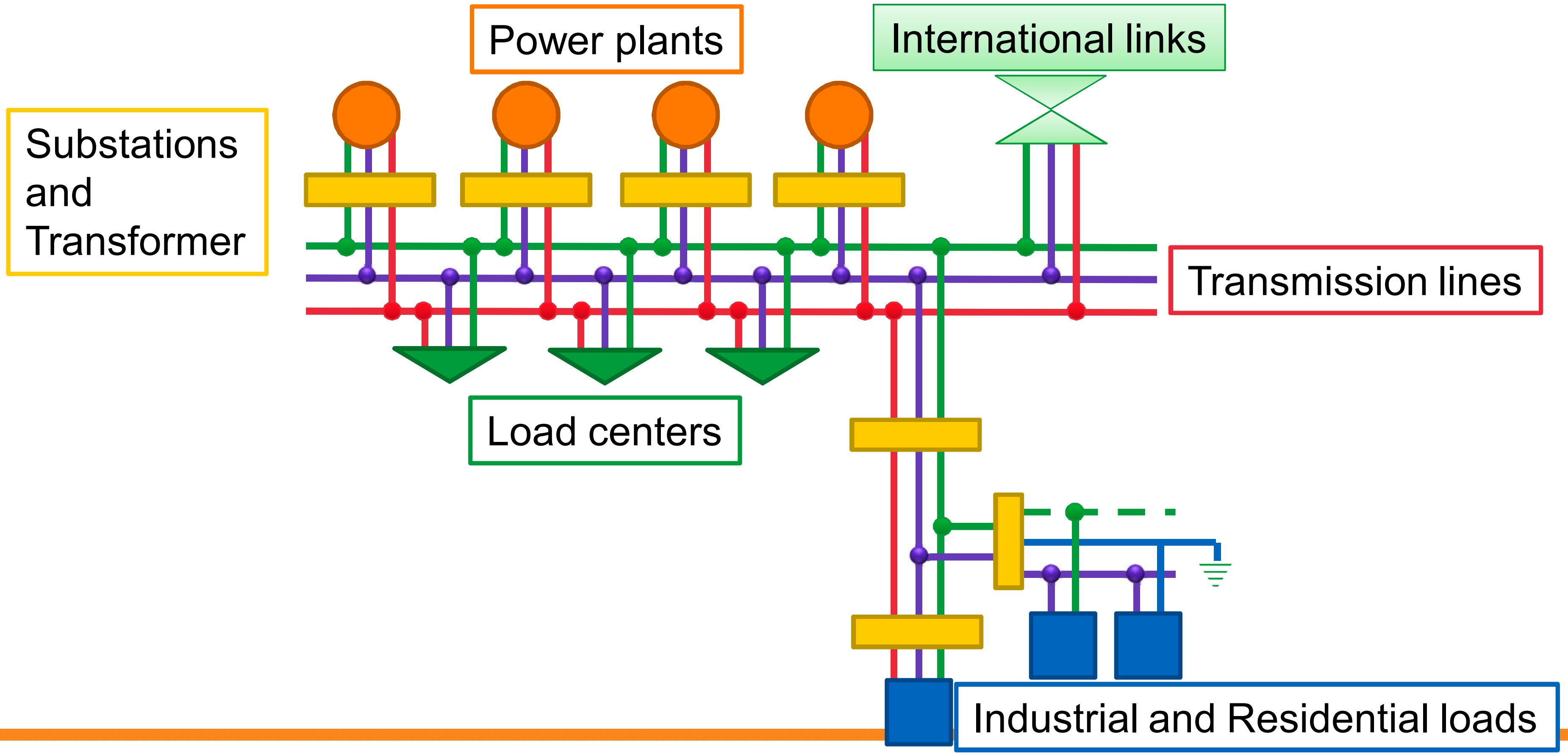
Electrical Machines

- Lecture outcomes (what you are supposed to learn):
  - List different types of rotating electrical machines
  - Recognize the advantages and disadvantages of each type
  - Describe the applications of electrical machines
  - Understand the working principle of electrical machines
  - Describe the construction of electrical machines

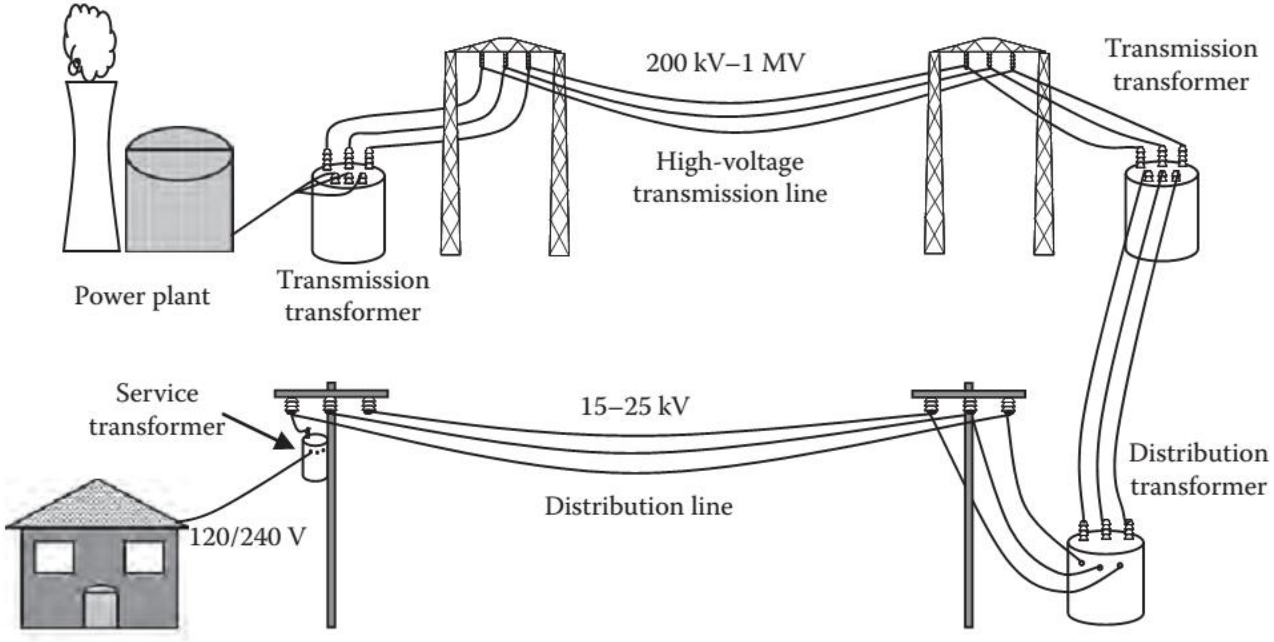
Introduction

- The quasi totality of the electric power generated worldwide is three-phase.



Introduction

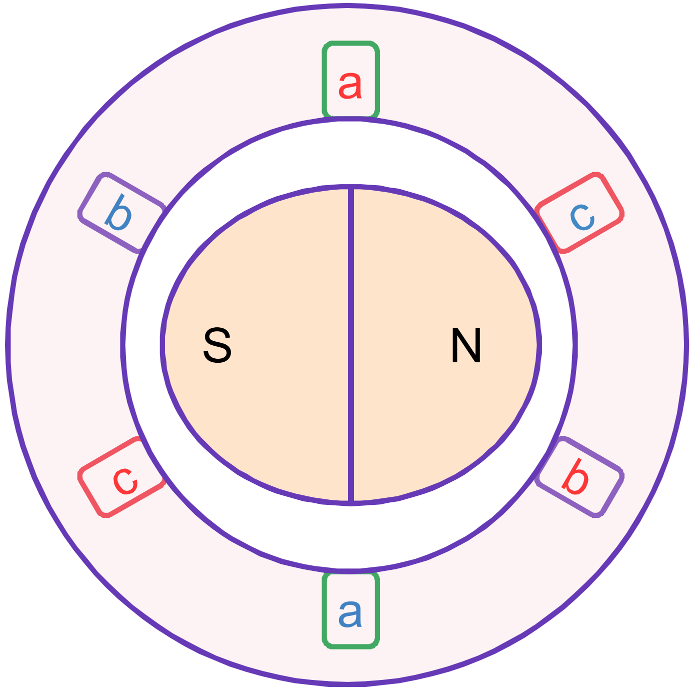
- Illustration of the electric energy transmission and distribution

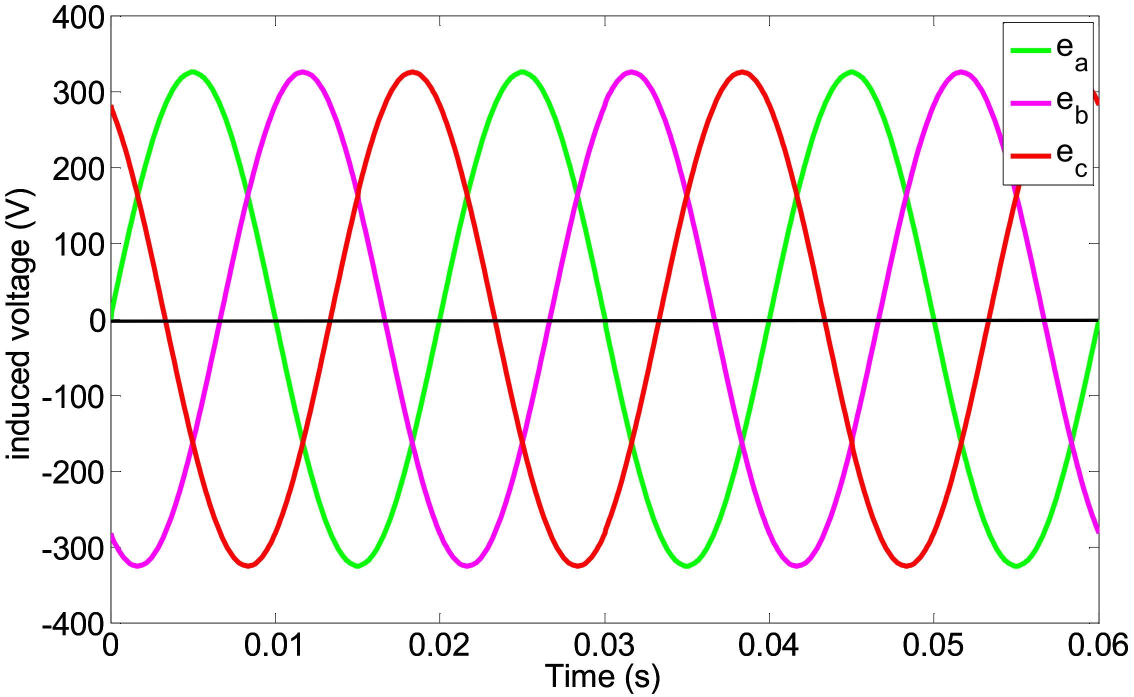


3-phase voltage generation

- Simple generator

$$e = N\frac{d\Phi}{dt}$$

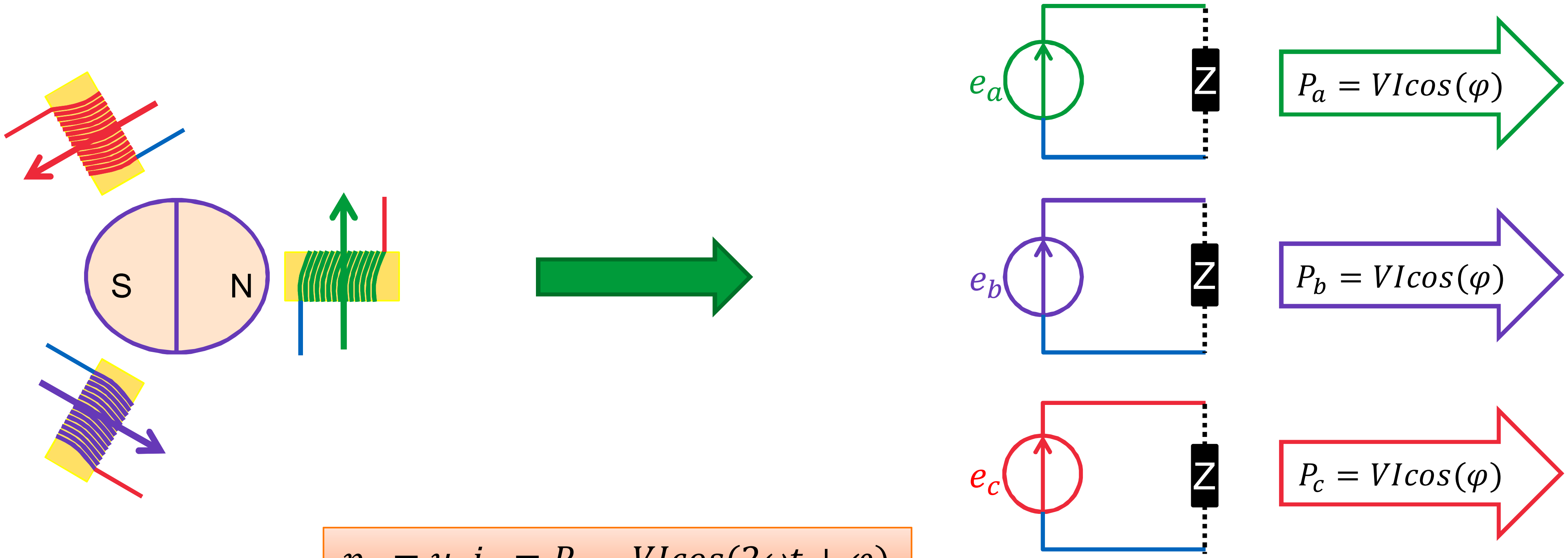




❑ Better utilization of iron and other materials

Connecting the 3-phase voltages

- 3 single-phase circuits at different phase angle!

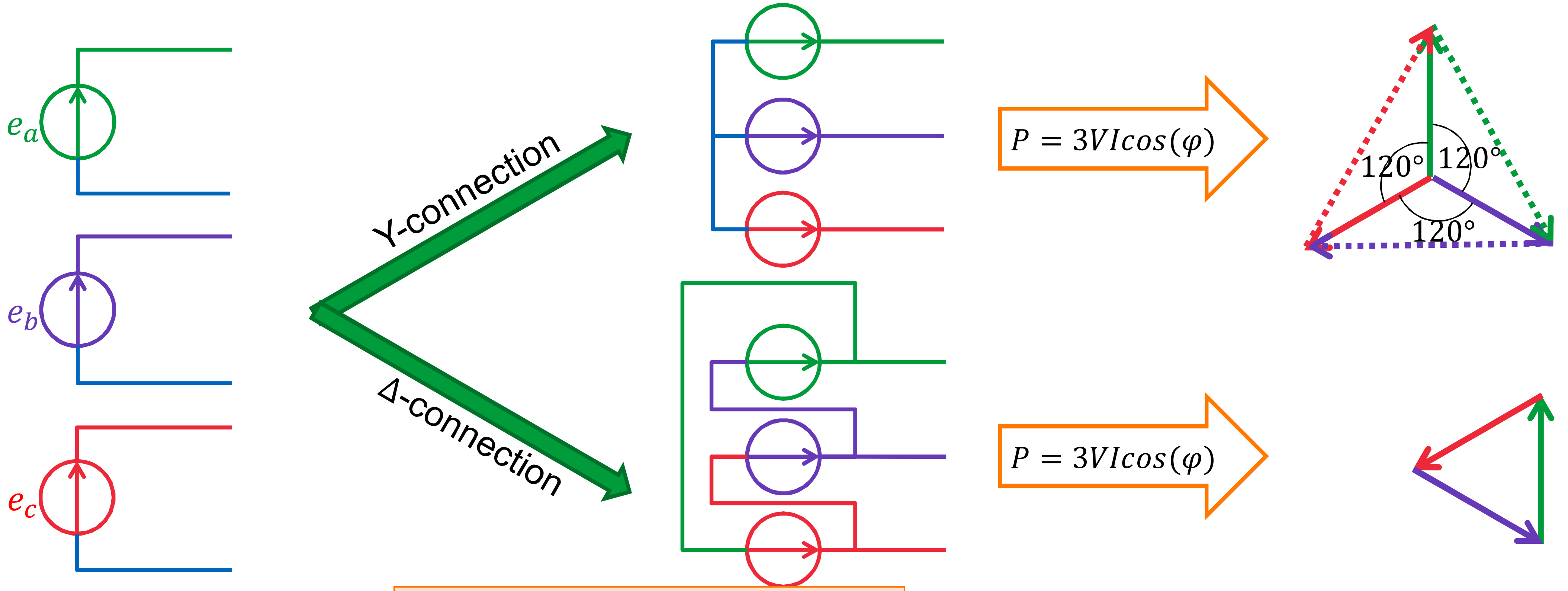


$$p_a = u_a i_a = P_a - VIcos(2\omega t + \varphi)$$

- ❑ The average power over one period is constant
- ❑ The instantaneous power is pulsating

Connecting the 3-phase voltages

- The potential difference is known but not the potentials !



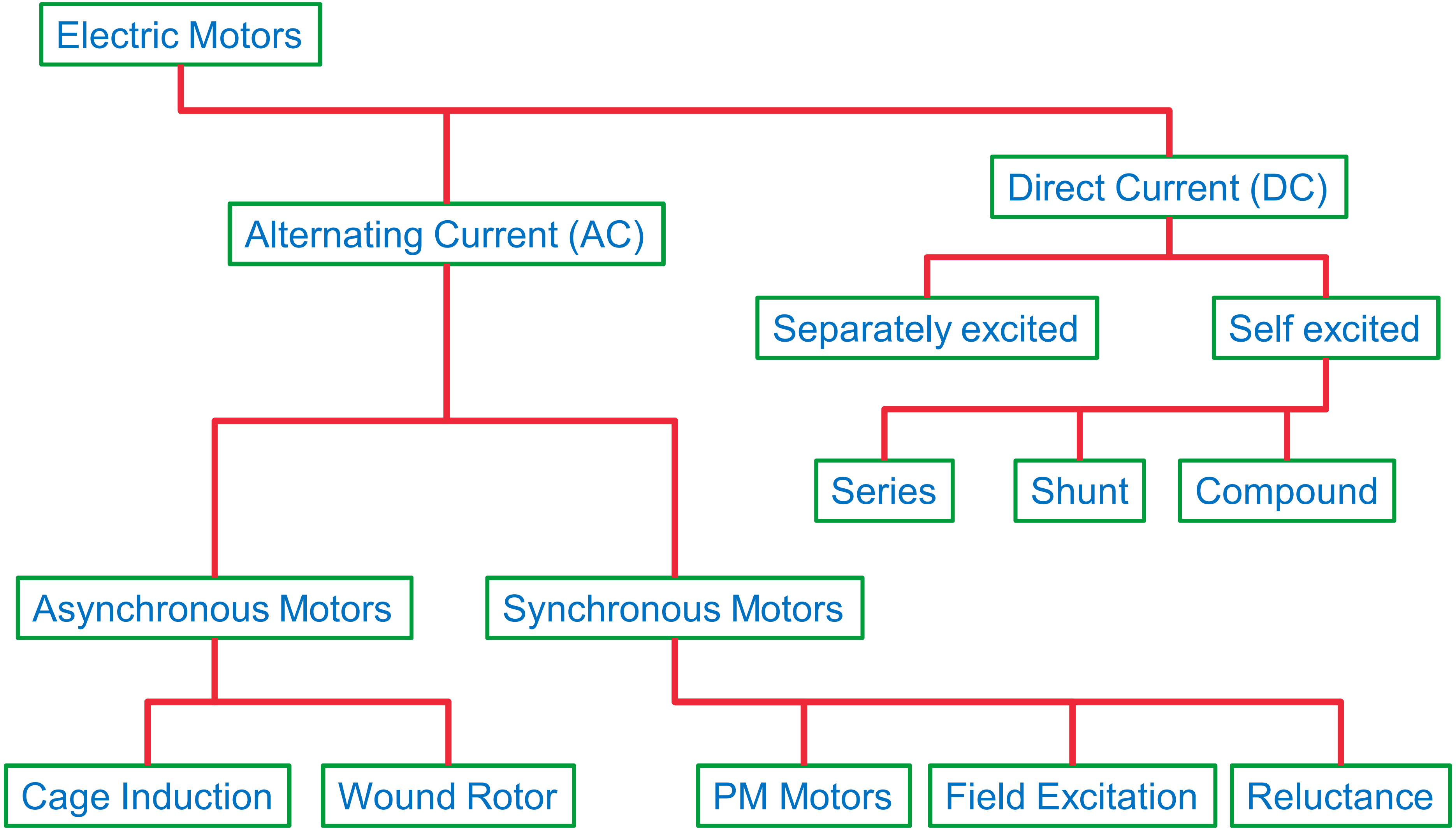
$$p = u_a i_a + u_b i_b + u_c i_c = 3P_a$$

- ❑ The same power can be transferred with only 3 wires instead of 6
- ❑ The instantaneous power of 3 phase system is constant over time

Rotating Machines

- Nearly 100% of the worldwide electrical energy is produced by rotating electrical machines.
- More than 65% of the electrical energy is consumed by electric motors in different industry applications.
- Tightened requirements on energy efficiency call for better motors and careful choice of motor drives.
- Multitude of motor drive solutions appeal for Engineering analytical and multidisciplinary skills.

Classification of Electric Machines



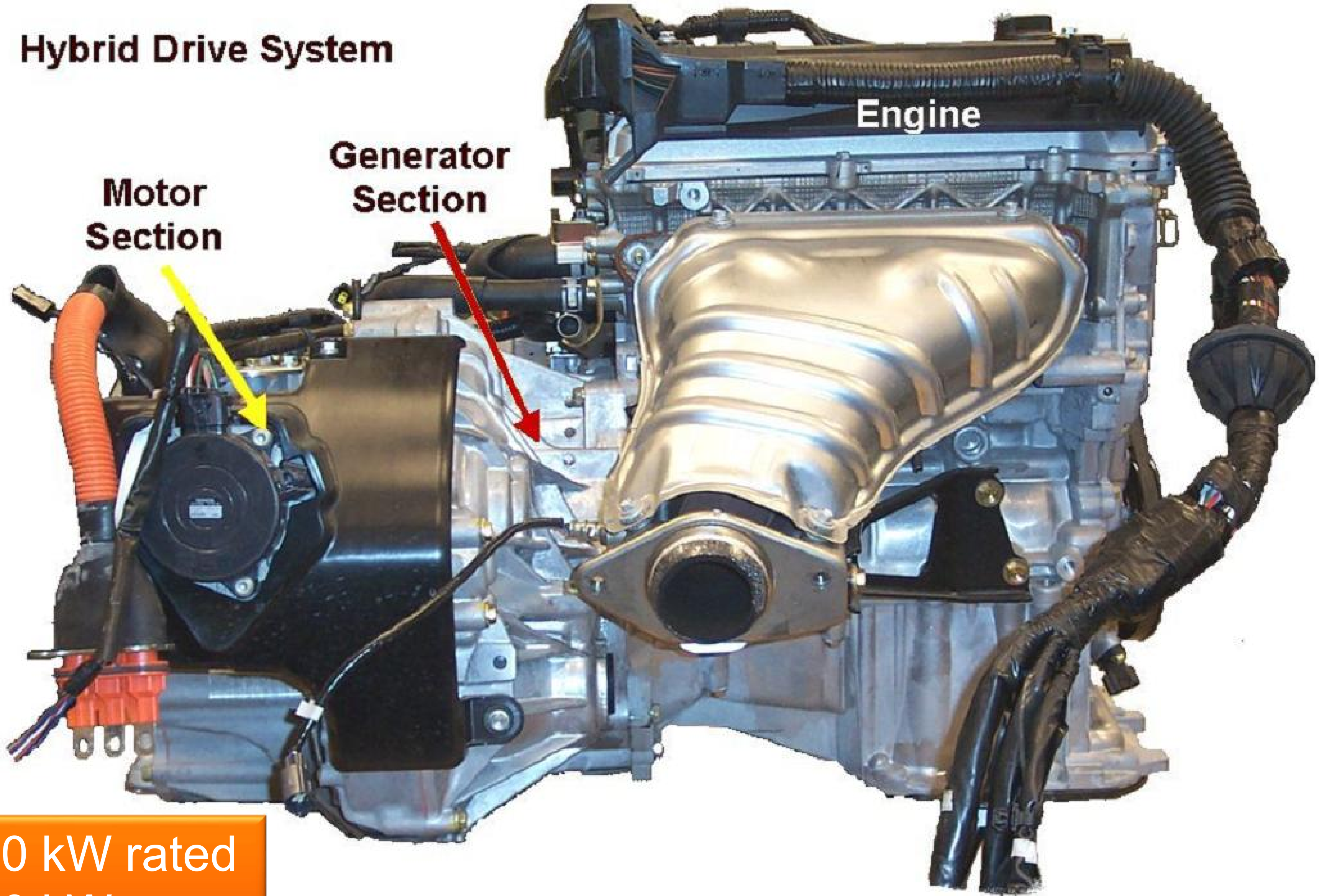
Motor Applications

- Industry applications
  - Grinding (hionta)
  - Milling (jauhaminen)
  - Pumping
  - Air compressing
  - Vacuum pumping
  - Hoists and lifts
    (nosturit ja hissit)

- Transport

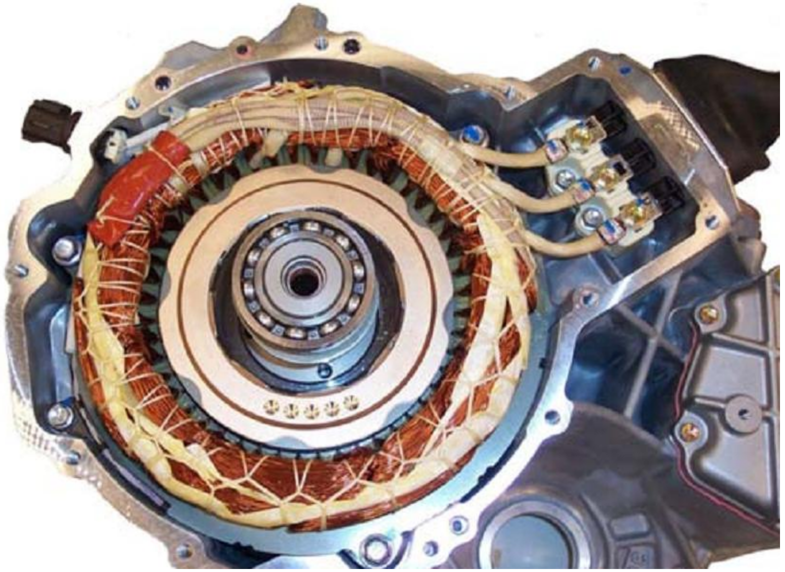
Large starting torque, extended speed range
  - Electric vehicles
  - Rail transport
  - Cruises and ships

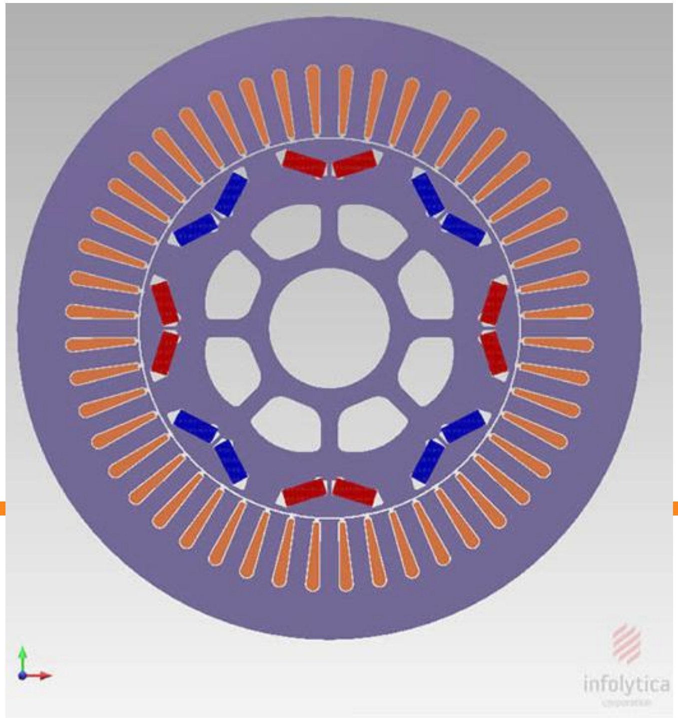
Prius hybrid



40 kW rated
50 kW max

Prius motor





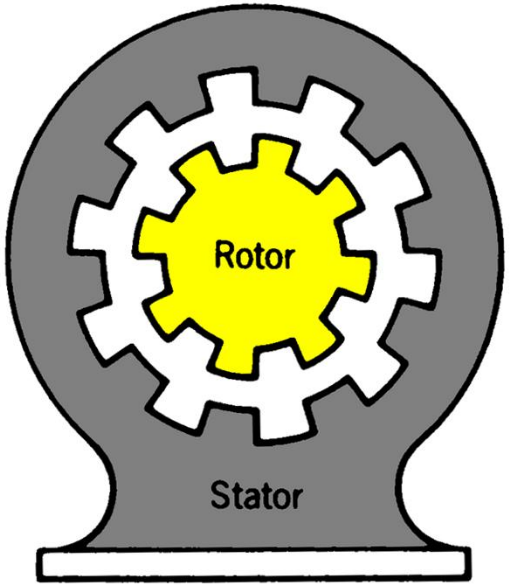
Generator Applications

- Power plants
  - Hydropower plants – low speed, large number of poles, salient
  - Thermo and nuclear power plants – High speed 2-4 poles cylindrical turbogenerators

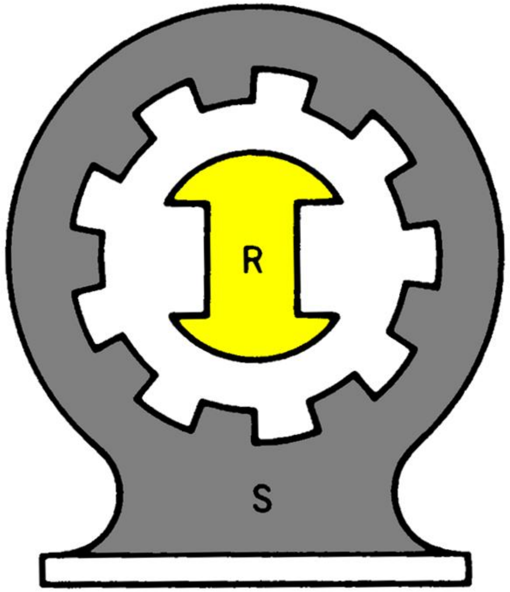
- Wind power
  - Cage induction machine
  - Doubly Fed IG (DFIG)
  - PM machines
    - High speed and low speed

- Emergency power supply
  - Salient pole synch machine
  - voltage regulation
- Car industry
  - DC generators
  - alternators

Basic structure of electric machine



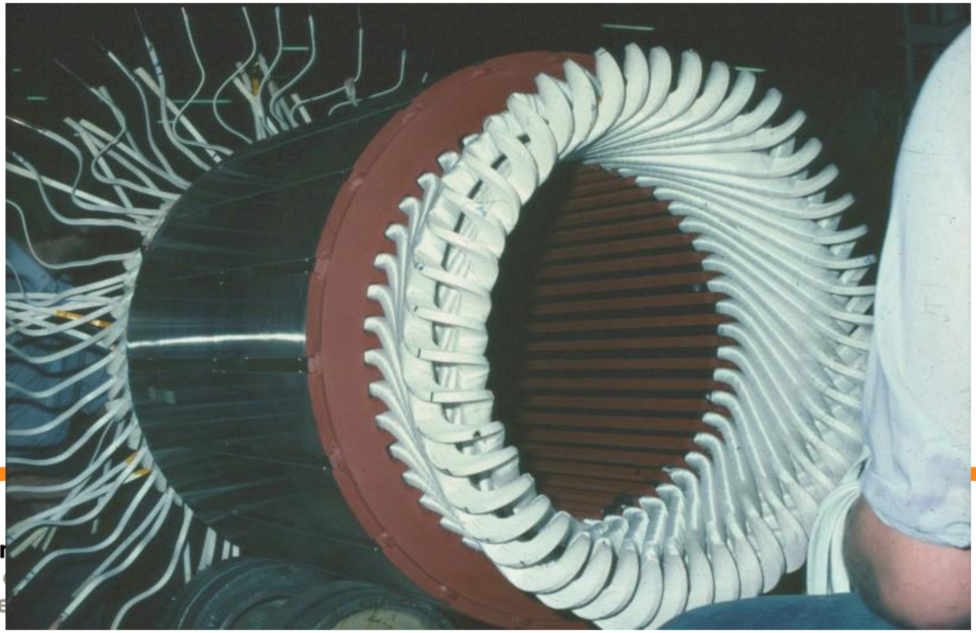
Cylindrical machine
Uniform air gap

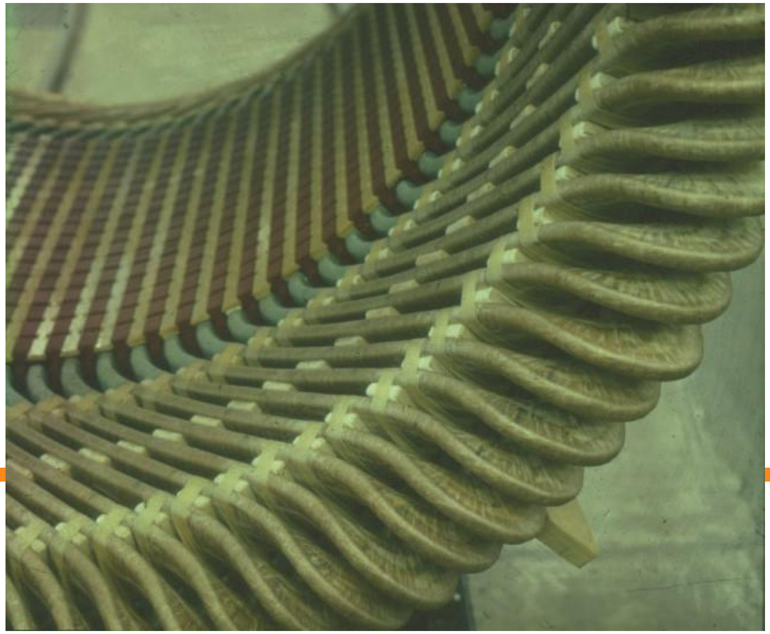


Salient pole machine
Non-uniform air gap

- Slots with conductors
- Iron core
- Laminations

Basic structure of electric machine





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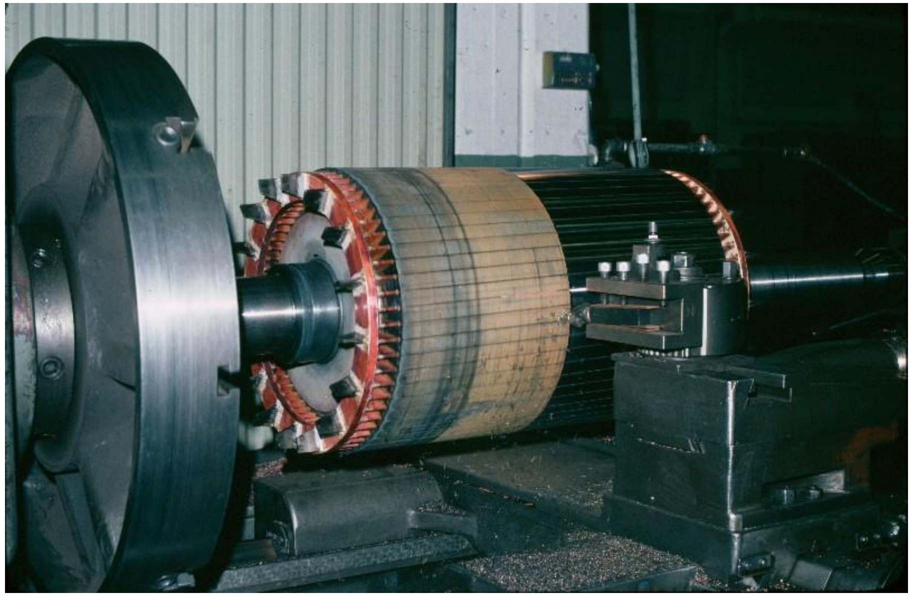
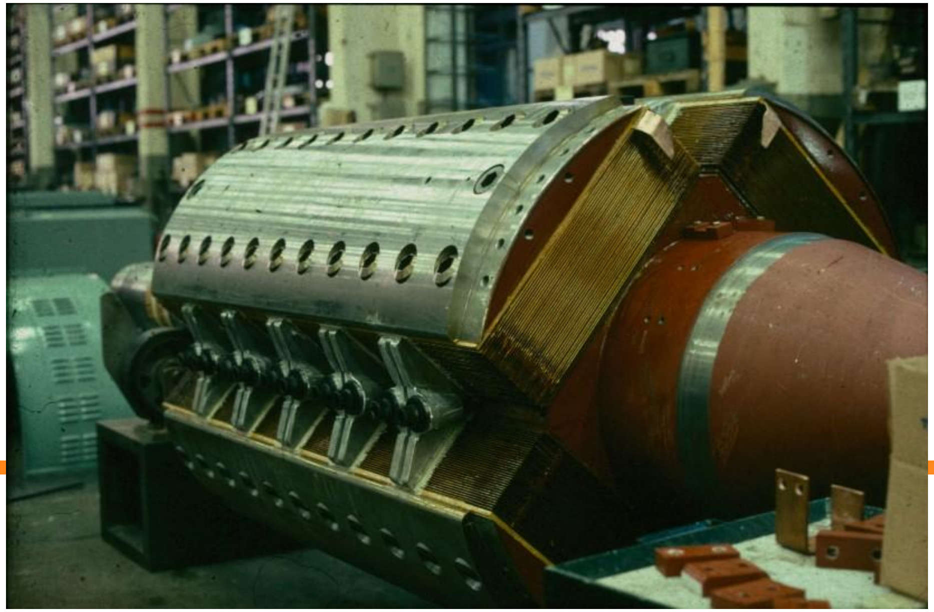
Basic structure of electric machine

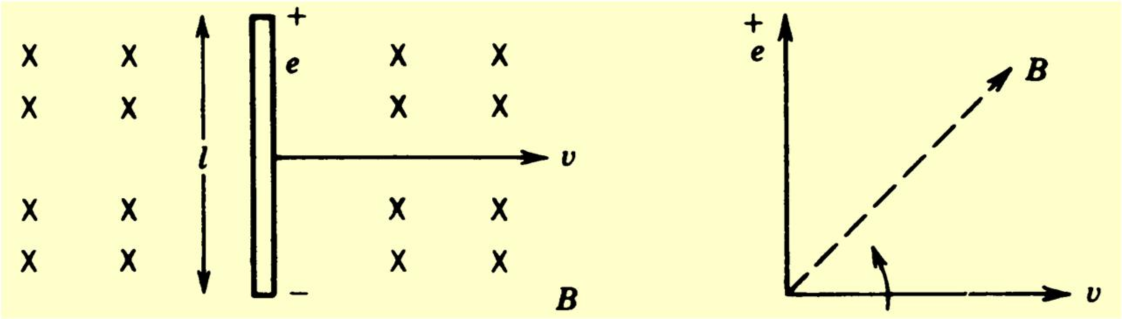




Electromagnetic energy conversion

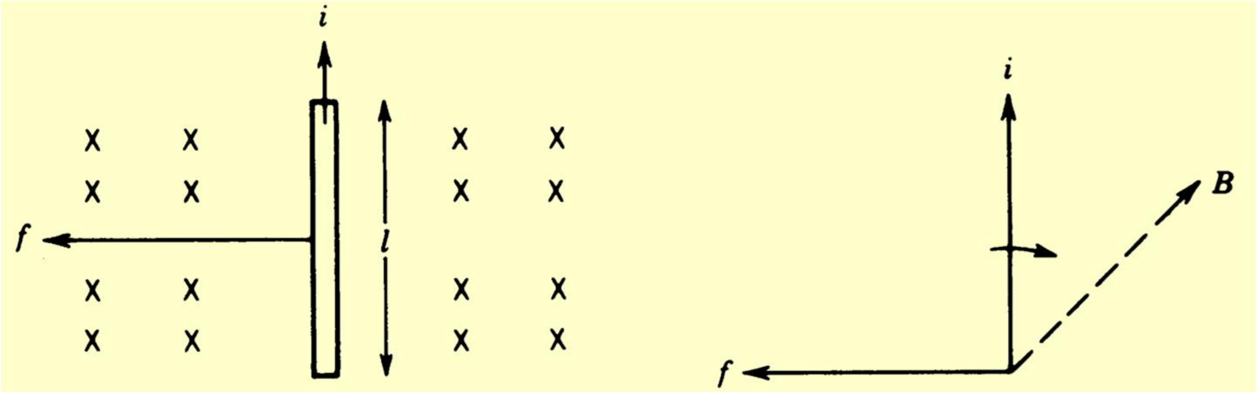
- Conductor moving in magnetic field
  Motional voltage

$$e = Blv$$



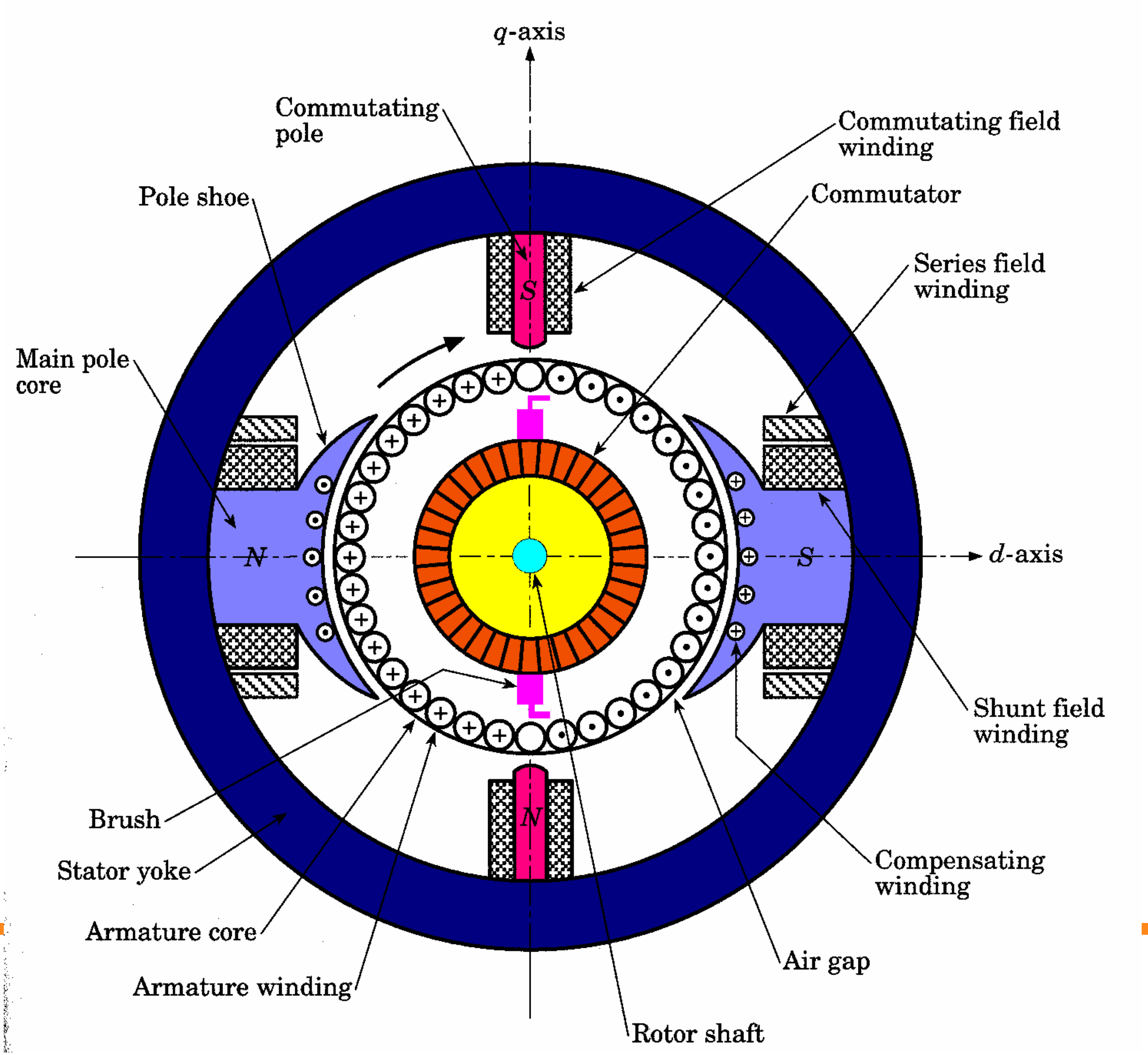
- Current carrying conductor in magnetic field
  Electromagnetic force

$$f = Bli$$

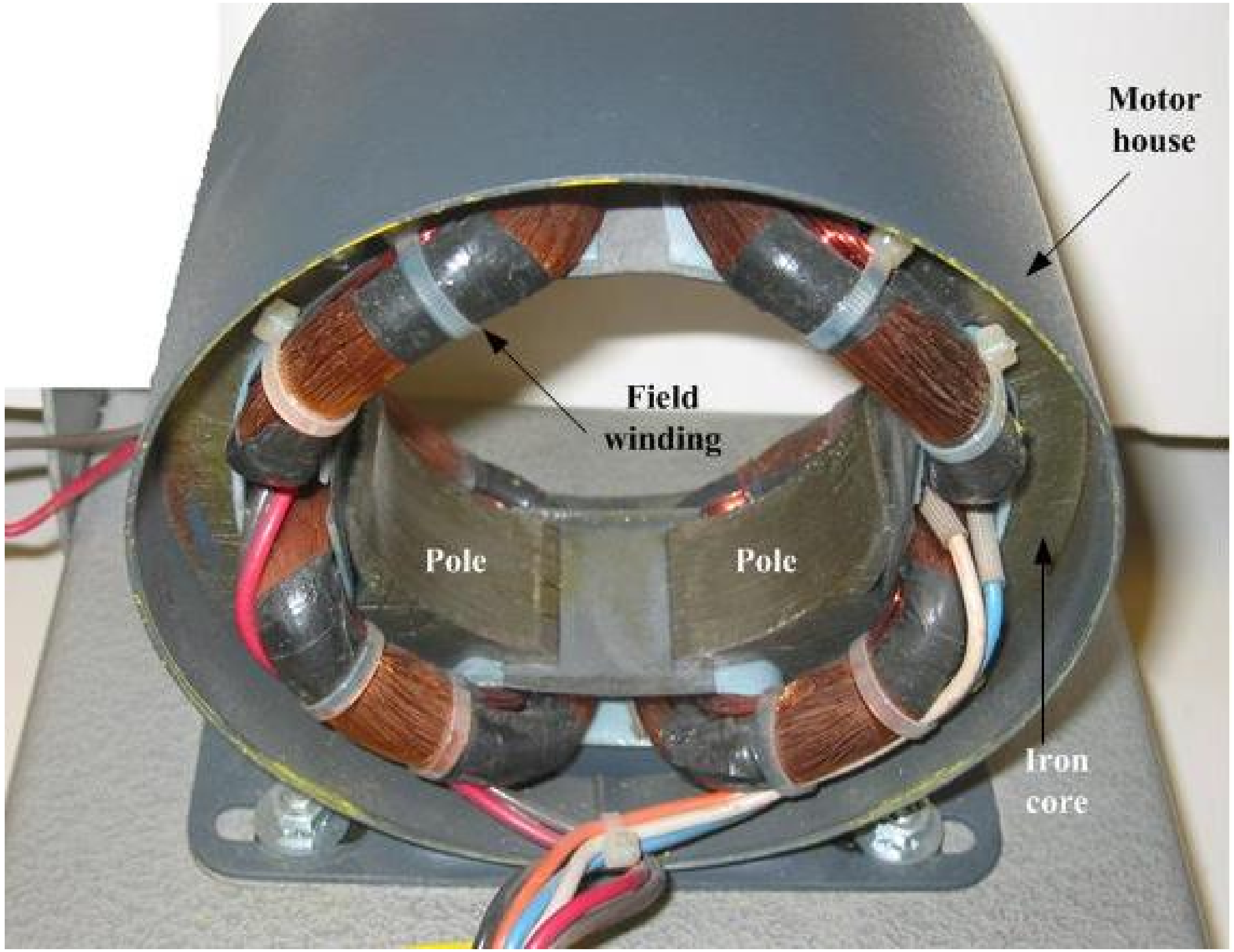


- Both phenomena occur simultaneously in energy conversion process

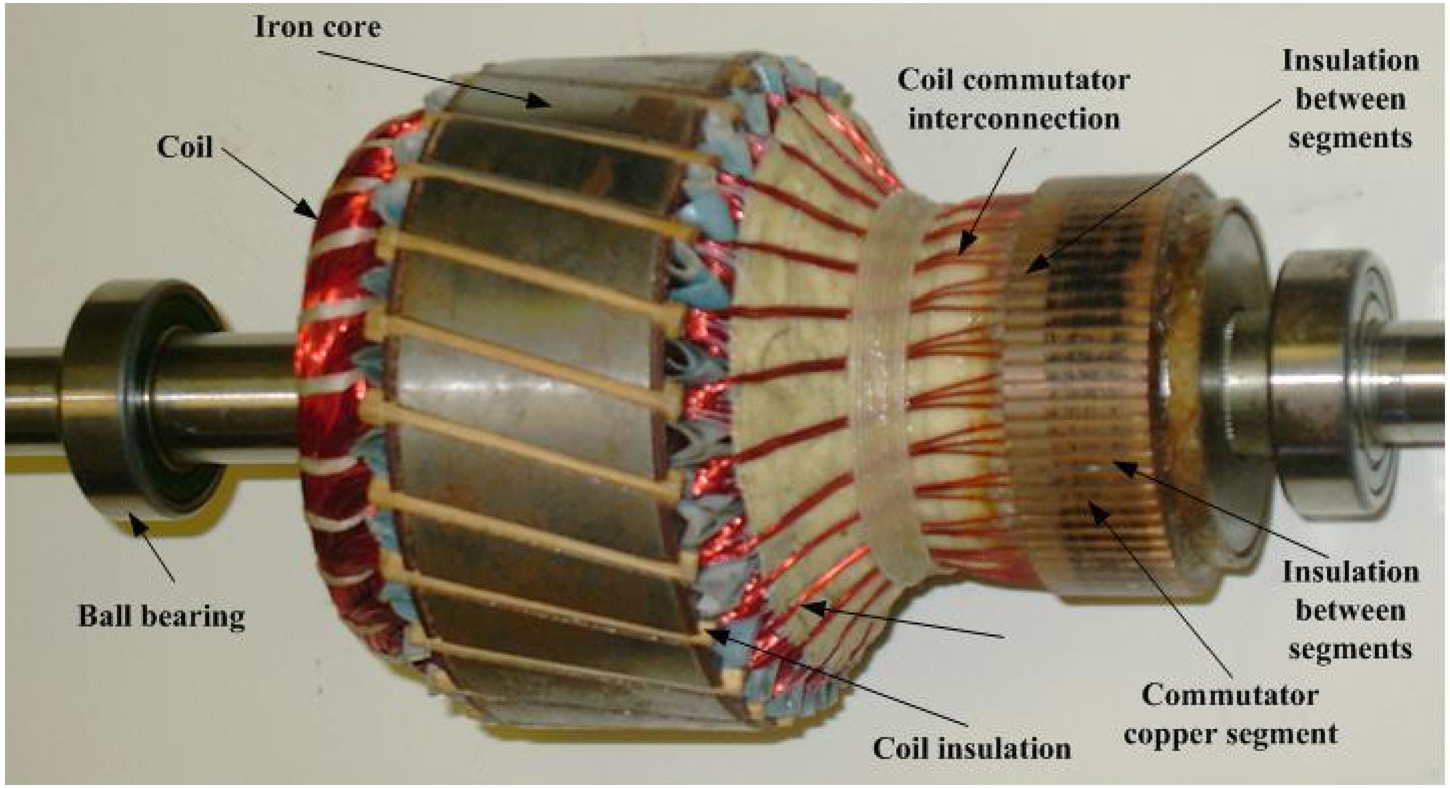
Cross section view of dc machine



Structure of the stator of dc machine



Structure of the rotor of dc machine

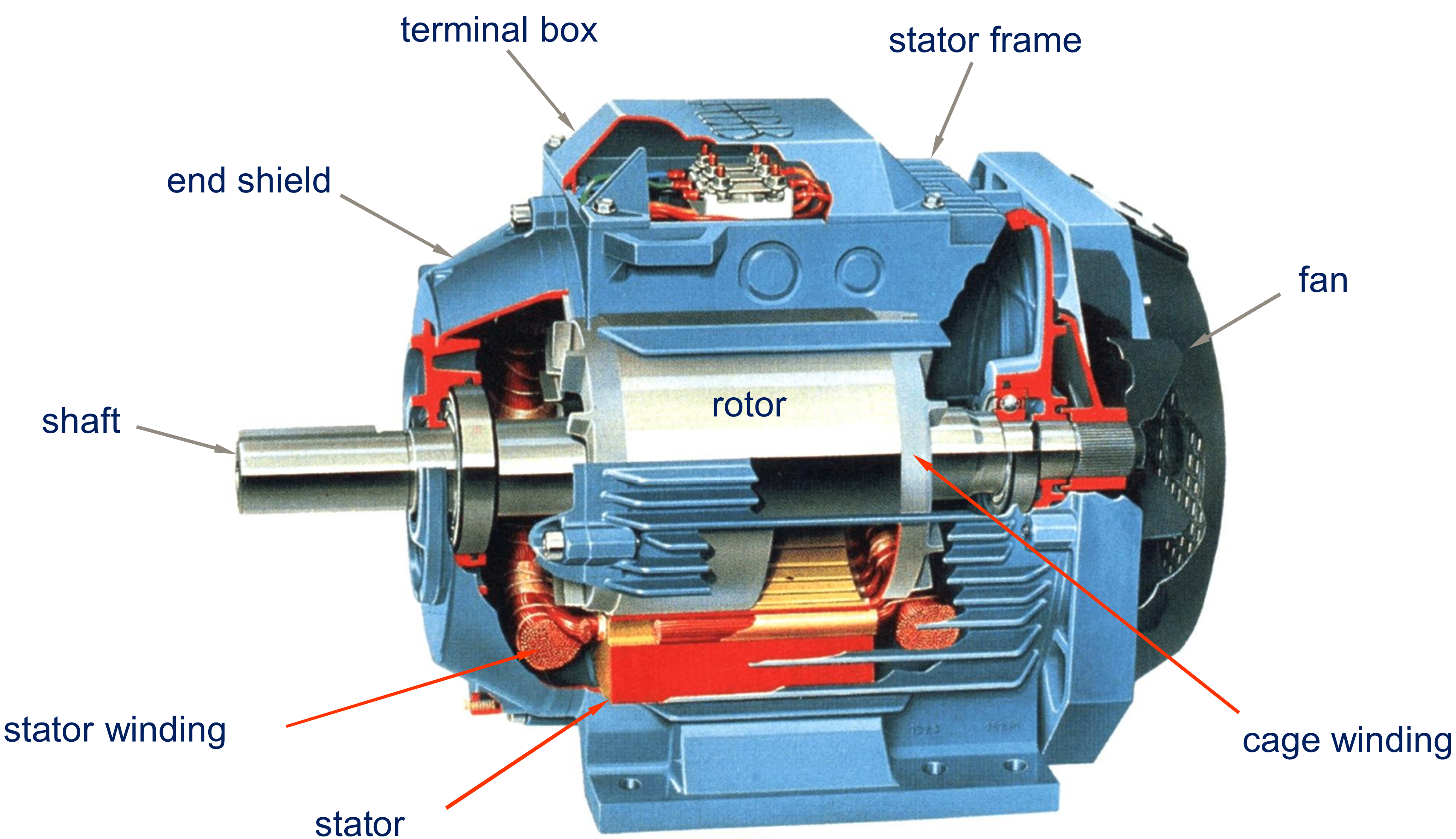


- Conductors interconnected to form windings
- Armature winding = in which voltage is induced
- Field winding = the one that produces the primary flux
- Permanent magnet can be used to produce the flux

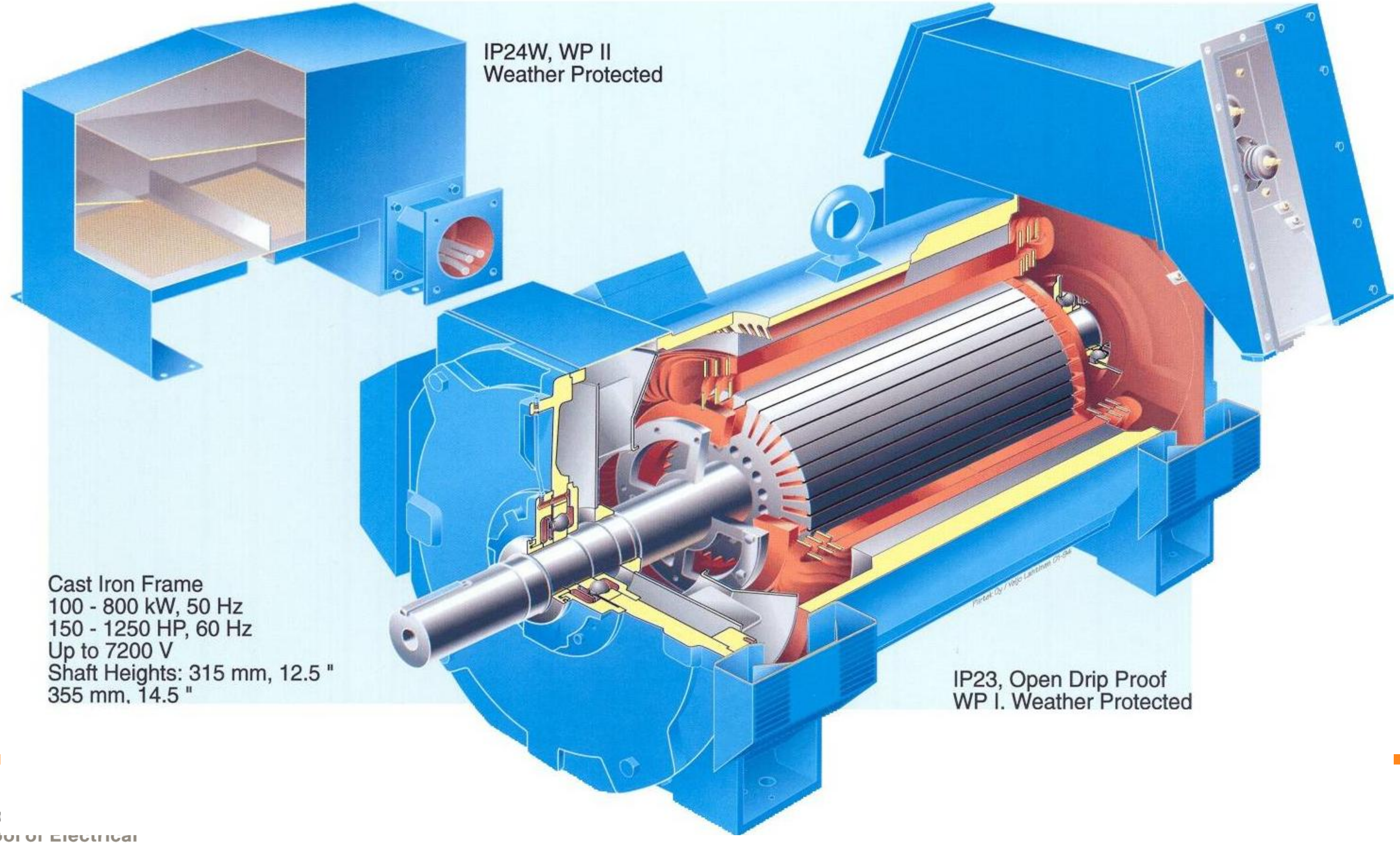
Operation of DC Machines

- 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 voltage
- Armature current distribution fixed in space
- MMF of armature winding along quadratic axis

Small induction machine - Construction



Large induction machine - Construction



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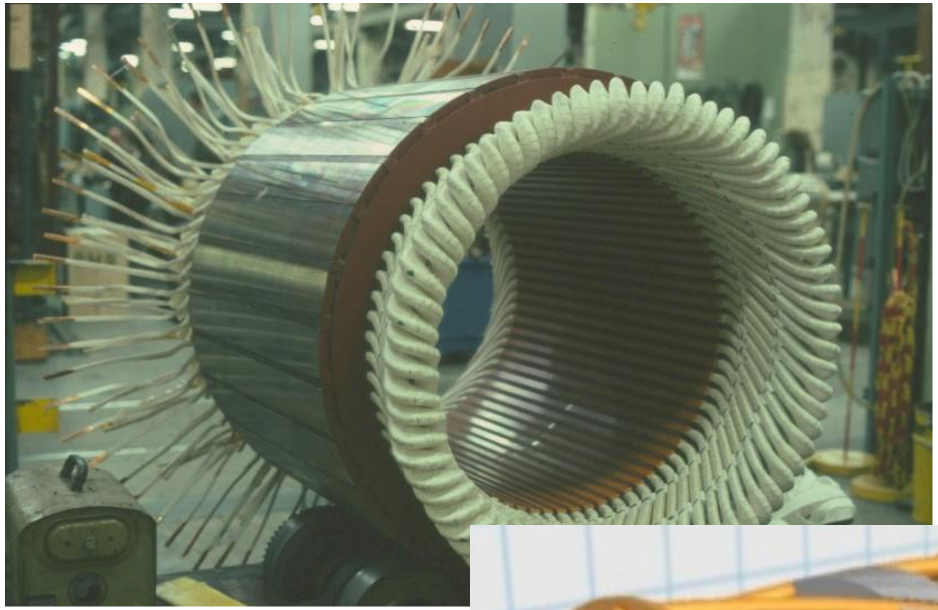
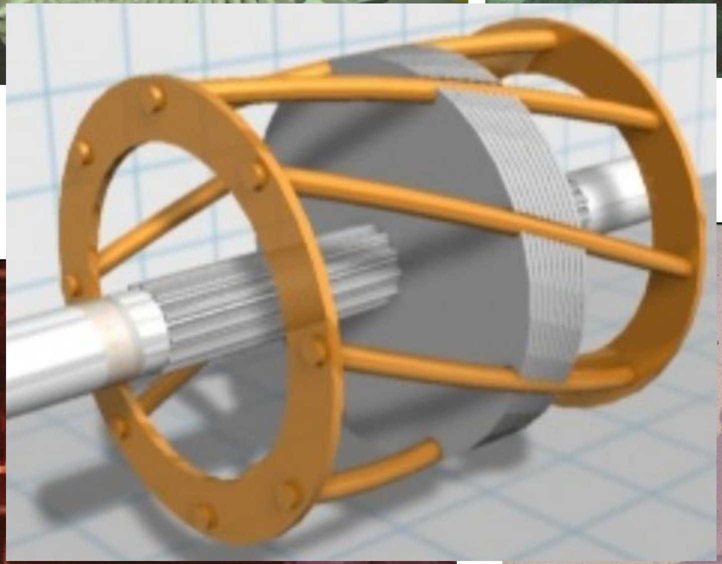
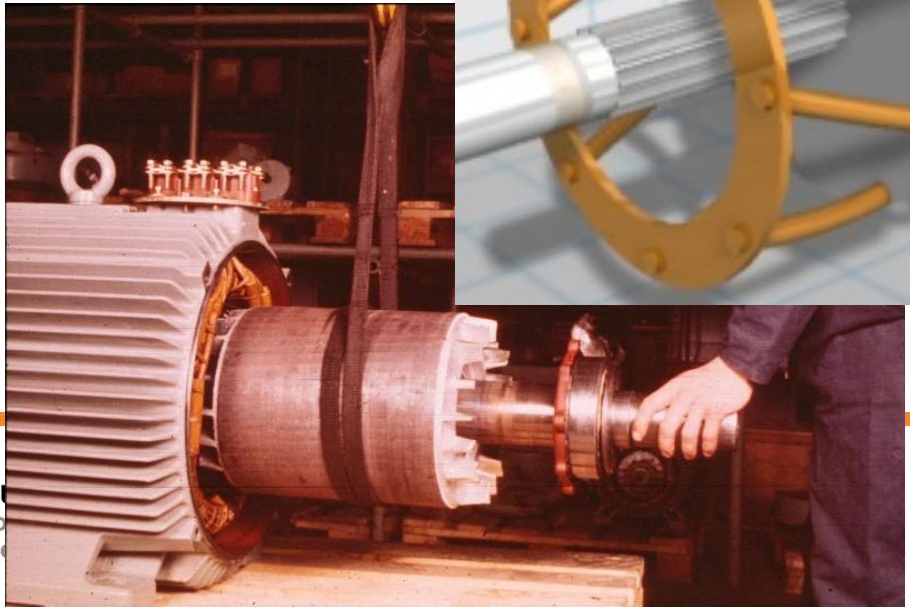
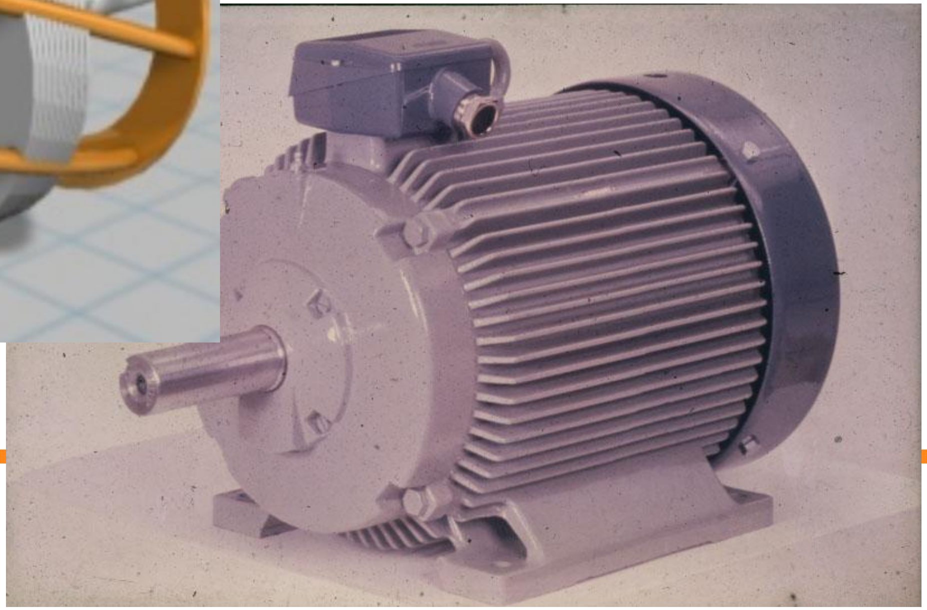
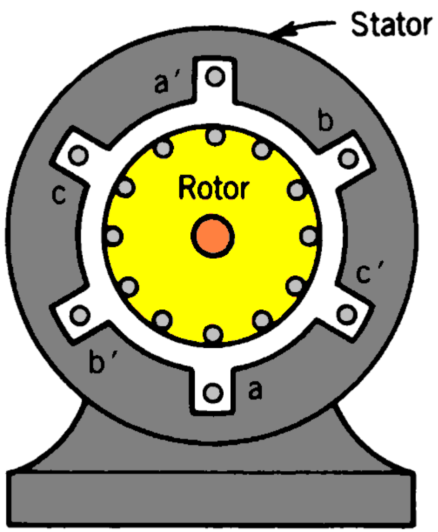


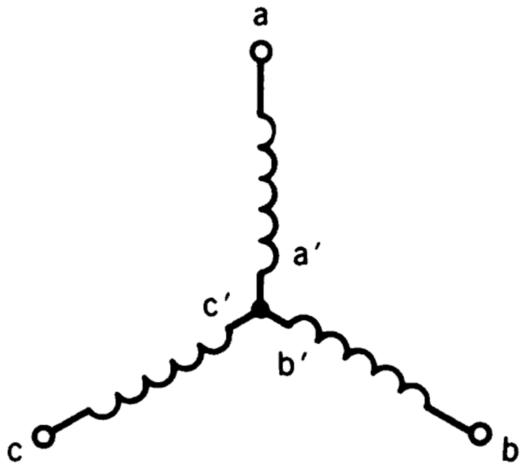


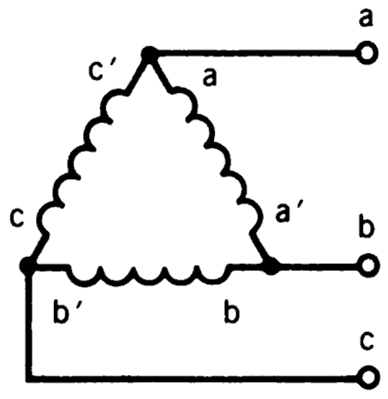




Operation principle of induction machine







- Three-phase windings displaced from each other by 120 degrees
- Phase coils produces sinusoidal distributed mmf wave
- Alternating currents in each coil produce pulsating mmf waves
- Mmf waves displaced by 120 degrees in space from each other
- Resultant mmf wave is rotating along the air gap with constant peak

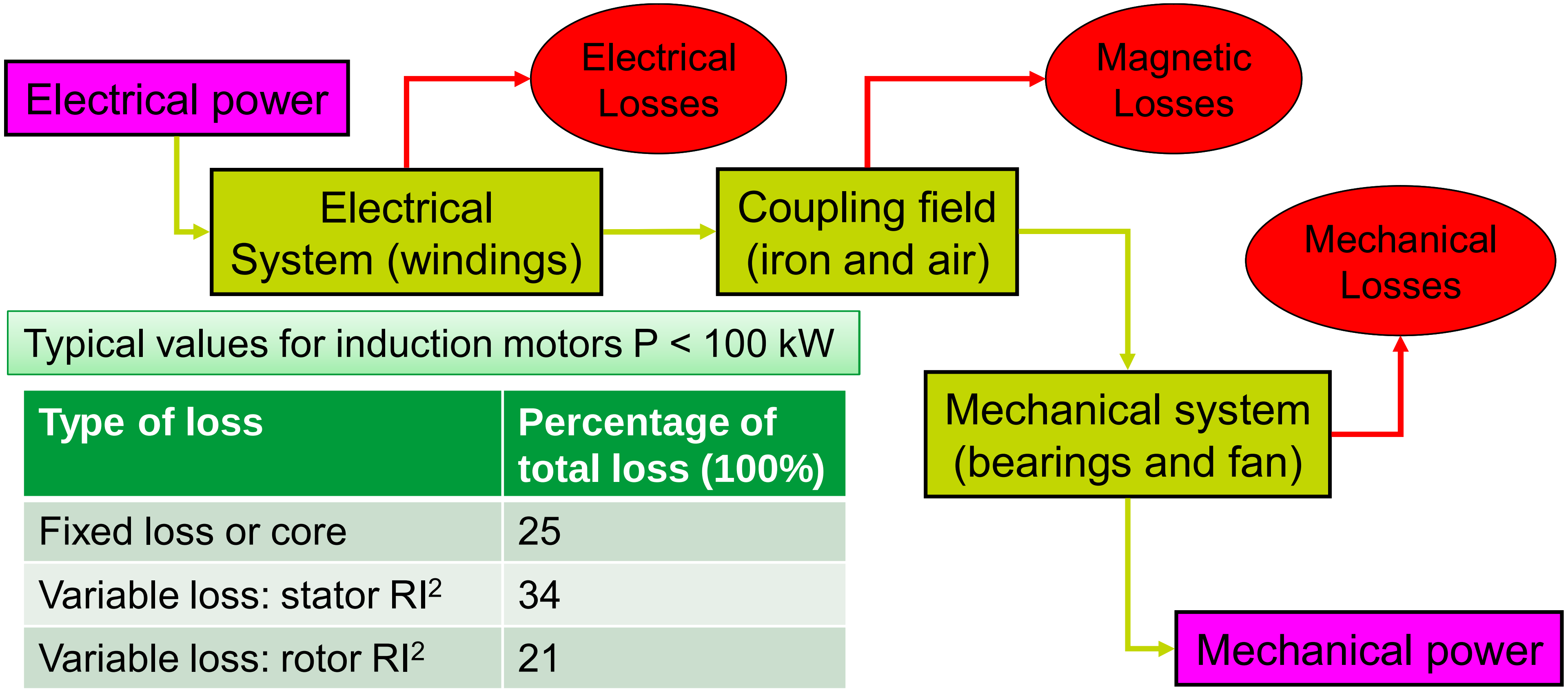
Running operation principles

- Rotor circuit is closed
- Induced voltages produce rotor currents
- Currents interacts with air gap field and produce torque
- Rotor starts to rotate
- Relative speed decreases
- Induced voltage decreases
- Speed settles to steady state value with torque balance

Principal characteristics

- Slip $$s = \frac{n_s - n}{n_s}$$
- frequency of rotor currents $$f_2 = \frac{p}{120}(n_s - n) = sf_1$$
- Rotor voltage $$E_{2s} = 4.44 f_2 N_2 \Phi_p K_{W2} = sE_2$$
- speed of rotor field
  - with respect to the rotor is $$n_2 = \frac{120 f_2}{p} = sn_s$$
  - with respect to the stator is $$n + n_2 = n_s$$

Energy conversion 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

$$P_{in} = \sqrt{3}\, U I \cos\theta \qquad P_{out} = T_{mech}\,\omega_{mech} \qquad \mathrm{Eff} = \frac{P_{out}}{P_{in}}$$

European commitments

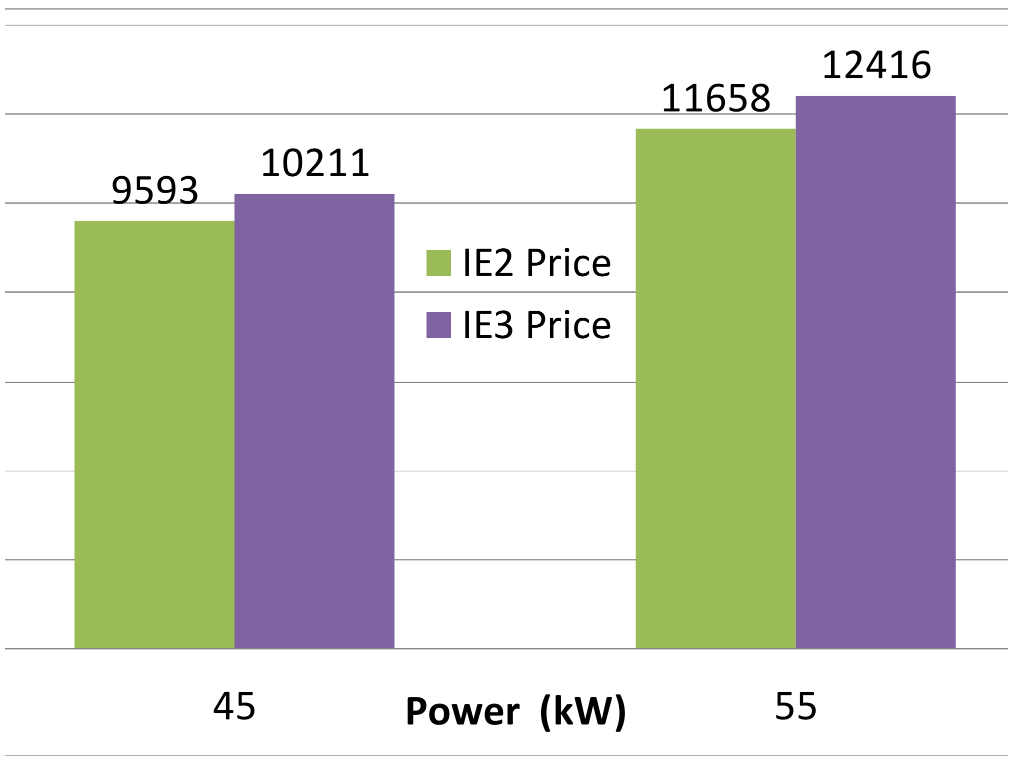
By the year 2020, the plan of the European Commission called for:

- 20% energy saving
- 20% reduction in greenhouse gas emissions
- 20% share of renewable energy in overall EU energy consumption
- 10% renewable energy component in transport fuel

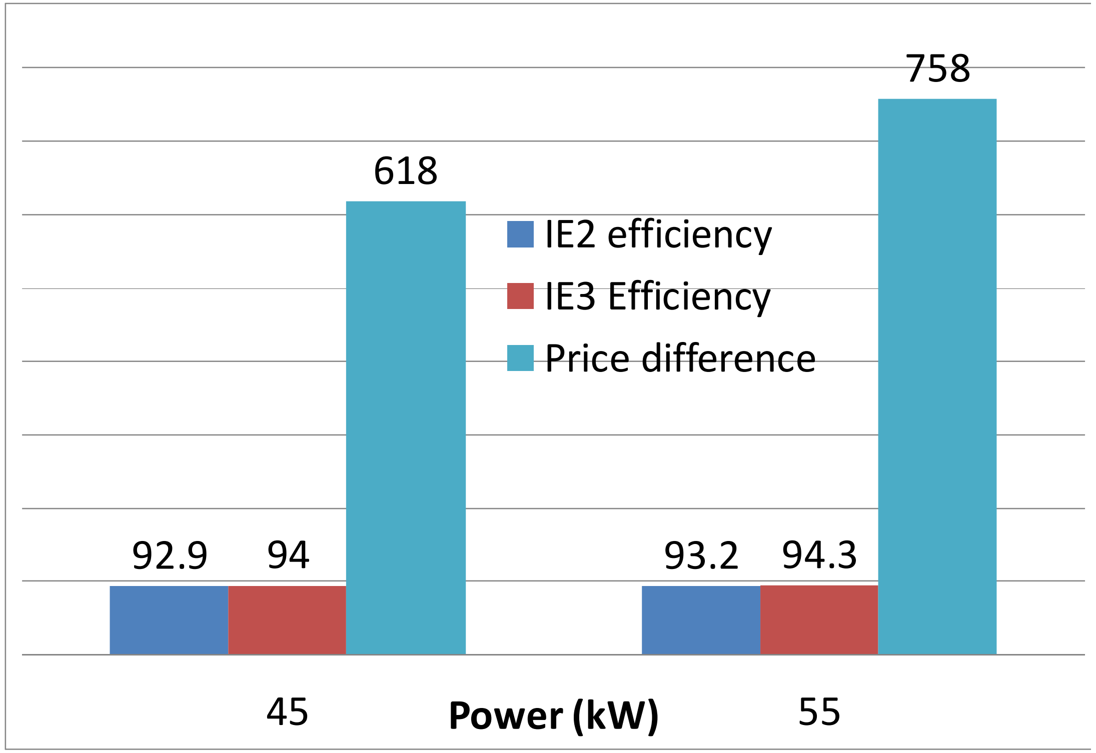
International efficiency (IE) of motors

- Efficiency classes of low-voltage (< 1000V) 3-phase 50/60 Hz squirrel cage induction motors from 0,75 kW to 375 kW, with 2-, 4- or 6-poles:
  - IE4 = a non-identified efficiency level for future technology such as PM motor technology
  - IE3 = high efficiency
  - IE2 = standard efficiency
  - IE1 = low efficiency
- The efficiency requirements are mandatory for motors and variable speed drives

At what cost efficiency is improved?

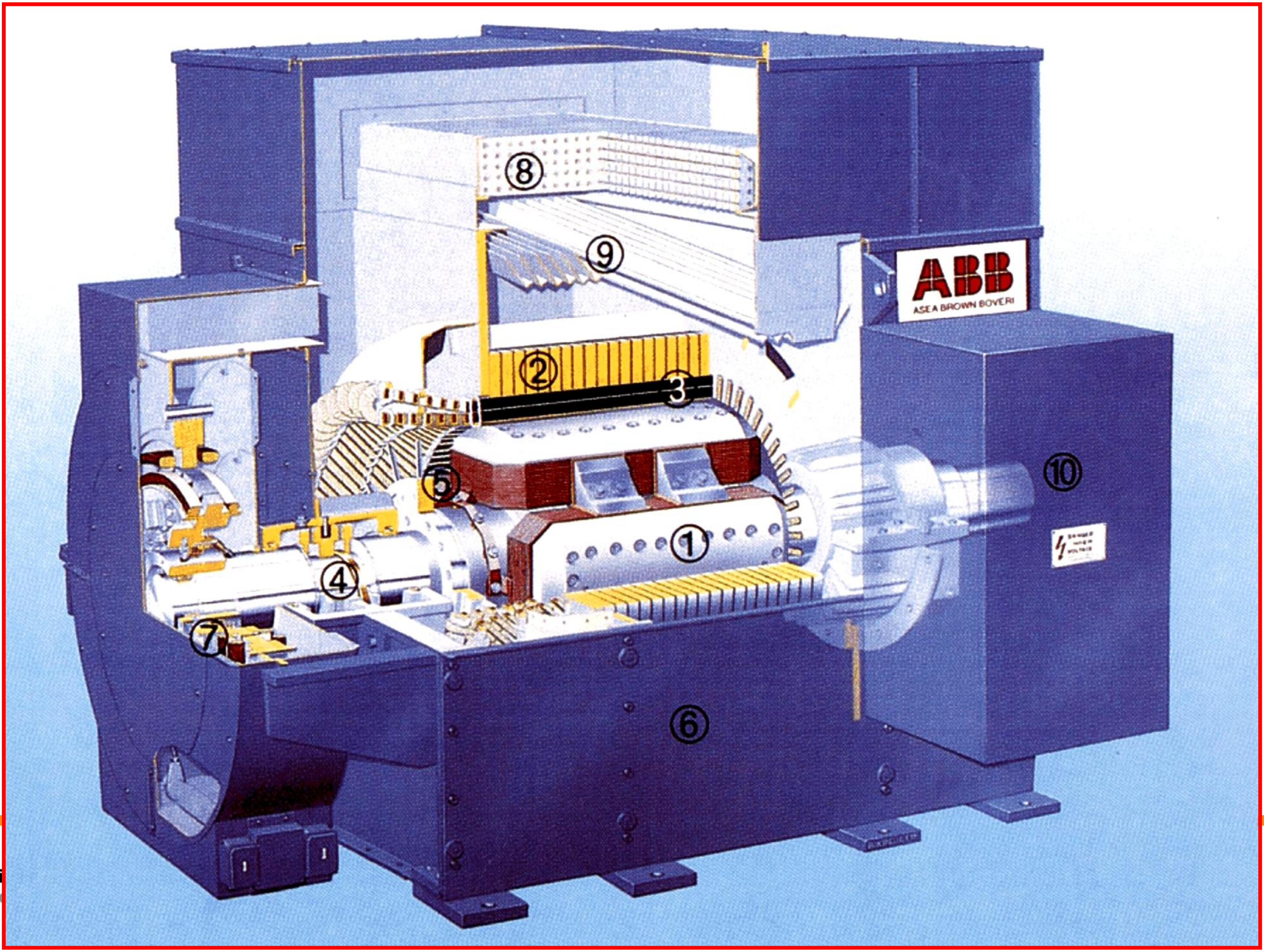


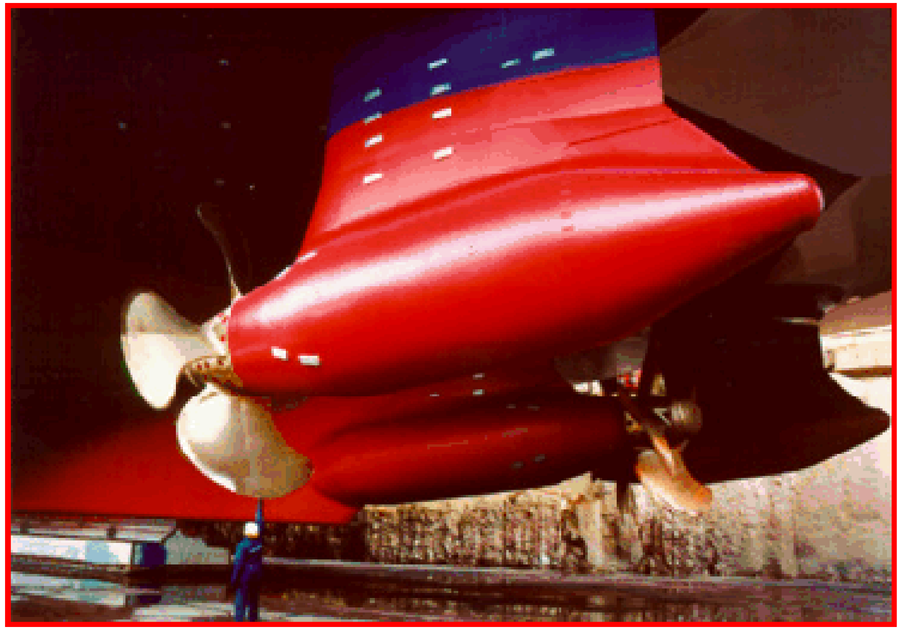
6,5 % price increase
From IE2 to IE3

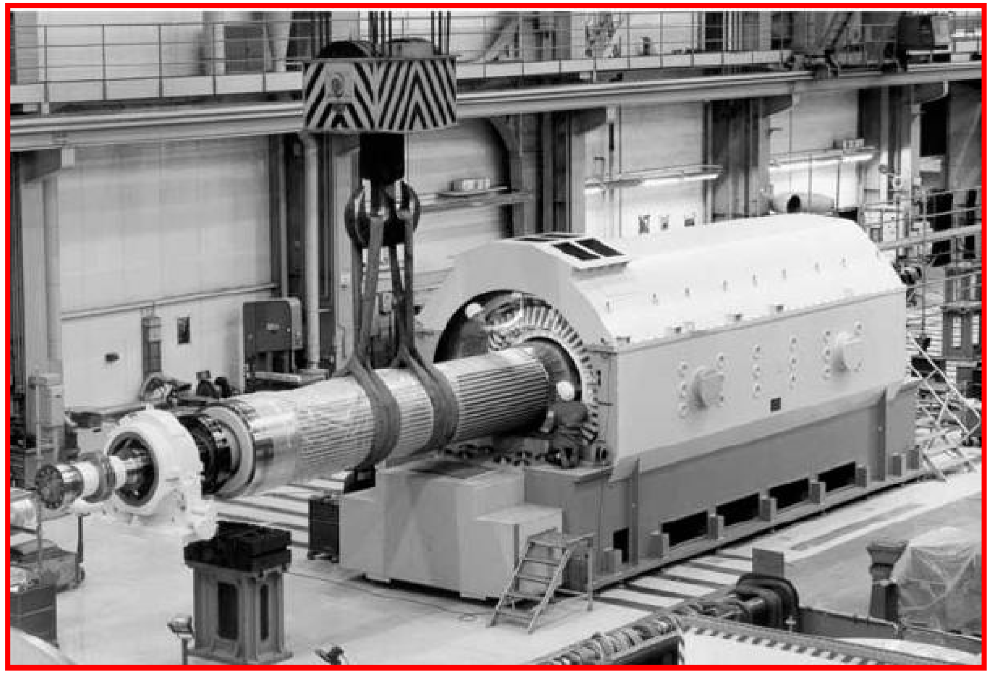


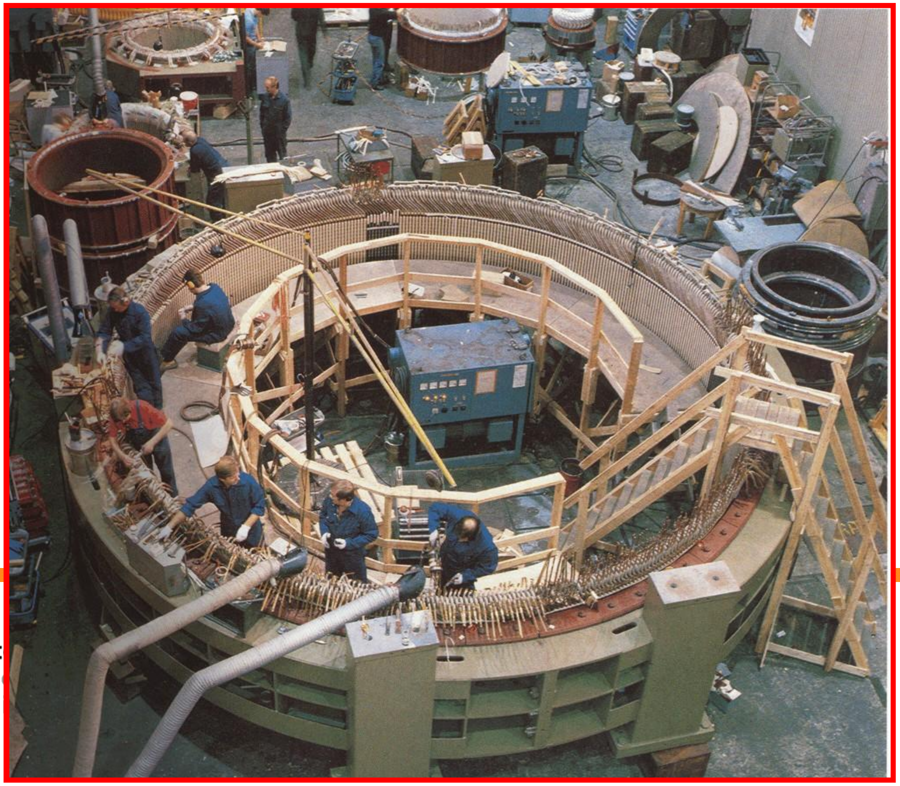
But ! Compute the saving on 10 years 10 h/day ! Energy cost 0.3 €/kWh

Structure of synchronous machines









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Main characteristics

- rotates at constant speed for a given supply frequency.
- primary generation devices of the electric power system.
- Operates both as generator and motor
- can draw either a lagging or a leading reactive current from the supply system.

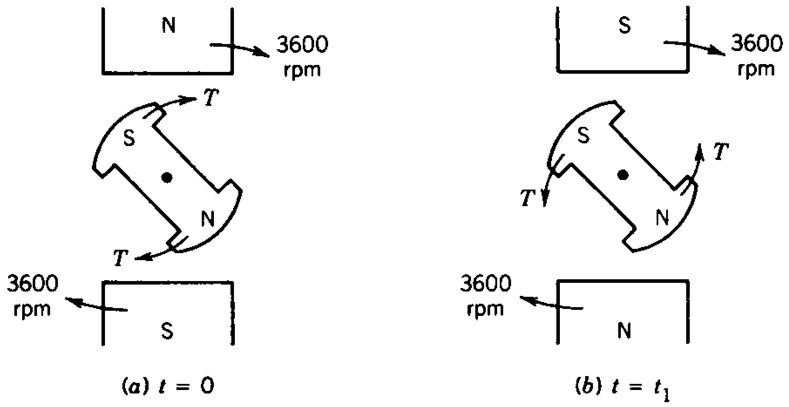
Usage of different types of synch. machines

- Non-salient pole generator
  - high speed (2 - 4 poles)
  - large power (100 - 1600 MVA)
  - steam and nuclear power plants

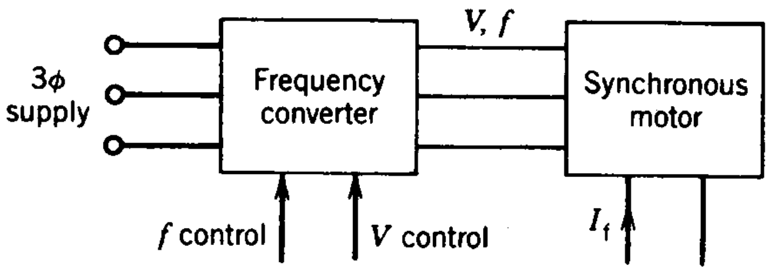
- Salient pole generator
  - small and mid-size power (0 – 800 MVA)
  - small motors for electrical clocks and other domestic devices
  - mid size generators for emergency power supply
  - mid size motors for pumps and ship propulsion
  - large size generators in hydro-electric power plants

Starting

- high inertia of the rotor prohibits direct connection into supply net



- variable-frequency supply or start as an induction motor



Power factor control

- Real Power

$$P = 3V_t I_a \cos\phi \qquad P = 3\frac{V_t E_f}{X_s}\sin\delta$$

- constant power

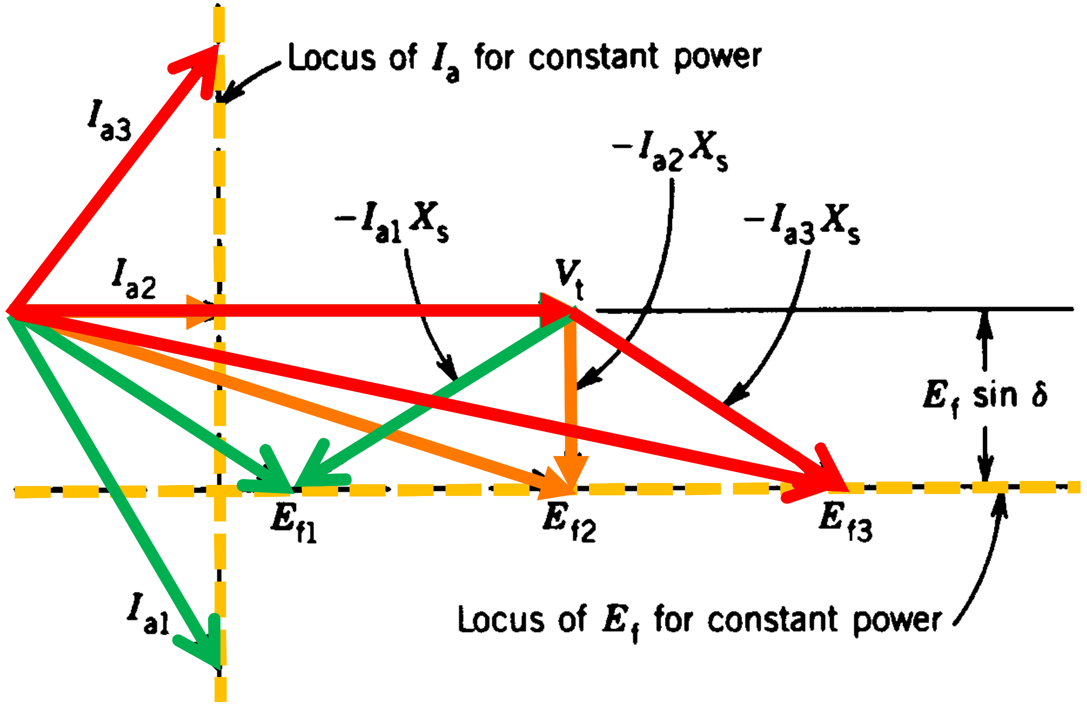
$$|I_a \cos\phi| = \text{const.}$$

$$E_f \sin\delta = \text{const}$$

- reactive current

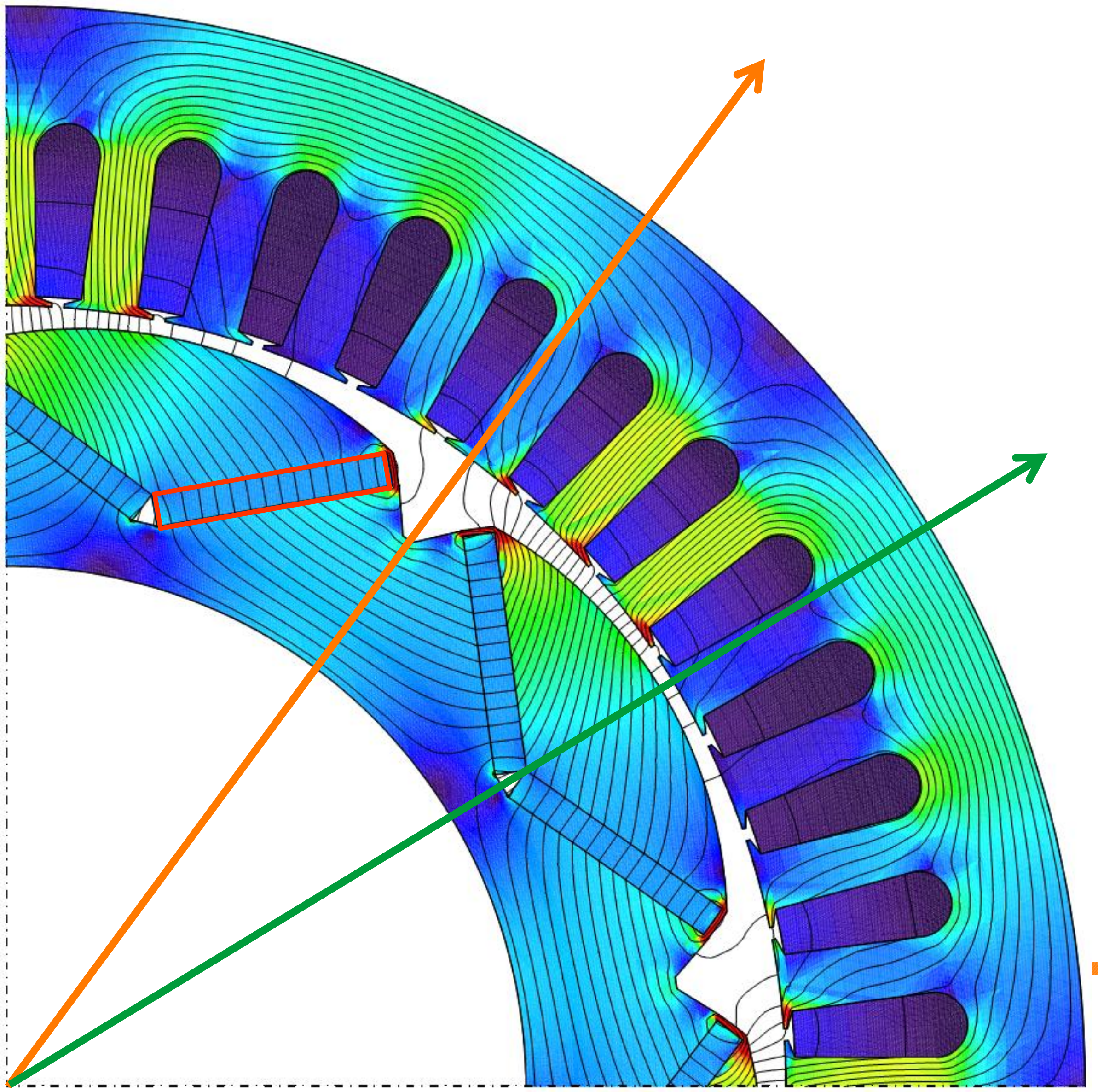
can be controlled

by field current

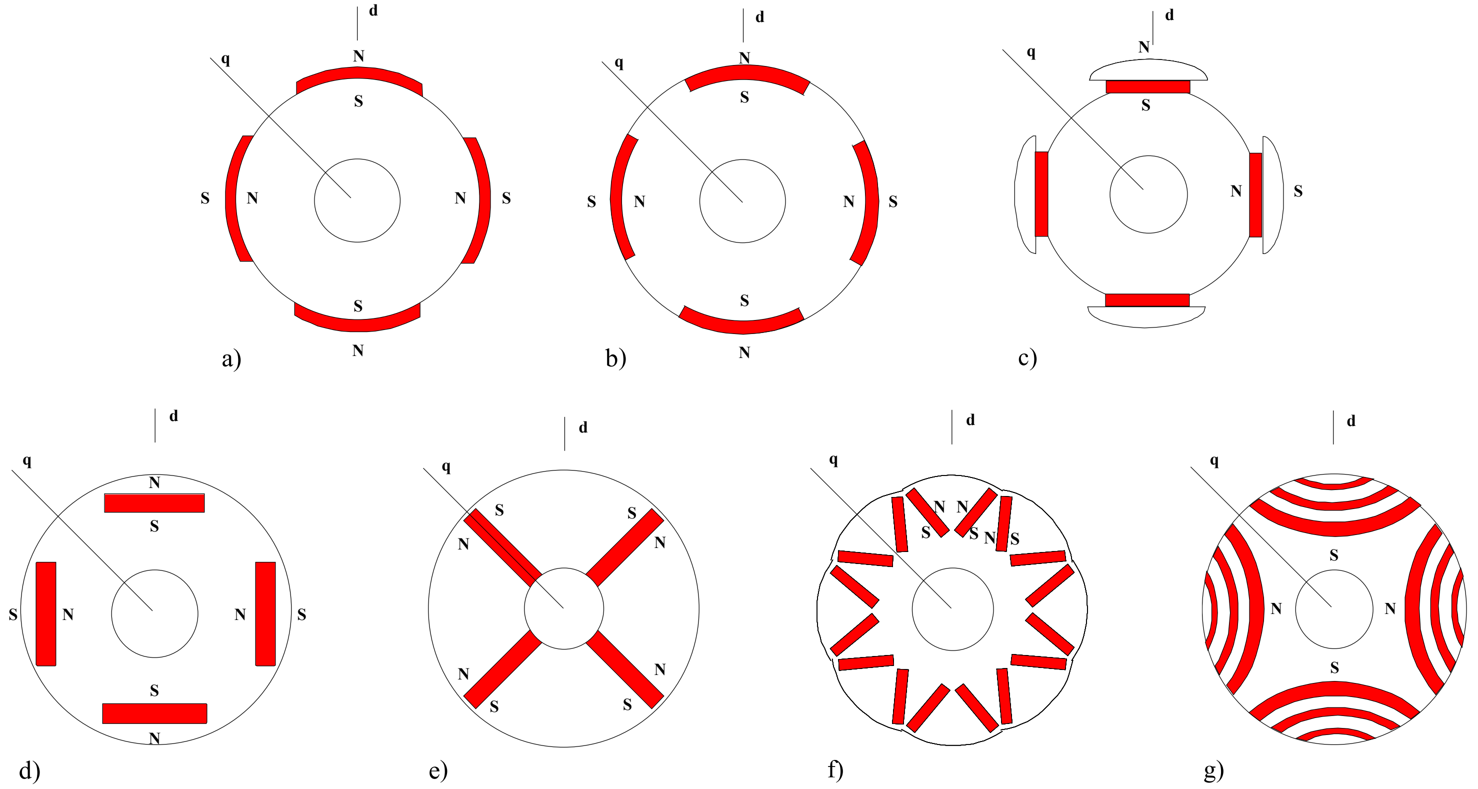


Permanent Magnet Machine

- No field current
- No filed control
- Cost of PM
- Power factor ?



PM rotor configurations



a) surface mounted magnets
b) inset rotor with surface magnets
c) surface magnets with pole shoes
d) embedded circumferential magnets
e) embedded radial magnets
f) embedded V-magnets with shaped air-gap
g) permanent magnet assisted synchronous reluctance