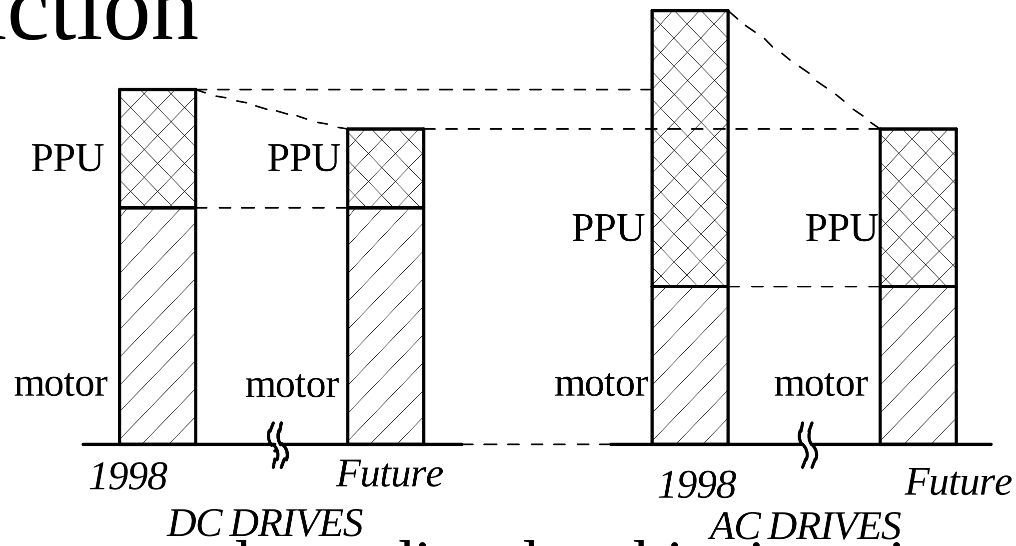
Chapter 7

DC Machines

1. Brush commutated
2. Electronically commutated

Introduction



Cost of dc vs. ac drives

- Demise prematurely predicted – ubiquitous in speed control.
- Merits
  - Cost: dc advantage over ac.
  - Ease of control – servo capability
  - Cheaper Power Processing Unit
- Drawbacks
  - Mechanical commutator and brushes require maintenance. Not a problem with electronically-commututated machines.

Classification of DC drives

- Brushed drive
  - Field wound
    - Series or universal

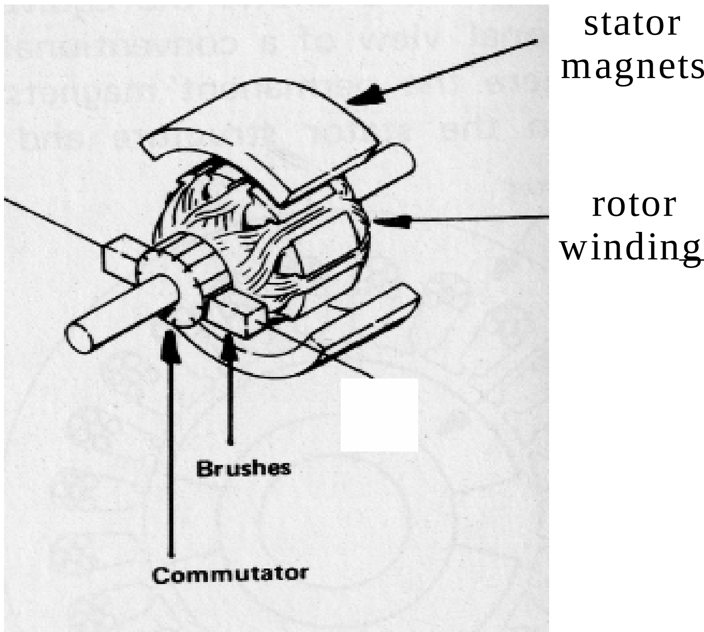
      e.g.
    - Shunt
    - Separately excited
    - Compound
  - Permanent magnet

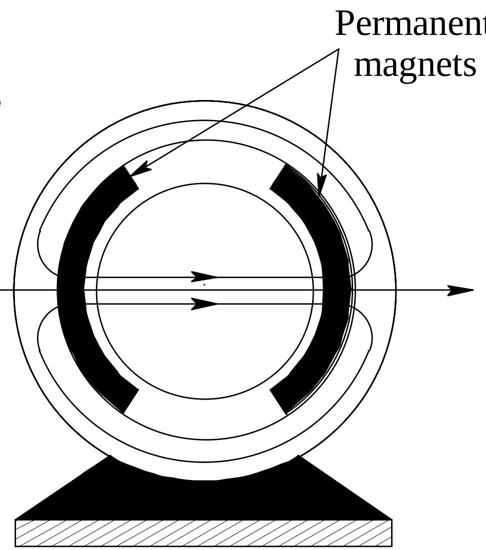
    e.g..

- Brushless or Electronically commutated

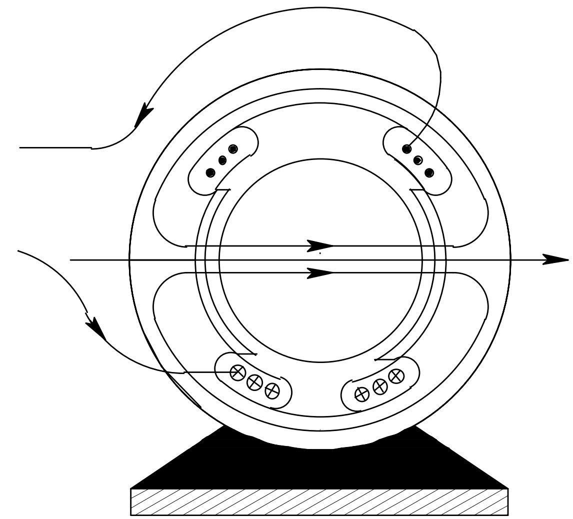
  e.g.

Structure of Brushed DC motors - stator





ϕ_f produced by permanent magnets

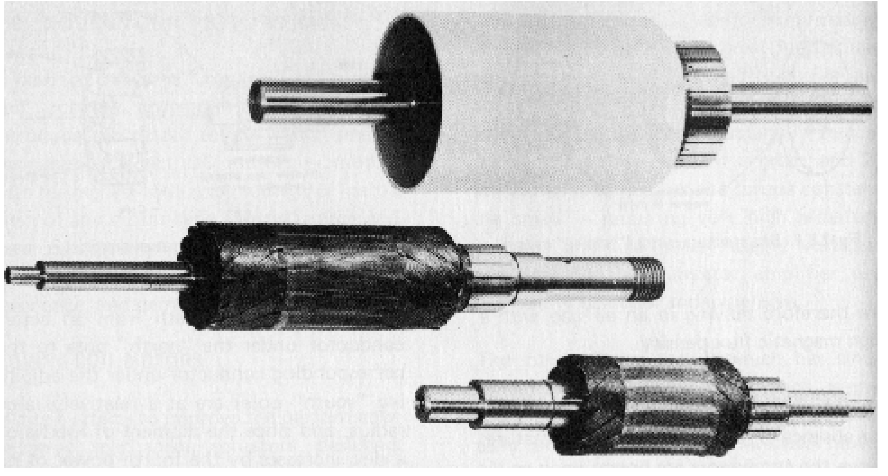


ϕ_f produced by stator winding current

- Stator
  - Establishes field flux, ϕ_f

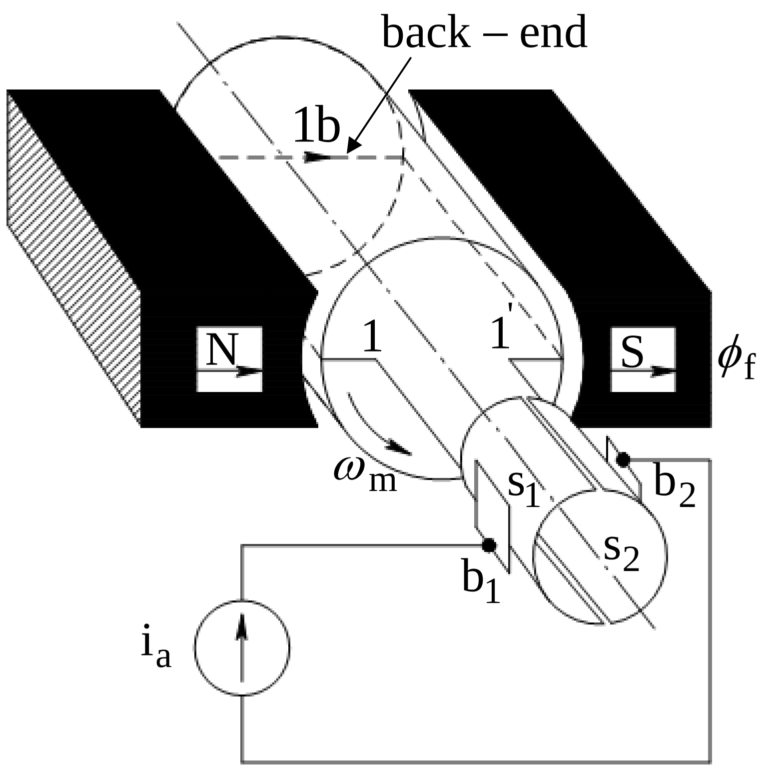
Structure of brushed DC motors - rotor

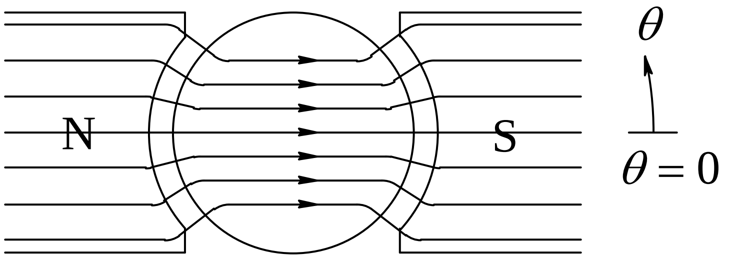
- Rotor
  - Armature winding
  - Commutator and brushes

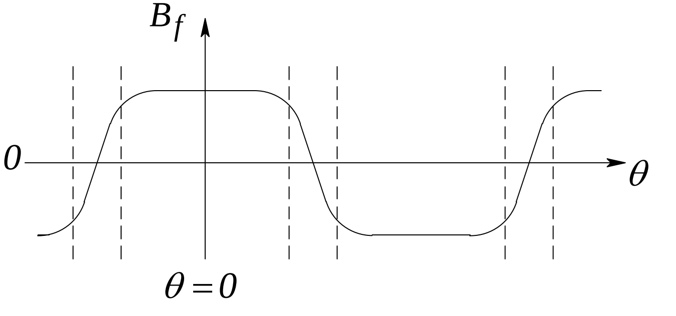


Operating Principles of a DC Motor

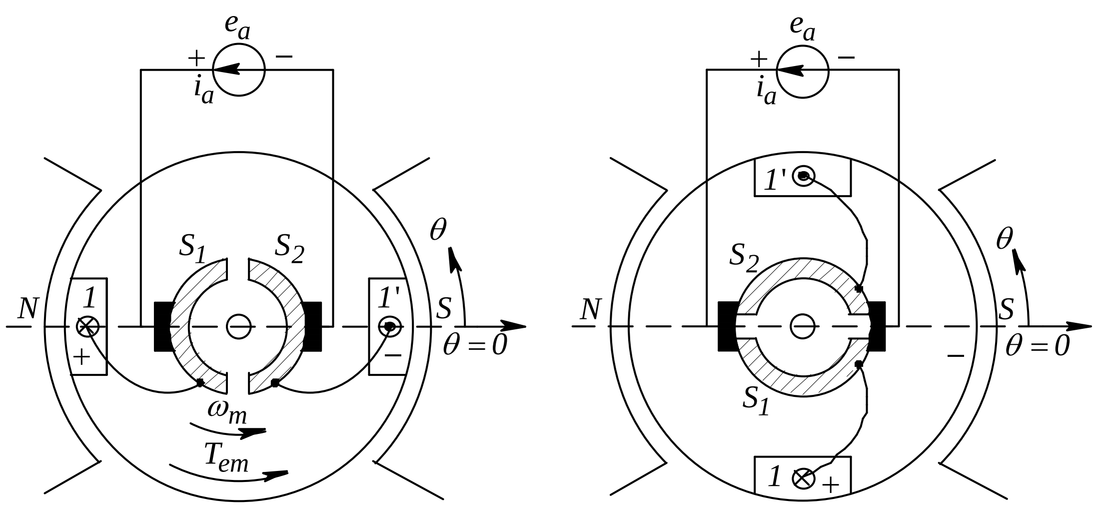
- Field flux density in the airgap

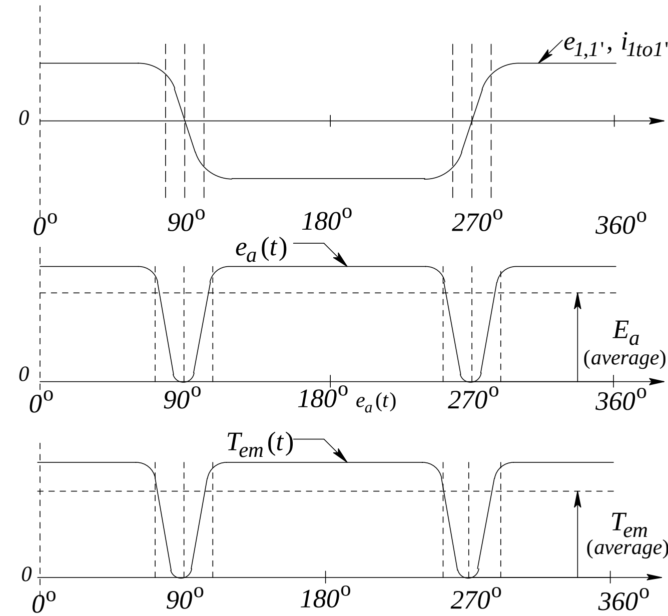






Operating principles - Commutator Action





Problem: large torque pulsations!

Basic torque and back emf equations for a primitive two-pole two-coil machine

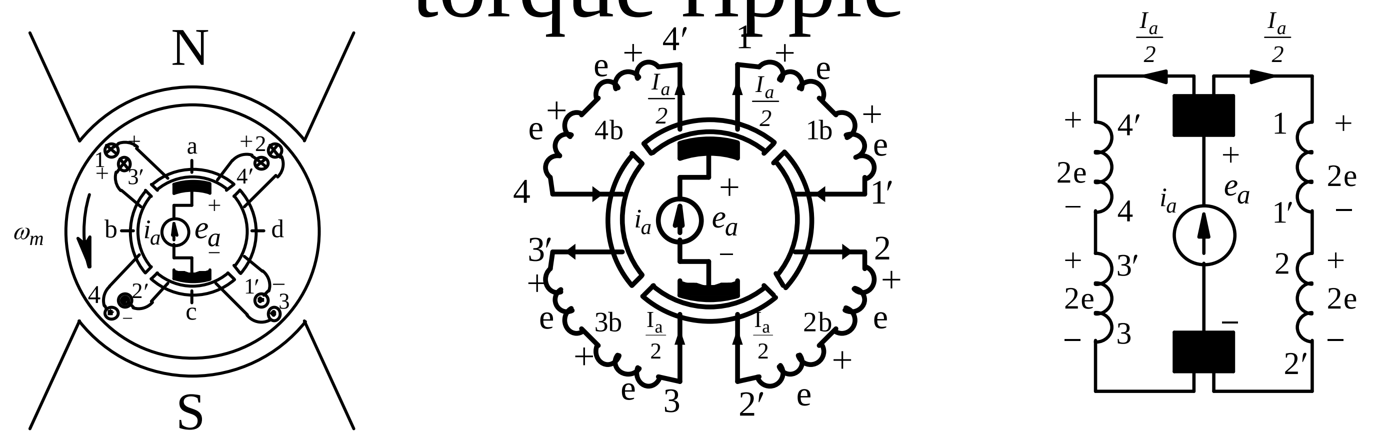
Ampere's Force Law

Faraday's Law

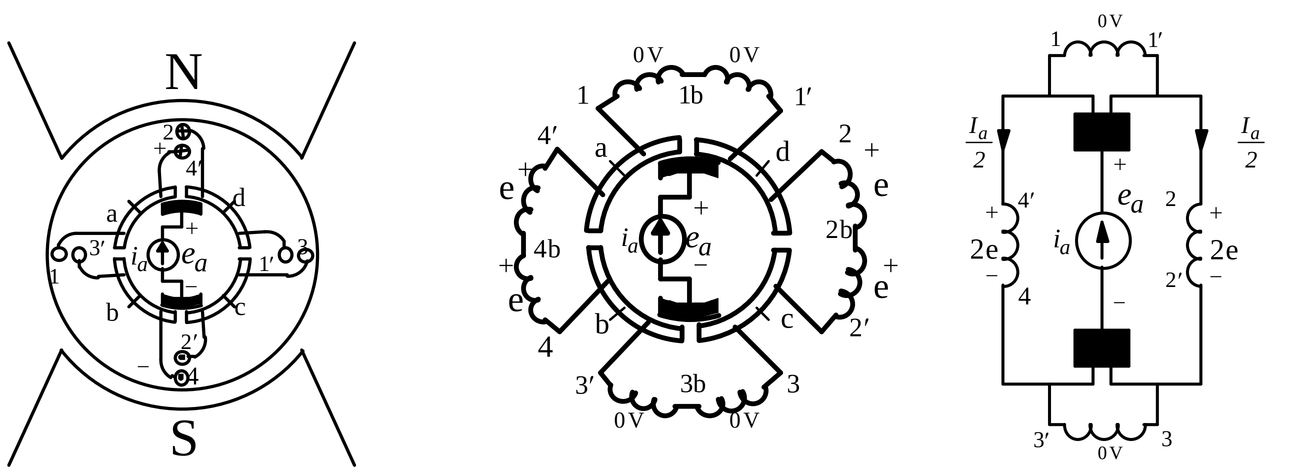
$$d\phi = B_f \, \pi r l = \textit{flux density x pole area}$$

$$dt = T/2 = 1/2f = \pi/\omega = \textit{half revolution}$$

Four-coil wave-wound example to reduce torque ripple

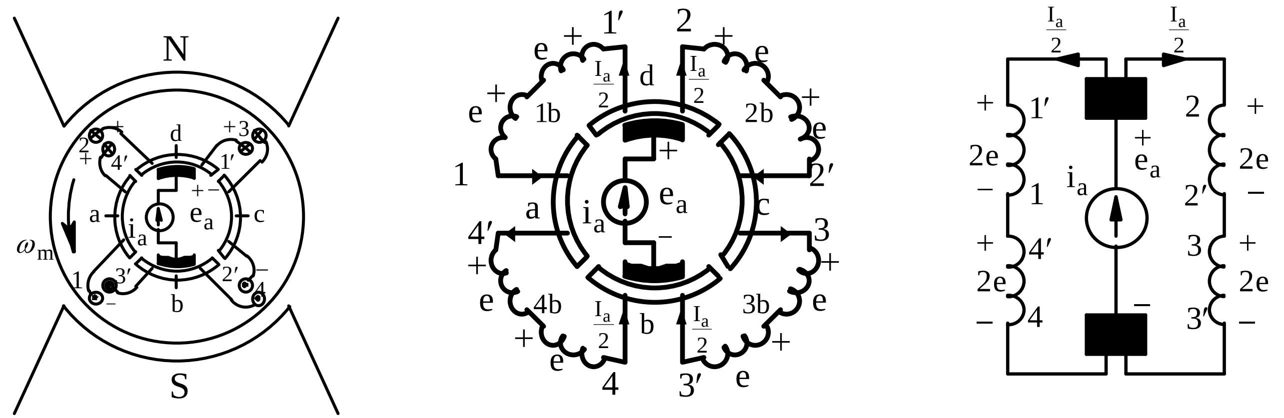


at $\theta = 0^o$



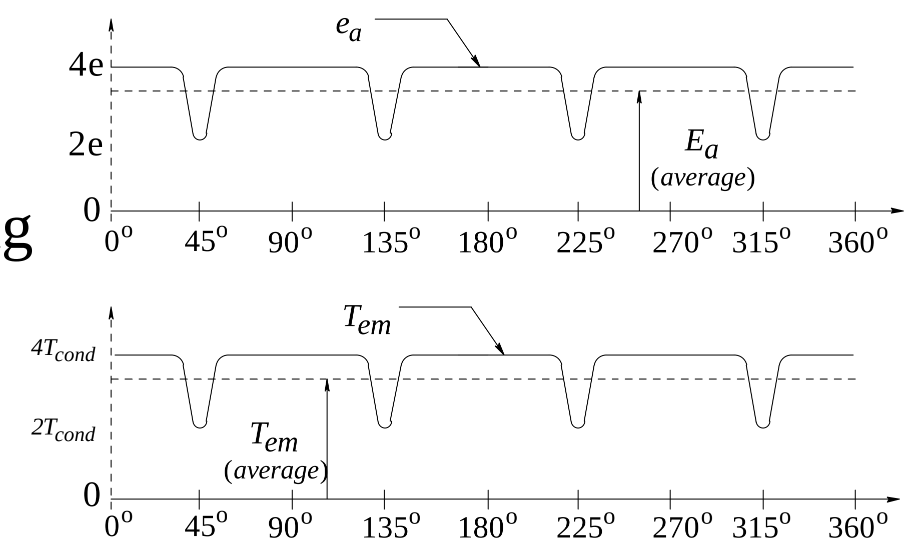
CCW rotation by 45°

Four-coil wave-wound example (cont'd)



CCW rotation by 90^o

Torque and emf pulsations can be reduced by increasing the number of conductors



Summary of operating principles for two-pole, four-coil machine

- ♦ i_a divides equally between two parallel circuits
- ♦ Torque produced on each conductor has the same direction
- ♦ Direction of i_a determines direction of torque

- ♦ Induced voltage in each circuit is equal to the sum of voltages induced in each coil.
- ♦ Polarity of induced emf depends only on the direction of rotation.

In M.K.S. Units $k_E = k_T$

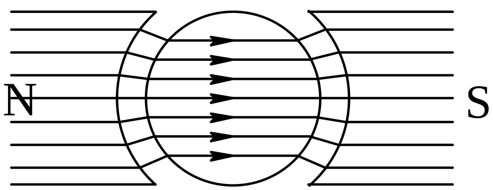
Wave and Lap windings

- DC machines typically have multiple coil sets to minimize ripple.
- Wound using either **lap** or **wave** constructions.

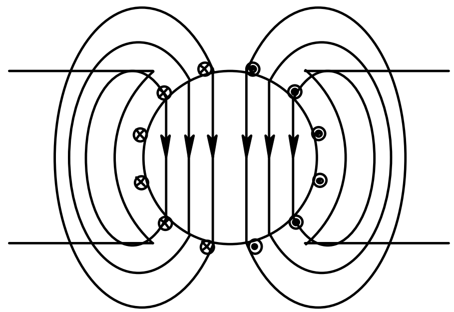
Wave:

Lap:

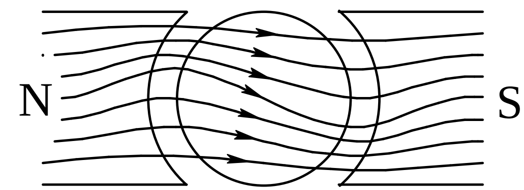
Armature reaction



stator flux

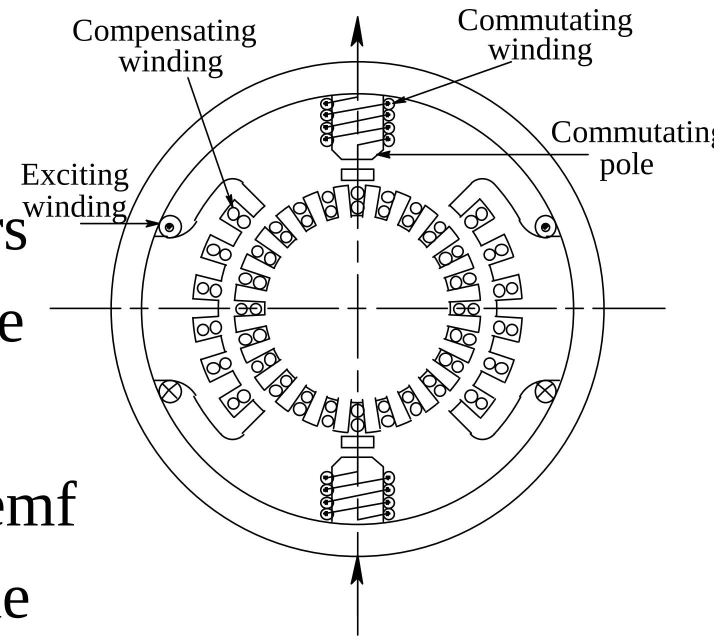


rotor flux



resultant flux

- ❑ Assuming magnetic structure does not saturate:
  - ◆ Increased torque in some conductors is compensated by decreased torque in other conductors
  - ◆ Same reasoning holds for induced emf
- ❑ Compensating winding to reduce the effect of armature reaction



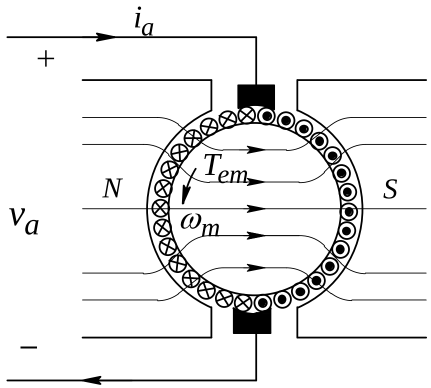
Armature reaction

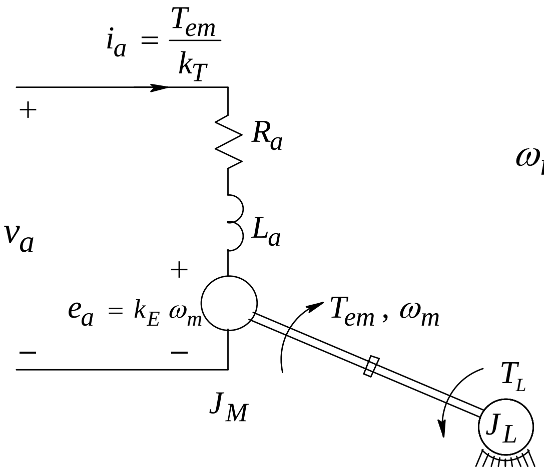
Permanent Magnets

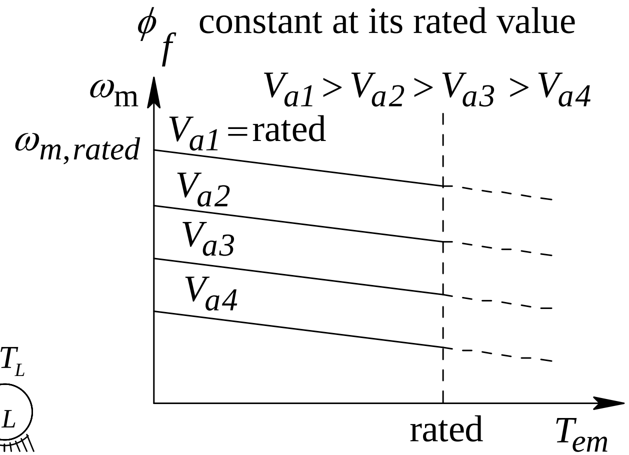
- Rare earth: Neodymium-iron-boron (Nd-Fe-B), Somarium cobalt – used in high performance machines (Toyota Prius)
- Alnico 5 and 8 (iron, nickel, aluminum and cobalt) – low coercivity, brittle
- Ferrite, also known as ceramic (iron oxide, barium) – widely used, inexpensive, good mechanical characteristics

Permanent Magnets

DC Machine Equivalent Circuit







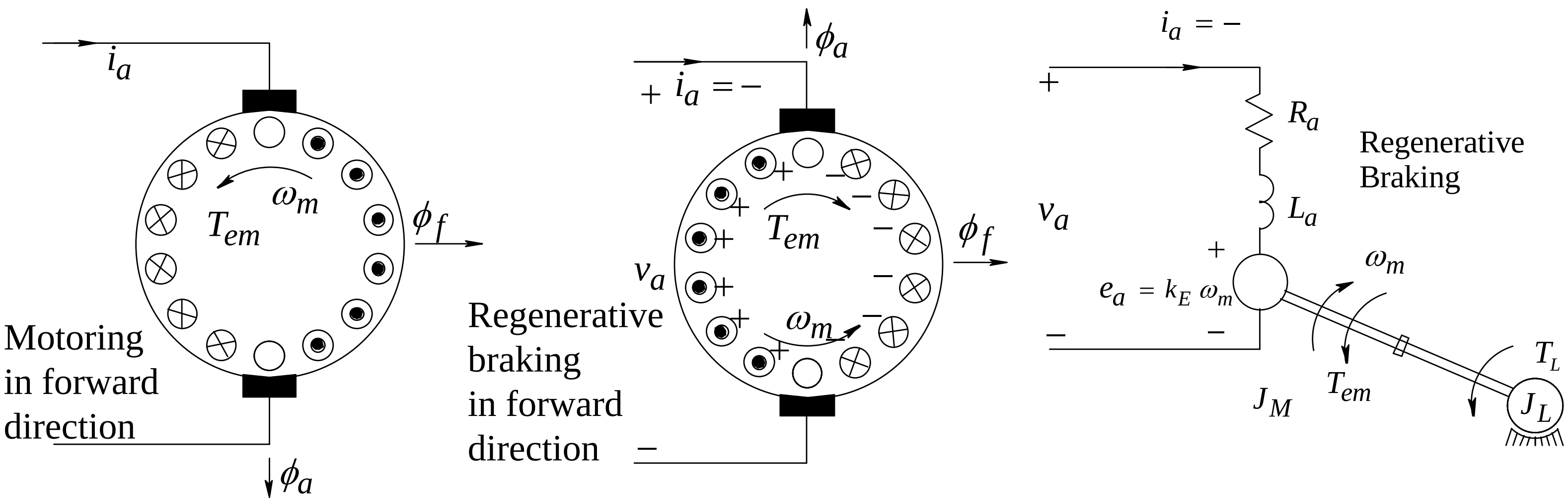
Basic equations

Steady State

$$I_a = \frac{T_{em}(=T_L)}{k_T} \qquad \omega_m = \frac{V_a - I_a R_a}{k_E}$$

Torque-speed characteristic equation

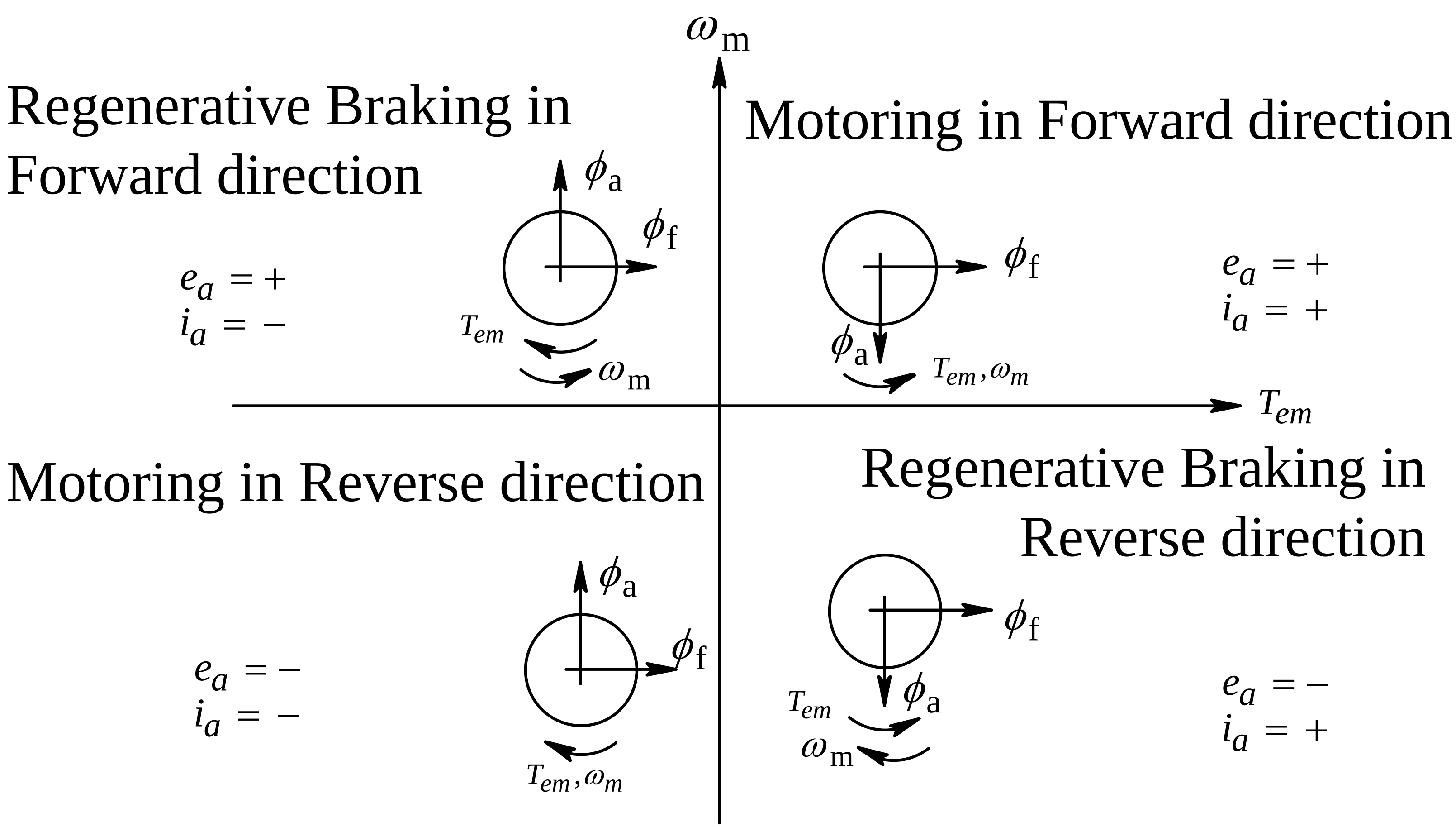
Operating Modes



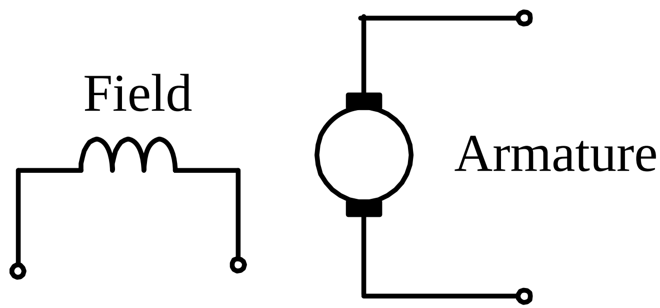
- Regenerative Braking: Feeding energy back while braking
  - current and torque direction reversed
  - same polarity of induced emf

- Operation in reverse direction: polarity of applied voltage reversed
  - Motoring $i_a < 0$
  - Regenerative braking $i_a > 0$

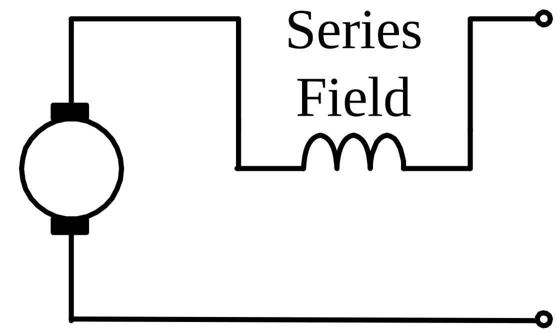
Four Quadrant Operation



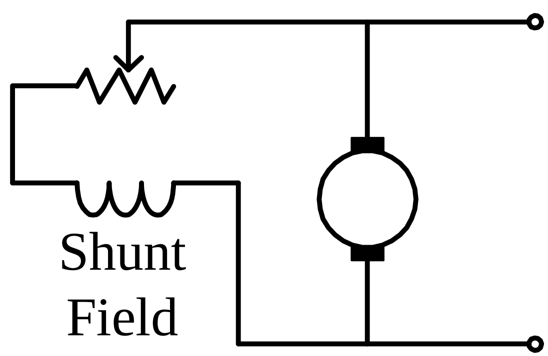
Field-wound Machines



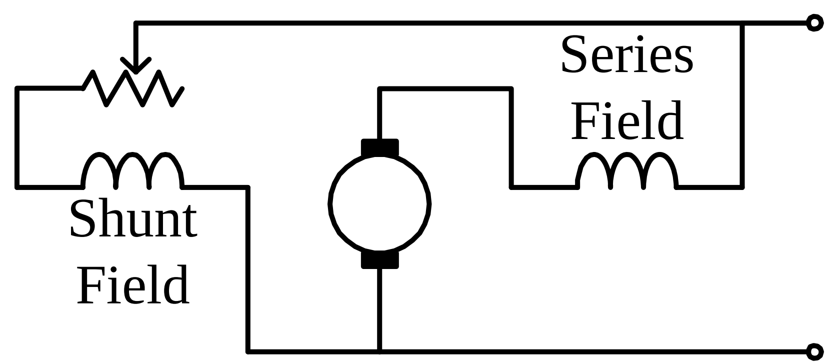
Separately-excited



Series, universal



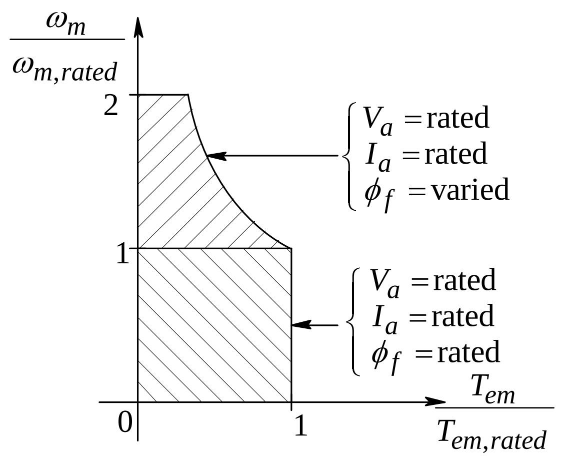
Shunt



Compound

Flux weakening in wound field machines

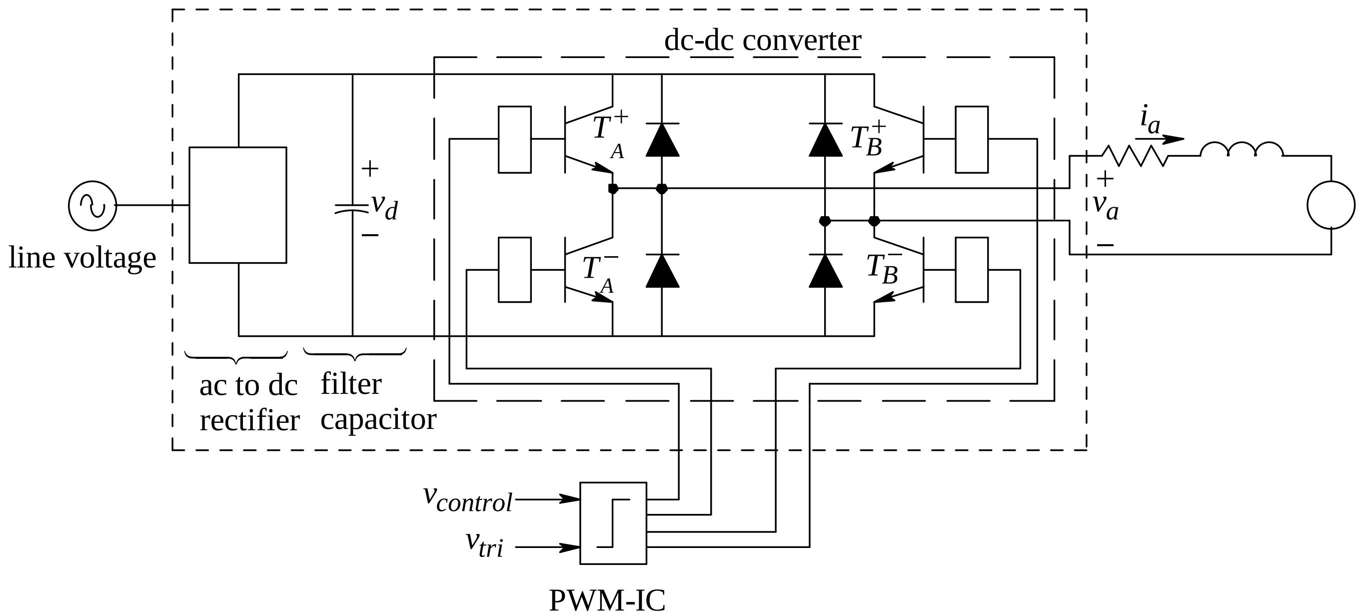
to Allow Overspeed Operation



- Below rated speed, k_T maximum to ensure maximum torque/Ampere thereby minimizing resistive losses
- Above rated speed, B_f reduced to keep V_a at its rated value.
- B_f reduced by reducing I_f
- k_T and k_E changed; $k_T = k_t B_f$; $k_E = k_e B_f$; $k_t = k_e$
- Since I_a is limited to its rated value maximum, T_{em} reduces

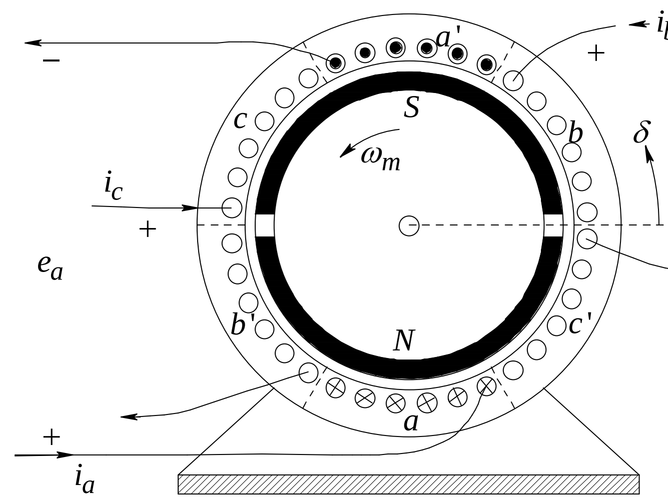
Power Processing Unit for DC Drives

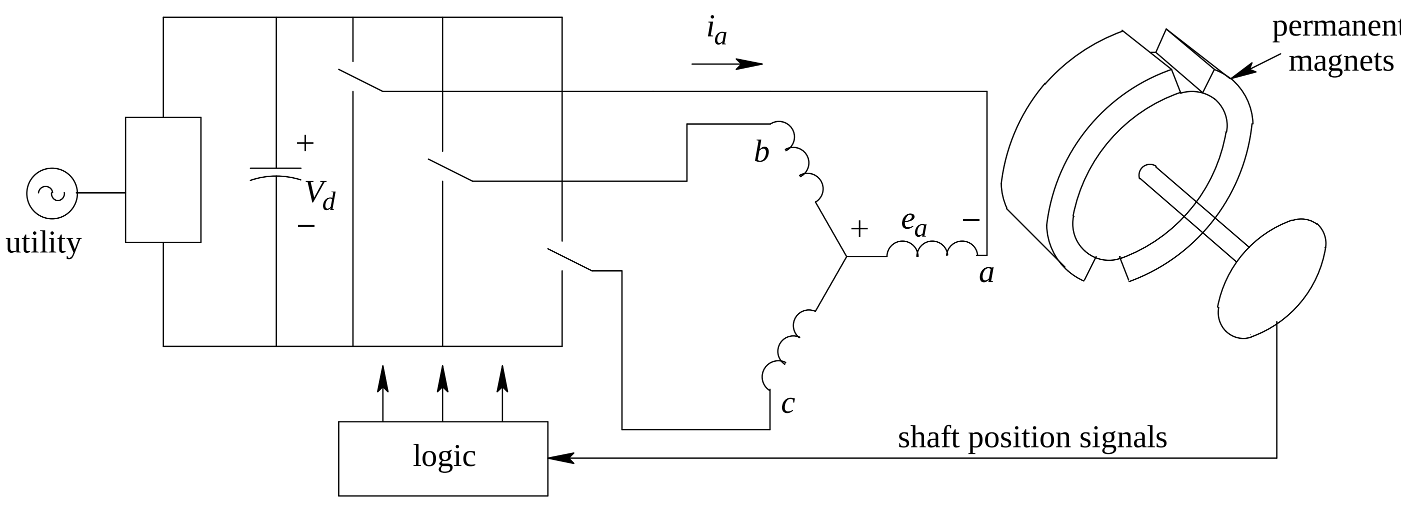
- Draw power from utility - power quality problems
  Ideally power flow should be reversible
- Provide nearly dc voltage and current to the dc motor



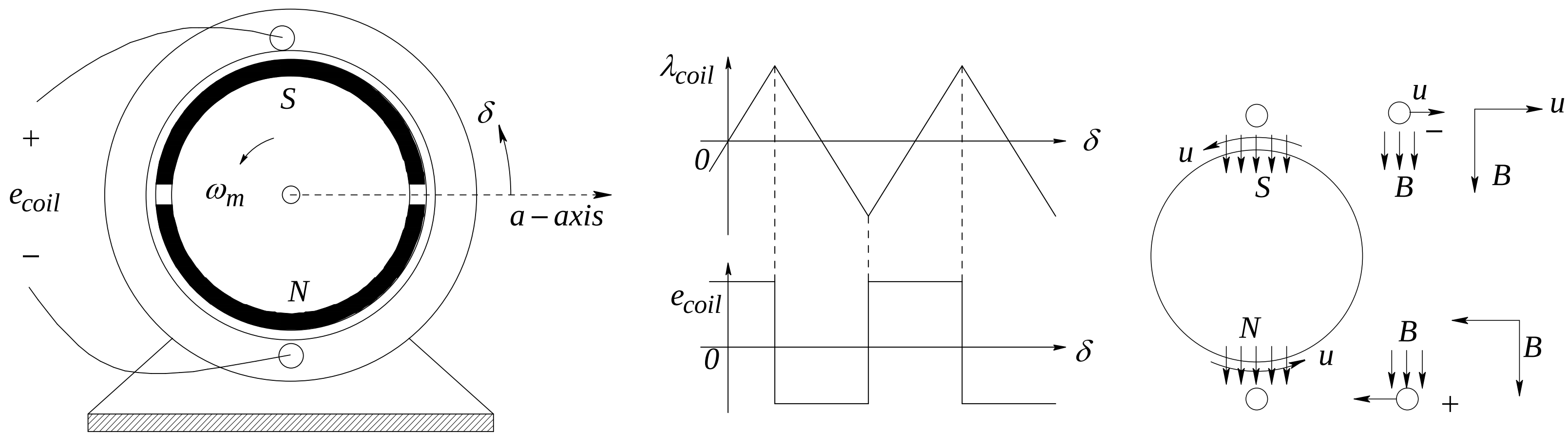
Electronically Commutated Motor Drives (Trapezoidal waveform brush-less dc)

- "Inside out" machines
- Electronically commutated armature
- At any instant, only two sets of windings carry currents. As the rotor turns, different pairs of windings are chosen.





Rotating Field & Stationary Conductors



- Flux linkage of a single turn coil

$$\lambda_{coil} = (\pi r l) B_f \left(\delta / (\pi / 2)\right) \qquad (-\pi/2 \le \delta \le \pi/2)$$

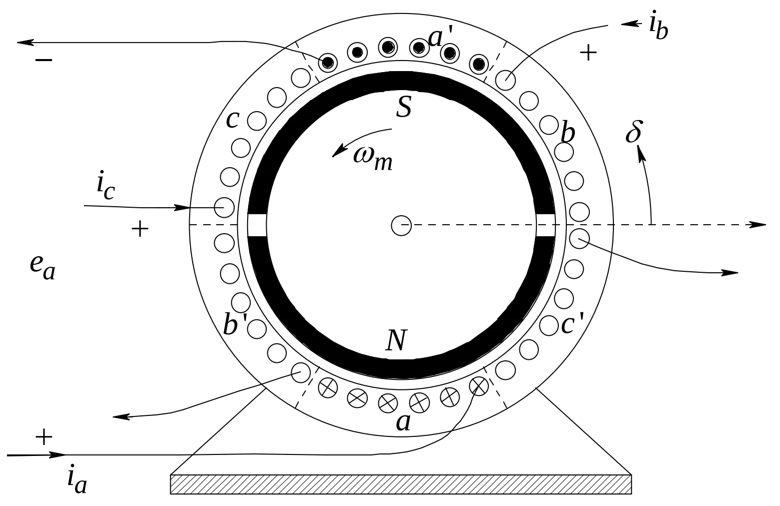
- emf induced

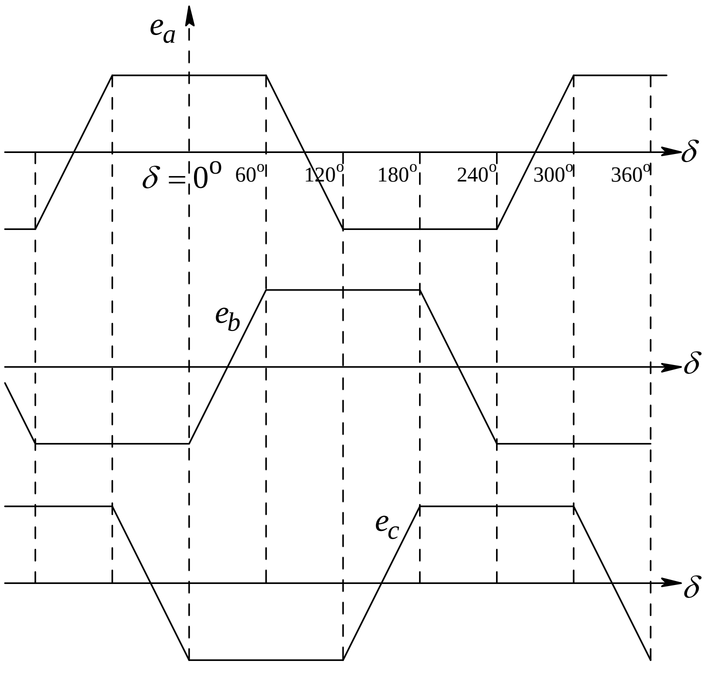
total induced emf $= 2 N_s B_f l r \omega_m$

(when all turns are under common pole)

- Polarity determined by assuming field to be stationary and and the conductor moving in opposite direction

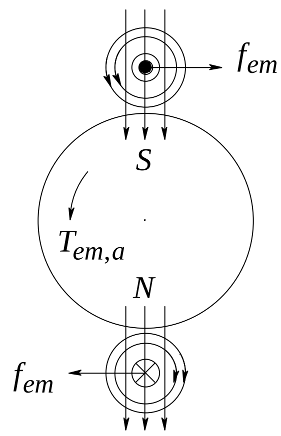
Induced emf

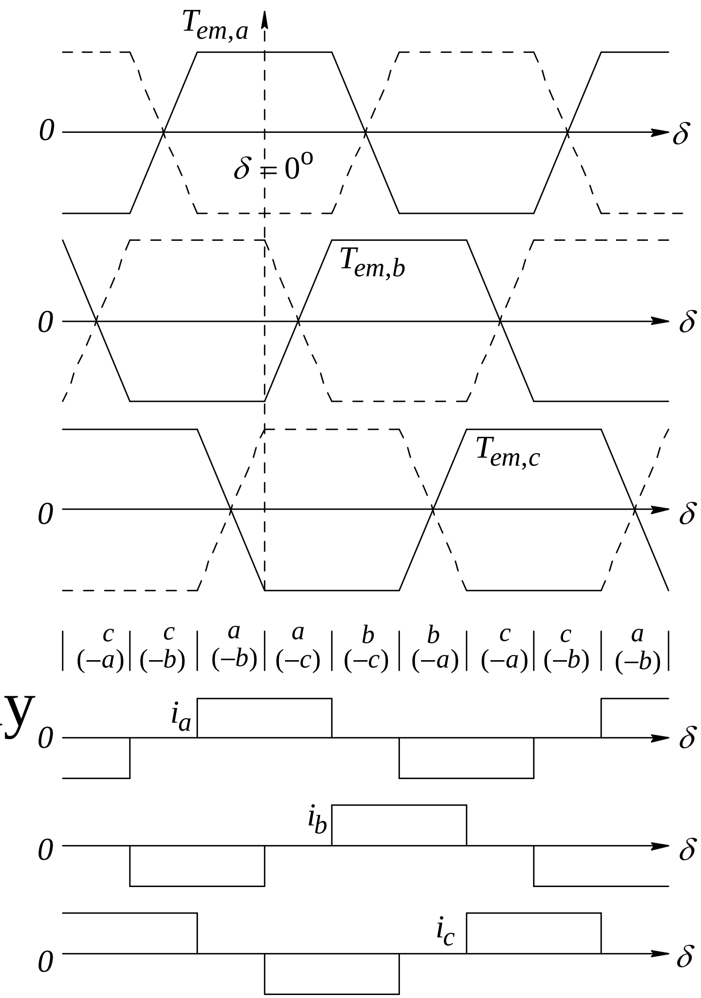




- In flat regions all turns are under same pole
- In sloped regions some turns are under *N* pole while others are under *S* pole

Torque Production



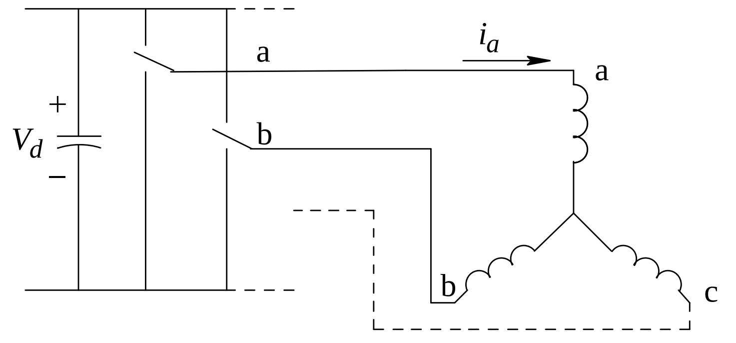


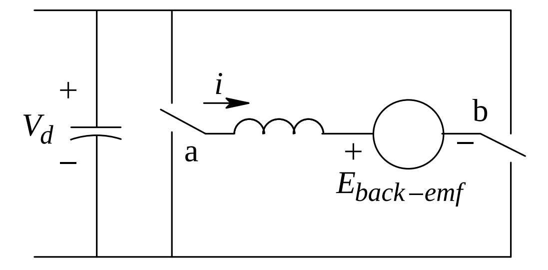
- Force on conductors $f = Bli$

  torque on rotor CCW
- Excite two phases simultaneously

  Total

❑ Equivalent circuit

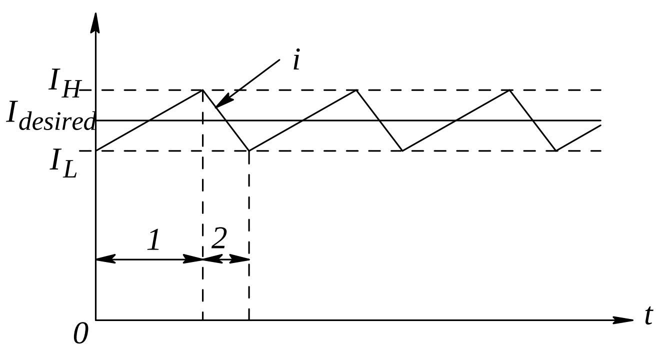




Phase-to-phase back induced emf

$$k_E = k_T$$

❑ Hysteresis current control



Position 1: Pole *a* high, Pole *b* low
Position 2: Pole *a* low, Pole *b* high
After 60^o rotor rotation, a new pair of poles (*a*,*c*) are used

Summary

- What is the breakdown of costs in dc-motor drives relative to ac-motor drives?
- What are the two broad categories of dc motors?
- What are the two categories of power-processing units?
- What is the major drawback of dc motors?
- What are the roles of commutator and brushes?
- What is the relationship between the voltage-constant and the torque-constant of a dc motor? What are their units?
- Show the dc-motor equivalent circuit. What does the armature current depend on? What does the induced back-emf depend on?
- What are the various modes of dc-motor operation? Explain these modes in terms of the directions of torque, speed, and power flow.

Summary

- How does a dc-motor torque-speed characteristic behave when a dc motor is applied with a constant dc voltage under an open-loop mode of operation?
- What additional capability can be achieved by flux weakening in wound-field dc machines?
- What are various types of field windings?
- Show the safe operating area of a dc motor and discuss its various limits.
- Assuming a switch-mode power-processing unit, show the applied voltage waveform and the induced emf for all four modes (quadrants) of operation.
- What is the structure of trapezoidal-waveform electronically-commutated motors?

Summary

- How can we justify applying the equation in a situation where the conductor is stationary but the flux-density distribution is moving?
- How is the current controlled in a switch-mode inverter supplying ECM?
- What is the reason for torque ripple in ECM drives?