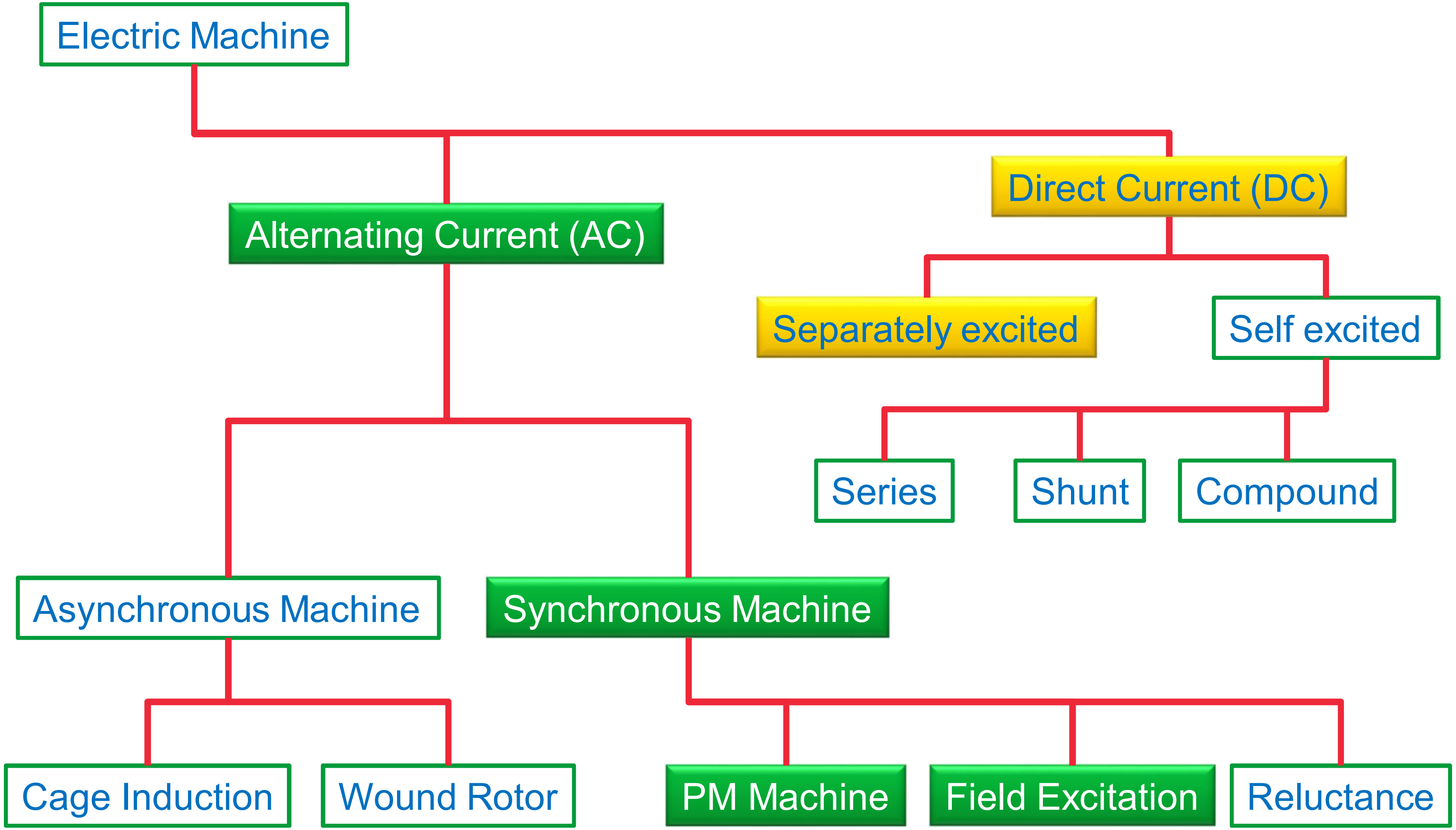
Synchronous Machines

- Lecture outcomes (what you are supposed to learn):
  - Explain the working principle of a synchronous machine
  - List different parts of a synchronous machine and their role
  - Describe how the rotating field is produced in AC machines
  - Explain the difference between synchronous and asynchronous machines
  - Explain the voltage and frequency control with a synchronous generator

Classification of Electric Machines



Electric Machine

Alternating Current (AC)

Direct Current (DC)

Separately excited

Self excited

Series

Shunt

Compound

Asynchronous Machine

Synchronous Machine

Cage Induction

Wound Rotor

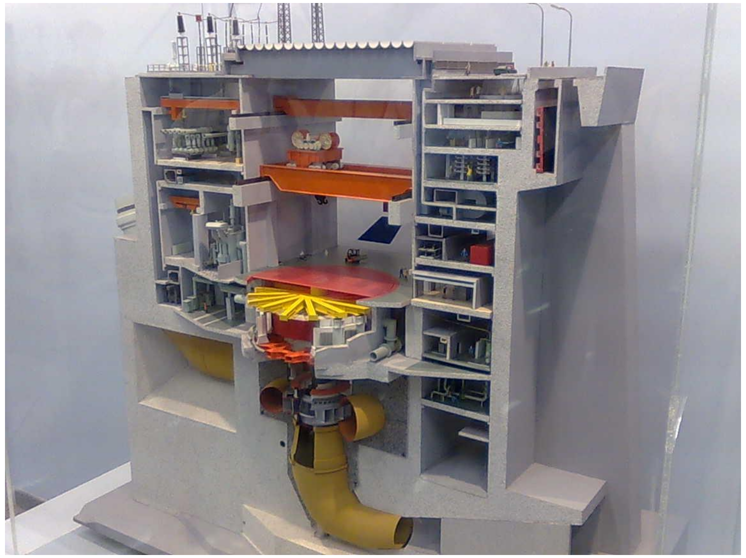
PM Machine

Field Excitation

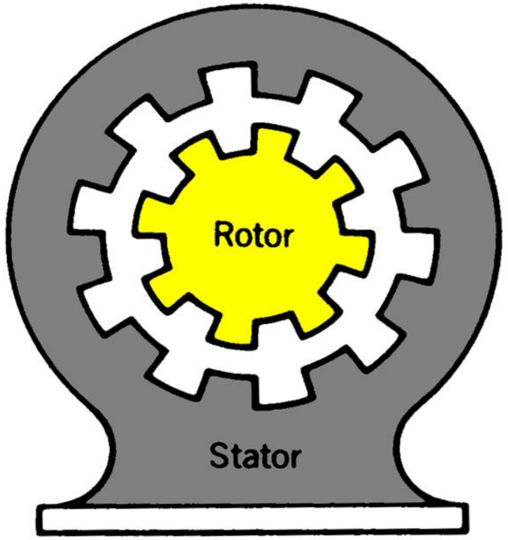
Reluctance

Applications of synchronous machines

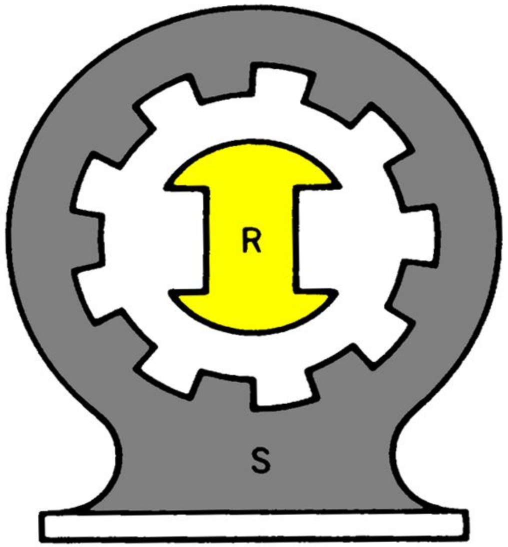
- Power plants generators
  - Hydropower plants (100-800 MVA) – low speed, large number of poles, salient pole
  - Thermal power plants (100-1600 MVA)– High speed 2-4 poles cylindrical turbogenerators
- Wind power
  - Permanent magnet machines, high speed and low speed
- Emergency power supply
  - Salient pole synchronous machine
  - Voltage regulation
- Traction and Industry motors
  - Permanent magnet motors and frequency converters for speed control
  - Direct On Line and reactive power compensation



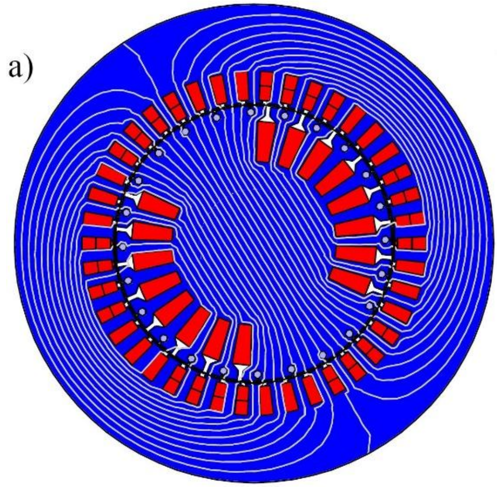
Basic structure of an electric machine



Cylindrical machine
Uniform air gap

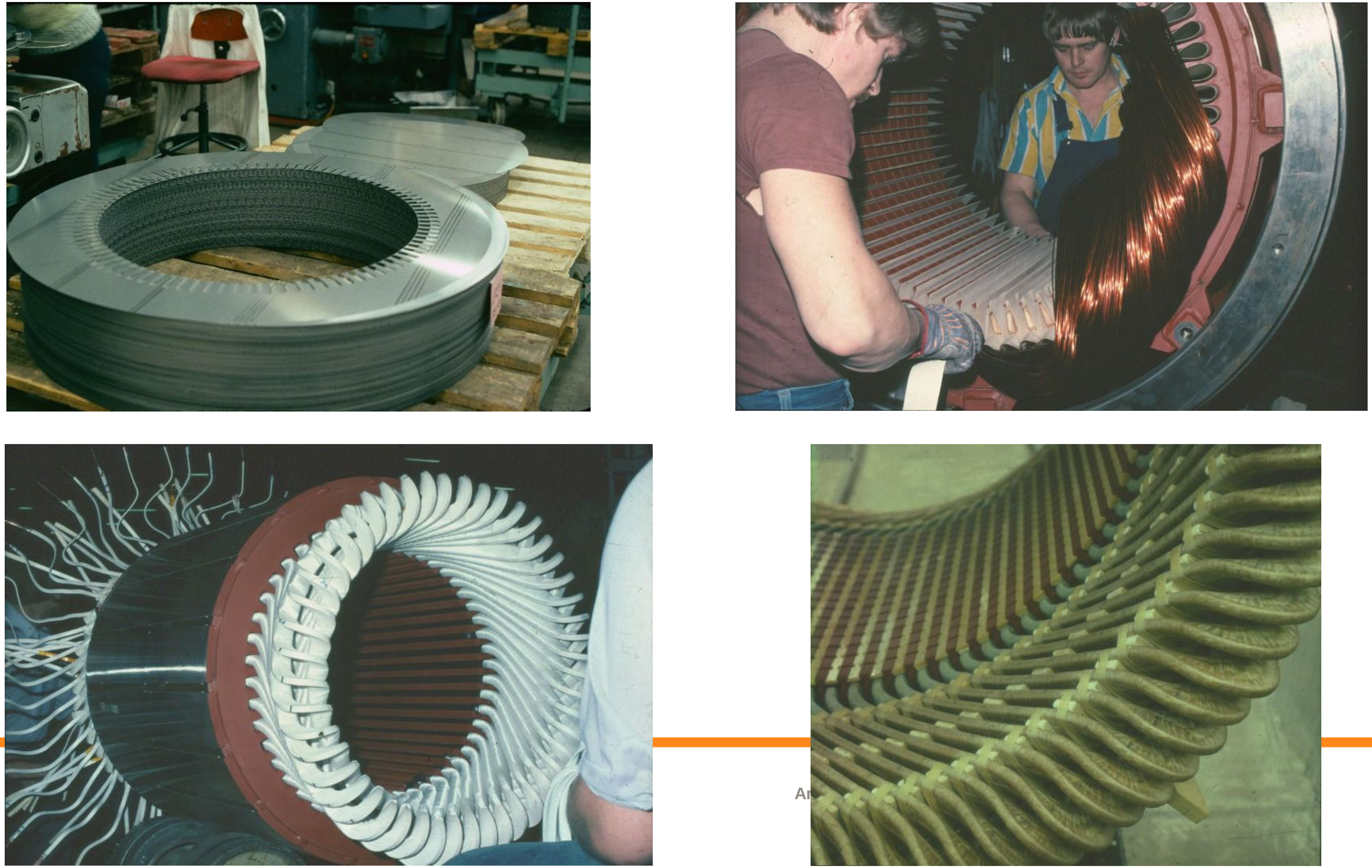


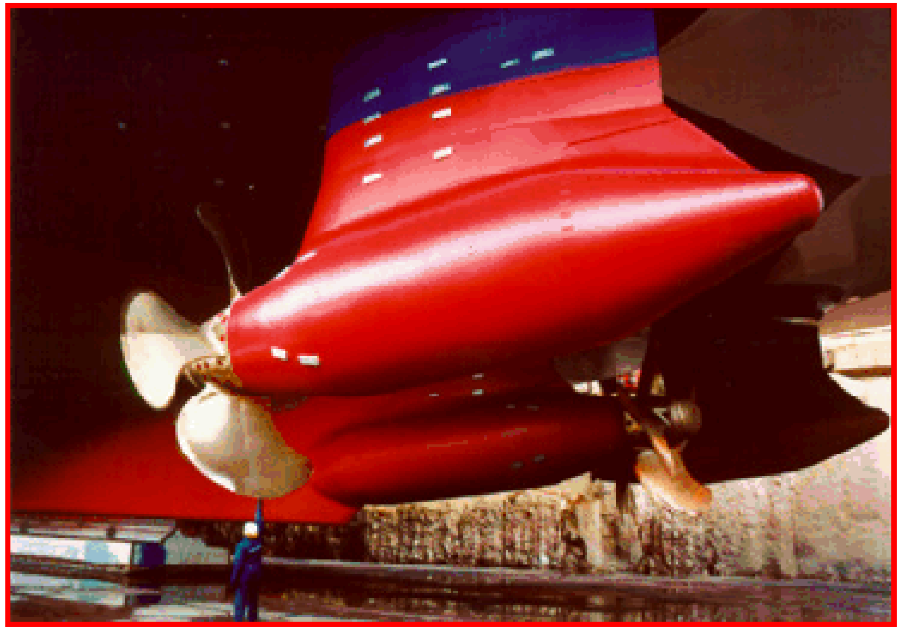
Salient pole machine
Non-uniform air gap

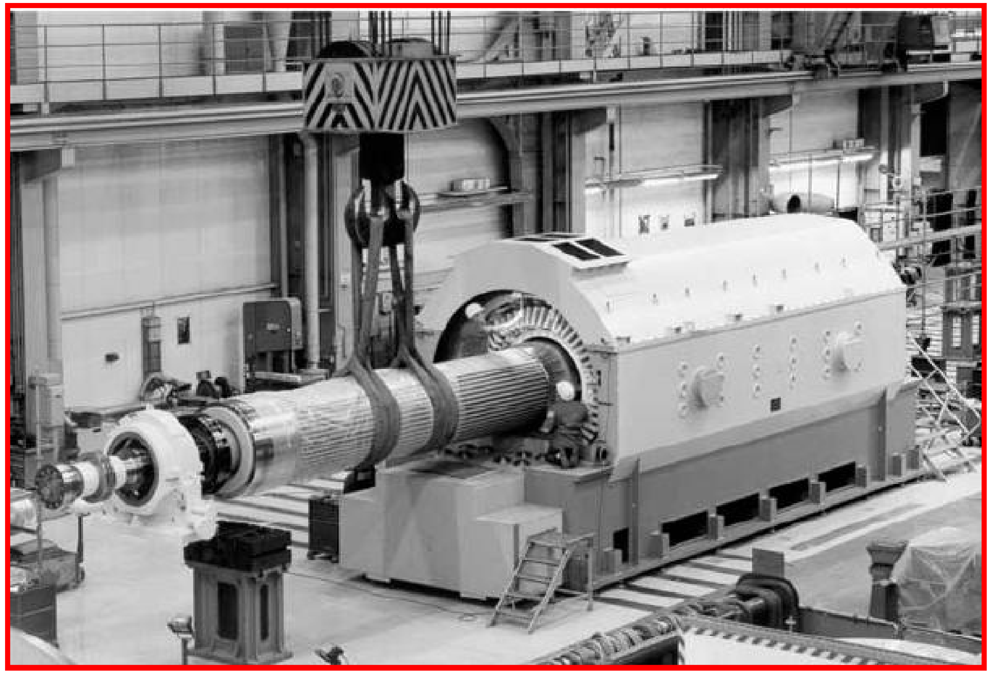


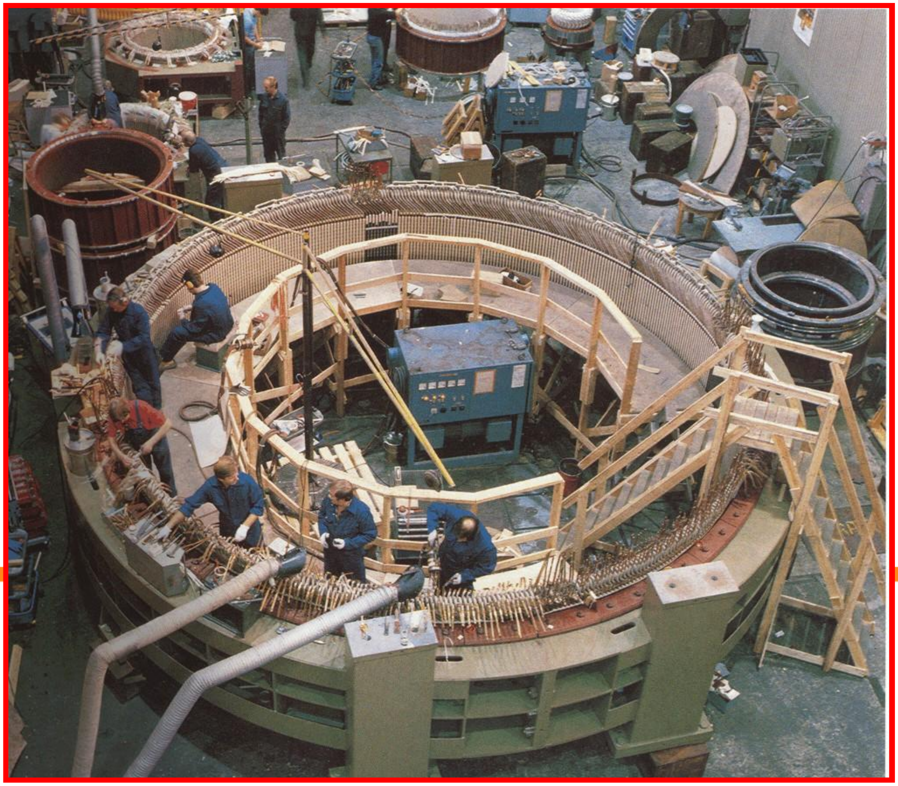
- Slots with conductors = windings
- Iron core to amplify and guide the flux
- Lamination to reduce eddy current losses
- Rotor mounted on a shaft and supported by bearings

Basic structure of electric machine

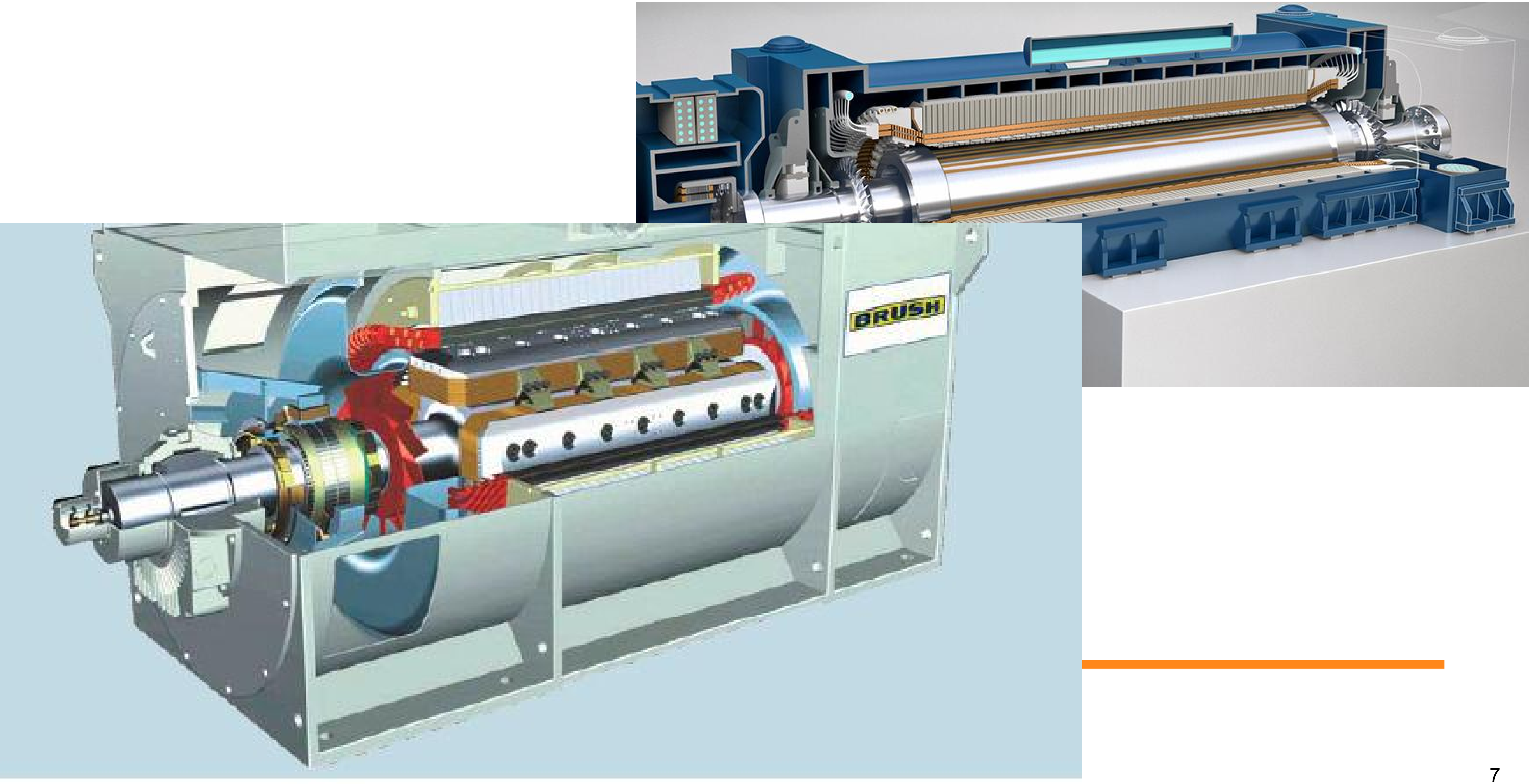








Structure of synchronous machines



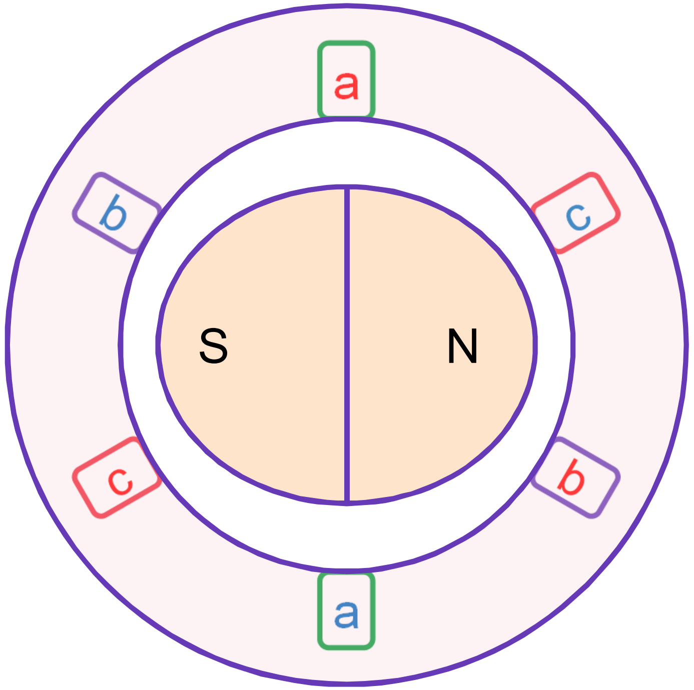
Main characteristics of a synchronous machine

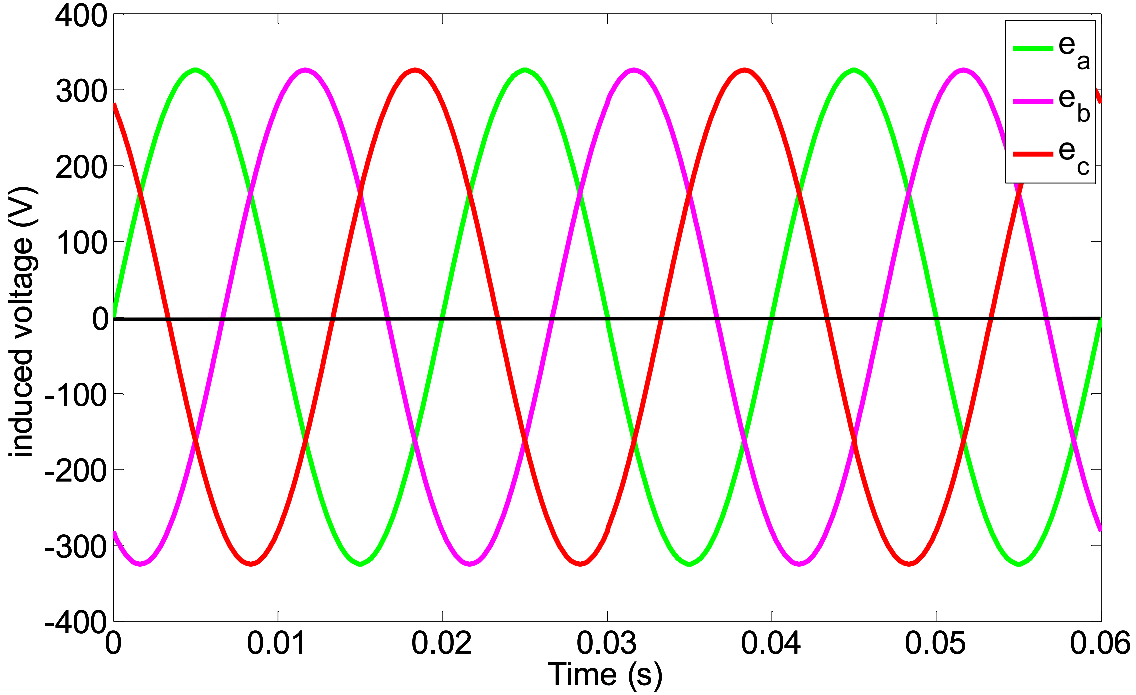
- Rotates at constant speed for a given supply frequency.
- Primary generation devices of the electric power system.
- Operates both as generator and motor
- Can draw either a lagging or a leading reactive power from the supply.
- Permanent magnet allows for high power density

Generation of three-phase voltages

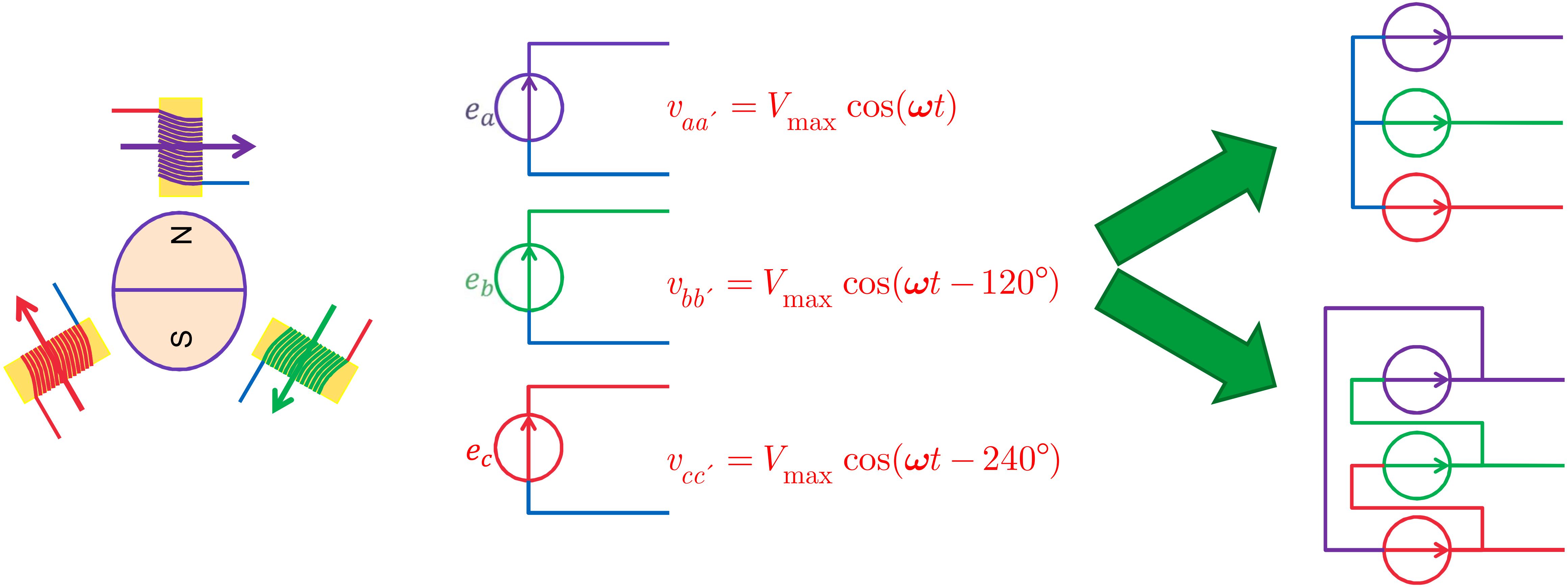
- Simple three-phase generator

$e = nBl\omega$





Generation of three-phase voltages

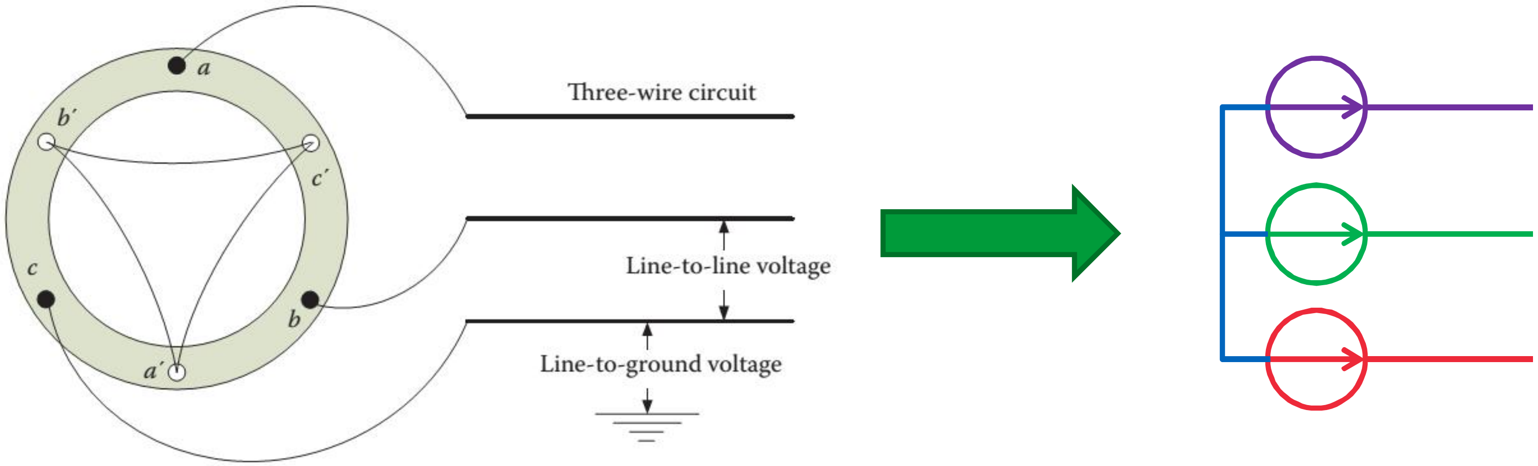


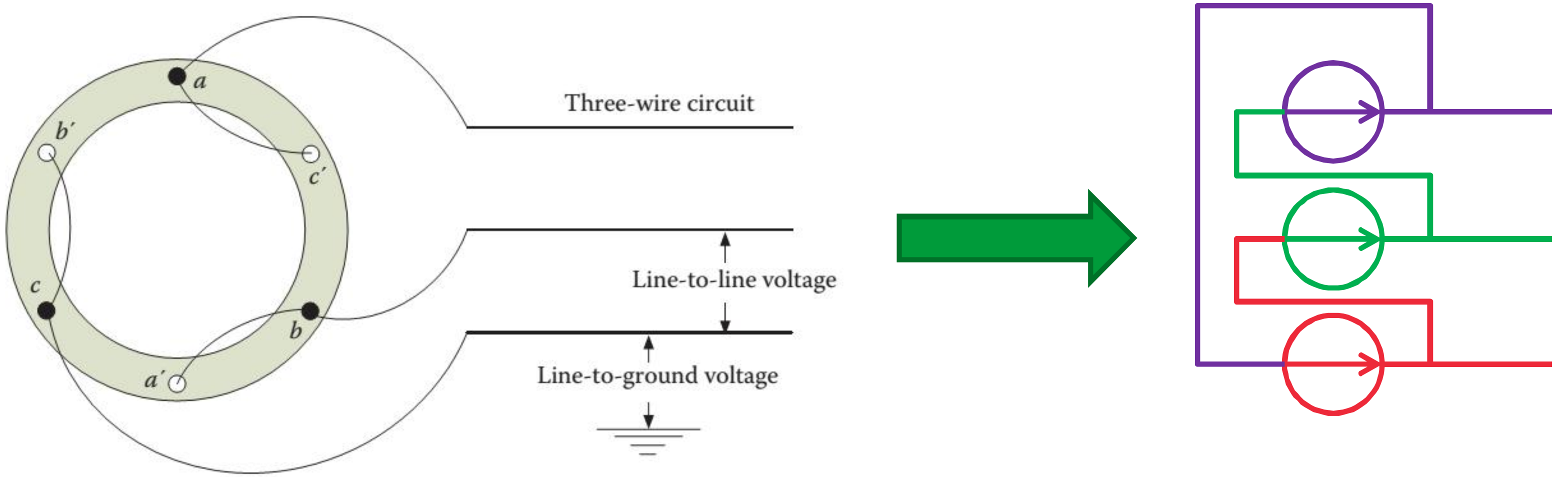
$$v_{aa'} = V_{\max}\cos(\omega t)$$

$$v_{bb'} = V_{\max}\cos(\omega t - 120°)$$

$$v_{cc'} = V_{\max}\cos(\omega t - 240°)$$

Connecting the 3-phase voltages

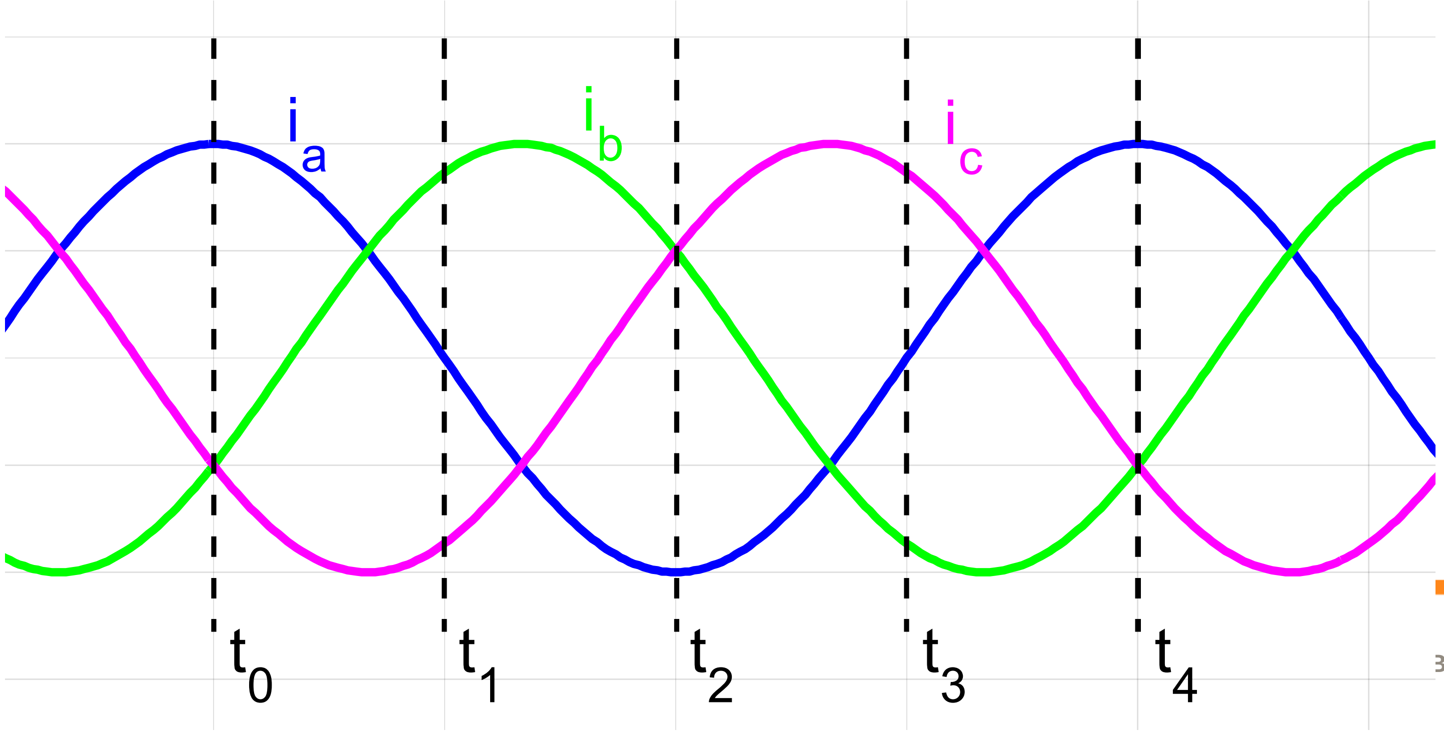


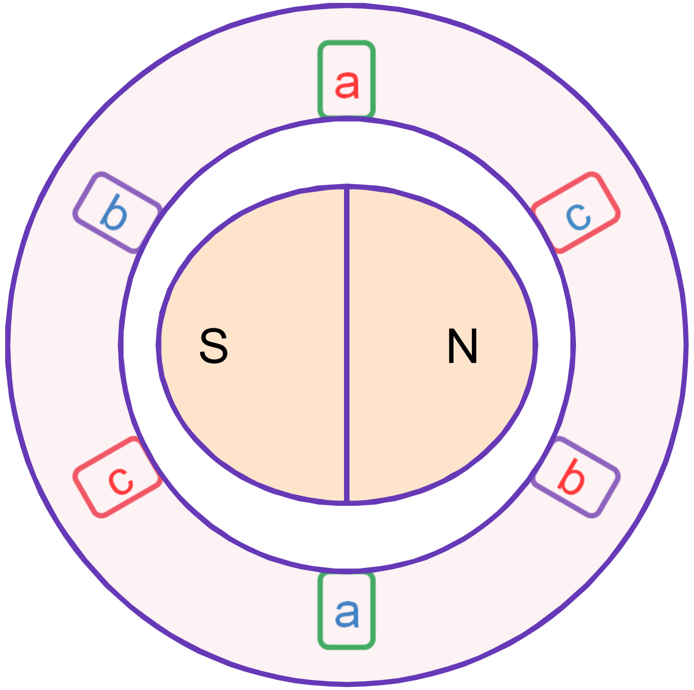


Rotating magnetic field - currents

- balanced three-phase currents

$$i_a = I_m \cos \omega t$$
$$i_b = I_m \cos(\omega t - 120°)$$
$$i_c = I_m \cos(\omega t + 120°)$$





Magnetomotive force

$$F = Ni$$

Flux $\varphi \propto F$

Rotating magnetic field – phase MMFs

at time t_0

$$i_a = I_m \qquad F_a = F_{max}$$

$$i_b = -\frac{I_m}{2} \qquad F_b = -\frac{1}{2}F_{max}$$

$$i_c = -\frac{I_m}{2} \qquad F_c = -\frac{1}{2}F_{max}$$

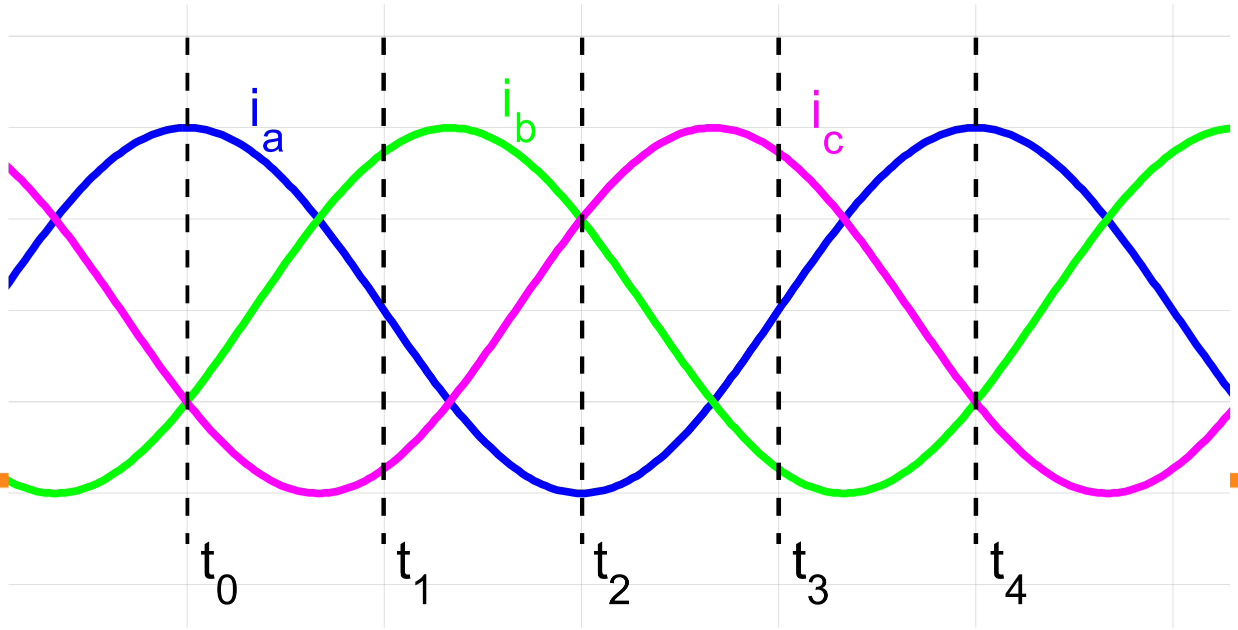
at time t_1

$$i_a = 0 \qquad F_a = 0$$

$$i_b = \frac{\sqrt{3}}{2}I_m \qquad F_b = \frac{\sqrt{3}}{2}F_{max}$$

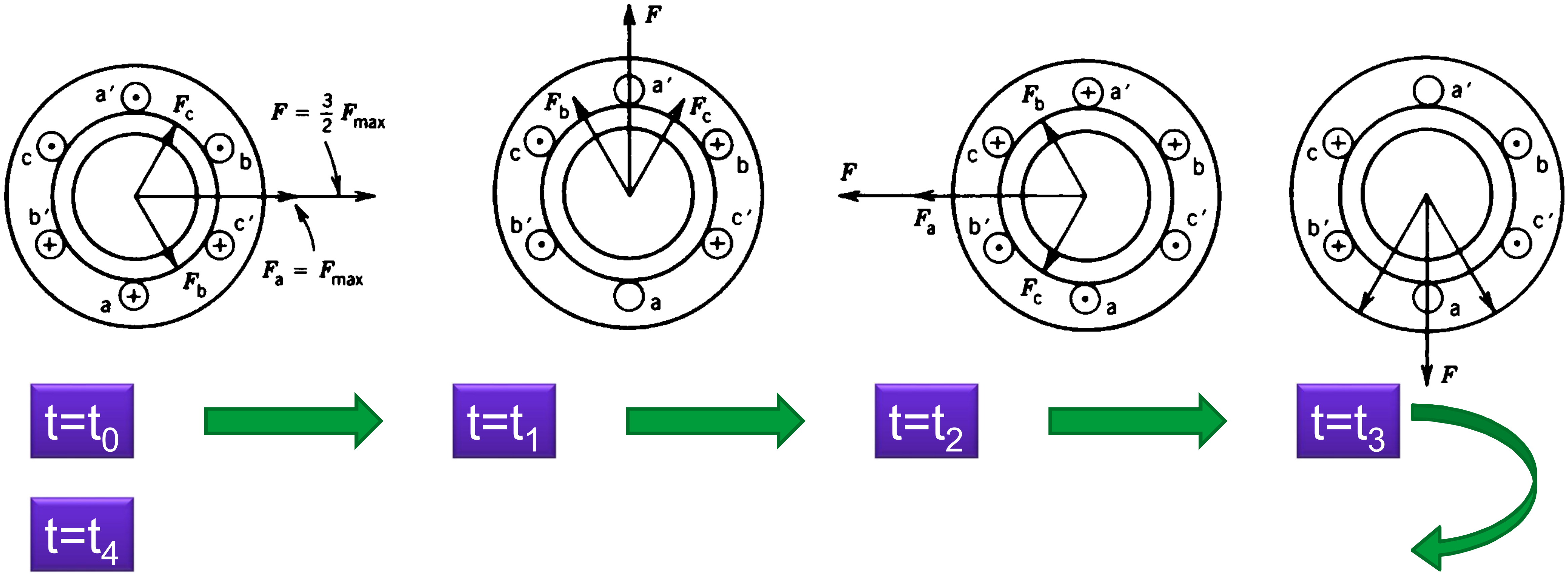
$$i_c = -\frac{\sqrt{3}}{2}I_m \qquad F_c = -\frac{\sqrt{3}}{2}F_{max}$$

$$\overline{F} = \frac{3}{2}F_{max}\angle 0°$$



$$\overline{F} = \frac{3}{2}F_{max}\angle 90°$$

Resulting MMF– graphical method



$t=t_0$

$t=t_1$

$t=t_2$

$t=t_3$

$t=t_4$

Anouar Belahcen

Properties of resulting MMF

- The resultant mmf vector retains its sinusoidal distribution in space

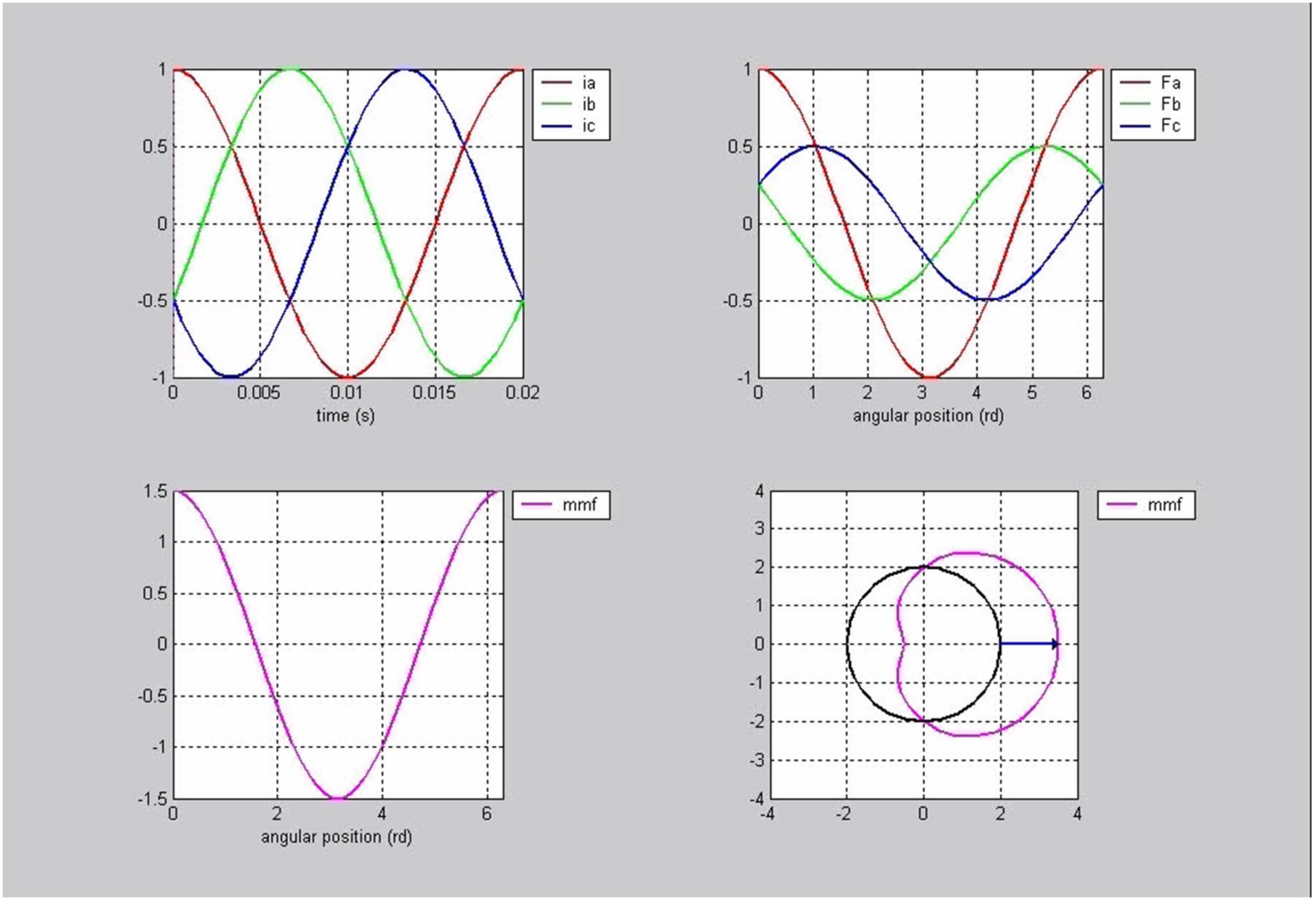
$$F = \frac{3}{2} F_{\max}$$

- It moves around the air gap – one revolution per period

$$n == \frac{60 \times f}{p}$$

p= number of pole pairs

- Reversal of currents phase sequence ⟹ change in direction of rotation


ia
ib
ic
1
0.5
0
-0.5
-1
0
0.005
0.01
0.015
0.02
time (s)
Fa
Fb
Fc
1
0.5
0
-0.5
-1
0
1
2
3
4
5
6
angular position (rd)
mmf
1.5
1
0.5
0
-0.5
-1
-1.5
0
2
4
6
angular position (rd)
mmf
4
3
2
1
0
-1
-2
-3
-4
-4
-2
0
2
4

Induced voltages

- sinusoidal flux density distribution in space

$$B(\theta) = B_{\mathrm{max}} \cos\theta$$

- flux per pole

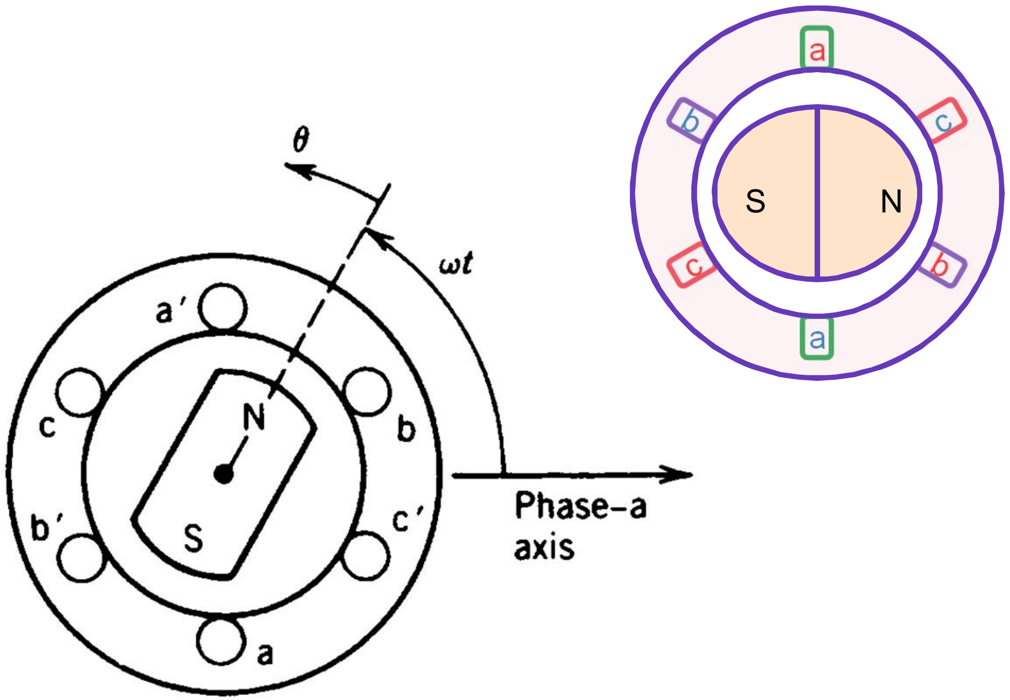
$$\Phi_{\mathrm{p}} = \int_{-\pi/2}^{\pi/2} B(\theta) lr \, d\theta = 2 B_{\mathrm{max}} lr$$

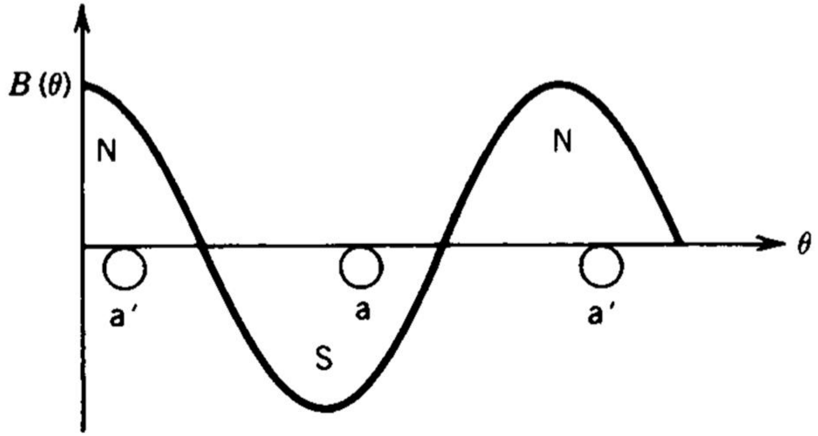
- flux linkage

$$\lambda_{\mathrm{a}}(\omega t) = N \Phi_{\mathrm{p}} \cos\omega t$$

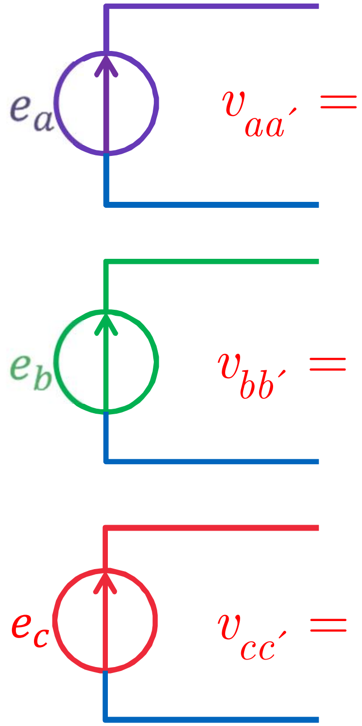
- induced voltage

$$e_{\mathrm{a}} = -\frac{d\lambda_{\mathrm{a}}}{dt} = E_{\mathrm{max}} \sin\omega t$$





Induced voltages



$$v_{aa'} = V_{\max} \cos(\omega t)$$

$$v_{bb'} = V_{\max} \cos(\omega t - 120°)$$

$$v_{cc'} = V_{\max} \cos(\omega t - 240°)$$

$$e_\mathrm{a} = E_\mathrm{max} \sin \omega t$$

$$e_\mathrm{b} = E_\mathrm{max} \sin(\omega t - 120°)$$

$$e_\mathrm{c} = E_\mathrm{max} \sin(\omega t + 120°)$$

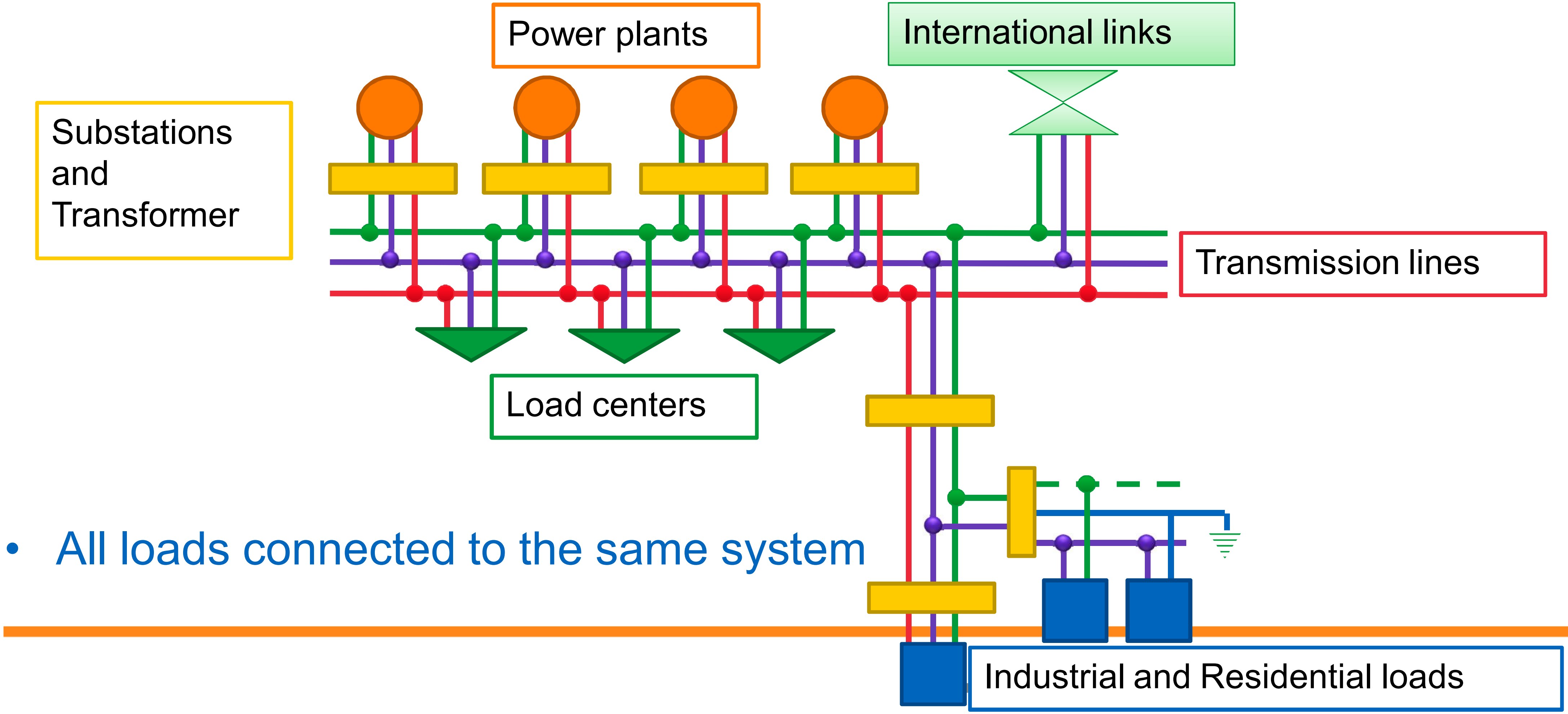
$$E_\mathrm{max} = \omega N_{ph} \Phi_\mathrm{p} \qquad E_\mathrm{rms} = \frac{2\pi}{\sqrt{2}} f N_{ph} \Phi_\mathrm{p}$$

- for distributed winding with winding factor K_w

$$E_\mathrm{rms} = \frac{2\pi}{\sqrt{2}} f N_\mathrm{ph} \Phi_\mathrm{p} K_w \qquad K_w \approx 0.85 \ldots 0.95 \qquad E_\mathrm{f} = k \times n \times \Phi_\mathrm{f}$$

The infinite bus or power grid

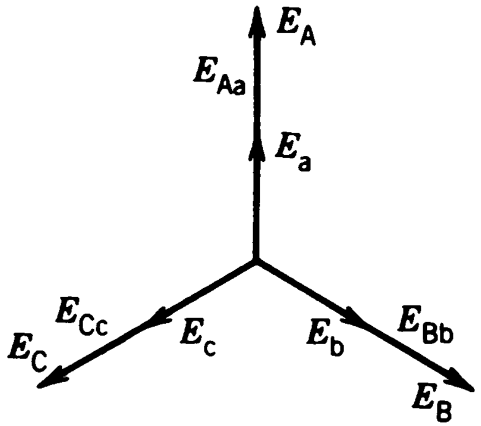
- All power plant connected to the same electric system

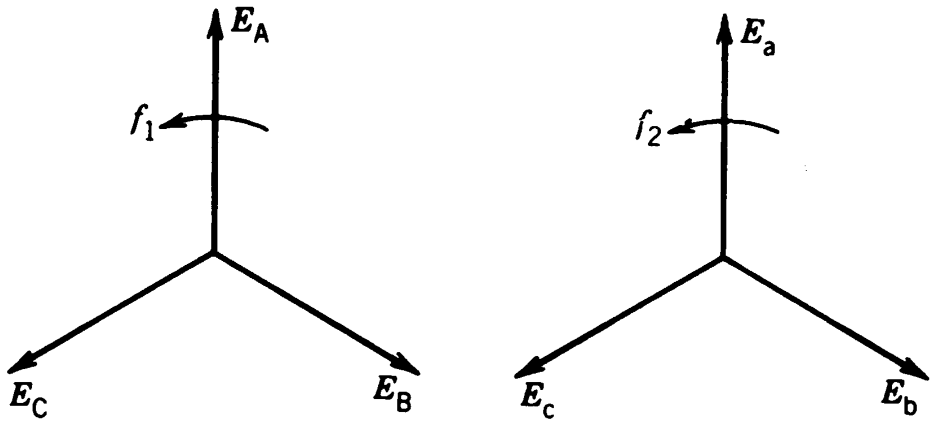


- All loads connected to the same system

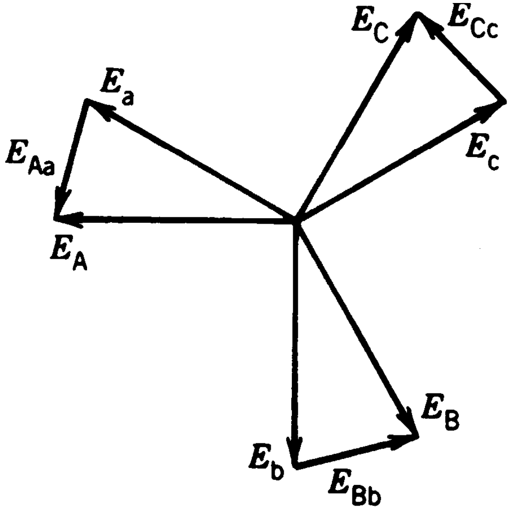
Paralleling with the infinite bus

- Paralleling the synchronous machine and the grid requires that they have the same
  - voltage
  - frequency
  - phase sequence
  - phase





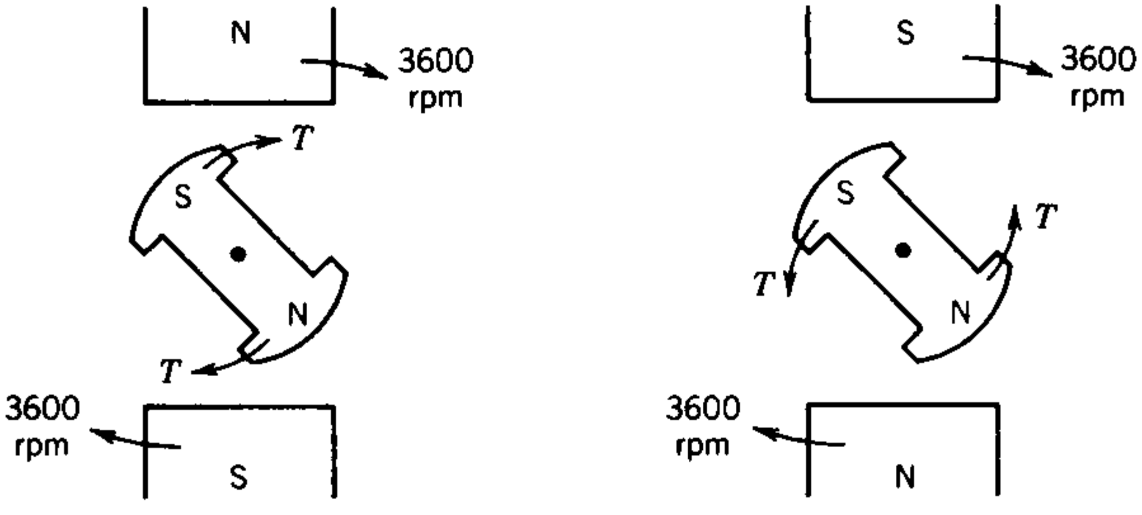
Instant $t = t_1$



Instant $t = t_2$

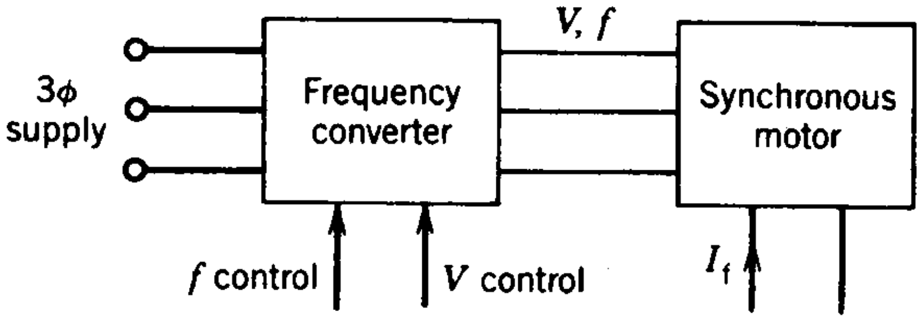
Starting a synchronous motor

- high inertia of the rotor prohibits direct connection into supply net
- variable-frequency supply or start as an induction motor



(a) $t = 0$

(b) $t = t_1$



Equivalent circuit and operation quantities

$$V_t = |V_t|\underline{|0^\circ}$$

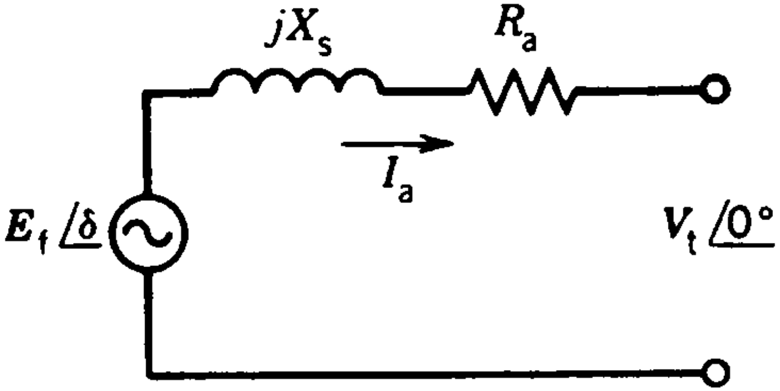
$$E_f = |E_f|\underline{|\delta}$$

$$Z_s = R_a + jX_s = |Z_s|\underline{|\theta_s}$$

$$S = V_t I_a^*$$

$$I_a^* = \left(\frac{E_f - V_t}{Z_s}\right)^* = \frac{E_f^*}{Z_s^*} - \frac{V_t^*}{Z_s^*}$$

$$= \frac{|E_f|}{|Z_s|}\underline{|\theta_s - \delta} - \frac{|V_t|}{|Z_s|}\underline{|\theta_s}$$

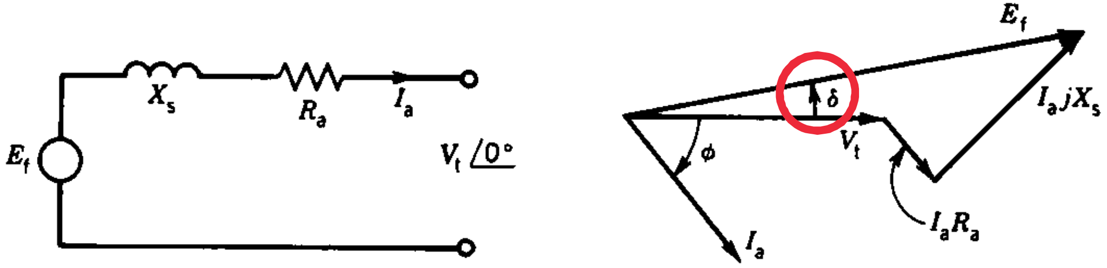


convention: lagging reactive power positive

Phasor diagram

- terminal voltage taken as the reference vector
- generator load angle positive

$$E_{\mathrm{f}} = V_{\mathrm{t}} + I_{\mathrm{a}} R_{\mathrm{a}} + I_{\mathrm{a}} jX_{\mathrm{s}} = \left|E_{\mathrm{f}}\right|\underline{|\delta}$$

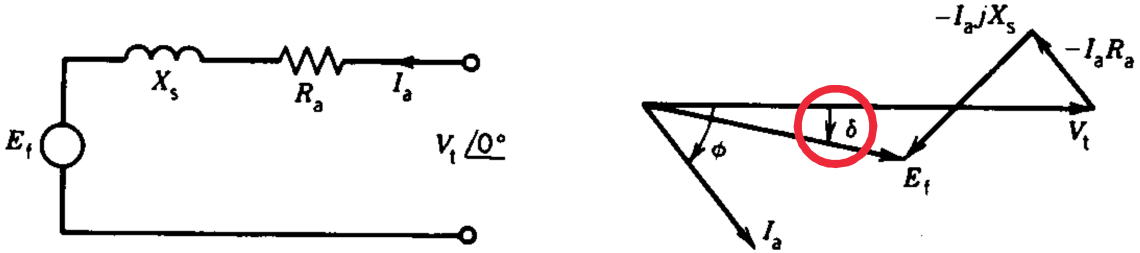


- motor load angle negative

$$V_{\mathrm{t}} = E_{\mathrm{f}} + I_{\mathrm{a}} R_{\mathrm{a}} + I_{\mathrm{a}} jX_{\mathrm{s}}$$

$$E_{\mathrm{f}} = V_{\mathrm{t}}\underline{|0^\circ} - I_{\mathrm{a}} R_{\mathrm{a}} - I_{\mathrm{a}} jX_{\mathrm{s}}$$

$$= \left|E_{\mathrm{f}}\right|\underline{|\delta}$$



- convention: generating current flows out of the machine

Per phase power

- complex power

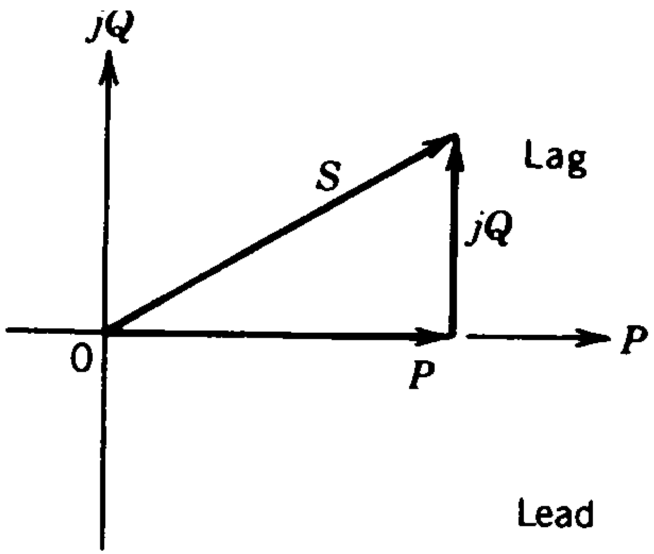
$$S = \frac{|V_\mathrm{t}||E_\mathrm{f}|}{|Z_\mathrm{s}|}\underline{|\theta_\mathrm{s} - \delta} - \frac{|V_\mathrm{t}|^2}{|Z_\mathrm{s}|}\underline{|\theta_\mathrm{s}}$$

- real power

$$P = \frac{|V_\mathrm{t}||E_\mathrm{f}|}{|Z_\mathrm{s}|}\cos(\theta_\mathrm{s} - \delta) - \frac{|V_\mathrm{t}|^2}{|Z_\mathrm{s}|}\cos\theta_\mathrm{s}$$

- reactive power

$$Q = \frac{|V_\mathrm{t}||E_\mathrm{f}|}{|Z_\mathrm{s}|}\sin(\theta_\mathrm{s} - \delta) - \frac{|V_\mathrm{t}|^2}{|Z_\mathrm{s}|}\sin\theta_\mathrm{s}$$



Power and torque

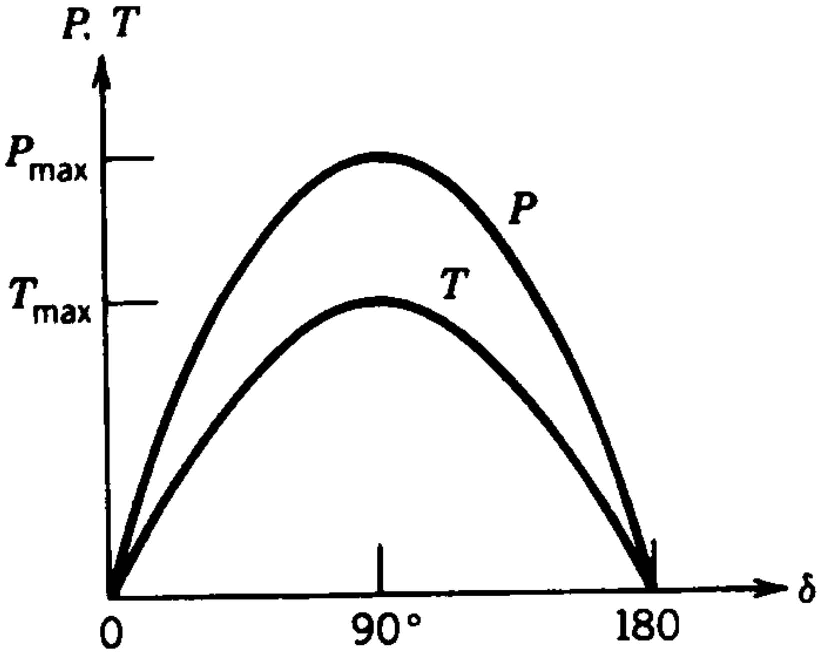
- real power (neglecting R_a)

$$P_{3\phi} = \frac{3|V_t||E_f|}{|X_s|}\sin\delta = P_{\max}\sin\delta$$

Similar to power line power transfer

- torque

$$T = \frac{P_{3\phi}}{\omega_{syn}} = \frac{3}{\omega_{syn}}\frac{|V_t||E_f|}{X_s}\sin\delta = T_{\max}\sin\delta$$



Power factor control

- Real Power

$$P = 3V_\mathrm{t} I_\mathrm{a} \cos\phi \qquad P = 3\frac{V_\mathrm{t} E_\mathrm{f}}{X_\mathrm{s}} \sin\delta$$

- constant power

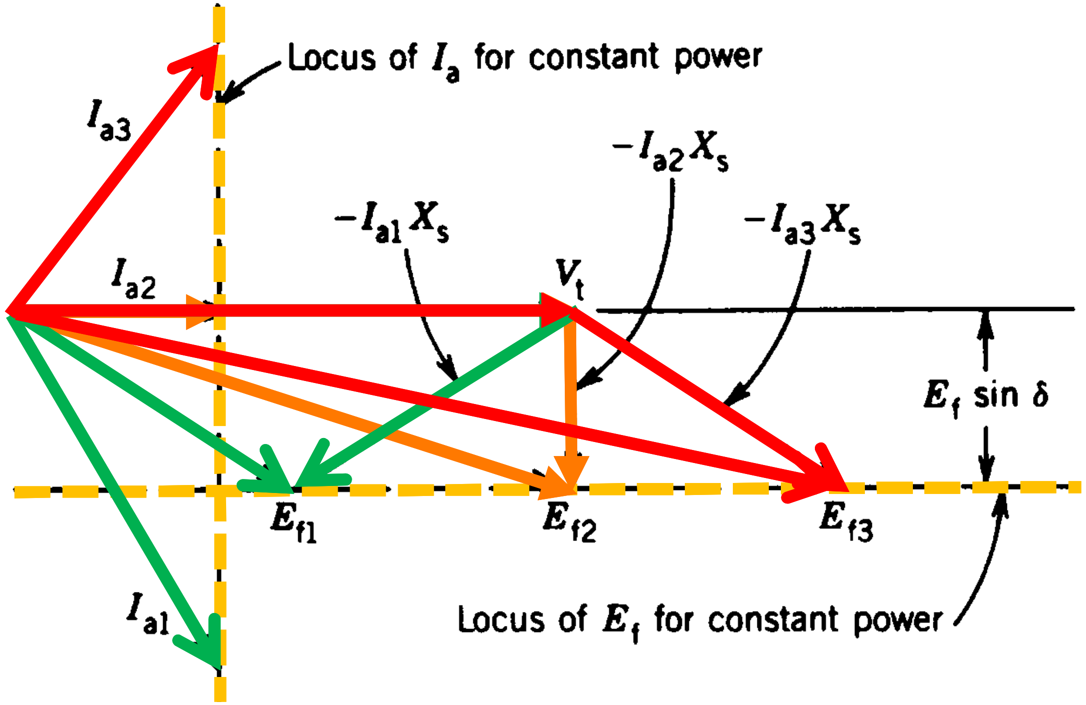
$$\left| I_\mathrm{a} \cos\phi \right| = \text{const.}$$

$$E_\mathrm{f} \sin\delta = \text{const}$$

- reactive current

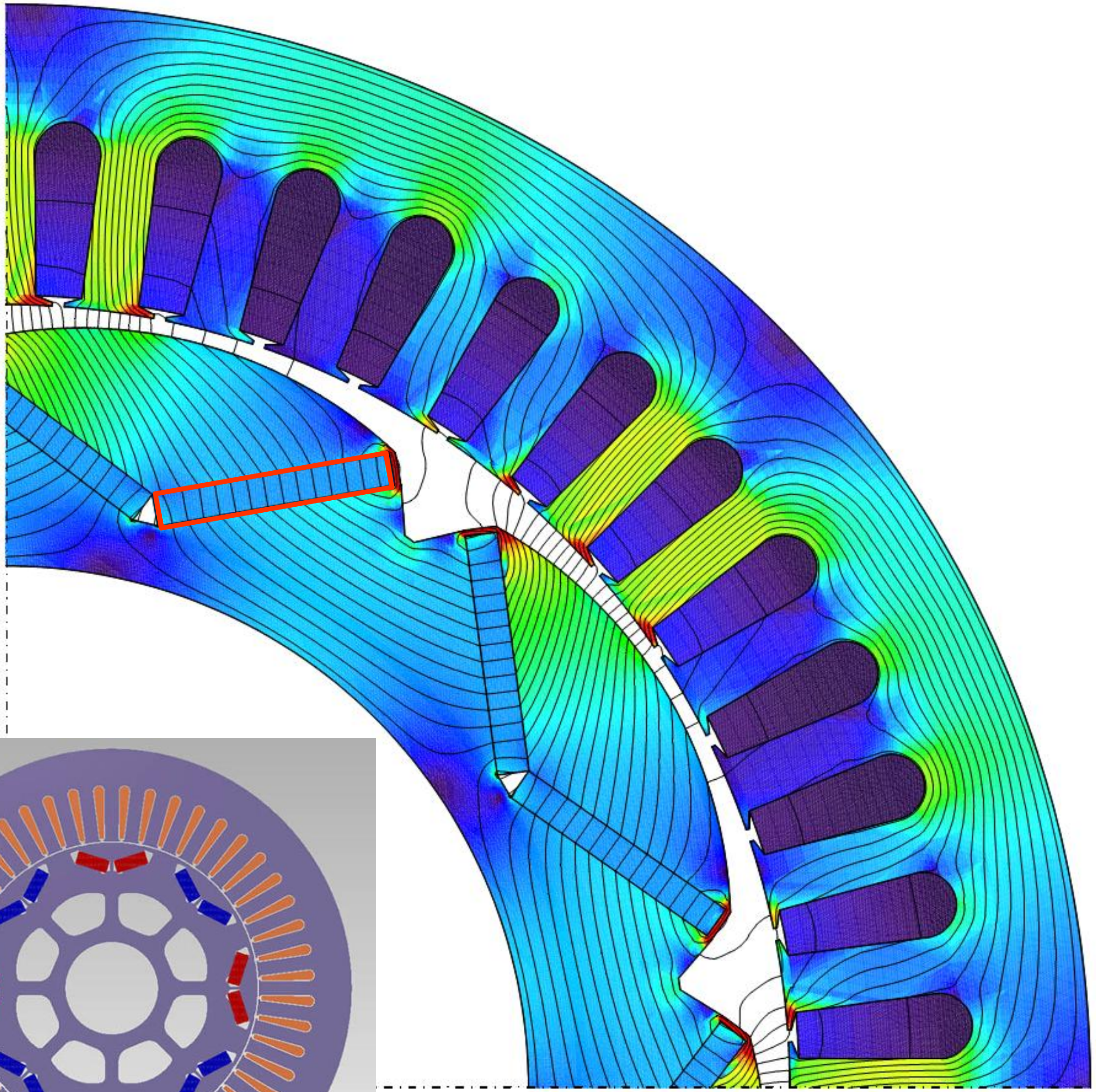
can be controlled

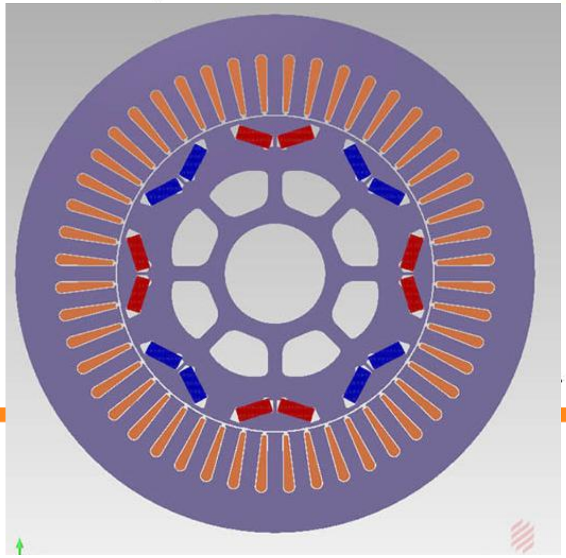
by field current



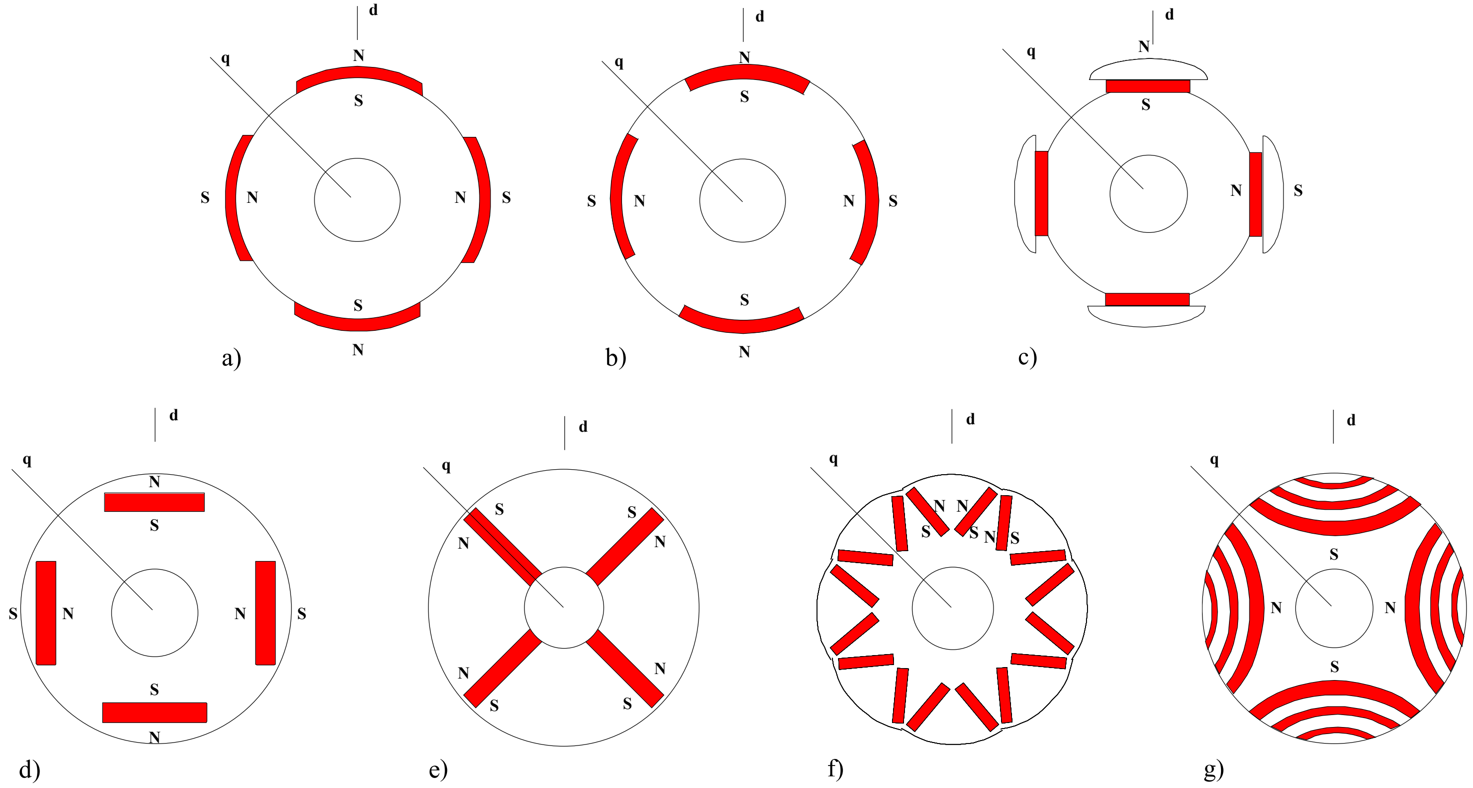
Permanent Magnet Machine

- 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