Introduction to Electric Machines

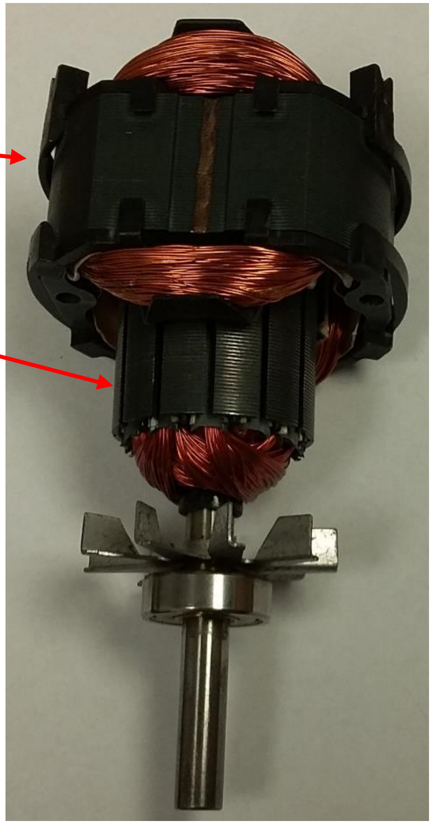
DC Motors and Generators

Introduction

- At this point of our class we begin the study of electric motors and generators.
- We will consider first DC machines.
- In future lectures we will study also
  - AC machines
  - Stepper motors

Electric Machine Components

- The fixed part of the machine is called *stator*.
- The rotating part is called *rotor*.



- The stator and/or the rotor contain coils of wire (electromagnets) producing a magnetic field when an electric current flows through them.

Electric Machine Components

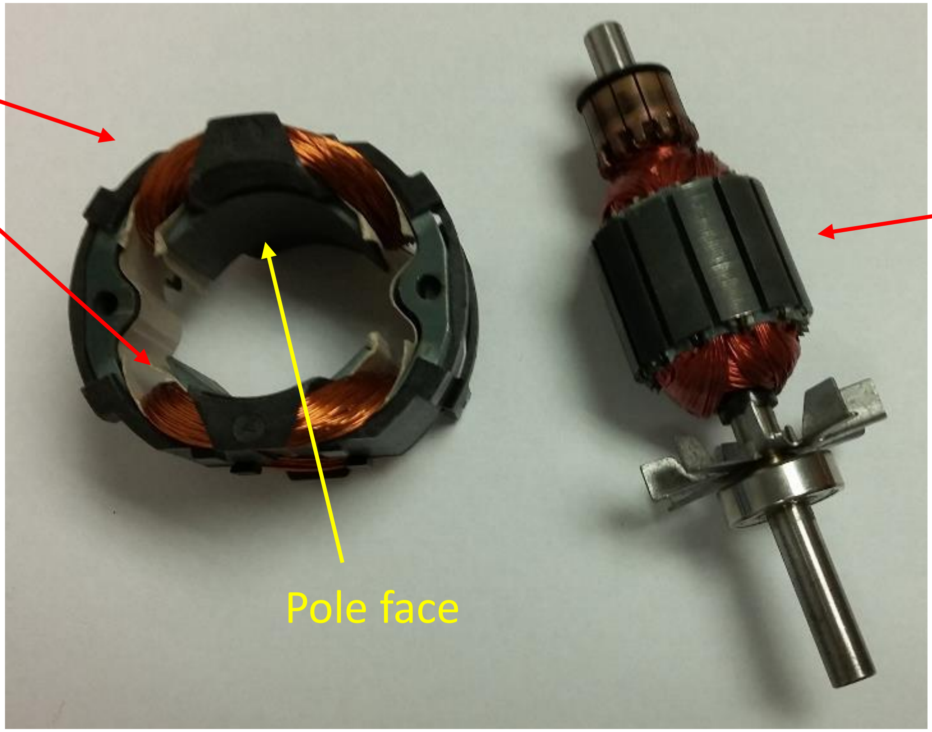
- The armature is the main current-carrying component.
  - The armature current is alternating even for DC motors.
  - This distinguishes the armature from the electromagnets of the *field poles*, if any, which have DC current.

- The *armature windings* are the coils of the armature.
- The *field windings* are the coils of the field poles.

Electric Machine Components

- In a DC motor, torque is created based on the interaction between the constant magnetic field of the *field poles* and the (alternating) magnetic field of the *armature*.
- Commonly, the field poles are on the stator and the armature is the rotor.

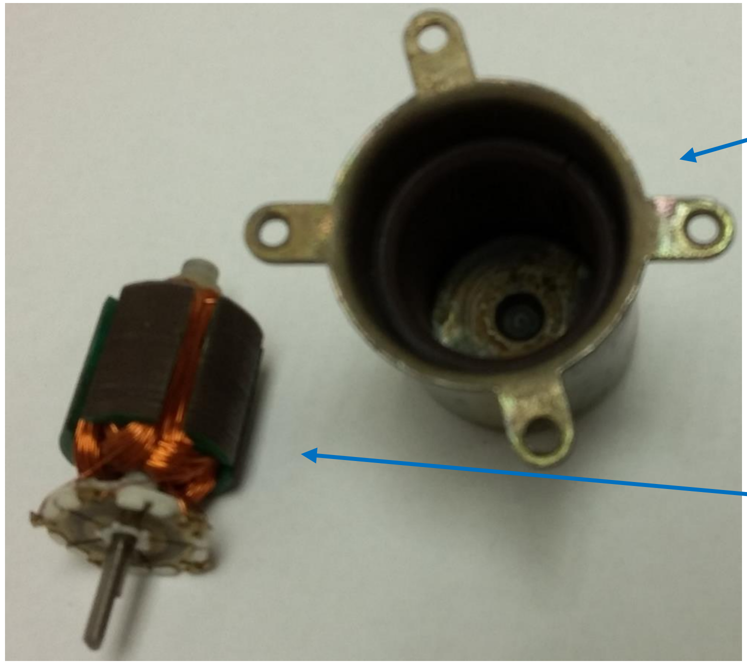
Stator with two field poles



The rotor of this motor is the armature

Electric Machine Components

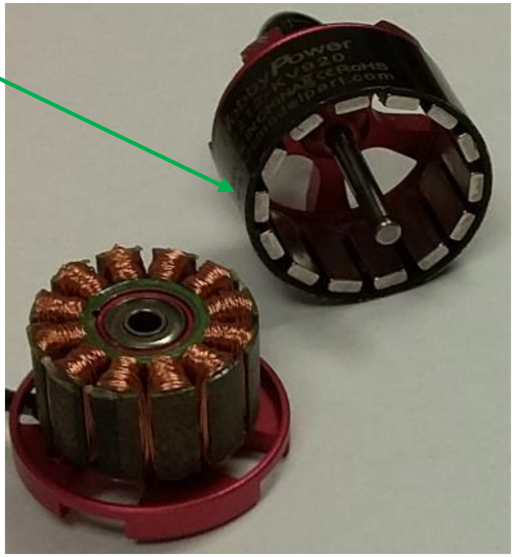
- Field poles can be made with permanent magnets instead of electromagnets.
- Commonly the field poles are on the stator and the armature is the rotor.
- Sometimes the armature is the stator and the field poles are on the rotor.



The stator has 2 permanent magnet poles

The rotor is the armature

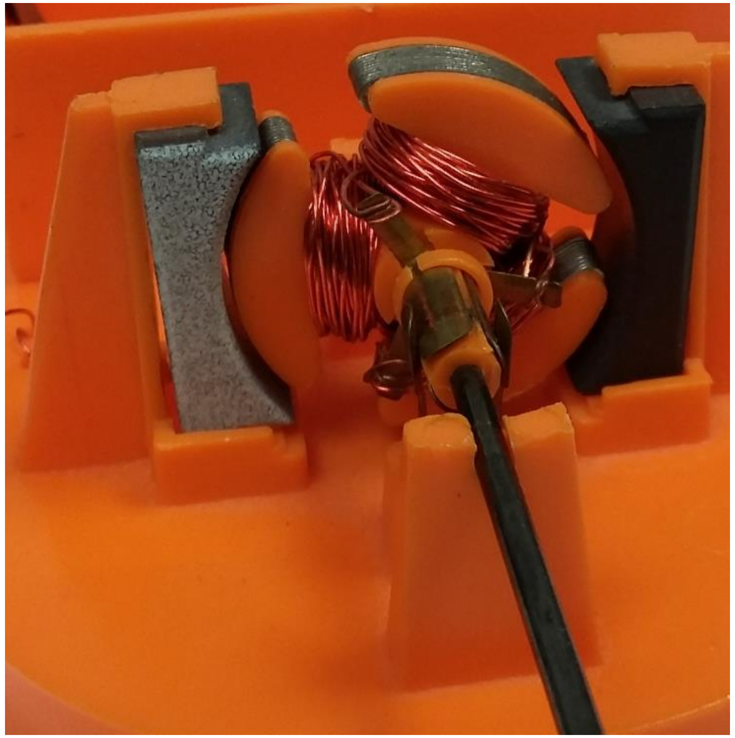
Rotor with 14 permanent magnet poles

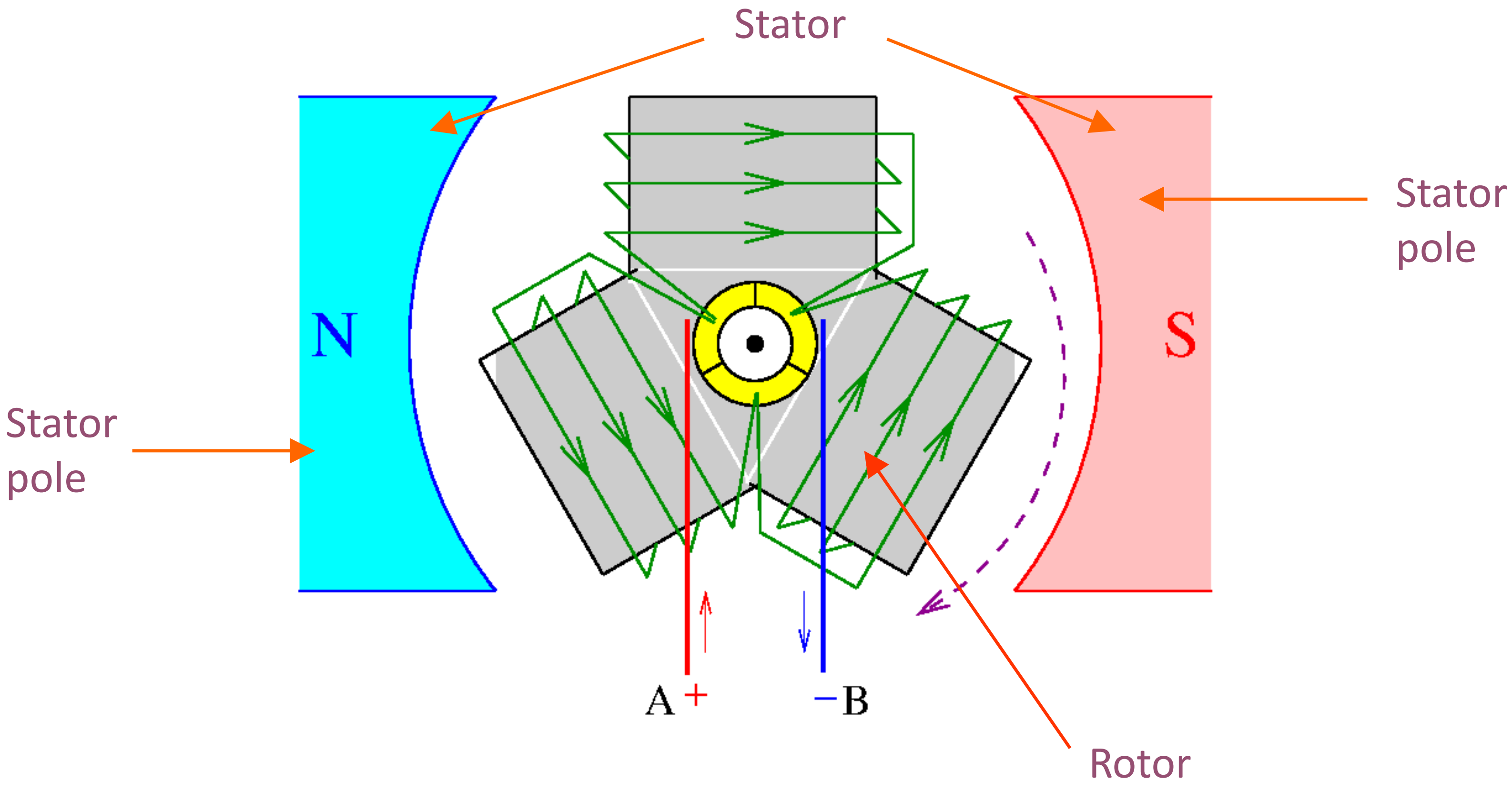


For this motor, the stator is the armature

Electric Machine Components

- One of the simplest DC machines has 3 poles on the rotor (armature) and 2 permanent magnet stator poles.





Electric Machine Principle

- The relative motion between the armature and the field poles creates a time-varying magnetic flux in the armature.
- A time-varying flux φ creates a voltage e, by Faraday's law:

$$e = \frac{d\varphi}{dt}$$

- The voltage induced in the armature is called *back electromotive force*.
- The open-circuit voltage of generators is the *back emf*.
- This voltage is proportional to:
  - Motor speed ω (because $d\varphi/dt$ is proportional to ω).
  - The flux Φ per field pole (because φ is proportional to Φ).

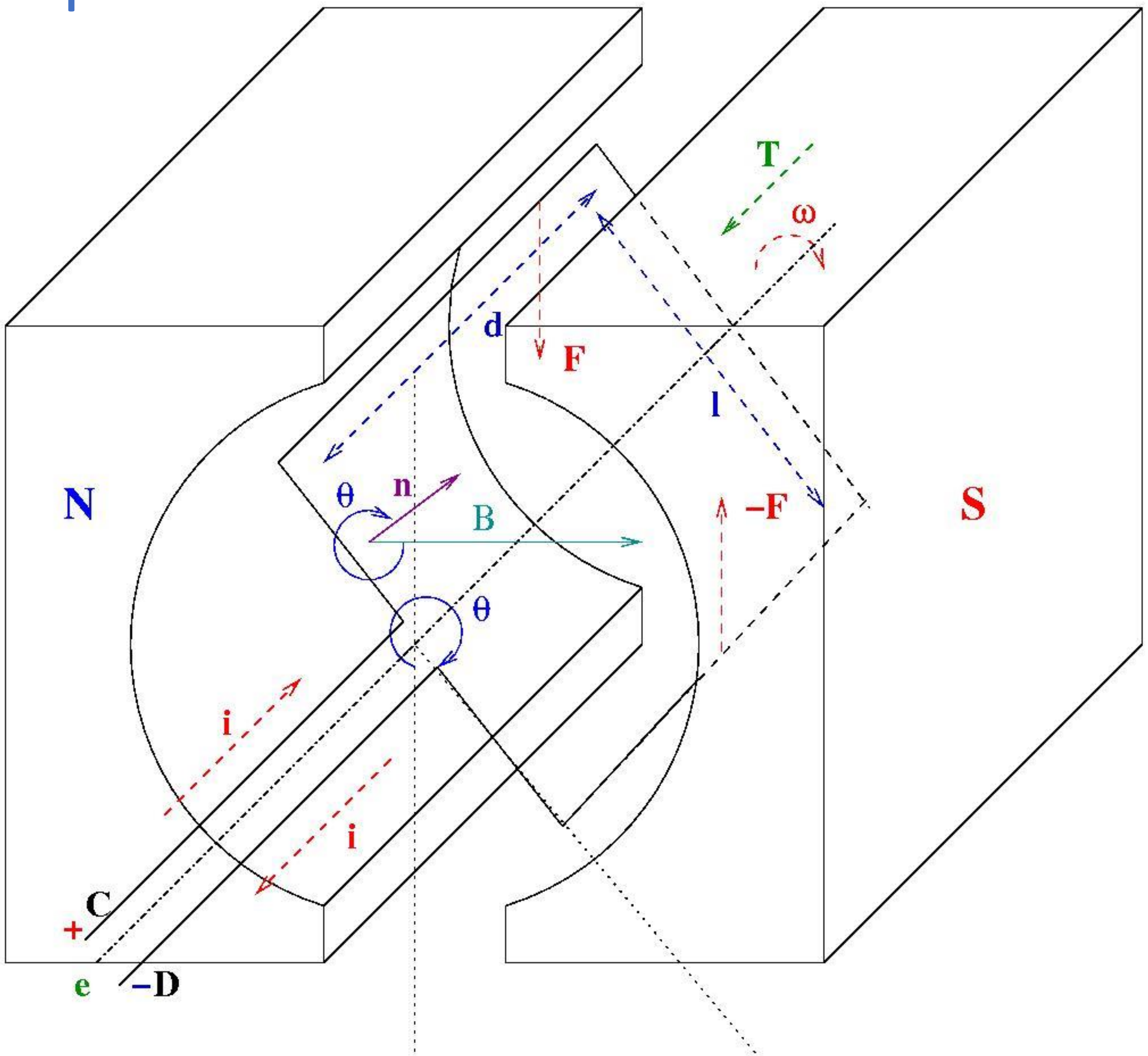
Electric Machine Principle

- The interaction between the magnetic fields of the field poles and the armature poles creates torque.
- Torque is proportional to:
  - The armature current.
  - The flux Φ per field pole.

Electric Machine Principle

- The operation of a DC machine can be explained by considering a single conductive frame turning in a magnetic field.
- Let ω be the angular velocity.
- $\theta = \omega t$ is the angle of the frame.
- Let $A = d \cdot l$ be the area of the frame.
- Let B be the flux density.
- The flux of the frame is $\varphi = BA\cos\theta$.
- The back emf is

$$e = \frac{d\varphi}{dt} = \frac{d(BA\cos(\omega t))}{dt}$$
$$= -BA\omega\sin(\omega t)$$



Electric Machine Principle

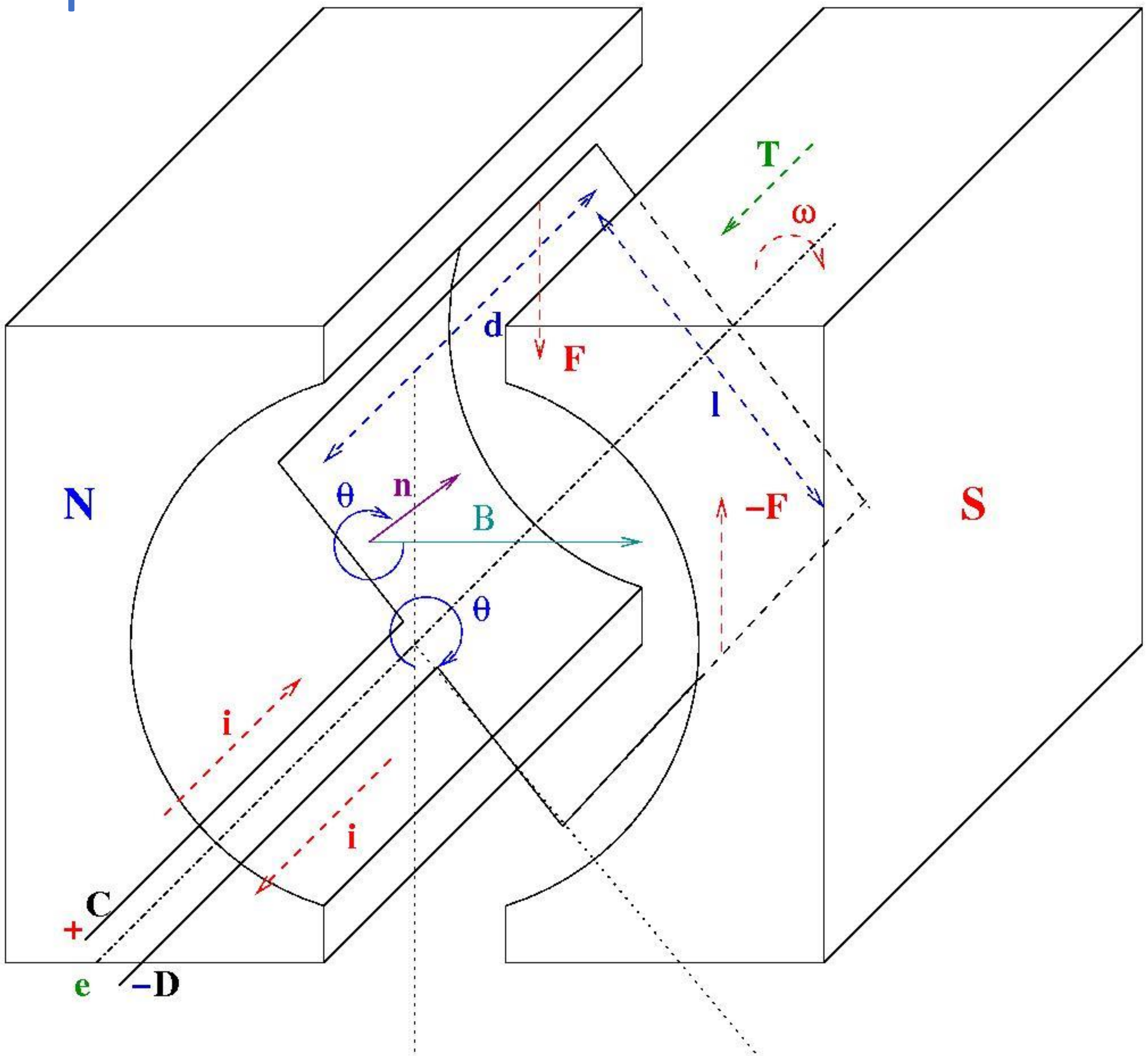
- Suppose a current i flows through the frame.
- The upper segment of length d will have a force:

$$\boldsymbol{F} = i \cdot \boldsymbol{d} \times \boldsymbol{B}$$

  where $\boldsymbol{d}$ points in the direction of i.

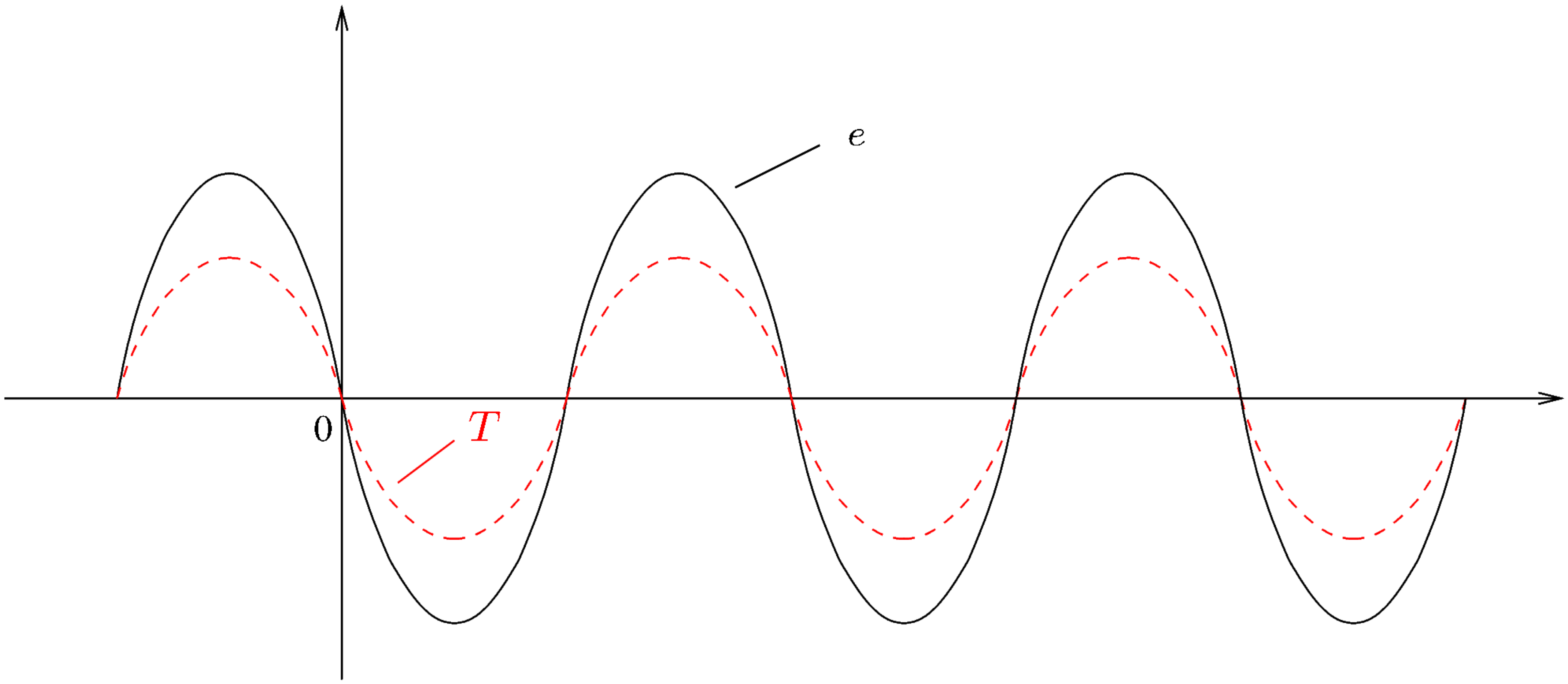
- The lower segment has an equal force in the opposite direction.
- This results in a torque $\boldsymbol{T} = \boldsymbol{l} \times \boldsymbol{F}$.
- Note that

$$\begin{aligned} T &= -ildB\sin(\theta) \\ &= -iBA\sin(\omega t) \end{aligned}$$



Electric Machine Principle

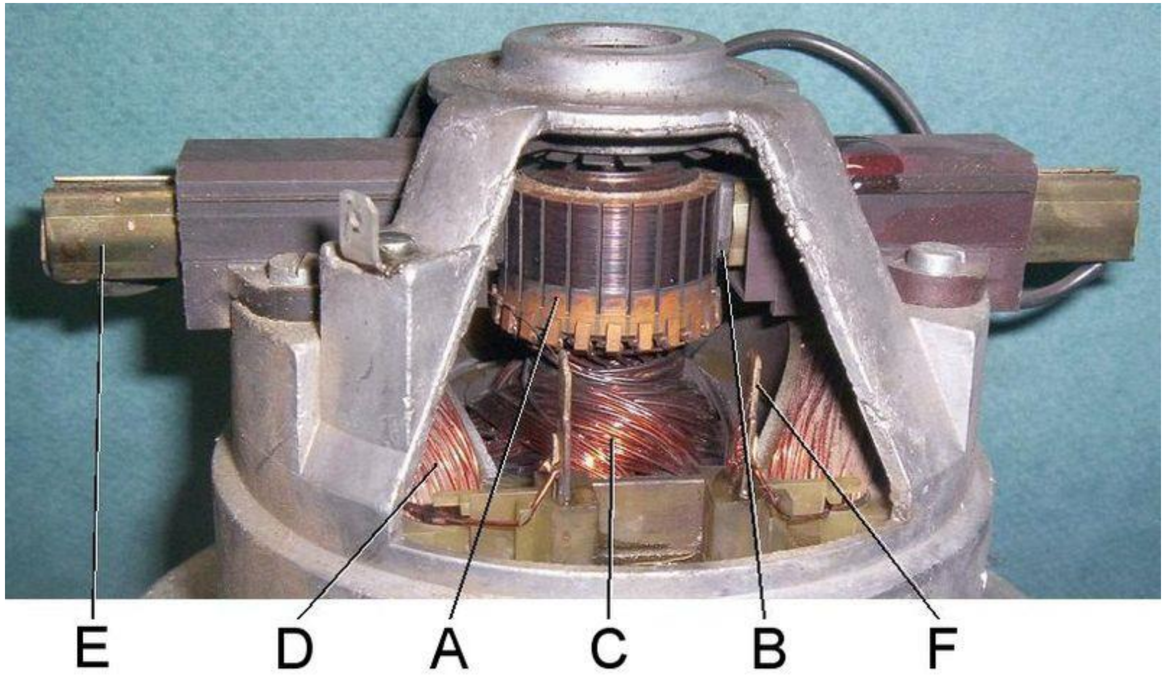
- We have shown that $e = -BA\omega \sin(\omega t)$ and $T = -iBA \sin(\omega t)$.
- Unless i is time varying, the torque is a zero-mean sinusoidal function of time!
- *To achieve a non-zero average torque, we need a time-varying armature current.*



Electric Machine Principle

- The simplest way to ensure a time-varying armature current is by means of mechanical commutation.
- As the motor shaft rotates, the polarity of the voltage applied to the armature coils is switched mechanically.
- This is done by means of a rotary switch called *commutator*.
- The commutator is a cylinder attached rigidly to the motor shaft.
- It has parallel contact segments.
- A number of fixed contacts, called *brushes*, touch the commutator.
- As the commutator rotates, the brushes touch different contact segments.

Electric Machine Principle



A commutator image from Wikipedia

(*Universal_motor_commutator.jpg*, in the public domain.

Retrieved on April 4, 2020, from
https://en.wikipedia.org/wiki/Commutator_(electric) .)

Commutator in a universal motor from a vacuum cleaner. Parts:

(A) Commutator

(B) Brush

(C) rotor (armature) windings

(D) stator (field) windings

(E) brush guides

Electric Machine Principle

Rotor with 12 poles

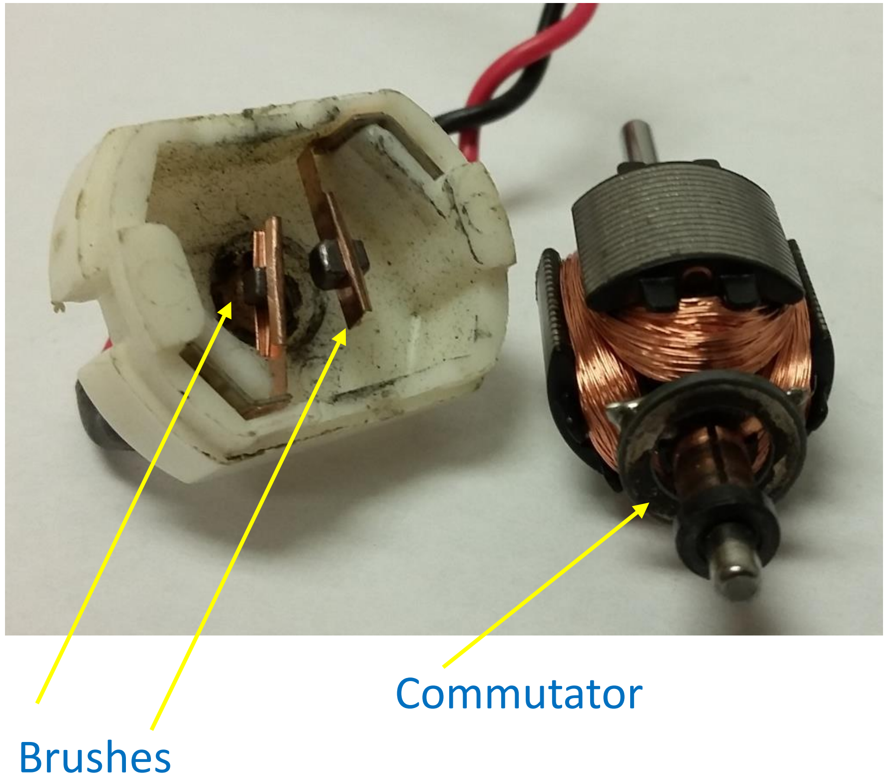
Stator with two permanent magnet poles

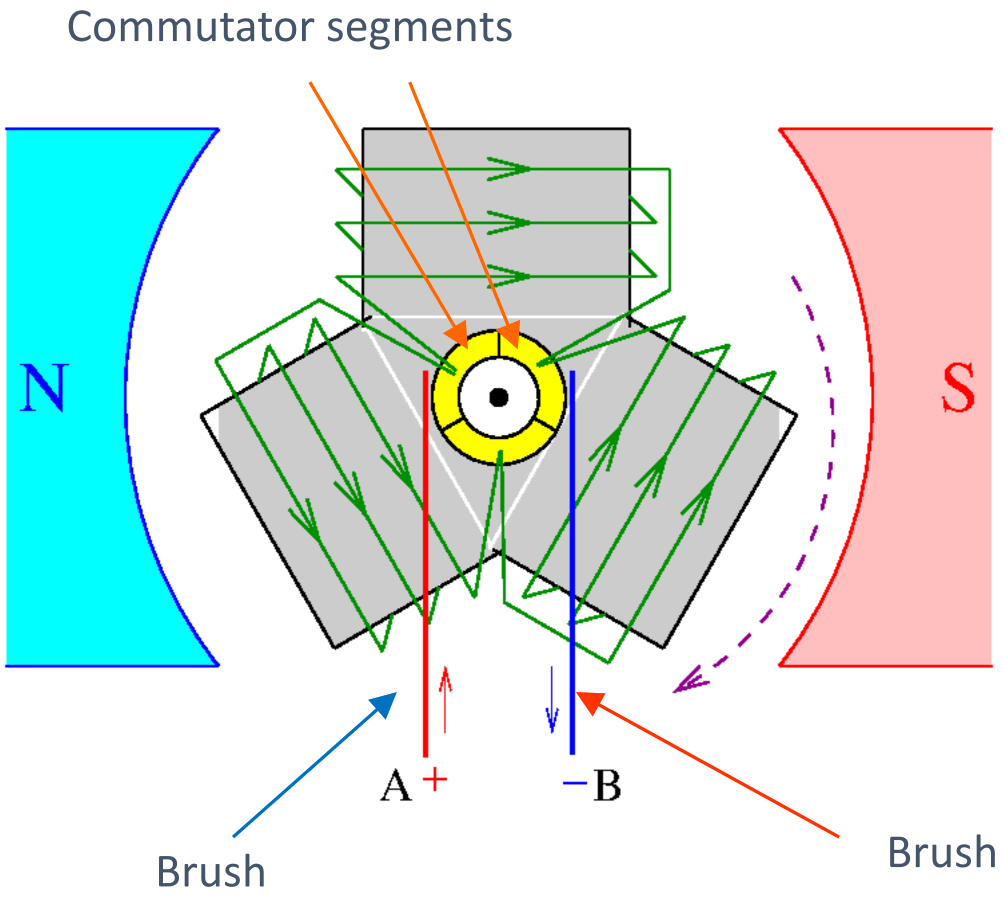
Spring-loaded brushes

Commutator with 12 segments

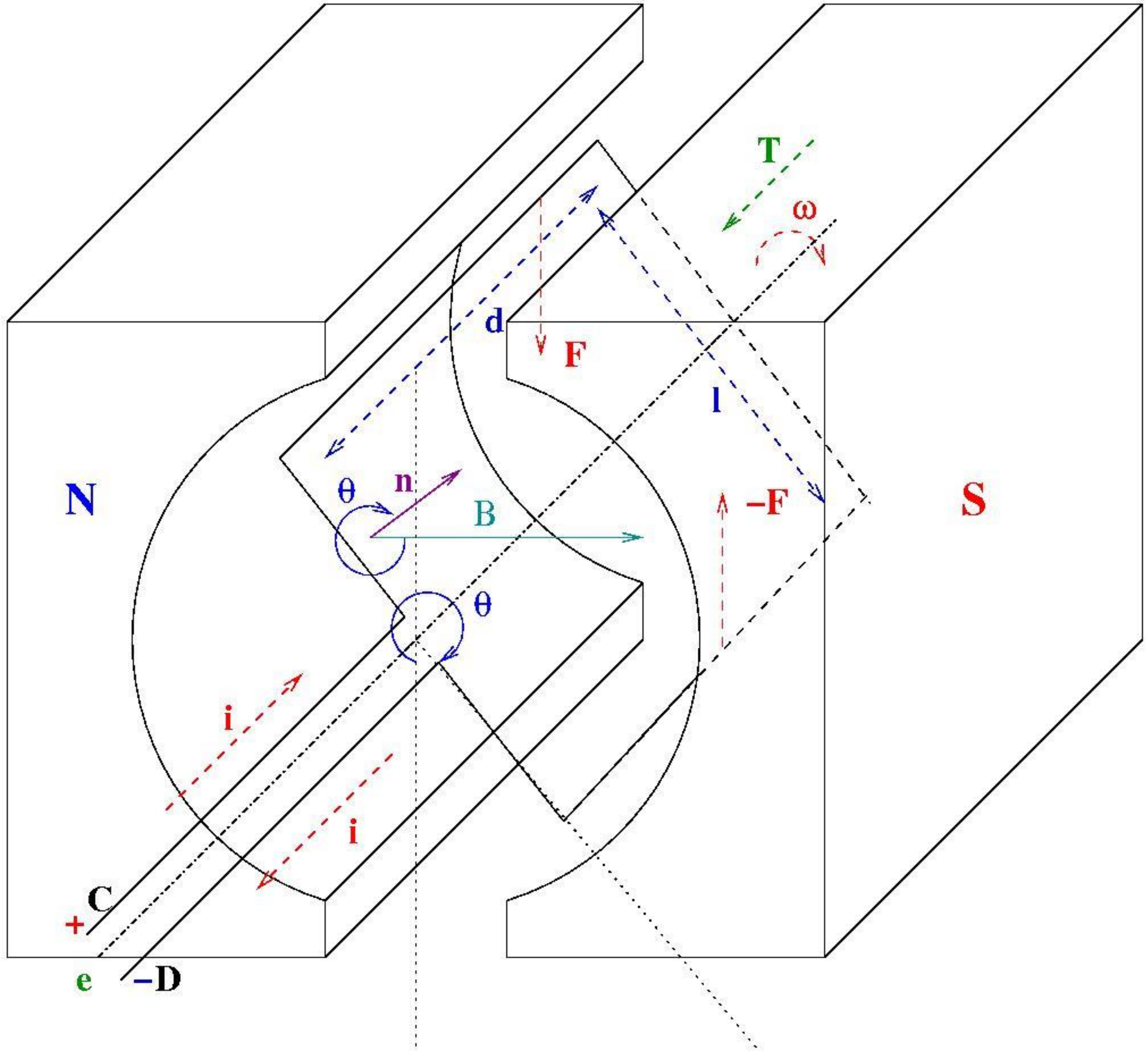
Electric Machine Principle

The figure at the right shows the two brushes and the three commutator segments of a machine with three poles on the armature.



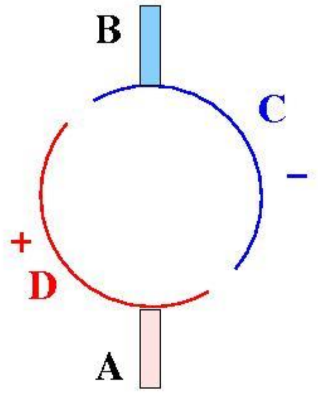


Electric Machine Principle



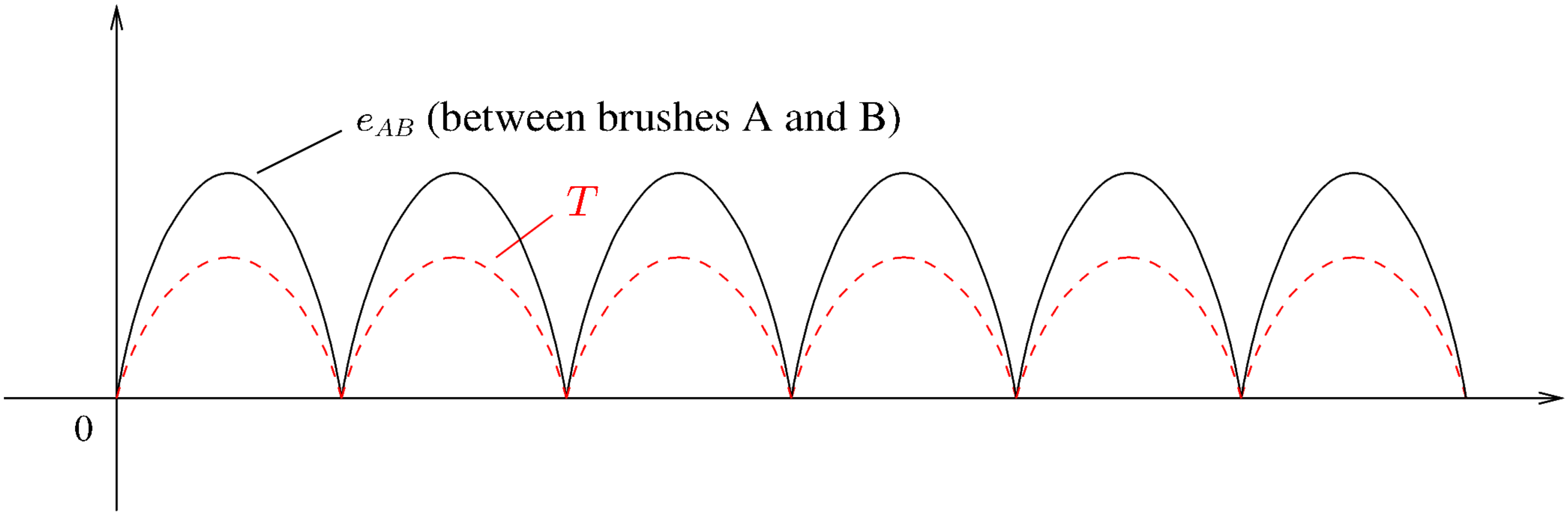
- A commutator could be added to the rotating frame considered earlier.
- Instead of powering the machine at C and D, we power it at the brushes A and B.
- The brushes touch periodically the contact segments connected to C and D.
- In this way, the direction of the current is switched so that the torque does not change sign.

THE COMMUTATOR



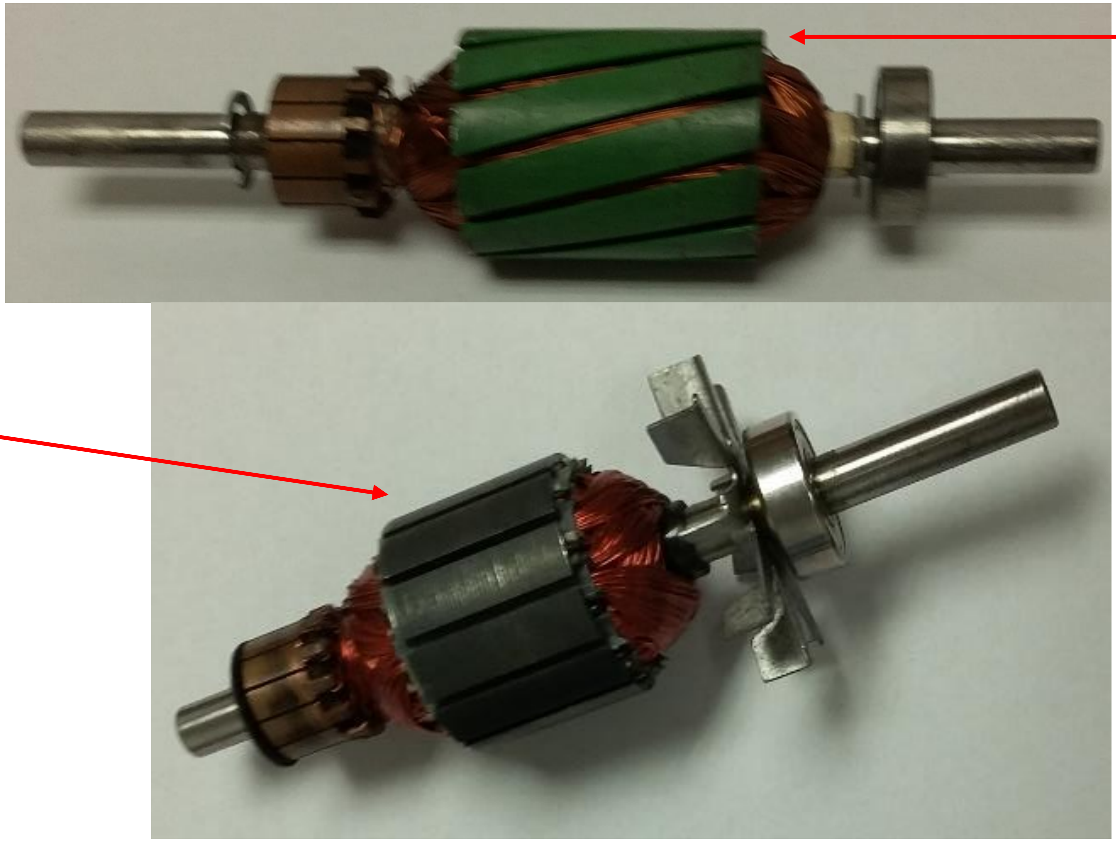
Electric Machine Principle

- With a commutator, the torque has always the same sign.
- When the machine is used as a generator, the generated voltage will not change sign.
- The graphs were obtained for a very simple machine.
- The torque and the back emf pulsate also for more complex machines, though not as much.



Electric Machine Principle

- The torque and the back emf pulsate also for more complex machines, though not as much.
- This issue can be reduced or eliminated with a skewed armature design.



DC Machine Equations

- The average back emf obeys the equation:

$$E = k_a \Phi \omega$$

  where
  - ω is the speed.
  - Φ is the flux per field pole.
  - k_a is a constant dependent on the design of the machine.
- The *electromagnetic torque* satisfies:

$$T = k_a \Phi I_a$$

  where I_a is the average armature current.
- Note that $EI_a = T\omega$ (conservation of power).
- The actual (average) torque of the motor is less than the electromagnetic torque because of losses.

DC Machine Equations

- The flux Φ per field pole:
  - Is constant when the field poles are permanent magnets.
  - Is proportional to the current i_f of the field windings when the field poles are electromagnets: $\Phi = k_f i_f$, where k_f is a constant.
- The field and armature windings are connected
  - to different circuits for a *separately excited motor*;
  - in series for a *series motor* (aka *universal motor*);
  - in parallel for a *shunt motor*.