16-Generator and Motor Principles Part 1

ECEGR 3500

Text: 12.1-12.7

Electrical Energy Systems

Professor Henry Louie

Introduction

- We now discuss basic principles of electromechanical energy conversion
- Motor: conversion of electrical energy into mechanical energy
  - Movement of a current carrying conductor due to a magnetic field
- Generator: conversion of mechanical energy into electrical energy
  - Movement of a current carrying conductor by an external force in opposition to a magnetic field

Introduction

- Energy conversion is reversible except for losses
- No such thing as a 100 percent efficient machine
  - Losses are manifested as heat, vibrations, noise
- Focus on machines that use magnetic fields to facilitate the energy conversion process

Lorentz Force Equation

- Lorentz Force Equation

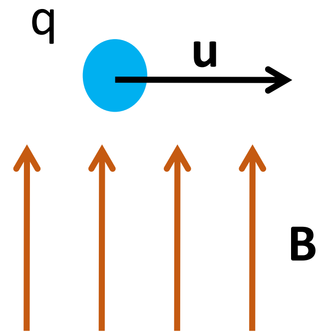
  $\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$

- where
  - F: force (Newton)
  - E: electric field (V/m)
  - v: velocity (m/s)
  - B: flux density (Wb/m^2)

Ampere's Force Law

- Assume a charge q, is moving with velocity **u** through a magnetic field
- By the Lorentz Force equation

$$\mathbf{F} = q(\mathbf{E} + \mathbf{u} \times \mathbf{B})$$
$$\mathbf{F} = q\mathbf{u} \times \mathbf{B}$$



- A force is exerted on the charge

  in the direction out of the slide

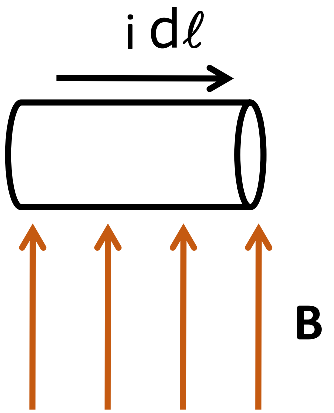
Ampere's Force Law

- A moving charge is current, therefore

$$\mathbf{F} = q\mathbf{v} \times \mathbf{B}$$

$$\mathbf{F} = \int_c i\,d\ell \times \mathbf{B}$$

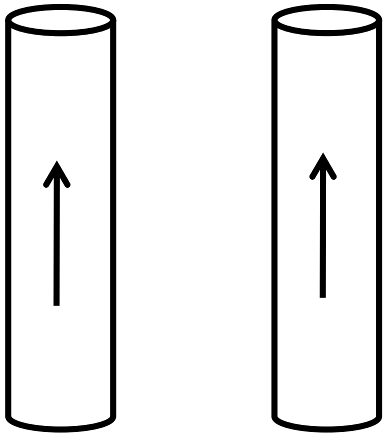
- This is Ampere's force law
- Used to compute torque in machines



Note: $d\ell$ (vector) is the direction of the current

Example

- Consider two conductors, each with current I flowing in the same direction
- Are the conductors attracted to each other or repelled from each other?



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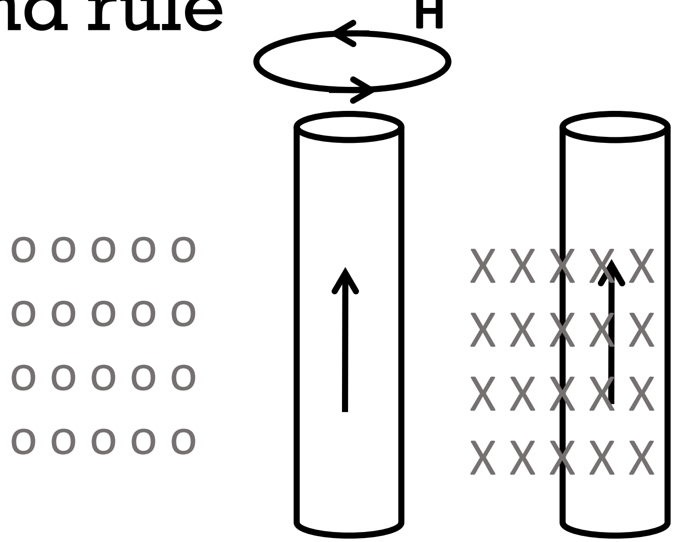
Example

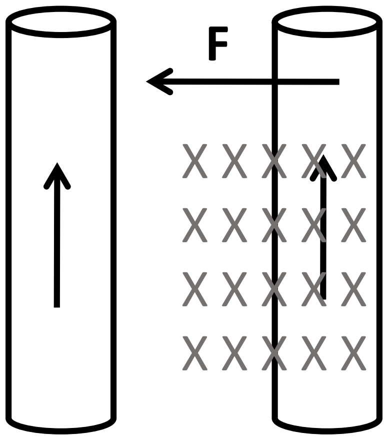
- Consider the magnetic field associated with conductor 1
- From the right hand rule



B field into the paper

Example

- Using
$$\mathbf{F} = q\mathbf{u} \times \mathbf{B}$$
$$\mathbf{F} = \int_c i d\ell \times \mathbf{B}$$
- Force on conductor 2 is toward conductor 1
- We can also see that the force on conductor 1 is toward conductor 2

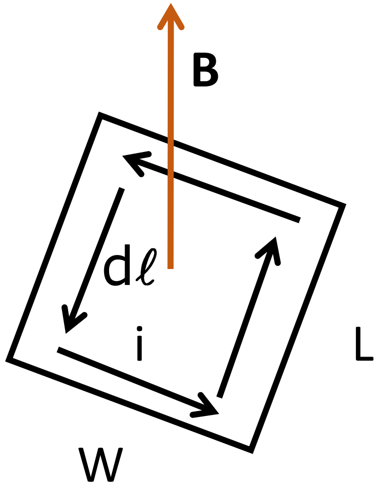


B field into the paper

Torque on a Current Loop

- Consider a loop with width W and length L and current i flowing through it
- Assume a uniform magnetic field **B** is present and perpendicular to the loop

$$\mathbf{F} = \int_c i d\ell \times \mathbf{B}$$

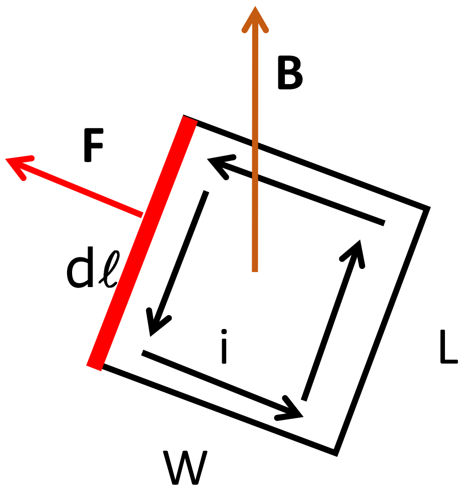


Torque on a Current Loop

- Consider the side in red
- The direction of the force on this side is computed from

$$\mathbf{F} = \int_c i d\ell \times \mathbf{B}$$

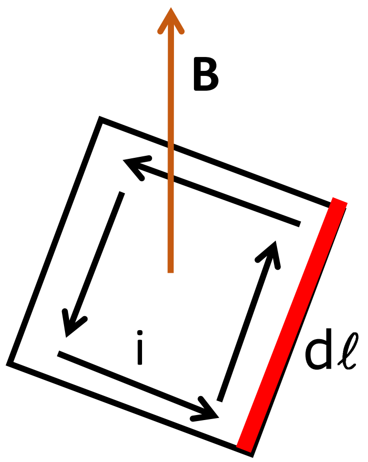
and therefore is in the direction shown



Torque on a Current Loop

Find the direction force on the side colored in red

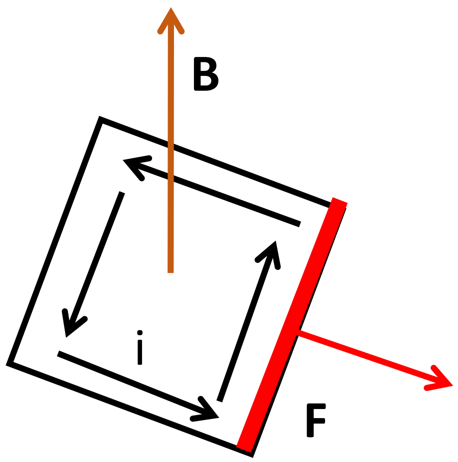
$$\mathbf{F} = \int_c i d\ell \times \mathbf{B}$$



Torque on a Current Loop

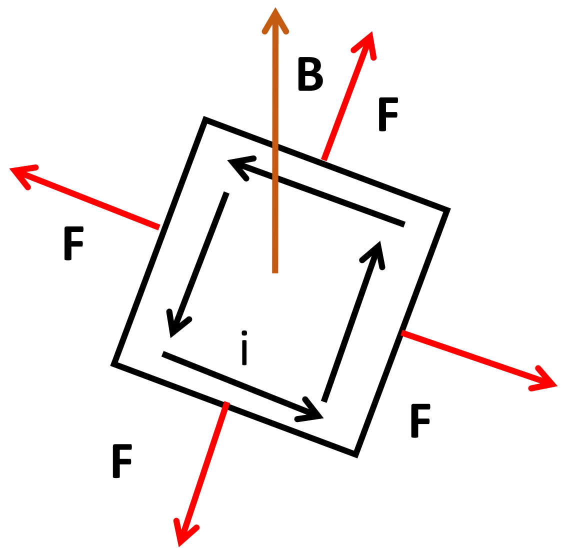
It will be equal in magnitude and opposite in direction as the other side

$$\mathbf{F} = \int_c i d\ell \times \mathbf{B}$$



Torque on a Current Loop

- We can show that the forces on each side of the conductor net to zero
- No torque developed
- No movement of the conductor

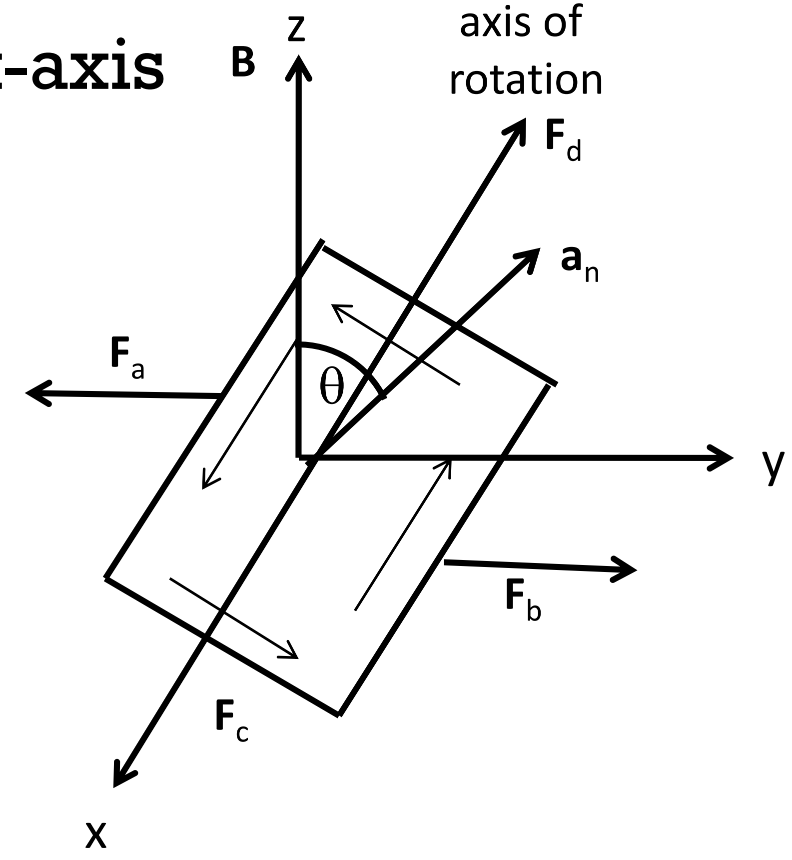


Torque on a Current Loop

- Consider a loop rotated on the x-axis
- From $\mathbf{F} = \int_c i d\ell \times \mathbf{B}$

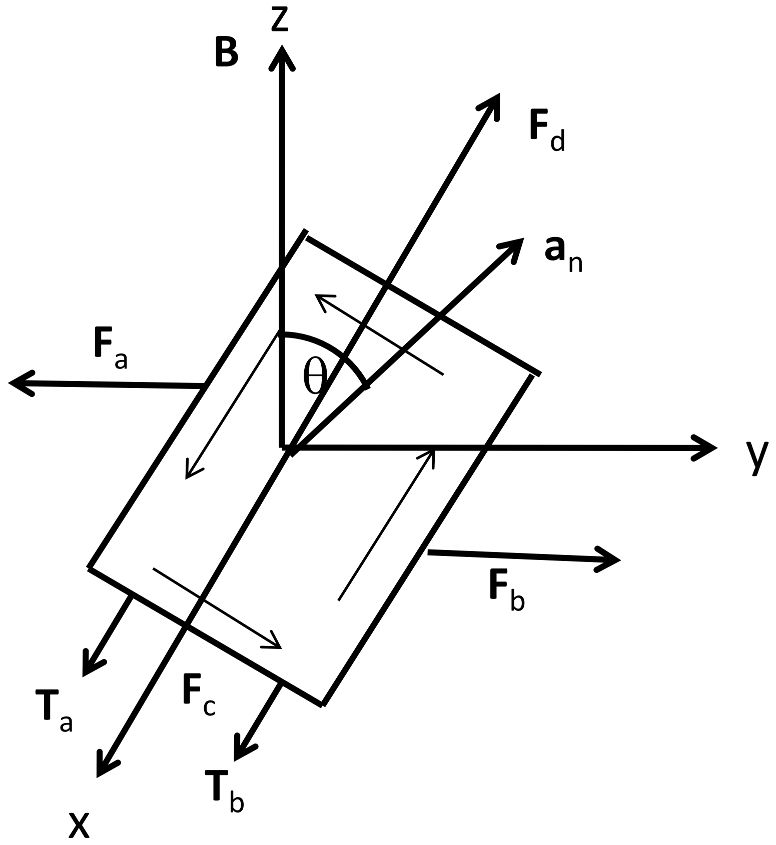
$$\mathbf{F}_a = -\mathbf{B} i L \boldsymbol{a}_y$$

$$\mathbf{F}_b = \mathbf{B} i L \boldsymbol{a}_y$$



Torque on a Current Loop

- A torque develops that tends to rotate the loop



Torque on a Current Loop

- The torque **T** is: $\mathbf{T} = \mathbf{r} \times \mathbf{F}$
- Therefore the torque on the a and b sides is:

$$\mathbf{T}_a = BiL(W/2)\sin\theta\,\boldsymbol{a}_x$$

$$\mathbf{T}_b = BiL(W/2)\sin\theta\,\boldsymbol{a}_x$$

- The total torque on the loop is:

$$\mathbf{T} = BiA\sin\theta\,\boldsymbol{a}_x$$ using A= LW

- If there are N coils:

$$\mathbf{T} = BiAN\sin\theta\,\boldsymbol{a}_x$$

Basic Principles of Machines

- Recall that a relative motion between a conductor and constant magnetic field induces an emf
  - A coil can rotate in a fixed magnetic field
  - A fixed coil in a rotating (varying) magnetic field

$$\mathbf{F} = \int_c i d\ell \times \mathbf{B}$$

- DC machines: stationary magnetic field, rotating coil
- AC machine: stationary coils, rotating magnetic field

Basic Principles of Machines

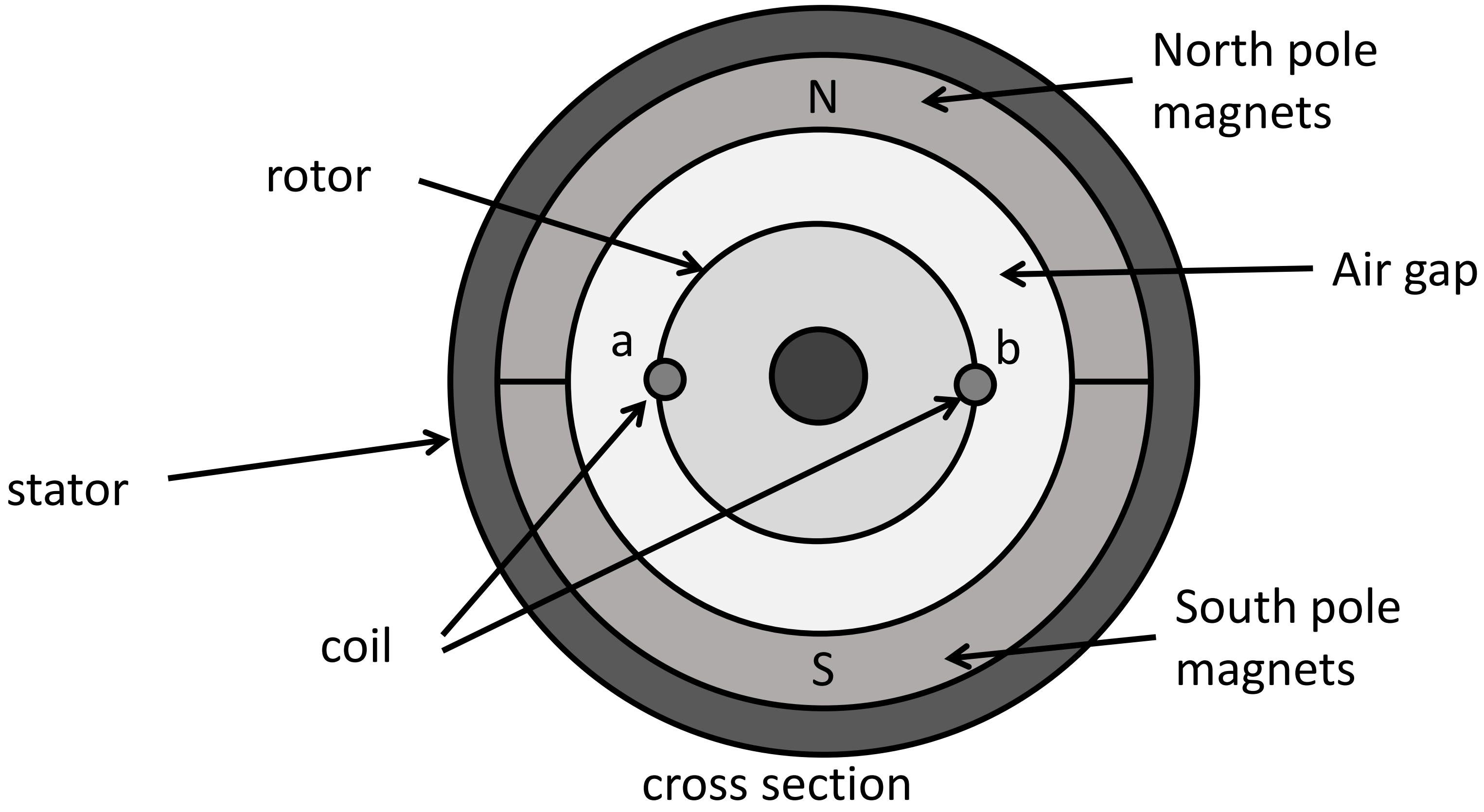
- Generically:
  - Rotating part is known as the *rotor* (also known as the *armature* in dc machines)
  - Stationary part is known as a *stator*
- Rotor and stator are made from highly permeable material
- A small air gap between stator and rotor allows the rotor to rotate
  - Air gap consumes most of the mmf (similar to large voltage drop)

Basic Principle of Machines

- How can a constant magnetic field be set up?
  - Permanent magnet (PM)
  - Electromagnet (also known as a wound machine)
  - Both have advantages and disadvantages
- For clarity, we will assume PM machines for now

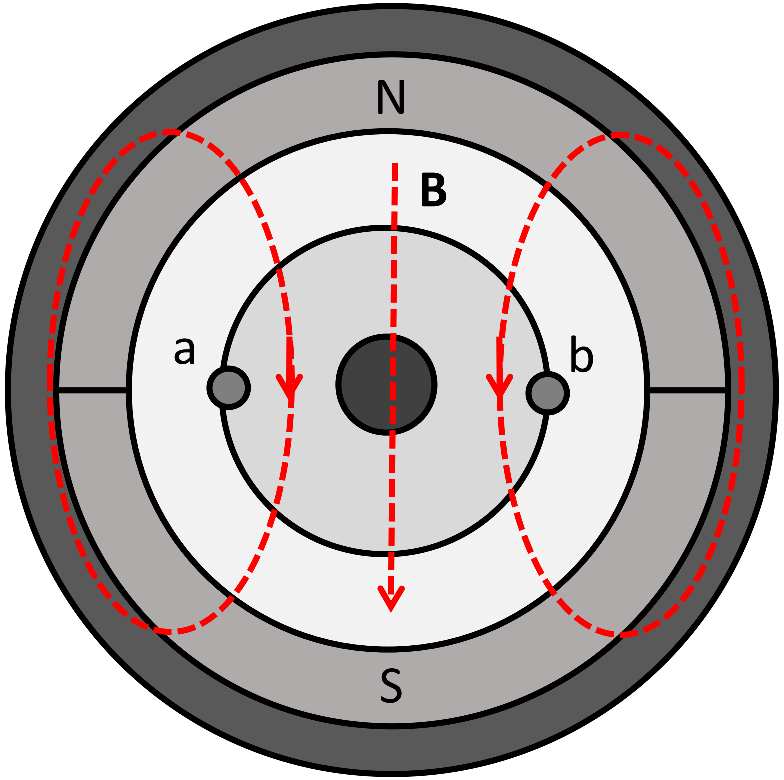
Generator Action

Consider an idealized cylindrical rotating machine with two poles (North and South)



Generator Action

- Ends of the coil are placed 180° apart
  - *full pitch*
- As the rotor rotates, one end of the coil enters N, just as the other enters S
- Note the magnetic field approximation



Generator Action

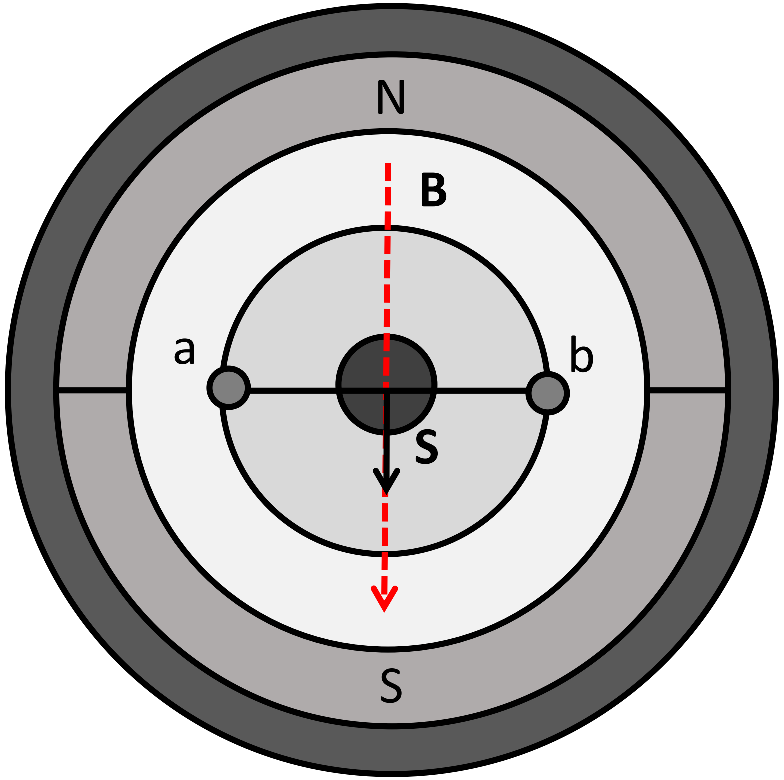
- Assume **B** and d**S** are normalized values so that

$$|\mathbf{B}||d\mathbf{S}| = 1.0$$

- If the coil is at rest, no emf is induced

$$e = -\int_s \frac{\partial \mathbf{B}}{\partial t} \bullet d\mathbf{s} = -N\frac{d\Phi}{dt}$$

N =1 for single-turn coils

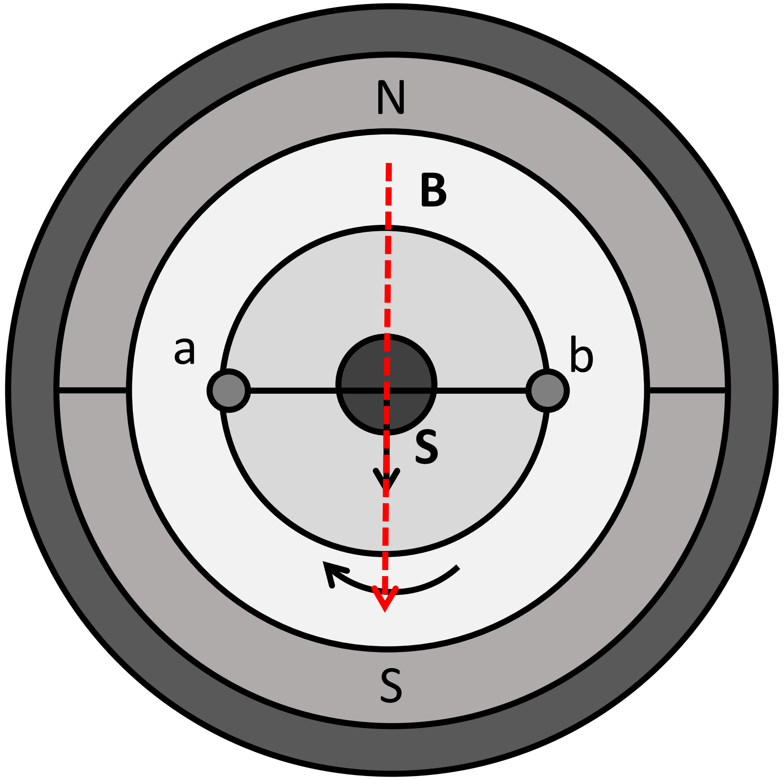


Generator Action

- θ_m: angle of rotation (angle between **B** and **S**)

  $$\mathbf{B} \bullet \mathbf{S} = |\mathbf{B}||\mathbf{S}| \cos\theta_m = 1.0$$

- Flux through the coil is maximum (**B** and **S** are aligned)
- Following slides: rotor is rotated CW by an external torque

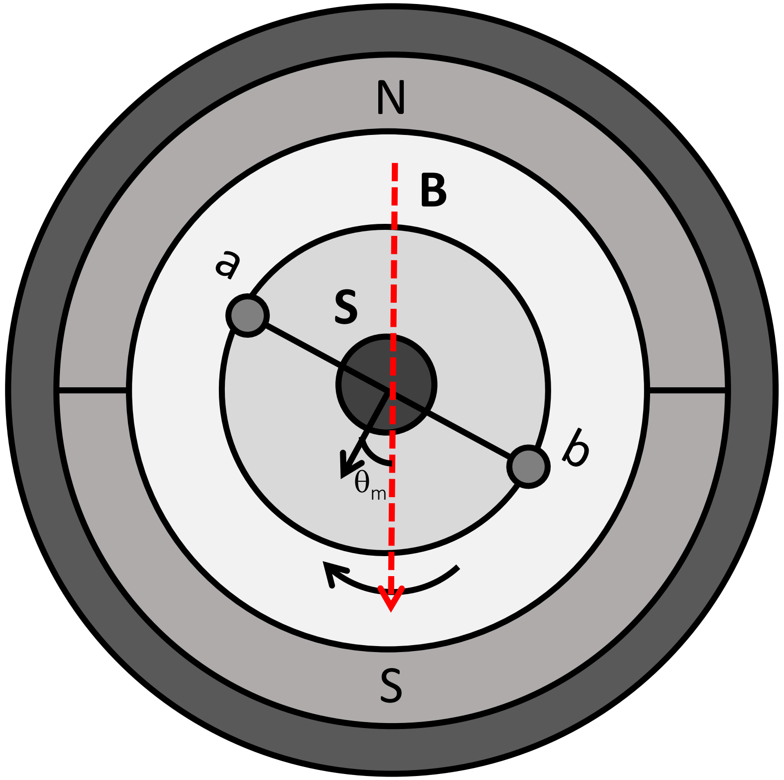


$\theta_m = 0^o$

Generator Action

- Now the coil has 30°
- Has the flux increased or decreased?
  - Decreased

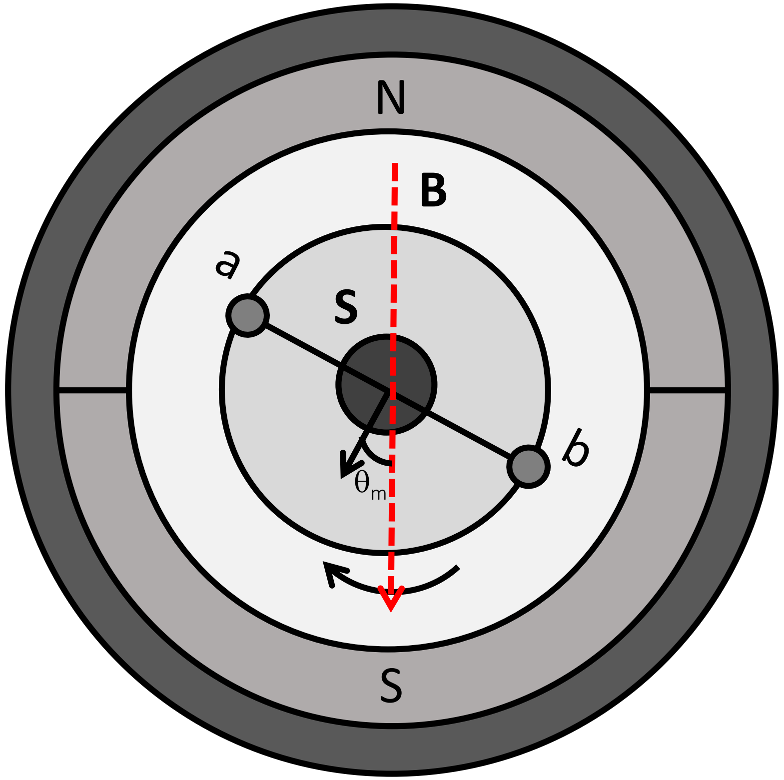
$|\mathbf{B}||\mathbf{S}|\cos\theta_m = 0.866$



$\theta_m = 30°$

Generator Action

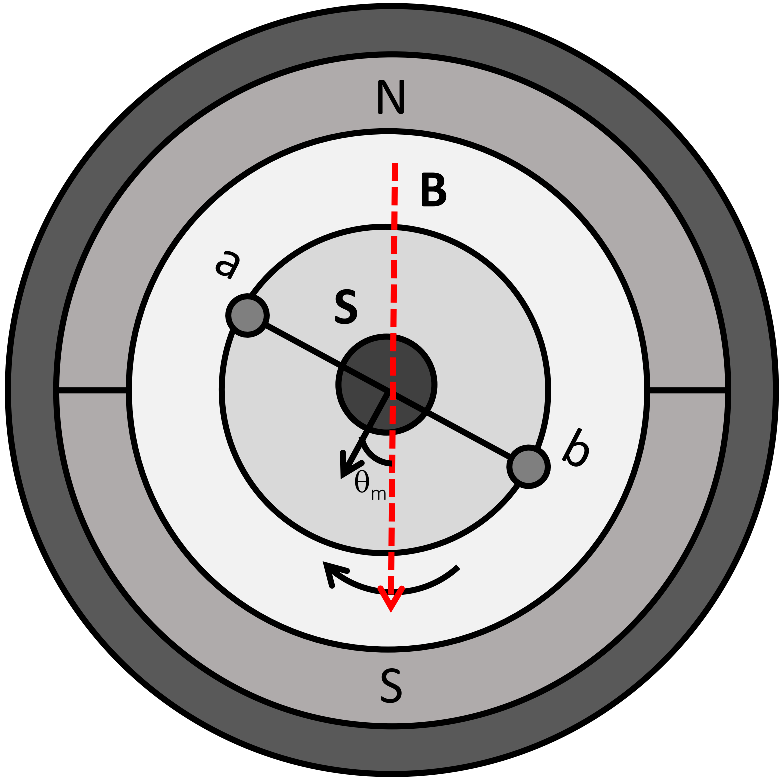
- If the ends of the coil are connected to a closed circuit, what direction does the current flow due to the induced emf?
- Is the current into a and out b, or into b and out a?



$\theta_m = 30^o$

Generator Action

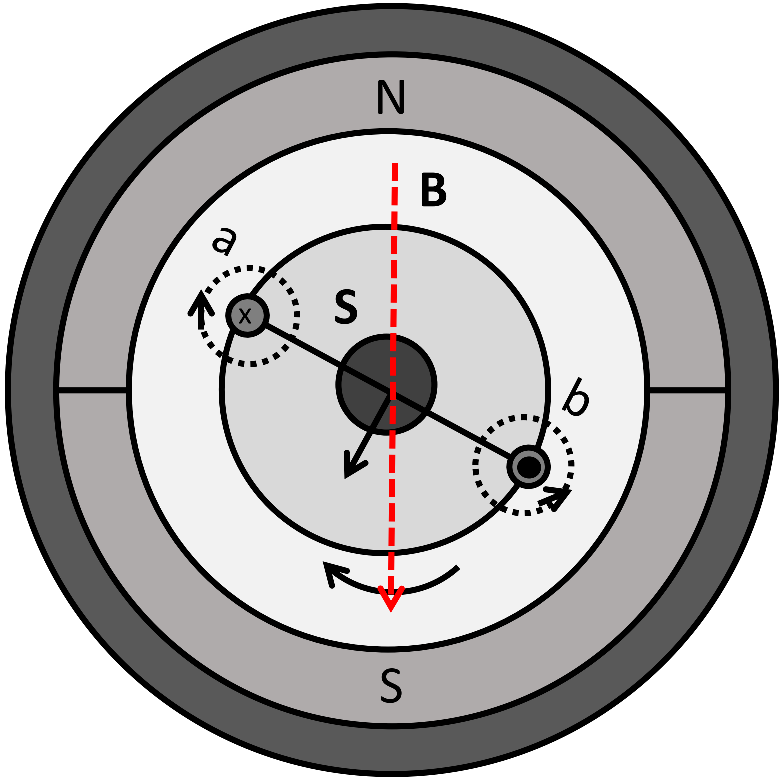
- Recall that the induced current flows in such a way that the flux it creates opposes the change in flux that caused it



$\theta_m = 30^o$

Generator Action

- If the induced current is going into a and out b, then the associated magnetic fields would be as shown
- Does this increase or decrease the flux through the coil?
    - Increases it, so it is the correct direction
    - The induced emf is therefore positive from a to b



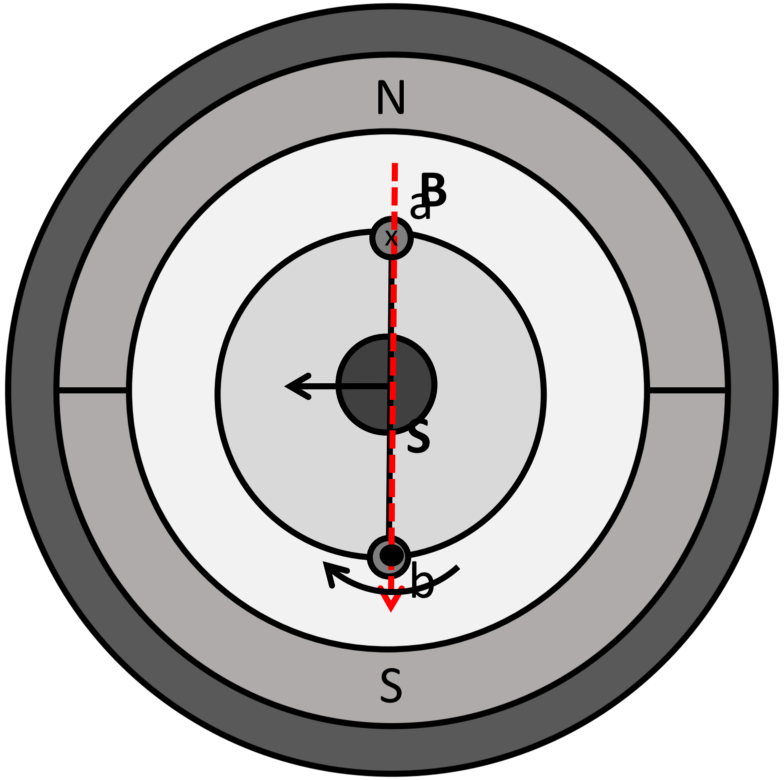
$\theta_m = 30^o$

Generator Action

- Flux is at a minimum

  $$|\mathbf{B}||\mathbf{S}|\cos\theta_m = 0$$

- $d\Phi/dt$ is large
  - Large voltage is induced
- Flux has still decreased, so current is still into a and out of b



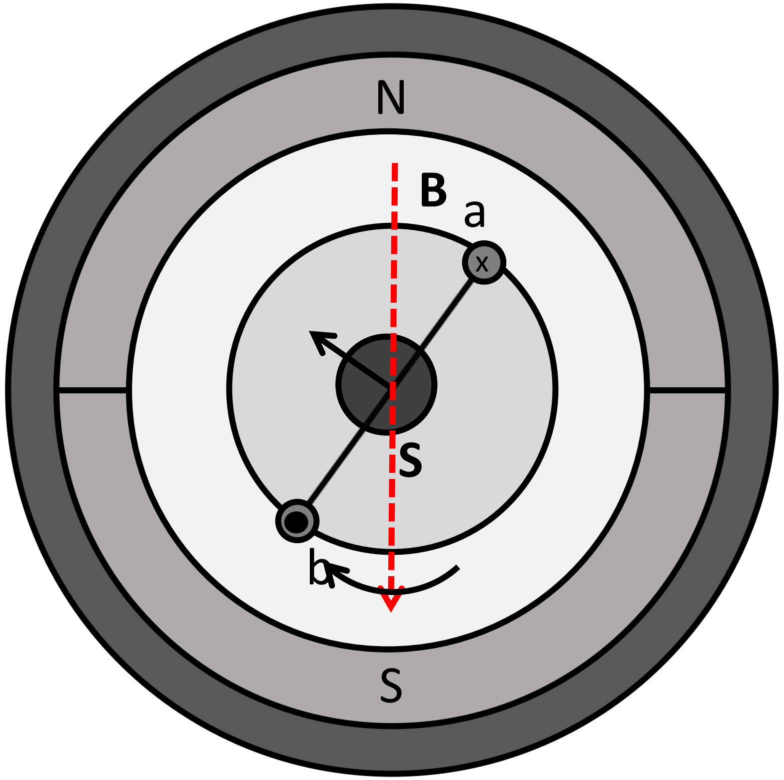
$\theta_m = 90^o$

Generator Action

- Flux is now in opposite direction through coil (negative)

$$|\mathbf{B}||\mathbf{S}|\cos\theta_m = -0.50$$

- Induced current still flows into a and out of b



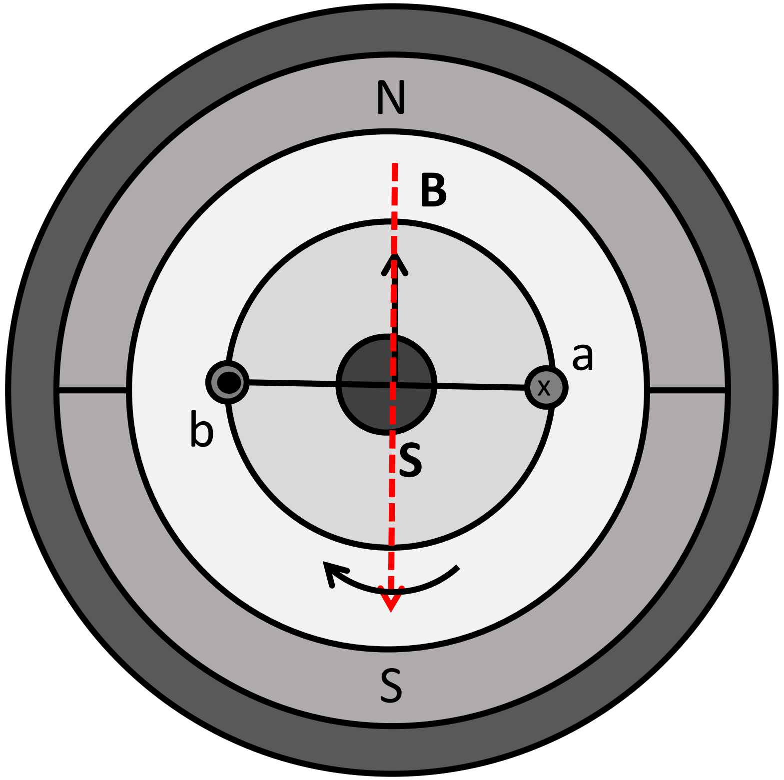
$\theta_m = 120^o$

Generator Action

- Flux is at its maximum negative value

  $$|\mathbf{B}||\mathbf{S}|\cos\theta_m = -1$$

- $d\Phi/dt$ is small
  - small voltage is induced
- Flux has still decreased, so current is still into a and out of b

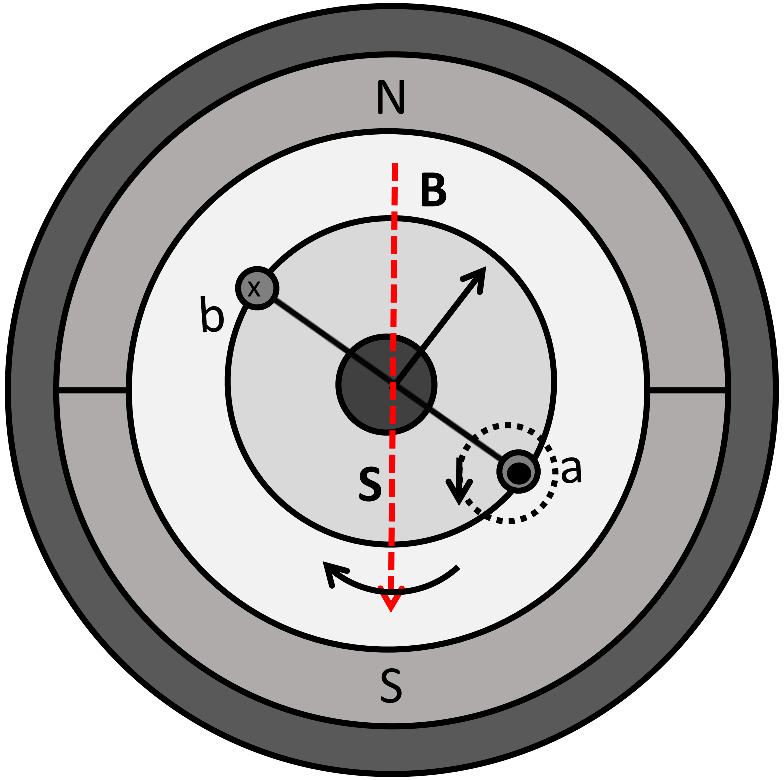


$\theta_m = 180^o$

Generator Action

- Flux starts to increase toward zero

  $|\mathbf{B}||\mathbf{S}|\cos\theta_m = -0.766$
- Induced current should act to decrease the flux
  - What direction is the current?
  - Into b and out of a
  - <u>Polarity of voltage reverses</u>
- Induced current stays in this direction until a full rotation is complete



$\theta_m = 220^o$

Generator Action

- Observations
  - Induced voltage lags flux by 90°
  - Induced voltage varies as a sinusoid
  - One full mechanical rotation equals one full electrical rotation (for 2-pole machines)
  - Alternating current is produced

Generator Action

- Analytically, the flux linking the coil is

$$\Phi = \Phi_P \cos\theta$$

  - Φ : flux linking the coil (Wb)
  - Φ_p: flux per pole (Wb)
  - θ: angular position of the coil (degrees electrical)

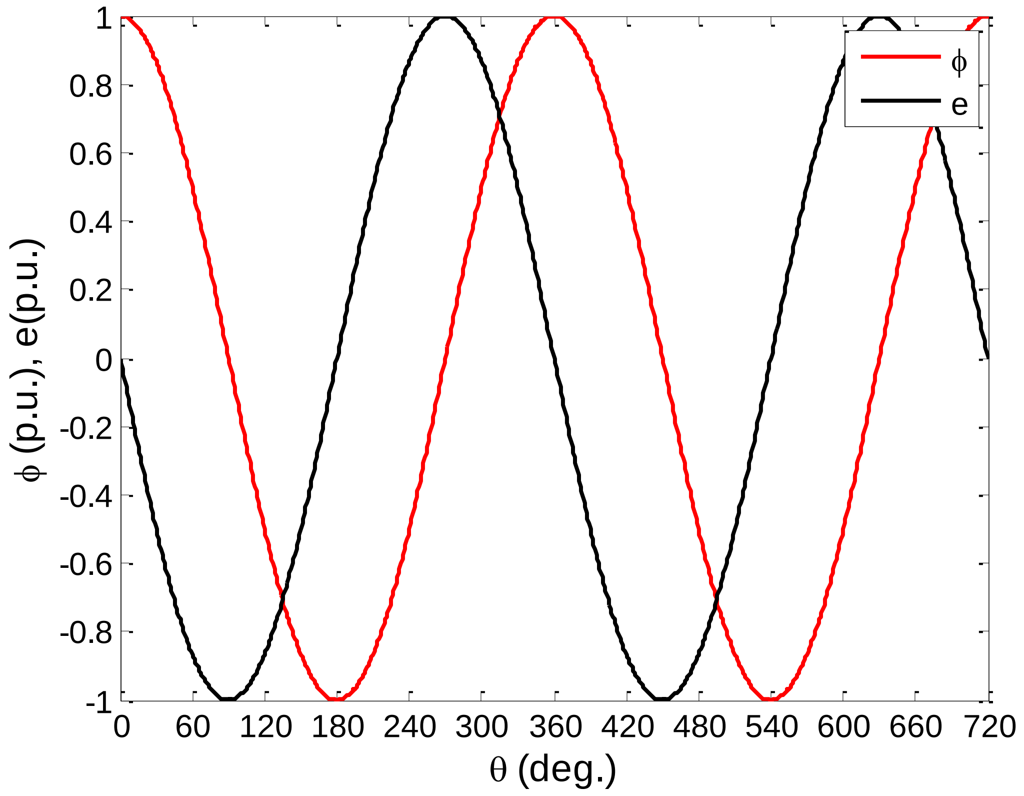
- The induced emf is:

Electrical and mechanical degrees are the same in 2-pole machines

$$\mathbf{e} = -\frac{d\Phi}{dt} = \Phi_P \sin\theta \frac{d\theta}{dt} = \Phi_P \omega \sin\theta$$

- Note that $\frac{d\theta}{dt} = \omega$ is the angular frequency of the coil

Generator Action



Generator Action

- Which of the following increases the induced voltage of the generator?
  - Decreasing the angular velocity
  - Increasing the flux per pole

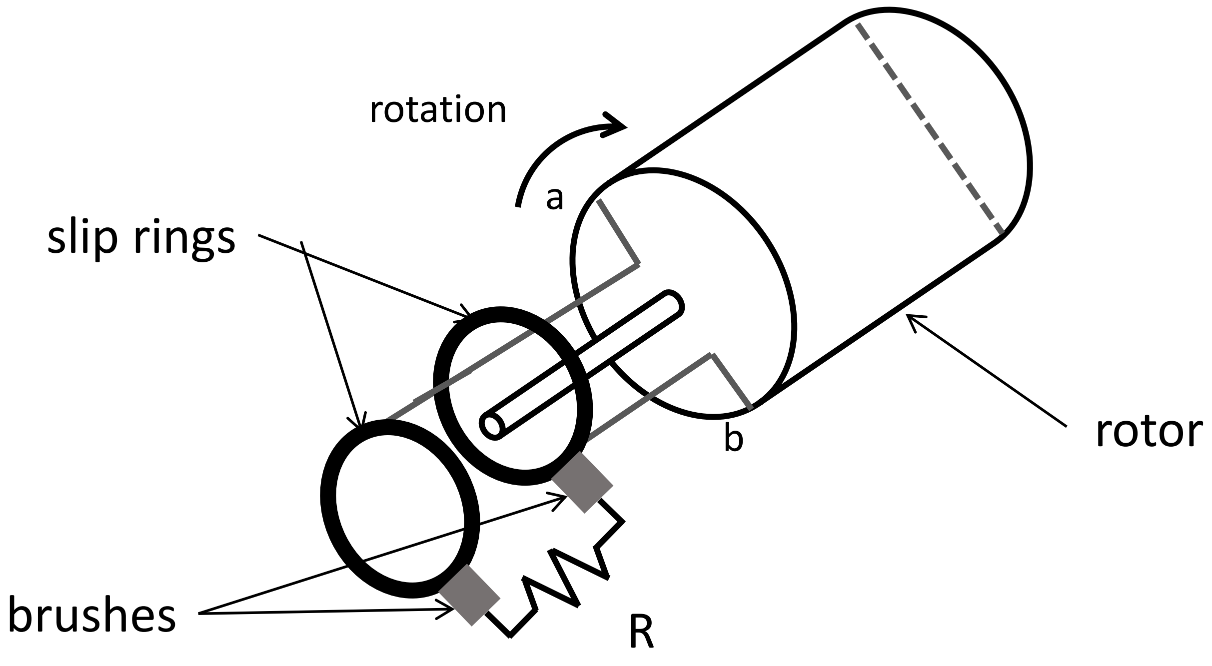
Generator Action

- Which of the following increases the induced voltage of the generator?
  - Decreasing the angular velocity
  - Increasing the flux per pole
    - Also increasing the angular velocity

AC Machine

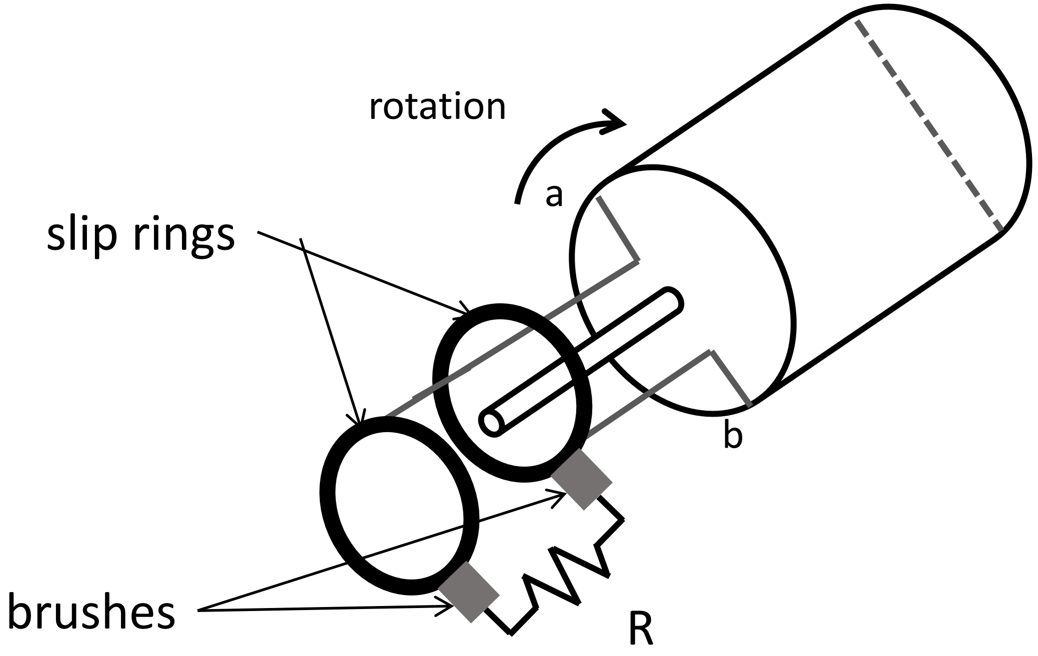
How do we connect a circuit to a rotating coil?

- Use slip rings and brushes



AC Machine

- Slip rings are conductive rings connected to the coil
- Coil end a is connected to the slip ring on the left
- Coil end b is connected to the slip ring on the right
- Slip rings rotate with the rotor
- Stationary brushes are spring loaded and push against the slip rings for a low resistance connection
- <u>Current through R is AC</u>

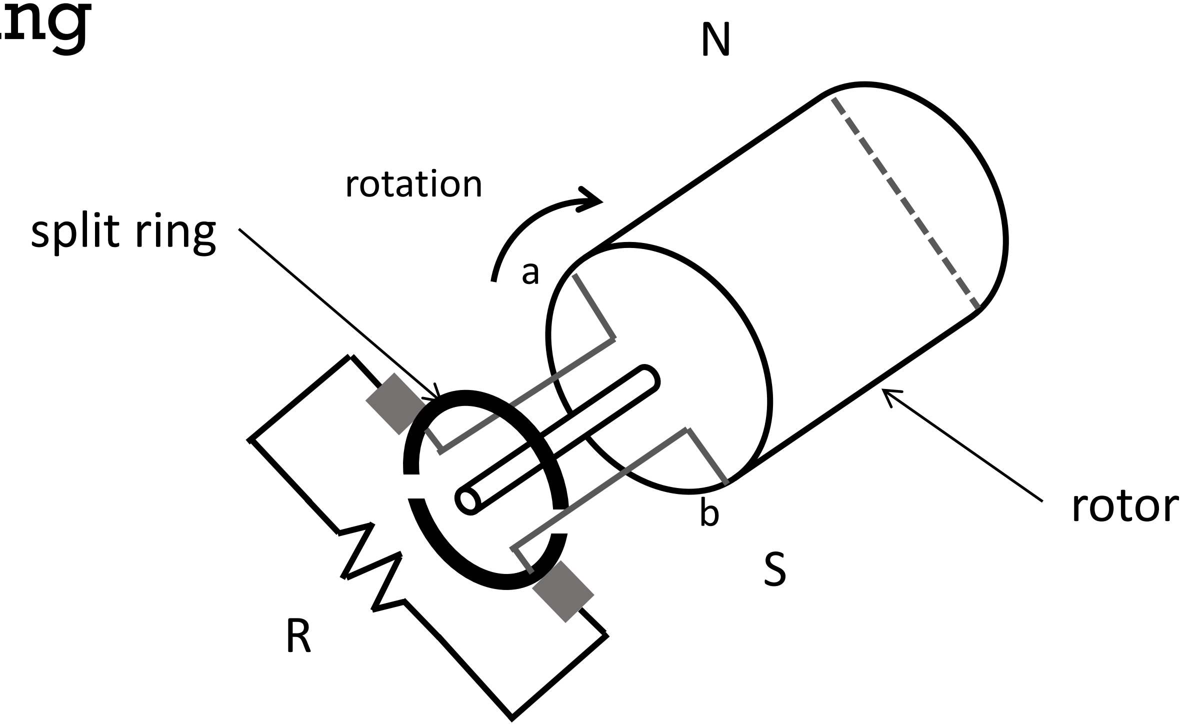


AC Machine

- A more efficient way to realize AC generator is to use permanent magnets (PMs) in the rotor to establish a rotating magnetic field and use the stator windings to connect to the load

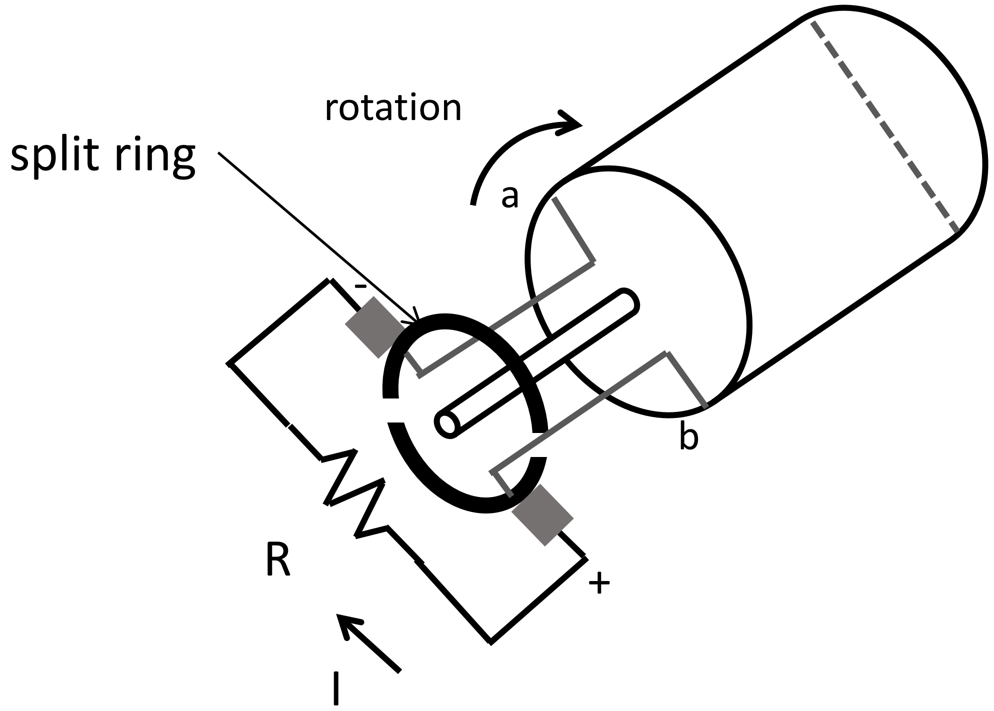
DC Machine

For a DC output, replace the slip rings with a single split ring



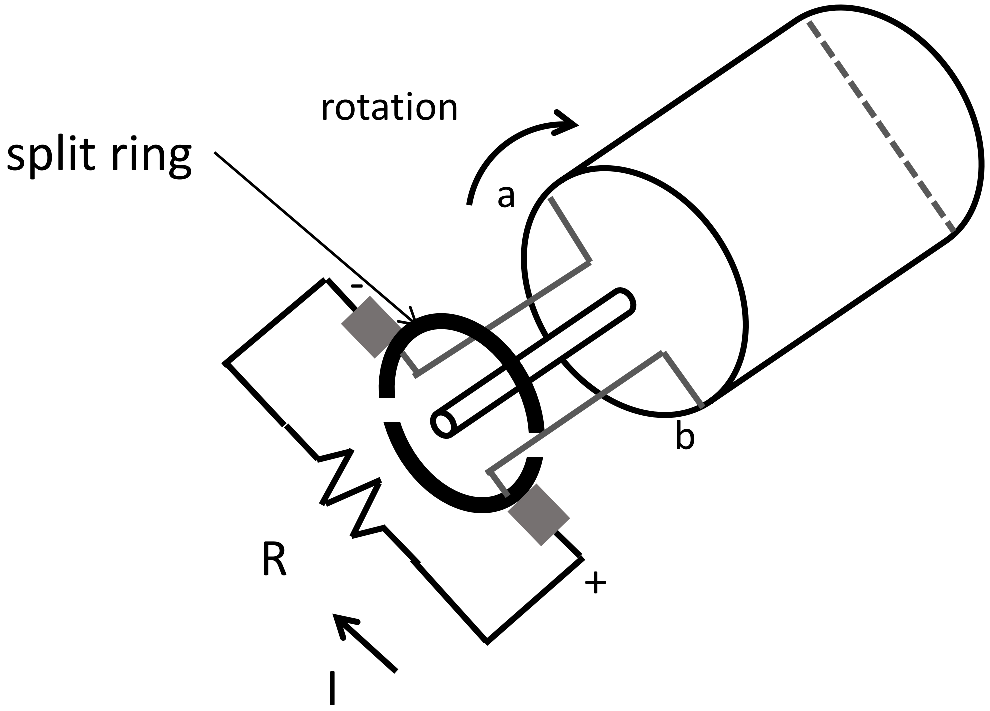
DC Machine

- Coil ends a and b are attached to either half of the split ring
- Stationary brushes are used to connect the split ring to the load R
- <u>Current flows in one direction, but it is not constant</u>



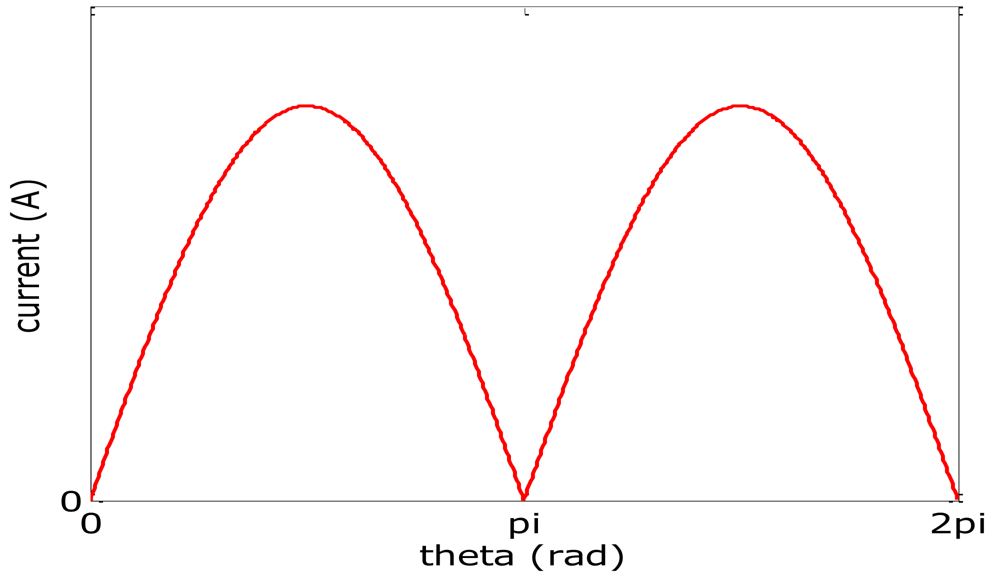
DC Machine

What does the current waveform through the load R look like?



DC Machine

- What does the current waveform through the load R look like?
- It is not a constant, but it is unidirectional



Summary

- Generators convert mechanical energy to electrical energy
- Motors convert electrical energy to mechanical energy
- Rotating coil in constant magnetic field generates AC voltage in coil
- For a 2-pole machine, 1 mechanical rotation produces one full sine wave
- Brushes and slip rings for AC output
- Brushes and split ring of DC output