

# CHAPTER 6

## INTRODUCTION TO MOTORS AND GENERATORS

# Objective

- Describe the necessary conditions for motor and generator operation.
- Calculate the force on a conductor carrying current in the presence of the magnetic field.
- Calculate the voltage induced on a conductor in the presence of the changing magnetic field.
- Apply left-hand motor rule to determine the direction of rotation in a motor.
- Apply right-hand generator rule to determine the polarity of induced voltage.
- Describe the construction features and principles of operation of the AC synchronous machine.
- Describe the construction features and principles of operation of the DC machine.

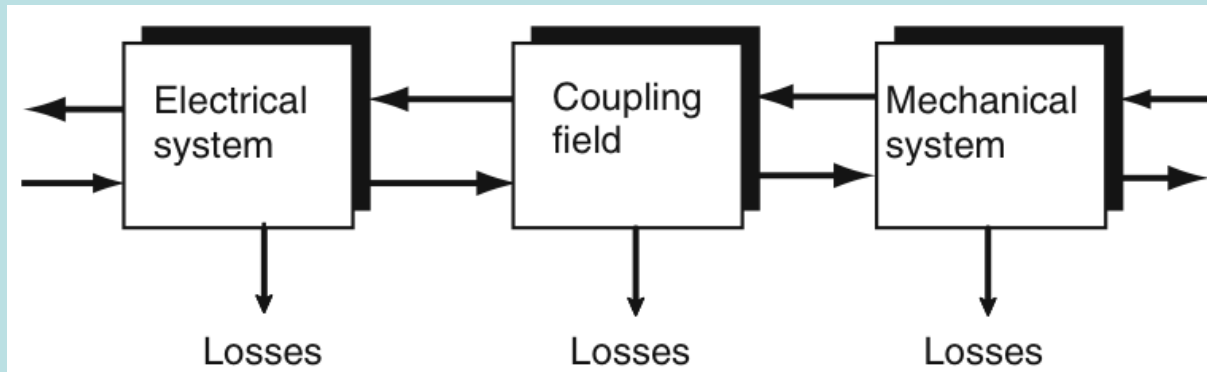
# Introduction

Electricity is provided by **generators**, devices that **convert mechanical energy into electrical energy**.

**Motors**, on the other hand, **convert electrical energy into mechanical motion** and work.

This process of changing the form of energy is called **electromechanical energy conversion**.

A flow chart of the energy conversion process:



The electrical system and the mechanical system are joined together by a **coupling field** which could be electrical or magnetic

The systems are not ideal, so there are losses at every stage.

Efficiency thus becomes an important consideration when selecting a machine.

### ***Motor:***

An electric current interacts with a magnetic field to cause an electromagnetic torque, which drives some load.

The load provides a mechanical torque, which opposes the electromagnetic torque.

### ***Generator:***

A mechanical torque is applied to turn conductors through a magnetic field and generate electric current.

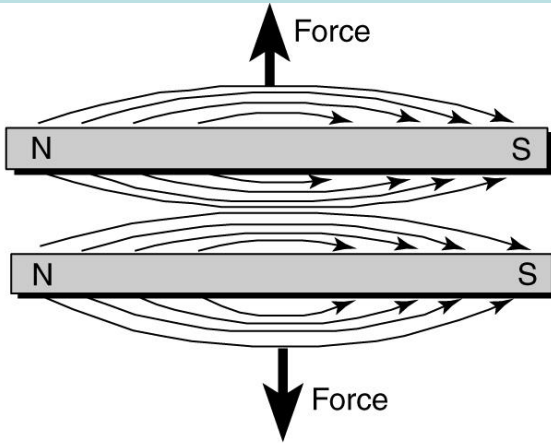
The mechanical torque is opposed by an electromagnetic torque that results from the interaction of the current with the magnetic field.

# FIVE ELECTROMAGNETIC PRINCIPLES

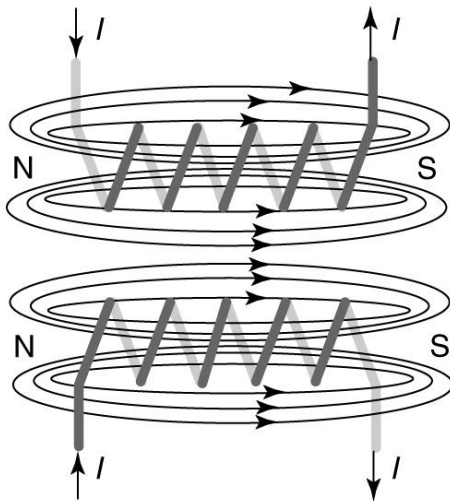
Need to know them to understand the operation of electric machines.

1. An electromotive force (EMF) will produce a current that is proportional to the conductivity of the path. This is commonly known as Ohm's law.
2. An electric current constitutes a magnetomotive force (MMF) that produces magnetic flux proportional to the permeability of the path. This is often referred to as Ohm's law for magnetic circuits.
3. A magnetic field will exert a force on a current-carrying conductor. This is the basis for motor action.
4. A conductor moving through a magnetic field will have an EMF induced in it. Similarly, if a magnetic flux passing through a coil changes with time, an EMF will be induced in the coil. This is Faraday's law, which is the basis for generator action.
5. The polarity of the EMF induced in a coil will cause a current that will oppose any change in the magnetic flux. This is a corollary to Faraday's law, known as Lenz's law.

# Motor Action (Electromagnetic Force)



(a)



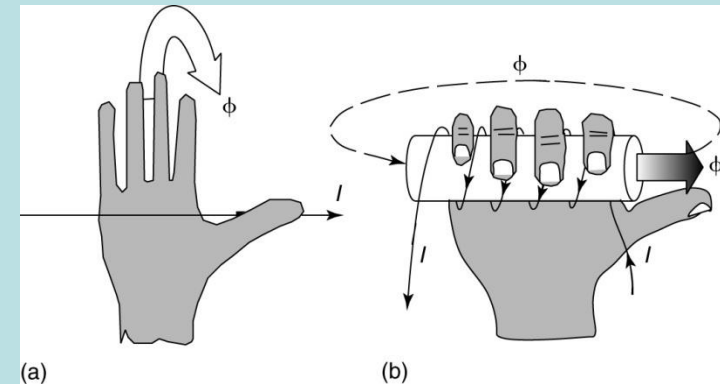
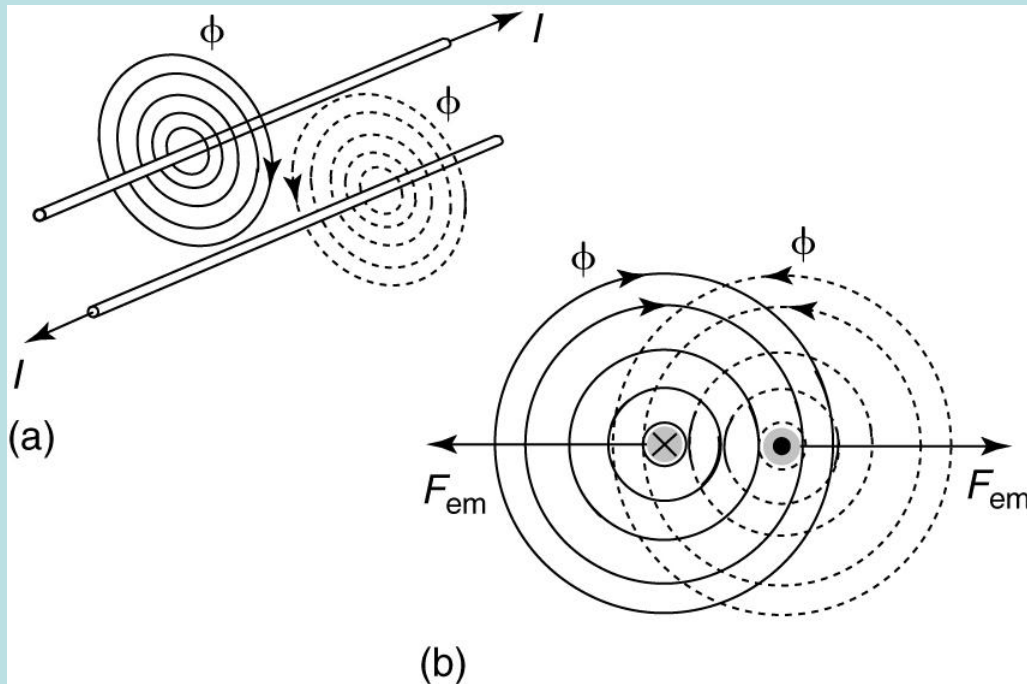
(b)

Two magnets can be used to create a force.

Two magnets have the same direction, their magnetic fluxes add together between them.

We can use a coil to create an electromagnet that has magnetic flux just like a permanent magnet.

Because current is flowing in the coils, they produce magnetic flux in the directions shown, which can be determined by the right-hand rule.



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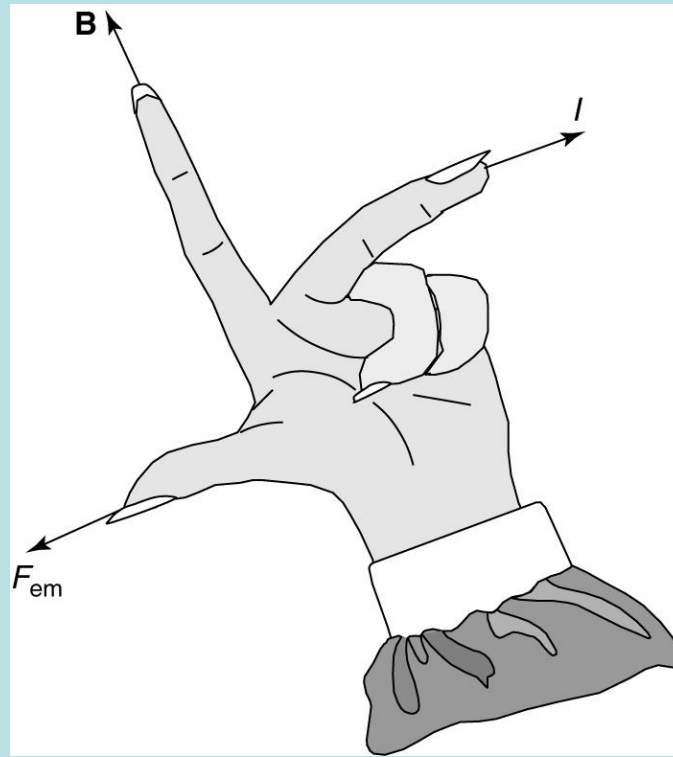
There will thus be a force that will try to push the two coils apart. Since the force is created by the magnetic field of an electric coil, the force is called the electromagnetic force.

Figure shows two views of parallel conductors that are carrying currents in opposite directions, and magnetic fluxes produced by these currents.

The current in a conductor and the magnetic field around the conductor are related by the right-hand rule. The currents are in opposite directions, so are the fluxes.

The conductor on the left side has magnetic flux surrounding it in the clockwise direction, while the right conductor has flux surrounding it in the counterclockwise direction.

## Left-Hand rule



From electromagnetic field theory: the flux (or flux density), the current, and the force are mutually perpendicular, just like the XYZ axes of the Cartesian coordinate system.

They can be related by a left-hand rule: the index finger shows the direction of magnetic flux, and the middle finger (when pointing perpendicular to the index finger) shows the direction of the current.

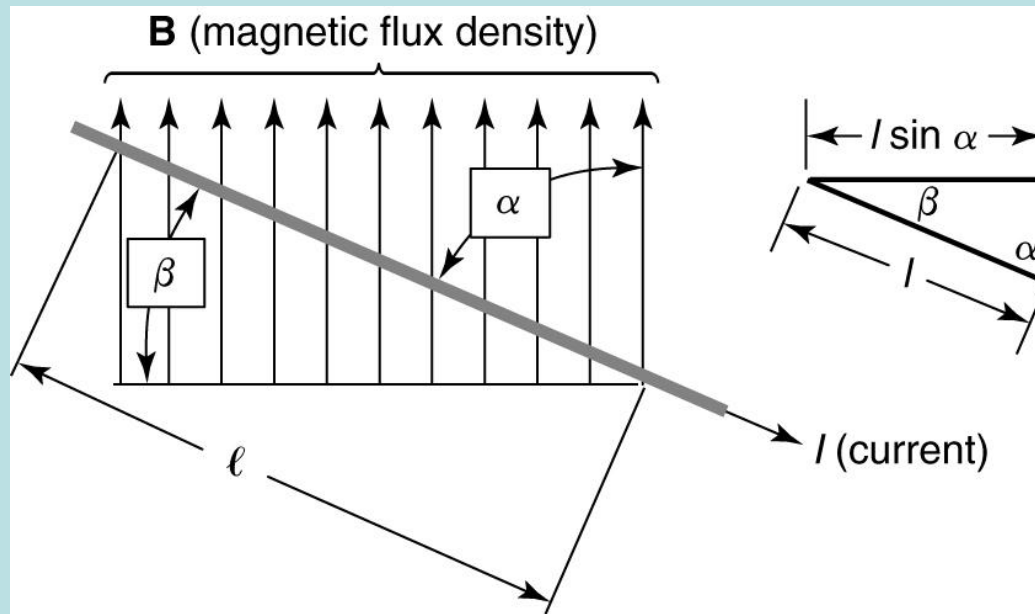
The outwardly extending thumb, then, points in the direction of the electromagnetic force.

When the flux and current are perpendicular the force magnitude is given by

$$F_{em} = BIl$$

where B is the flux density, I is the current, and F is the induced force.





If the flux and current intersect at an angle greater than zero but less than  $90^\circ$ , there will still be a force, but it will be diminished.

In particular, the force will be determined by the components of flux and current that are mutually perpendicular.

Figure shows a conductor of length  $l$  that is carrying current in the presence of an external magnetic field. In this case, the current is not perpendicular to the flux. The angle between them is  $\alpha$ , so the angle  $\beta$  is equal to  $90^\circ - \alpha$ .

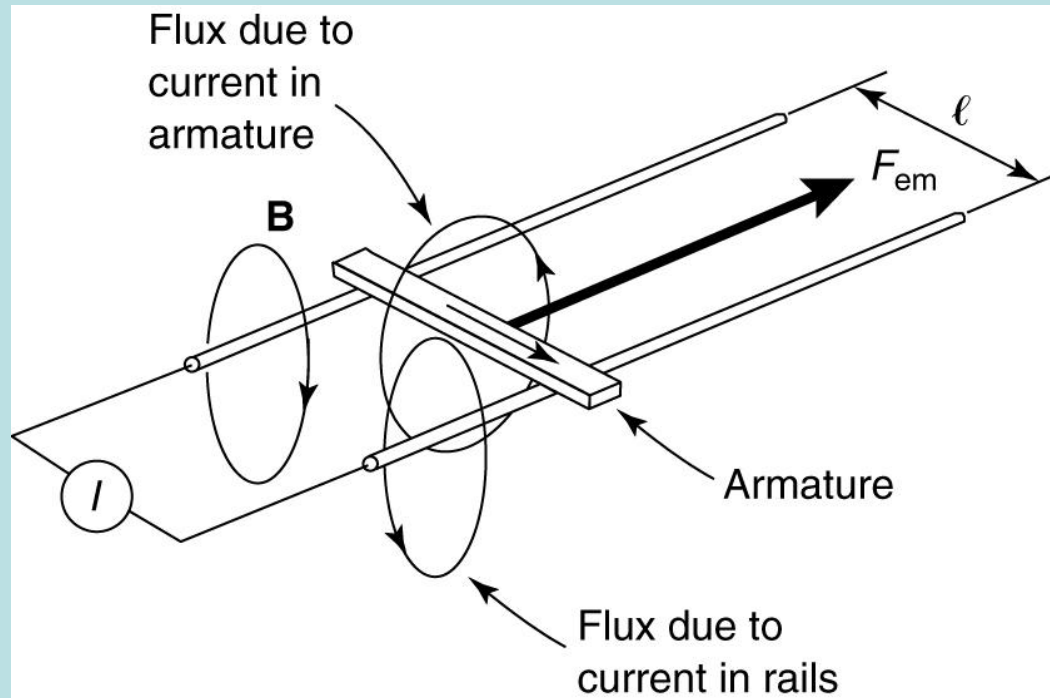
The angle  $\beta$  is referred to as the skew angle.

We could split the current into two components, one that is perpendicular to the flux and one that is in the same direction as the flux. The component of the current that is perpendicular to the flux is  $I \sin(\alpha)$  or  $I \cos(\beta)$ .

Thus, the force on the conductor is:

$$F_{em} = BIl \sin \alpha = BIl \cos \beta$$

## A simple linear motor



A conductor (called the armature) is free to move along a set of rails.

Current is applied so as to flow down the left rail across the armature, and back on the right rail.

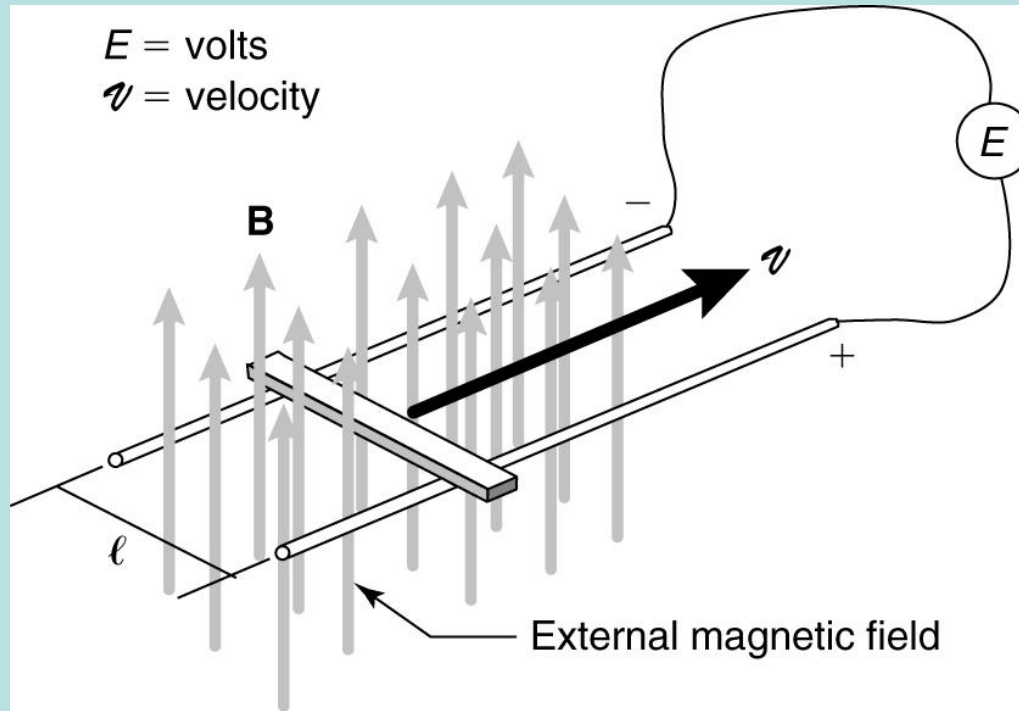
Due to the flown current, a magnetic field is established in the loop bounded by the source, the rails, and the armature.

The current in both rails and the armature causes magnetic flux between the rail in the same direction.

There is no rail current beyond the armature, so the flux density is lower on the far side of the armature and there is a force on the armature that propels it down the rails.

The magnetic flux and the current are perpendicular.

## A linear generator



Voltage is generated in the coils by either rotating the coils through a magnetic field or by rotating magnetic poles past stationary windings.

A linear generator has two conducting rails and a movable, conducting cross piece, the armature.

If a conductor cuts magnetic flux then a voltage is induced in it.

The generator is operated by physically pulling the armature down the rails at some velocity,  $v$ .

$x$  is the distance of the armature from the left end, then the area of the window created by the rails and the armature is

$$A = lx$$

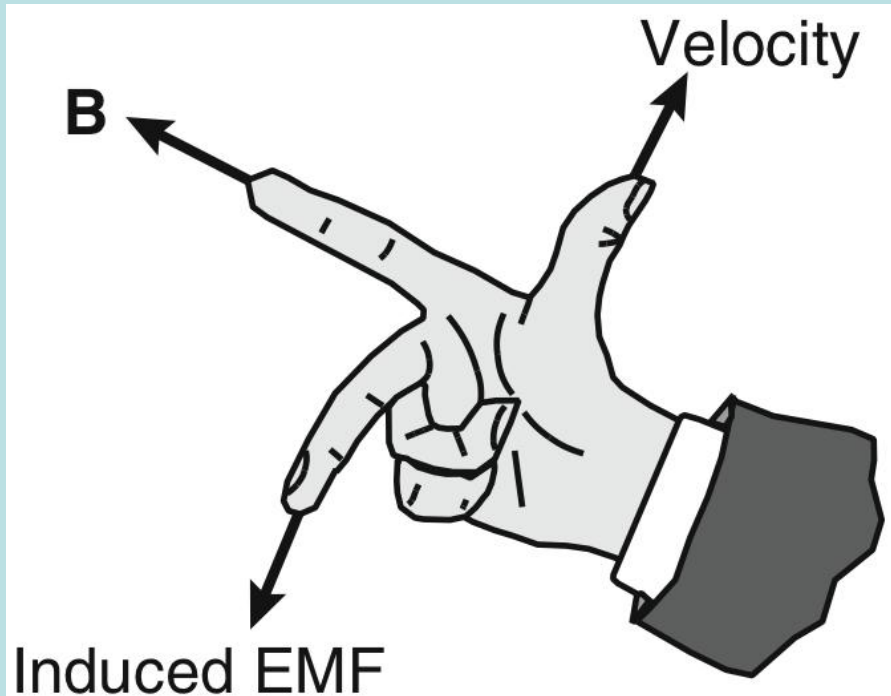
Flux passing through the window is:

$$\phi = Blx$$

The voltage generated as a function of the changing in time flux:

$$E = N \frac{d\phi}{dx}$$

$$E = N \frac{d}{dt}(Blx) = NBl \frac{dx}{dt}$$



In this case there is only one turn:

$$E = Blv$$

We can use the right-hand generator rule to determine the direction of induced EMF in a conductor.

The voltage, the flux, and the velocity are mutually perpendicular.

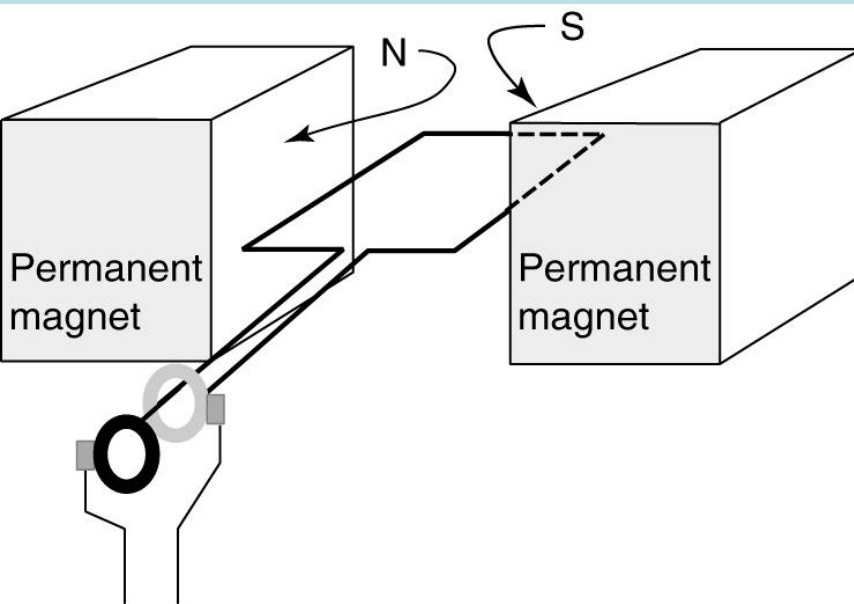
The right-hand rule: the thumb indicates the direction of velocity, the index finger indicates the direction of magnetic flux, and the middle finger the direction of the induced EMF.

As in the case of the linear motor, the velocity might not be perpendicular to the flux.

If alpha is the angle between the velocity and the flux, then we take the component of velocity that is perpendicular to the flux to find the voltage:

$$E = Blv[\sin \alpha]$$

# A simple AC machine



A simple permanent-magnet AC machine.

The single-turn coil is free to rotate between two magnetic poles of opposite polarity.

Magnetic flux goes from a north pole to a south pole, so there will be magnetic flux in the region between the poles where the coil is rotating.

The assembly that **rotates** is called the **rotor** of the machine, and the structure containing the **stationary poles** is called the **stator**.

The **rotor** delivers power and is also called the **armature**, and the **stator** provides a magnetic field and is thus called the **field**.

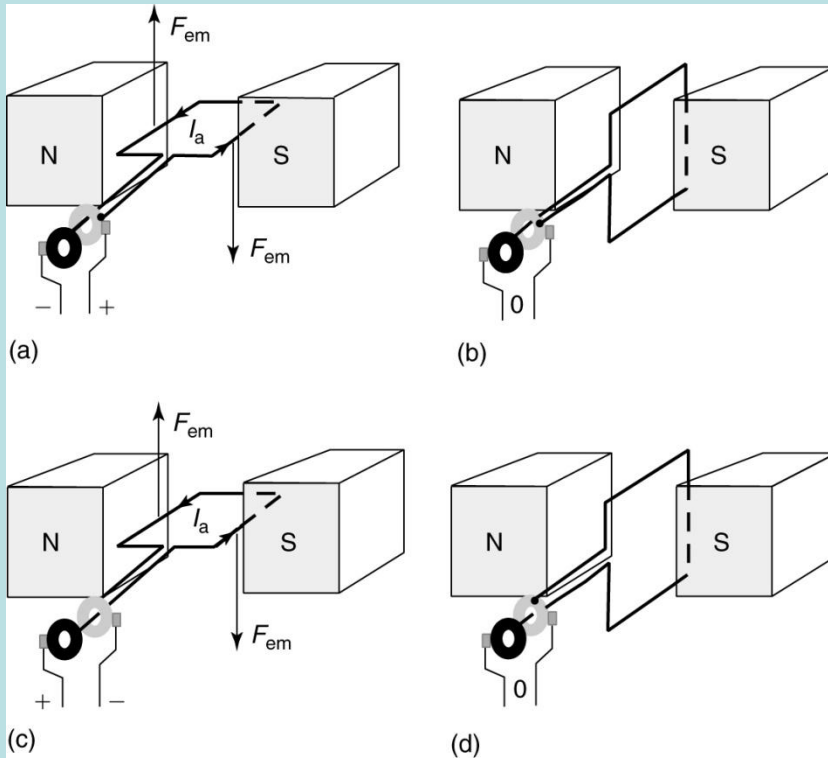
To connect the coil to a source or load, a slip ring is used. **Slip rings** are conducting rings placed around, but insulated from, the shaft of the rotor.

The conducting blocks of carbon or carbon and copper, called **brushes**, are placed against the slip rings to make the connection to the outside of the machine. ·

Thus, the rotating coil either **receives (motor operation)** or **delivers (generator operation)** AC electric power via the brushes and slip rings.

This simple machine can be operated as a motor or generator.

# AC Motor Operation



Operation of the simple AC machine as a motor.

## Position A

An AC voltage applied to the coil and the current flows in the coil.

Since there is a current flowing in the presence of a magnetic field there will be a force on the conductors, which is down on the right side of the coil and up on the left side (left-hand rule), creating a torque that causes the coil rotate clockwise.

## Position B

No torque would be created because the force on the top part of the coil would be up and that on the bottom part of the coil would be down.

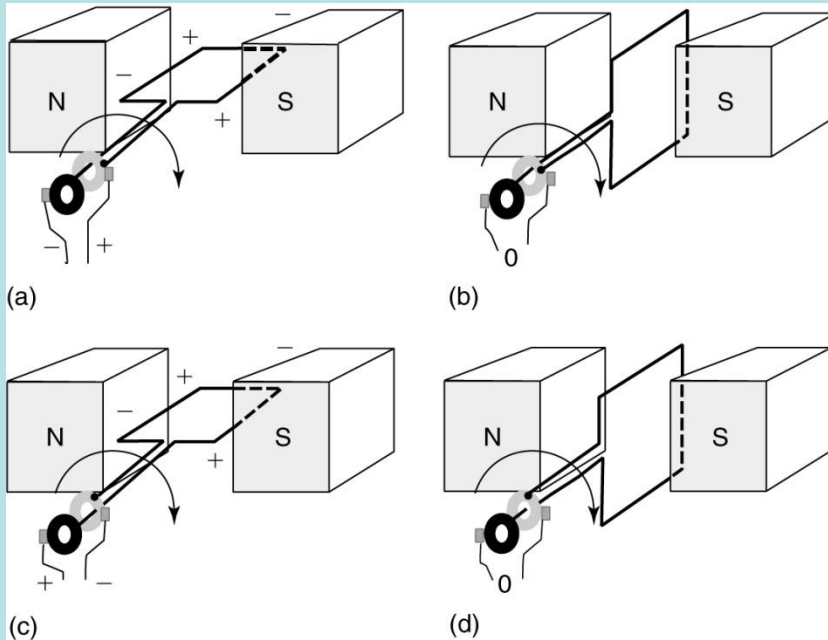
## Position C

The two coil sides have switched positions, so the polarity of the applied voltage must change to keep the rotor moving in the same direction.

## Position D

As the coil continues to rotate, it reaches the neutral position in which the coil has rotated 180°.

# AC Generator Operation



Operation of the simple AC machine as a generator.

## Position A

The coil is rotated in the direction shown and both coil sides are adjacent to magnetic poles, so they are cutting flux, which induces a voltage in each-side of the coil.

## Position B

The conductor's velocity is parallel to the flux and no voltage is generated.

## Positions C and D

As the coil continues to rotate, the conductor connected to the dark slip ring comes under the south pole, so the dark ring becomes the positive terminal. This is an AC generator.

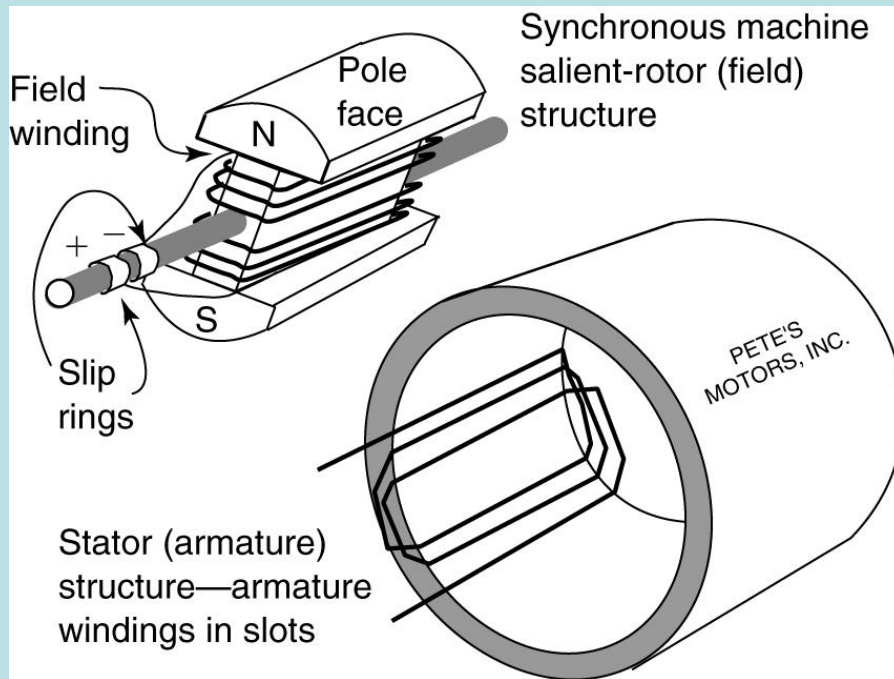
One revolution delivers one cycle of voltage, so the frequency of the voltage would be equal to the number of revolutions per second.

If the machine was driven at a constant speed, the frequency would also be constant.

The voltage generated by this machine is sinusoidal, and is found using equation below:

$$E_{rms} = 4.44fN\phi_p$$

# A PRACTICAL AC SYNCHRONOUS MACHINE



In a simple permanent-magnet AC implements a rotating armature coil, which means the power to run the motor or the power from the generator must be transmitted through the brushes and slip rings. For large machines it is not very efficient.

AC synchronous machines are built with the armature on the stator and the field on the rotor.

The rotor is located inside the stator.

Instead of a permanent magnet, this machine uses an electromagnet to create the field.

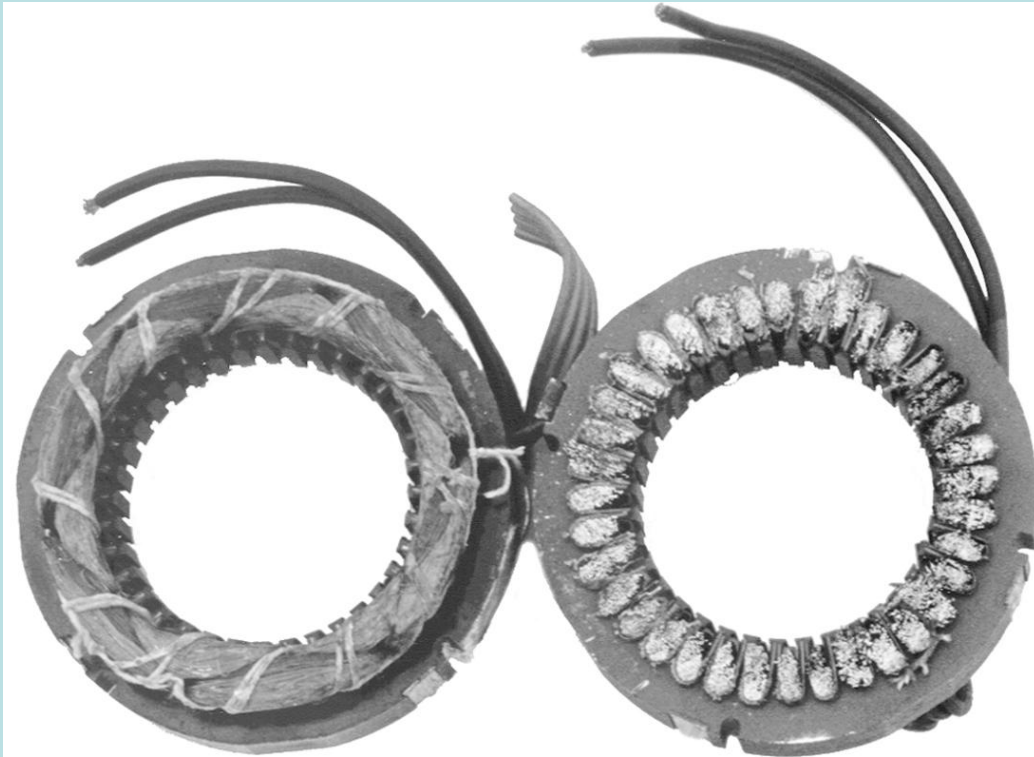
A DC voltage is applied to the coils on the rotor, creating north and south poles.

The rotor winding is called the field.

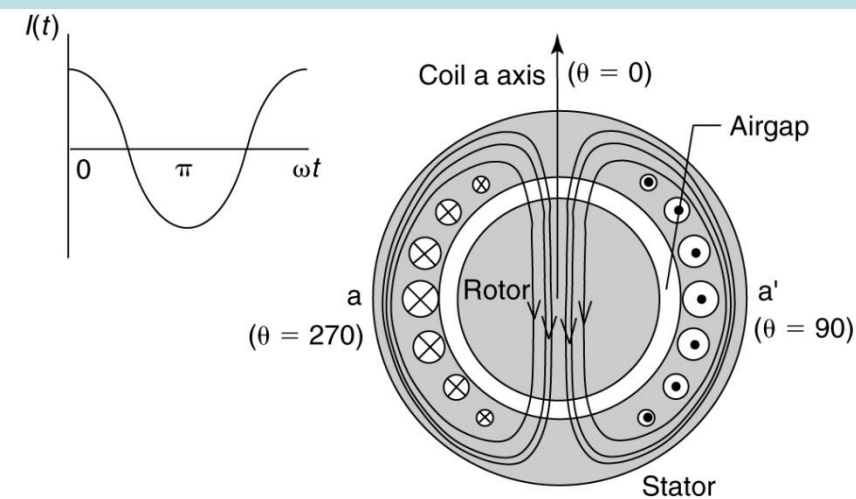
The DC current to the rotor is called the excitation or the field current



# The Rotating Magnetic Field

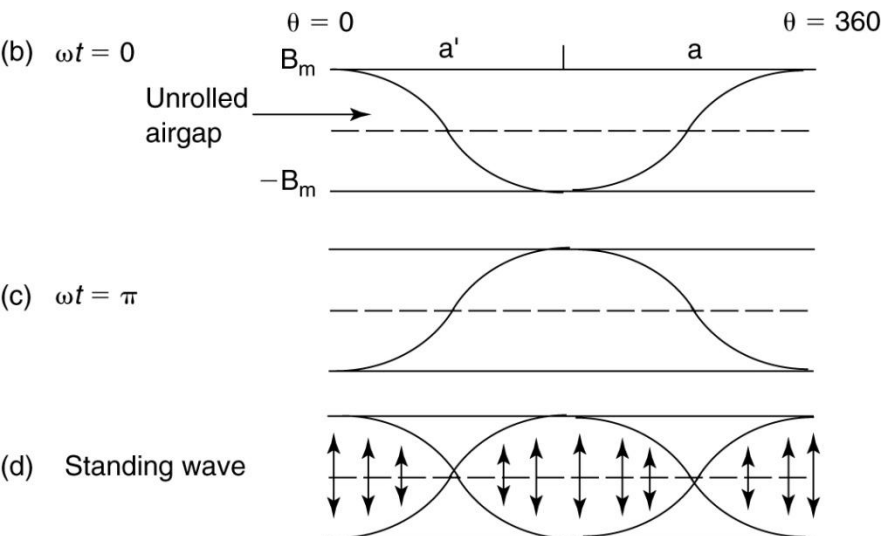


Left: AC stator winding.  
Right: end turns cut off to expose  
coils in slots.



(a) Current and flux distribution at  $\omega t = 0$

Airgap flux distribution



(d) Standing wave

One Phase Case:

AC current is applied to the coil:  $I_m \cos(\omega t)$

X- current into the page; • - current out of page

At  $t=0$  the current will cause magnetic flux through the rotor in the down direction (right-hand rule).

At  $\theta = 0^\circ$  the flux is entering the airgap from the stator-define to be positive.

At  $\theta = 180^\circ$  the flux is entering the airgap from the rotor-define to be negative.

"Unpeeled" airgap:

At  $\omega t=0$   $B(\theta) = B_m \cos(\theta)$   $B_m(I_m)$  (b)

Current reverses at  $\omega t = \pi$  (c)

The flux density in the airgap is a standing wave (d)

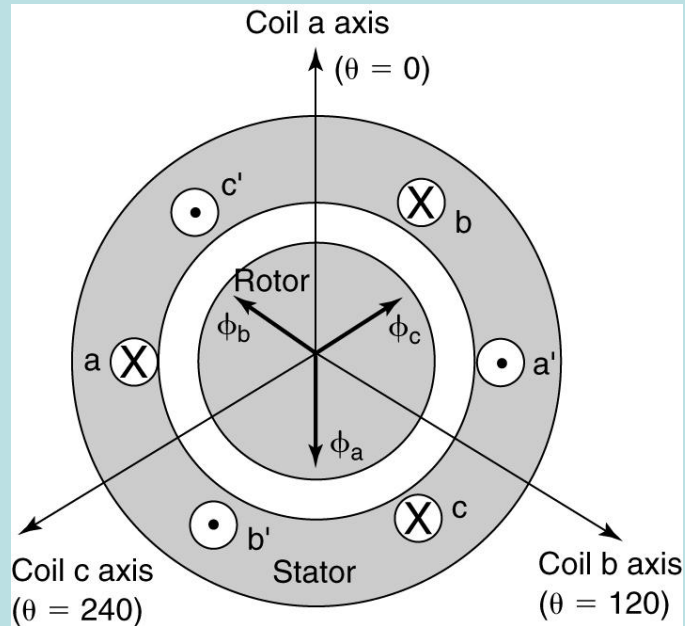
$$B(\theta, t) = B(\theta) \cos(\omega t) = B_m \cos(\omega t) \cos(\theta)$$

$$\cos(\omega t) \cos(\theta) = 0.5 [\cos(\theta - \omega t) + \cos(\theta + \omega t)]$$

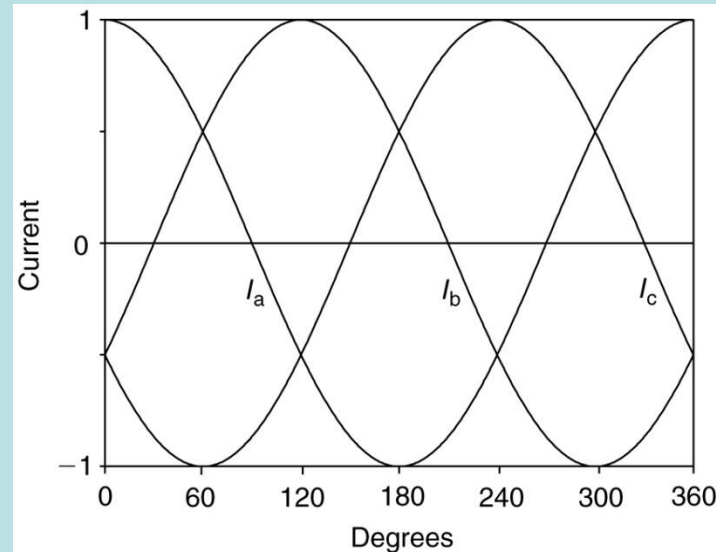
Traveling wave in forward direction

Traveling wave in backward direction

# The 3-Phase Stator Winding



The flux distribution due to the coil “b” is 120 degrees behind coil “a” and the flux due to the coil “c” is 120 degrees behind coil “b”.



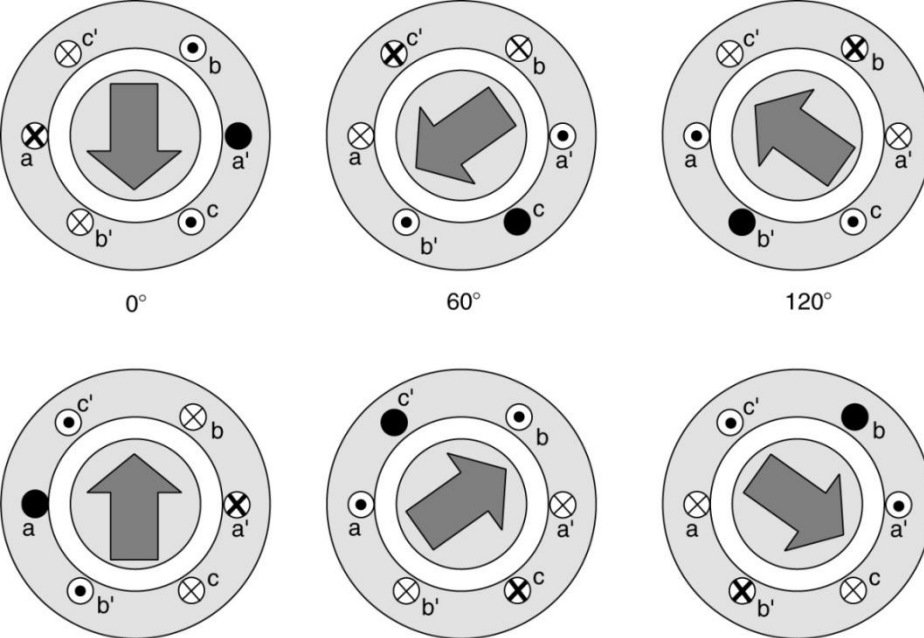
A balanced 3-phase set of currents is applied to the coil:

$$i_a(t) = I_m \cos(\omega t)$$

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

$$i_c(t) = I_m \cos(\omega t - 240^\circ)$$

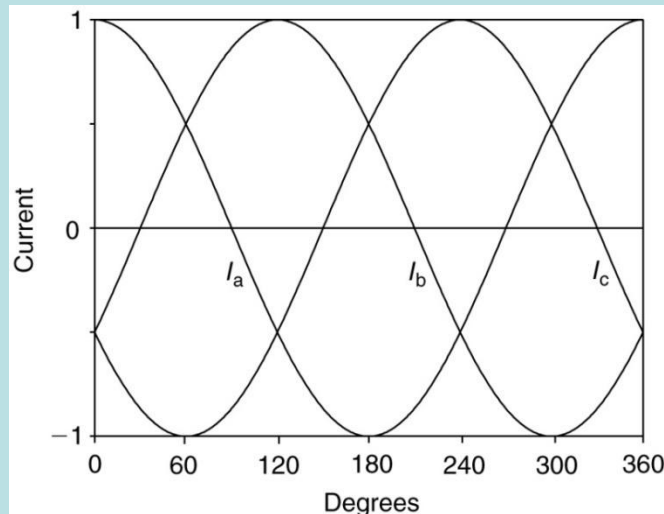
Each current will create a magnetic flux distribution, but the 3-phases are displaced both in time and in space.



At  $\omega t = 0$  the current in phase “a” is at a positive max. While the other 2 phases have negative currents With an amplitude of  $\frac{1}{2}$ . By the right hand flux rule the net stator flux is directed in downward direction- S pole forms at the bottom and N pole at the top.

At  $\omega t = 60$   $I_c$  has reached its negative peak;  $I_a$  and  $I_b$  Are both at  $\frac{1}{2}$  of the positive peak. The pattern of dots and Xs has rotated and the direction of the stator flux has moved by 60 degrees.

Continue every 60 degrees, each 60 degrees increment in time causes 60 degrees rotation in the magnetic flux.



**X**- positive current with max. magnitude.  
**X**- positive current with min. magnitude.  
 Big dot- negative current with max magnitude.  
 Small dot- negative current with min. magnitude.

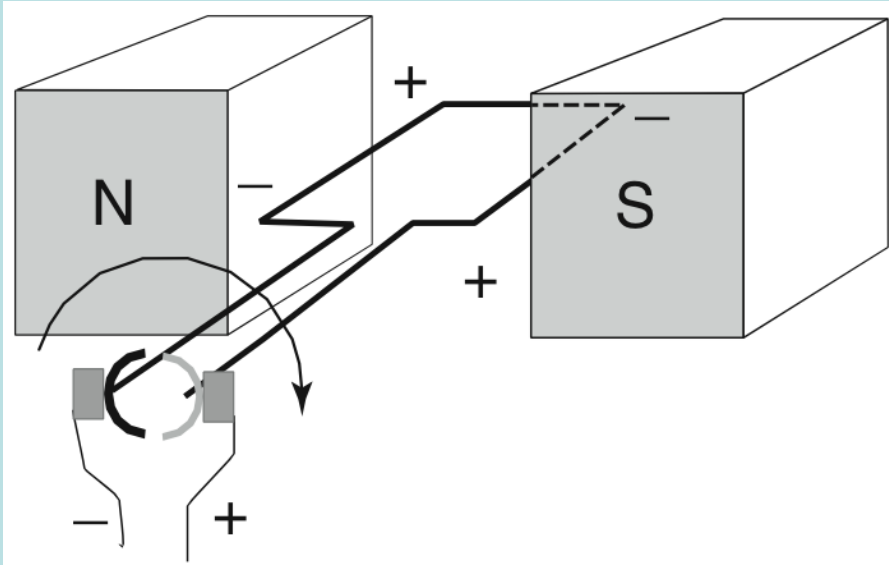
The rotation speed of the stator field is called synchronous speed.

For a 2-pole machine, the speed of the stator field in RPM is 60 times the frequency.

$$n_s = \frac{120 \times f}{P} \text{ in RPM}$$

$$n_s = \frac{2 \times f}{P} \text{ in Rev/s}$$

# A Simple DC Machine.



The elementary permanent-magnet machine is very similar to the AC machine.

Instead of a pair of slip rings to connect to the ends of the coil, there is a single split ring - **commutator**

Each end of the coil is connected to one-half of the ring, and two brushes ride on the split ring.

If the coil is rotated between the magnets an AC voltage will be induced in the coil (generator operation).

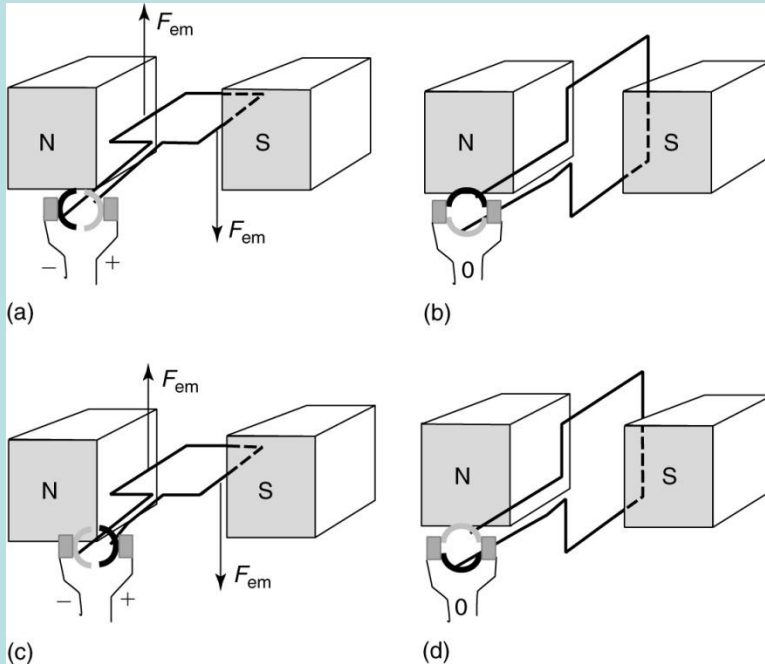
For motor operation an AC voltage must be applied to the coil to make it rotate continuously.

To operate the machine from a DC source, it is necessary to convert the DC source to AC in the coil for motor operation or to convert the AC from the coil to DC for generator operation.

The split ring is called a commutator and has the function of converting between AC in the armature and DC at the machine terminals.

The action of changing the connections between the brushes and the coil sides is called commutation.

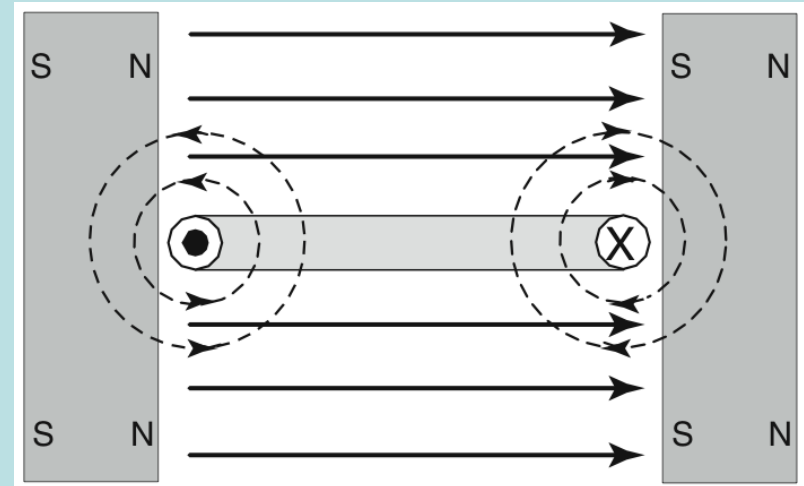
# Motor Operation



The simple DC machine operating as a motor.

The voltage applied as shown, current flows into the right side of the coil and out of the left side.

Since the current is flowing in the presence of a magnetic field, there will be a force on the conductors.

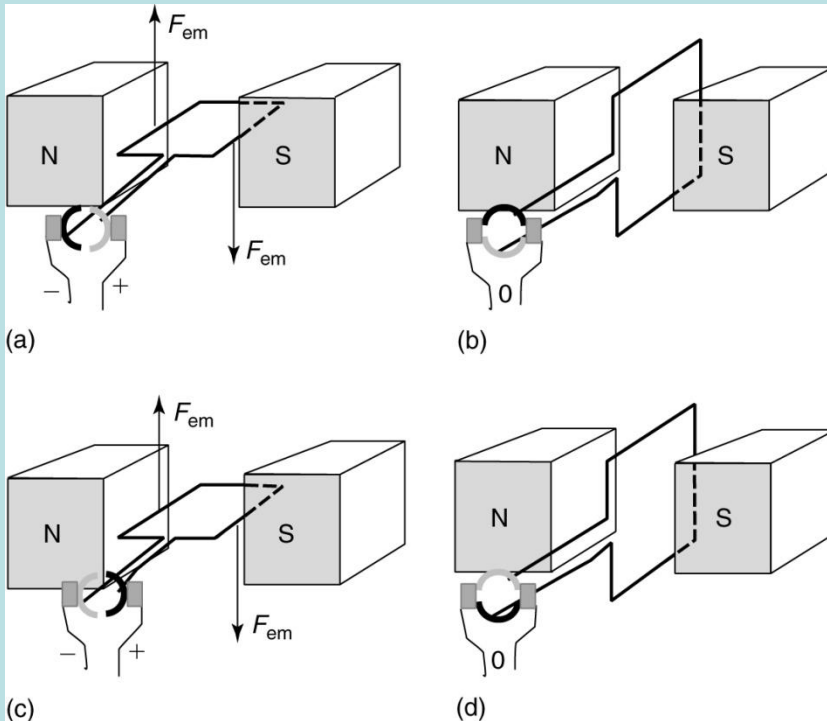


A cross-sectional view of the simple DC motor. The flux due to the permanent magnets goes from north pole to south pole (the straight arrows). The flux due to the current will surround the conductors (dotted circles).

The conductor's flux adds to the permanent magnet flux above the right conductor and subtracts below it. Thus, there will be a downward force on the right side of the coil.

On the left side of the coil, the current is out of the page, causing counterclockwise flux that results in more flux below the conductor.

There will be an upward force on the left side of the coil. The forces on the two sides of the coil will cause the coil to rotate.



### Position 2:

Here the brushes are shorting out the coil as they move from one side of the commutator to the other. There is no current in the coil and there is no force on the conductors. This is called the magnetically neutral position.

### Position 3:

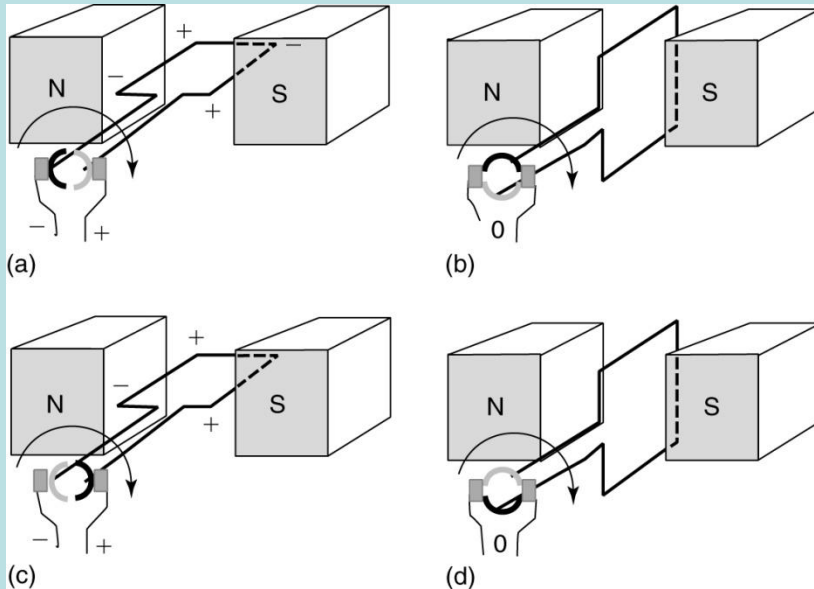
The positions of the commutator segments and the coil sides have reversed. The commutator has inverted the DC source to provide AC to the coil.

### Position 4:

The commutation back to the original state.

# Generator Operation

The simple DC machine operating as a generator.



Position 1:

Both coil sides are cutting flux at a maximum rate, as their velocity is perpendicular to the flux.

Position 2:

As the coil rotates to the vertical position the coil sides are no longer cutting flux, and the brushes are commutating from one side of the split ring to the other.

The brushes temporarily short out the coil, but there is no voltage induced since the coil velocity is parallel to the flux in this position.

Position 3:

As the coil continues to turn, a voltage is again induced, but because the coil side under the north pole is still connected to the left brush, the voltage polarity at the terminals remains unchanged.

Position 4:

Finally, the coil returning to the neutral position again.

This machine generates AC voltage in the coil, but produces a DC voltage at the machine terminals due to the rectifying action of the commutator.



# Efficiency and Losses

Efficiency is important for several reasons:

1. A less efficient machine will cost more to operate.
2. The losses in the machine are converted to heat, which raises the operating temperature of the machine.

The life of insulation is strongly related to the operating temperature.

The machine must be designed to tolerate the heat created by its losses.

Efficiency is the power out divided by the power in:

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

Defining the losses in the machine as  $P_{loss}$ :

$$\eta = \frac{P_{out}}{P_{out} + P_{loss}} \times 100\%$$

$$\eta = \frac{P_{in} - P_{loss}}{P_{in}} \times 100\%$$

$$\eta = \left(1 - \frac{P_{loss}}{P_{in}}\right) \times 100\%$$

Note: The electric machines are rated in terms of power out.

A 50 HP motor is capable of delivering 50 HP to a load and a 100kVA generator is capable of delivering 100kVA.

Therefore the input power to the motor would be greater than 50 HP and the input to the generator would be greater than 100 kVA times the power factor of the generator load.

# Type of Losses

## **Copper Losses:**

Resistive losses in the winding of a machine are frequently referred to as copper losses. The resistance of a conductor varies with temperature and frequency.

## **Mechanical Losses**

This category includes friction and windage losses. Friction occurs in the bearings that support the rotor shaft and between brushes and commutators or slip rings. Windage is basically the fluid friction due to the rotor and fan assembly.

## **Core Losses**

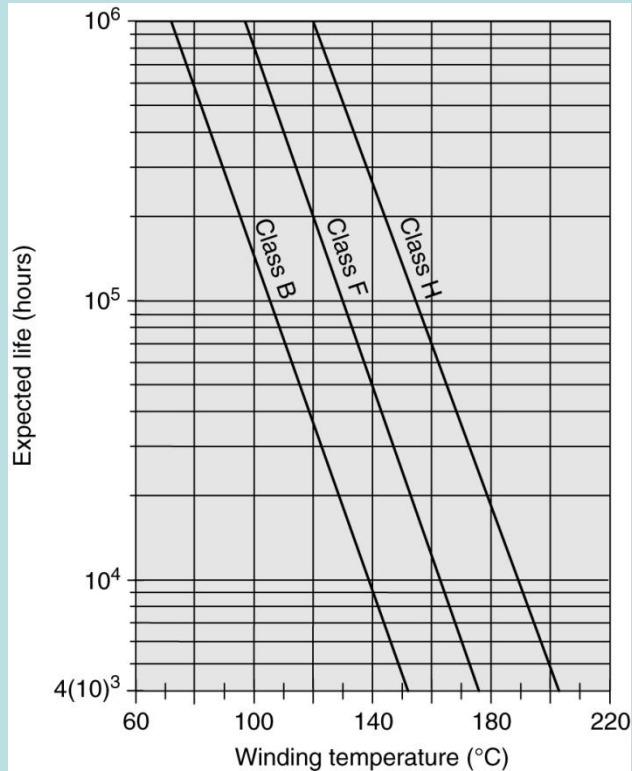
Core losses include the hysteresis and eddy current losses in the steel of the machine.

## **Stray Losses**

Any other losses and by convention, stray loss is taken to be 1 % of the output of DC machines.

# Machine Lifetime

The primary factor that affects an electrical machine's lifetime is excess heat. Heat causes the temperature of the machine to increase, resulting in a decreased life for the machine. The primary failure mechanism of electric machines is the insulation in the machine. Insulation deteriorates naturally with time due to oxidation and other chemical reactions.



## Lifetime:

Several classes of insulation, three of which are used commonly in electric machines-classes B, F, and H.

The higher the letter in alphabet, the higher the temperature the insulation can withstand.

The lifetime of the insulation is significantly reduced as the temperature of operation increases.

## Cooling:

Small electric machines are air-cooled either by convection or by blowing air through or around the machine. Large machines require active cooling to eliminate the heat created by the losses. Active cooling techniques that are used include water, oil and hydrogen cooling. Coolant can be forced through channels in the stator iron or through the windings themselves.

# Summary

We have examined the principles of motor and generator operation.

We have looked at the major construction features of AC synchronous machines and DC machines.

Motor interaction relies on the interaction of two magnetic fields, whereas generators rely on the cutting of magnetic flux by conductors.

In AC machines, the magnetic field typically rotates; it is stationary in DC machines.

We described the fundamentals of efficiency and the losses that are present in electric machines and some ways to increase the lifetime of the machine.

## IMPORTANT NUMBERED EQUATIONS FROM THIS CHAPTER

$$F_{em} = B\ell\ell \quad (6-1)$$

$$F_{em} = B\ell\ell \sin \alpha = B\ell\ell \cos \beta \quad (6-2)$$

$$E = B\ell v \quad (6-3)$$

$$E = B\ell v [\sin(\alpha)] \quad (6-4)$$

$$E_{rms} = 4.44 f N \phi_p \quad (6-5)$$

$$\theta_{elec} = \frac{P}{2} \times \theta_{mech} \quad (6-6)$$

$$n_s = \frac{120 \times f}{P} \text{ in RPM} \quad (6-7)$$

$$n_s = \frac{2 \times f}{P} \text{ in rev/s} \quad (6-8)$$

$$\eta = \frac{\text{Power out}}{\text{Power in}} \times 100\% = \frac{P_{out}}{P_{in}} \times 100\%$$

$$\eta = \frac{P_{out}}{P_{out} + P_{loss}} \times 100\% \quad (6-9)$$

$$\begin{aligned} \eta &= \frac{P_{in} - P_{loss}}{P_{in}} \times 100\% \\ &= \left(1 - \frac{P_{loss}}{P_{in}}\right) \times 100\% \end{aligned} \quad (6-10)$$