Introduction to Electrical Engineering

Course Code: EE 103

Department: Electrical Engineering

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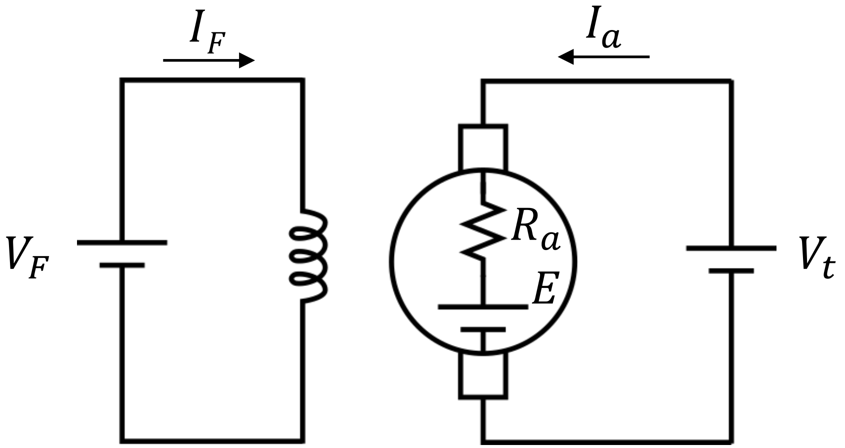
Review:

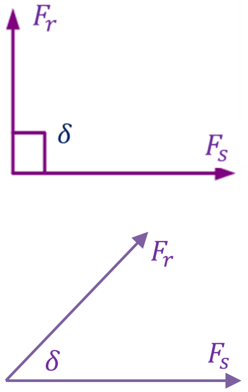
$$EI_a = V_t I_a - I_a^2 R_a$$

$$T = \frac{EI_a}{\omega} = \frac{(K\phi\omega)I_a}{\omega} = K\phi I_a$$



Advantages of DC machines:

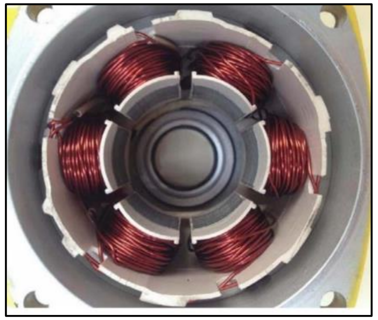
- The armature and field MMF can be controlled independently
- Torque control is simple
- 'Torque per ampere' is maximum



Limitations of DC machines:

- Commutator and brushes wear over time → require regular maintenance
- Short-circuiting commutator segments give rise to spark → can not be used in explosive environments

- In DC machine → Stator field is 'time-invariant'
  → Stator winding is concentrated and connected to a DC supply

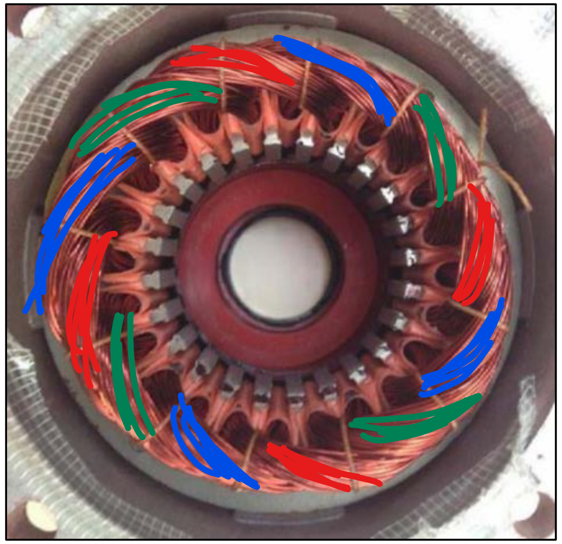


Wikipedia

Asynchronous machine: Stator → AC, Rotor → AC

- Induction motor is also known as asynchronous machine
- Of all the motors used, more that 80% are Induction motor*
- "Almost 70% of the machinery in industrial applications uses three-phase induction motors"$

- In induction machine → Stator winding is distributed

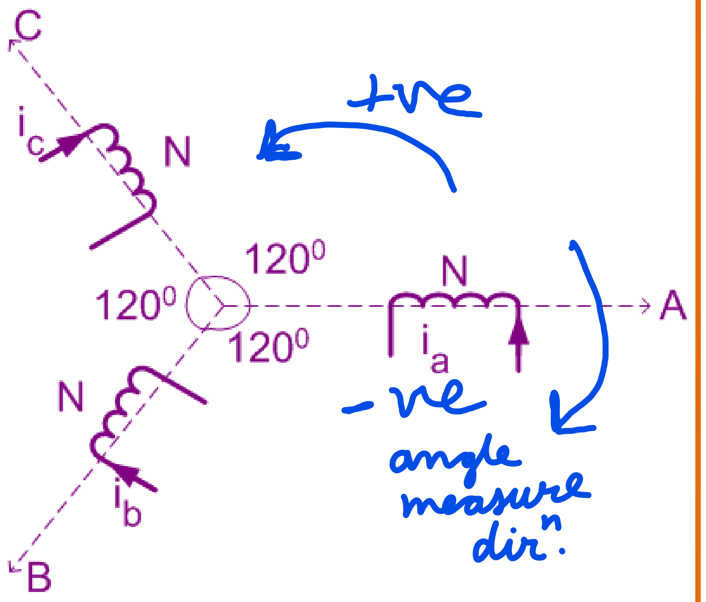


*Induction Motor Market Size, Share & Industry Analysis, https://www.fortunebusinessinsights.com/industry-reports/induction-motor-market-101639
$ Induction Motor Market - Growth, Trends, and Forecast (2020 - 2025), https://www.mordorintelligence.com/industry-reports/induction-motor-market

Induction machine

- Consider 3 coils of 'N' turns, displaced in space by 120°
- Let i_a, i_b & i_c are given as

$$i_a = I_m \sin(\omega_s t)$$
$$i_b = I_m \sin\left(\omega_s t - \frac{2\pi}{3}\right),$$
$$i_c = I_m \sin\left(\omega_s t - \frac{4\pi}{3}\right), \qquad \text{where } \omega_s = 2\pi f$$



- Current in each coil produces a pulsating magnetic field
- Amplitude & direction depend on the instantaneous value of 'I' flowing through it
- Each phase winding produces a similar magnetic field displaced by 120° in space from each other

$$B = \frac{\mu_0 I R^2}{2(R^2+x^2)^{3/2}}$$

Induction machine

Magnitude and position of the resultant field can be determined as follows

- Resolve the field produced by individual coil along x & y axes
- Determine $\sum x$ & $\sum y$ components
- Resultant,

$$\boxed{\begin{aligned} R &= \sqrt{(\sum x)^2 + (\sum y)^2} \\ \theta &= \tan^{-1}\frac{\sum y}{\sum x}, \text{ w.r.t axis of coil 'A'} \end{aligned}}$$

$$i_a + i_b + i_c = 0$$

$$\sum x = Ni_a + Ni_b\cos(-120) + Ni_c\cos(-240)$$
$$= Ni_a - \frac{1}{2}Ni_b - \frac{1}{2}Ni_c$$
$$\because i_a + i_b + i_c = 0, \Rightarrow \sum x = \frac{3}{2}Ni_a$$

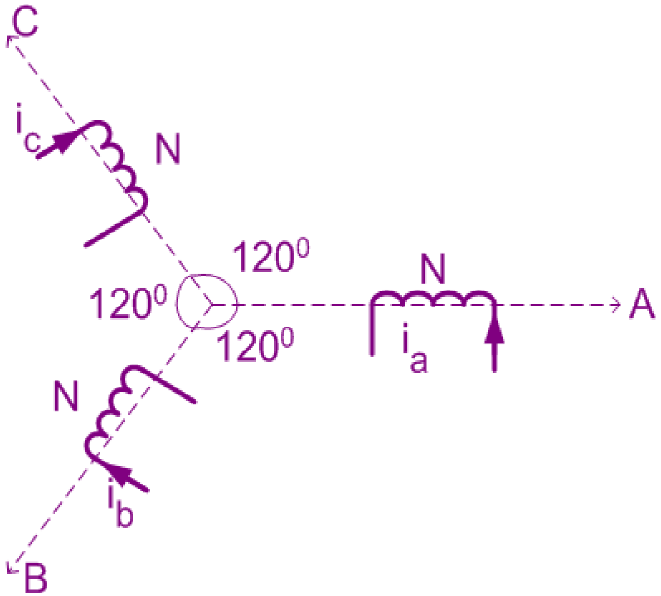
$$\sum y = 0 + Ni_b\sin(-120) + Ni_c\sin(-240)$$
$$= -\frac{\sqrt{3}}{2}Ni_b + \frac{\sqrt{3}}{2}Ni_c$$
$$\Rightarrow \sum y = \frac{\sqrt{3}}{2}N(i_c - i_b)$$

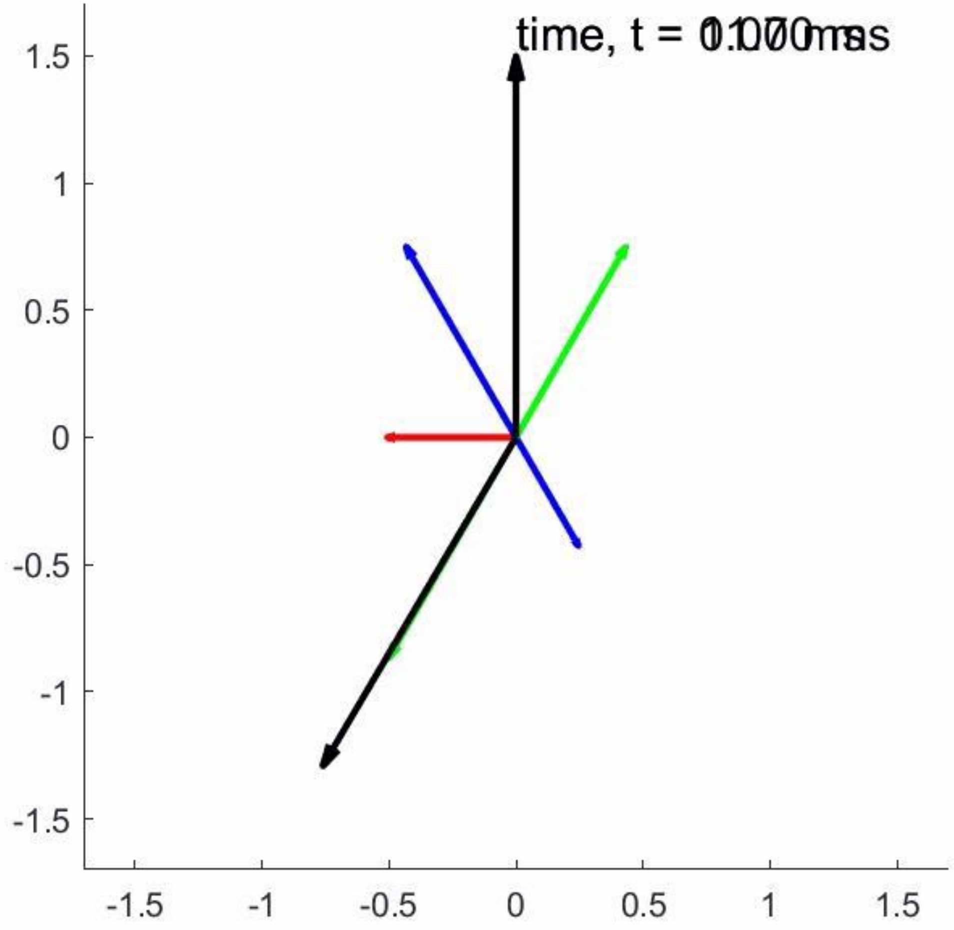
i_a, i_b & i_c are sinusoidal varying quantities

$$i_a = I_m \sin(\omega_s t)$$
$$i_b = I_m \sin\left(\omega_s t - \frac{2\pi}{3}\right),$$
$$i_c = I_m \sin\left(\omega_s t - \frac{4\pi}{3}\right),$$

$\omega_s t$	i_a	i_b	i_c	$\sum x$	$\sum y$	R	θ
$0°$	0	$-\frac{\sqrt{3}}{2} I_m$	$\frac{\sqrt{3}}{2} I_m$	0	$\frac{3}{2} N I_m$	$\frac{3}{2} N I_m$	$\frac{\pi}{2}$
$30°$	$\frac{I_m}{2}$	$-I_m$	$\frac{I_m}{2}$	$\frac{3}{4} N I_m$	$\frac{3\sqrt{3}}{4} N I_m$	$\frac{3}{2} N I_m$	$\frac{\pi}{3}$
$90°$	I_m	$-\frac{I_m}{2}$	$-\frac{I_m}{2}$	$\frac{3}{2} N I_m$	0	$\frac{3}{2} N I_m$	0
$180°$	0	$\frac{\sqrt{3}}{2} I_m$	$-\frac{\sqrt{3}}{2} I_m$	0	$\frac{3}{2} N I_m$	$\frac{3}{2} N I_m$	$\frac{-\pi}{2}$

Three phase currents and the resultant MMF





Three phase currents and the resultant MMF

Observations:

- Magnitude of 'R' is constant and equal to $\frac{3}{2}NI_m$ where I_m is the peak value
- Input 'I' completes 1/4 cycle, 'R' rotates by 90°
- Input 'I' completes 1/2 cycle, 'R' rotates by 180°

Conclusion:

- The result of displacing 3 windings by 120° in space and displacing the winding 'I' by 120° in time phase is a single revolving field of constant magnitude
- For a given winding arrangement, speed of rotation is determined by supply frequency of the input alone
- This speed of rotation of field is called 'synchronous speed' and it is denoted by N_s

$N_s = \frac{120f}{P}$ → N_s is in RPM, f is the supply frequency in Hz, and P is the number of poles which ?

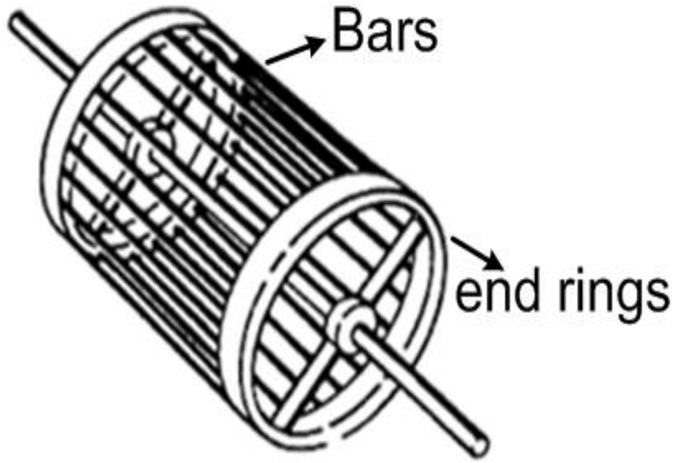
(How did we arrive at this expression?? Hint: Compare induced voltage angular frequency with rotational speed of the coil

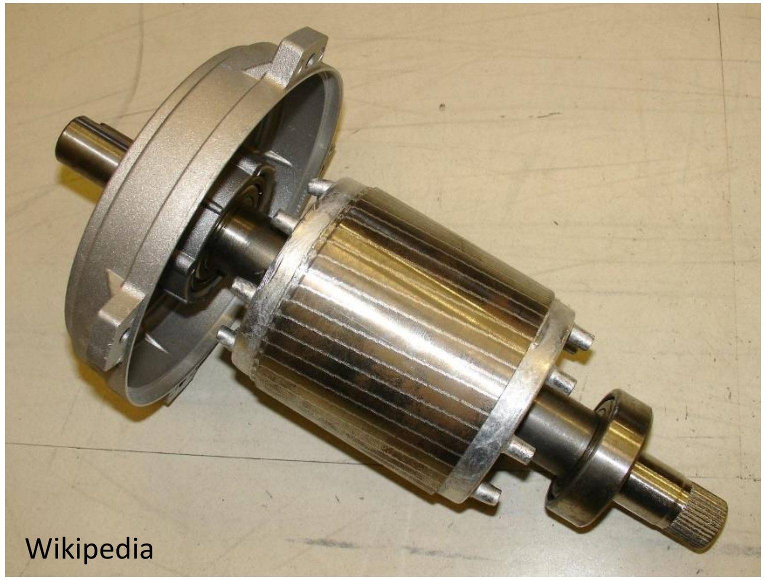
Rotor: two types of construction

1. squirrel cage $\rightarrow$ aluminum/ copper bars are embedded in the rotor slots and permanently shorted at both ends by Al/Cu end rings

$\Rightarrow$ electrically closed circuit

$\Rightarrow$ no additional 'R' can be connected



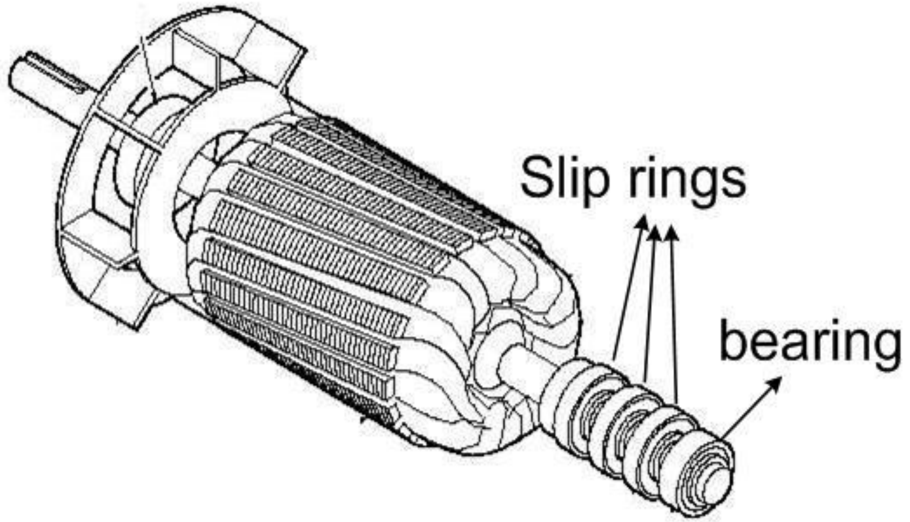


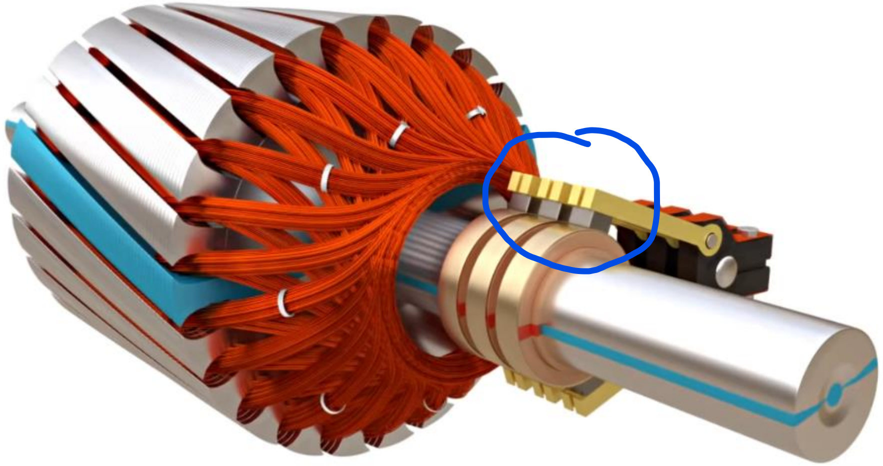
Rotor: two types of construction

2. slip ring rotor: three phase winding is placed in rotor slots

$\Rightarrow$ three terminals of the windings are connected to three rings fixed to rotor shaft

$\Rightarrow$ external 'R'/'Z'/'V' source can be connected to these rings via. brushes



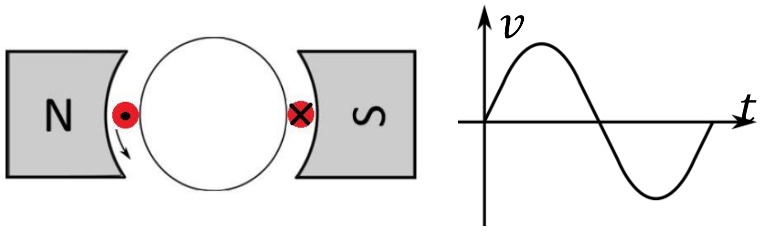


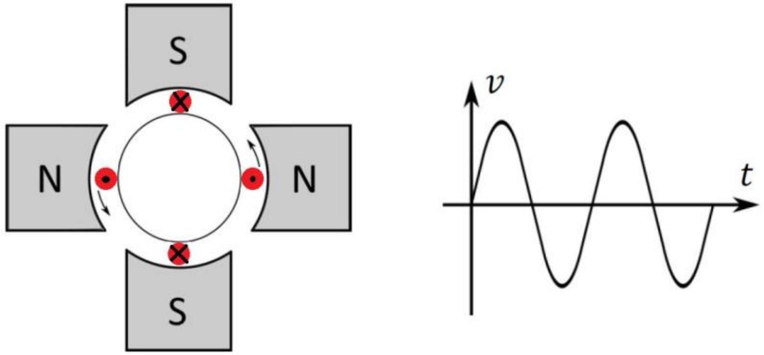
Youtube: Slip ring Induction Motor, How it works ?

- Number of cycles induced voltage completes in one rotation depends on number of poles
- Thus, if the conductors are rotated at 3000 rpm, the frequency of the induced emf for

  2-pole → 50 Hz
  4-pole → 100 Hz

$$\boxed{N_s = \frac{120f}{P}}$$





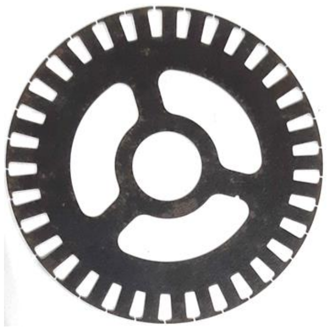
Suppose, we want the induced voltage of 50 Hz in 4-pole machine → Decrease the rotational speed to 1500 rpm

In case of induction machine, 3 coils of 'N' turns, displaced in space by 120°, and excited by i_a, i_b & i_c as follows

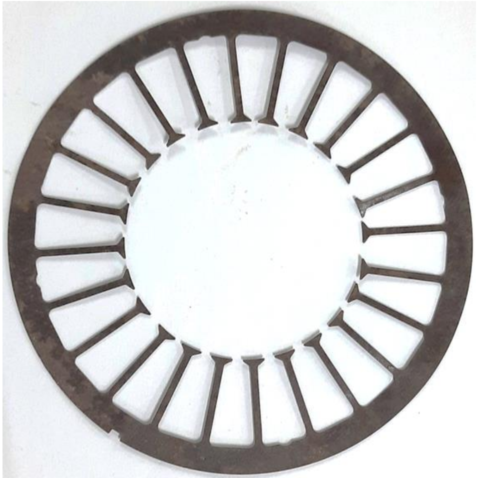
$$i_a = I_m \sin(\omega_s t)$$
$$i_b = I_m \sin\left(\omega_s t - \frac{2\pi}{3}\right),$$
$$i_c = I_m \sin\left(\omega_s t - \frac{4\pi}{3}\right), \qquad \text{where } \omega_s = 2\pi f$$

- For this arrangement (2-poles), if f = 50 Hz, the synchronous speed is 3000 rpm.
- If winding arrangement is modified to have 4-pole, then the synchronous speed of 3000 will result in f = 100 Hz.
- But, if f = 50 Hz for 4-pole machine, then synchronous speed will be 1500 rpm (half of 3000 rpm)

Stator for Concentrated winding

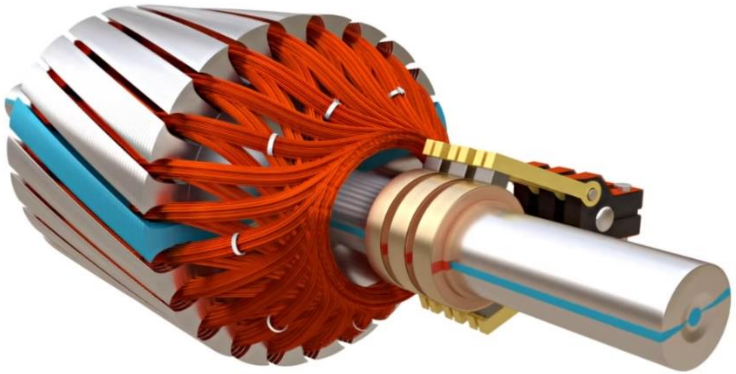


Rotor

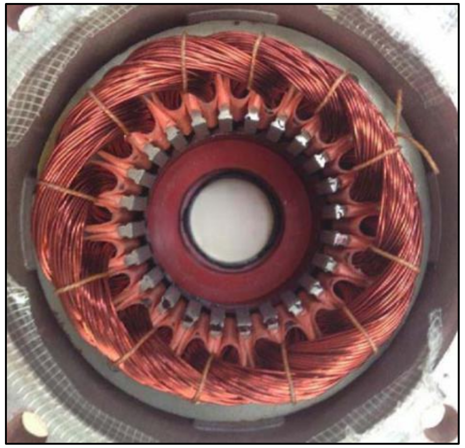


Stator for distributed winding

Squirrel Cage Rotor



Slip Ring Rotor



Stator with Distributed winding

- Windings in the stator of an induction motor are distributed → To produce sinusoidal MMF distribution in space

Induction motor: Principle of operation

?

- In both the rotor types, when the rotor is at rest, synchronously rotating stator field induces voltage of stator supply frequency in the rotor
  ∵ rotor is at rest, relative speed between stator field & rotor is
  $N_s - 0 = N_s \rightarrow$ maximum
  ∵ relative speed between field and conductor (rotor) is maximum,
  → induced emf, and therefore, rotor 'I' is maximum.

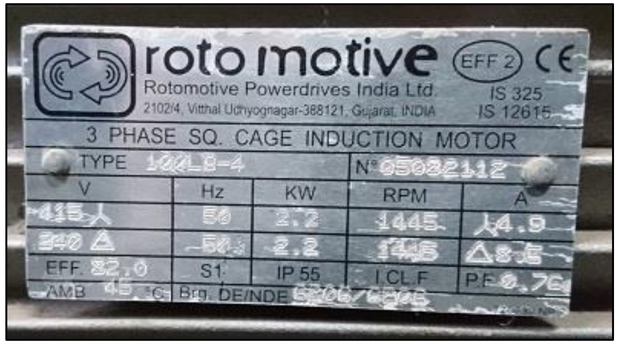
- Now, for any current in rotor there is an equivalent 'I' in stator
  (discussed in 2nd course)
  ∴ if an IM is started at rated 'V' & 'f', a high 'I' will be drawn from the source

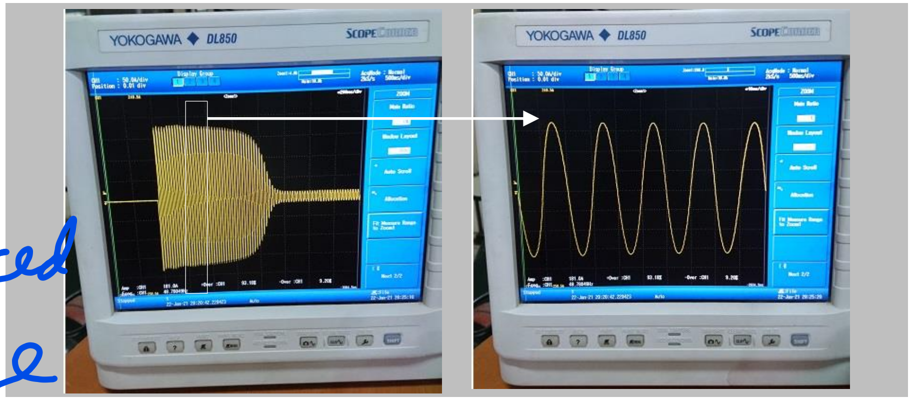
  only if it's given or induced induced voltage

→ This high 'I' could be ≅ (6 - 7) times the rated current of motor

?

Name plates of IM





Induction motor: Principle of operation

- Current carrying conductor placed in magnetic field experiences a force
  ∴ conductor (rotor) starts rotating
- As the speed ↑, relative speed between stator field & rotor ↓

As a result:

→ Induced 'V' in the rotor and hence the current ↓

→ Frequency of induced 'V' & 'I' in rotor ↓

→ rotor eventually reach a steady state speed N_r where, $N_r < N_s$

F_s, F_r, N_s, N_r, Rotor speed, stator speed?

$N_s = \frac{120f}{P}$

- N_r can not be = N_s because at $N_r = N_s$, relative speed between rotor (conductor) and stator field is zero

  → no emf, and therefore, no 'I' and no force or torque

- $N_s - N_r$ → slip speed

- Slip: $s = \frac{N_s - N_r}{N_s}$

Induction motor: Speed Control

- Consider a 4-pole, 50 Hz, Induction motor → $N_s = \frac{120 \times 50}{4} = 1500$ RPM
- $N_r \approx$ 1485 RPM when no external torque is applied
- Apply external torque (T_L) to the shaft
- Rotor will slow down → $(N_s - N_r) \uparrow \therefore$ 'V' induced in the rotor increased $\therefore$ 'I' $\uparrow$
- Torque developed (T_e) by the rotor $\uparrow$
- N_r will fall untill $T_e > T_L$
- At steady state, $T_e = T_L$ (neglecting friction)
- Corresponding speed is less than 1485 RPM → $\therefore$ speed of IM varies with application of external load

$T = K \phi I_a$

→ This variation is 2 - 3% of N_s, which is small!! What if a wide variation is required? (Fan, electric vehicle)

- We have to change the N_s (in FANS, 'N_s' is not changed!)
- N_s can be changed by changing the supply frequency..
- To reduce the speed, 'f' $\downarrow$ Recall that: $V = 4.44 f \phi_m N_{turns}$
- If the 'V' is kept constant and 'f' is reduced, ϕ_m tries to $\uparrow$ → this should not be done (discussed in 3rd course)
- Instead, ϕ_m is kept constant. This can be done by keeping $\boxed{\frac{V}{f} = \text{constant}}$

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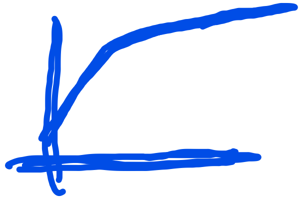
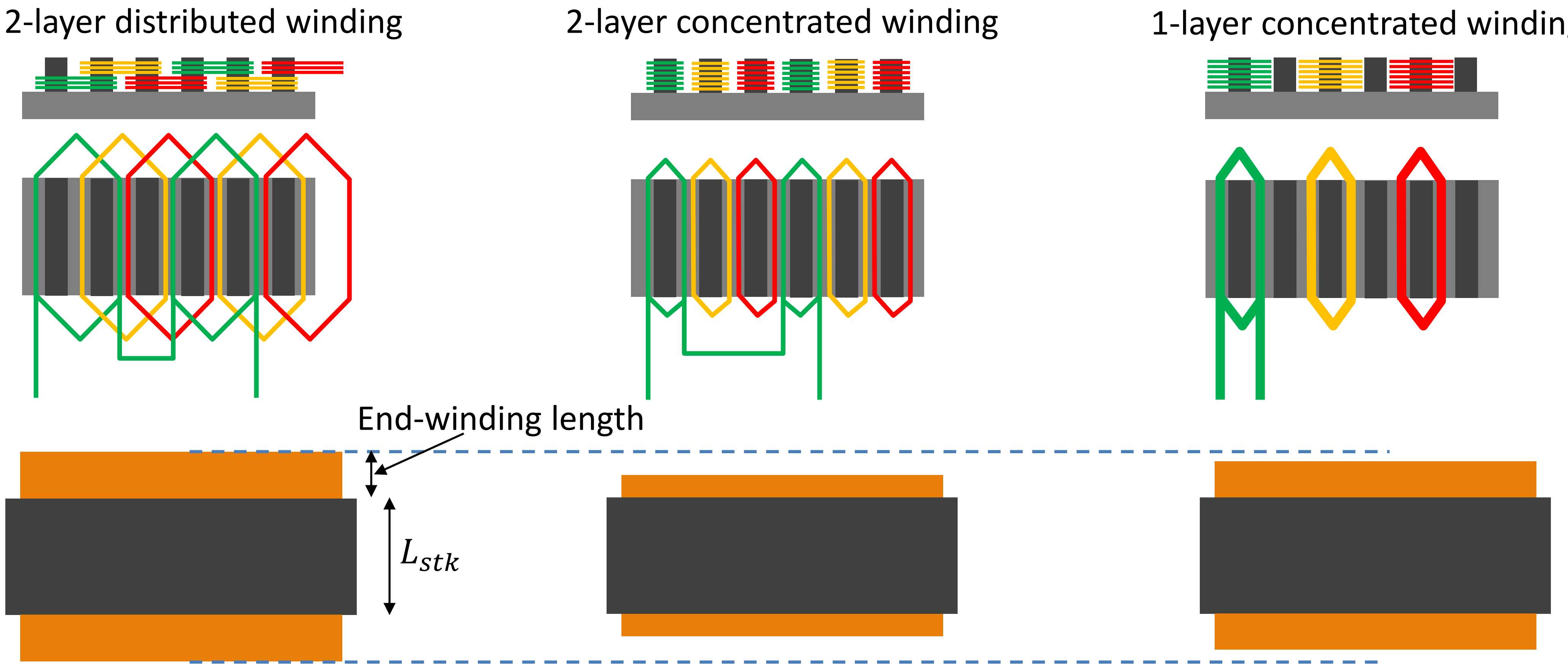


⇒ both, 'V' and 'f' are changed

Distributed and Concentrated Windings



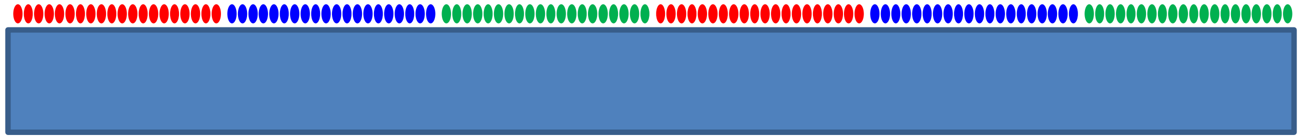
Distributed winding:

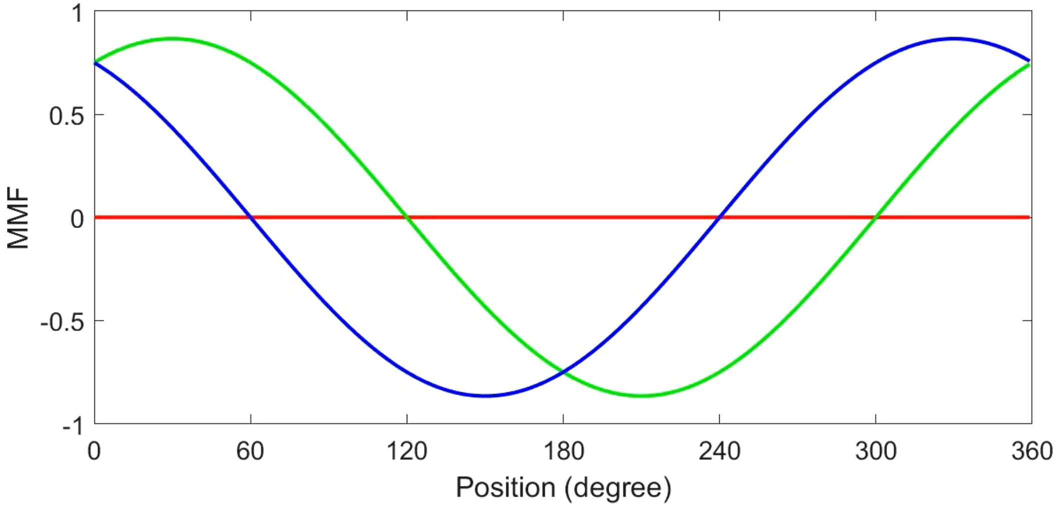
→ Larger end-windings → Larger copper losses

→ Larger frame size required

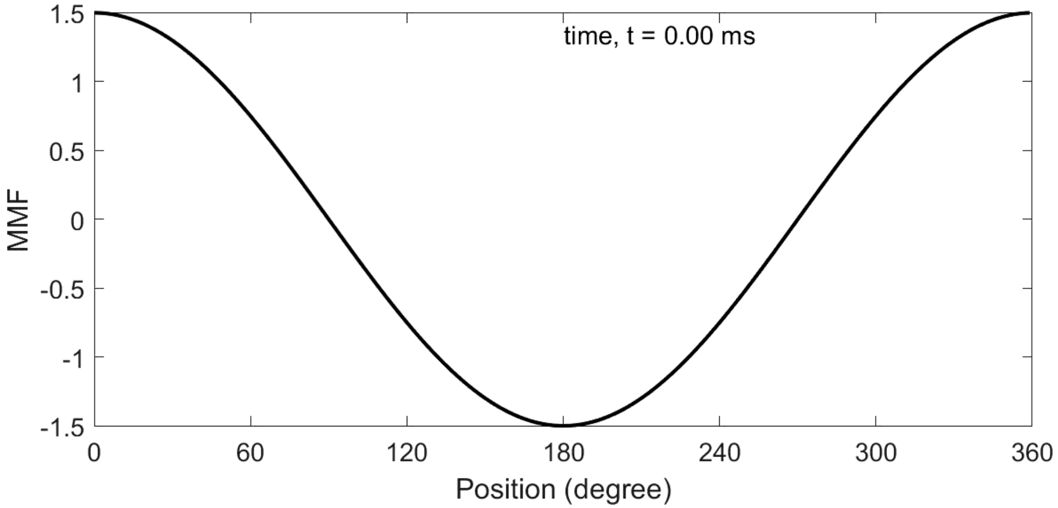
→ Lower harmonic content in MMF

Stator MMF due to distributed windings

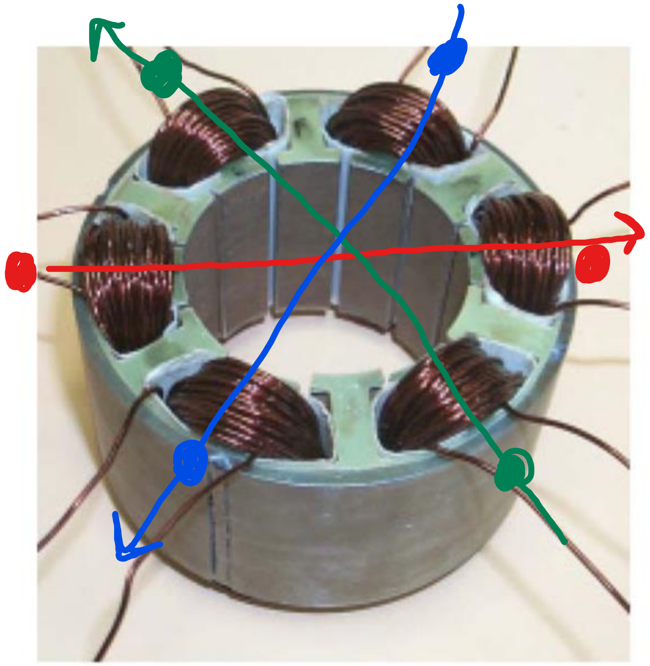


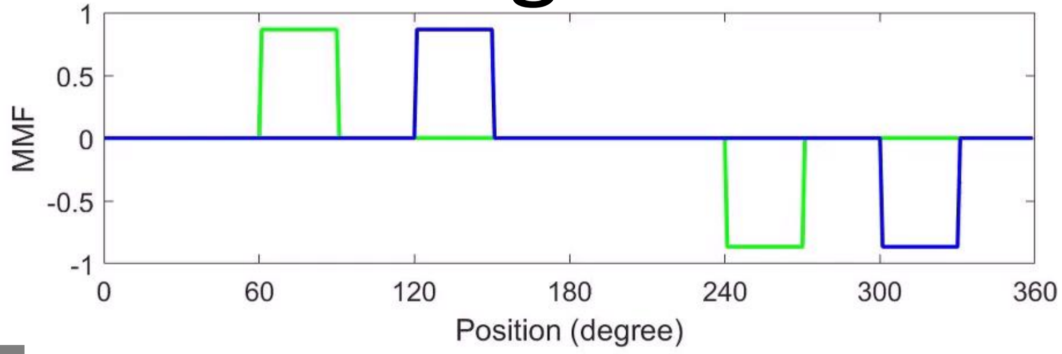


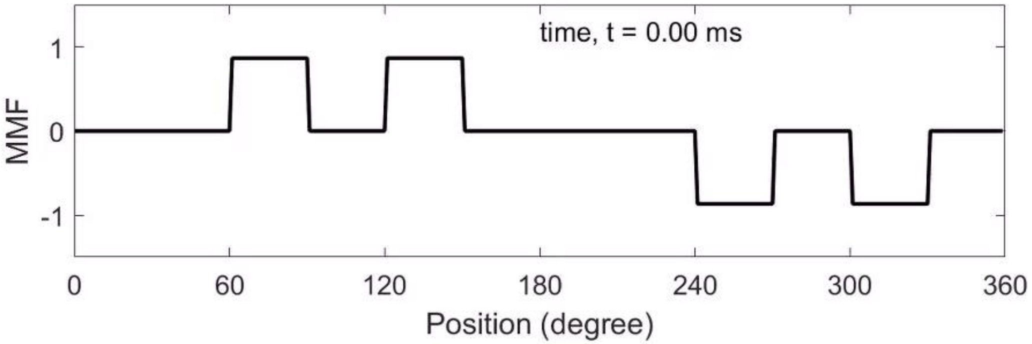
https://www.icrfq.net/motor-winding/

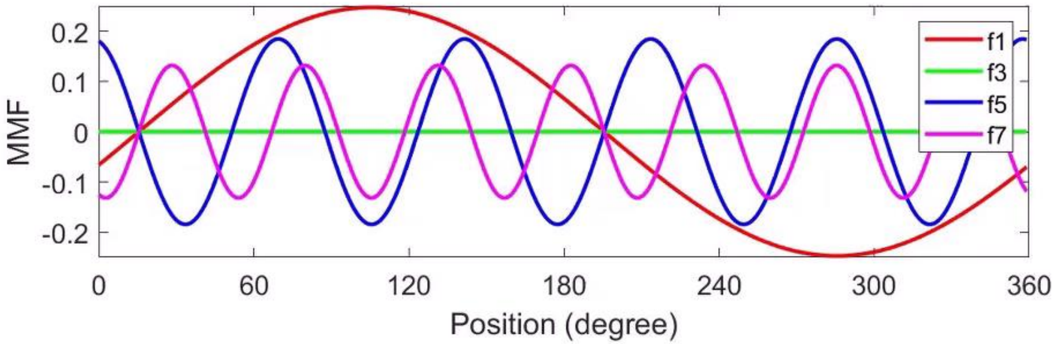


Stator MMF due to concentrated windings

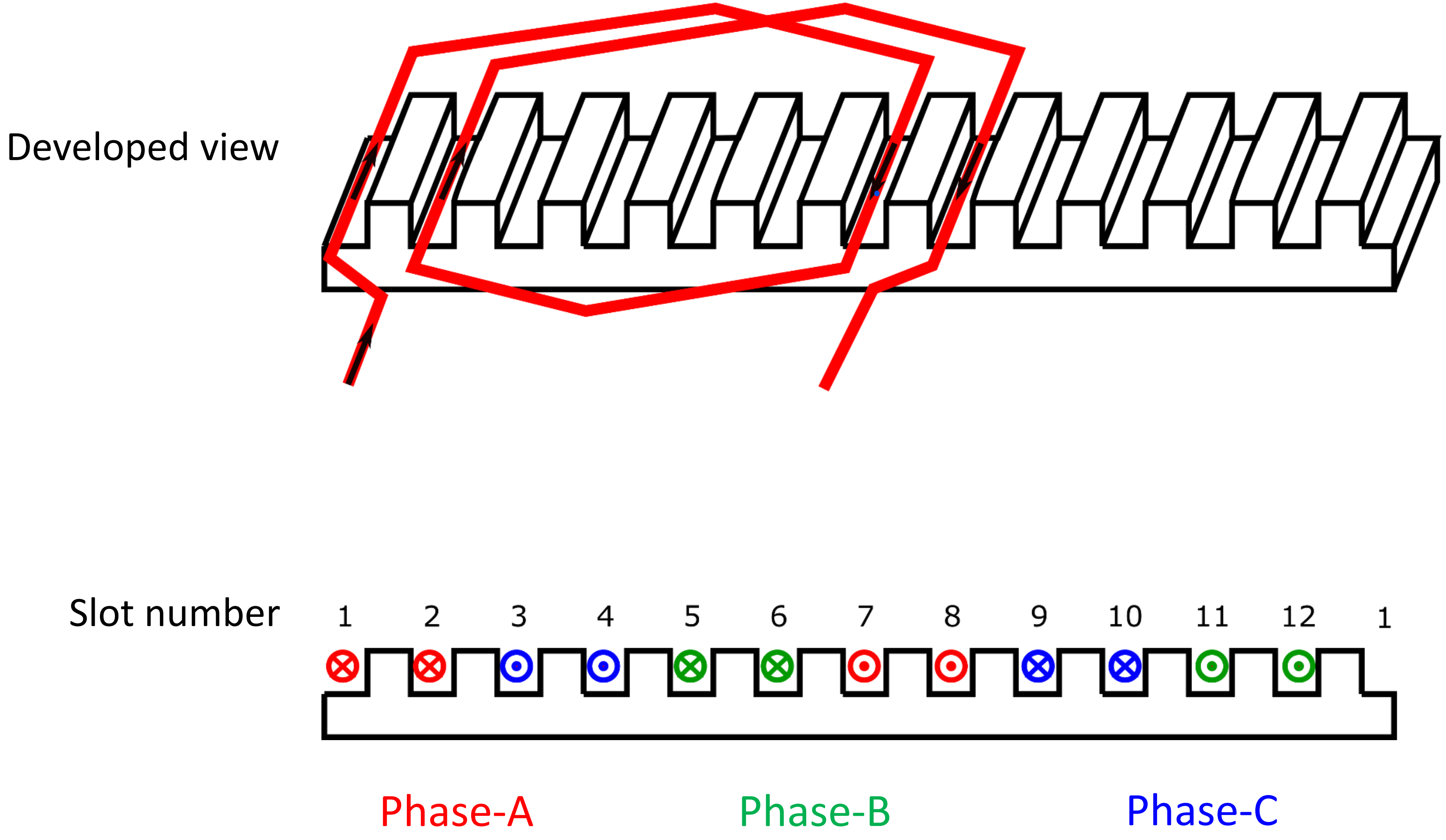








Distributed winding with spp = 2 (12-slot, 2-pole)



Synchronous Motor

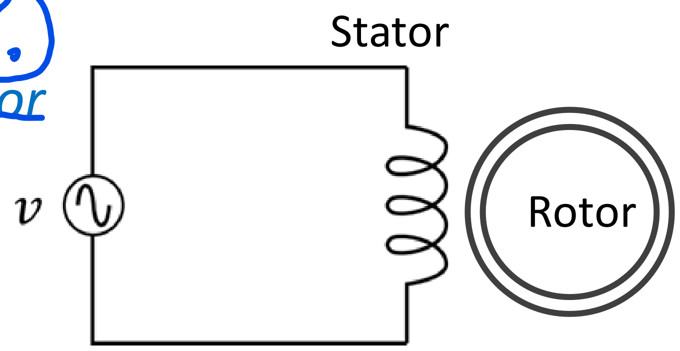
Generally,

- Stator of Induction Motor = Stator of Synchronous Machine
- Rotor → Winding excited by DC or Permanent Magnet (PMSM/ BLDC)

When Stator Winding of 3-phase IM is connected to 3-phase supply,

- Rotor starts rotating → Self Starting
- Synchronous Motor → Not a Self Starting Motor

?



So, are single phase motors

(1-phase supply will produce pulsating field)

- Average Torque =0

?

When Stator Winding of 3-phase, 2-pole IM (=SM) is connected to 3-phase, 50Hz supply,

- F_s starts rotating at 3000rpm $\left(\frac{120f}{P}\right)$

Synchronous Motor

Since the field produced by rotor is DC

- *Speed of* F_r *=Speed of Rotor* (N_r)
- *At* $t = 0, N_r = 0$ *(Rotor is stationary)*

  $= 0^+, N_r = 0$ *(Speed cannot change instantaneously, Rotor has its own inertia)*

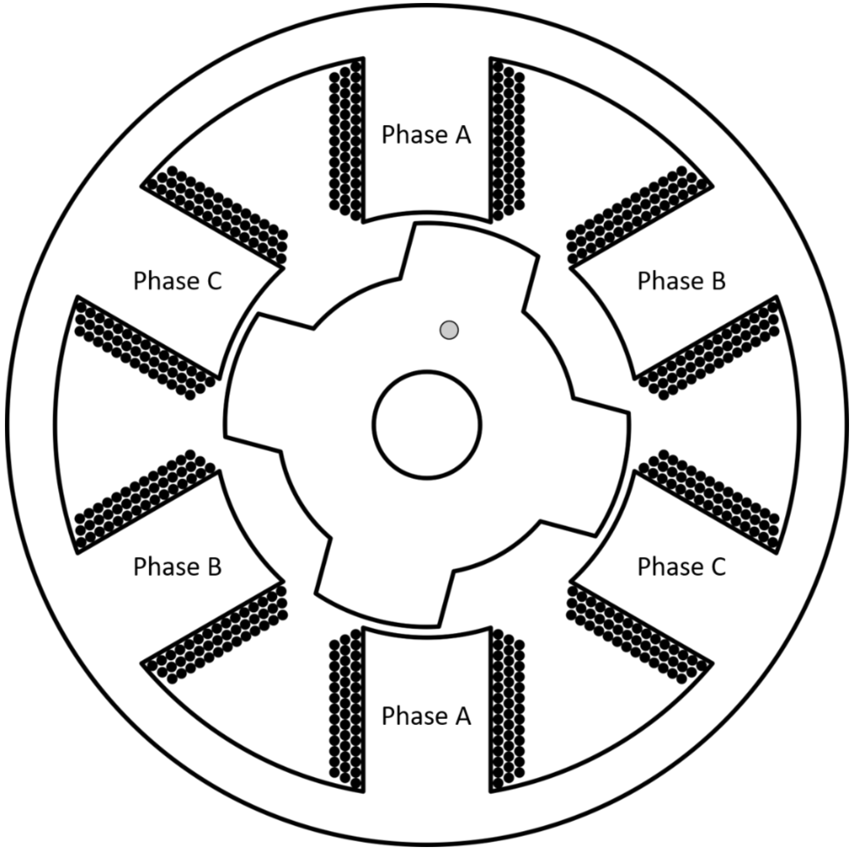
- *Speed of* $F_s \neq$ *Speed of* F_r, $\boxed{T_{avg} = 0}$?

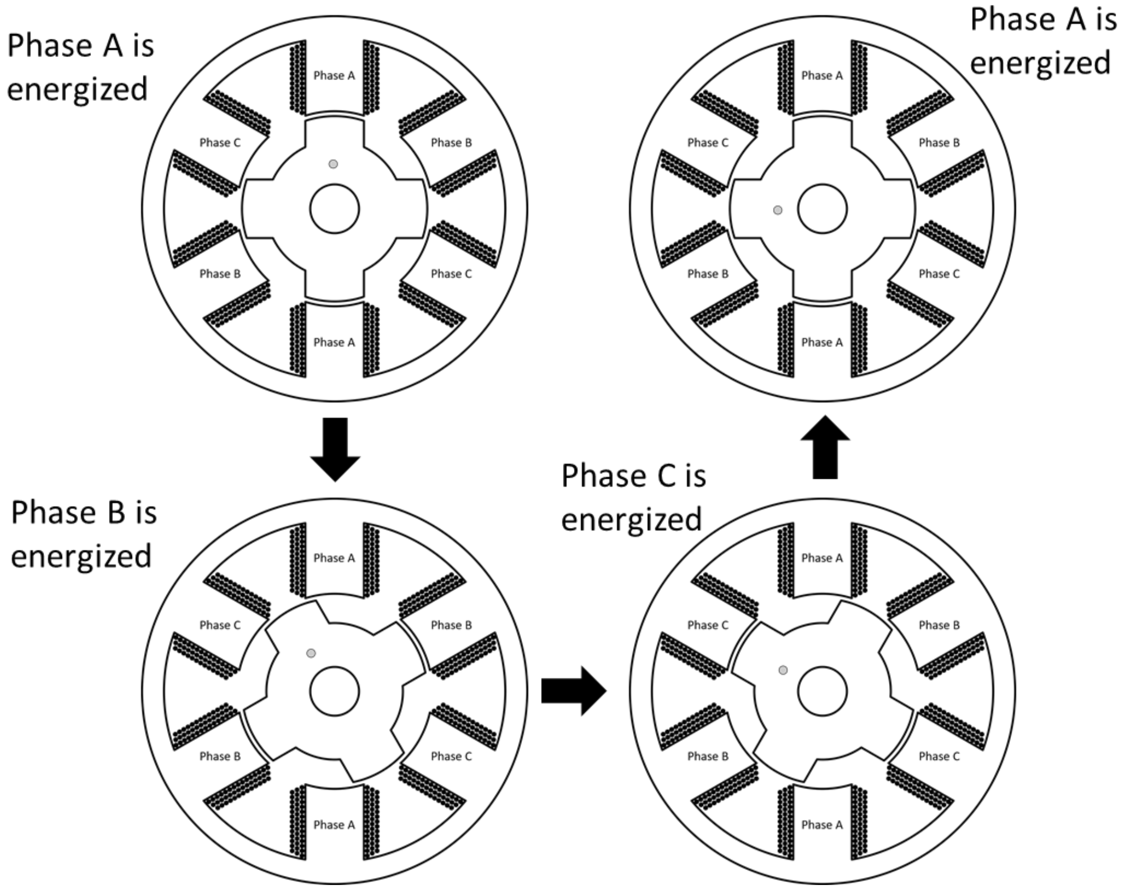
T_{avg} *is finite, when Speed of* $F_s =$ *Speed of* F_r, $(N_s = N_r)$

⟹ Hence the name Synchronous Motor

Torque production without a current carrying conductor in a magnetic field..

- Consider the following 'assembly'
- Rotor is made of ferromagnetic material
- No. of stator teeth not equal to rotor teeth





- Continuous rotation is achieved by repeating the sequence of phase excitation
- What would happen if the rotor is simply 'cylindrical'? Why??