PHYS 1442 – Section 001
Lecture #12

Wednesday, June 26, 2013

Dr. Jaehoon Yu

- Chapter 21
  - Lenz's Law
  - EMF Induction in Moving Conductor
  - Generation of Electricity
  - Transformer
  - Mutual and Self Inductance
  - Energy Stored in Magnetic Field
  - Alternating Current and AC Circuits

Announcements

- 2nd term exam
  - In class tomorrow, June 27
  - Non-comprehensive exam
    - Covers CH20.1 – what we finish today (CH 21 – 8)
  - BYOF (Bring your own formula sheet)
  - This exam can replace your first term exam if better
  - If you miss the exam you will get an F no matter how well you have been doing in the class!
- Your planetarium extra credit
  - Please bring your planetarium extra credit sheet by the beginning of the exam Monday, July 8
  - Be sure to tape one edge of the ticket stub with the title of the show on top and your name on the sheet

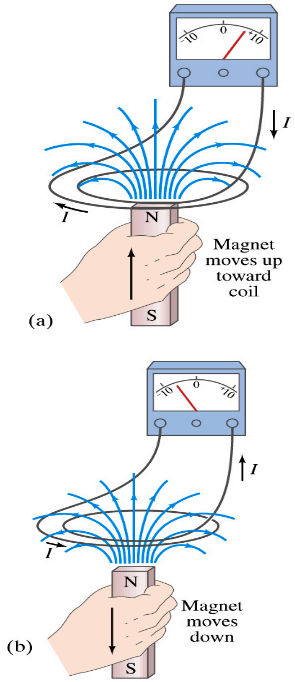
Special Projects

1. Derive the unit of speed from the product of the permitivity and permeability, starting from their original units. (5 points)
2. Derive and compute the speed of light in free space from the four Maxwell's equations. (20 points for derivation and 3 points for computation.)
3. Compute the speed of the EM waves in copper, water and one other material which is different from other students. (3 points each)

- Due of these projects are the start of the class Wednesday, July 3!

Lenz's Law

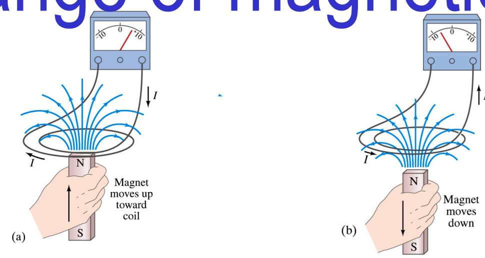
- It is experimentally found that
  - An induced emf gives rise to a current whose magnetic field opposes the original change in flux ➔ This is known as **Lenz's Law**
  - In other words, an induced emf is always in the direction that opposes the original change in flux that caused it.
  - We can use Lenz's law to explain the following cases in the figures
    - When the magnet is moving into the coil
      - Since the external flux increases, the field inside the coil takes the opposite direction to minimize the change and causes the current to flow clockwise
    - When the magnet is moving out
      - Since the external flux decreases, the field inside the coil takes the opposite direction to compensate the loss, causing the current to flow counter-clockwise



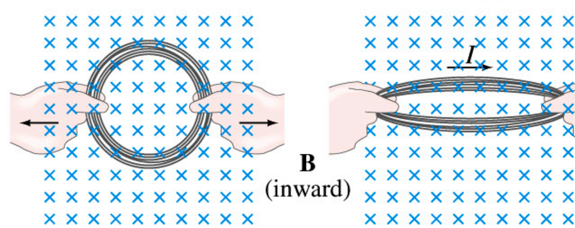
- Which law is Lenz's law result of?
  - Energy conservation. Why?

Induction of EMF

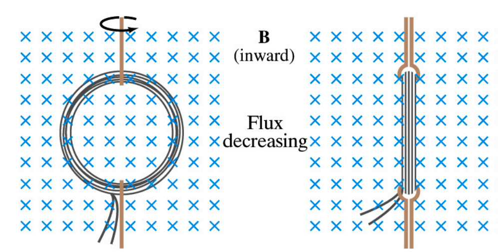
- How can we induce emf?
- Let's look at the formula for magnetic flux
- $$\Phi_B = \sum \vec{B} \cdot \Delta\vec{A} = \sum B \cos\theta \Delta A$$
- What do you see? What are the things that can change with time to result in change of magnetic flux?
  - Magnetic field



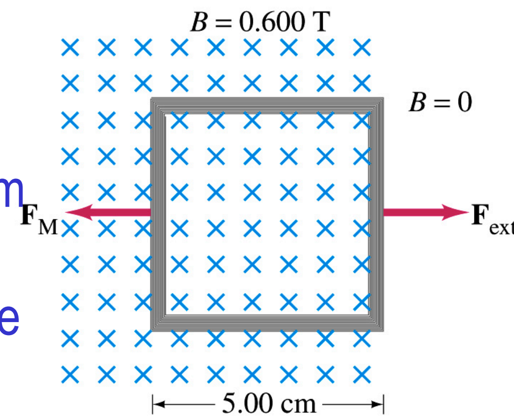
  - The area of the loop



  - The angle θ between the field and the area vector



Example 21 – 5

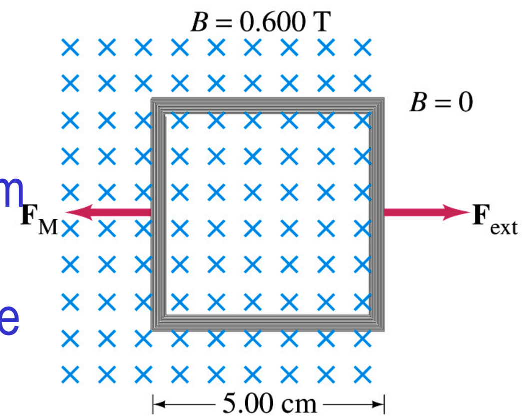


Pulling a coil from a magnetic field. A square coil of wire with side 5.00cm contains 100 loops and is positioned perpendicular to a uniform 0.600-T magnetic field. It is quickly and uniformly pulled from the field (moving perpendicular to B) to the region where B drops abruptly to zero. At t=0, the right edge of the coil is at the edge of the field. It takes 0.100s for the whole coil to reach the field-free region. Find (a) the rate of change in flux through the coil, (b) the emf and current induced, and (c) how much energy is dissipated in the coil if its resistance is 100Ω. (d) what was the average force required?

What is the procedure to solve this problem?

1. Compute the magnetic flux change.
2. Compute the emf generated by the change of flux using $\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t}$ Faraday's law
3. Compute the current using Ohm's law $I = \frac{\varepsilon}{R}$
4. Compute the energy loss using $E = Pt = I^2 Rt$
5. Compute the magnetic force using $F = NIlB$

Example 21 – 5



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What should be computed first? The initial flux at t=0.

The flux at t=0 is $\Phi_B = \vec{B}\cdot\vec{A} = BA = 0.600T\cdot\left(5\times10^{-2}m\right)^2 = 1.50\times10^{-3}Wb$

The change of flux is $\Delta\Phi_B = 0 - 1.50\times10^{-3}Wb = -1.50\times10^{-3}Wb$

Thus the rate of change of the flux is

$$\frac{\Delta\Phi_B}{\Delta t} = \frac{-1.50\times10^{-3}Wb}{0.100s} = -1.50\times10^{-2}\,Wb/s$$

Example 21 – 5, cnt'd

Thus the total emf induced in this period is

$$\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t} = -100\cdot\left(-1.50\times10^{-2}\,Wb/s\right) = 1.5V$$

The induced current in this period is

$$I = \frac{\varepsilon}{R} = \frac{1.5V}{100\Omega} = 1.50\times10^{-2}\,A = 15.0mA$$

Which direction would the induced current flow? Clockwise! Why?

To counter against the flux reduction!!

The total energy dissipated is

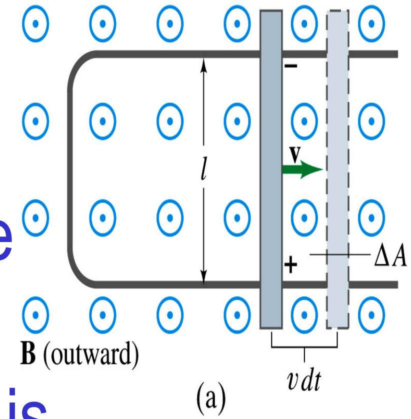
$$E = Pt = I^2Rt = \left(1.50\times10^{-2}\,A\right)^2\cdot100\Omega\cdot0.100s = 2.25\times10^{-3}\,J$$

Force for each coil is $\vec{F} = I\vec{l}\times\vec{B}$ Force for N coil is $\vec{F} = NI\vec{l}\times\vec{B}$

$$\left|F\right| = NIlB = 100\cdot\left(1.50\times10^{-2}\,A\right)\cdot\left(5\times10^{-2}\right)\cdot0.600T = 0.045N$$

This is due to the fact that forces on two of the sides cancel, while one side stays out side the area covered by the B field, leaving only one side to apply the force.

EMF Induced on a Moving Conductor



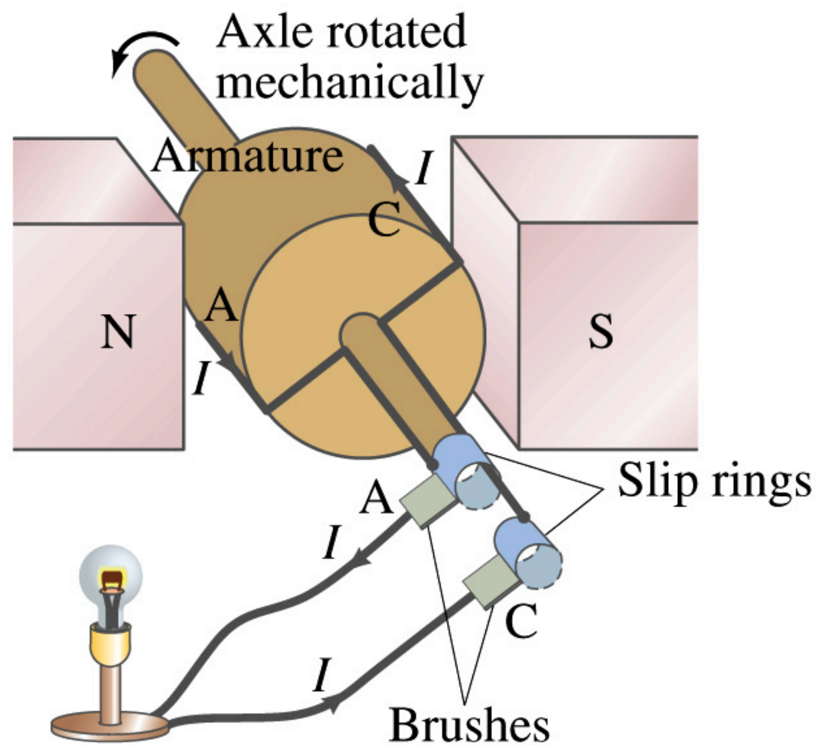
- Another way of inducing emf is using a U shaped conductor with a movable rod resting on it.
- As the rod moves at a speed v, it travels $v\Delta t$ in time Δt, changing the area of the loop by $\Delta A = lv\Delta t$.
- Using Faraday's law, the induced emf for this loop is

$$|\varepsilon| = \frac{\Delta\Phi_B}{\Delta t} = \frac{B\Delta A}{\Delta t} = \frac{Blv\Delta t}{\Delta t} = Blv$$

  – This equation is valid as long as B, l and v are perpendicular to each other. What do we do if they are not?
    - Use the scalar product of vector quantities
- An emf induced on a conductor moving in a magnetic field is called a **motional emf**

Electric Generators

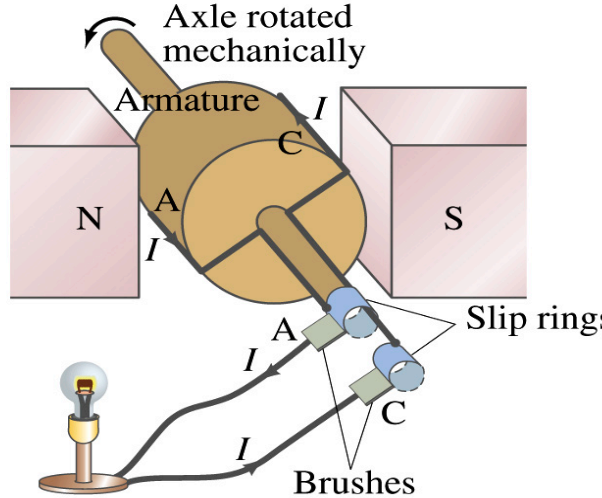
- What does a generator do?
  - Transforms mechanical energy into the electrical energy
  - What does this look like?
    - An inverse of an electric motor which transforms electrical energy to mechanical energy
  - An electric generator is also called a dynamo



- Whose law does the generator based on?
  - Faraday's law of induction

How does an Electric Generator work?

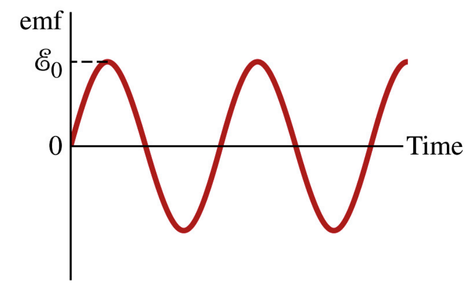
- An electric generator consists of
  - Many coils of wires wound on an armature that can rotate by mechanical means in a magnetic field
- An emf is induced in the rotating coil
- Electric current is the output of a generator



- Which direction does the output current flow when the armature rotates counterclockwise?
  - The conventional current flows outward on wire A toward the brush
  - After half the revolution the wire A will be where the wire C is and the current flow on A is reversed
- Thus the current produced is alternating its direction

How does an Electric Generator work?

- Let's assume the loop is rotating in a uniform B field w/ constant angular velocity ω. The induced emf is
- $$\varepsilon = -\frac{\Delta\Phi_B}{\Delta t} = -\frac{\Delta}{\Delta t}\left(\vec{B}\cdot\vec{A}\right) = -\frac{\Delta}{\Delta t}\left[BA\cos\theta\right]$$
- What is the variable that changes above?
  - The angle θ. What is $\Delta\theta/\Delta t$?
    - The angular speed ω.
  - So $\theta=\theta_0+\omega t$
  - If we choose $\theta_0=0$, we obtain
  - $$\varepsilon = -BA\frac{\Delta}{\Delta t}\left[\cos\omega t\right] = BA\omega\sin\omega t$$
  - If the coil contains N loops: $$\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t} = NBA\omega\sin\omega t = \varepsilon_0\sin\omega t$$
  - What is the shape of the output?
    - Sinusoidal w/ amplitude $\mathscr{E}_0$=NBAω



- US AC frequency is 60Hz. Europe is at 50Hz
  - Most the U.S. power is generated at steam plants

Example

An AC generator. The armature of a 60-Hz AC generator rotates in a 0.15-T magnetic field. If the area of the coil is 2.0x10^{-2}m^{2}, how many loops must the coil contain if the peak output is to be $\mathcal{E}_0$=170V?

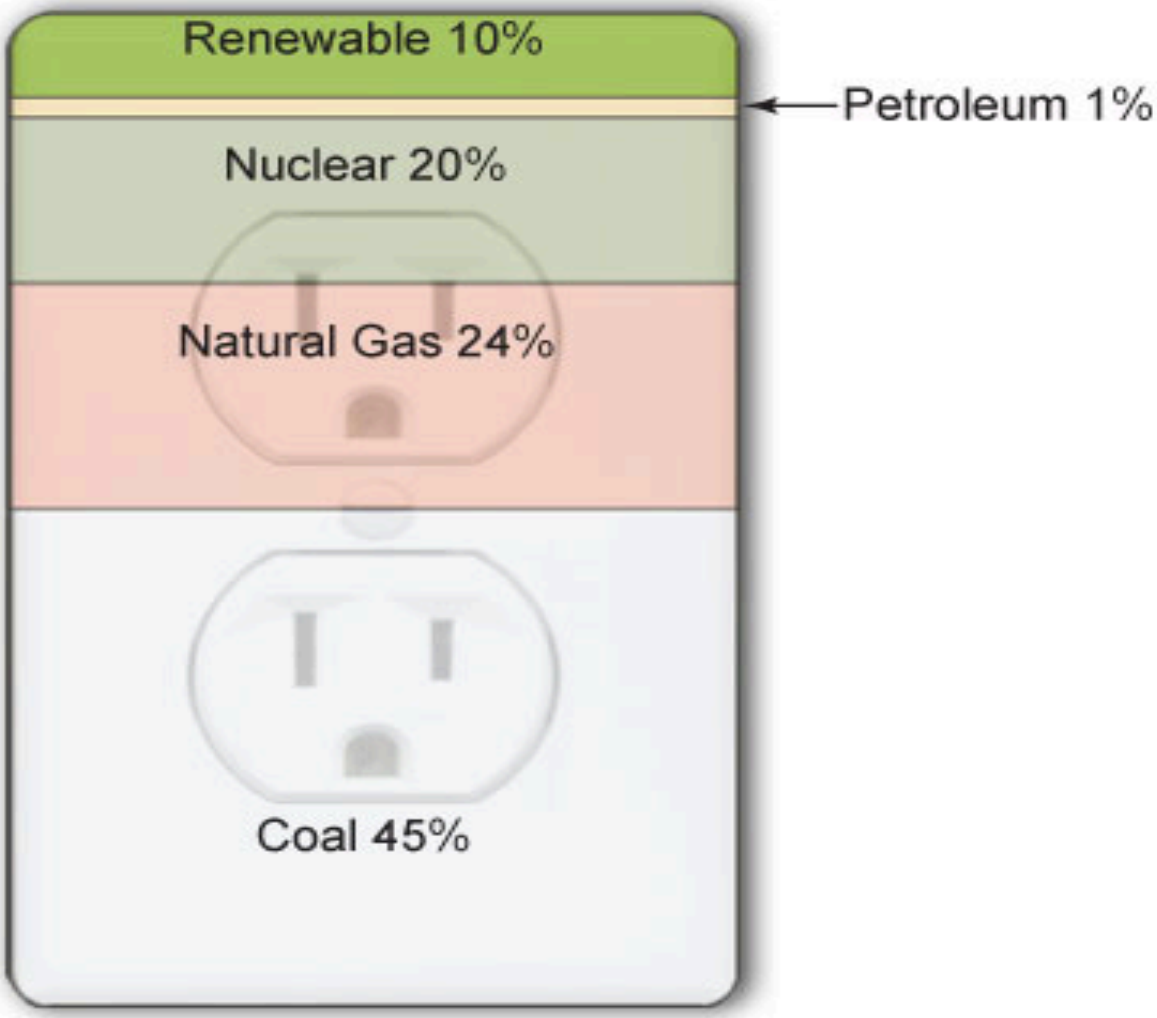
The maximum emf of a generator is $\varepsilon_0 = NBA\omega$

Solving for N $N = \dfrac{\varepsilon_0}{BA\omega}$

Since $\omega = 2\pi f$ We obtain

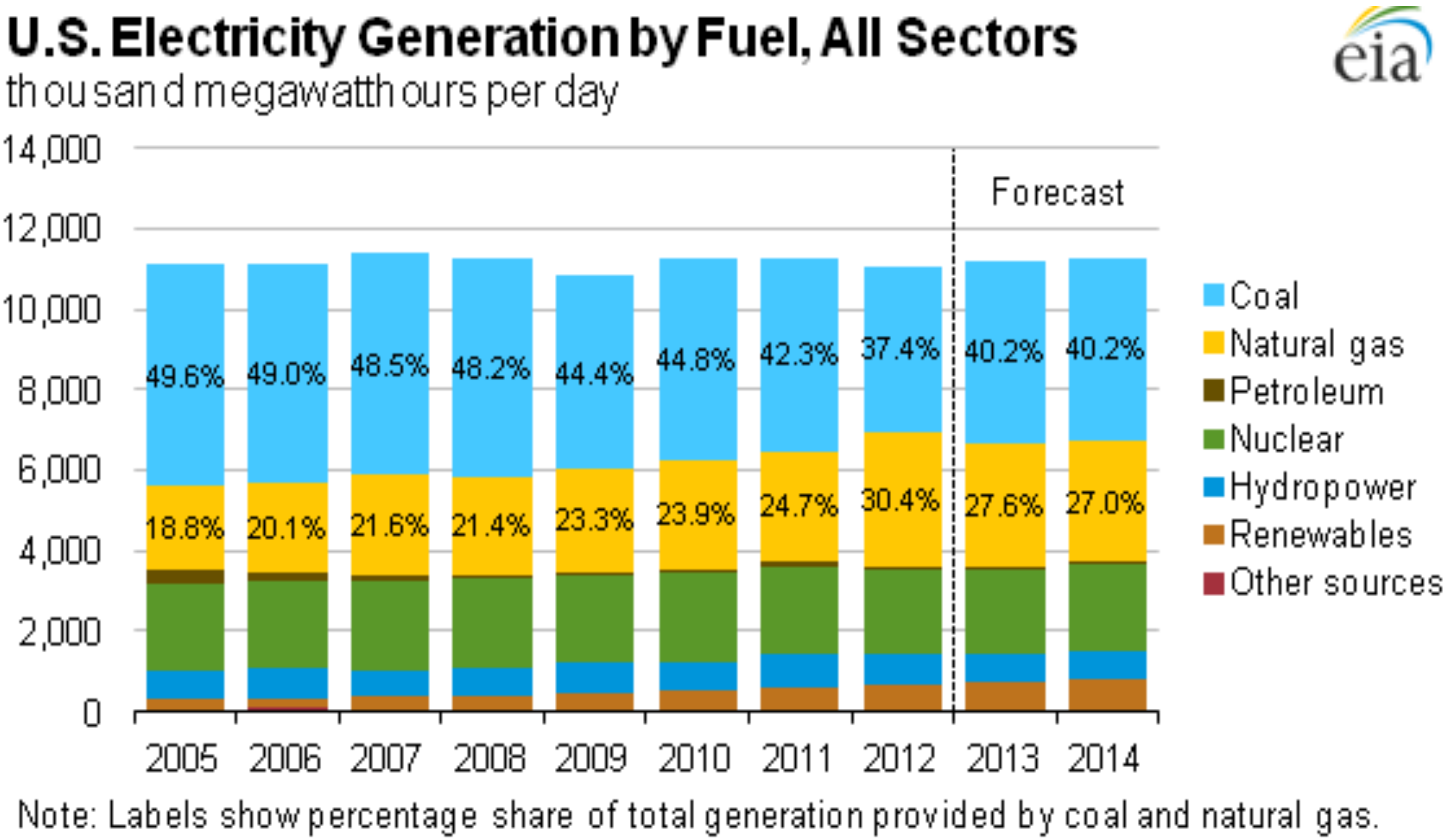
$$N = \frac{\varepsilon_0}{2\pi BAf} = \frac{170V}{2\pi \cdot (0.15T) \cdot \left(2.0\times10^{-2}m^2\right) \cdot \left(60s^{-1}\right)} = 150 turns$$

Sources of U.S. Electricity Generation, 2010



Source: U.S. Energy Information Administration, *Monthly Energy Review* (June 2011). Percentages based on Table 7.2a, preliminary 2010 data.

US Electricity Consumption by Source



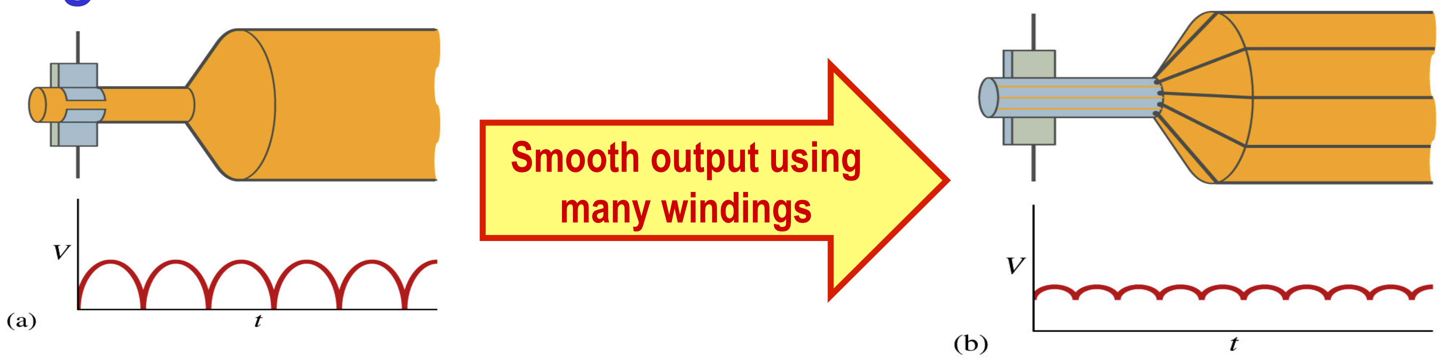
US Energy Information Administration http://www.eia.gov/electricity/

The World Energy Consumption

- In 2008, total worldwide energy consumption was 474 EJ (474×10^{18} J=132 PWh).
  - Equivalent to an average energy consumption rate of 15 terawatts (1.504×10^{13} W)
  - US uses 26.6 PWh (as of 2008)
- The potential for renewable energy
  - solar energy 1600 EJ (444,000 TWh)
  - wind power 600 EJ (167,000 TWh)
  - geothermal energy 500 EJ (139,000 TWh),
  - biomass 250 EJ (70,000 TWh)
  - hydropower 50 EJ (14,000 TWh) an
  - ocean energy 1 EJ (280 TWh)

A DC Generator

- A DC generator is almost the same as an AC generator except the slip rings are replaced by split-ring commutators



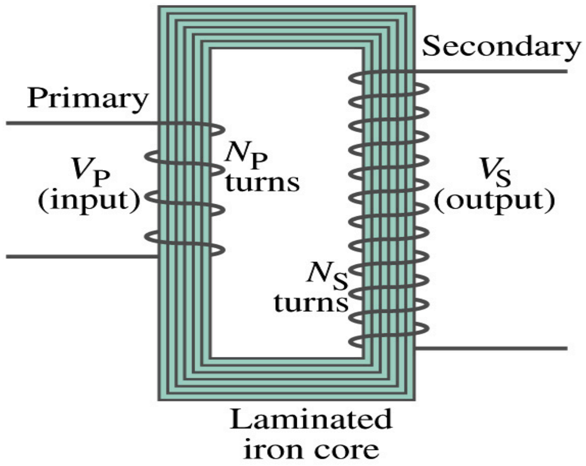
- Output can be smoothed out by placing a capacitor on the output
  - More commonly done using many armature windings

Eddy Currents (read more in CH. 21 – 6)

- Induced currents are not always confined to well-defined path
- In some cases where a conductor is moving in and out of the magnetic field, the Lenz's law causes flow of electrons that opposes the change in magnetic flux
  - This change is in the direction that impedes the production of emf
  - And thus causes energy losses
- These currents are called eddy currents
  - Just like the eddy currents in the water that pulls the boat in the opposite direction of the movement

Transformer

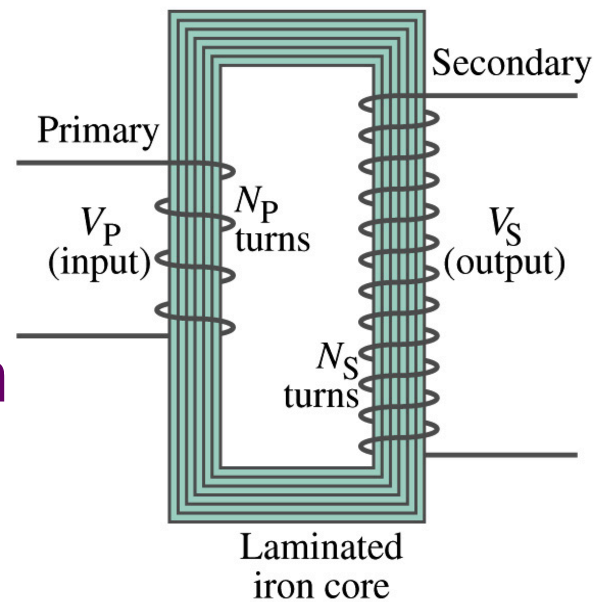
- What is a transformer?
  - A device for increasing or decreasing an AC voltage
  - A few examples?
    - TV sets to provide High Voltage to picture tubes, portable electronic device converters, transformers on the pole, etc
- A transformer consists of two coils of wires known as the primary and the secondary
  - The two coils can be interwoven or linked by a laminated soft iron core to reduce losses due to Eddy current
- Transformers are designed so that all magnetic flux produced by the primary coil pass through the secondary



How does a transformer work?

- When an AC voltage is applied to the primary, the changing B it produces will induce voltage of the same frequency in the secondary wire
- So how would we make the voltage different?
  - By varying the number of loops in each coil
  - From Faraday's law, the induced emf in the secondary is
  - $V_S = N_S \frac{\Delta \Phi_B}{\Delta t}$
  - The input primary voltage is
  - $V_P = N_P \frac{\Delta \Phi_B}{\Delta t}$
  - Since $\Delta\Phi_B/\Delta t$ is the same, we obtain
  - $\boxed{\frac{V_S}{V_P} = \frac{N_S}{N_P}}$

Transformer Equation



Transformer Equation

- The transformer equation does not work for DC current
  - Since there is no change of magnetic flux!!
- If $N_S > N_P$, the output voltage is greater than the input so it is called a step-up transformer while $N_S < N_P$ is called step-down transformer
- Now, it looks like energy conservation is violated since we can get more emf from smaller ones, right?
  - Wrong! Wrong! Wrong! Energy is always conserved!
  - A well designed transformer can be more than 99% efficient
  - The power output is the same as the input:
  - $V_P I_P = V_S I_S$
  - $\boxed{\frac{I_S}{I_P} = \frac{V_P}{V_S} = \frac{N_P}{N_S}}$

The output current for step-up transformer will be lower than the input, while it is larger for step-down x-former than the input.

Ex. 21 – 11 Portable Radio Transformer

Portable radio transformer. A transformer for home use of a portable radio reduces 120-V AC to 9.0V AC. The secondary contains 30 turns, and the radio draws 400mA. Calculate (a) the number of turns in the primary (b) the current in the primary and (c) the power transformed.

(a) What kind of a transformer is this? A step-down x-former

Since $\frac{V_P}{V_S}=\frac{N_P}{N_S}$ We obtain $N_P = N_S\frac{V_P}{V_S} = 30\frac{120V}{9V} = 400turns$

(b) Also from the transformer equation $\frac{I_S}{I_P}=\frac{V_P}{V_S}$ We obtain

$$I_P = I_S\frac{V_S}{V_P} = 0.4A\frac{9V}{120V} = 0.03A$$

(c) Thus the power transformed is

$$P = I_S V_S = (0.4A)\cdot(9V) = 3.6W$$

How about the input power? The same assuming 100% efficiency.

Example 21 – 12: Power Transmission

Transmission lines. An average of 120kW of electric power is sent to a small town from a power plant 10km away. The transmission lines have a total resistance of 0.4Ω. Calculate the power loss if the power is transmitted at (a) 240V and (b) 24,000V.

We cannot use $P=V^2/R$ since we do not know the voltage along the transmission line. We, however, can use $P=I^2R$.

(a) If 120kW is sent at 240V, the total current is

$$I=\frac{P}{V}=\frac{120\times10^3}{240}=500A.$$

Thus the power loss due to transmission line is

$$P=I^2R=(500A)^2\cdot(0.4\Omega)=100kW$$

(b) If 120kW is sent at 24,000V, the total current is

$$I=\frac{P}{V}=\frac{120\times10^3}{24\times10^3}=5.0A.$$

Thus the power loss due to transmission line is

$$P=I^2R=(5A)^2\cdot(0.4\Omega)=10W$$

The higher the transmission voltage, the smaller the current, causing less loss of energy. This is why power is transmitted w/ HV, as high as 170kV.