ECE 325 – Electric Energy System Components
6- Three-Phase Induction Motors

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THE UNIVERSITY OF TENNESSEE KNOXVILLE

Content

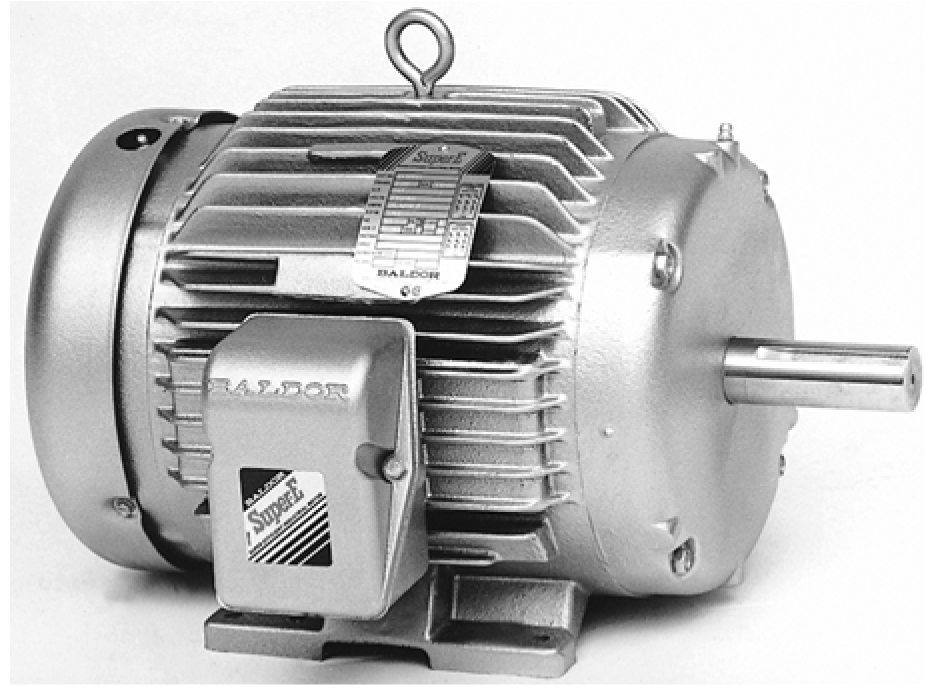
(Materials are from Chapters 13-15)

- Components and basic principles
- Selection and application
- Equivalent circuits

Understanding the Nameplate

- 3-phase, 60Hz, AC induction motor
- Rated power: 30.0 hp (=22.4kW)
- Service factor: 1.15 (i.e. 115% of rated power for short-term use)
- Rated full-load current: 35.0A
- Rated voltage: 460V
- Rated speed: 1765rpm
- Continuous duty at ambient 40^{o}C
- Full-load nominal efficiency: 93.0%
- Frame size: shaft height of 28/4=7 inches; body's length of 6
- Insulation class: F (155^{o}C for 20,000 hours lifetime)
- NEMA design: B (normal starting torque combined with a low current)
- Start inrush kVA: G (5.60-6.29kVA)

http://www.pdhonline.org/courses/e156/e156content.pdf



AC Induction Motor

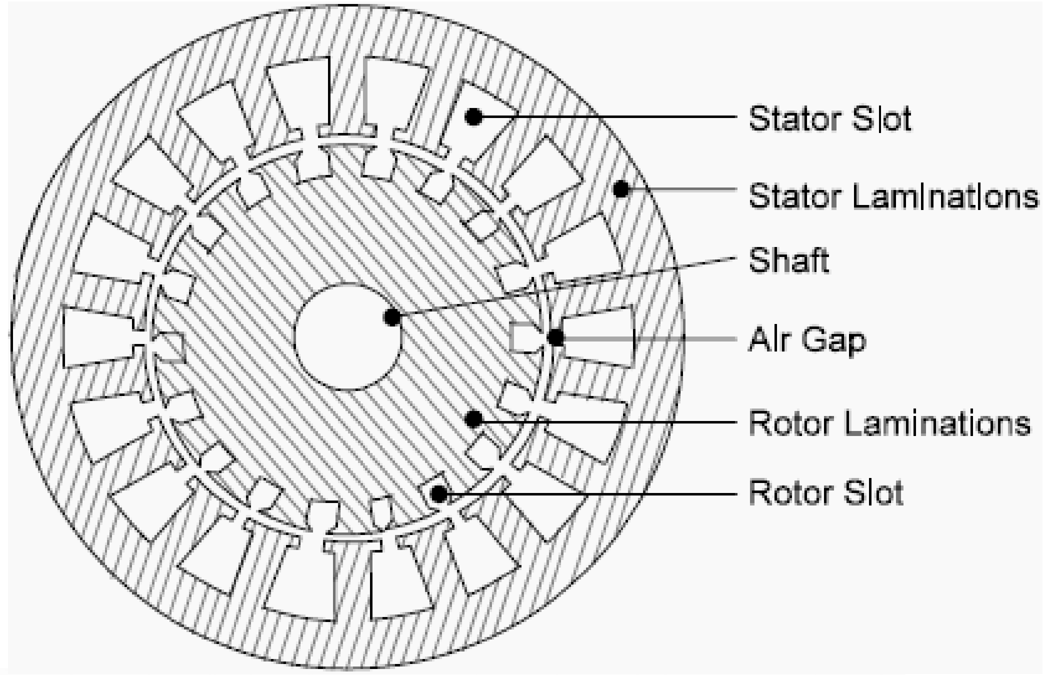
HIGH EFFICIENT

ORD. NO.	1LA0264SE41			E NO.			
TYPE	RGZESD			FRAME	286T		
H.P.	30.0			SERVICE FACTOR	1.15		3 PH
AMPS.	35.0			VOLTS	460		
R.P.M	1765			HERTZ	60		
DUTY	CONT 40^{0}C AMB			DATE CODE			
CLASS INSUL	F	NEMA DESIGN	B	KVA CODE	G	NEMA NOM. EFF	93.0
SH END BRG	50RU03K30			OPP END BRG	50BC03JPP3		

Made in Mexico

Principal components

- Stator (stacked laminations)
- Rotor (stacked laminations)
  - Wound rotor
  - Squirrel-cage rotor
- Air gap (0.4mm-4mm)



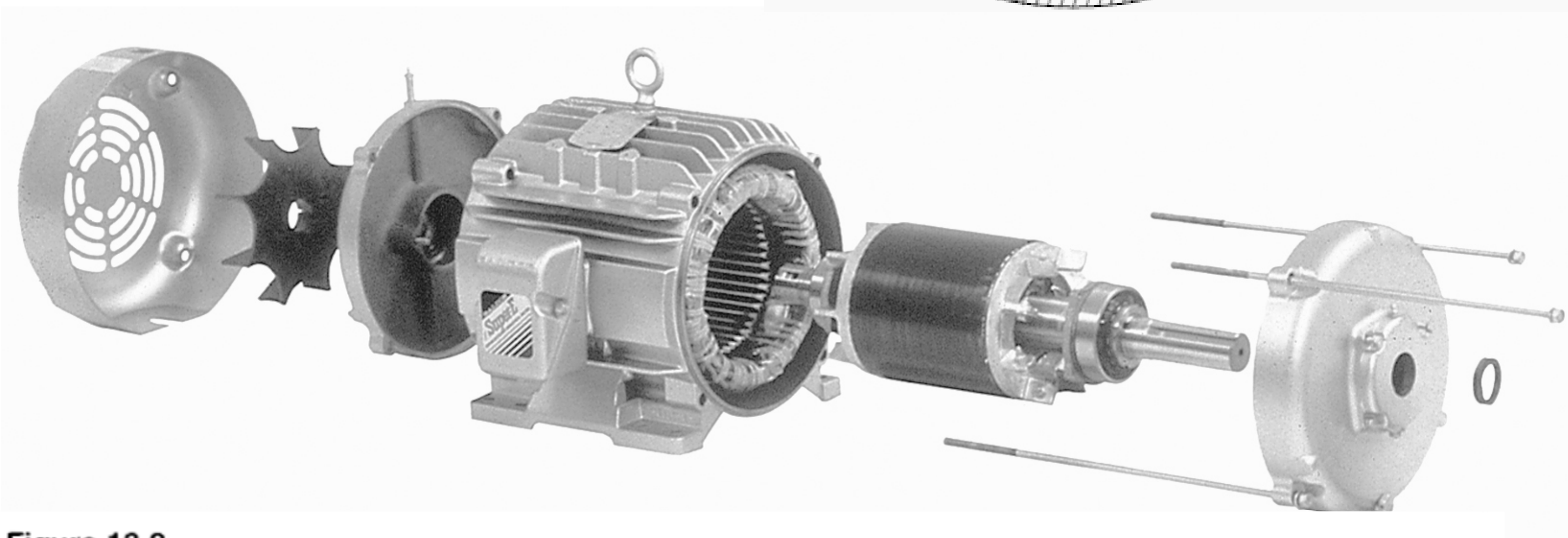
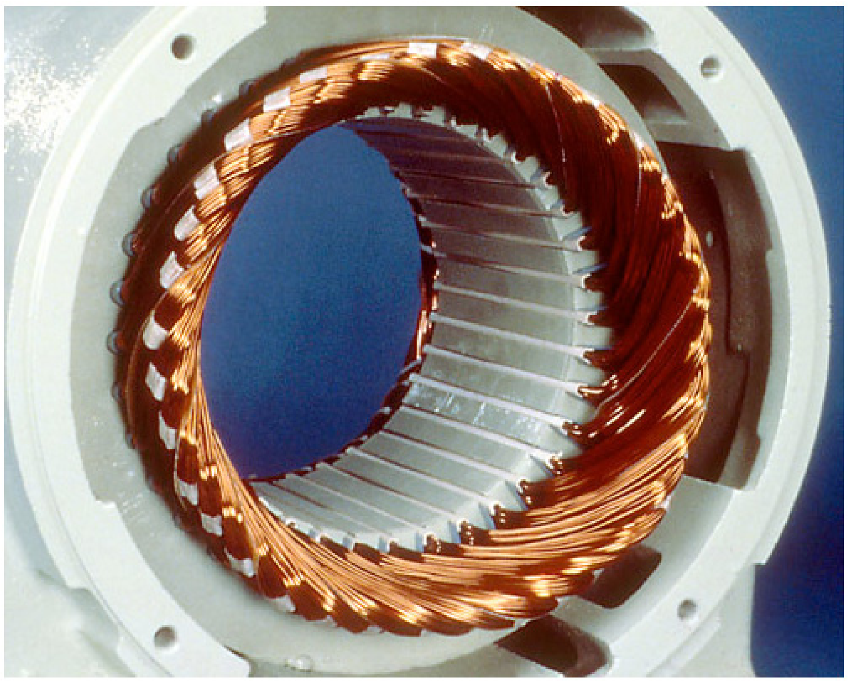


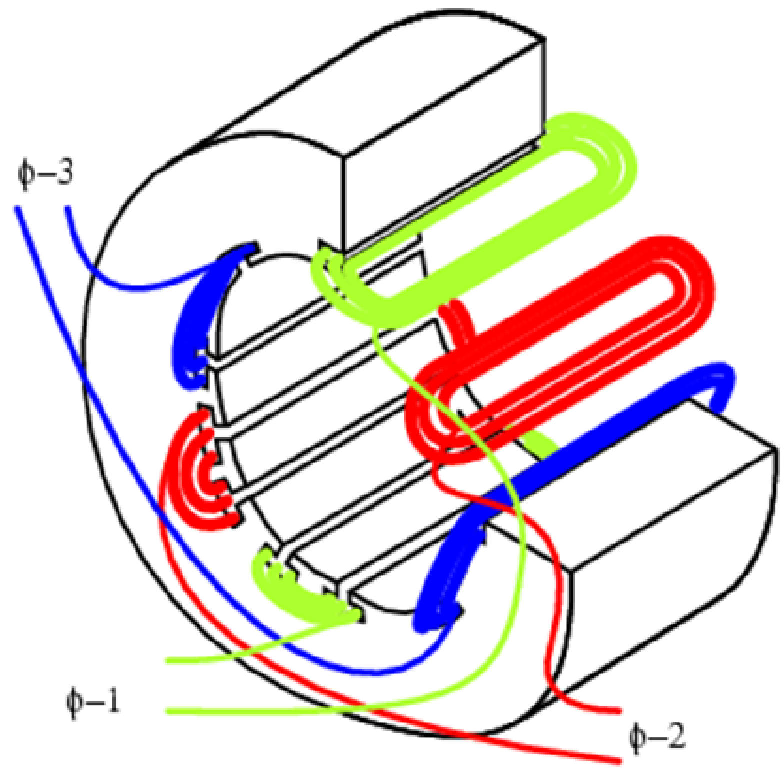
Figure 13.2
Exploded view of the cage motor of Fig. 13.1, showing the stator, rotor, end-bells, cooling fan, ball bearings, and terminal box. The fan blows air over the stator frame, which is ribbed to improve heat transfer.
(Courtesy of Baldor Electric Company)

Stator

- Hollow, cylindrical core made up of stacked laminations.
- Stator winding is placed in the evenly spaced slots punched out of the internal circumference of the laminations.

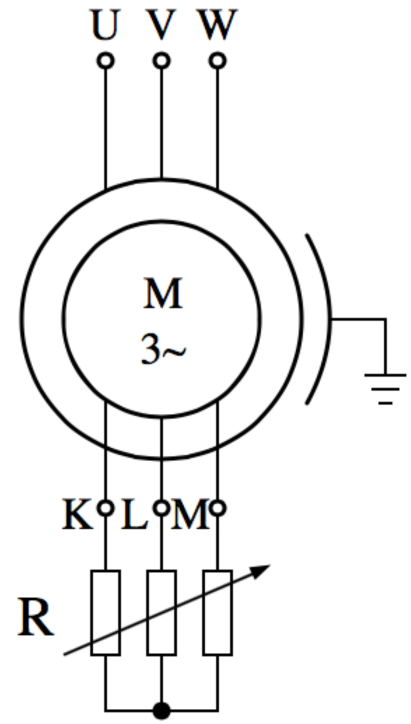


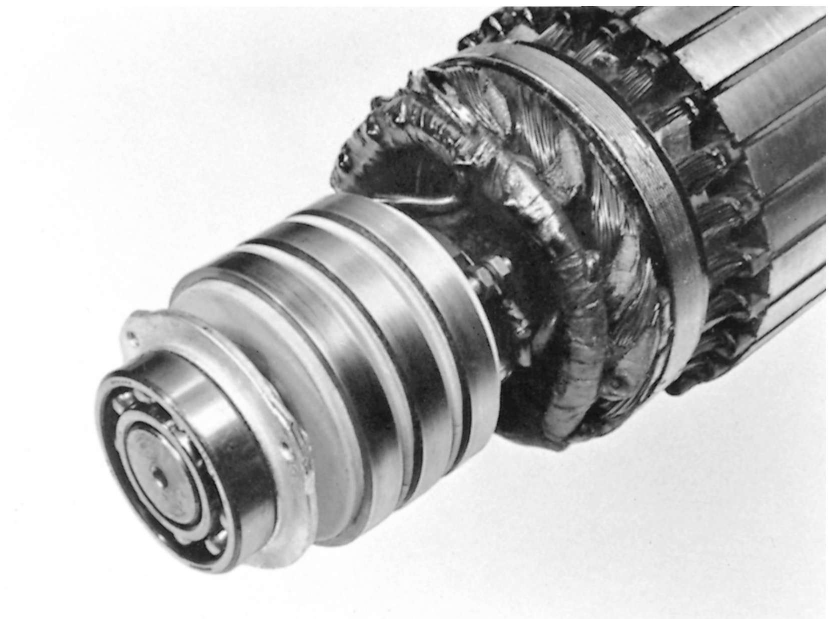
(Source: EASA.com)



Wound Rotor

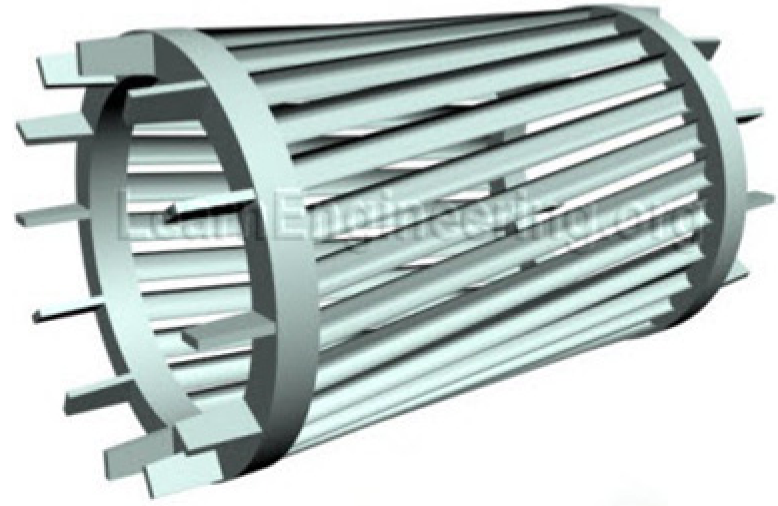
- Has a 3-phase winding (usually in Y-connection) uniformly distributed in rotor slots, similar to the stator winding
- Rotor winding terminals are connected to three slip-rings which revolve with the rotor.
- 3 stationary brushes connect the rotor winding to external resistors during the start-up period and are short-circuited during normal operations.

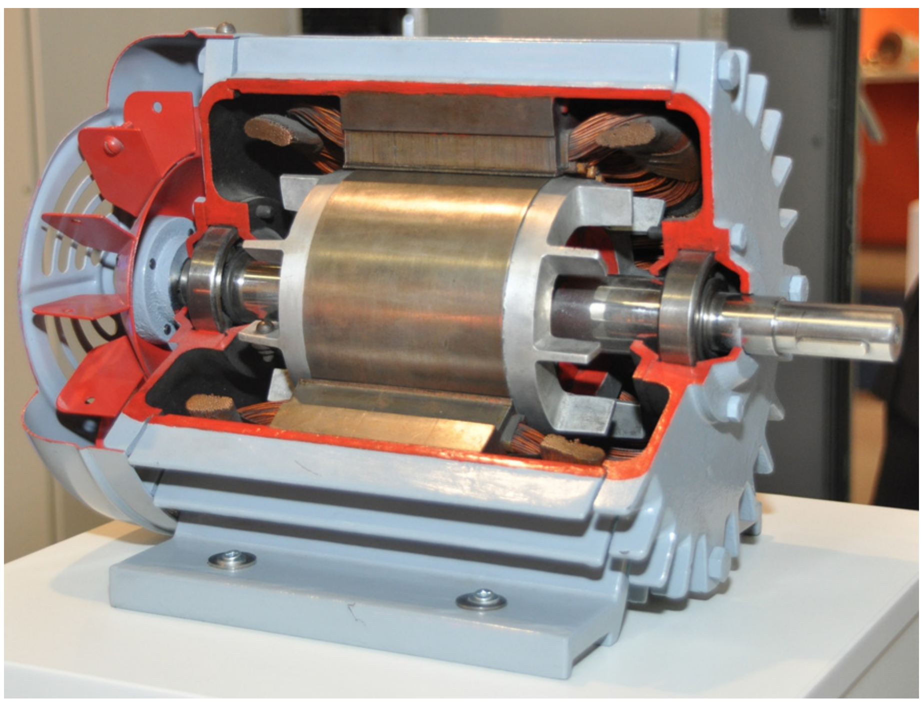




Squirrel-Cage Rotor

- More adopted in induction motors
- Instead of a winding, copper bars are pushed into the slots in the laminations
- Welded to two copper end-rings, all bars are short-circuited at two ends, so as to resemble a “squirrel cage”
- In small and medium motors, the “cage” (bars and end-rings) are made of aluminum.





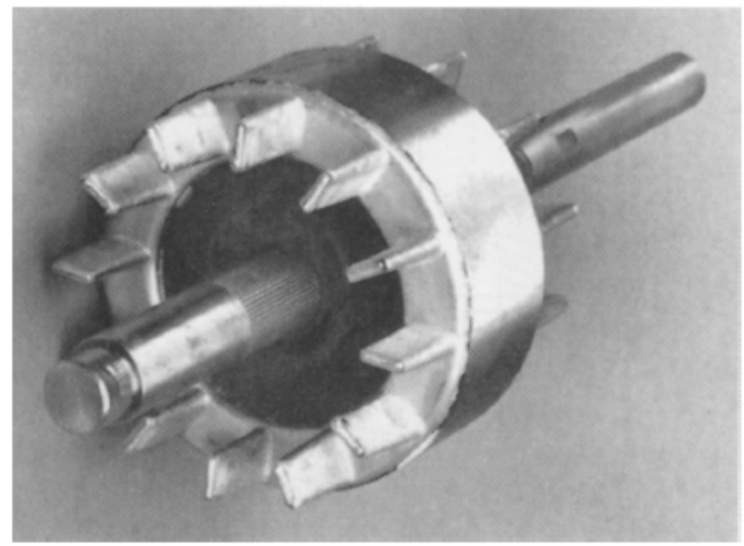
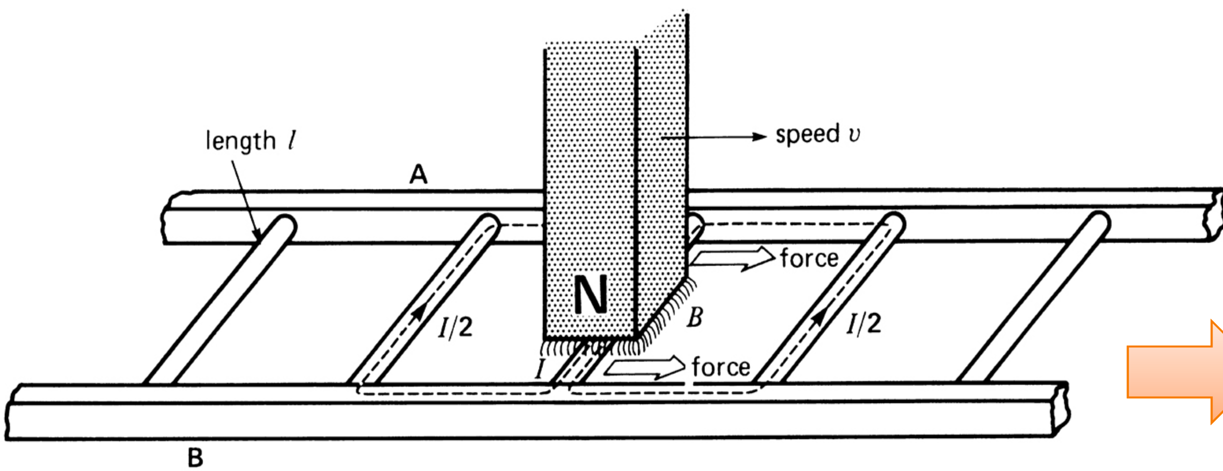


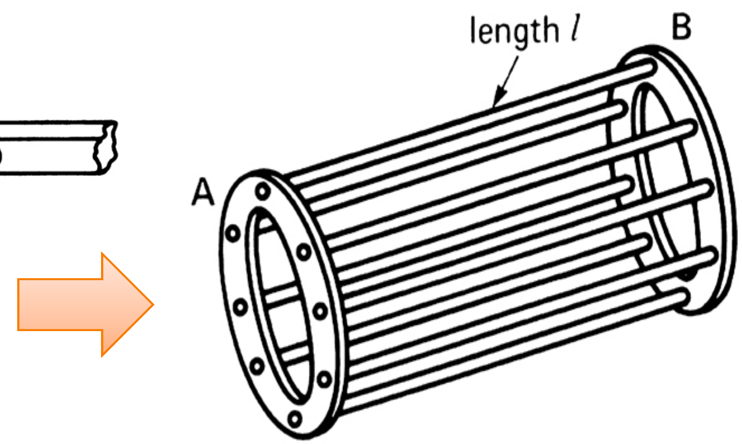
Figure 13.3a
Die-cast aluminum squirrel-cage rotor with integral cooling fan.
(Courtesy of Lab-Volt)

Principle of Operation: Faraday's Law and Lorentz Force

- A magnet moving above a conducting ladder induces a voltage $E=Blv$ and a current I in the conductor underneath according to Faraday's law (the right-hand rule).
- Cut by the moving flux, the current-carrying conductor experiences a Lorentz force (the left-hand rule) always acting in a direction to drag it along the moving magnet
- When the system reaches a steady state, the ladder moves in the same direction as the magnet but has a lower speed $<v$ (why?)
- Roll up the ladder into a cylindrical squirrel-cage rotor and replace the magnet by a stator → an induction motor



Parallel conductors are short-circuited by end-bars A and B



Conductors are short-circuited by end-rings A and B)

Rotating magnetic field

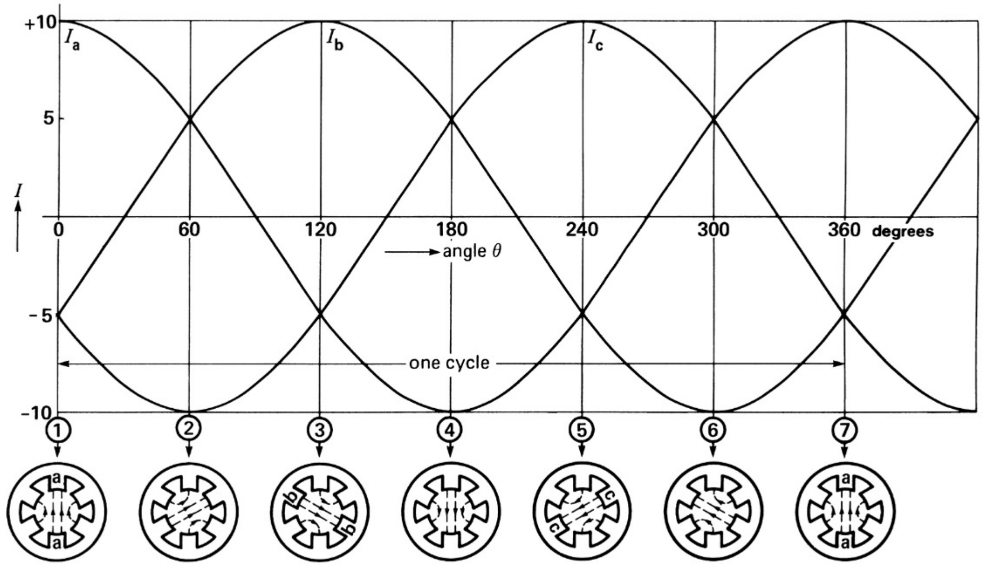
- Consider a stator having 6 salient poles with Y-connected stator windings carrying balanced 3-phase alternating currents.

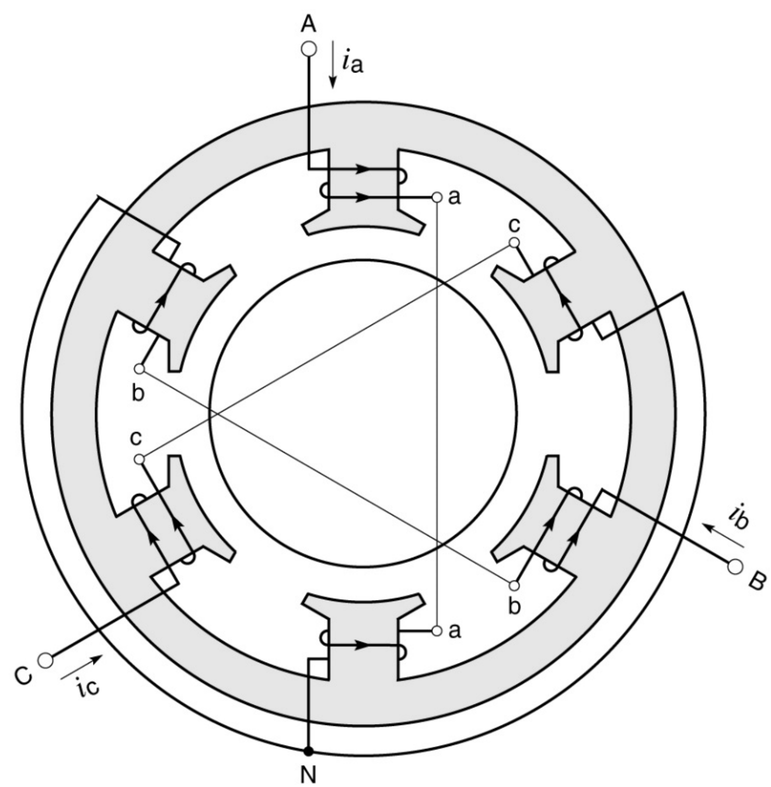
$$i_a(t) = 10\cos\theta \qquad = 10\cos(\omega t)$$

$$i_b(t) = 10\cos(\theta - 120^\circ) = 10\cos(\omega t - 120^\circ)$$

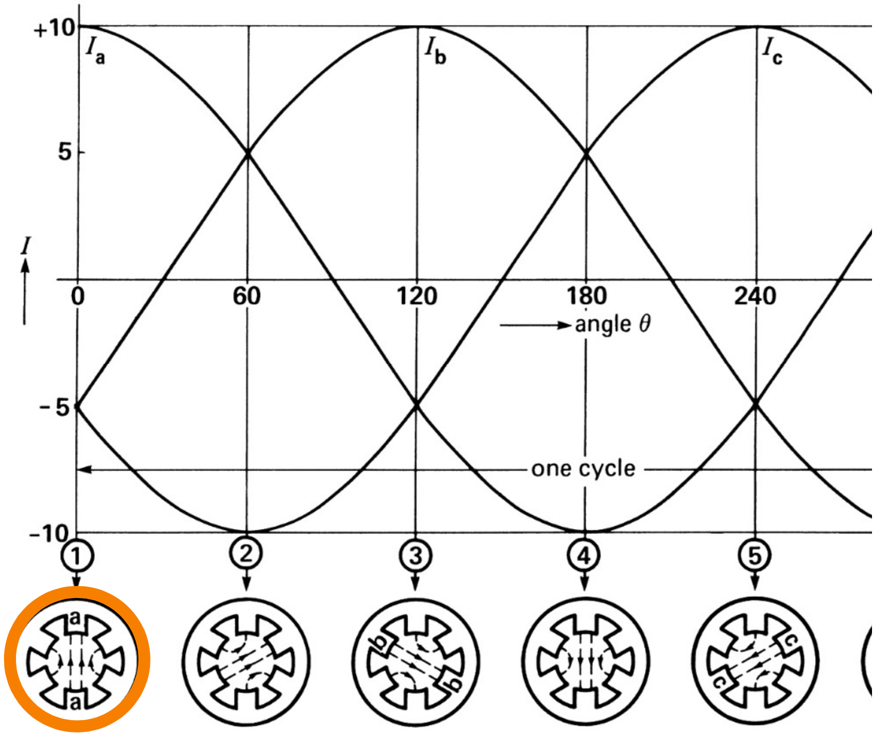
$$i_c(t) = 10\cos(\theta + 120^\circ) = 10\cos(\omega t + 120^\circ)$$

Positive currents: always flowing into terminals A, B and C

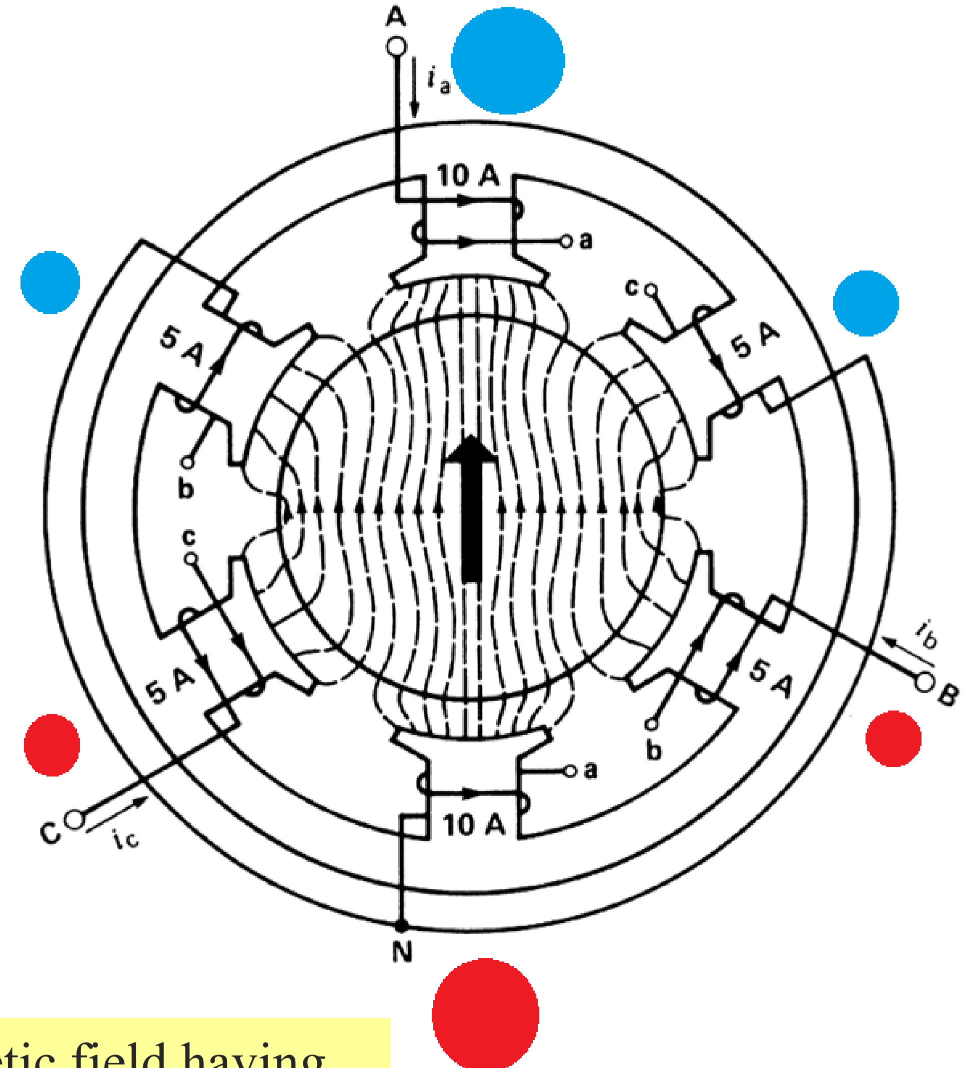




Rotating Magnetic Field: Instant 1

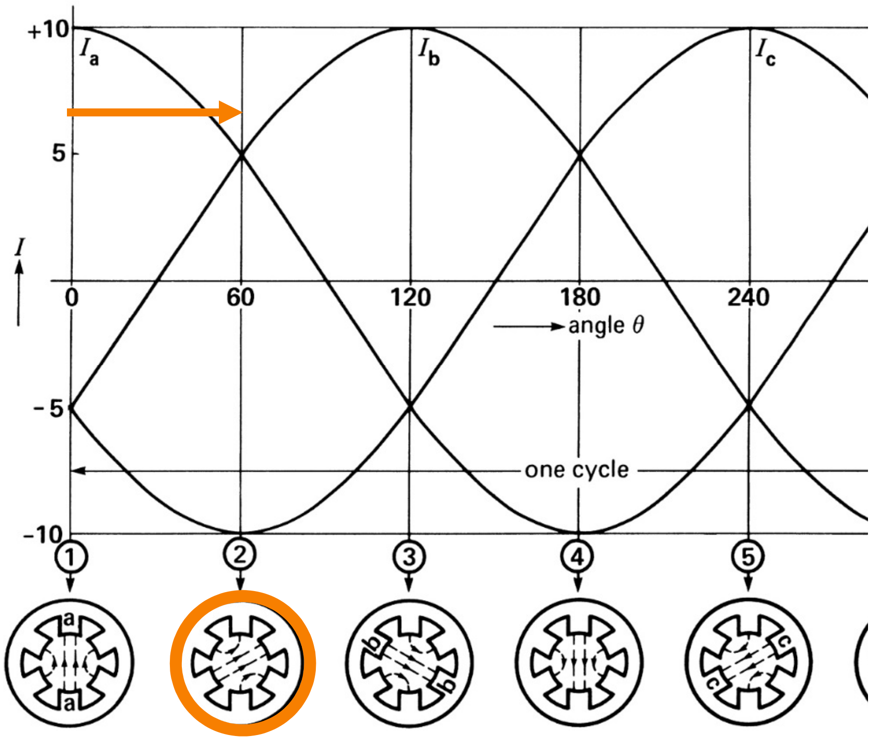


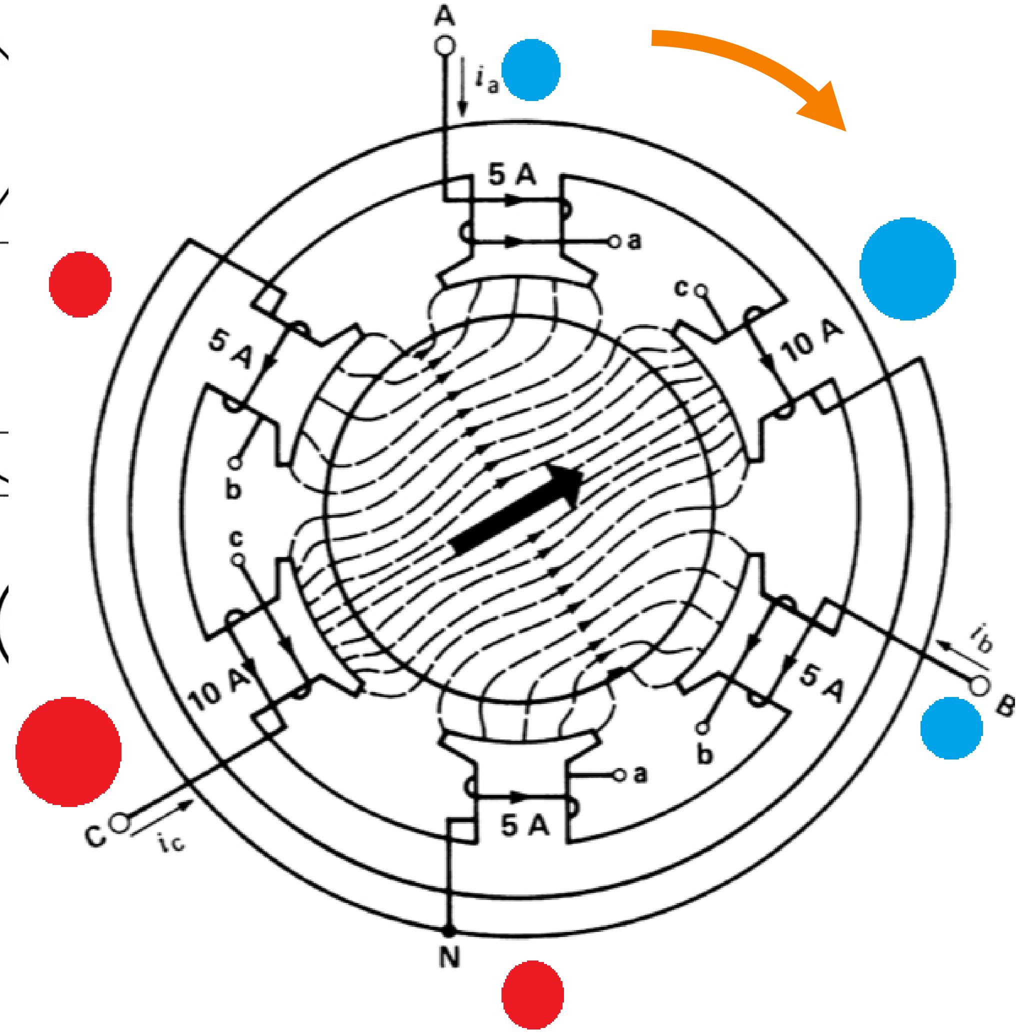
$$i_a = 10\ A$$
$$i_b = -5\ A$$
$$i_c = -5\ A$$



- **θ=0:** 6 poles together produce a magnetic field having essentially one broad N pole and one broad S pole

Rotating Magnetic Field: Instant 2

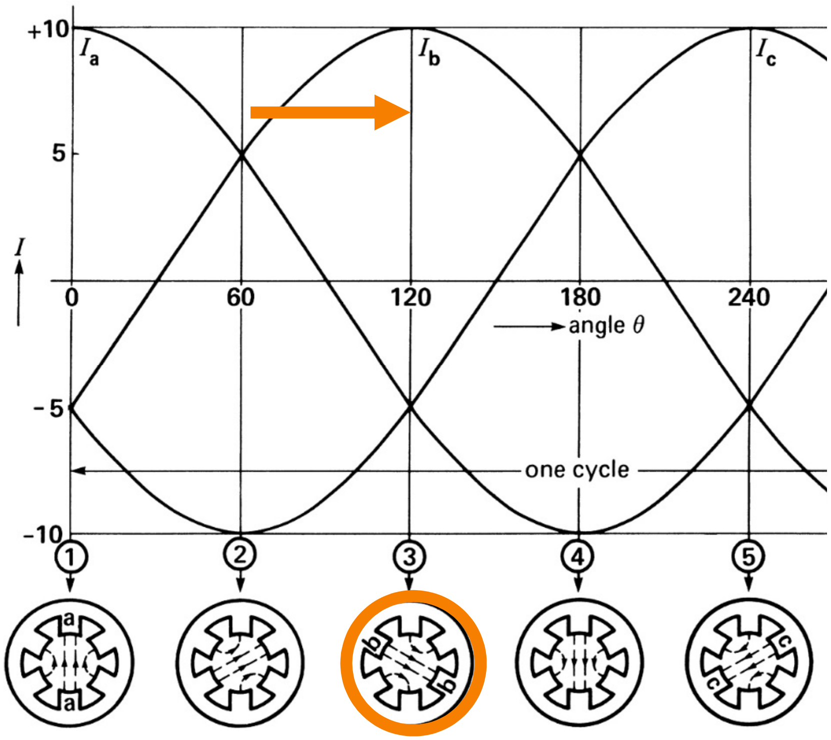


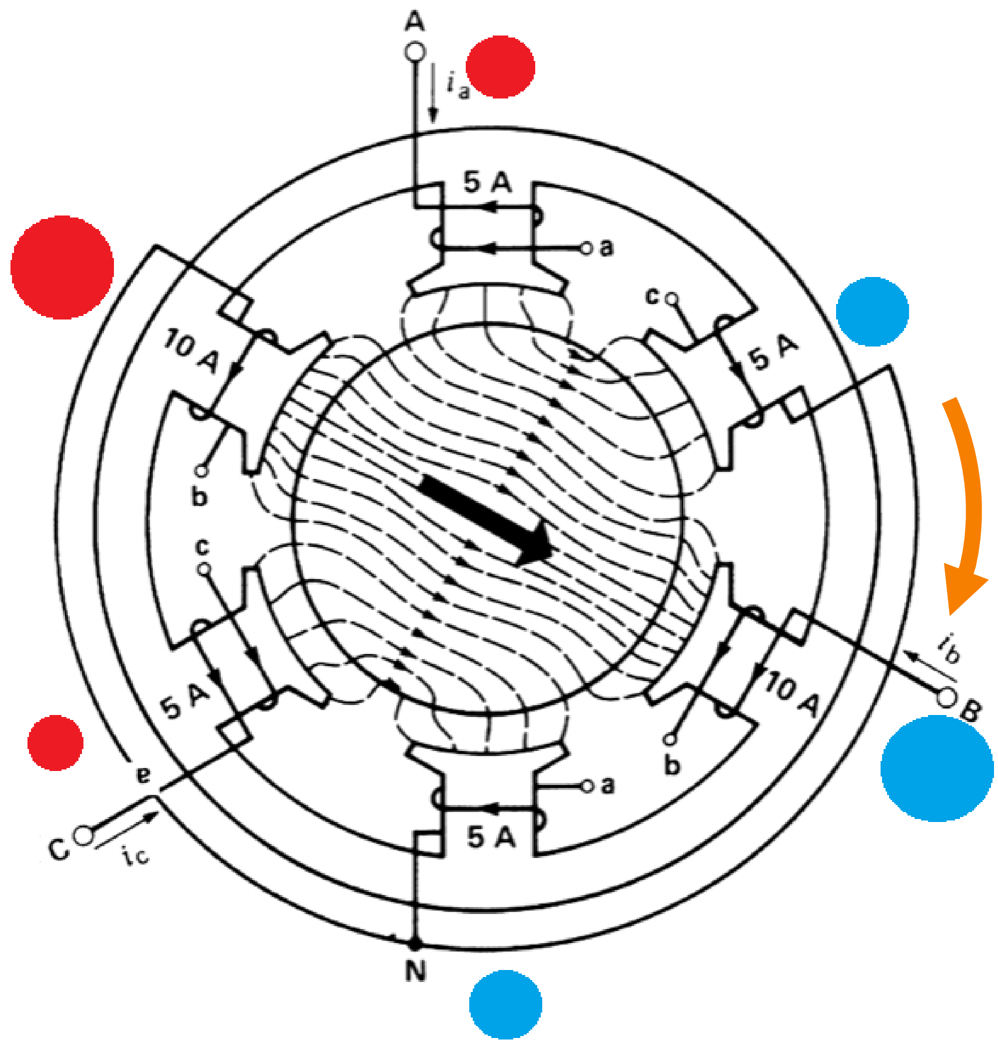


$$i_a = 5\ A$$
$$i_b = 5\ A$$
$$i_c = -10\ A$$

- **θ→60º:** the magnetic field moves CW by 60º; its angular speed equals ω

Rotating Magnetic Field: Instant 3



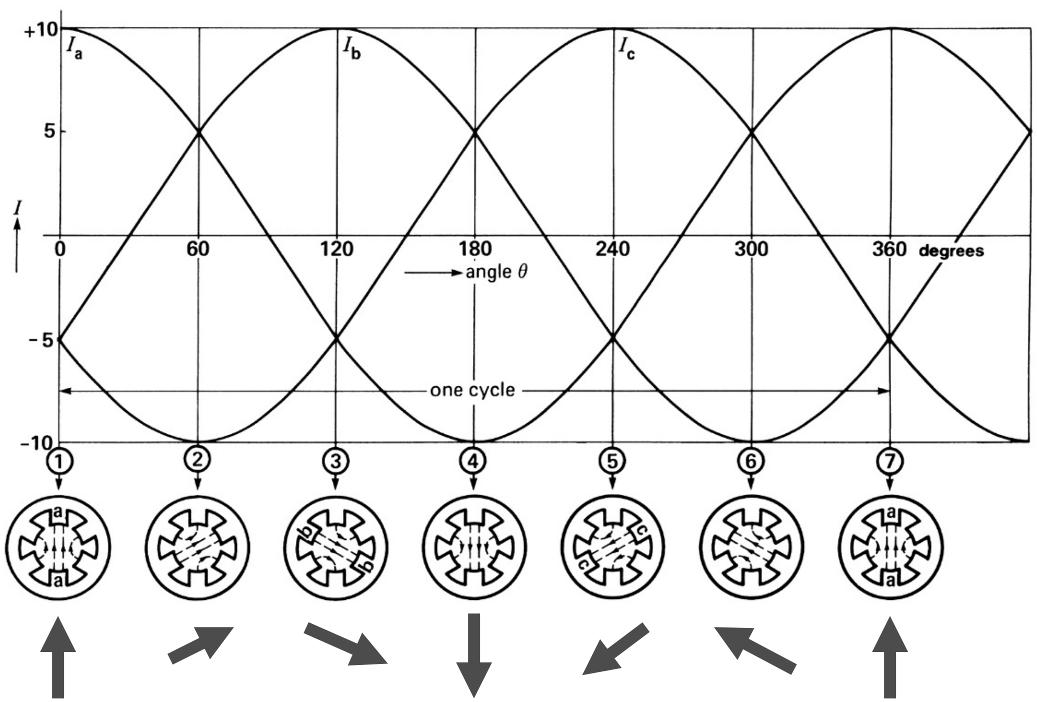


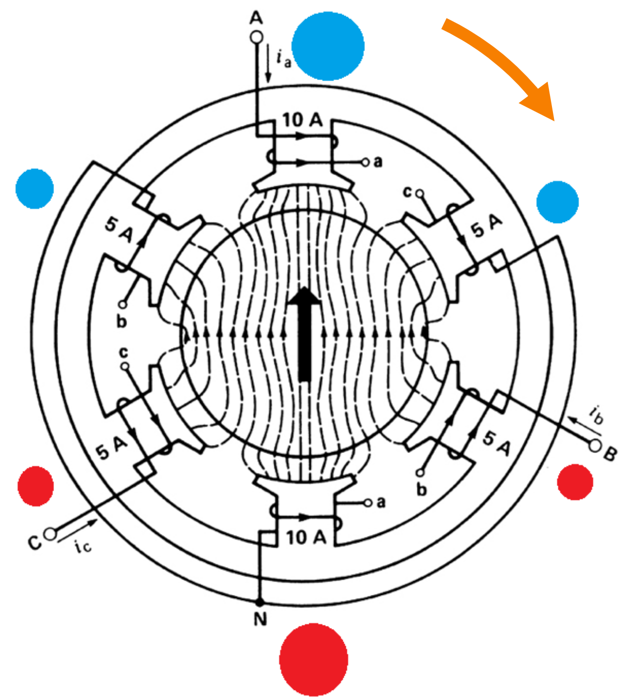
$$i_a = -5\ A$$
$$i_b = 10\ A$$
$$i_c = -5\ A$$

- **θ→120º:** the magnetic field moves CW by 120º; its angular speed equals ω

Rotating Magnetic Field

- The stator produces a magnetic field having one pair of N-S poles
  - The field rotates 360º during one cycle of the stator current.
  - The speed of the rotating field is synchronized with the frequency *f* of the source, so it is called **synchronous speed** =60*f* (r/min) or 2π*f* (rad/s)
  - With the phase sequence A-B-C (CW), the magnetic field rotates CW.
  - If we interchange any two of the three lines connected to the stator, the new phase sequence will be A-C-B (CW) and the magnetic field will rotate CCW at the synchronous speed





Phase group and Synchronous Speed

- In practice, instead of using a single coil per pole, the coil is sub-divided into 2 or more coils lodged and staggered in adjacent slots connected in series as a phase group
- Each phase group produces one N/S pole, so using more phase groups allows us to increase a number (denoted by p) of poles
  No. of groups = No. of phases × No. of poles = 3 × p
- **Synchronous speed** $n_s = 120f / p$ [r/min]

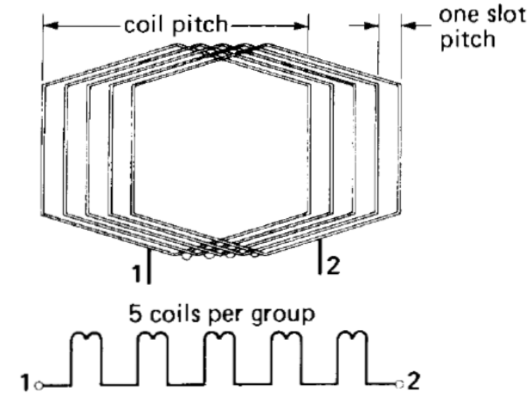
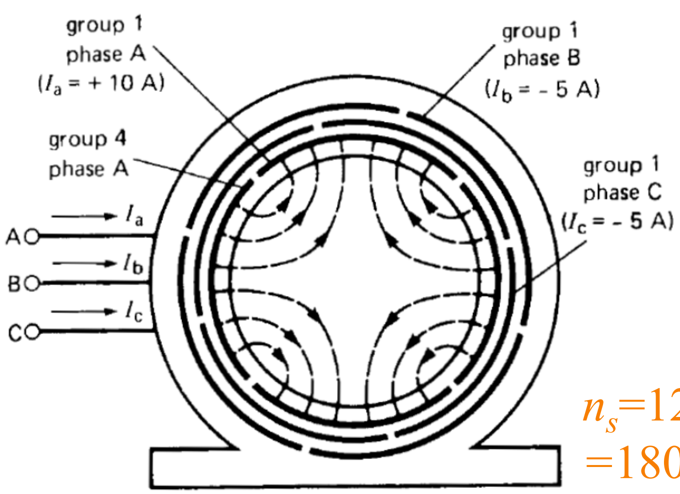
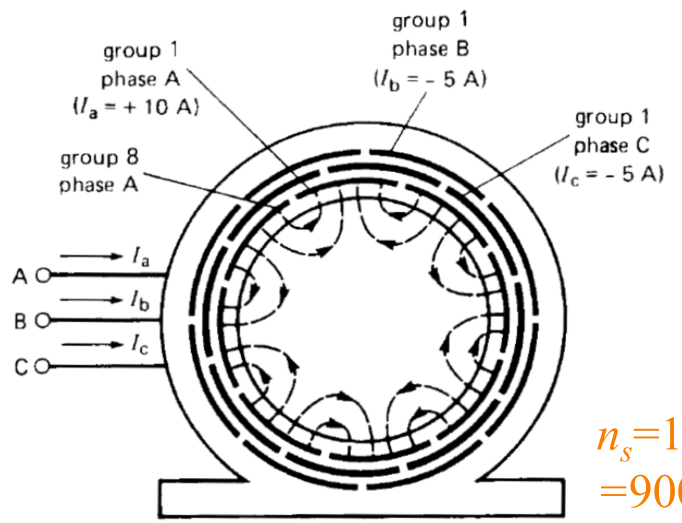


Figure 13.20
The five coils are connected in series to create one phase group.



$n_s = 120f / 4 = 30f$
$= 1800$ r/min

Figure 13.10b
Four-pole, full-pitch, lap-wound stator and resulting magnetic field when $I_a = +10$ A and $I_b = I_c = -5$ A.

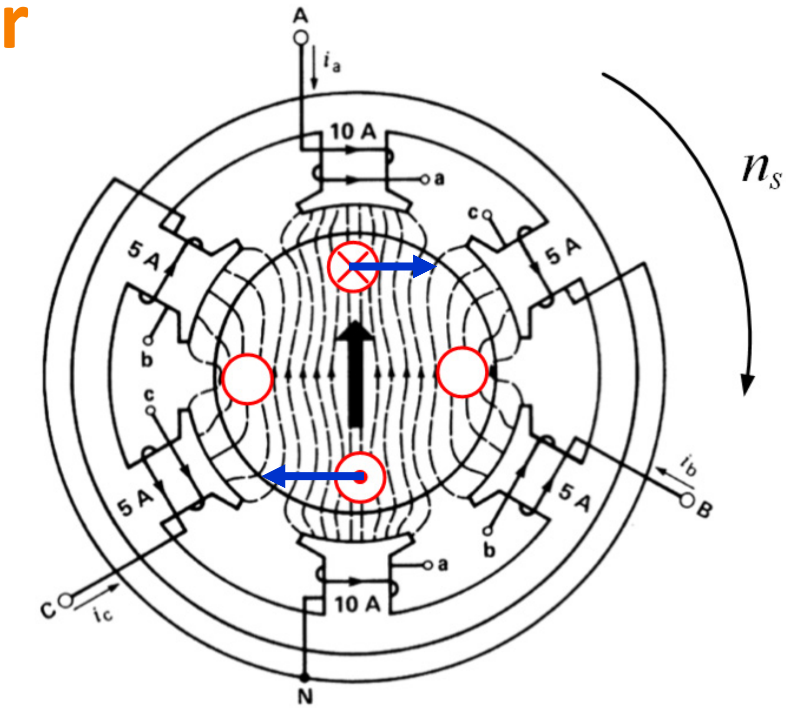


$n_s = 120f / 8 = 15f$
$= 900$ r/min

Figure 13.11
Eight-pole, full-pitch, lap-wound stator and resulting magnetic field when $I_a = +10$ A and $I_b = I_c = -5$ A.

Starting of an induction motor

1. The magnetic field produced by the stator current rotates CW at synchronous speed n_s.
2. Relative to the magnetic field, the rotor rotates CCW.
3. According to Faraday's Law (right-hand rule), the rotor windings (bars) have induced voltages in the directions as indicated.
4. Large circulating currents are created in rotor windings (bars) by the induced voltages
5. The currents have the maximum values at the staring point because the rotor has the maximum speed relative to the magnetic field.
6. The rotor windings start to rotate CW subjected to Lorentz forces (left-hand rule) in the directions as indicated
7. The rotor will accelerate until the total Lorentz force equals the friction
8. Once the rotor starts rotating CW, its speed relative to the filed will decrease, so its winding currents and Lorentz forces will decrease



Can the rotor reach n_s?

- No, **the rotor's speed $n<n_s$ at a steady state** (if $n=n_s$, then its currents and Lorentz forces would be zero and friction would slow the rotor down).
- Since friction is very small, the rotor speed $n \approx n_s$ at no load conditions

Slip

- **Slip**: is the difference between synchronous speed n_s and rotor speed n, expressed as a per unit or percent of synchronous speed.

$$s = \frac{n_s - n}{n_s} = \frac{\omega_s - \omega_r}{\omega_s} = \frac{f_2}{f} \qquad \text{(pu)}$$

f: frequency of the source connected to the stator [Hz]

f_2: frequency of the voltage and current induced in the rotor [Hz]

n_s=120f / p: synchronous speed [r/min]

n: rotor speed [r/min]

ω_r=2π(f -f_2)=πn/30, ω_s=2πf=πn_s/30 [rad/s] corresponding angular speeds of n and n_s