Electric Motors and Generators

- **Electric Machine** — device that can convert either mechanical energy to electrical energy or electrical energy to mechanical energy
  - mechanical to electrical: *generator*
  - electrical to mechanical: *motor*
  - all practical motors and generators convert energy from one form to another through the action of a magnetic field

- **Transformer** — device that converts *ac* electric energy at one voltage level to *ac* electric energy at another voltage level
It operates on the same principles as generators and motors, i.e., it depends on the action of a magnetic field to accomplish the change in voltage level.

- **Magnetic Field** acts as the medium for transferring and converting energy.

- Motors, Generators, and Transformers are ubiquitous in modern daily life. Why?
  - Electric power is:
    - Clean, Efficient, Easy to transmit over long distances
    - Easy to control, Environmental benefits
Maxwell’s Equations

Gauss’s Law

Faraday’s Law

Extension of Ampere’s Law

\[ \nabla \cdot \mathbf{E} = 4\pi \rho \] (\( \rho \) = CHARGE DENSITY; \( \mathbf{E} \) = ELECTRIC FIELD) SAYS \( \mathbf{E} \) DIVERGES OUTWARD FROM PLUS CHARGES AND INWARD TO MINUS CHARGES.

\[ \nabla \times \mathbf{E} = -\frac{1}{c} \frac{dB}{dt} \] \( (B = MAGNETIC FIELD) \) SAYS \( \mathbf{E} \) CURLS AROUND CHANGING \( \mathbf{B} \) FIELDS. \( (c = SPEED OF LIGHT) \)

\[ \nabla \cdot \mathbf{B} = 0 \] SAYS \( \mathbf{B} \) NEVER DIVERGES, ALWAYS LOOPS AROUND.

\[ \nabla \times \mathbf{B} = \frac{4\pi}{c} \mathbf{J} + \frac{1}{c} \frac{d\mathbf{E}}{dt} \] SAYS \( \mathbf{B} \) CURLS AROUND CURRENTS \( (\mathbf{J} = CURRENT DENSITY) \) AND CHANGING \( \mathbf{E} \) FIELDS.
Linear DC Machine

\[ \vec{F} = i(\vec{\ell} \times \vec{B}) \]

\[ e_{\text{ind}} = (\vec{v} \times \vec{B}) \cdot \vec{\ell} \]

\[ V_B - iR - e_{\text{ind}} = 0 \]

\[ F_{\text{net}} = ma \]
• **Observations**
  – The same machine acts as both motor and generator.
    • Generator: externally applied forces are in the direction of motion
    • Motor: externally applied forces are opposite to the direction of motion
  – Electrically
    • $e_{\text{ind}} > V_B$, machine acts as a generator
    • $e_{\text{ind}} < V_B$, machine acts as a motor
  – Whether the machine is a motor or a generator, both induced force (motor action) and induced voltage (generator action) are present at all times.
  – This machine was a generator when it moved rapidly and a motor when it moved more slowly, but whether it was a motor or a generator, it always moved in the same direction.
Without current, this inductor has neither electric nor magnetic fields.

A steady current produces only a steady magnetic field.

Ampere + Faraday + Lenz

An increasing current produces an increasing magnetic field in the inductor, which in turn produces an electric field. The emf resulting from that electric field opposes the current increase.

A decreasing current produces a decreasing magnetic field in the inductor, which in turn produces another electric field. The resulting emf opposes the current decrease.
Some Observations

- Mechanical motion can be used to produce electric power – electric generators.
- Electric power can be used to produce mechanical motion – electric motors.
- Motors are everywhere!
- Generators are less common – power plants, cars, emergency power equipment.
- Motors come in many shapes and sizes, e.g. washing machine, cell phone, fan, etc., and operate from either direct current or alternating current.
• **Some Questions**

– How can a moving object push electric charges through a wire and produce electricity?
– How does the power company determine how much power it needs to generate?
– If everyone turned off their lights, would the power company still have to generate the same amount of electricity?
– How can magnetic forces cause something to spin?
– Why can’t a motor be built exclusively from permanent magnets?
– What determines which way a motor spins?
– Why are some motors safe near flammable chemicals while others are not?
• **AC Electric Generators: Mechanical Power Becomes Electric**

  – The spinning magnet of a generator produces an alternating magnetic field within a coil of wire and thereby induces an alternating emf in it.

  – The only important difference between a transformer and a generator is in what produces the alternating magnetic field.

  – Both devices have a coil wrapped around a magnetizable core. But, in place of the transformer’s primary coil, the generator has a spinning magnet or rotor.

  – The core forms a magnetic bridge between rotor and coil, conveying the rotor’s magnetic field into the coil even when they are separated in space.
What happens with the lamp unplugged? Now plug in the lamp. What happens?

Transformer: electricity produces magnetism produces electricity
• Question
  – When you pedal a high-tech exercise bicycle, you are spinning the rotor of an electric generator. That generator supplies power to a heating filament with an adjustable electrical resistance.
  – How should the bicycle alter that electrical resistance to make pedaling more difficult?
• The induced emf in a generator depends on three factors:
  – number of turns in the coil
  – magnetic field strength
  – frequency at which the magnetic field alternates

• **Linear DC Machine**

\[
\vec{F} = i (\vec{\ell} \times \vec{B})
\]

\[
e_{\text{ind}} = (\vec{v} \times \vec{B}) \cdot \vec{\ell}
\]

\[
V_B - iR - e_{\text{ind}} = 0
\]

\[
F_{\text{net}} = ma
\]
• **Question**
  – During periods of excessive power consumption, the electric grid occasionally reduces the voltage it supplies by about 5%. What can a generator do to lower its output voltage without changing its alternation frequency?
• **AC Electric Motors: Electric Power Becomes Mechanical**
  
  – Motors and generators are the same in structure. It acts as a generator when you do work on its rotor and as a motor when you extract work from its rotor.
  
  – What is reversed about them is the direction of current flow.

**AC Synchronous Motor**
The rotor turns in perfect synchrony with current from an AC electric power source. When this type of motor is plugged into a 60-Hz electrical outlet, its rotor spins exactly 60 times per second (or an integer fraction of that if the rotor has multiple pairs of poles.)
• **DC Electric Motors**
  – Most portable devices are powered by batteries and direct current.
  – What would happen if you sent direct current through the coil of an AC synchronous motor?
- What has to happen to keep the rotor spinning?
- Flipping a coil’s magnetism is as simple as reversing its current.
- There are two common approaches: brushless DC motors and brushed DC motors.
- A brushless DC motor is a synchronous AC motor plus a high-tech switch that reverses current whenever the rotor’s poles have aligned with opposite poles on the stationary coil.

**Brushless DC Motor**
A brushless DC motor uses an electromagnet to spin its magnetic rotor. A sensor monitors the orientation of the rotor and reverses current in the electromagnet each time the rotor aligns with the magnetic field.
A brushed DC motor spins its electromagnet rotor in the field of a permanent magnet. Each time the rotor aligns with the magnetic field, its commutator reverses the current in the electromagnet.

The electromagnetic coil is on the rotor and the permanent magnet is stationary.