PHYS 1441 – Section 002
Lecture #20

Monday, Nov. 26, 2018

Dr. Jaehoon Yu

- Chapter 29:EM Induction & Faraday's Law
  - Lenz's Law
  - Generation of Electricity
  - Transformer
  - Electric Field Due to Changing Magnetic Flux
- Chapter 30: Inductance
  - Inductance
  - Mutual and Self Inductance

Announcements – I

- Class feedback review ongoing!
  - We will do this in class this Wednesday, Nov. 28 after the quiz. So please bring your devices
- Quiz 3 results
  - Class average: 40/55 → equivalent to 72.4/100
    - Previous quizzes: 74/100 and 55/100
  - Top score: 55/55
- Term 2 results
  - Class average: 73/96 → equivalent to 76/100
    - Previous exams: 61/100 and 71/100
  - Top score: 90/96

Announcements – II

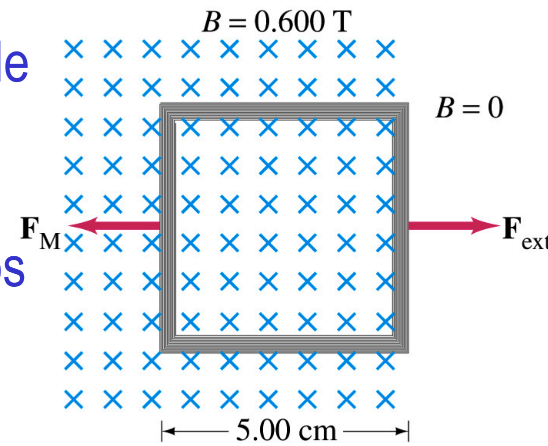
- Quiz #4
  - Beginning of the class this Wednesday, Nov. 28
  - Covers: CH28.6 – what we finish today, Nov. 26
  - Bring your calculator but DO NOT input formula into it!
    - Cell phones or any types of computers cannot replace a calculator!
  - BYOF: You may bring a one 8.5x11.5 sheet (front and back) of **handwritten** formulae and values of constants
  - No derivations, word definitions or solutions of any kind!
  - No additional formulae or values of constants will be provided!
- Final comprehensive exam
  - In class 1:00 – 2:20pm, Wed. Dec. 5
  - Covers CH21.1 through what we finish next Monday, Dec. 3
  - BYOF

Reminder: Special Project #5

- Make a list of the power consumption and the resistance of all electric and electronic devices at your home and compile them in a table. (10 points total for the first 10 items and 0.5 points each additional item.)
- Estimate the cost of electricity for each of the items on the table using your own electric cost per kWh (if you don't find your own, use $0.12/kWh) and put them in the relevant column. (5 points total for the first 10 items and 0.2 points each additional items)
- Estimate the the total amount of energy in Joules and the total electricity cost per day, per month and per year for your home. (8 points)
- Spreadsheet can be downloaded from the class web page: http://www-hep.uta.edu/~yu/teaching/fall18-1444-002/fall18-1444-002.html
- Due: Beginning of the class this Wednesday, Nov. 28

Example 29 – 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 a 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 the 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 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 29 – 5, cnt'd

Thus the total emf induced in this period is

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

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

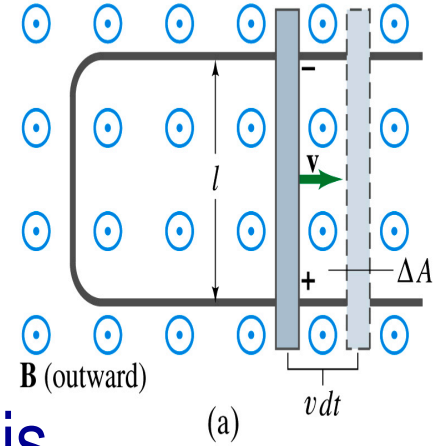
The total energy dissipated is

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

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

$$\left|F\right| = NIlB = 100\cdot\left(1.50\times10^{-2}\,A\right)\cdot\left(4\times5\times10^{-2}\right)\cdot0.600T = 0.045N$$

EMF Induced on a Moving Conductor



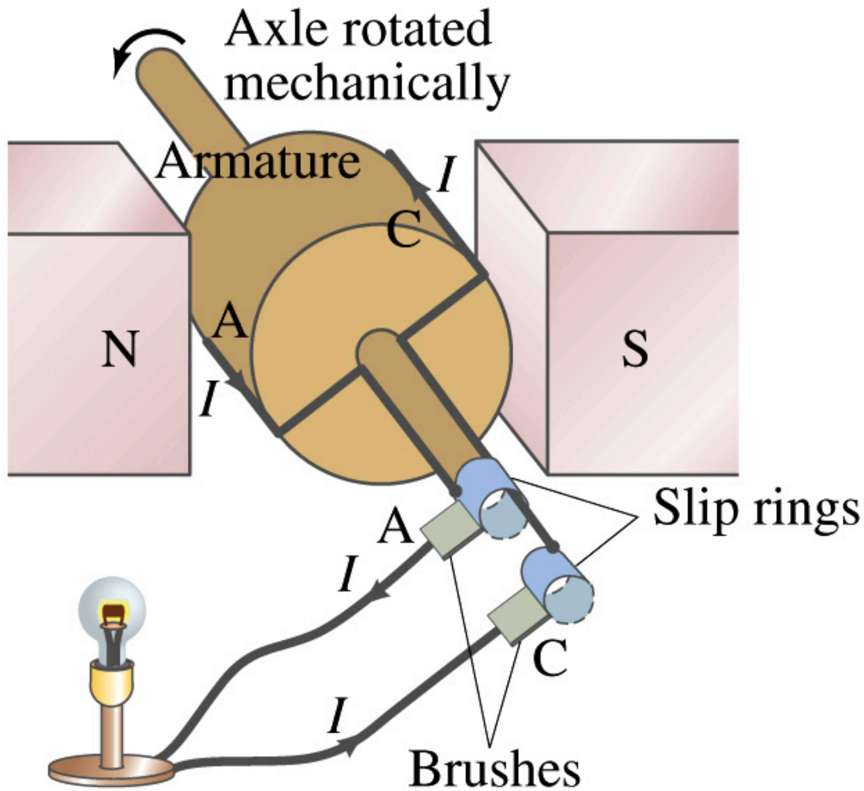
- Another way of inducing emf is using a U shaped conductor with a movable rod resting on it.
- As the rod moves at speed v, it travels $v$dt in time dt, changing the area of the loop by dA=lvdt.
- Using Faraday's law, the induced emf for this loop is

$$|\varepsilon| = \frac{d\Phi_B}{dt} = \frac{BdA}{dt} = \frac{Blvdt}{dt} = Blv$$

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

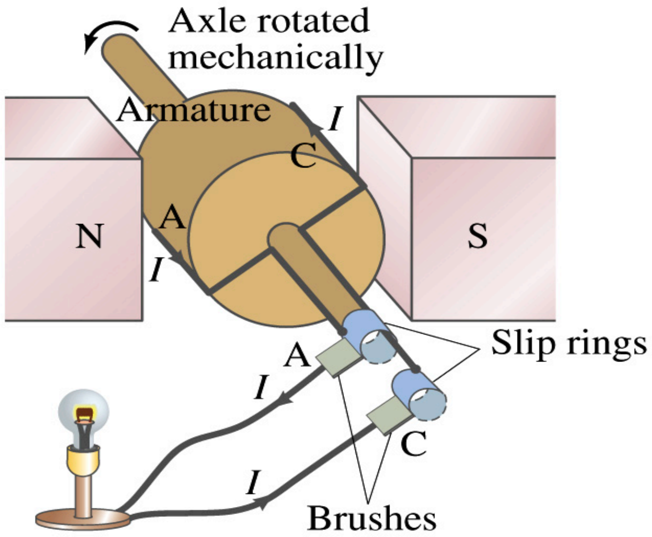
Electric Generators

- What does a generator do?
  - Transforms mechanical energy into 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

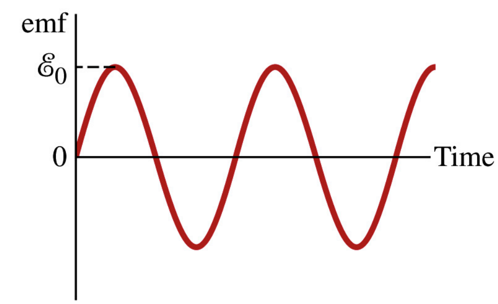
How does an Electric Generator work?



- 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/ a constant angular velocity ω. The induced emf is
- $\varepsilon = -\frac{d\Phi_B}{dt} = -\frac{d}{dt}\int \vec{B}\cdot d\vec{A} = -\frac{d}{dt}\left[BA\cos\theta\right]$
- What is the variable that changes above?
  - The angle θ. What is dθ/dt?
    - The angular speed ω.
  - So $\theta=\theta_0+\omega t$
  - If we choose $\theta_0=0$, we obtain
  - $\varepsilon = -BA\frac{d}{dt}\left[\cos\varpi t\right] = BA\varpi\sin\varpi t$
  - If the coil contains N loops: $\varepsilon = -N\frac{d\Phi_B}{dt} = NBA\varpi\sin\varpi t = \varepsilon_0\sin\varpi t$
  - What is the shape of the output?
    - Sinusoidal w/ an amplitude $\varepsilon_0=NBA\omega$



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

Example 29 – 9

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 $2.0 \times 10^{-2} m^2$, how many loops must the coil contain if the peak output is to be $\varepsilon_0 = 170V$?

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

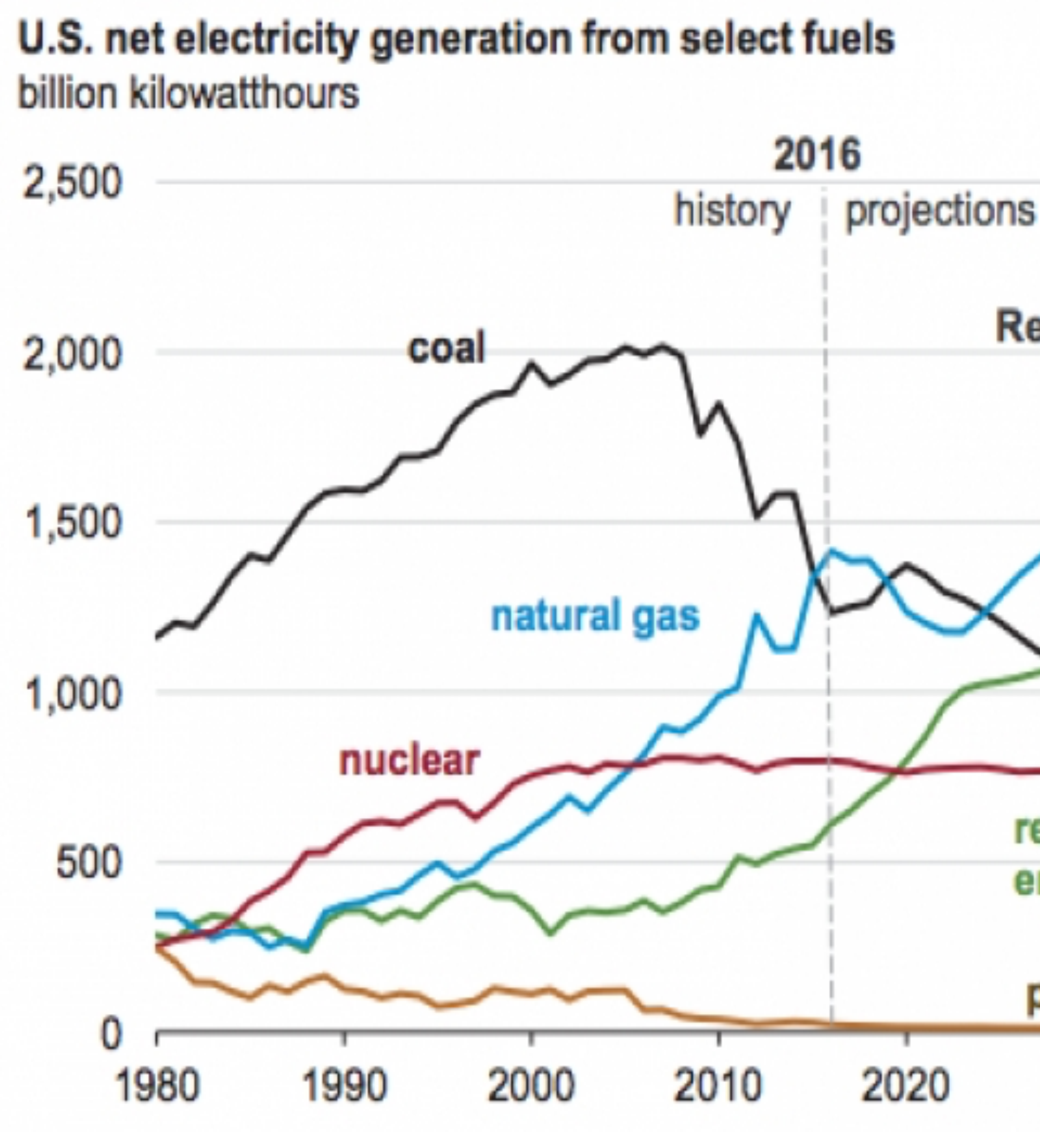
Solving for N

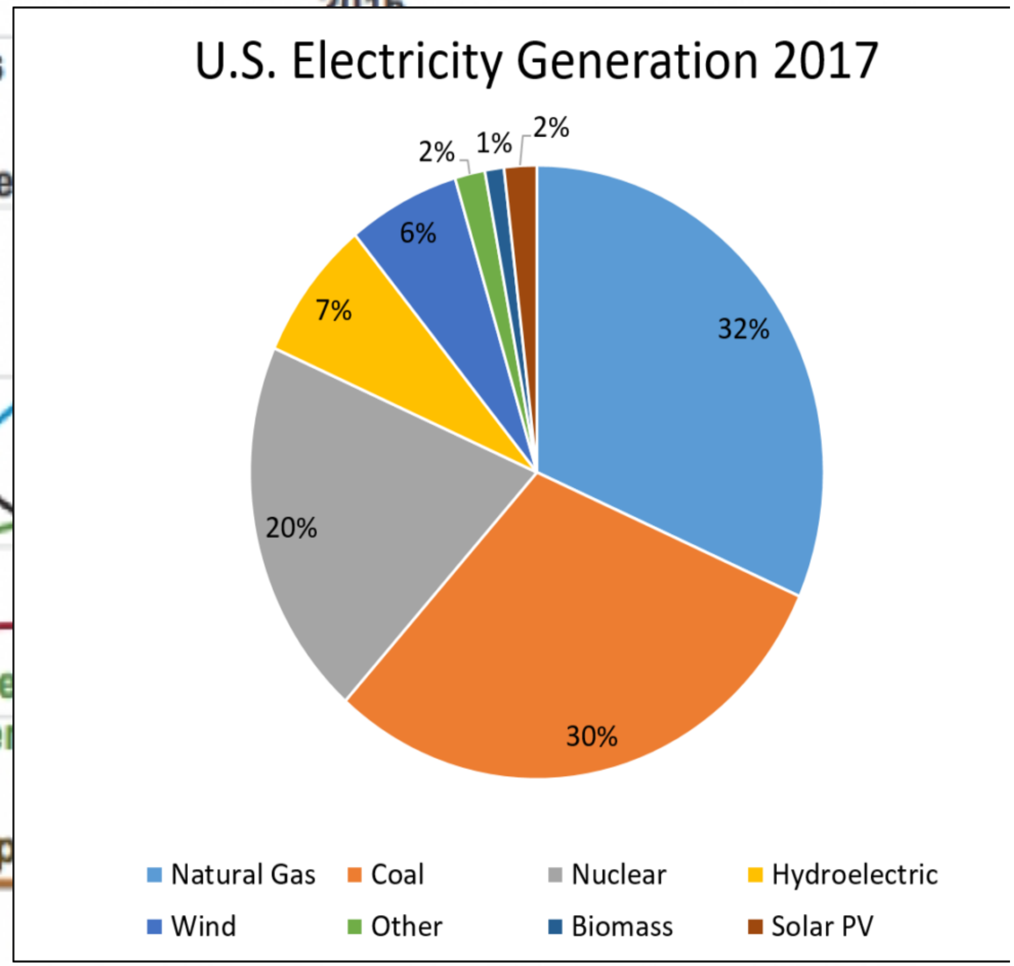
$$N = \frac{\varepsilon_0}{BA\varpi}$$

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

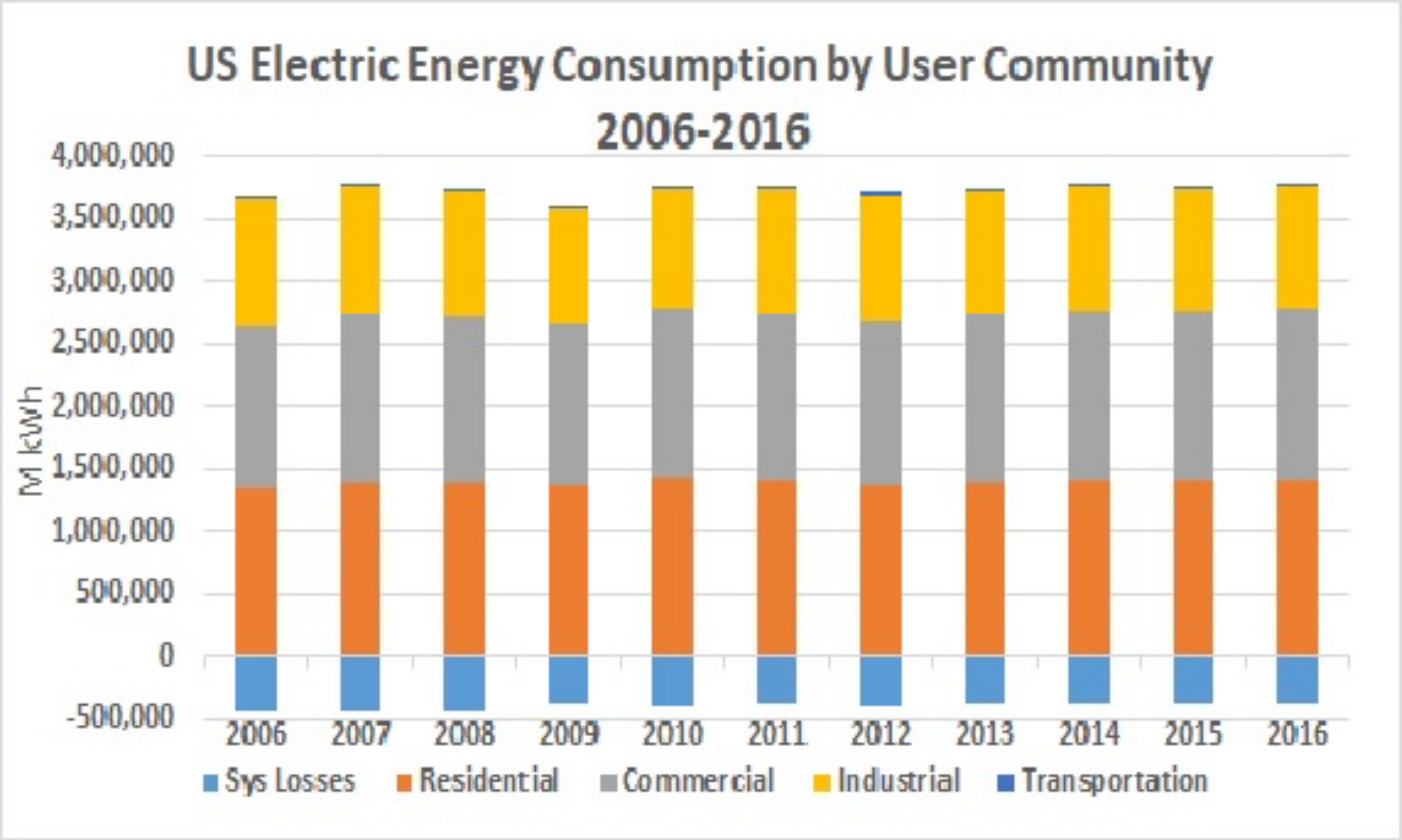
$$N = \frac{\varepsilon_0}{2\pi BAf} = \frac{170V}{2\pi \cdot (0.15T) \cdot \left(2.0 \times 10^{-2} m^2\right) \cdot \left(60 s^{-1}\right)} = 150 turns$$

US Electricity Sources





US Electric E Consumption by Users



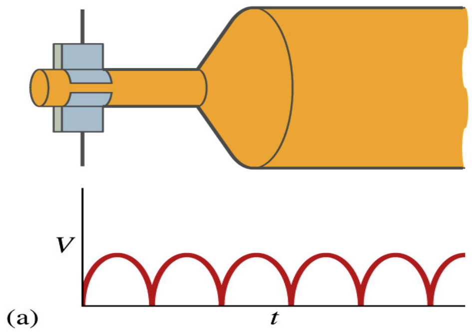
US Energy Information Administration http://www.eia.gov/electricity/

The World Energy Consumption

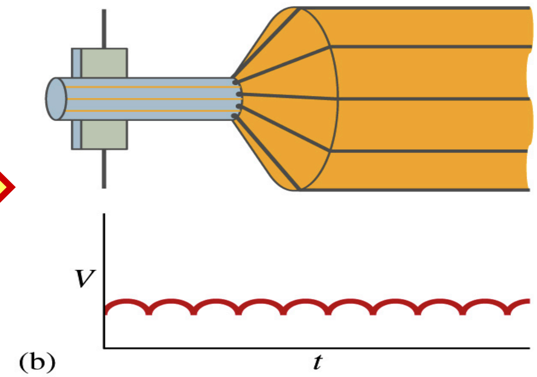
- In 2013, total worldwide energy consumption was 567 EJ (567×10^{18} J=157 PWh)➔ expected >1000EJ by 2050
  - Equivalent to an average energy consumption rate of 18 terawatts (1.8×10^{13} W)
  - US uses 39.1 PWh (1.38kWh/person, as of 2014)
- The potential for renewable energy
  - solar energy 1600 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)
  - Read this paper if you want to learn more

A DC Generator

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



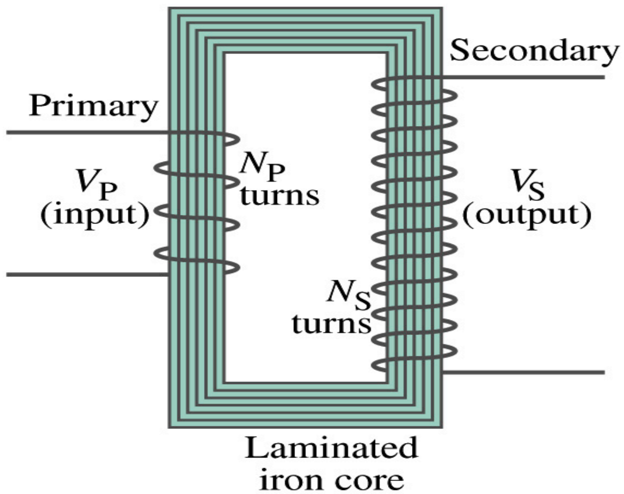
Smooth output using many windings



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

Transformer

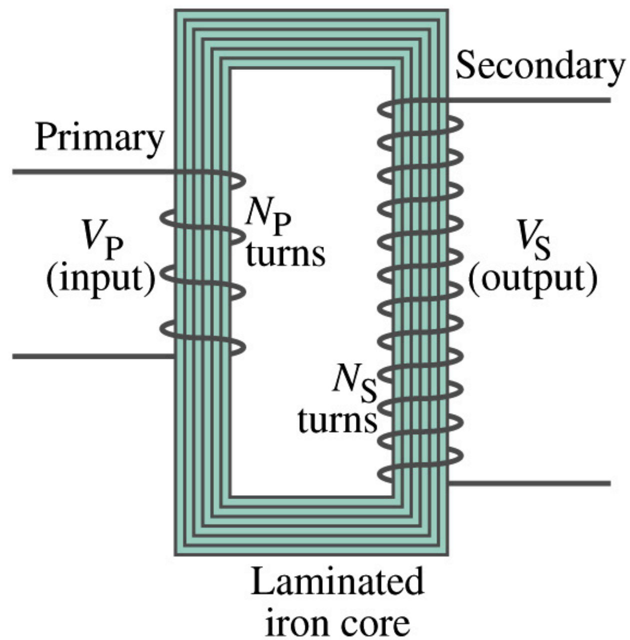
- What is a transformer?
  - A device for increasing or decreasing an AC voltage
  - A few examples?
    - TV sets to provide the high voltage to picture tubes, portable electronic device converters, transformers on the pole, etc
- A transformer consists of two coils of wires known as the primary and 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
  - $V_S = N_S \frac{d\Phi_B}{dt}$
  - The input primary voltage is
  - $V_P = N_P \frac{d\Phi_B}{dt}$
  - Since $d\Phi_B/dt$ 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 a step-up transformer will be lower than the input, while it is larger for a step-down x-former than the input.

Example for A 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 $N_P = N_S \frac{V_P}{V_S} = 30\frac{120V}{9V} = 400 turns$

(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 29 – 13: 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 $I=\dfrac{P}{V}=\dfrac{120\times10^3}{240}=500A.$

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

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.

Electric Field due to Magnetic Flux Change

- When the electric current flows through a wire, there is an electric field in the wire that moves electrons
- We saw, however, that changing magnetic flux induces a current in the wire. What does this mean?
  - There must be an electric field induced by the changing magnetic flux.
- In other words, a changing magnetic flux produces an electric field
- This result applies not just to wires but to any conductor or any region in space

Generalized Form of Faraday's Law

- Recall the relationship between the electric field and the potential difference $V_{ab} = \int_a^b \vec{E} \cdot d\vec{l}$
- Induced emf in a circuit is equal to the work done per unit charge by the electric field
- $\varepsilon = \int_a^b \vec{E} \cdot d\vec{l}$
- So we obtain

$$\oint \vec{E} \cdot d\vec{l} = -\frac{d\Phi_B}{dt}$$

- The integral is taken around a path enclosing the area through which the magnetic flux Φ_B is changing.