CAN102
Electromagnetism and Electromechanics

2023/24-S2

Lecture 19 AC Machinery Fundamentals

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AC Machinery Fundamentals

✓ A simple loop in a uniform magnetic field

- Induced voltage
- Induced torque

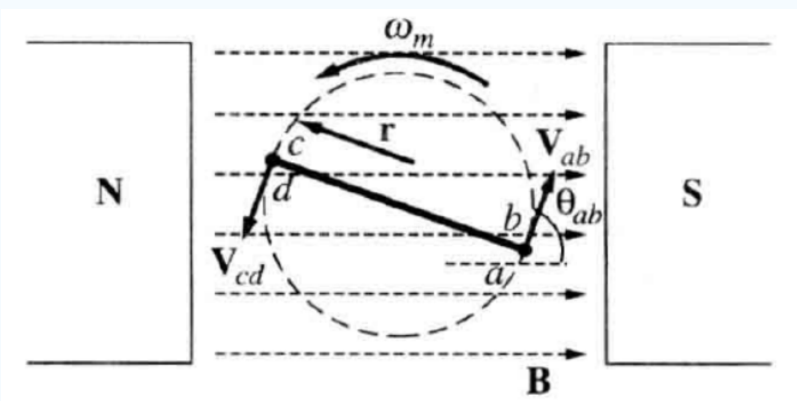
✓ Rotating Magnetic Field

- The rotating magnetic field concept
- Reversing the direction of magnetic field rotation
- The relationship between electrical frequency and the speed of magnetic field rotation

A simple loop in a uniform magnetic field

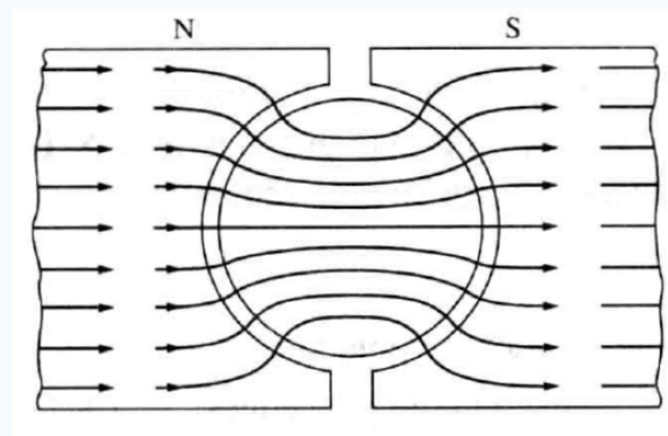
◆ **Uniform magnetic field**

- The magnetic field **B** is constant but not perpendicular to the surface (a cylinder) of the rotor.



◆ Curved magnetic field

- The magnetic field **B** is constant and perpendicular to the surface (a cylinder) of the rotor everywhere under the (N/S) poles faces and rapidly falls to zero beyond the pole edges.

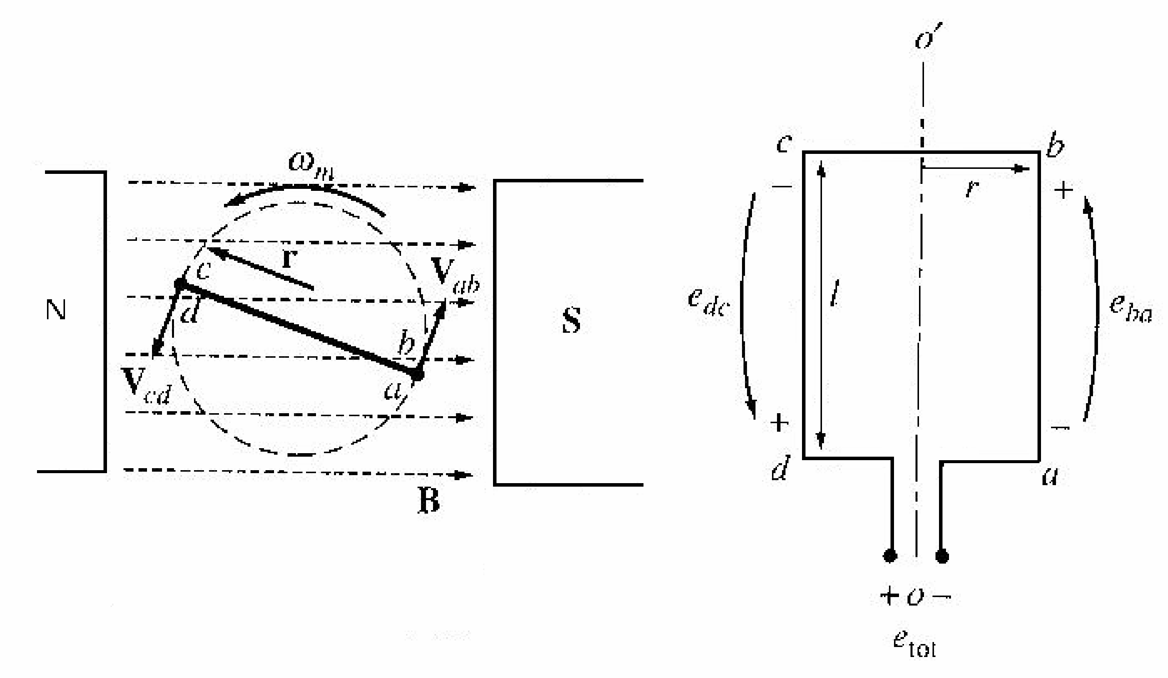


A simple loop in a uniform magnetic field

◆ Induced voltage in a moving loop

To determine the total voltage induced e_{tot} on the loop, examine each segment of the loop separately and sum all the resulting voltages. The voltage on each segment is given by equation

$$e_{ind} = (\mathbf{v} \times \mathbf{B}) \bullet \mathbf{l}$$



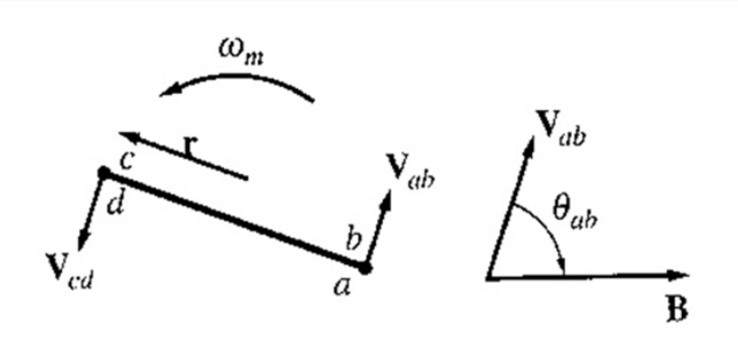
A simple loop in a uniform magnetic field

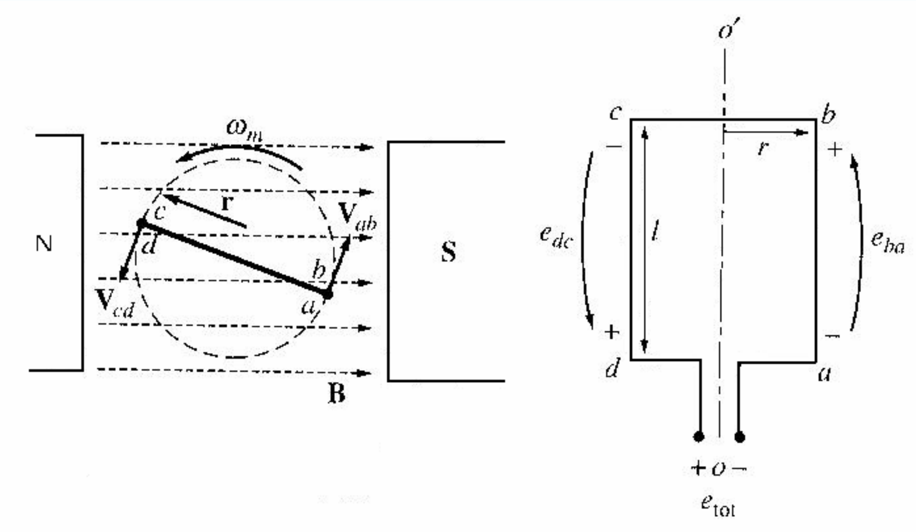
◆ Induced voltage in a moving loop

1. Segment *ab*

The velocity of the wire is tangential to the path of rotation, while the magnetic field **B** points to the right. The quantity **v** × **B** points into the page, which is the same direction as segment *ab*. Thus, the induced voltage on this segment is:

$$e_{ba} = (\mathbf{v} \times \mathbf{B}) \bullet \mathbf{l} = vBl \sin\theta_{ab} \qquad \text{into the page}$$





A simple loop in a uniform magnetic field

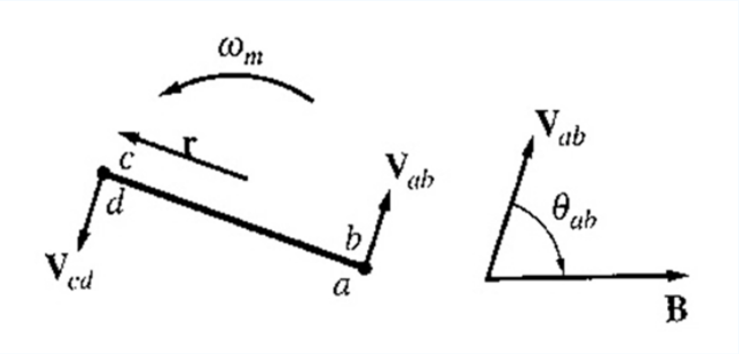
◆ Induced voltage in a moving loop

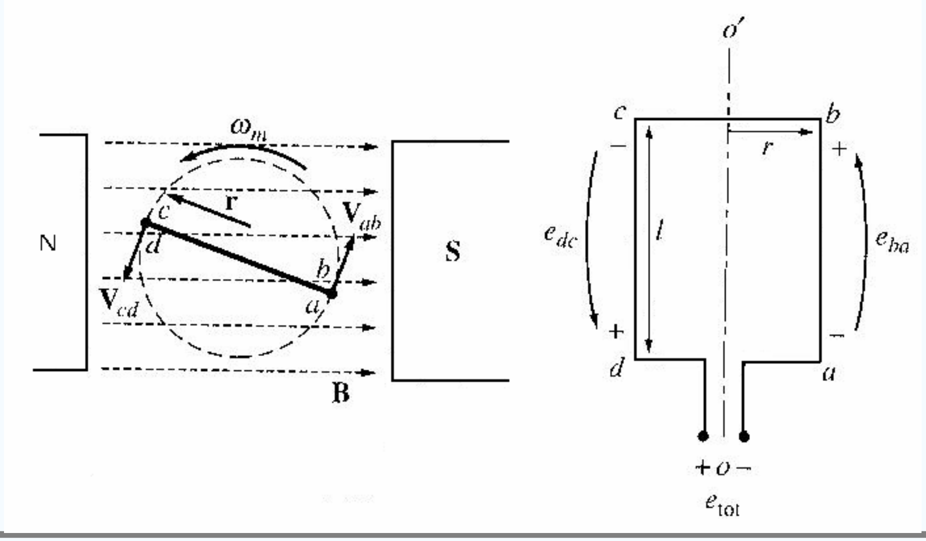
2. Segment *bc*

Since the length l is in the plane of the page, **v** × **B** is perpendicular to **l** for segment *bc*. Thus: $e_{cb} = 0$

3. Segment *da*

same as segment *bc*, **v** × **B** is perpendicular to l . Thus, $e_{da} = 0$





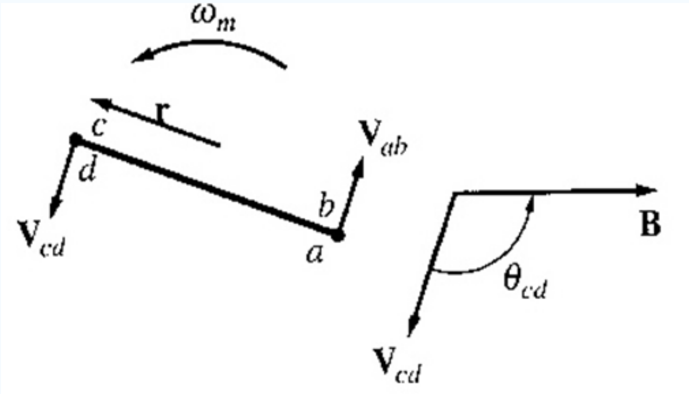
A simple loop in a uniform magnetic field

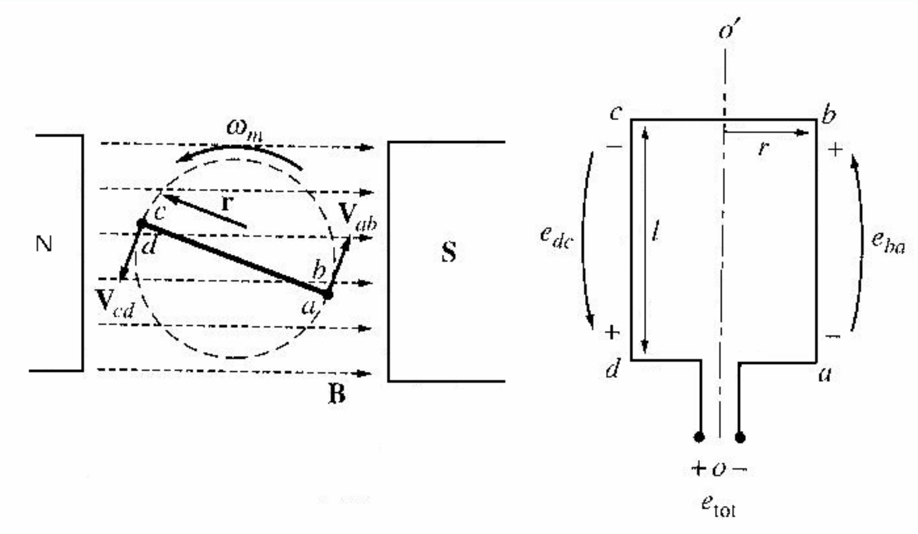
◆ Induced voltage in a moving loop

4. Segment *cd*

The velocity of the wire is tangential to the path of rotation, while **B** points to the right. The quantity **v** × **B** points out of the page, which is the same direction as segment *cd*. Thus,

$$e_{dc} = (\mathbf{v} \times \mathbf{B}) \bullet \mathbf{l} = vBl \sin \theta_{cd} \qquad \text{out of the page}$$





A simple loop in a uniform magnetic field

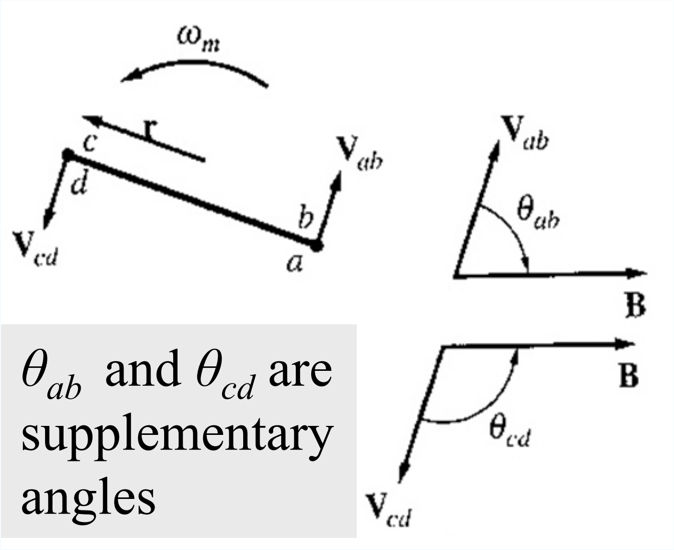
◆ Induced voltage in a moving loop

Total induced voltage on the loop

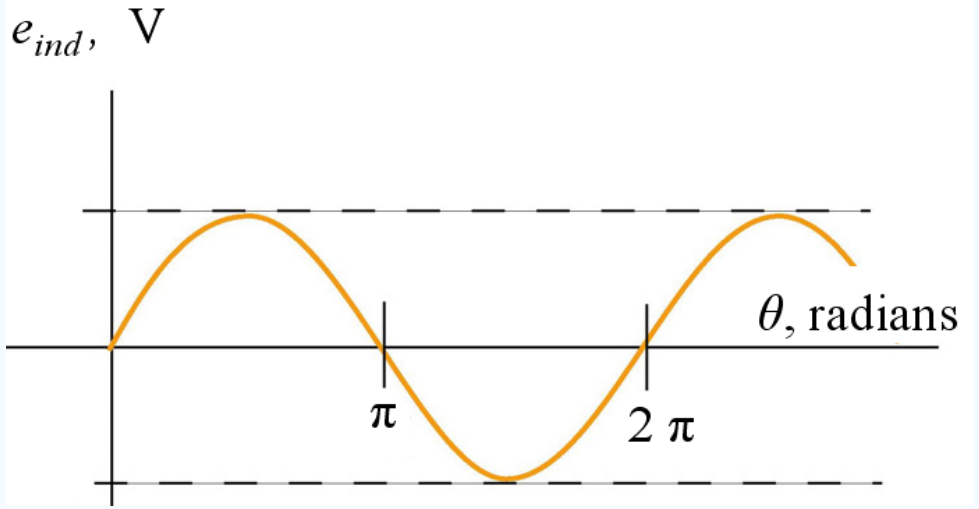
$e_{ind} = e_{ba} + e_{cb} + e_{dc} + e_{ad} = vBl \sin\theta_{ab} + vBl \sin\theta_{cd}$

since $\theta_{ab} = 180^{o} - \theta_{cd}$ and $\sin\theta = \sin(180^{o} - \theta)$, the total induced voltage on the loop becomes:

$$\boxed{e_{ind} = 2\, vBl \sin\theta}$$



θ_{ab} and θ_{cd} are supplementary angles



The induced voltage is shown as a function of angle.

A simple loop in a uniform magnetic field

◆ **Induced voltage in a moving loop** $\boxed{e_{ind} = 2\, vBl \sin\theta}$

Alternative expression of induced voltage for real AC machines

If the loop is rotating at a constant angular velocity ω, then the angle θ of the loop will increase linearly with time.

$$\theta = \omega t$$

also, the tangential velocity v of the edges of the loop is:

$$v = r\omega$$

where r is the radius from axis of rotation out to the edge of the loop and ω is the angular velocity of the loop. Hence,

$$e_{ind} = 2r\omega Bl \sin\omega t$$

since area of loop , $A = 2rl$ and maximum flux through the loop $\Phi_{\max} = AB$

$$e_{ind} = AB\omega \sin\omega t$$

$$e_{ind} = \Phi_{\max}\omega \sin \omega t$$

A simple loop in a uniform magnetic field

- **Induced voltage in a moving loop** $\boxed{e_{ind} = 2\, vBl \sin\theta}$

Alternative expression of induced voltage for real AC machines

$$\boxed{e_{ind} = \Phi_{\max}\,\omega \sin \omega t}$$

The voltage generated in the loop is a sinusoid whose magnitude is equal to the product of the flux inside the machine and the speed of rotation of the machine. This also true of real AC machines. In general, the voltage in a real machine will depend on three factors:

1. Flux level (the **B** component)
2. Speed of Rotation (the **v** component)
3. Machine Constants (such as: the number of loops, machine materials, …)

A simple loop in a uniform magnetic field

◆ Induced torque in a current-carrying loop

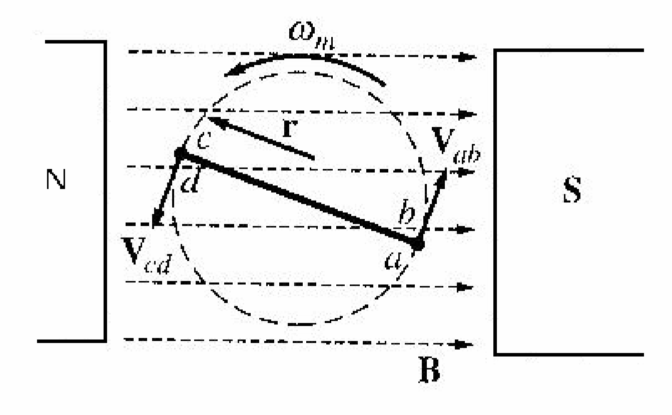
To determine the magnitude and direction of the torque, we examine the force and torque on each segment of the loop.

They are given by:

$$\mathbf{F} = i(\mathbf{l} \times \mathbf{B}) \qquad \text{and}$$

$$\tau = (\text{force})(\text{perpendicular distance})$$

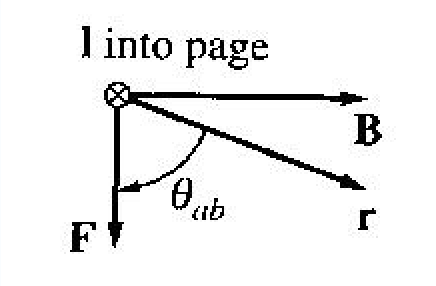
$$= (F)(r \sin\theta) = rF \sin\theta$$

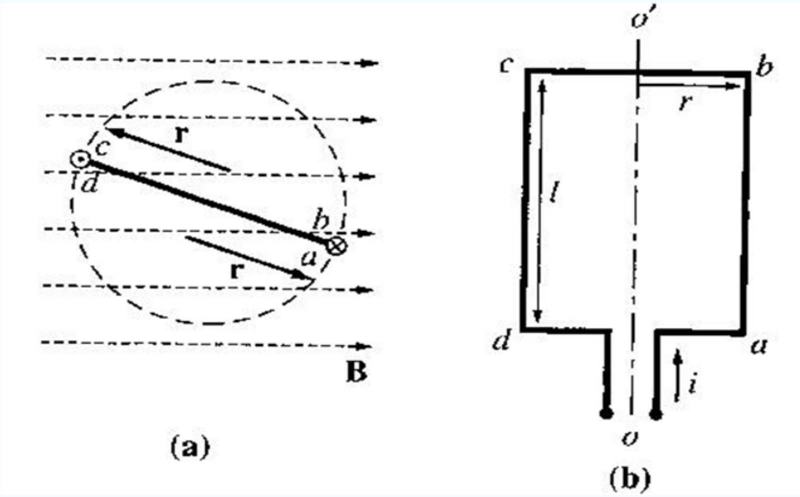


A simple loop in a uniform magnetic field

◆ Induced torque in a current-carrying loop

Assume that the rotor loop is at some arbitrary angle θ with the magnetic field, and that current is flowing in the loop.





1. Segment *ab*

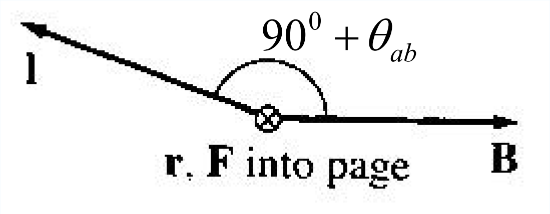
The direction of the current is into the page, while the magnetic field **B** points to the right. (**l** × **B**) points down.

$$\mathbf{F} = i(\mathbf{l} \times \mathbf{B}) = ilB$$

$$\tau_{ab} = F(r\sin\theta_{ab}) = rilB\sin\theta_{ab}$$ Clockwise

A simple loop in a uniform magnetic field

◆ Induced torque in a current-carrying loop

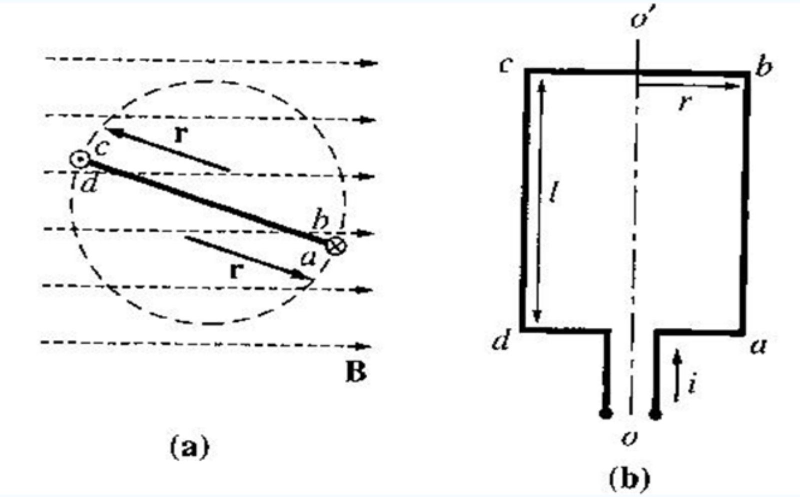


2. Segment *bc*

The direction of the current is in the plane of the page, while the magnetic field **B** points to the right. (**l** x **B**) points into the page. $\mathbf{F} = i(\mathbf{l} \times \mathbf{B}) = ilB\sin(90^0 + \theta_{ab})$

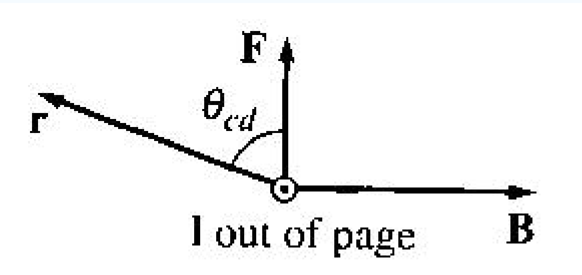
The force and the shaft are parallel and the angle $\theta_{bc} = 0$.

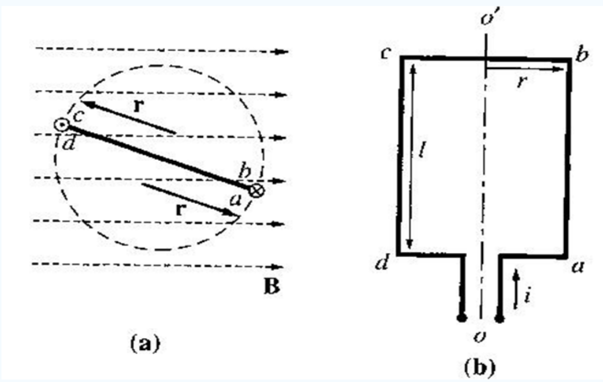
Then: $\tau_{bc} = F(r\sin\theta_{bc}) = 0$

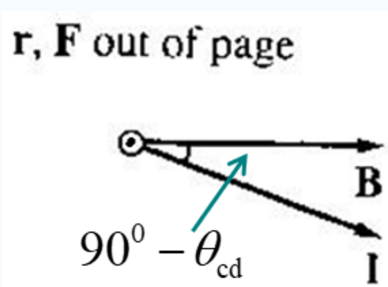


A simple loop in a uniform magnetic field

◆ Induced torque in a current-carrying loop







3. Segment *cd*

The direction of the current is out of the page, while the magnetic field **B** points to the right. (**l** x **B**) points up.

$$\mathbf{F}=i(\mathbf{l}\times\mathbf{B})=ilB$$

$$\tau_{cd}=F(r\sin\theta_{cd})=rilB\sin\theta_{cd}$$

Clockwise

4. Segment *da*

The direction of the current is in the plane of the page, while the magnetic field **B** points to the right. (**l** x **B**) points out of the page.

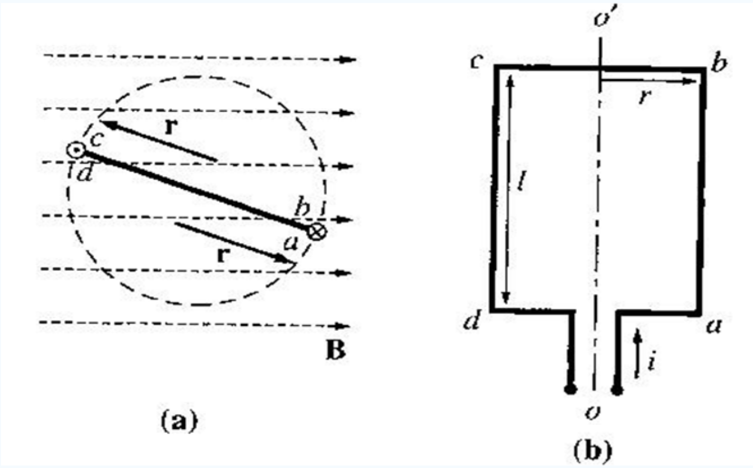
The force and the shaft are parallel and the angle $\theta_{da}=0$.

Then: $\mathbf{F}=i(\mathbf{l}\times\mathbf{B})=ilB\sin(90^0-\theta_{\mathrm{cd}})$

$$\tau_{bc}=F(r\sin\theta_{bc})=0$$

A simple loop in a uniform magnetic field

◆ **Induced torque in a current-carrying loop**



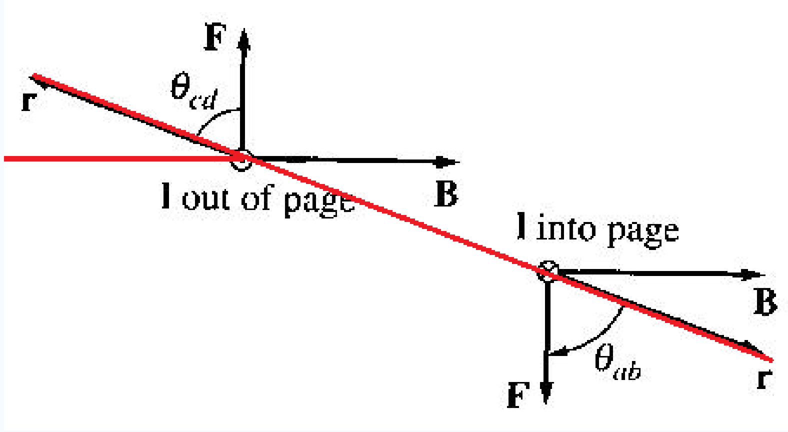
The total induced torque on the loop:

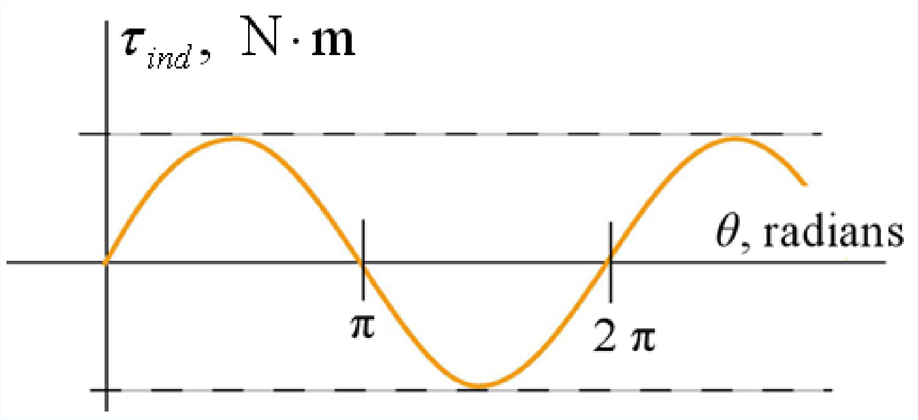
$$\tau_{total} = \tau_{ab} + \tau_{bc} + \tau_{cd} + \tau_{da}$$

$$= rilB\sin\theta_{ab} + rilB\sin\theta_{cd}$$

$$= 2rilB\sin\theta$$

θ_{ab} and θ_{cd} are vertical angles.





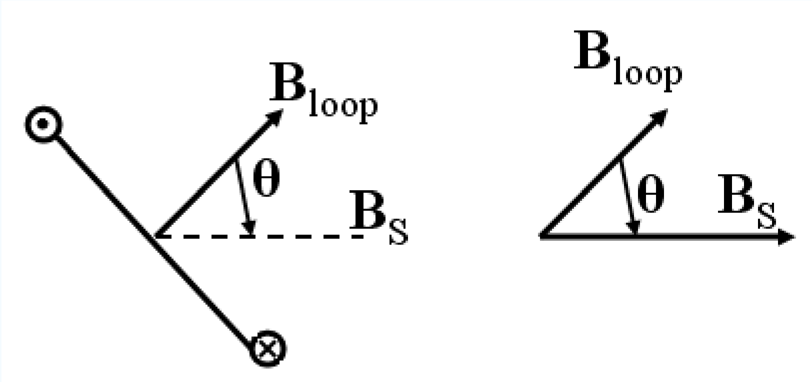
A simple loop in a uniform magnetic field

◆ **Induced torque in a current-carrying loop**

Alternative expression of induced torque for a real machine

If the current in the loop is as shown, that current will generate a magnetic flux density $\mathbf{B}_{\text{loop}}$ with the direction shown. The magnitude of $\mathbf{B}_{\text{loop}}$ is:

$$B_{loop} = \frac{\mu i}{G}$$



Where G is a factor that depends on the geometry of the loop.

(Refer to Lecture 9 Page 12-13)

A simple loop in a uniform magnetic field

- **Induced torque in a current-carrying loop**

$$\boxed{\tau_{ind} = 2rilB\sin\theta}$$

Alternative expression of induced torque for a real machine

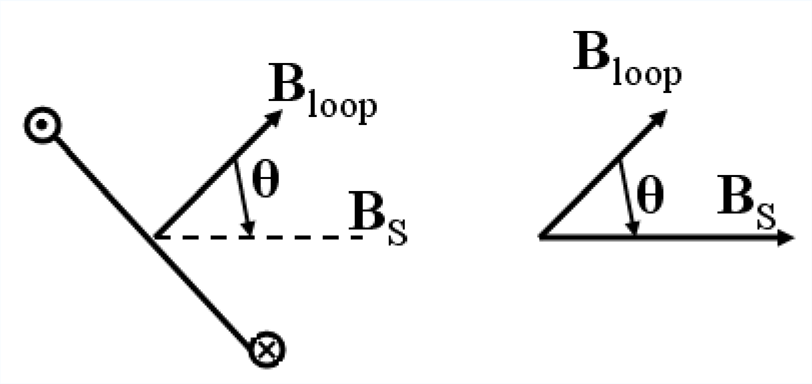
The area of the loop A is $2rl$

$$B_{loop} = \frac{\mu i}{G}$$

$$\tau_{ind} = \frac{AG}{\mu} B_{loop} B_S \sin\theta$$

$$= kB_{loop} B_S \sin\theta$$

$$\boxed{\boldsymbol{\tau}_{ind} = k\mathbf{B}_{loop} \times \mathbf{B}_S}$$



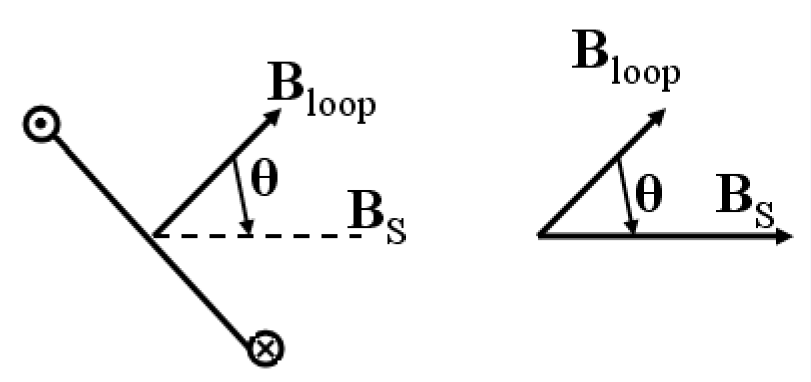
Where $k=AG/\mu$ is a factor depending on the construction of the machine, B_S is used for the stator magnetic field to distinguish it from the magnetic field generated by the rotor, and θ is the angle between $\mathbf{B}_{loop}$ and $\mathbf{B}_S$.

A simple loop in a uniform magnetic field

- **Induced torque in a current-carrying loop** $\boxed{\tau_{ind} = 2rilB\sin\theta}$

Alternative expression of induced torque for a real machine

$$\boxed{\boldsymbol{\tau}_{ind} = k\mathbf{B}_{loop} \times \mathbf{B}_S}$$



From here, we may conclude that torque is dependent upon:

- Strength of rotor magnetic field
- Strength of stator magnetic field
- Angle between two fields
- Machine constants – represent the construction of the machine (geometry, etc.)

The Rotating Magnetic Field

$$\boxed{\boldsymbol{\tau}_{ind} = k\mathbf{B}_{loop} \times \mathbf{B}_S}$$

If two magnetic fields are present in a machine, then a torque will be created which will tend to line up the two machine fields, making the angle is equal to 0.

If one magnetic field is produced by the stator of an AC machine and the other one is produced by the rotor of the machine, then a torque will be induced in the rotor which will cause the rotor to turn and align itself with the stator magnetic field.

If there were some way to **make the stator magnetic field rotate**, then the induced torque in the rotor would cause it to constantly "chase" the stator magnetic field around in a circle.

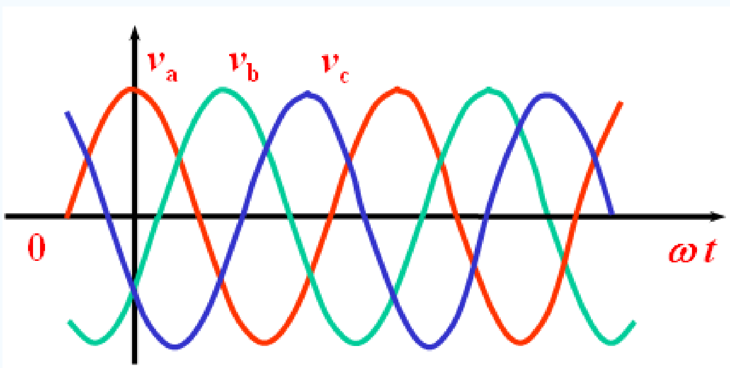
The basic principle of all AC motors operation

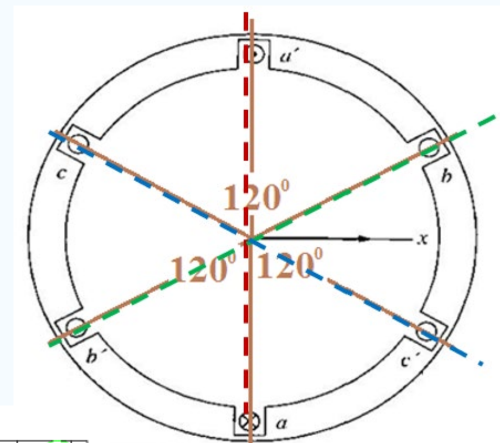
How to make the stator magnetic field rotate?

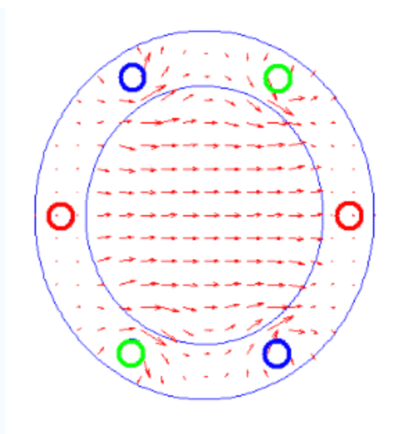
The Rotating Magnetic Field

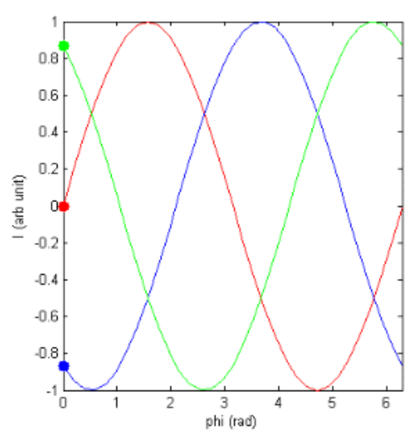
Fundamental principle:

If a three-phase set of currents, each of **equal magnitude** and **differing in phase by 120°**, flows in a three-phase winding, then it will produce a rotating magnetic field of constant magnitude.



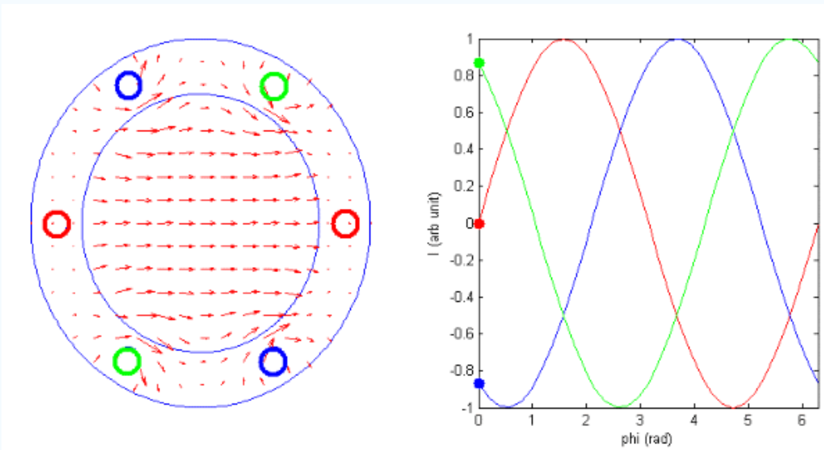






The Rotating Magnetic Field

The rotating magnetic field concept is illustrated below – empty stator containing 3 coils 120º apart. It is a 2-pole winding (one north and one south).

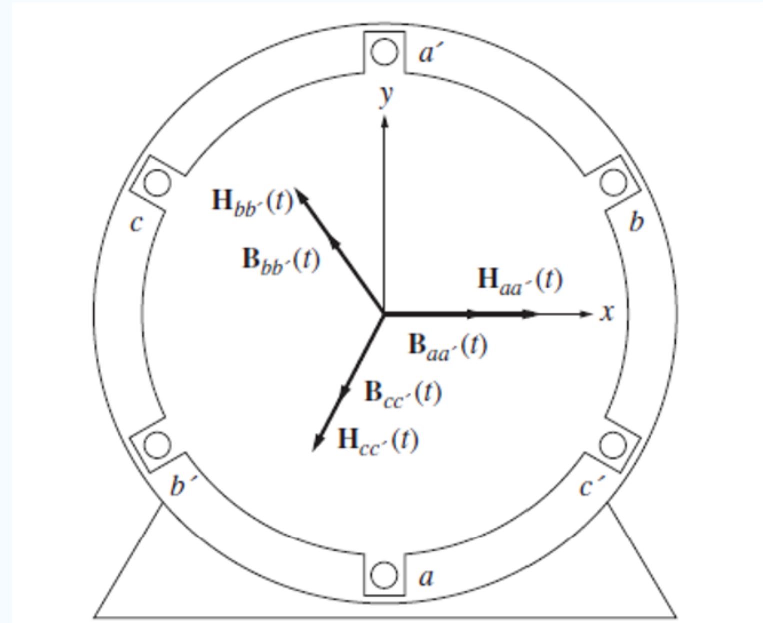


Assume currents in the 3 coils are:

$$i_{aa'}(t) = I_M \sin \omega t \ A$$

$$i_{bb'}(t) = I_M \sin(\omega t - 120°) A$$

$$i_{cc'}(t) = I_M \sin(\omega t - 240°) A$$



(a)

(a) A simple three phase stator. Currents in this stator are assumed positive if they flow into the unprimed end and out the primed end of the coils.

The Rotating Magnetic Field

Assume currents in the 3 coils are:

Phase

$$i_{aa'}(t) = I_M \sin \omega t \; A$$

$$i_{bb'}(t) = I_M \sin(\omega t - 120°) A$$

$$i_{cc'}(t) = I_M \sin(\omega t - 240°) A$$

Ampere's Law

L9-P19

Then the magnetic field intensity created by the three coils:

Spatial angle

$$\mathbf{H}_{aa'}(t) = H_M \sin \omega t \angle 0° \quad \text{A} \bullet \text{turns / m}$$

$$\mathbf{H}_{bb'}(t) = H_M \sin(\omega t - 120°) \angle 120° \quad \text{A} \bullet \text{turns / m}$$

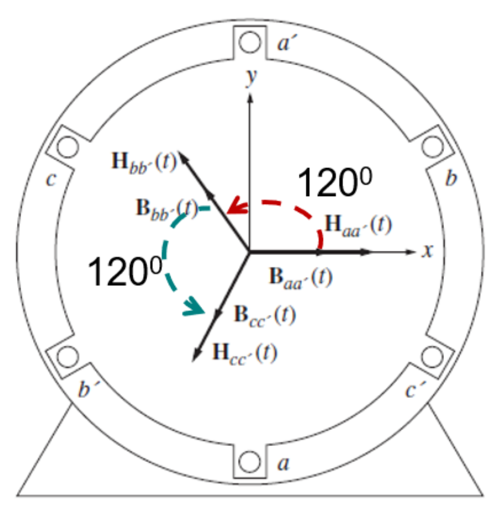
$$\mathbf{H}_{cc'}(t) = H_M \sin(\omega t - 240°) \angle 240° \quad \text{A} \bullet \text{turns / m}$$

$$B_M = \mu H_M$$

$$\mathbf{B}_{aa'}(t) = B_M \sin \omega t \angle 0° \quad \text{T}$$

$$\mathbf{B}_{bb'}(t) = B_M \sin(\omega t - 120°) \angle 120° \quad \text{T}$$

$$\mathbf{B}_{cc'}(t) = B_M \sin(\omega t - 240°) \angle 240° \quad \text{T}$$

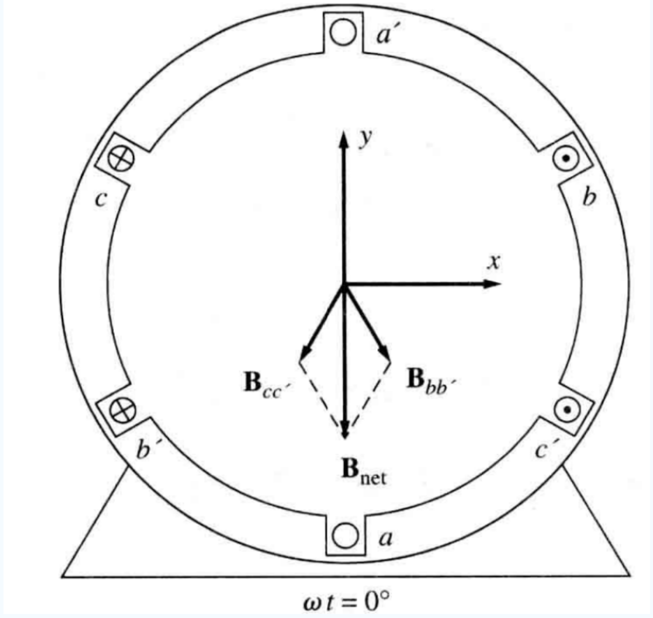


The Rotating Magnetic Field

$$\mathbf{B}_{aa'}(t) = B_M \sin \omega t \angle 0^\circ \quad \text{T}$$
$$\mathbf{B}_{bb'}(t) = B_M \sin (\omega t - 120^\circ) \angle 120^\circ \quad \text{T}$$
$$\mathbf{B}_{cc'}(t) = B_M \sin (\omega t - 240^\circ) \angle 240^\circ \quad \text{T}$$

At $\omega t = 0$:

$$\mathbf{B}_{aa'} = 0$$
$$\mathbf{B}_{bb'} = B_M \sin (-120^\circ) \angle 120^\circ$$
$$\mathbf{B}_{cc'} = B_M \sin (-240^\circ) \angle 240^\circ$$



The total magnetic field:

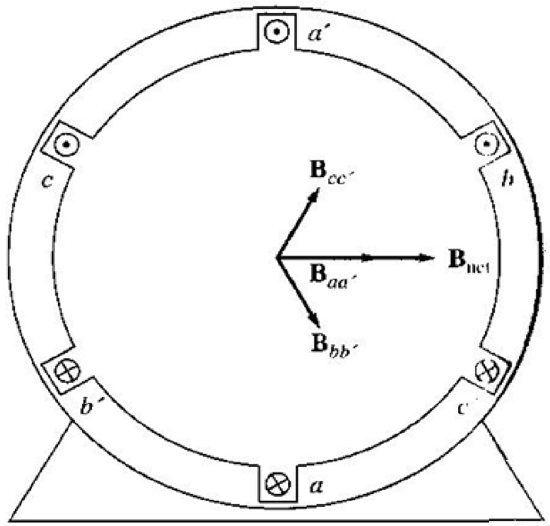
$$\mathbf{B}_{net} = \mathbf{B}_{aa'} + \mathbf{B}_{bb'} + \mathbf{B}_{cc'}$$
$$= 0 + \left(-\frac{\sqrt{3}}{2}B_M\right)\angle 120^\circ + \left(\frac{\sqrt{3}}{2}B_M\right)\angle 240^\circ$$
$$= \left(\frac{\sqrt{3}}{2}B_M\right)\left[-\left(\cos 120^\circ \hat{\mathbf{x}} + \sin 120^\circ \hat{\mathbf{y}}\right) + \left(\cos 240^\circ \hat{\mathbf{x}} + \sin 240^\circ \hat{\mathbf{y}}\right)\right]$$
$$= \left(\frac{\sqrt{3}}{2}B_M\right)\left(\frac{1}{2}\hat{\mathbf{x}} - \frac{\sqrt{3}}{2}\hat{\mathbf{y}} - \frac{1}{2}\hat{\mathbf{x}} - \frac{\sqrt{3}}{2}\hat{\mathbf{y}}\right)$$
$$= \left(\frac{\sqrt{3}}{2}B_M\right)\left(-\sqrt{3}\,\hat{\mathbf{y}}\right) = -1.5B_M\,\hat{\mathbf{y}} = 1.5B_M \angle -90^\circ$$

The Rotating Magnetic Field

$$\mathbf{B}_{aa'}(t) = B_M \sin \omega t \angle 0° \quad \text{T}$$
$$\mathbf{B}_{bb'}(t) = B_M \sin (\omega t - 120°) \angle 120° \quad \text{T}$$
$$\mathbf{B}_{cc'}(t) = B_M \sin (\omega t - 240°) \angle 240° \quad \text{T}$$

At $\omega t = 90°$:

$$\mathbf{B}_{aa'} = B_M \angle 0°$$
$$\mathbf{B}_{bb'} = -0.5\, B_M \angle 120°$$
$$\mathbf{B}_{cc'} = -0.5\, B_M \angle 240°$$



$\omega t = 90°$

The total magnetic field:

$$\mathbf{B}_{net} = \mathbf{B}_{aa'} + \mathbf{B}_{bb'} + \mathbf{B}_{cc'}$$
$$= B_M \angle 0° + \left(-\frac{1}{2} B_M\right) \angle 120° + \left(-\frac{1}{2} B_M\right) \angle 240°$$
$$= B_M \left[\hat{\mathbf{x}} - \frac{1}{2}\left(\cos 120° \hat{\mathbf{x}} + \sin 120° \hat{\mathbf{y}}\right) - \frac{1}{2}\left(\cos 240° \hat{\mathbf{x}} + \sin 240° \hat{\mathbf{y}}\right)\right]$$
$$= B_M \left(\hat{\mathbf{x}} - \frac{1}{2}\left(-\frac{1}{2}\hat{\mathbf{x}} + \frac{\sqrt{3}}{2}\hat{\mathbf{y}}\right) - \frac{1}{2}\left(-\frac{1}{2}\hat{\mathbf{x}} - \frac{\sqrt{3}}{2}\hat{\mathbf{y}}\right)\right)$$
$$= B_M \left(\hat{\mathbf{x}} + \frac{1}{2}\hat{\mathbf{x}} \right) = 1.5 B_M \hat{\mathbf{x}} = 1.5 B_M \angle 0°$$

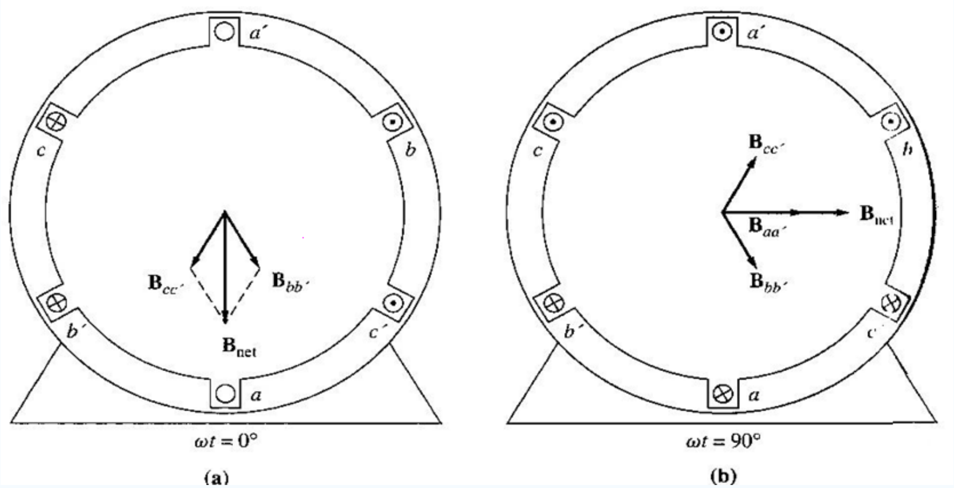
The Rotating Magnetic Field

At any time t, the magnetic field will have the same magnitude 1.5 B_M and it will continue to rotate at angular velocity ω.

$$B_{net}(t) = B_M \sin \omega t \angle 0° + B_M \sin(\omega t - 120°) \angle 120° + B_M \sin(\omega t - 240°) \angle 240° \; T$$

We may convert the total flux density into unit vector forms to give:

$$\boxed{\mathbf{B}_{net}(t) = 1.5 B_M \left(\sin \omega t \, \hat{\mathbf{x}} - \cos \omega t \, \hat{\mathbf{y}} \right)}$$



The magnitude of the field is a constant $1.5B_M$ and the angle changes continually in a **counterclockwise** direction at angular velocity ω.

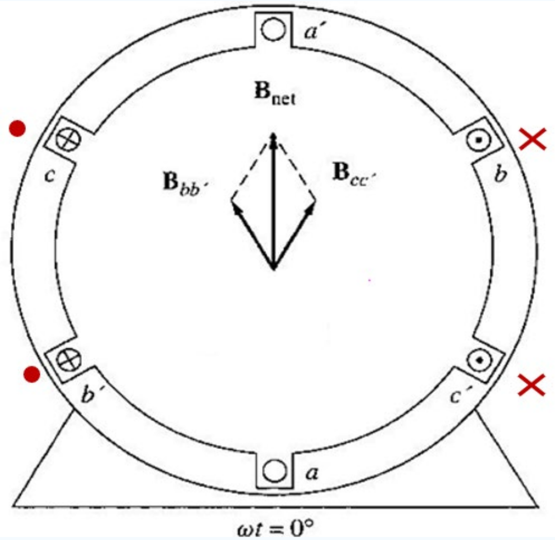
The Rotating Magnetic Field

Reversing the direction of Magnetic Field Rotation

If the current in any two of the 3 coils is swapped, the direction of the magnetic field's rotation will be reversed.

Phases *B* and *C* are switched. Now the flux densities equation are:

$$\mathbf{B}_{aa'}(t) = B_M \sin \omega t \angle 0° \quad \text{T}$$
$$\mathbf{B}_{bb'}(t) = B_M \sin (\omega t - 240°) \angle 120° \quad \text{T}$$
$$\mathbf{B}_{cc'}(t) = B_M \sin (\omega t - 120°) \angle 240° \quad \text{T}$$



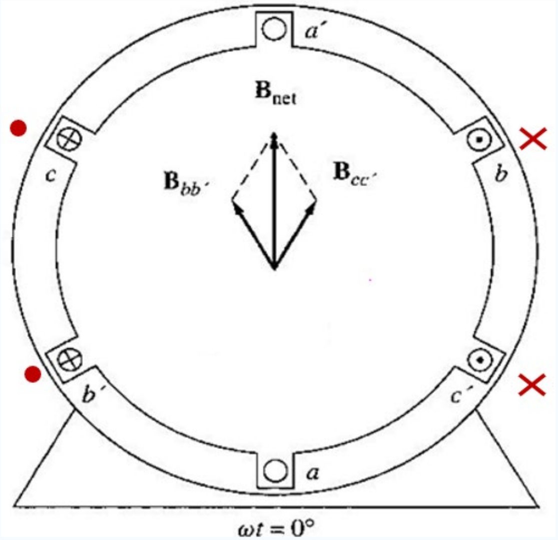
The Rotating Magnetic Field

Reversing the direction of Magnetic Field Rotation

$$\mathbf{B}_{aa'}(t) = B_M \sin \omega t \angle 0^\circ \quad \text{T}$$
$$\mathbf{B}_{bb'}(t) = B_M \sin (\omega t - 240^\circ) \angle 120^\circ \quad \text{T}$$
$$\mathbf{B}_{cc'}(t) = B_M \sin (\omega t - 120^\circ) \angle 240^\circ \quad \text{T}$$

At $\omega t = 0^\circ$:

$$\mathbf{B}_{aa'} = 0$$
$$\mathbf{B}_{bb'} = B_M \sin(-240^\circ)\angle 120^\circ \; T$$
$$\mathbf{B}_{cc'} = B_M \sin(-120^\circ)\angle 240^\circ \; T$$



The total magnetic field:

$$\mathbf{B}_{net} = \mathbf{B}_{aa'} + \mathbf{B}_{bb'} + \mathbf{B}_{cc'}$$
$$= 0 + \left(\frac{\sqrt{3}}{2} B_M\right)\angle 120^\circ + \left(-\frac{\sqrt{3}}{2} B_M\right)\angle 240^\circ$$
$$= \left(\frac{\sqrt{3}}{2} B_M\right)\left[\left(\cos 120^\circ \hat{\mathbf{x}} + \sin 120^\circ \hat{\mathbf{y}}\right) - \left(\cos 240^\circ \hat{\mathbf{x}} + \sin 240^\circ \hat{\mathbf{y}}\right)\right]$$
$$= \left(\frac{\sqrt{3}}{2} B_M\right)\left(-\frac{1}{2}\hat{\mathbf{x}} + \frac{\sqrt{3}}{2}\hat{\mathbf{y}} + \frac{1}{2}\hat{\mathbf{x}} + \frac{\sqrt{3}}{2}\hat{\mathbf{y}}\right) = \left(\frac{\sqrt{3}}{2} B_M\right)\left(\sqrt{3}\,\hat{\mathbf{y}}\right) = 1.5 B_M \hat{\mathbf{y}} = 1.5 B_M \angle 90^\circ$$

The Rotating Magnetic Field

Reversing the direction of Magnetic Field Rotation

$$\mathbf{B}_{aa'}(t) = B_M \sin \omega t \angle 0° \quad \text{T}$$
$$\mathbf{B}_{bb'}(t) = B_M \sin (\omega t - 240°) \angle 120° \quad \text{T}$$
$$\mathbf{B}_{cc'}(t) = B_M \sin (\omega t - 120°) \angle 240° \quad \text{T}$$

At $\omega t = 90°$:

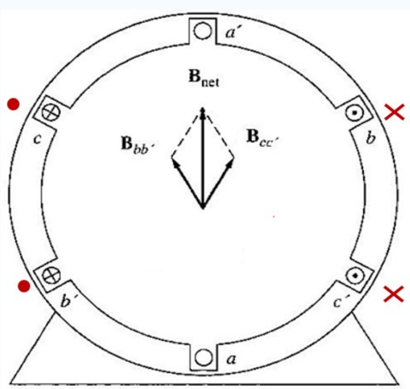
$$\mathbf{B}_{aa'} = B_M \angle 0°$$
$$\mathbf{B}_{bb'} = -0.5 B_M \angle 120° \; T$$
$$\mathbf{B}_{cc'} = -0.5 B_M \angle 240° \; T$$

The total magnetic field: $\mathbf{B}_{net} = \mathbf{B}_{aa'} + \mathbf{B}_{bb'} + \mathbf{B}_{cc'}$

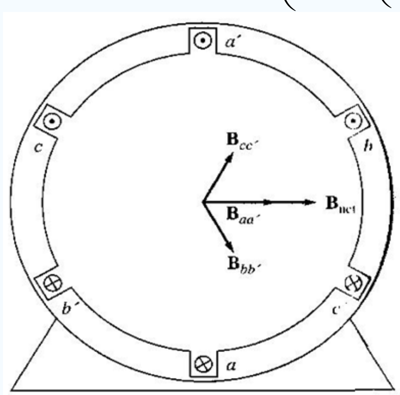
$$= B_M \angle 0° + \left(-\frac{1}{2} B_M\right)\angle 120° + \left(-\frac{1}{2} B_M\right)\angle 240°$$

$$= B_M \left[\hat{\mathbf{x}} - \frac{1}{2}\left(\cos 120° \hat{\mathbf{x}} + \sin 120° \hat{\mathbf{y}}\right) - \frac{1}{2}\left(\cos 240° \hat{\mathbf{x}} + \sin 240° \hat{\mathbf{y}}\right)\right]$$

$$= B_M \left(\hat{\mathbf{x}} - \frac{1}{2}\left(-\frac{1}{2}\hat{\mathbf{x}} + \frac{\sqrt{3}}{2}\hat{\mathbf{y}}\right) - \frac{1}{2}\left(-\frac{1}{2}\hat{\mathbf{x}} - \frac{\sqrt{3}}{2}\hat{\mathbf{y}}\right)\right) = 1.5 B_M \hat{\mathbf{x}} = 1.5 B_M \angle 0°$$



$\omega t = 0°$



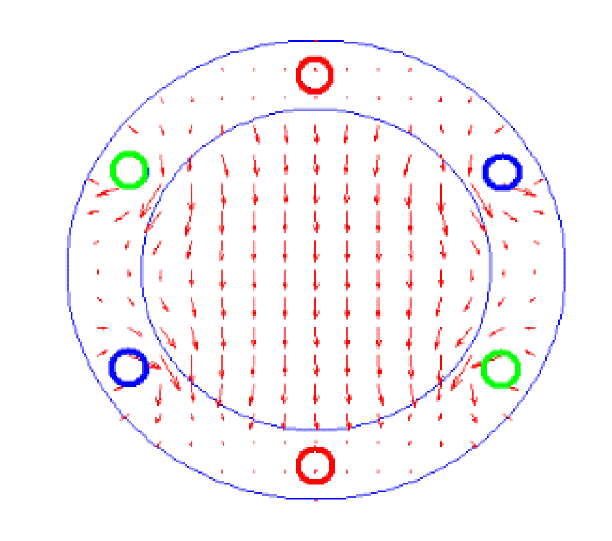
$\omega t = 90°$

$$\boxed{\mathbf{B}_{net}(t) = 1.5 B_M \left(\sin \omega t \, \hat{\mathbf{x}} + \cos \omega t \, \hat{\mathbf{y}}\right)}$$

Now, the magnetic field rotates in a **clockwise** direction.

Electrical Frequency and Magnetic Field Rotation

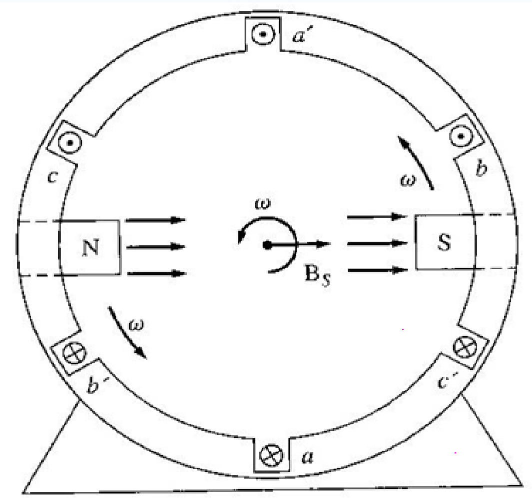
The rotating magnetic field in the stator can be represented as a north pole and a south pole.



Two poles

These magnetic poles complete **one mechanical rotation** around the stator surface for **each electrical cycle** of the applied current.

When the machine is **two poles** structure, the mechanical speed of rotation of the magnetic field in revolutions per second is equal to electric frequency in hertz:



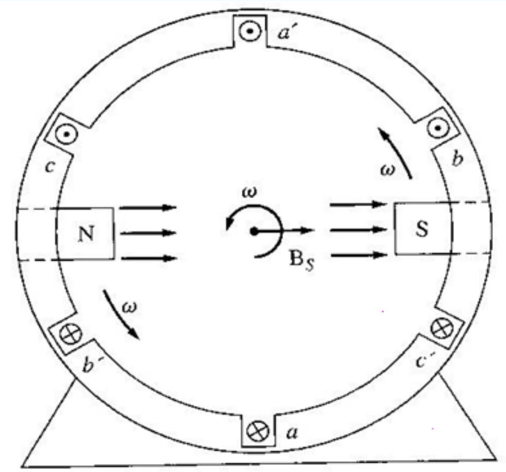
Electric frequency of current = Mechanical speed of rotation of magnetic field

$$f_e \text{ (hertz)} = f_m \text{ (revolutions per second)}$$
$$\omega_e \text{ (radians per second)} = \omega_m \text{ (radians per second)}$$

Electrical Frequency and Magnetic Field Rotation

The windings occur in the order ***a – c' – b – a' – c – b'***

Two poles

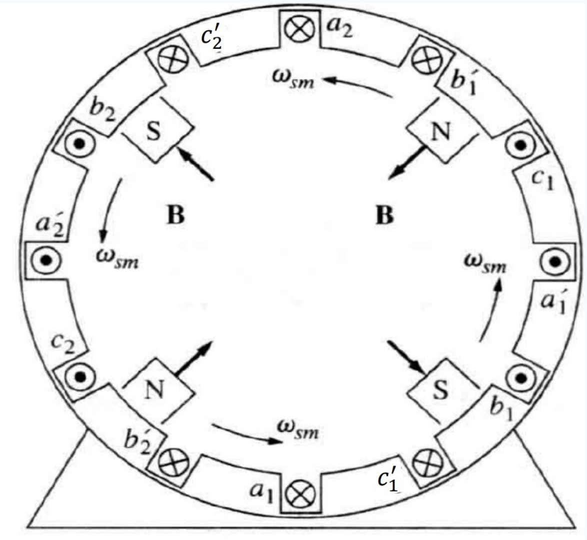


If we double the amount of windings with the sequence of windings as follows:

$a_1 - c_1' - b_1 - a_1' - c_1 - b_1' - a_2 - c_2' - b_2 - a_2' - c_2 - b_2'$

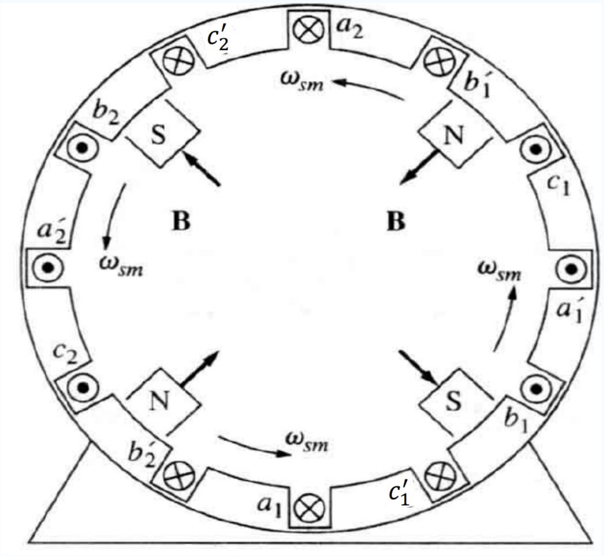
For a three-phase set of currents, this stator will have 2 north poles and 2 south poles produced in the stator winding, which can be considered as four poles.

Four poles



Electrical Frequency and Magnetic Field Rotation

For **4-pole** structure, a pole moves only halfway around the stator surface in one electrical cycle.



Since one electrical cycle is 360 electrical degrees, and mechanical motion is 180 mechanical degrees, the relationship between the electrical angle θ_e and the mechanical θ_m in this stator is:

$$\theta_e = 2\,\theta_m$$

The electrical frequency of the current is twice the mechanical frequency of rotation:

$$f_e = 2\,f_m$$

$$\omega_e = 2\,\omega_m$$

Electrical Frequency and Magnetic Field Rotation

Generally,

P represents the number of magnetic poles;

n_m represents the number of rotation per minute

$$\boxed{\begin{aligned} \theta_e &= \frac{P}{2}\theta_m \\ f_e &= \frac{P}{2} f_m \\ \omega_e &= \frac{P}{2}\omega_m \end{aligned}}$$

(Lecture 15 Page 16) $f_m = \dfrac{n_m}{60} \quad \Rightarrow \quad \boxed{f_e = \dfrac{n_m P}{120}}$

Summary

✓ A simple loop in a uniform magnetic field

- Induced voltage $e_{ind} = 2\ vBl \sin\theta$
- Induced torque $\tau_{ind} = 2rilB \sin\theta$

✓ Rotating Magnetic Field

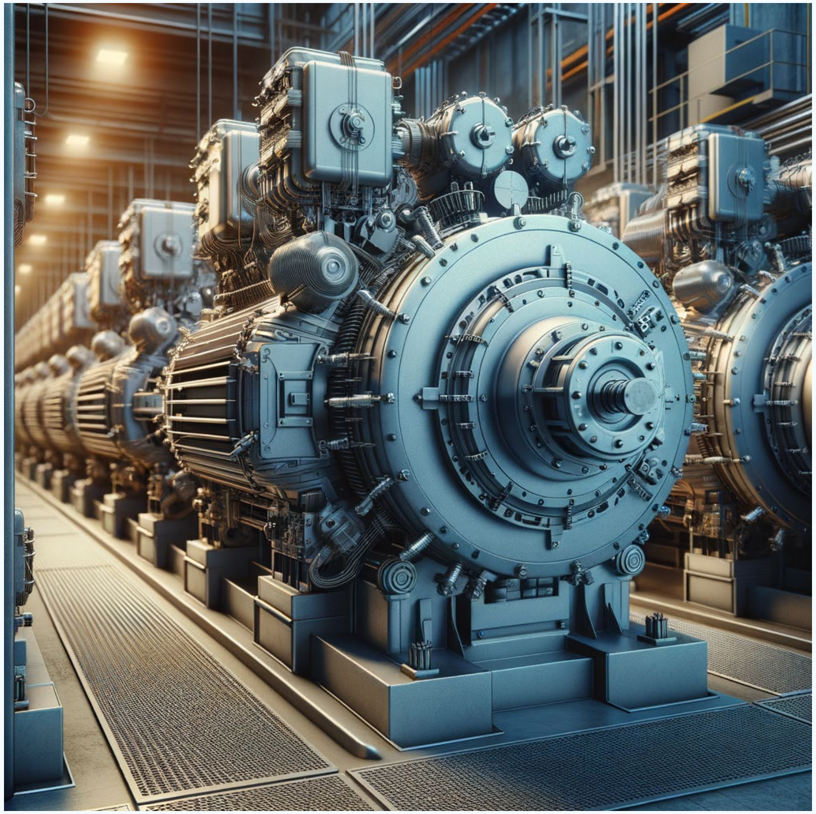
- The rotating magnetic field concept
- Reversing the direction of magnetic field rotation
- The relationship between electrical frequency and the speed of magnetic field rotation

$$\theta_e = \frac{P}{2}\theta_m$$

$$f_e = \frac{n_m P}{120} \qquad f_e = \frac{P}{2} f_m$$

$$\omega_e = \frac{P}{2}\omega_m$$

Next



Sychronous Generators

Thanks for your attention