Outcome of this lecture

At the end of this lecture you will be able to:

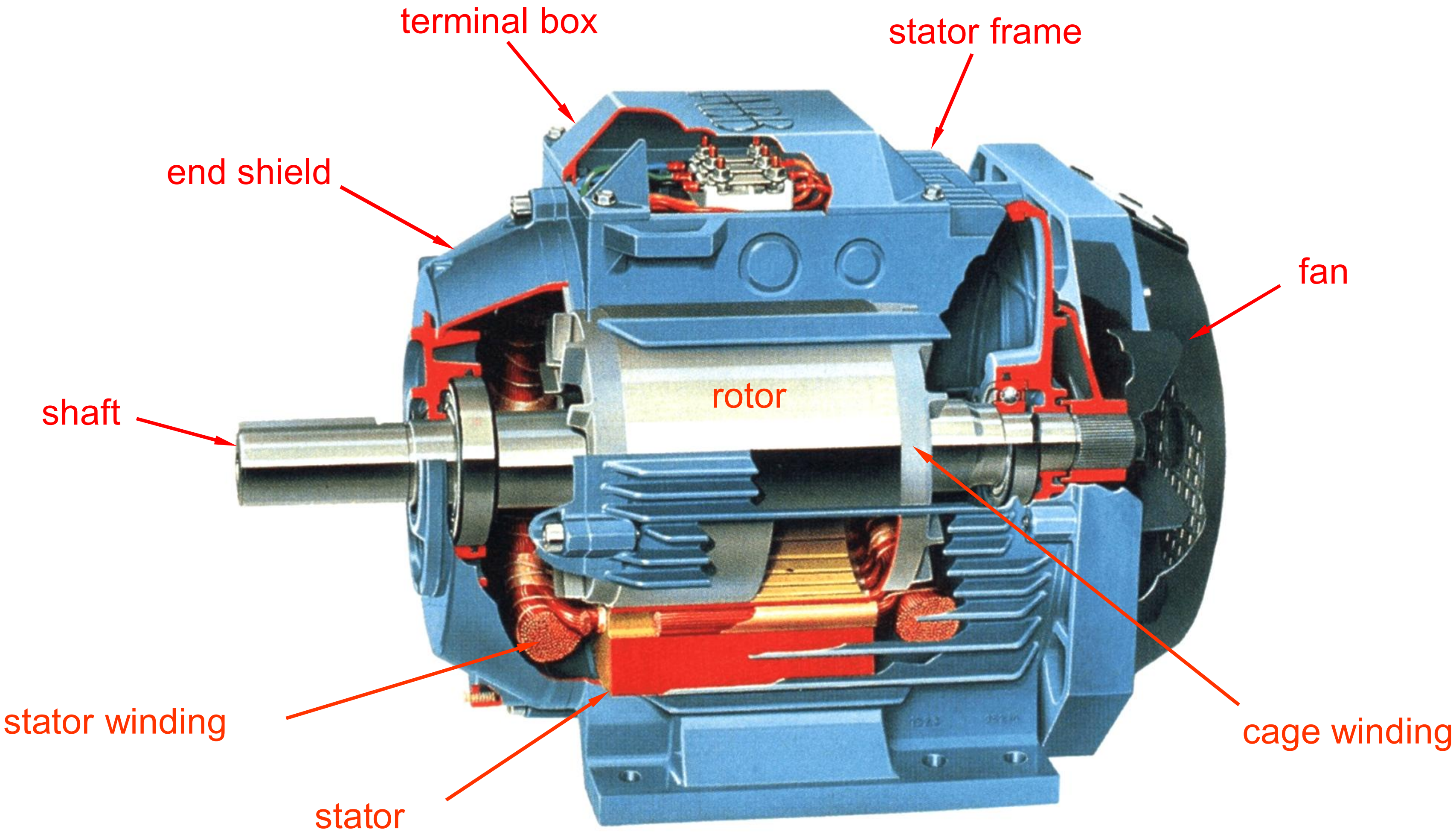
- List the different parts of an induction machine
- Explain the operation principles of the machine
- Use the equivalent circuit model of the machine
- Analyze the steady-state operation of the machine
- Distinguish between different control methods of the machine

Your understanding of the rotating field theory will be enhanced

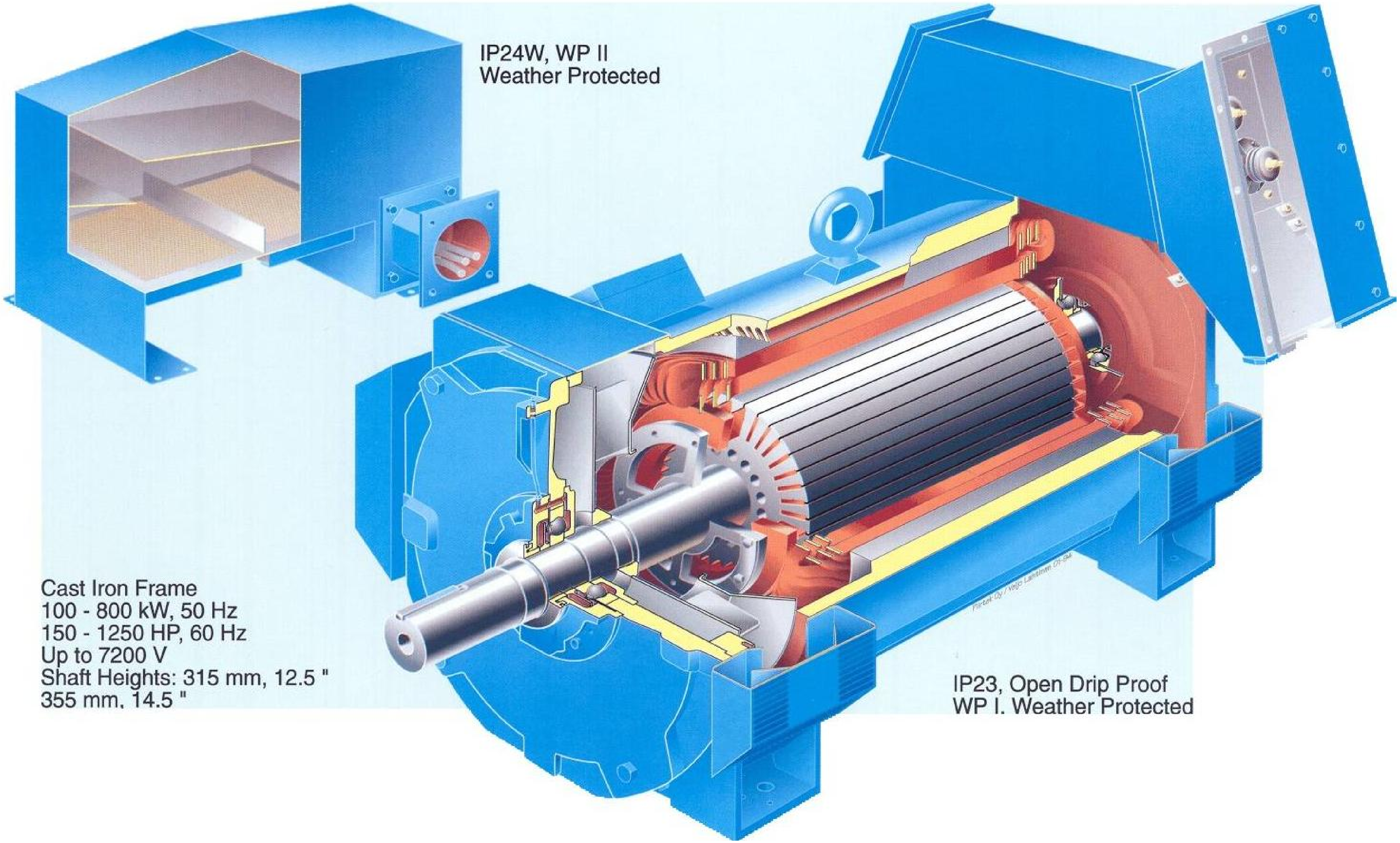
Contents of this lecture

- Structure and construction of Induction Machines
- Rotating magnetic field
- Operation modes of Induction Machines
- Equivalent Circuit of Induction Machines
- Performance characteristics of Induction Machines
- Basics of speed control of Induction Machines

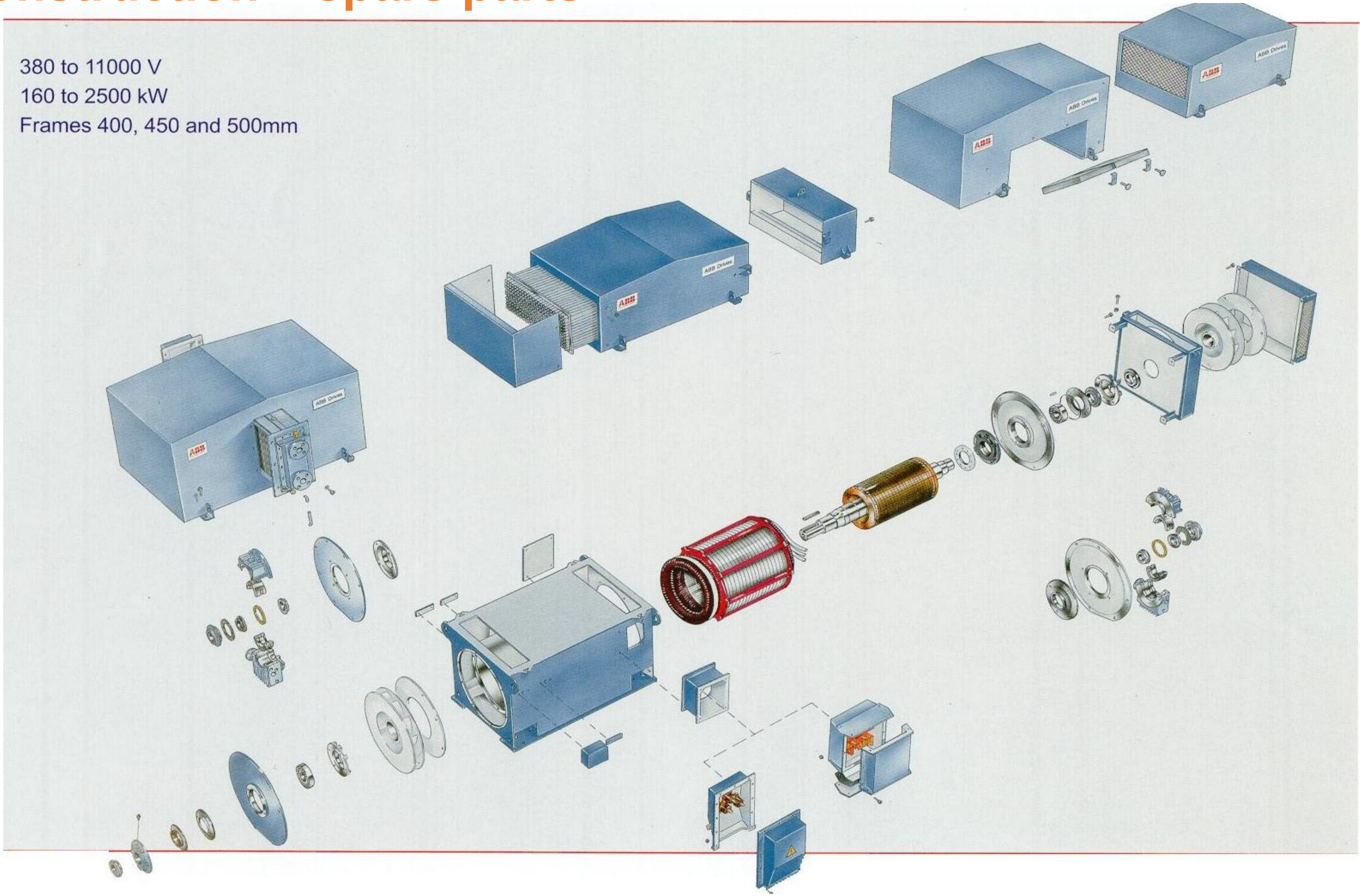
Construction – small machine



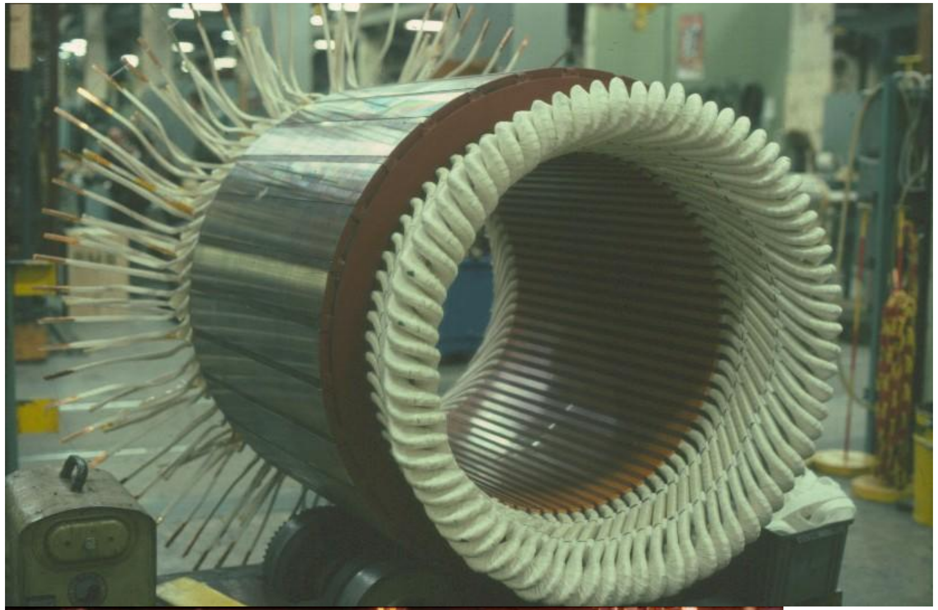
Construction – large machine

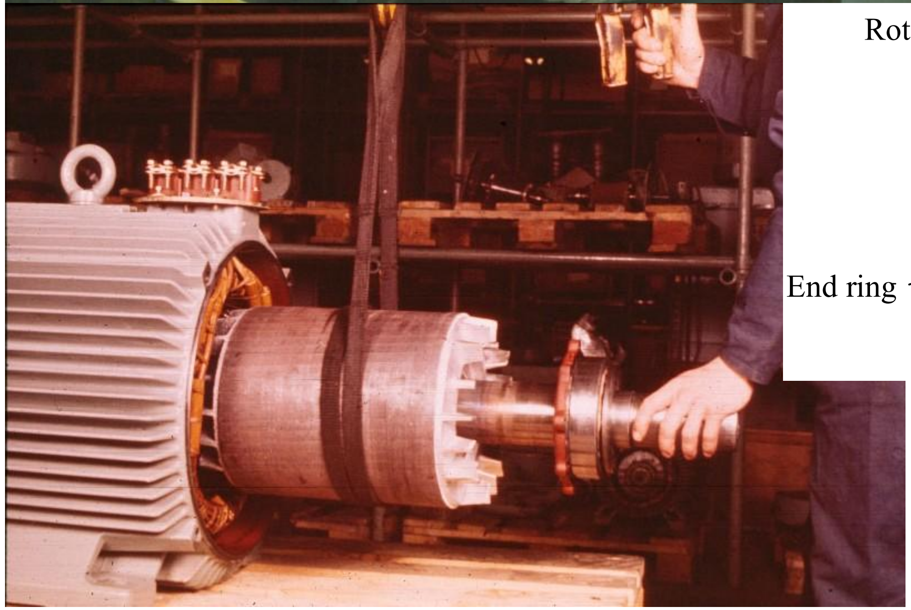


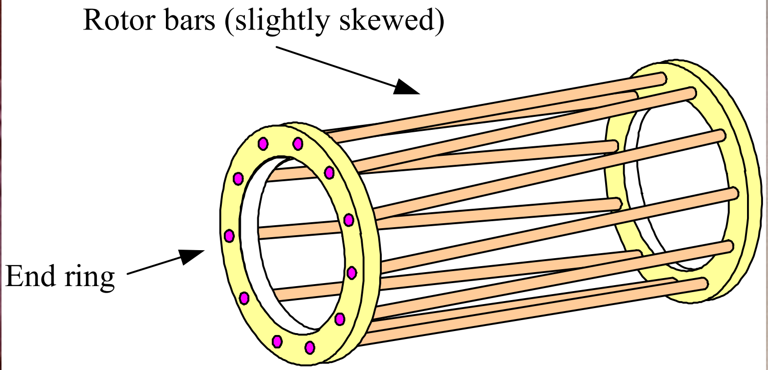
Construction – spars parts

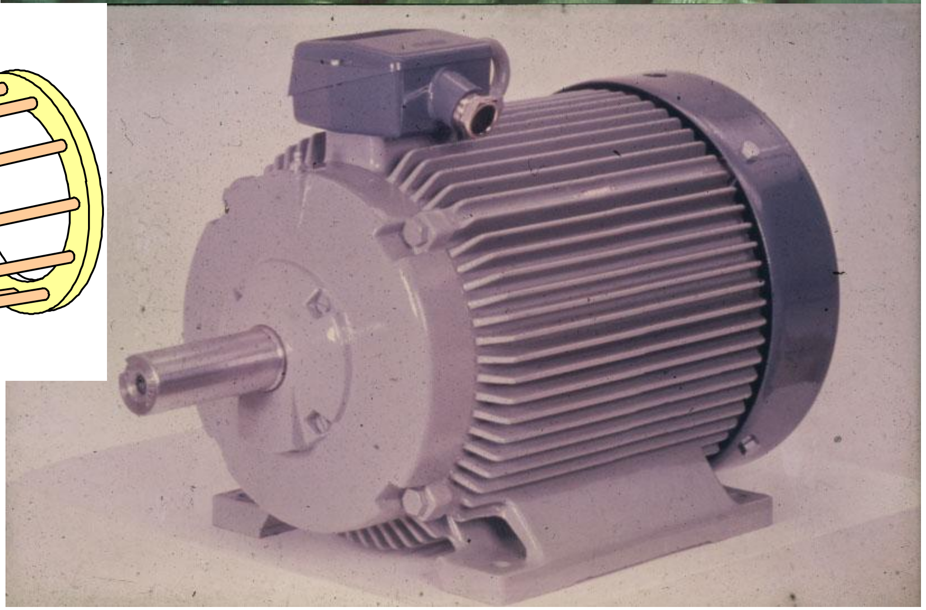


Active parts and mounting

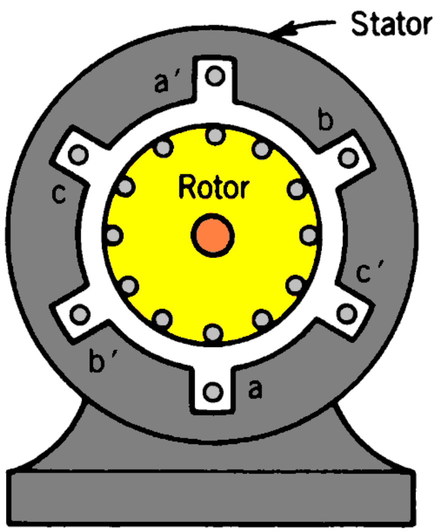


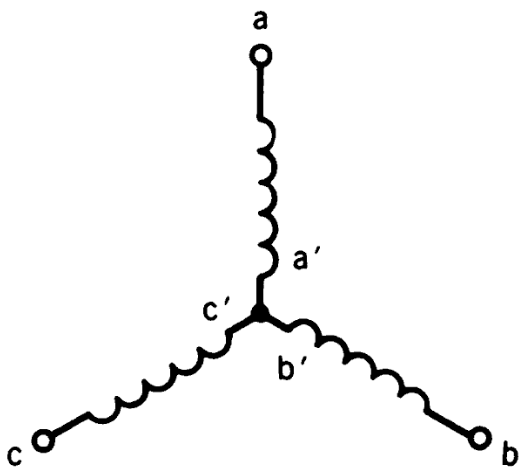


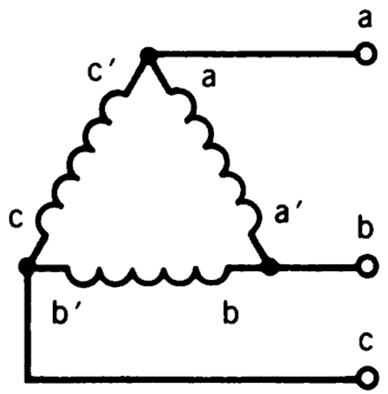




Basic operation principle





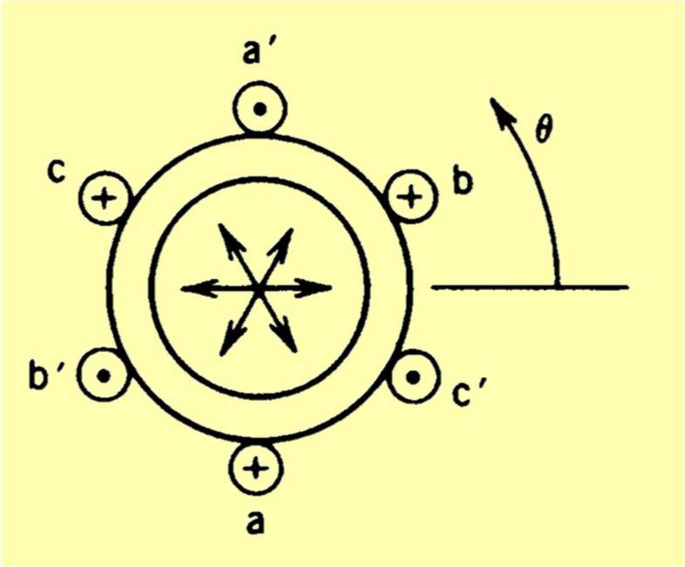


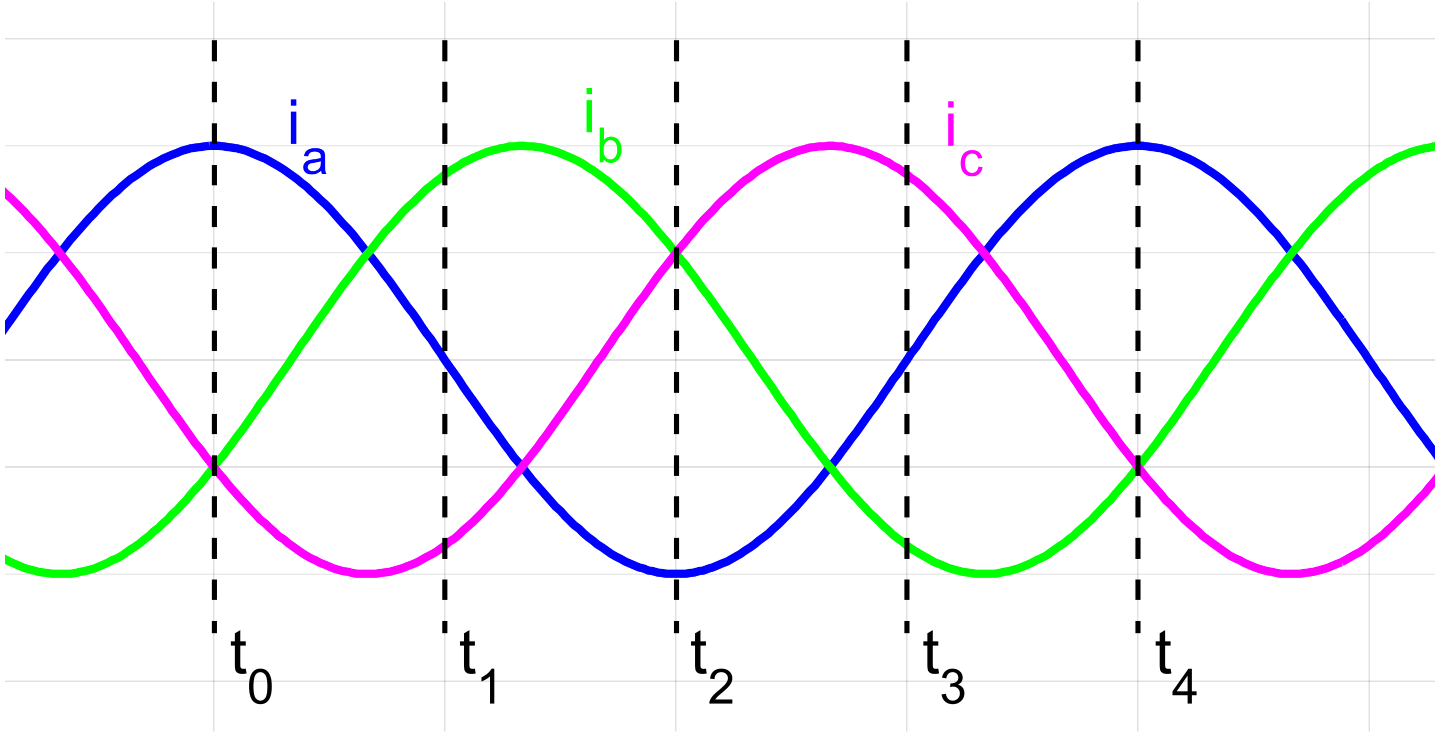
- Three-phase windings displaced from each other by 120 degrees in space
- Phase coils produces sinusoidal distributed mmf wave centered on coil axis
- Alternating currents in each coil produce pulsating mmf waves
- Mmf waves are displaced by 120 degrees in space from each other
- Resultant mmf wave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

Rotating magnetic field - currents

Balanced three-phase currents

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





Rotating magnetic field – phase MMFs

at time t_0

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

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

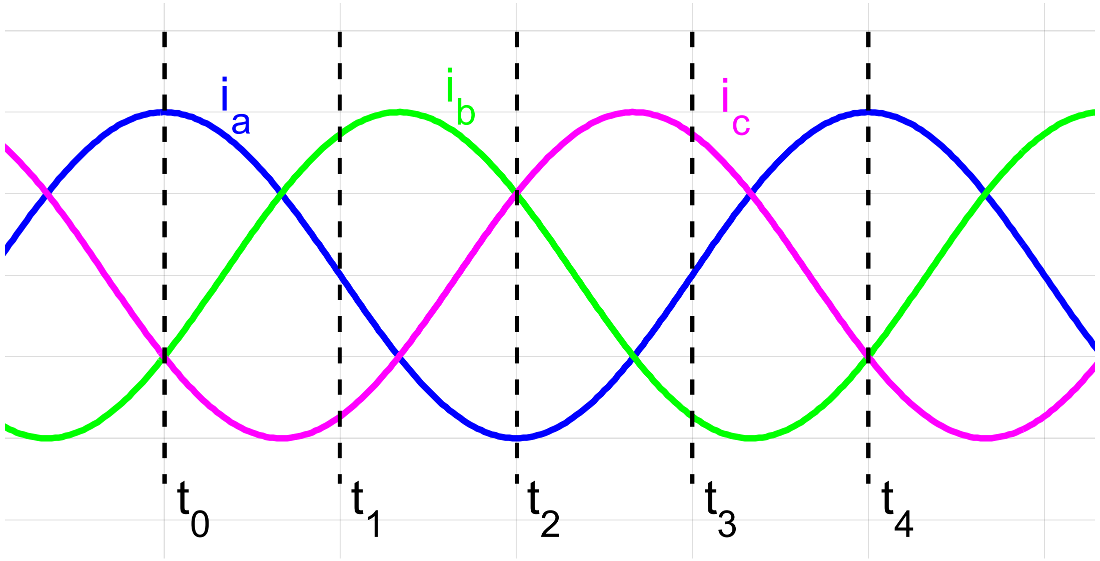
$$i_c = -\frac{I_m}{2} \qquad F_c = -\frac{1}{2}F_{max}$$

at time t_1

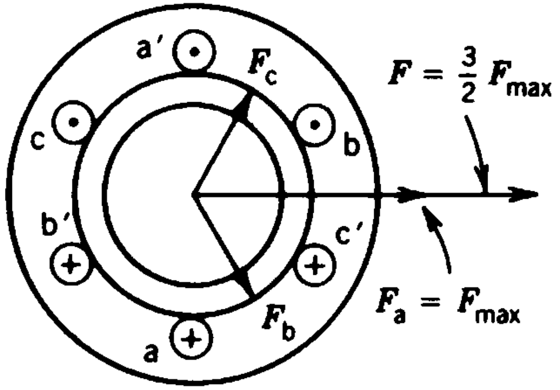
$$i_a = 0 \qquad F_a = 0$$

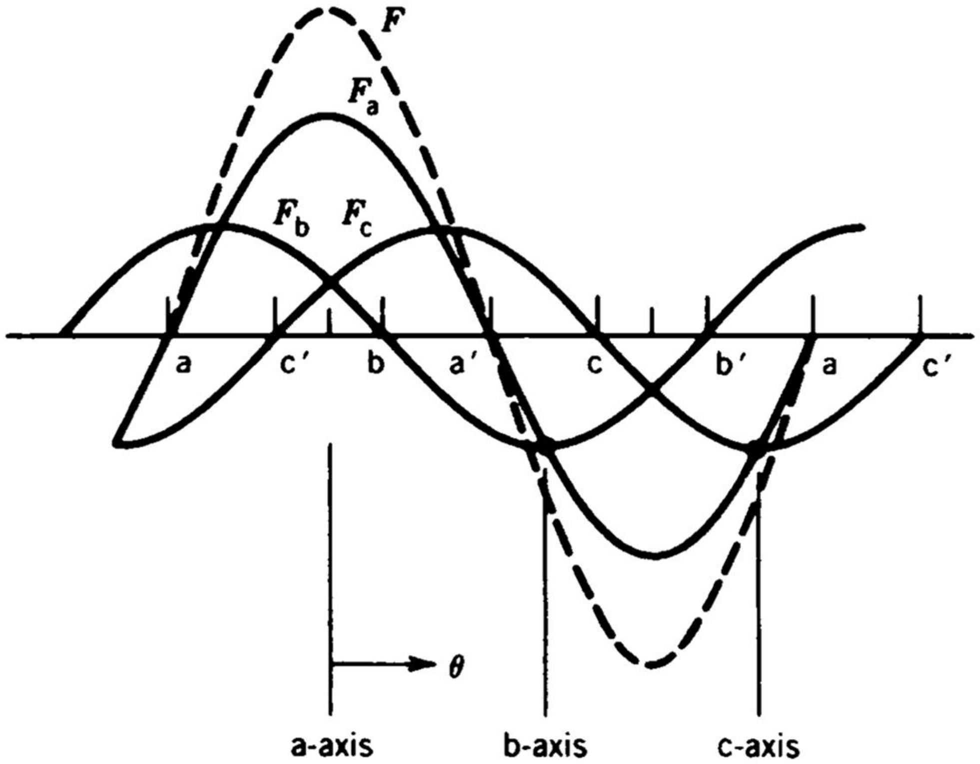
$$i_b = \frac{\sqrt{3}}{2}I_m \qquad F_b = \frac{\sqrt{3}}{2}F_{max}$$

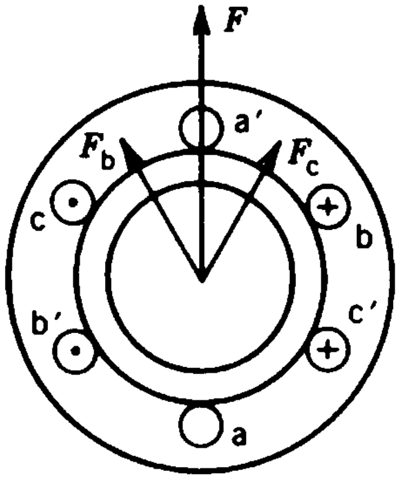
$$i_c = -\frac{\sqrt{3}}{2}I_m \qquad F_c = -\frac{\sqrt{3}}{2}F_{max}$$

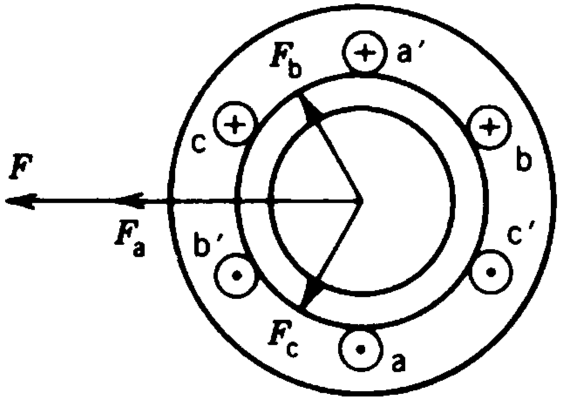


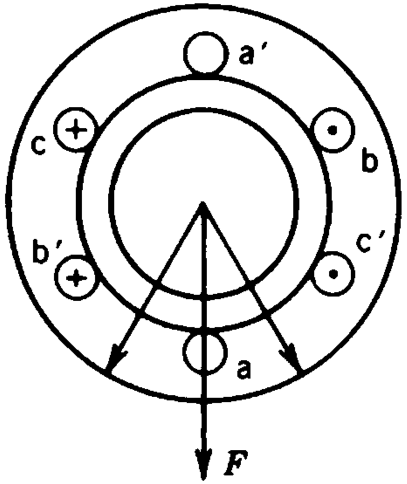
Resulting MMF– graphical method











Resulting MMF – analytical method

$$F_{\mathrm{a}}(\theta) = Ni_{\mathrm{a}}\cos\theta$$

$$F_{\mathrm{b}}(\theta) = Ni_{\mathrm{b}}\cos(\theta - 120°)$$

$$F_{\mathrm{c}}(\theta) = Ni_{\mathrm{c}}\cos(\theta + 120°)$$

$$i_{\mathrm{a}} = I_{\mathrm{m}}\cos\omega t$$

$$i_{\mathrm{b}} = I_{\mathrm{m}}\cos(\omega t - 120°)$$

$$i_{\mathrm{c}} = I_{\mathrm{m}}\cos(\omega t + 120°)$$

Resultant mmf wave

$$F(\theta) = Ni_{\mathrm{a}}\cos\theta + Ni_{\mathrm{b}}\cos(\theta - 120°) + Ni_{\mathrm{c}}\cos(\theta + 120°)$$

$$\cos A\cos B = \frac{1}{2}\cos(A - B) + \frac{1}{2}\cos(A + B)$$

$$F(\theta, t) = \frac{3}{2}NI_{\mathrm{m}}\cos(\omega t - \theta)$$

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

$$n = \frac{2}{p} f 60 = \frac{120 f}{\mathrm{p}}$$

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

Induced voltages

- Sinusoidal flux density distribution in space

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

- Flux per pole

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

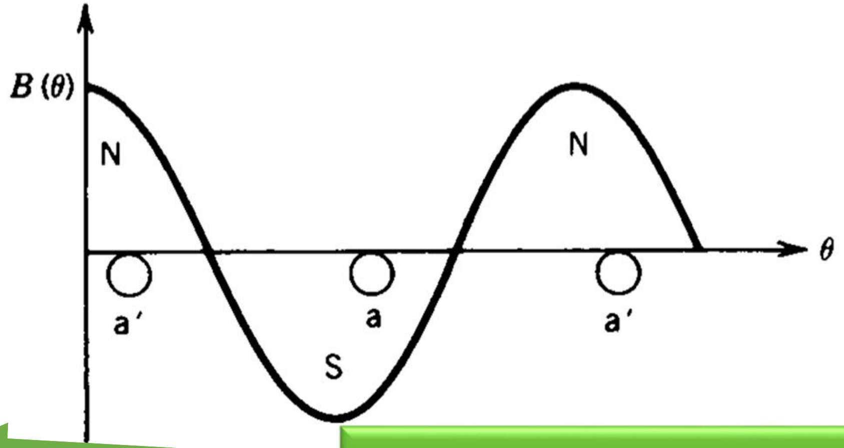
Derive this equation at home

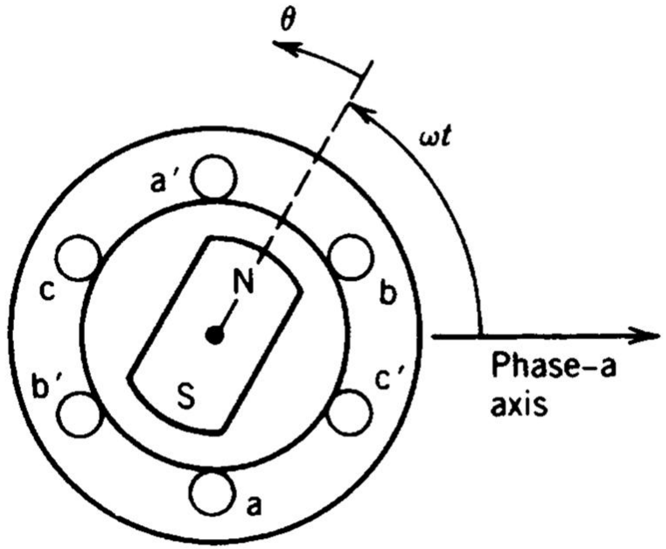
- Flux linkage

$$\lambda_a(\omega t) = N\Phi_p \cos\omega t$$

- Induced voltage

$$e_a = -\frac{d\lambda_a}{dt} = E_{\max} \sin\omega t$$





Induced voltages

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

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

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

$$E_{\max} = \omega N \Phi_{\mathrm{p}}$$

$$E_{\mathrm{rms}} = \frac{E_{\max}}{\sqrt{2}} = \frac{2\pi}{\sqrt{2}} f N \Phi_{\mathrm{p}}$$

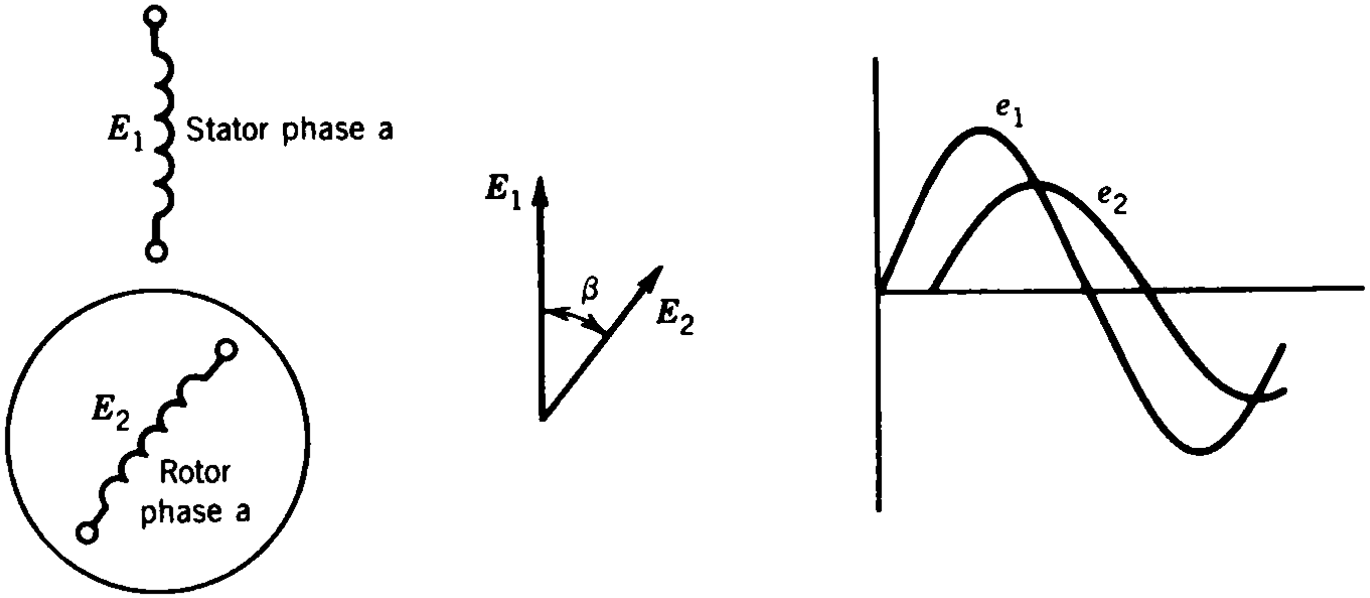
- Distributed winding with winding factor K_{w}

$$E_{\mathrm{rms}} = \frac{2\pi}{\sqrt{2}} f N_{\mathrm{ph}} \Phi_{\mathrm{p}} K_{w}$$

$$K_{w} \approx 0.85 \ldots 0.95$$

Standstill operation – phase shifter

- stationary wound rotor induction machine can be used as a phase shifter
  - Rotor open-circuited
  - Rotating field in the air gap – speed ns
  - Field induces voltages in stator and rotor windings – same frequency



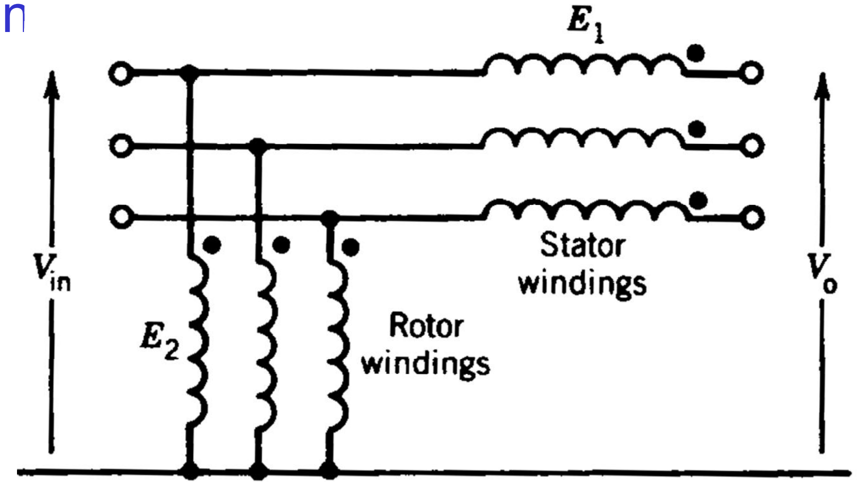
$$E_1 = \frac{2\pi}{\sqrt{2}} f_1 N_1 \Phi_p K_{W1}$$

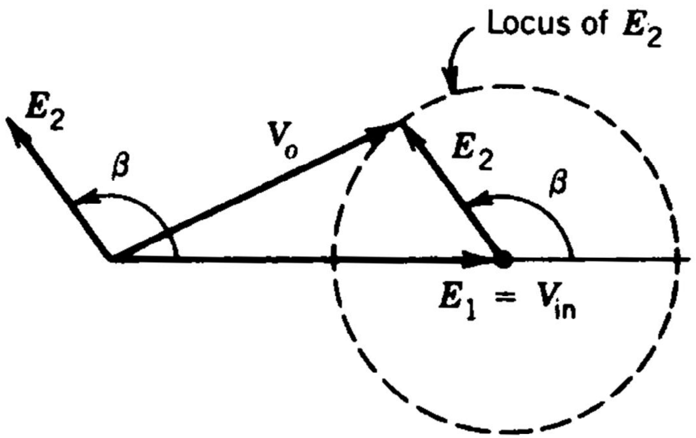
$$E_2 = \frac{2\pi}{\sqrt{2}} f_1 N_2 \Phi_p K_{W2}$$

$$\frac{E_1}{E_2} = \frac{N_1}{N_2}\frac{K_{W1}}{K_{W2}} \approx \frac{N_1}{N_2}$$

Standstill operation - induction regulator

- Can be used as a variable polyphase voltage source too
  - Continuous variation of voltage
  - No sliding connection





+ Continuous variation of the output voltage
+ No sliding electric connections
- High leakage inductances
- High magnetizing current
- High cost

$$E_1 = V_{in}$$

$$V_0 = E_1 + E_2$$

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 according to torque balance

Principal characteristics

- Slip $$s = \frac{n_s - n}{n_s}$$

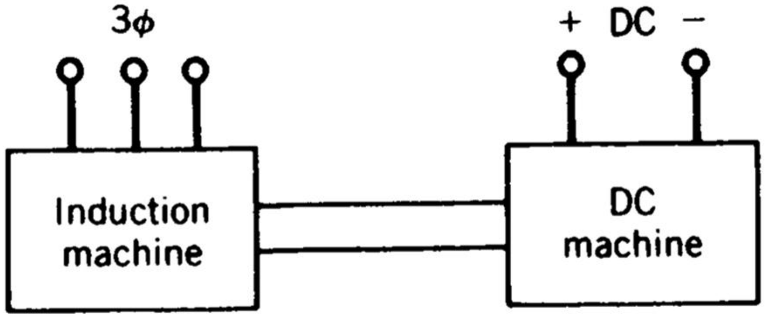
- Frequency of induced rotor currents $$f_2 = \frac{p}{120}(n_s - n) = sf_1$$

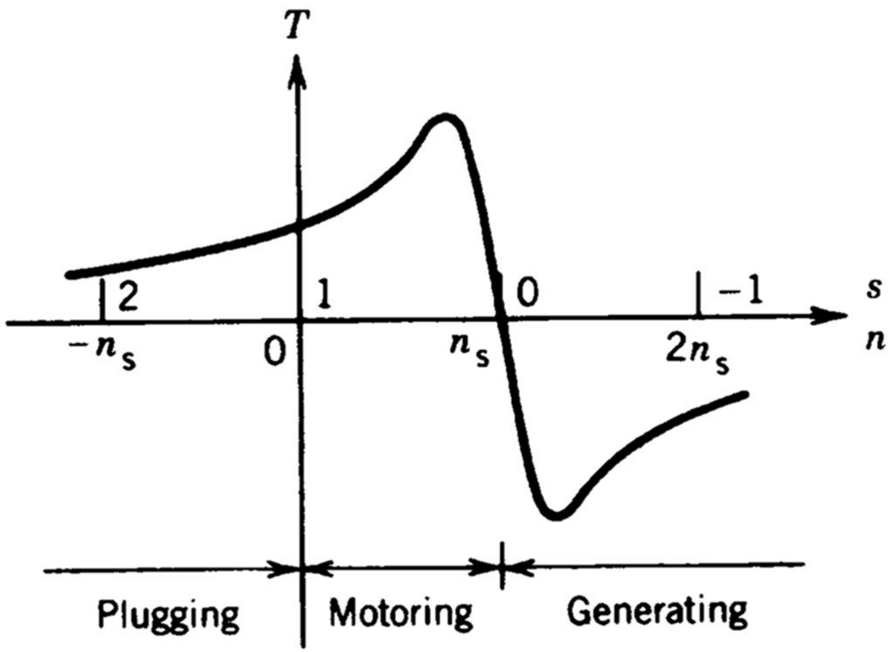
- Induced rotor voltage $$E_{2s} = \frac{2\pi}{\sqrt{2}} f_2 N_2 \Phi_p K_{W2} = sE_2$$

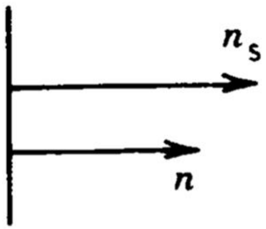
- Speed of induced rotor field with respect to the rotor is $$n_2 = \frac{120 f_2}{p} = sn_s$$

- Speed of induced rotor field with respect to the stator is $$n + n_2 = n_s$$

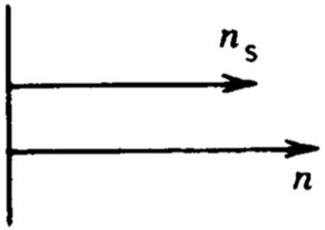
Running operation - modes



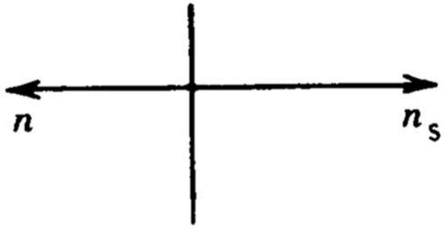




(*b*) Motoring
$0 \leqslant n \leqslant n_s$
$1 \geqslant s \geqslant 0$



(*c*) Generating
$n > n_s$
$s < 0$

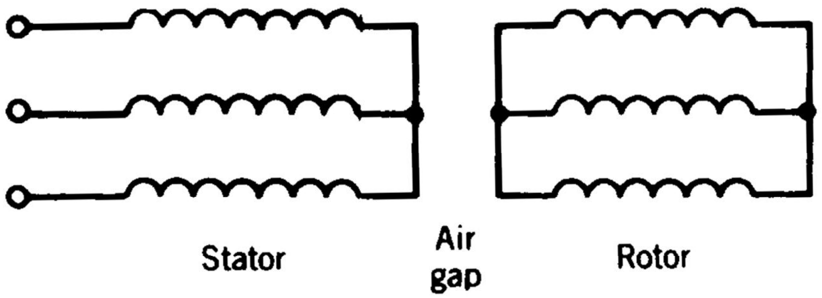


(*d*) Plugging
$n < 0$
$s > 1$

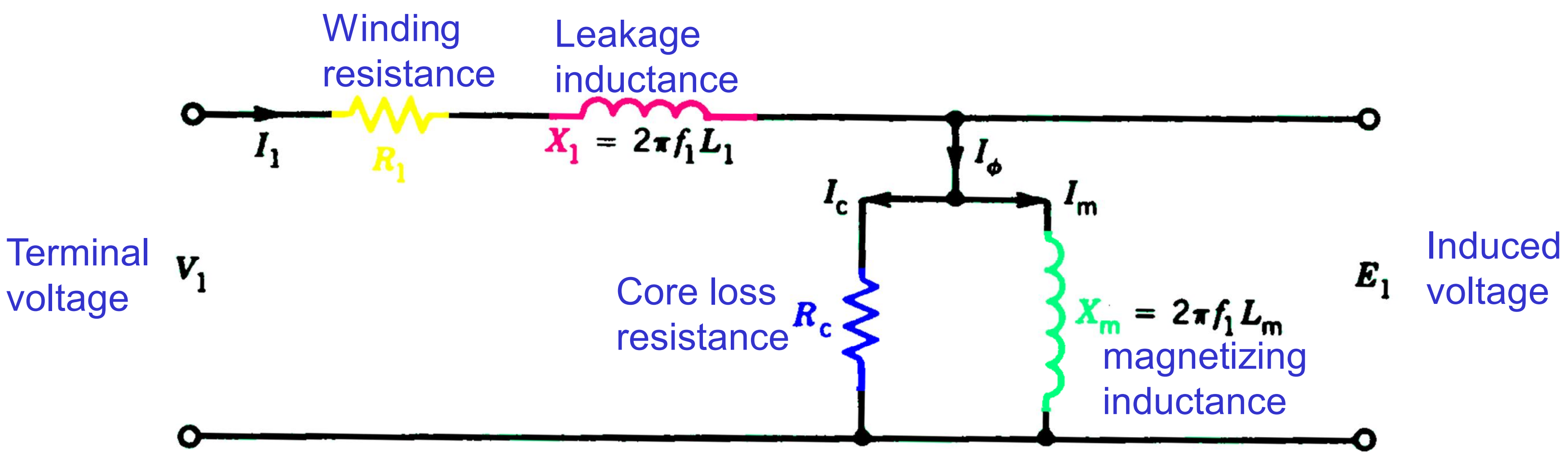
Equivalent circuit model

Assume three-phase wound-rotor induction machine

- Cage winding can be represented by an equivalent three-phase winding
- At steady-state the magnetic fields rotate at synchronous speed
- Resultant air gap field induce voltages in stator and rotor windings
  - Supply frequency f_1 in stator
  - slip frequency f_2 in rotor
- Equivalent circuit appears to be identical to that of a transformer



Stator side per-phase quantities



- Equivalent circuit similar to transformer primary

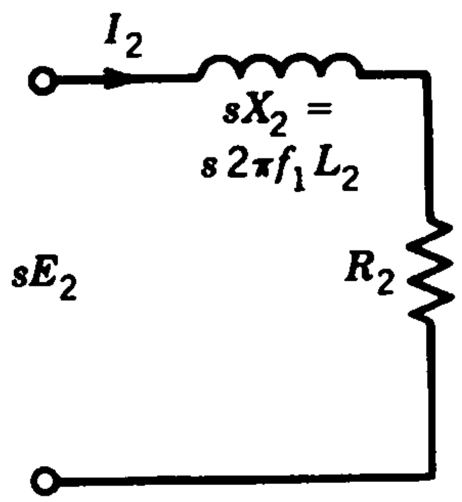
- Magnetizing current 20 – 50 % of stator current (1 – 5 % in transformer)

- X_1 larger than in transformer due to air gap and distributed windings

Rotor winding per-phase quantities

- E_2 induced voltage at standstill (f_1)
- R_2 winding resistance
- L_2 leakage inductance
- f_2 $= sf_1$

$$I_2 = \frac{sE_2}{R_2 + jsX_2} \qquad P_2 = I_2^2 R_2$$



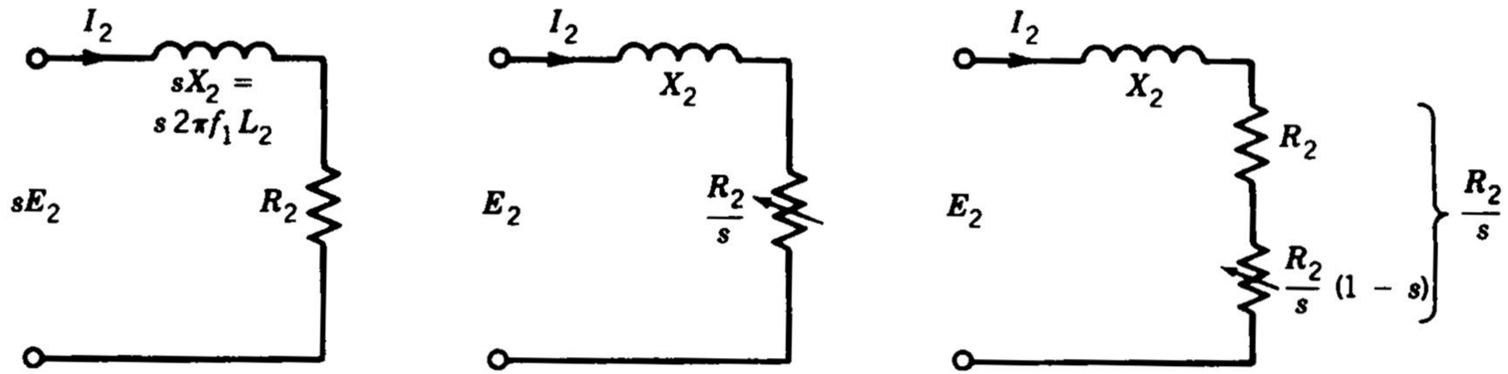
- rotor current can be expressed as

$$I_2 = \frac{E_2}{(R_2 / s) + jX_2}$$

Matching the rotor an stator

$$I_2 = \frac{sE_2}{R_2 + jsX_2} \quad \Rightarrow \quad I_2 = \frac{E_2}{(R_2/s) + jX_2}$$

- Although the amplitude and phase are the same **the frequency is different !**



- Power associated with the equivalent circuit (air-gap power)

$$P = I_2^2 \frac{R_2}{s} = \frac{P_2}{s}$$

Complete equivalent circuit

- Same frequency in stator and in rotor
- Turns ratio has to be taken into account
- The stator referred quantities

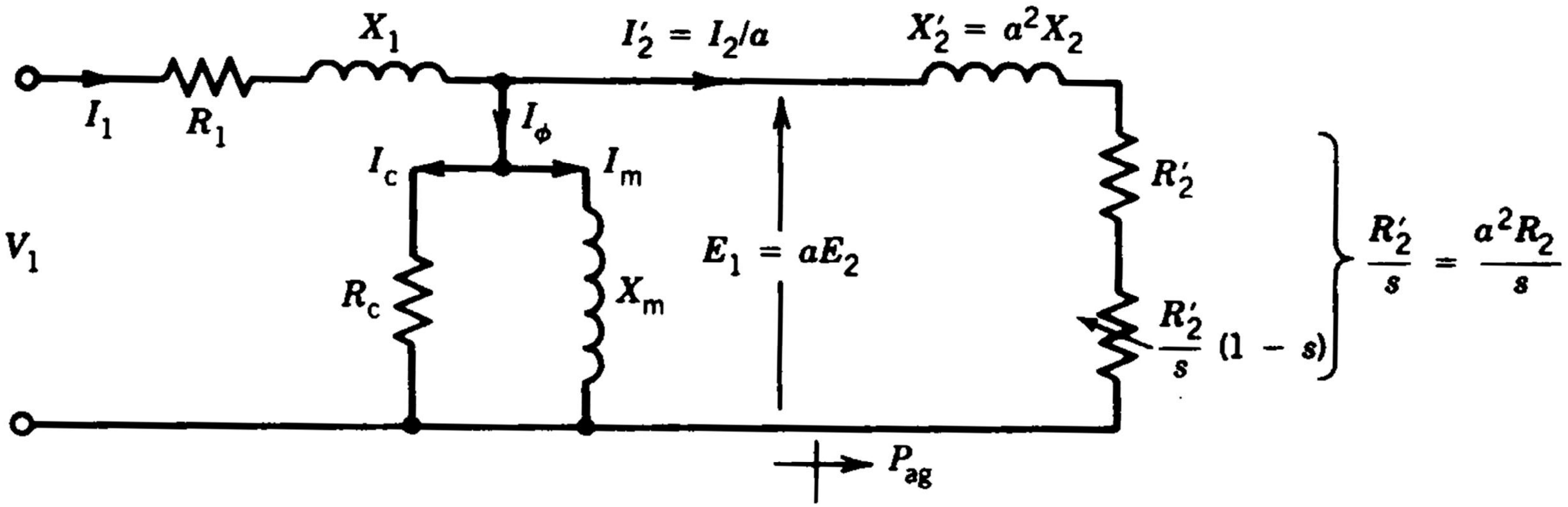
$$a = \frac{N_1}{N_2}$$

$$E_2' = E_1 = aE_2$$

$$I_2' = \frac{I_2}{a}$$

$$R_2' = a^2 R_2$$

$$X_2' = a^2 X_2$$



Equivalent circuit model - consequences

- Air gap power crosses the air gap
  - Includes rotor copper loss P_2 and mechanical power P_{mech}
  - A fraction s is dissipated in rotor resistance P_2
  - The fraction (1-s) is converted into mechanical power

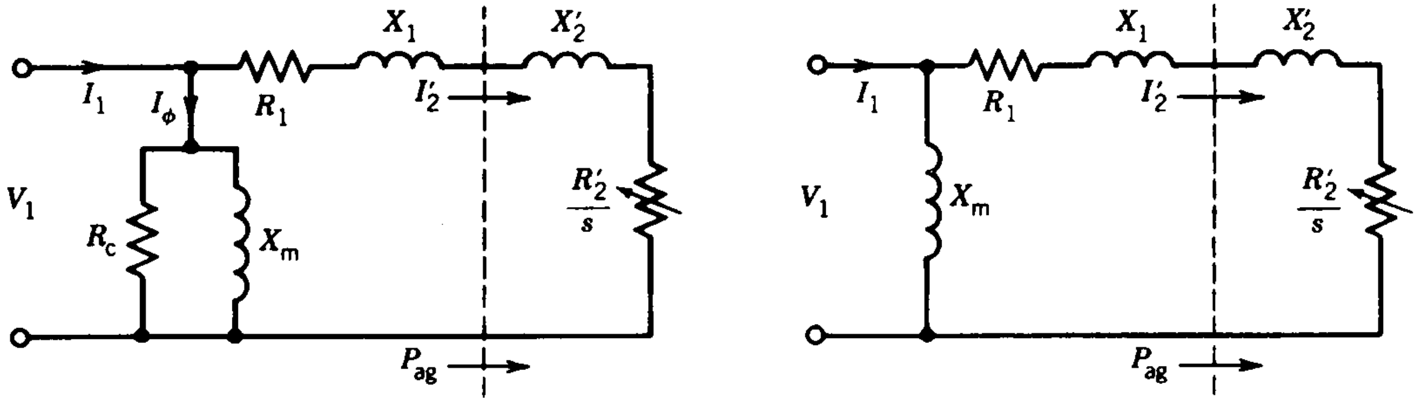
$$P = P_{ag} = I_2^2 \frac{R_2}{s} = I_2^2 \left[R_2 + \frac{R_2}{s}(1-s) \right] = P_2 + P_{mech}$$

$$P_2 = I_2^2 R_2 = sP_{ag} \qquad P_{mech} = I_2^2 \frac{R_2}{s}(1-s) = (1-s)P_{ag}$$

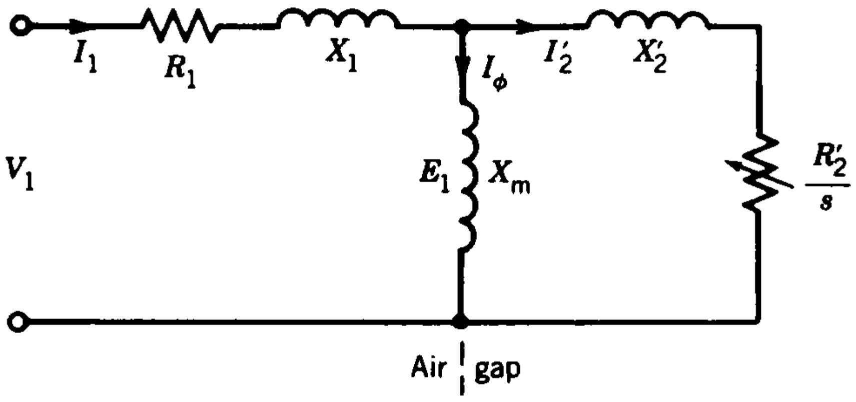
$$P_{ag} : P_2 : P_{mech} = 1 : s : 1-s$$

Different equivalent circuits

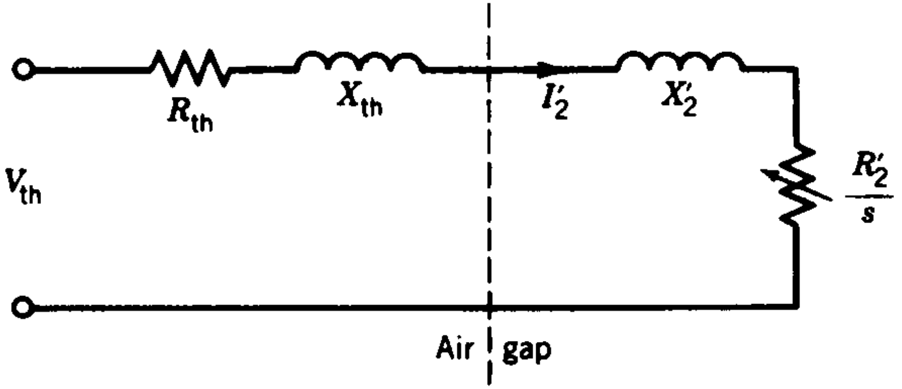
- approximate equivalent circuit



- IEEE-recommended equivalent circuit



Thevenin equivalent circuit



due to small R_1

$$V_{th} = \frac{X_m}{\left[R_1^2 + (X_1 + X_m)^2\right]^{1/2}} V_1 \approx \frac{X_m}{X_1 + X_m} V_1 = K_{th} V_1$$

$$Z_{th} = \frac{jX_m (R_1 + jX_1)}{R_1 + j(X_1 + X_m)} = R_{th} + jX_{th}$$

$$R_{th} \approx \left(\frac{X_m}{X_1 + X_m}\right)^2 R_1 = K_{th}^2 R_1$$

due to large X_m

$$X_{th} \approx X_1$$

Equivalent circuit parameters

- No-load test at nominal voltage and frequency
- Blocked rotor test at nominal current, reduced voltage and frequency
- DC-resistance measurement

- No-load power ⇨ core losses + windage and friction losses
- Blocked rotor ⇨ reactances

- Equivalent circuit used to predict performances characteristics:
  - Efficiency, power factor, current, starting torque, maximum (pull-out) torque, etc…

Torque

- Torque per phase T_{mech}

$$P_{mech} = T_{mech}\omega_{mech} = I_2^2 \frac{R_2}{s}(1-s)$$

$$\omega_{mech} = (1-s)\omega_{syn} \quad \Rightarrow \quad T_{mech}\omega_{syn} = I_2^2 \frac{R_2}{s} = P_{ag}$$

$$T_{mech} = \frac{1}{\omega_{syn}} P_{ag} = \frac{1}{\omega_{syn}} I_2^2 \frac{R_2}{s} = \frac{1}{\omega_{syn}} I_2'^2 \frac{R_2'}{s}$$

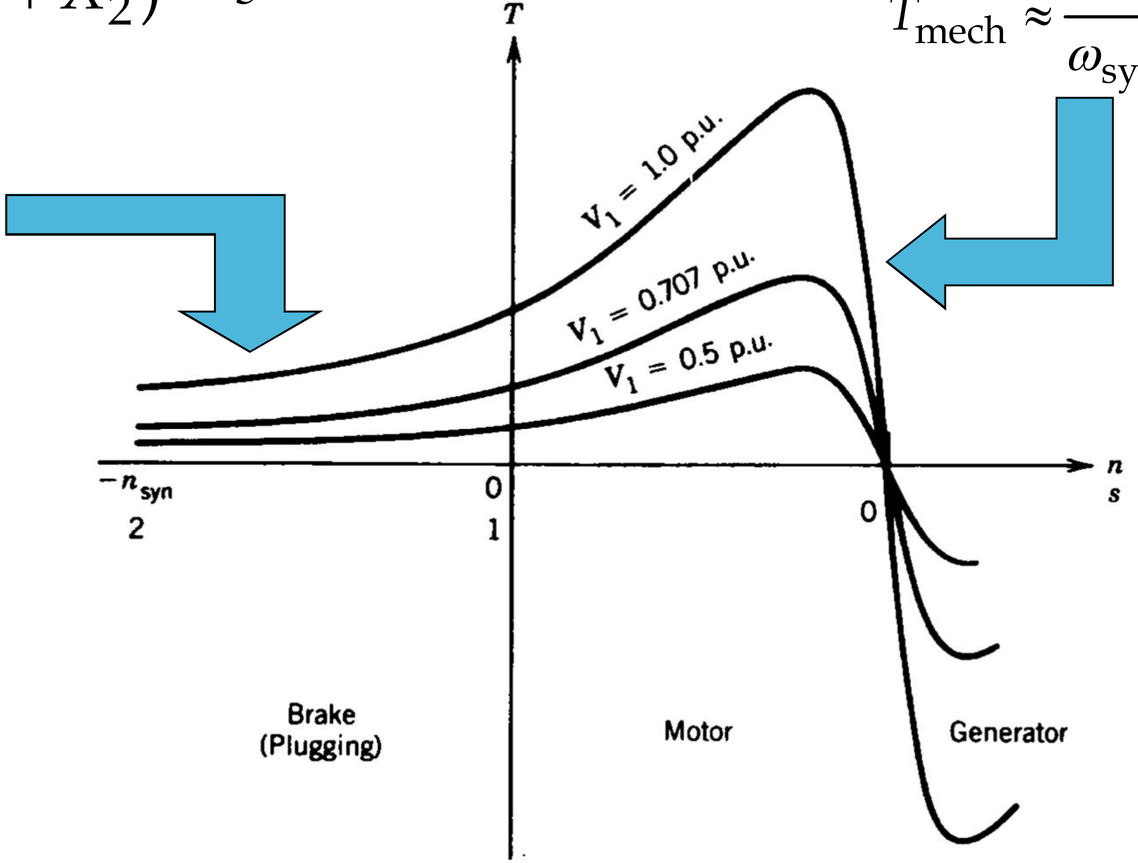
- 5 % difference in torque prediction depending on the kind of equivalent circuit

Torque profile

$$T_{mech} = \frac{1}{\omega_{syn}} \frac{V_{th}^2}{(R_{th} + R_2'/s)^2 + (X_{th} + X_2')^2} \frac{R_2'}{s}$$

$$T_{mech} \approx \frac{1}{\omega_{syn}} \frac{V_{th}^2}{(X_{th} + X_2')^2} \frac{R_2'}{s}$$

$$T_{mech} \approx \frac{1}{\omega_{syn}} \frac{V_{th}^2}{R_2'} s$$



- Total torque obtained by multiplying per phase torque by number of phases

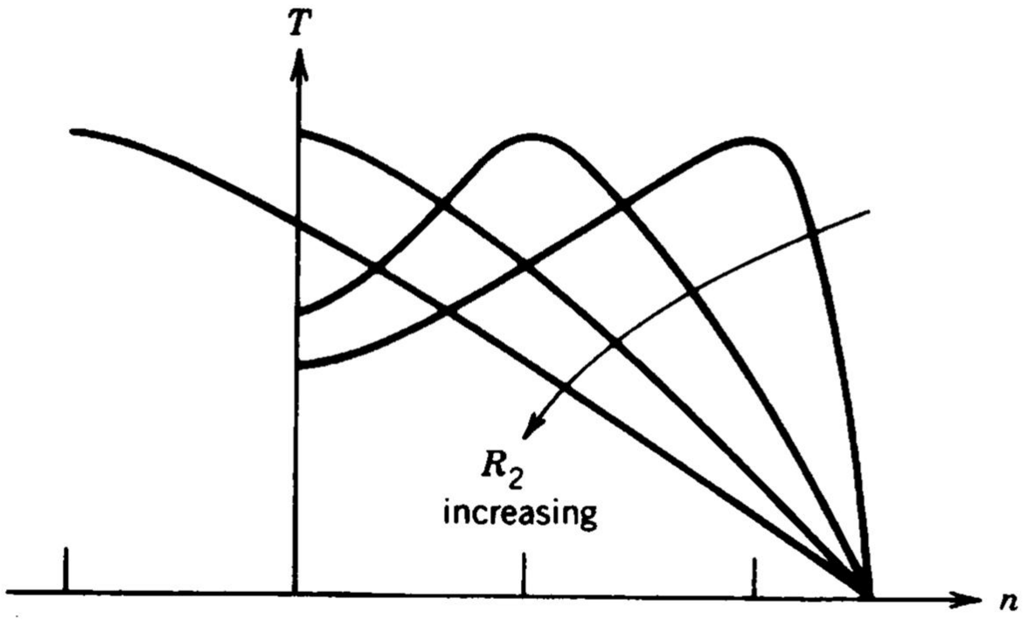
Maximum torque

- Maximum torque corresponds to: $$\frac{dT}{ds} = 0$$

$$T_{\max} \approx \frac{1}{2\omega_{\text{syn}}} \frac{V_{\text{th}}^2}{X_{\text{th}} + X_2'}$$

$$s_{T_{\max}} = \frac{R_2'}{\left[R_{\text{th}}^2 + (X_{\text{th}} + X_2')^2\right]^{1/2}}$$

$$\approx \frac{R_2'}{X_{\text{th}} + X_2'}$$



- Maximum torque independent from rotor resistance
- Corresponding speed depends on rotor resistance

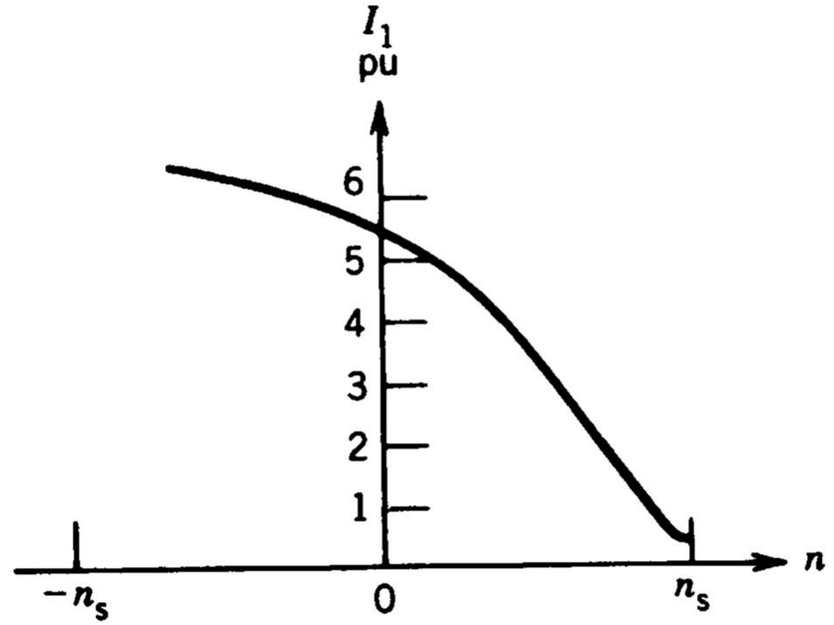
Current and power factor

- Typical starting current 5 – 8 times the rated current

$$Z_1 = R_1 + jX_1 + X_m // \left(\frac{R'_2}{s} + jX'_2 \right)$$

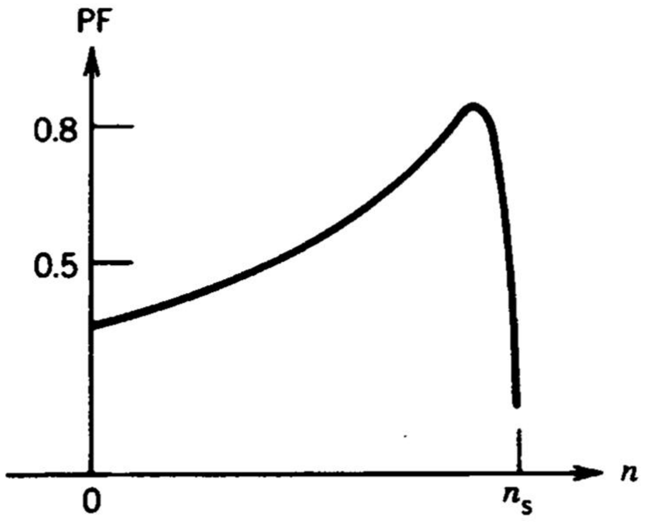
$$= |Z_1| \underline{|\theta_1}$$

$$I_1 = \frac{V_1}{Z_1} = I_\phi + I'_2$$



- Power factor

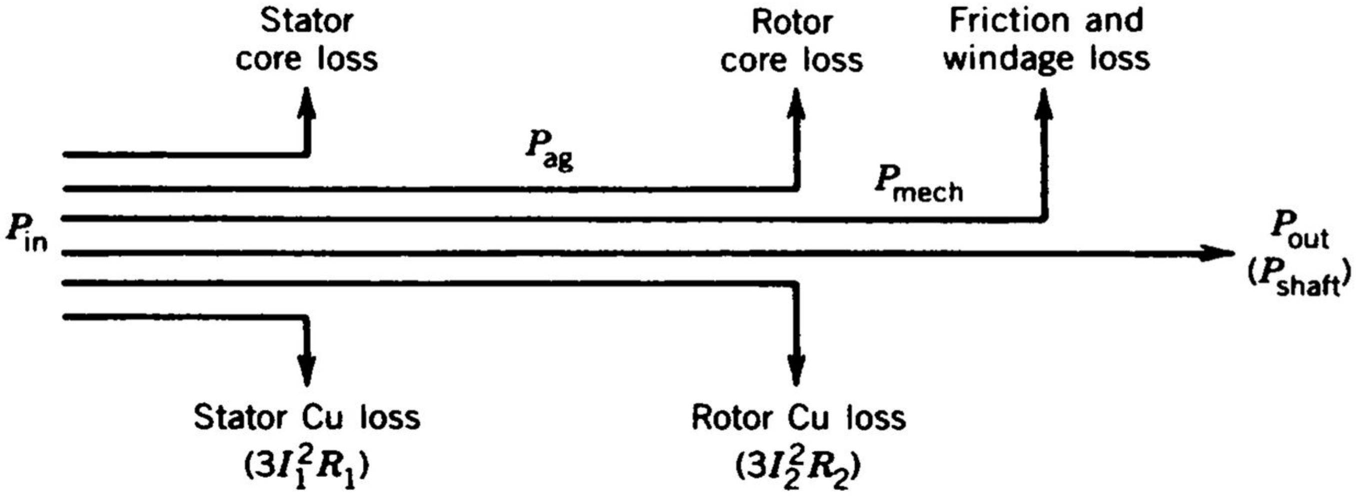
$$\text{PF} = \cos\theta_1$$



Efficiency

$$P_{in} = 3V_1 I_1 \cos\theta_1$$

$$\text{Eff} = \frac{P_{out}}{P_{in}}$$



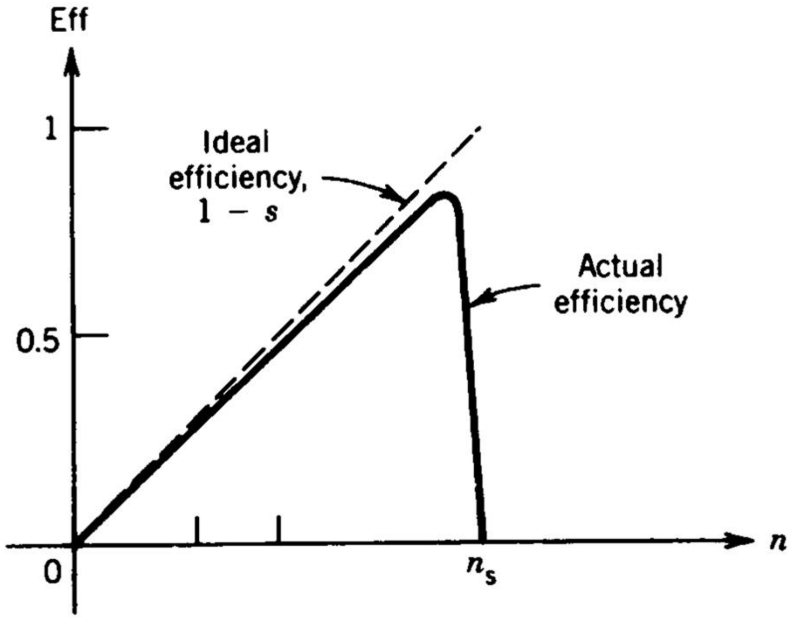
- Ideal efficiency = only rotor resistive losses

$$P_{in} = P_{ag}$$

$$P_2 = sP_{ag}$$

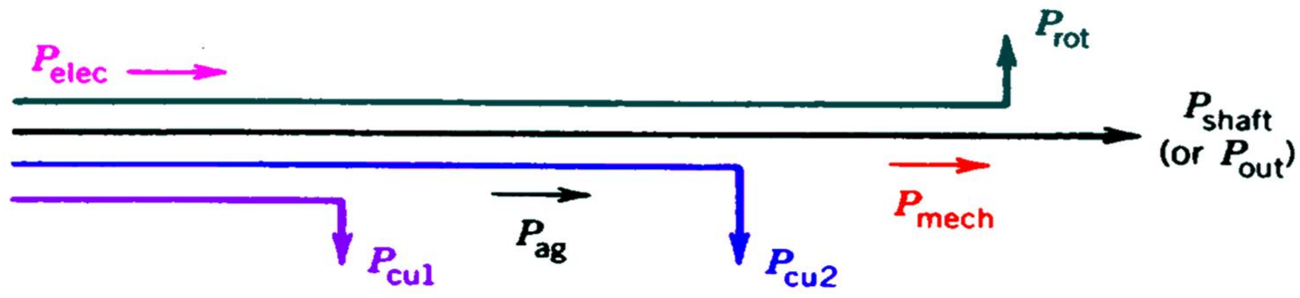
$$P_{out} = P_{mech} = P_{ag}(1-s)$$

$$\text{Eff}_{(ideal)} = \frac{P_{out}}{P_{in}} = 1-s$$



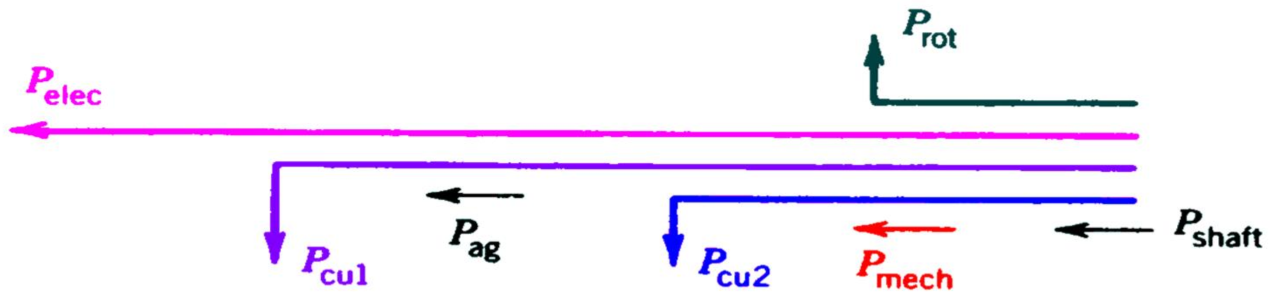
Power flow

- Motoring



(a)

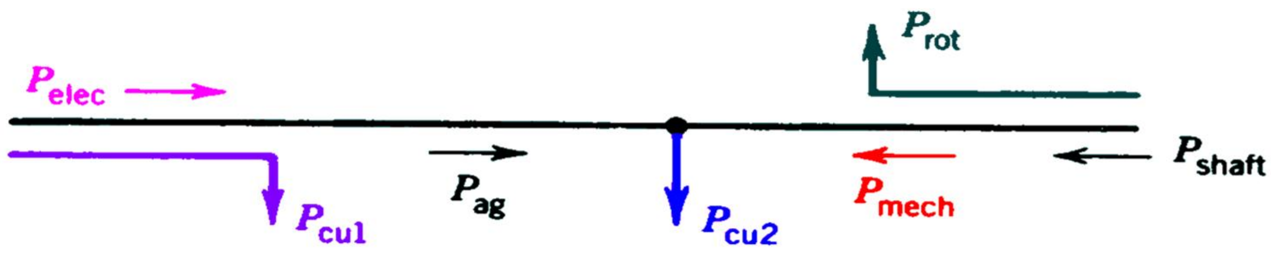
- Generating



(b)

- Plugging mode

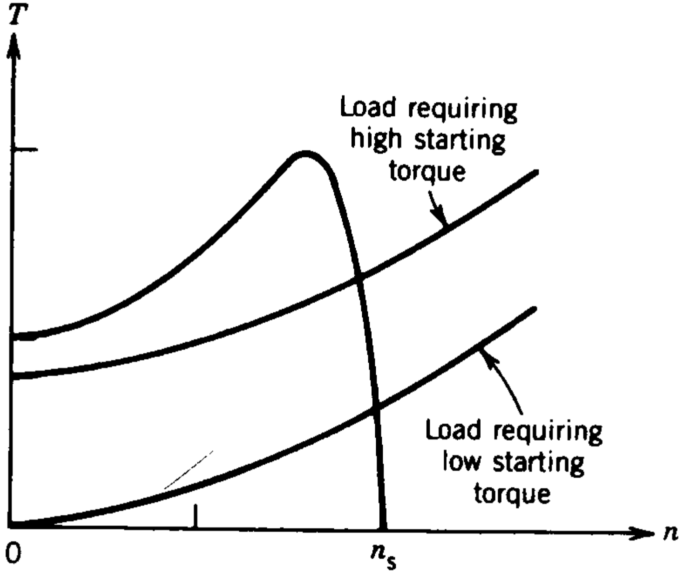
rotor losses !

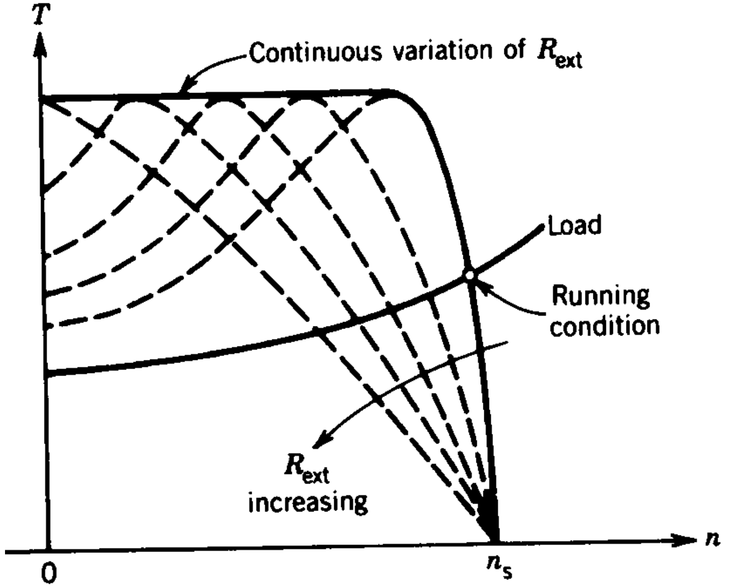


Effects of rotor resistance

- Small rotor resistance
  - + High efficiency
  - + Small nominal slip
  - - Small starting torque
  - - Large starting current

- Large rotor resistance
  - - Poor efficiency
  - - Large nominal slip
  - + Large starting torque
  - + Small starting current

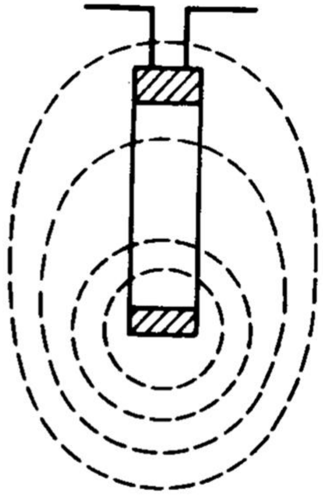




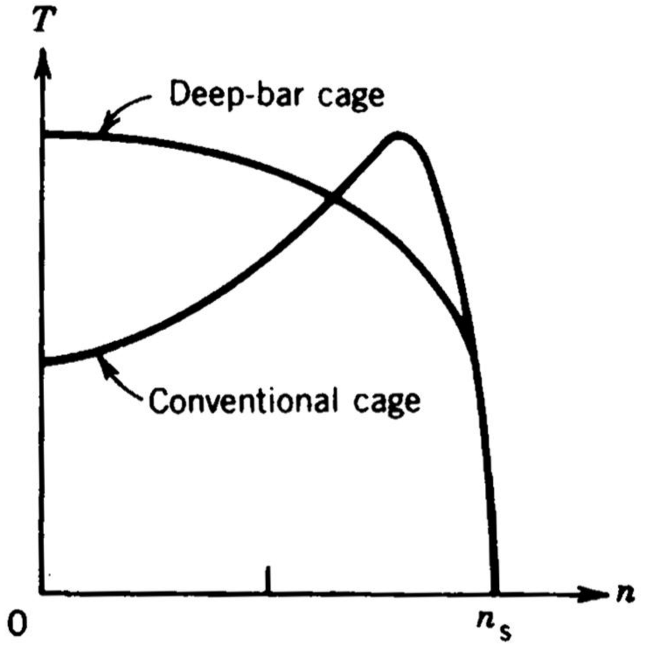
- In wound-rotor external resistance connected to rotor through the slip rings

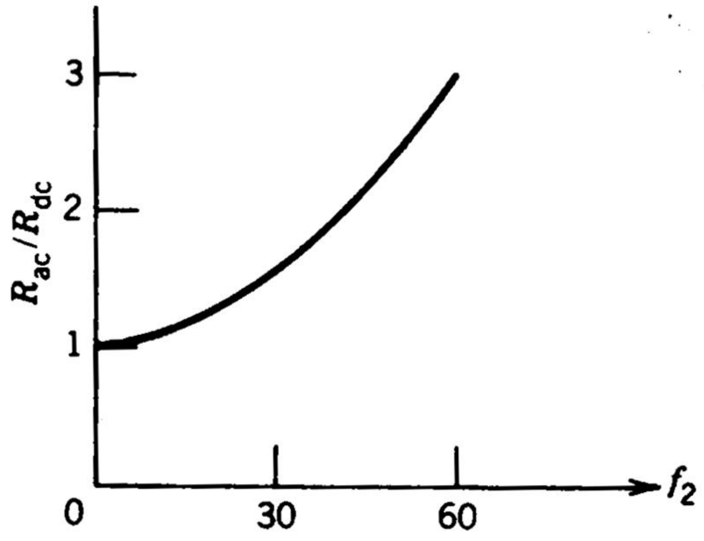
Deep-bar squirrel-cage

- Rotor frequency changes with speed



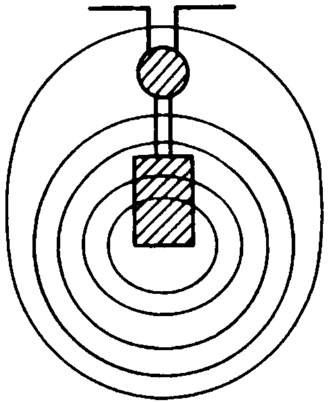
- Effective rotor resistance changes with frequency if adequate shape of rotor bars (skin effect)

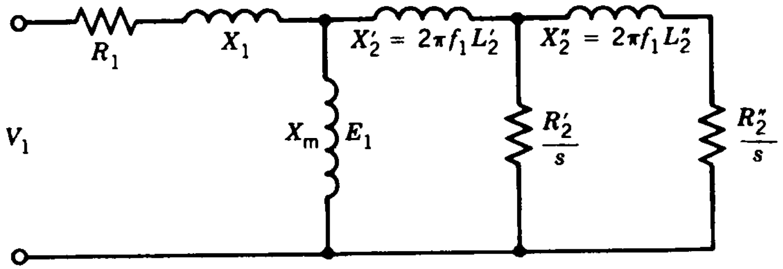




Double-cage rotor

- Two rotor cages each with its own end ring
- Outer cage with small cross section and high resistivity material
- Inner cage with larger cross section and low resistivity material
- At standstill rotor current flows in outer cage ⇨ large resistance
- At small slip current flows in both cages ⇨ smaller resistance
- Equivalent circuit formed by additional branches in the rotor

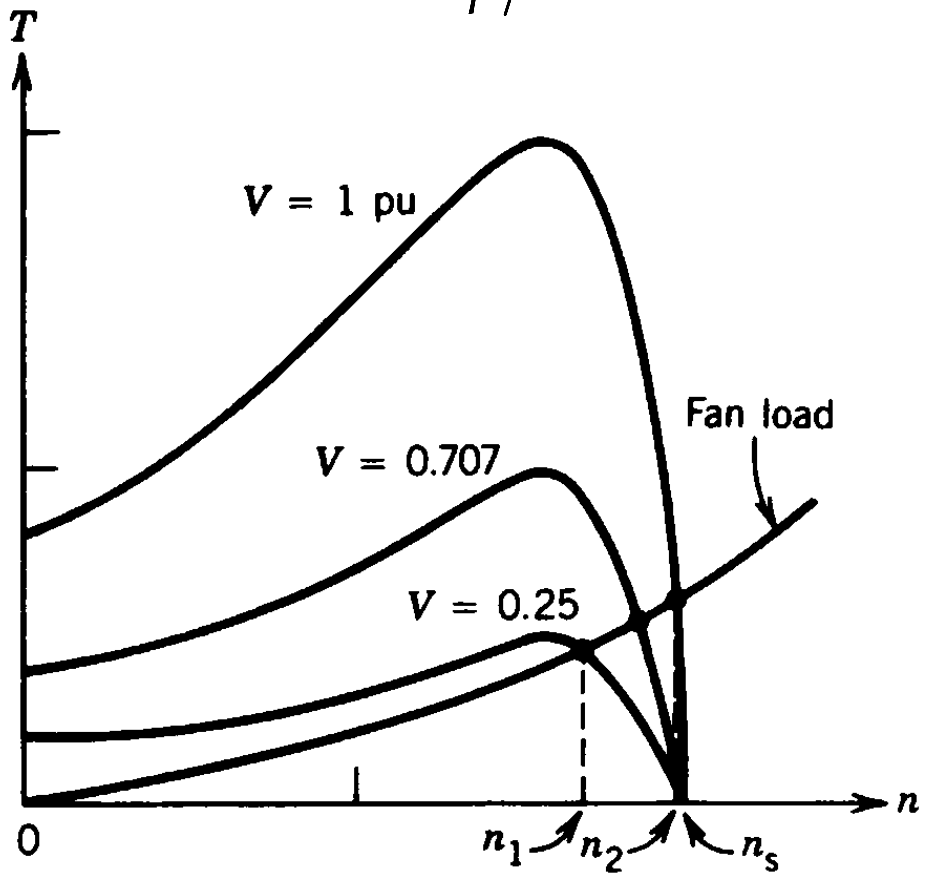




Speed control - basics

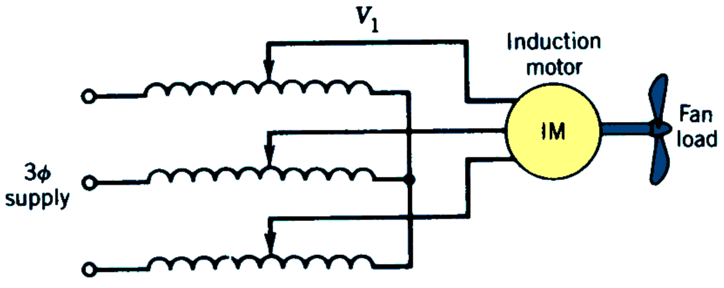
- Speed is determined by:
  - Supply frequency
  - Number of pole-pairs
  - Slip
- Pole changing
  - Discrete steps
  - Expensive
  - Normally ratio 2:1
  - Cage induction machine only
- line voltage control
  - Torque is proportional to V^2
  - Increased slip ➡ inefficient operation
  - Used with fans and pumps

$$n = \frac{f}{p/2}(1-s)$$



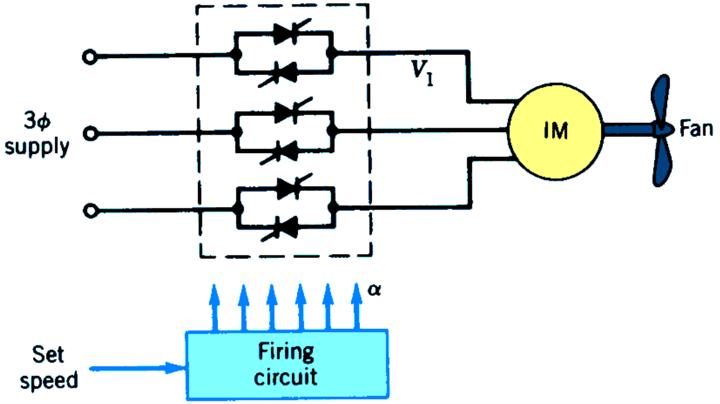
Line voltage control

- Auto transformer



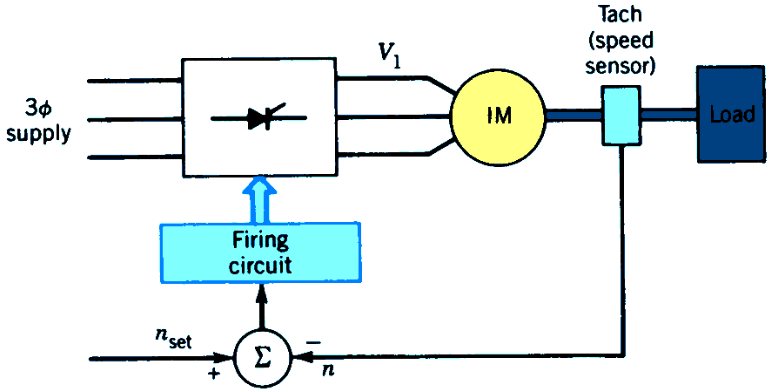
(a)

- Solid-state controller
  - Open loop operation



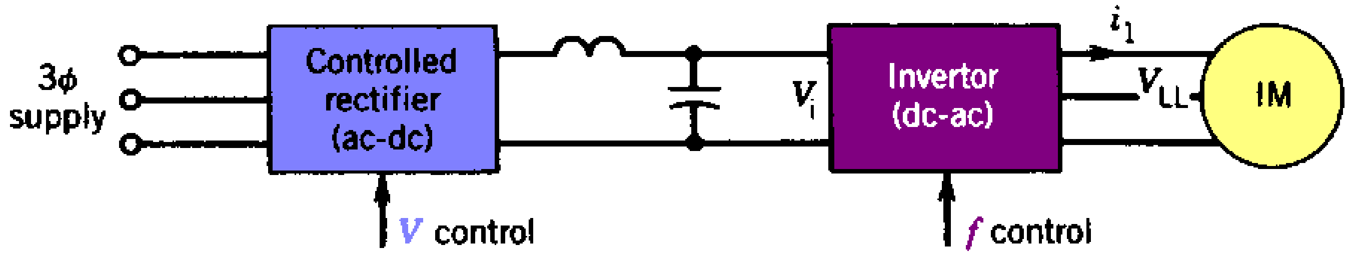
(b)

  - Closed loop operation
    - Precise speed control
    - Requires expensive sensor

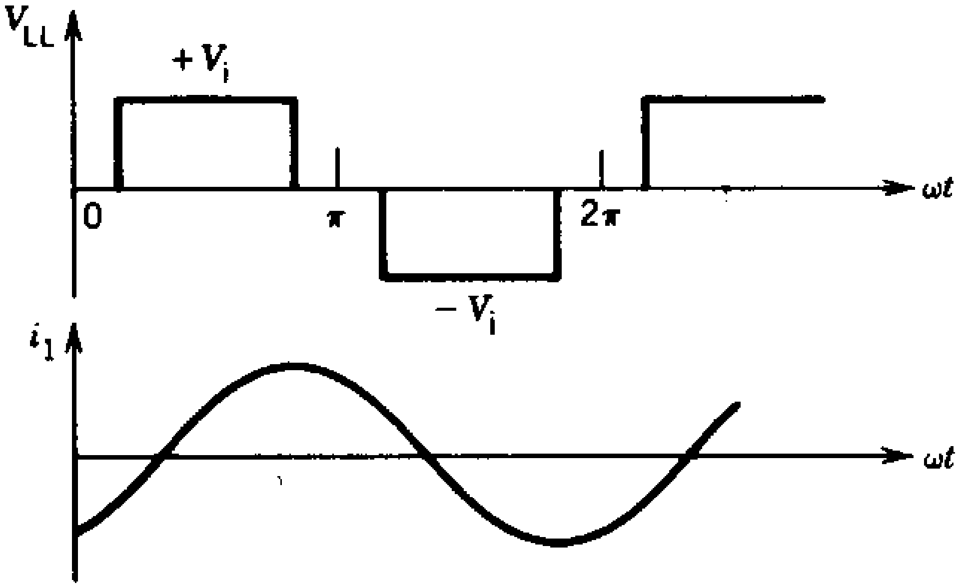


Line frequency control

$$n = \frac{f}{p/2}$$



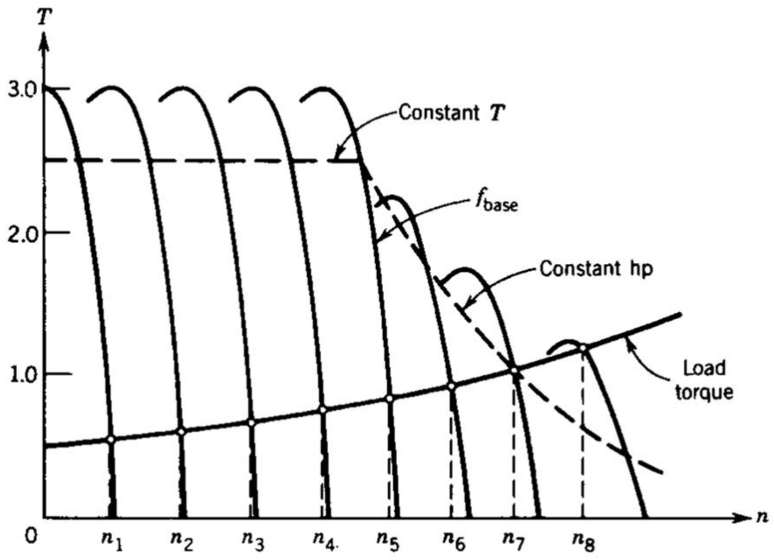
For non regenerative operation a diode bridge is used as rectifier and PWM inverter is used for frequency control



Scalar control

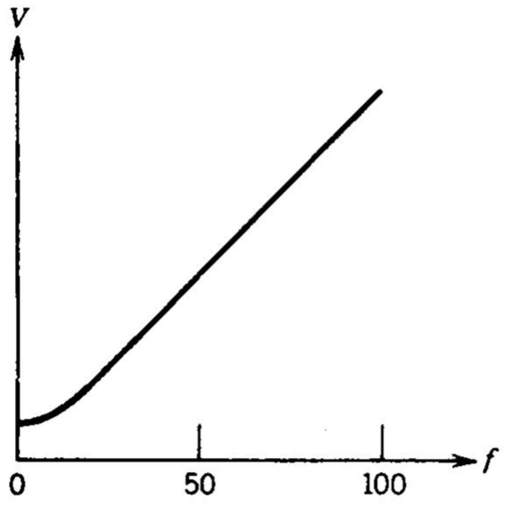
$$\Phi_p \propto \frac{E}{f}$$

$$\Phi_p \propto \frac{V}{f}$$



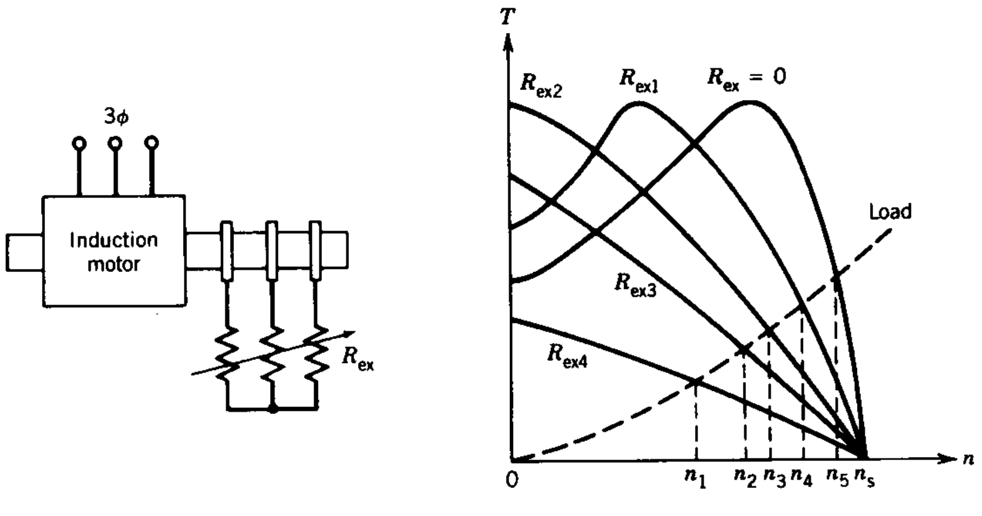
- Below nominal speed
  - Voltage-frequency ratio kept constant to avoid saturation
  - Constant flux and constant torque

- Above nominal speed
  - Voltage kept constant to avoid electric breakdown
  - Constant voltage and constant power



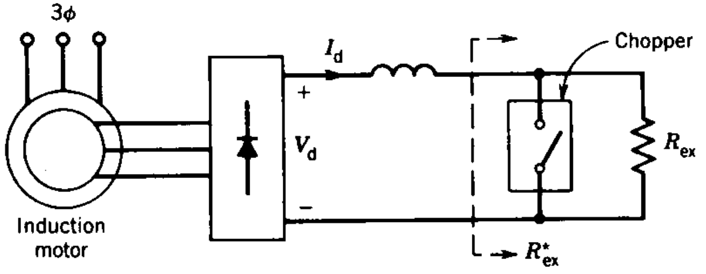
Rotor resistance control

- External 3-phase resistance



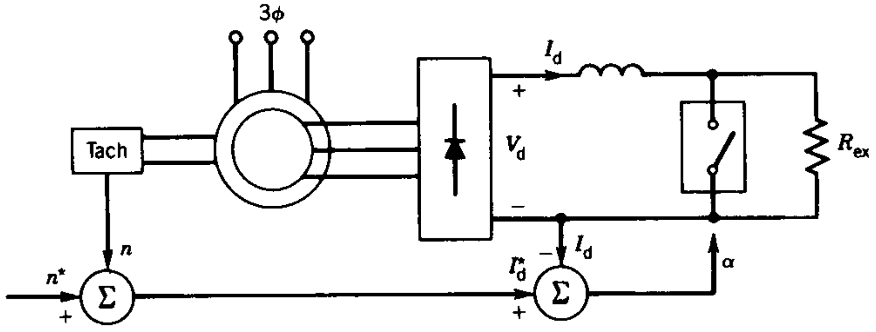
(a) (b)

- DC-resistance and chopper
  - Open or closed loop

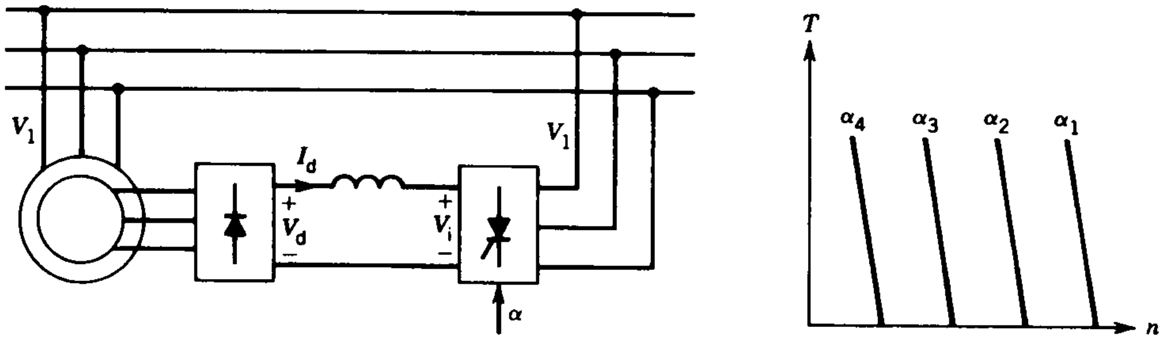


(c)

What about the efficiency ?



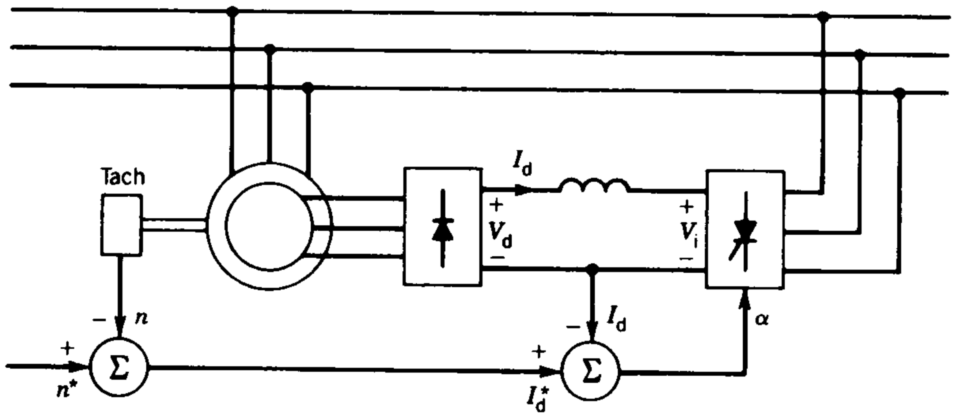
rotor slip energy recovery

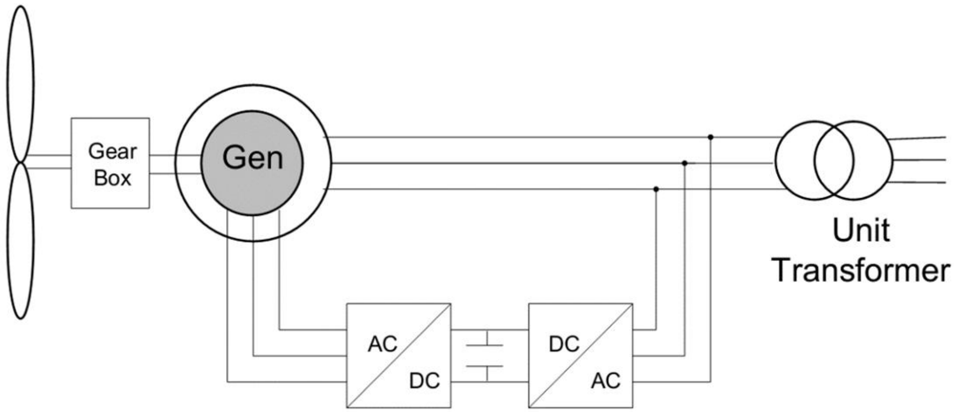


(a)

(b)

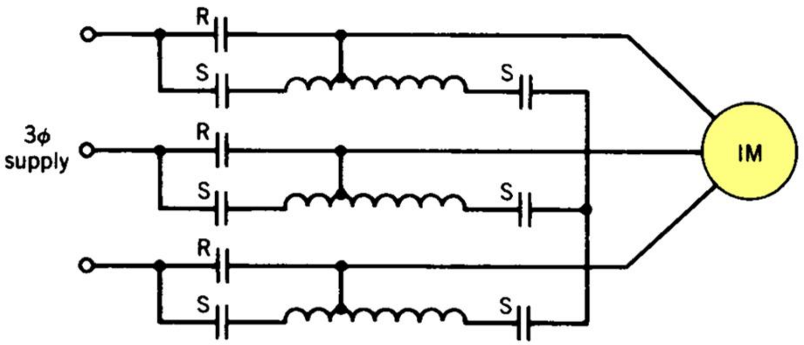
- Efficient use of rotor slip power
- Possibility to supply power from the rotor side as well

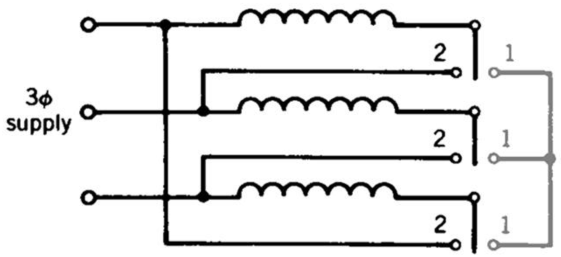




Starting of induction motors

- Direct connection
  - Starting current 5…8 IN
  - Line voltage drop
  - Long starting time
  - Overheating





- Reduced-voltage starting
  - Step-down autotransformer
  - Star-delta method
  - Solid state voltage controller
    - Reduced torque