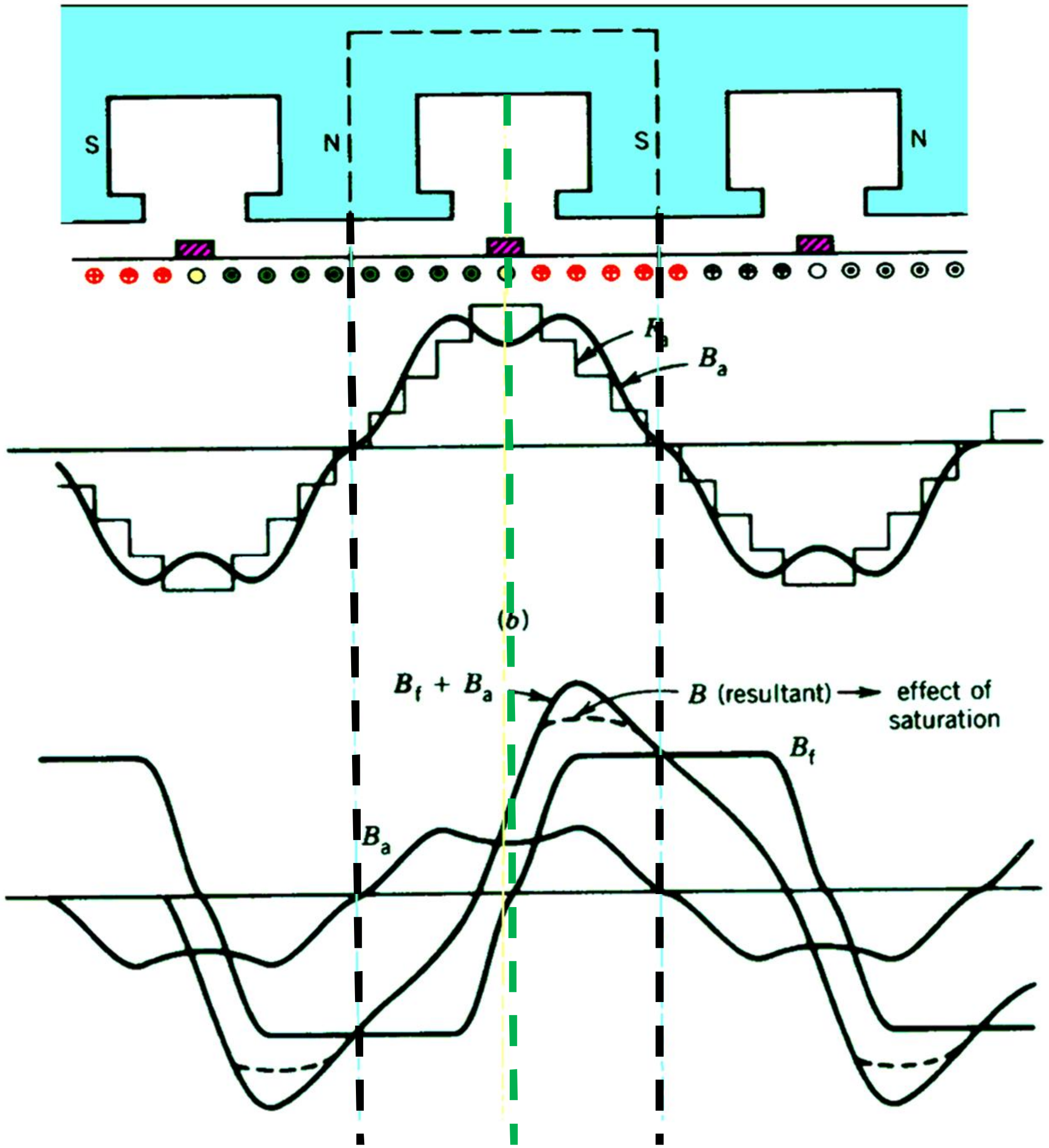
- Armature field



- Flux density increases in one half of the pole and decreases in the other half.

- Saturation reduces the flux per pole.

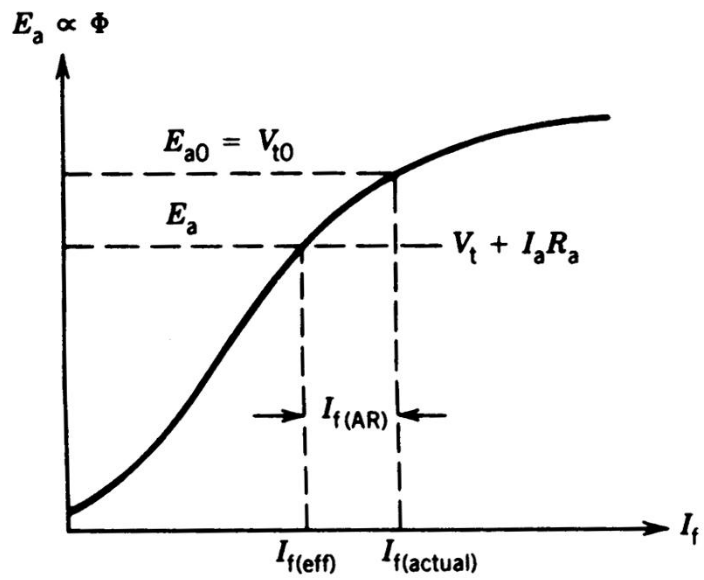
Armature Reaction



- Flux per pole decreases
- The zero flux density region moves from the q-axis

Armature Reaction

$$E_a = V_t + I_a R_a$$



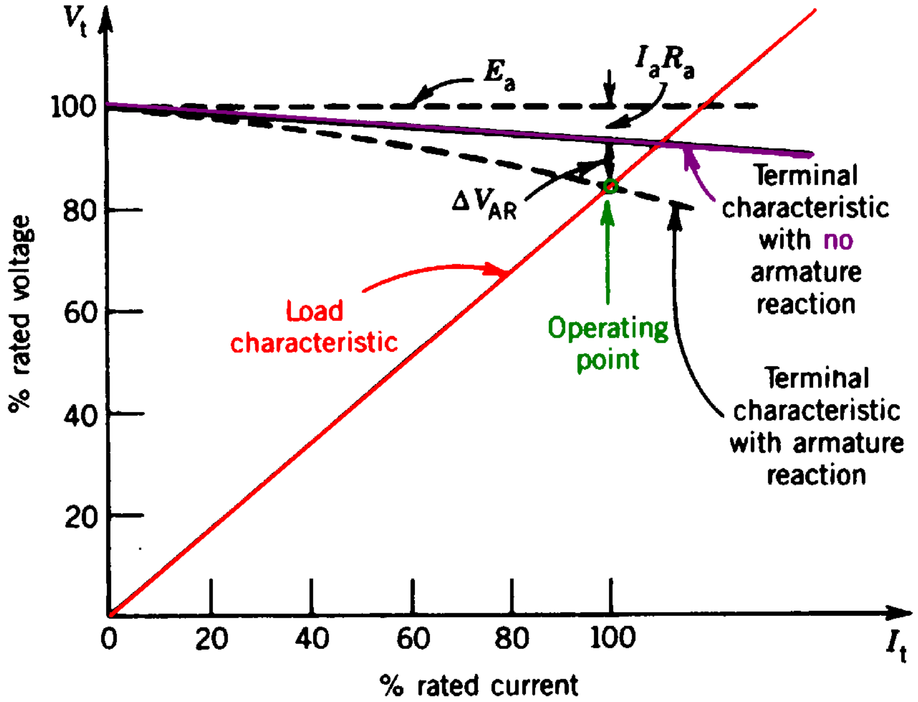
- Armature reaction in equivalent field current

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

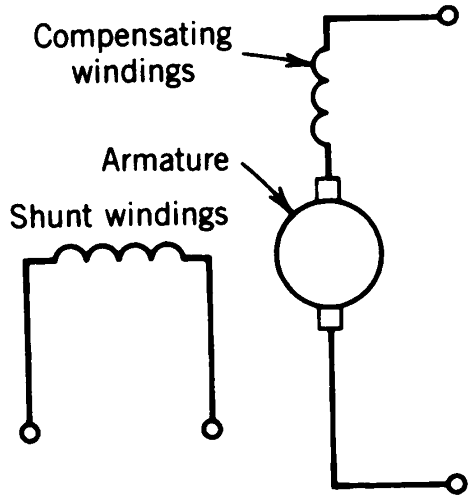
- Terminal characteristic

$$V_t = E_a - R_a I_a$$

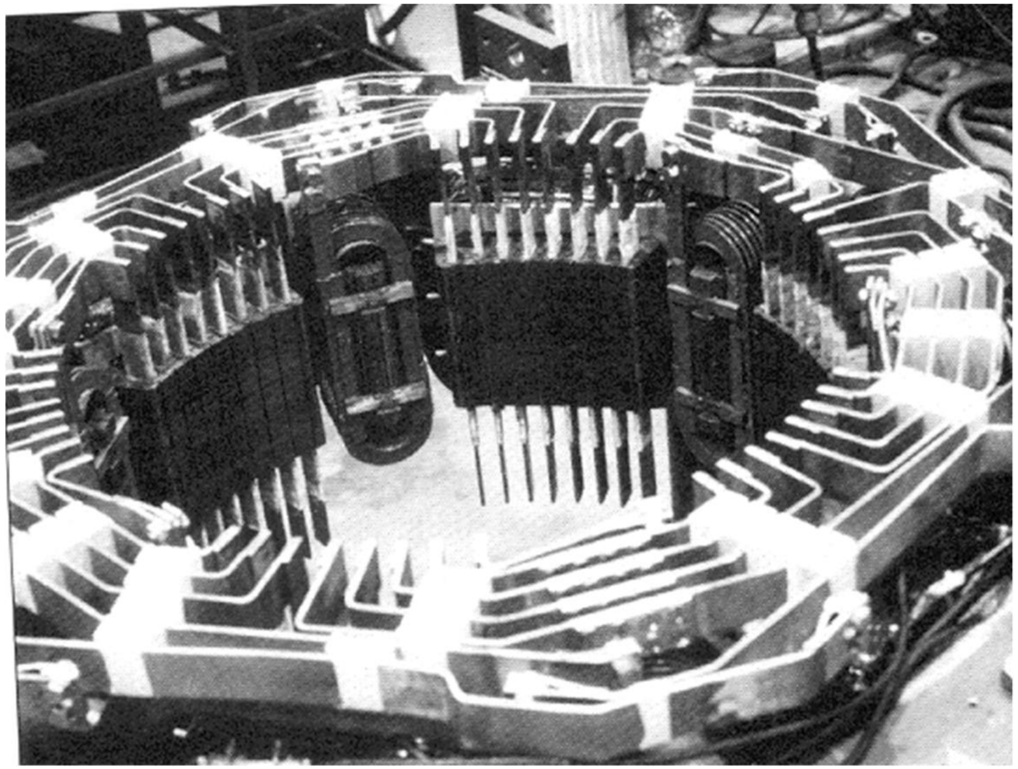
$$E_a = K_a \Phi \omega_m$$



Compensating Winding

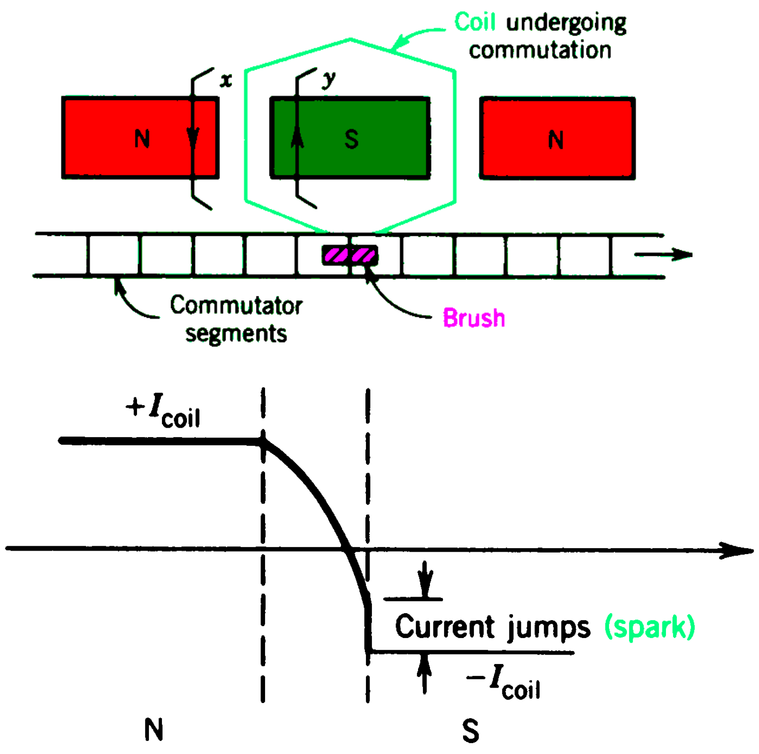


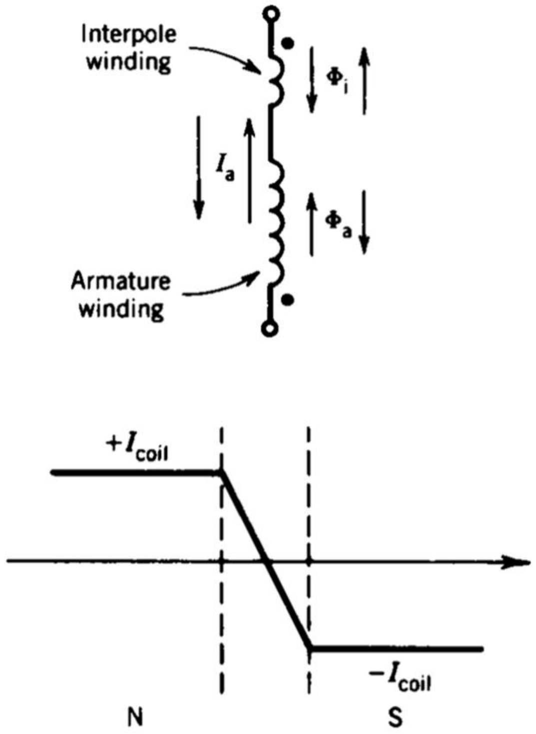
- Armature reaction
  - Poor commutation and sparking.
- Compensating winding fitted on the main pole faces and connected in series with armature winding.
  - Rotor mmf neutralized
- Expensive solution used only in large machines

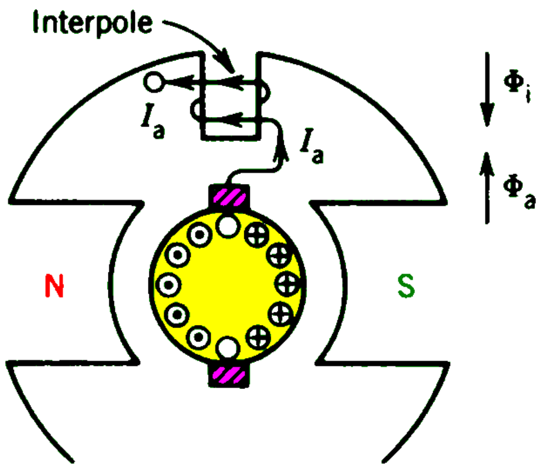


Interpoles or Commutator Poles

- Armature current reversal is delayed due to coil inductance
- Inter-pole is needed to compensate armature reaction.
- Used with compensating winding in large machines

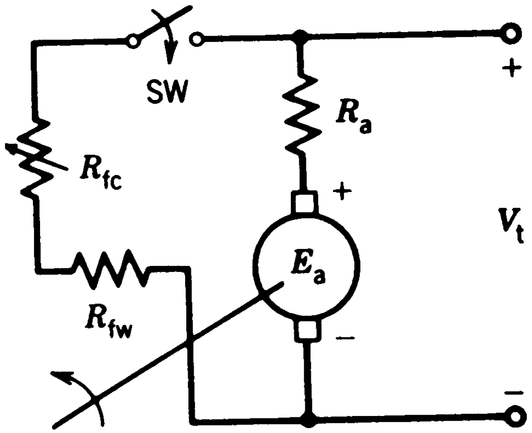


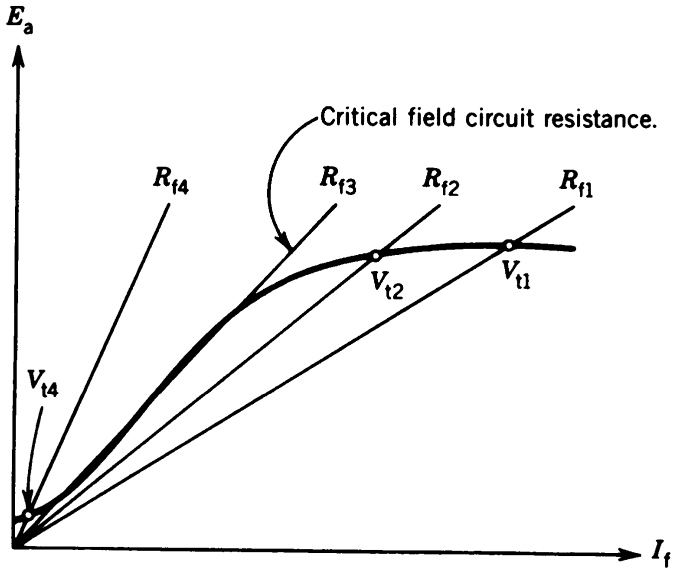


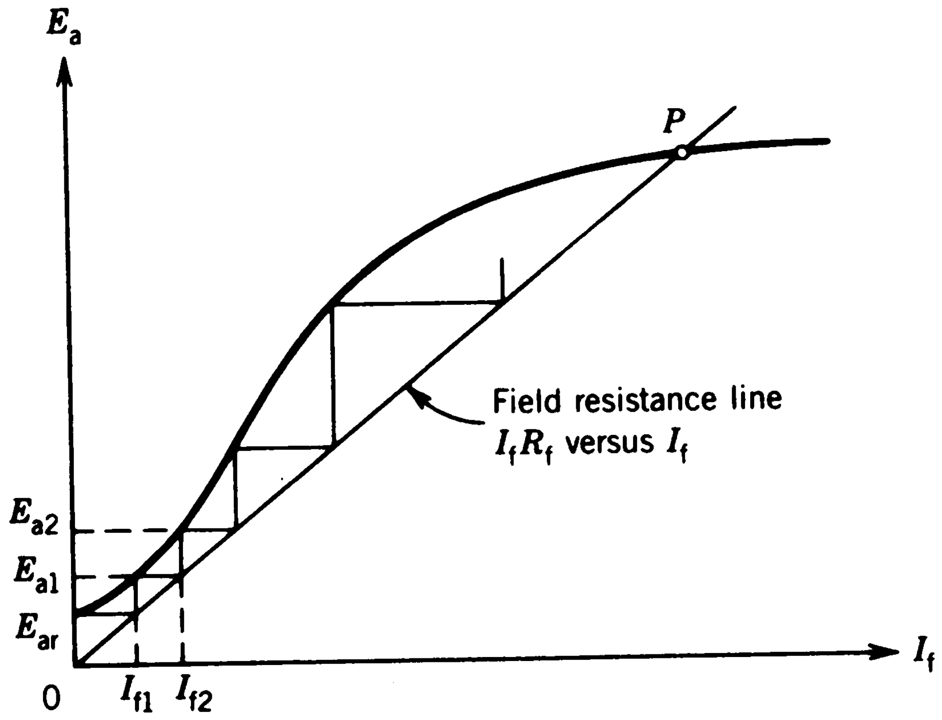


Shunt Generator - Voltage Buildup

- 3 conditions are necessary for voltage buildup:
  - Residual magnetism
  - Field mmf aids residual magnetism
  - $R_f < R_{fc}$







- Saturation results in a maximum armature voltage
- In reality voltage builds up following the magnetization curve

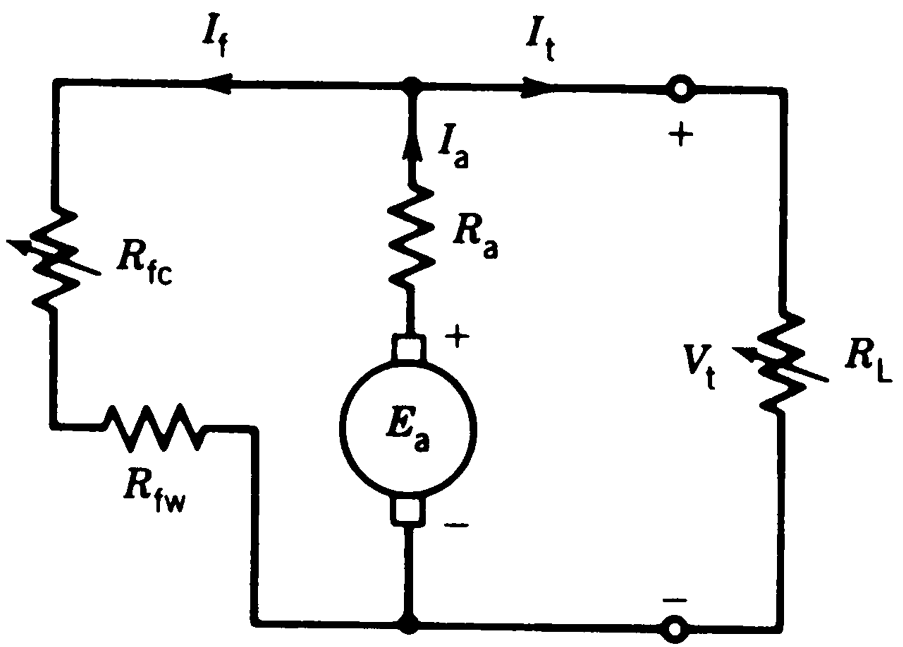
Shunt Generator - Characteristics

function of I_f

$$E_a = K_a \Phi \omega_m$$

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

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

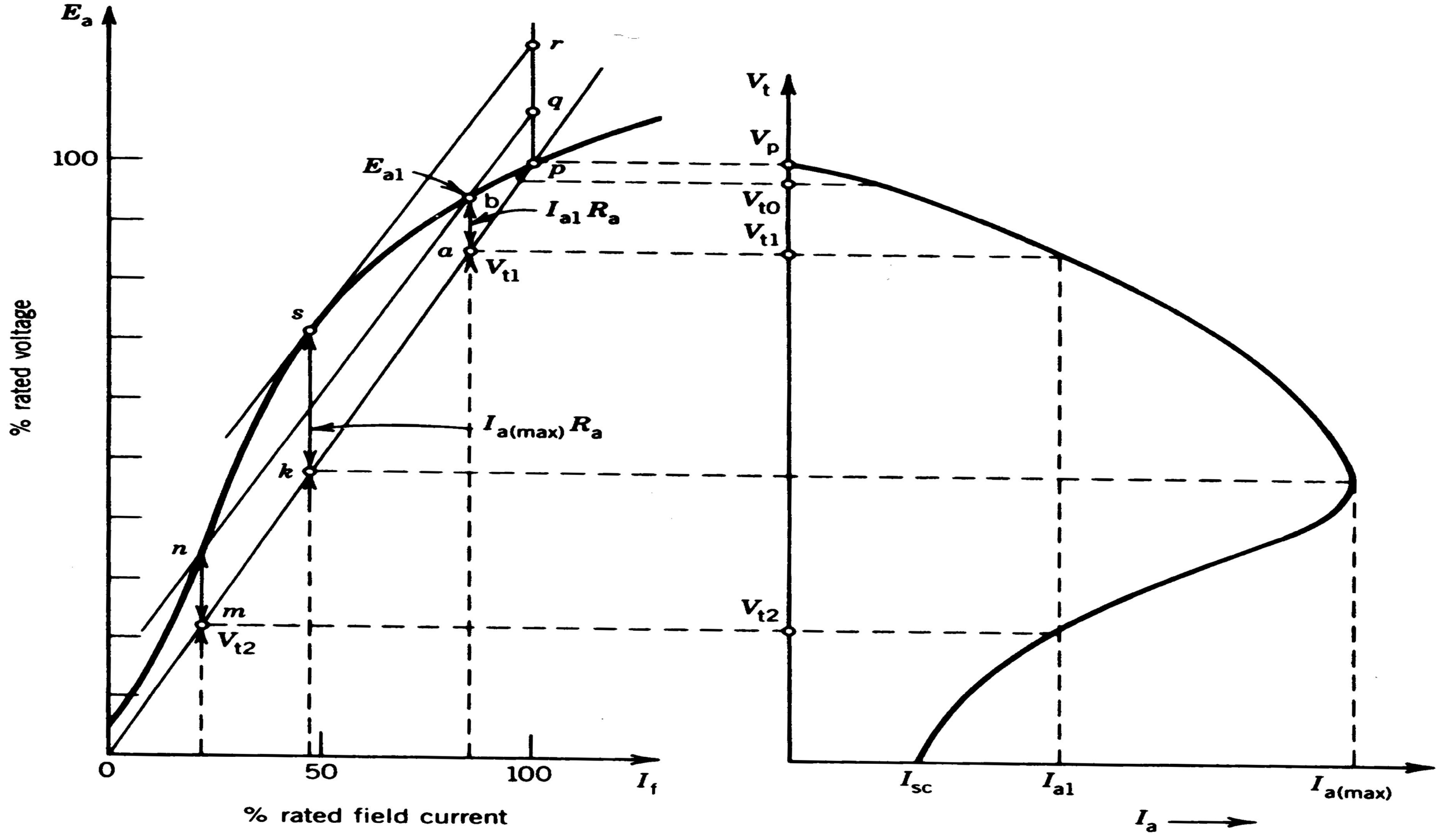


- For a given I_f we get V_t and I_a
- Plot V_t vs. I_a

- If I_t=0, I_a= I_f → $V_{t0} \neq V_p$

- Voltage drops faster with armature current

Field current drop

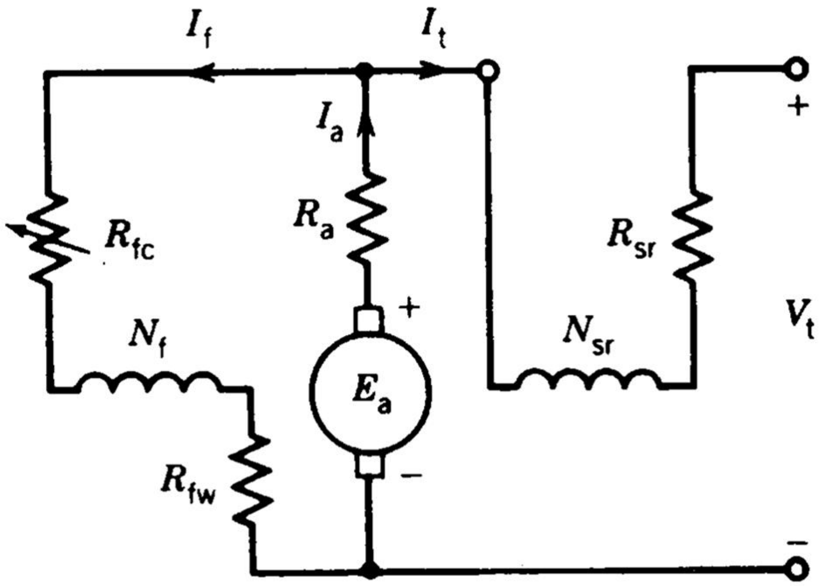


E_a
100
% rated voltage
r
q
p
E_{a1}
b
$I_{a1} R_a$
a
V_{t1}
s
$I_{a(max)} R_a$
k
n
m
V_{t2}
0
50
100
I_f
% rated field current
V_t
V_p
V_{t0}
V_{t1}
V_{t2}
I_{sc}
I_{a1}
$I_{a(max)}$
I_a

Compound DC Machines

- Shunt field winding provides the major portion of the mmf in the machine
- Series winding compensates voltage drop due to $R_a I_a$ and armature reaction

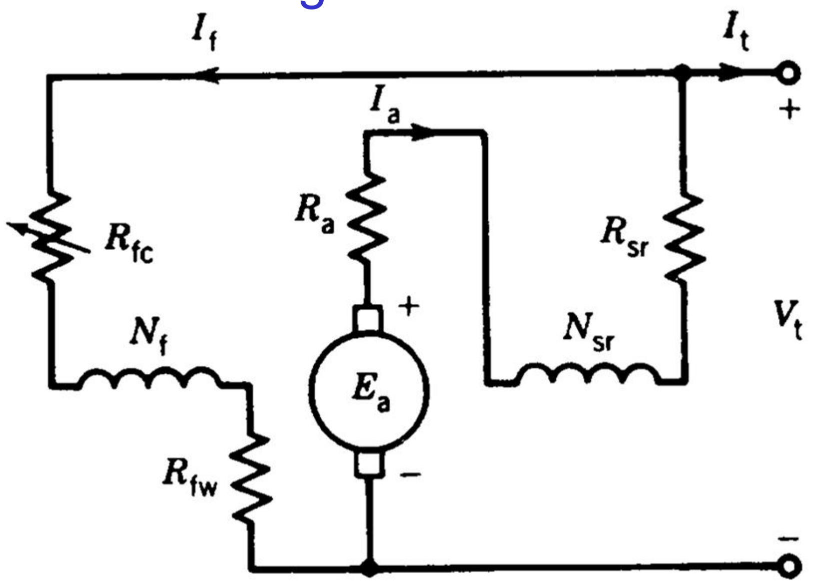
short-shunt



$$V_t = E_a - I_a R_a - I_t R_{sr}$$

$$I_t = I_a - I_f$$

long-shunt



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

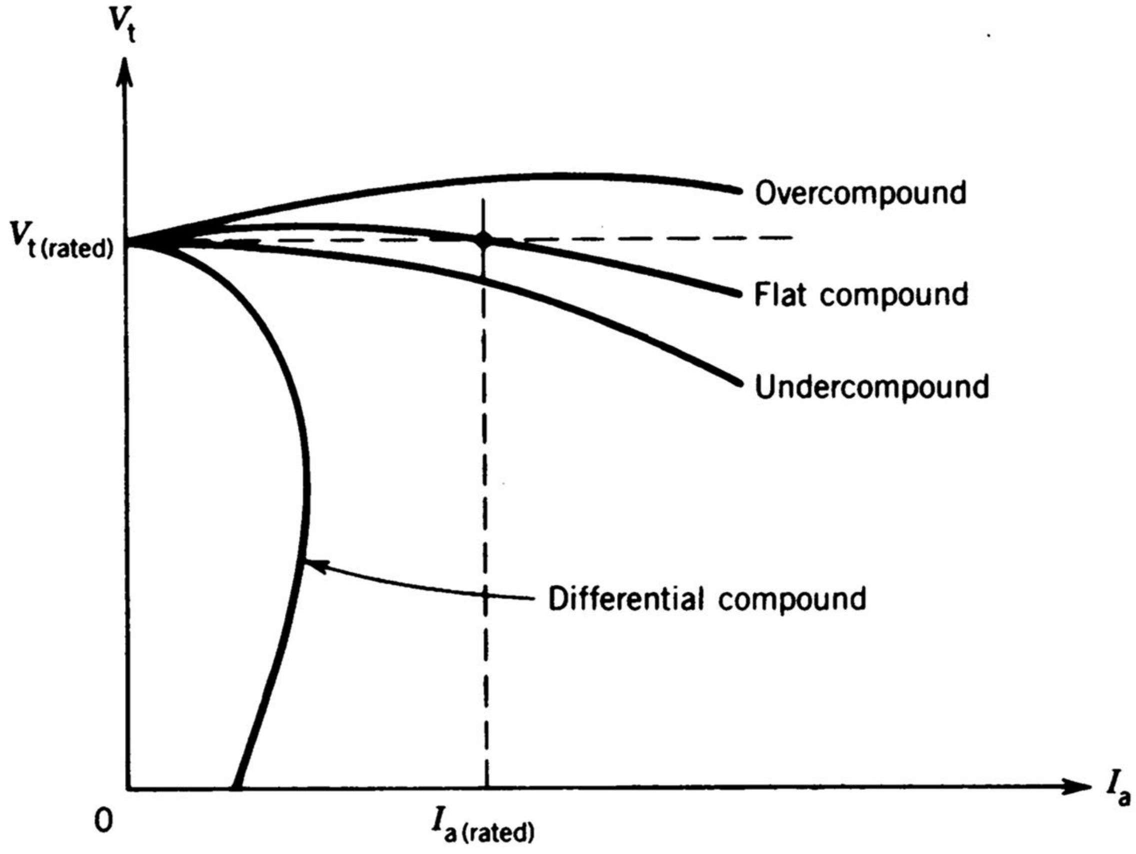
$$I_t = I_a - I_f \qquad I_f = \frac{V_t}{R_{fw} + R_{fc}}$$

Compound DC Machines

- Generated voltage and effective field current

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

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



- differential compound machine has almost constant current

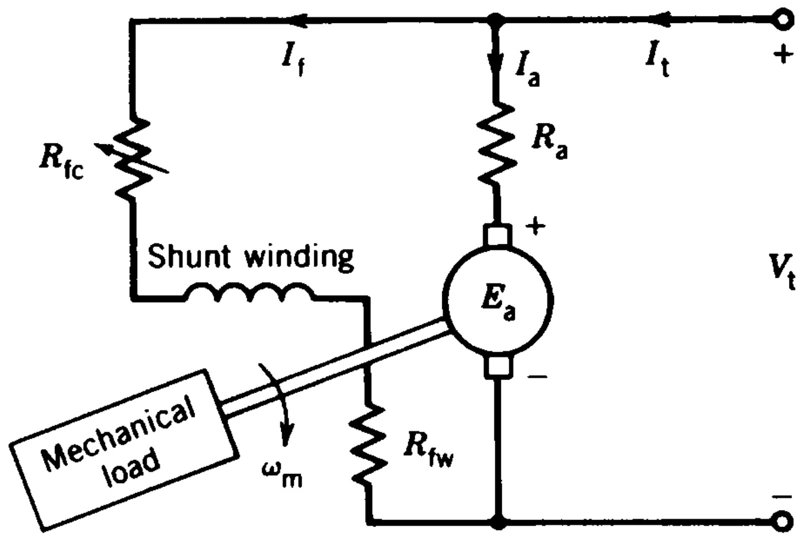
Shunt Motor

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

$$V_t = I_a R_a + E_a$$

$$I_t = I_a + I_f$$

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

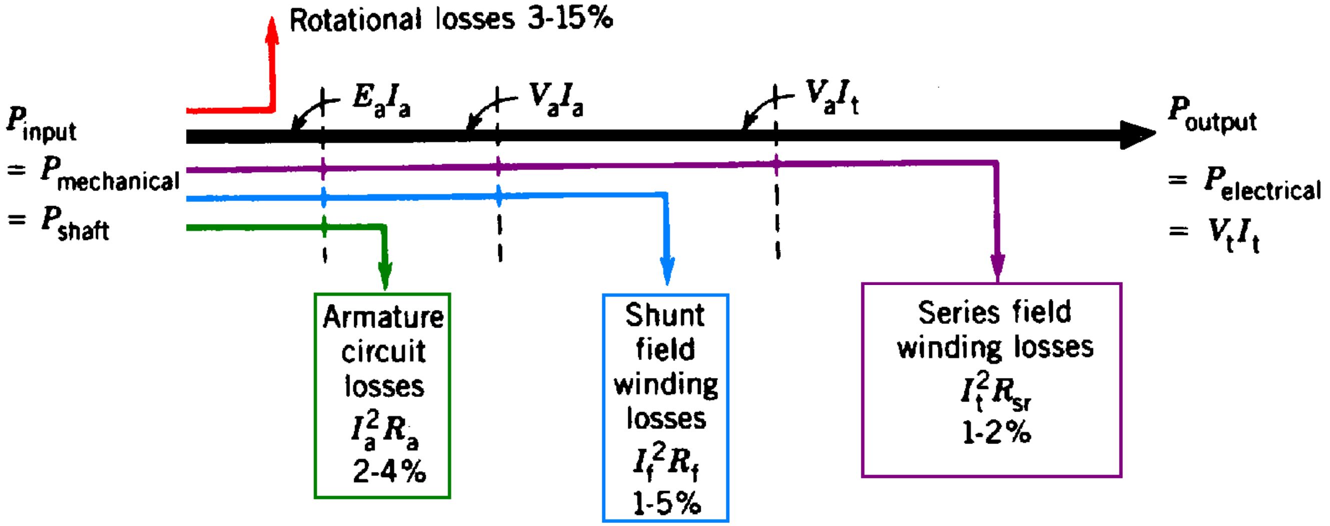


- Armature current and speed depend on the mechanical load

Power Flow and Efficiency

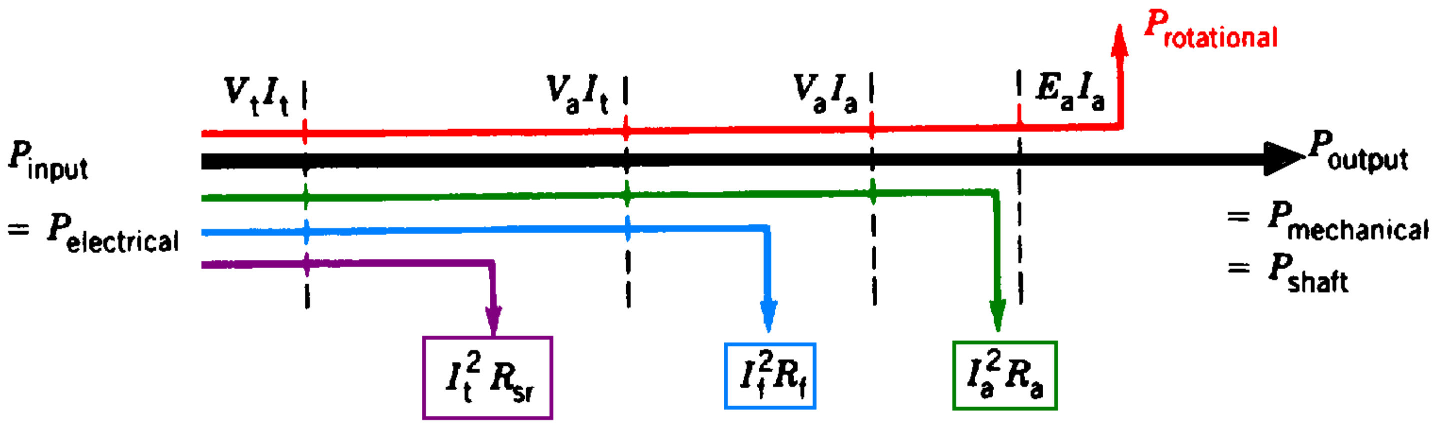
- Efficiency

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



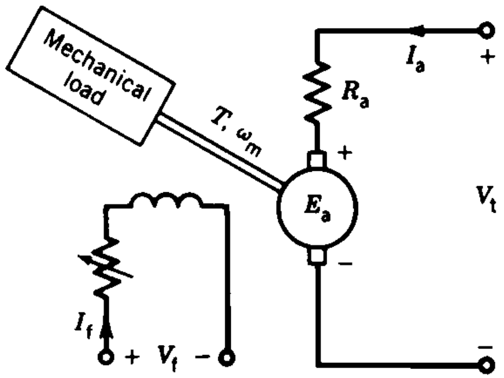
(*b*) Generator

- Core losses are included in the rotational losses



(*c*) Motor

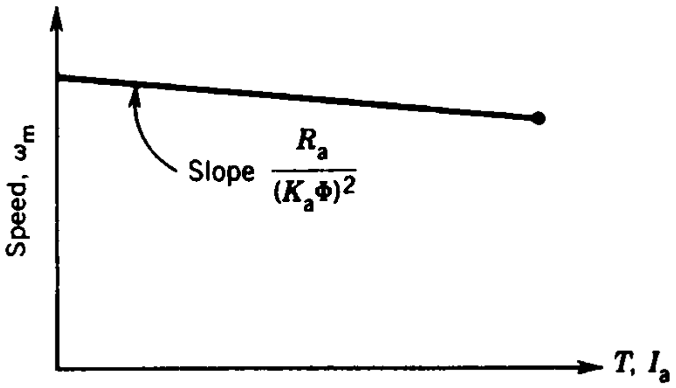
Separately Excited DC Motor Torque – Speed Characteristics



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

$$T = K_a \Phi I_a$$

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



- Constant flux and voltage ➡ Good speed regulation

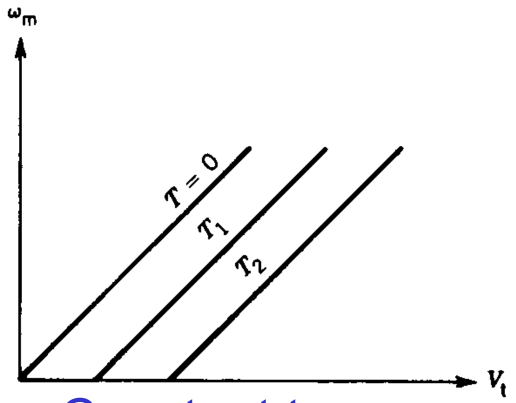
- Armature reaction decreases the flux ➡ Less speed drop

Speed control by:

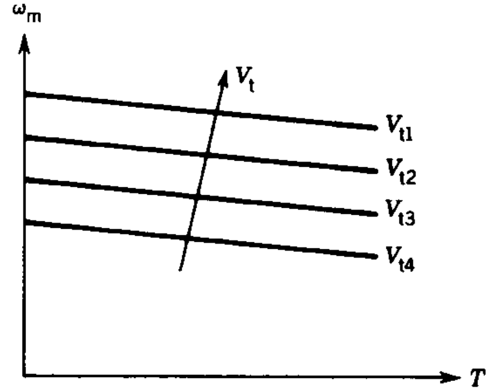
- Armature voltage control
- Field control
- Armature resistance control

Armature Voltage Control

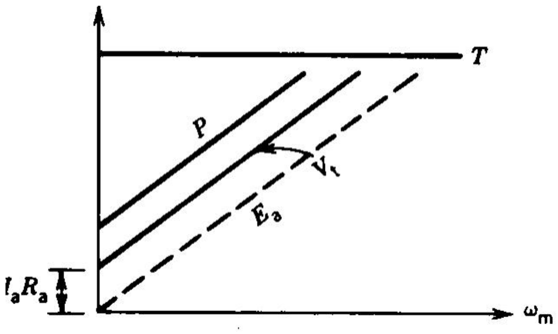
- rated field current and constant R_a → $\omega_m = K_1 V_t - K_2 T$

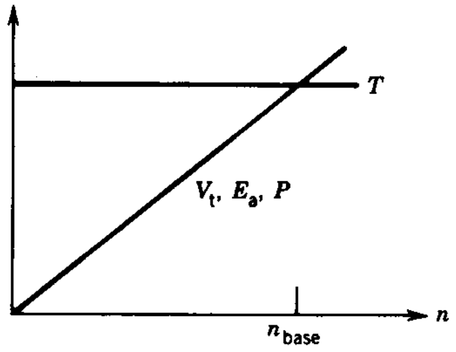


Constant torque



Constant voltage





- In actual applications I_a is kept constant (needs closed-loop operation)

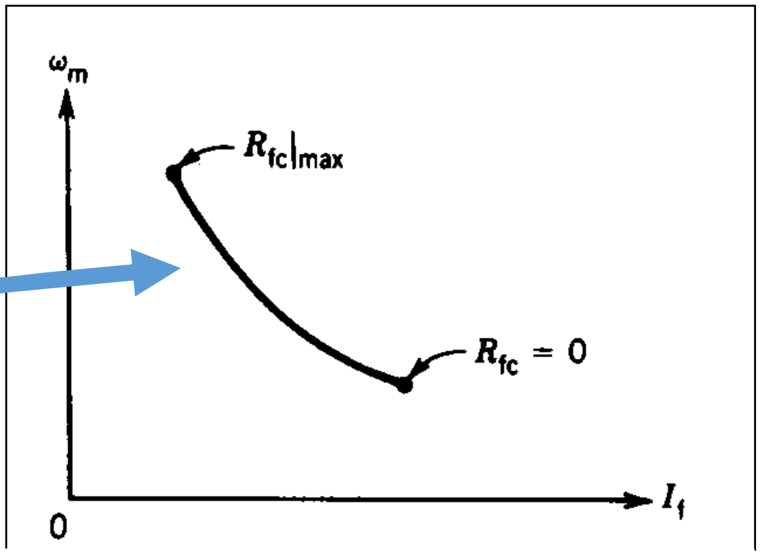
$T = K_a \Phi I_a$ → Constant torque

Field Control

- R_a and V_t constant
- I_f variable (rheostat R_{fc})
- Magnetic linearity assumed

$$K_a \Phi = K_f I_f$$

$$\omega_m = \frac{V_t}{K_f I_f} - \frac{R_a}{(K_f I_f)^2} T$$

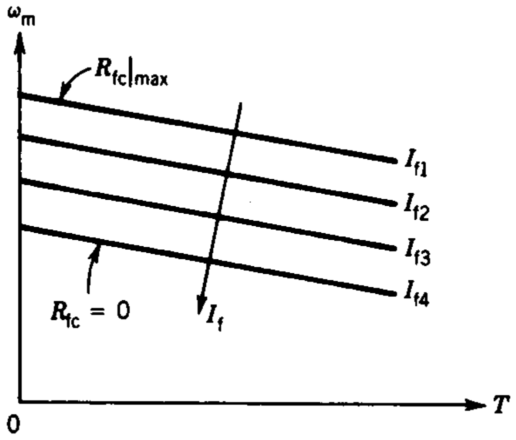


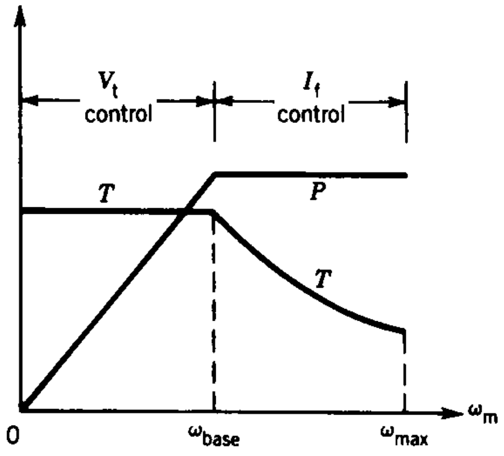
- No-load speed

$$\omega_m \approx \frac{V_t}{K_f I_f}$$

- Constant flux

$$\omega_m = K_3 - K_4 T$$





Field control

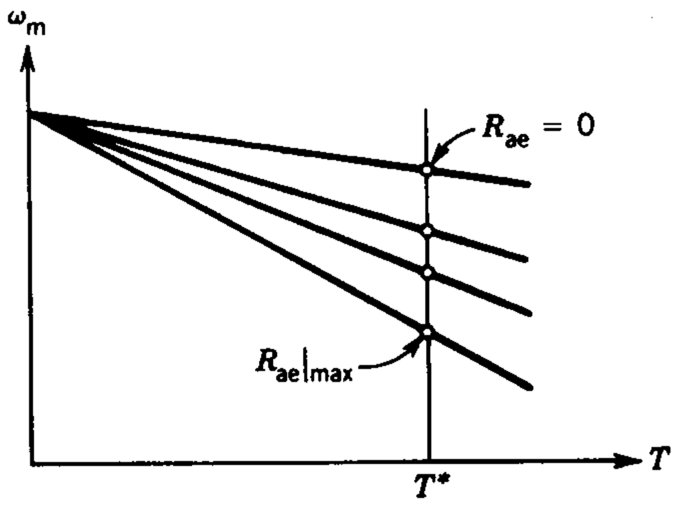
- Less expensive
- Slow
- Speed response sluggish

Armature Resistance Control

- V_t and I_f constant
- $R_a = R_a + R_{ae}$ variable

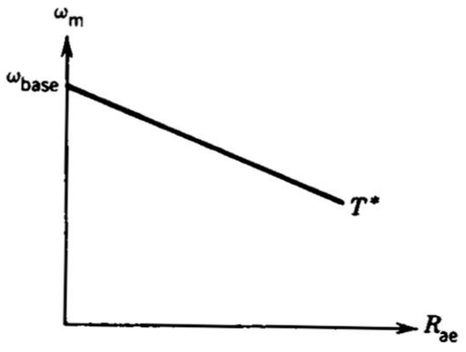
$$\omega_m = \frac{V_t}{K_a \Phi} - \frac{R_a + R_{ae}}{(K_a \Phi)^2} T$$

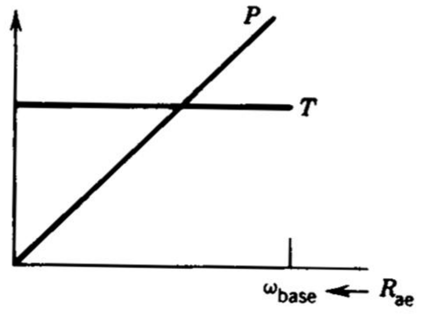
$$\omega_m = K_5 - K_6 T$$



- Method used still in transit system vehicles

- Low efficiency
- Expensive resistance needed to carry I_a





History not any more used

Series Motor

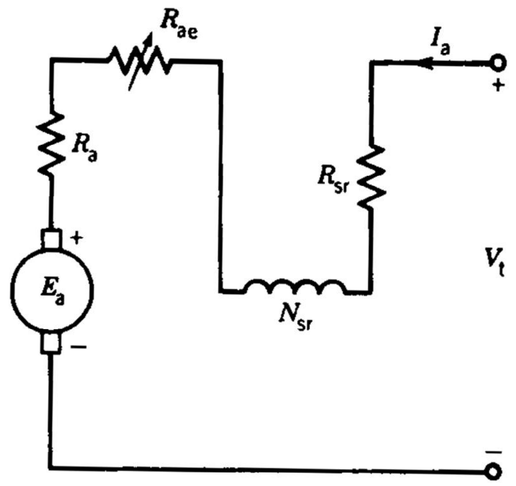
- Magnetic linearity

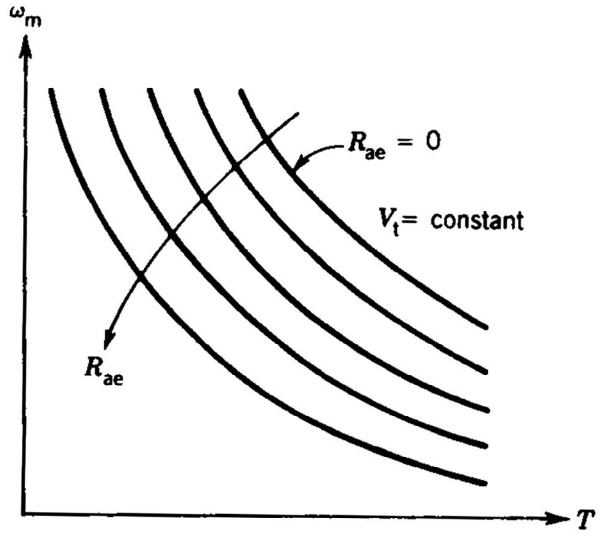
$$K_a \Phi = K_{sr} I_a$$

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

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

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





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

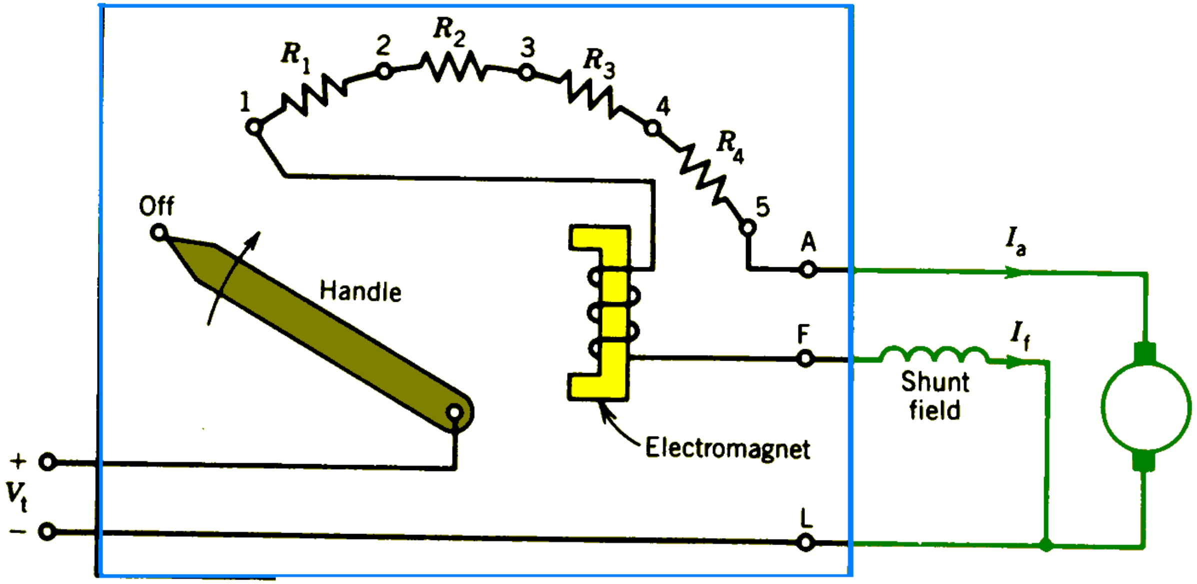
- Large starting torque
  - Subway car, automobile starter, hoist, crane, blender
- Speed control over a wide range

Starter

- Back emf is zero at start

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

$$I_a\Big|_{start} = \frac{V_t}{R_a}$$



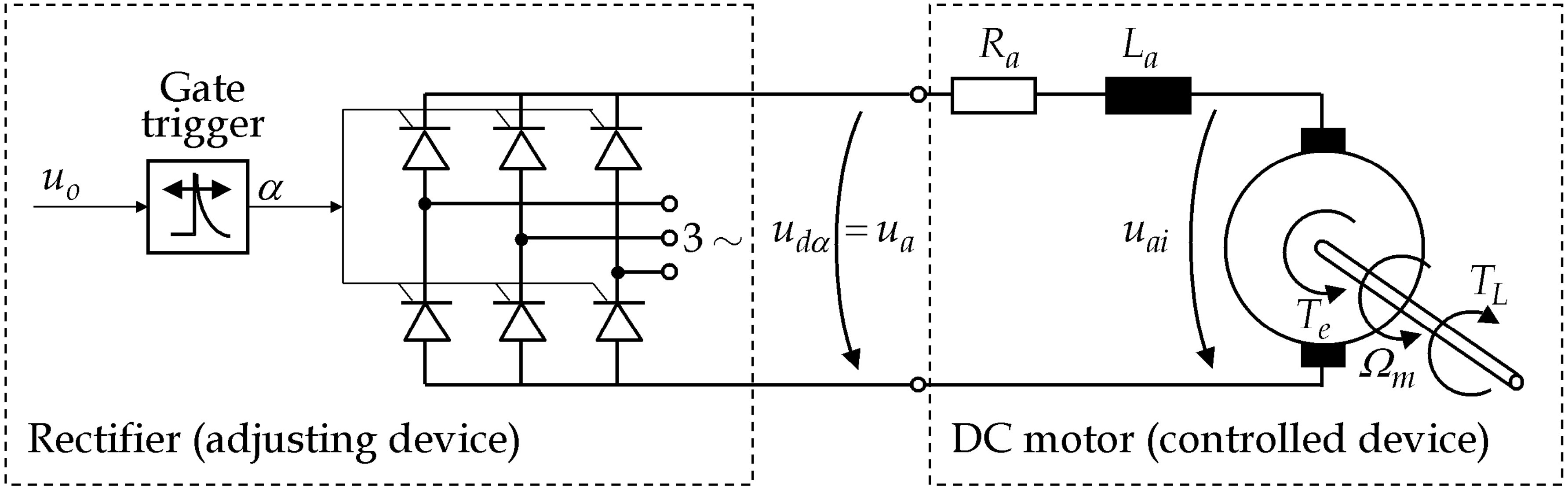
- Variable external resistance is used to reduce the starting current

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

- At normal operation the electromagnet holds the handle and the external resistance is zero

History not any more used

Modern, power electronics-based



- The angular speed is adjusted by means of the armature voltage u_a.
- Further speed increase can be achieved through field current control.
- The maximum speed is defined by mechanical considerations.