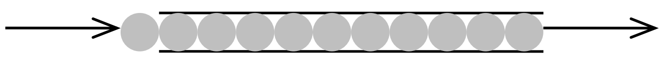
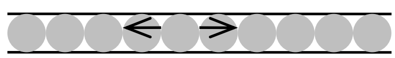
# Physics 30   Lesson 22A  AC & Transformers

## I.    Alternating current

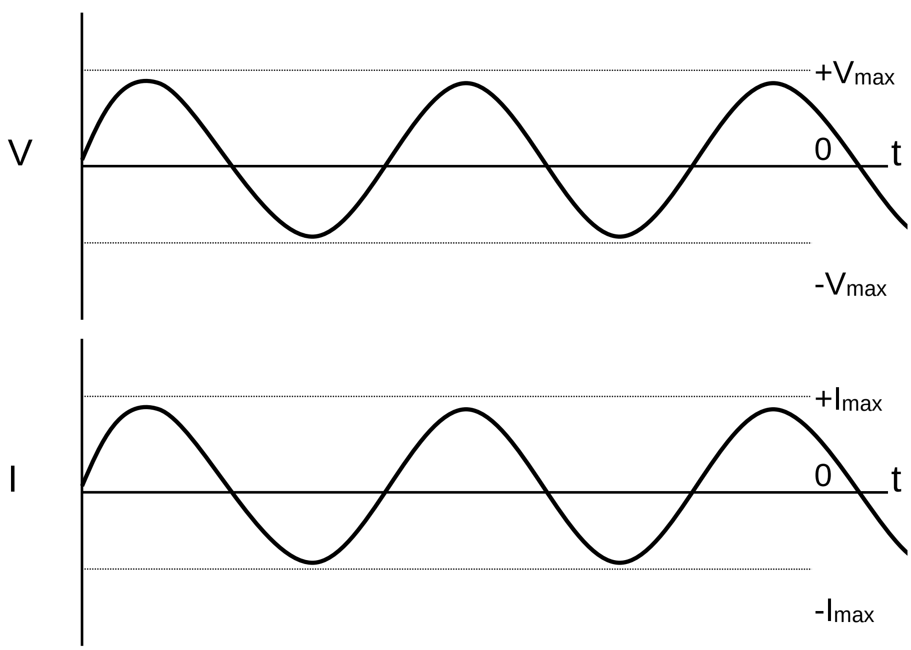
Many electric circuits use electrochemical cells (batteries) which involve *direct current* (DC). In DC electric power, the electrons flow down the wire. Electrons are forced into one end of a wire, which causes an electron to pop out the other end. Although the individual electrons move relatively slowly down the wire, the overall effect of pushing one electron in and another electron emerging is almost instantaneous. An analogy would be a set of ball bearings in a tube: When a ball bearing is pushed into the tube, another one immediately pops out the other end.



However, there are considerably more circuits that operate with *alternating current* (AC). For AC, the electrons vibrate back and forth across one location. AC power is *like* a mechanical wave – the energy passes through the medium via vibrations in the medium's particles. AC current is transmitted through the oscillations of the electrons in a conductor.



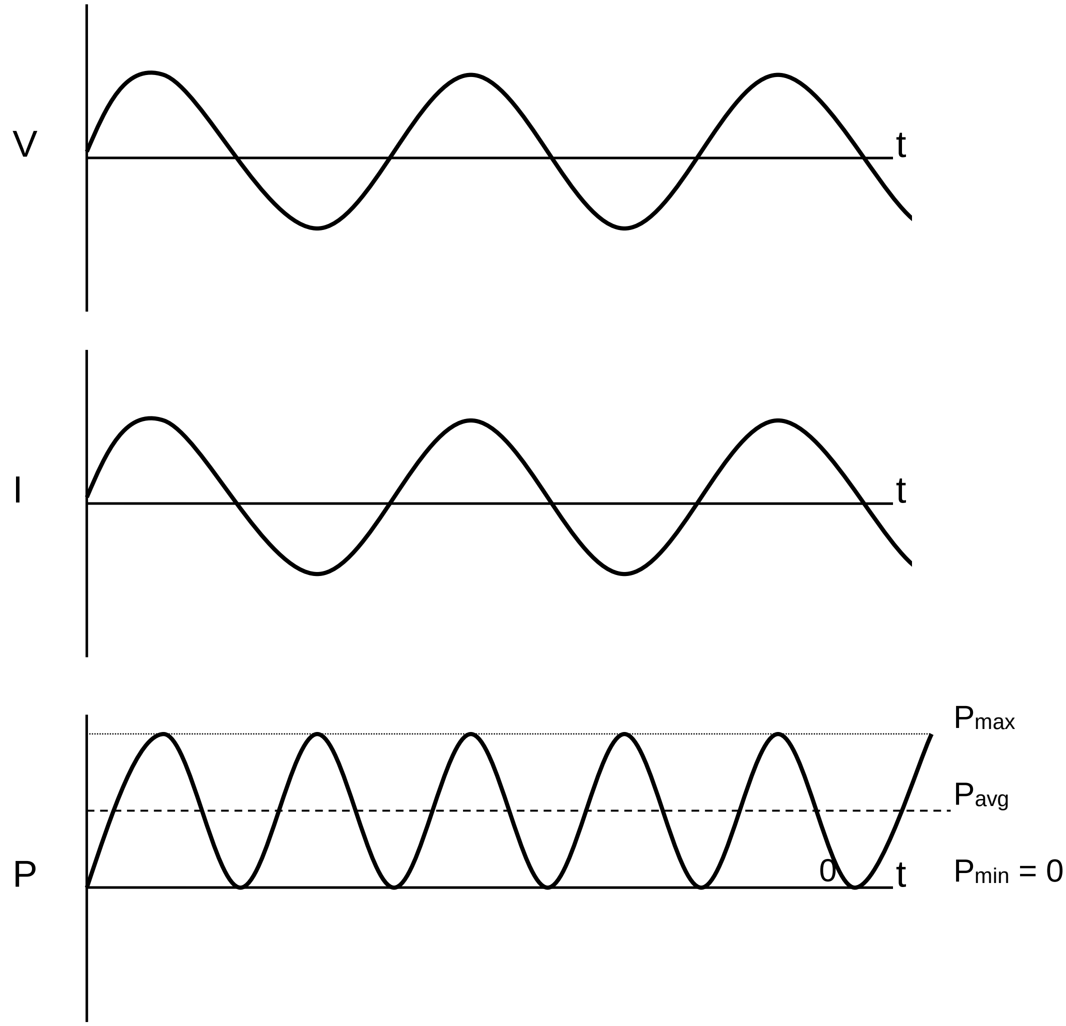
As we saw in Lesson 18, AC current is produced by an AC generator. When we graph the output of the potential difference and the current, we get the following graphs:




In Canada, household voltage has a peak value of 170 volts and has a frequency of 60 Hz.

Note that the voltage and current oscillate evenly between maximum positive and negative values, and the <u>average</u> voltage and <u>average</u> current for alternating current are both <u>zero</u>. This presents a problem. If the average voltage and current are both zero, how does AC electricity deliver energy to an appliance of some kind? The answer is found when we consider the *power*.

Recall from Lesson 18B that P = I V.  When we multiply the voltage and current graphs together, we find that the power also changes with time.  However, since the negative current multiplied by the negative potential difference results in a positive power value, power is always positive.




While the minimum power is zero, the maximum or peak power for alternating current is

$$P_{max} = I_{max}\,V_{max}$$

When the power of an AC circuit is measured it is customary to use the average power which is one-half the peak power

$$P_{avg} = \frac{I_{max}\,V_{max}}{2}$$

When we distribute the 2 into $\sqrt{2}\,x\,\sqrt{2}$, along with a slight rearrangement of the equation, we get a useful result.

$$P_{avg} = \frac{I_{max}\,V_{max}}{\sqrt{2}\times\sqrt{2}} = \frac{I_{max}}{\sqrt{2}} \times \frac{V_{max}}{\sqrt{2}}$$

Since $\frac{1}{\sqrt{2}}$ = 0.707 we get

$$P_{avg} = 0.707\ I_{max} \times 0.707\ V_{max}$$

0.707 $I_{max}$ is called the *effective current* in an AC circuit.

$$I_{eff} = 0.707\ I_{max}$$

Similarly, the *effective voltage* in an AC circuit is given by

$$V_{eff} = 0.707\ V_{max}$$

Note: Another name for effective voltage is *root mean square voltage*. $V_{eff} = V_{rms}$
Another name for effective current is *root mean square current*. $I_{eff} = I_{rms}$

When we refer to AC electricity we normally are referring to the <u>average power</u>, <u>effective current</u>, and <u>effective voltage</u>, unless stated otherwise. In addition, all of the power equations, as well as Ohm's Law, that we learned about in Lessons 18 to 18B, can be written conveniently in terms of effective or rms quantities:

$$I_{eff} = \frac{V_{eff}}{R} \qquad I_{max} = \frac{V_{max}}{R}$$

$$P = I_{eff}V_{eff} \qquad P_{max} = I_{max}V_{max}$$

$$P = I_{eff}^2 R \qquad P_{max} = I_{max}^2 R$$

$$P = \frac{V_{eff}^2}{R} \qquad P_{max} = \frac{V_{max}^2}{R}$$

All of these equations are analogous to the equations used for DC circuits.

*Example 1*

In Canada the maximum AC voltage in a regular home socket is typically 170 V. What is the corresponding effective voltage?

$V_{eff} = 0.707\ V_{max} = 0.707\ (170\ V) =$ **120 V**

*Example 2*

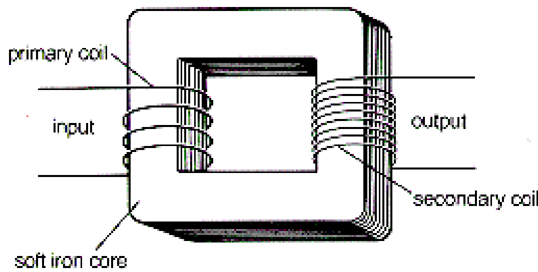
If an ac ammeter indicates a current of 5.5 A, what is the maximum and minimum current?

$I_{max} = I_{eff} / 0.707 = 5.5\ A / 0.707 =$ **7.8 A**

The minimum current is: $\mathbf{I_{min} = 0}$

## II. Transformers

Joseph Henry, who missed his chance at glory in 1831, went on to become the leader in studying the transformer. The basic idea behind the transformer is Faraday's Law – a changing magnetic field inside a coil of wire, induces a current in the wire. In the transformer, a circular soft iron core is used due to its ability to carry a magnetic field. Coils of wire are wrapped around both sides of the iron core.




If we use DC current in the primary circuit, the DC current induces a uniform, unchanging magnetic field in the iron core which has no effect on the secondary coil. The only time a current is induced in the secondary coil is when the DC is being turned on or off. It is much more convenient and efficient to connect the primary coil to an AC circuit. As the current in the primary coil changes direction it *automatically* induces a growing and collapsing magnetic field in the iron core, which *automatically* induces an AC current in the secondary coil.

If the primary and secondary coils contain the same number of turns, and assuming 100% efficiency with no power loss due to heat or sound, then the secondary coil will have the same voltage and current as the primary circuit. However, if the number of turns on the secondary side ($N_s$) is different from the number of turns on the primary side ($N_p$), there is a corresponding change in the voltage and current from one side of the transformer to the other. For example, if the primary coil of a transformer has 400 turns and is receiving a current ($I_p$) of 4.0 A and a voltage of 120 V AC ($V_p$), and the secondary coil has 800 turns, the resulting secondary current and voltage may be calculated via a simple mathematical ratio:

$$\frac{N_P}{N_S} = \frac{V_P}{V_S} = \frac{I_S}{I_P}$$

where $N_p$ number of turns in primary coil
$N_s$ number of turns in secondary coil
$V_p$ potential difference in primary coil
$V_s$ potential difference in secondary coil
$I_p$ current in primary coil
$I_s$ current in secondary coil

In the example:

$$\frac{N_p}{N_s} = \frac{V_p}{V_s} \qquad \frac{N_p}{N_s} = \frac{I_s}{I_p}$$

$$\frac{400}{800} = \frac{120\text{ V}}{V_s} \qquad \frac{400}{800} = \frac{I_s}{4.0\text{ A}}$$

$$V_s = 240\text{ V} \qquad I_s = 2.0\text{ A}$$

If the voltage on the secondary side is greater than the voltage on the primary side, the transformer is called a *step up transformer*. If the voltage on the secondary side is less than the voltage on the primary side, the transformer is called a *step down transformer*. The turns ratio formula can be used to calculate values for circuits on either side of the transformer assuming that it is 100% efficient. Always assume that the transformer is 100% efficient.

*Example 3*

The primary coil of a transformer has 600 turns and the secondary coil has 1800 turns. If the primary circuit has a potential difference of 90 V, what is the potential difference in the secondary coil?

$$\frac{N_p}{N_s} = \frac{V_p}{V_s}$$

$$\frac{600}{1800} = \frac{90\text{ V}}{V_s}$$

$$\mathbf{V_s = 270\ V}$$

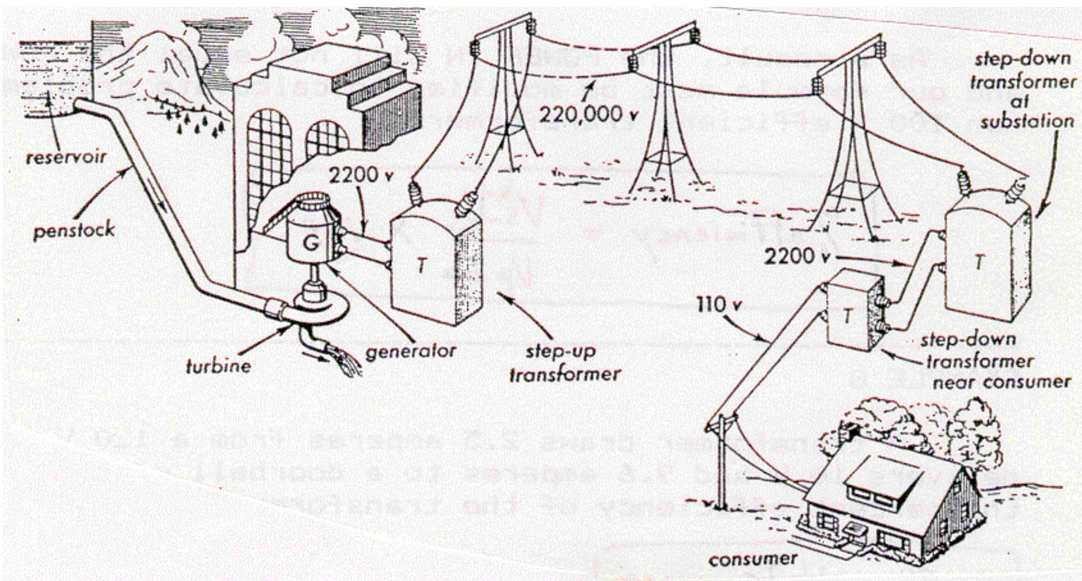
## III. AC Versus DC – power transmission

AC generators and DC generators are equally easy to design, build and operate, and they produce electricity with equal efficiency. Yet all of our large scale electrical systems are based on AC power generation. Why is this so? The reason lies in the fact that generating stations (hydro, coal, nuclear) are generally situated in out of the way places away from populated areas. When electrical energy is transmitted over long distances, energy lost as heat can become a costly problem.

In 1882, two years after Thomas Edison filed his patent for an improved light bulb, his company, the Edison Electric Light Company, began installing lighting systems in the United States. Edison's preference for using DC generators to produce electrical energy created a dilemma. Transmitting a given amount of power at a safe, low voltage requires a large current, which heats transmission lines ($P = I^2R$) and loses much of its energy as heat. Transmitting power with a low, efficient current required a high, unsafe voltage. Further, it is relatively difficult to step up DC power. The dilemma was solved using AC circuitry and transformers. At the site of power generation, a transformer steps up the voltage and lowers the current. Power is transmitted over long distances with relatively low losses. Near the point of use, another transformer steps down the voltage to a safe level. The first AC system was demonstrated in Paris in 1883, with experimental systems demonstrated in London and Italy. The American engineer, George Westinghouse, bought the patent rights to the latter.

While the Edison company enjoyed a near monopoly in the lighting business, the Westinghouse Electric Company in Pittsburgh installed its first electrical system using AC to provide power for incandescent lighting in Buffalo. Edison was alarmed by this new company, which claimed to produce and transmit electricity much more cheaply than his. He was determined to get rid of the competition. Edison joined forces with Harold P. Brown, designer of the electric chair, to demonstrate that AC power was unsafe. In July of 1888, Brown gave a lecture/demonstration in New York. After outlining his opposition to AC, Brown sent 1000 V of DC current from an Edison generator into a dog, causing it considerable distress but not killing it. Many of the audience left in disgust before Brown fired 880 V of AC into the dog, killing it. The plan to associate AC power with gruesome death was not successful.

The AC versus DC debate continued until 1891, when a high voltage AC line carrying sizable quantities of electricity from Frankfurt to Lauffen, Germany, a distance of 176 km. Tests indicated transmission efficiency was 77%. This tipped the balance in favor of AC, which was subsequently used in the construction of the Niagara Power Plant in 1893 by Westinghouse Electric. The first transmission of electrical energy to Buffalo, New York, took place in 1896 spawning a number of new industries. However, Edison's company did not suffer long as his company went on to become General Electric.




In the diagram above, at the generating station, electrical energy is passed through a step up transformer so that it can be transported over great distances through high voltage transmission lines. At a sub-station within a population center, the energy is passed through a step down transformer and transported over short distances down back alleys and underground to factories or homes. Every so often in the grid, the voltage is stepped down again to values that can be used in households.

## IV. Practice problems

1. A 500 W electric appliance is connected to an AC generator producing 120 V.
   A. What is the current flowing through the appliance? (4.17 A)
   B. What is the maximum current flowing through the appliance? (5.89 A)
   C. What is the minimum current flowing through the appliance? (0)

2. Calculate the resistance and the peak current in a 1000 W hair dryer connected to a 120 V line. What happens if it is connected to a 240 V line? (A clothes dryer usually runs off of the 240 V line in a home.) (14.4 Ω, 11.8 A, power becomes 4000 W)

3. An ac generator producing an effective voltage of 20 V is placed in parallel with 6.0 Ω and a 3.0 Ω resistors.
   a) What is the average power dissipated in the 6.0 Ω resistor? (66.7 W)
   b) What is the peak power dissipated in the circuit? (400 W)

4. What is the turns ratio in the transformer that steps voltage from a wall socket to the 15000 V required to accelerate electrons in the picture tube of a TV set? (1 to 125)

5. A step down transformer inside a stereo receiver has 330 turns in the primary coil and 25 turns in the secondary coil. The plug connects the primary coil to a 120 V wall socket which draws a current of 0.83 A when the receiver is on. Find
   a) the voltage across the secondary coil. (9.09 V)
   b) the current across the secondary coil. (11 A)
   c) the power consumed by the receiver circuits. (100 W)

6. Power Losses in Transmission

   Calculate the percentage of power lost as heat in a transmission line if 10 kW of electricity is transmitted along a cable with a total resistance of 1.0 Ω at an electric potential of 200 V. (Power loss is found using $P_{loss} = I^2R$)

   Find current:

   Calculate power loss:

   Calculate % loss:

   Calculate the percentage of power lost as heat in a transmission line if 10 kW of electricity is transmitted along a cable with a total resistance of 1.0 Ω at an electric potential of 2000 V.

   Find current:

   Calculate power loss:

   Calculate % loss:

   What must we do to transmit electricity more efficiently?

# V. Hand-in assignment

## Part A – Alternating power questions

1. Calculate the peak current in a 3.2 kΩ resistor connected to a 240 V ac source. (0.11 A)

2. An ac voltage, whose peak value is 180 V, is across a 220 Ω resistor. What is the value of the rms and peak current in the resistor? (0.578 A, 0.818 A))

3. What is the resistance of a 60 W, 120 V light bulb when it is turned on? (240 Ω)

4. The effective value of an alternating current passing through a 1.0 kW device is 3.0 A. What is the peak voltage across it? ($4.7 \times 10^2$ V)

5. What is the maximum instantaneous value of the power dissipated in a 100 W light bulb? (200 W)

6. A 15 Ω heater coil is connected to a 240 VAC line. What is the average power used? What are the maximum and minimum values of the instantaneous power? (3.8 kW, 7.7 kW, 0)

7. In the wire connecting an electric clock to a wall socket, how many times a day does the current reverse direction? ($5.184 \times 10^6$ times)

8. An ac voltage with a peak value of 65 V is applied across a 25 Ω resistor. What is the rms current in the resistor? (1.8 A)

9. A blow drier and a vacuum cleaner each operate with an ac voltage of 120 V. The current rating of the blow drier is 11 A, while that of the vacuum cleaner is 4.0 A. Determine the power consumed by (a) the blow drier and (b) the vacuum cleaner. (c) Determine the ratio of the energy used by the blow drier in 15 minutes to the energy used by the vacuum cleaner in ½ hour. (1.3 kW, 0.48 kW, 1.4:1)

10. Circuit breakers are resettable automatic switches that protect against a dangerously large total current. The switch works by “opening” the circuit to stop the current flow if it reaches a specified level of current. A 1650 W toaster, a 1090 W iron, and a 1250 W microwave oven are turned on in a kitchen. All three appliances are connected through a 20 A circuit breaker found at the 120 VAC power source.
    a) Find the equivalent resistance of the three devices. (How will they be hooked up, in parallel or in series?) (3.61 Ω)
    b) Determine the total current delivered by the source and determine whether the breaker will “open” or remain closed. (33.3 A)

## Part B – Transformer problems

11. The batteries in a portable CD player are recharged by a unit that plugs into a wall socket. Inside the unit is a step-down transformer with a turns ratio of 13:1. The wall socket provides 120 V. What voltage does the secondary coil of the transformer provide? (9.23 V)
12. In some parts of the country, insect "zappers" with their blue lights are a familiar sight in a summer evening. These devices use a high voltage to electrocute insects. One such device has a voltage of 4150 V which is obtained from a standard 120 V outlet through a transformer. If the primary coil has 17 turns, how many turns are in the secondary coil? (588 turns)

13. Electric doorbells found in many homes require 10.0 V to operate. To obtain this voltage from a standard 120 V outlet, a transformer is used. Is a step up or step down transformer required, and what is the turns ratio? (12:1)

14. A step down transformer (turns ration 8:1) is used with an electric train to reduce the voltage from the wall socket to a value needed to operate the train. When the train is running, the current in the secondary coil is 3.4 A. What is the current in the primary coil? (0.43 A)

15. The input to the primary coil of a transformer is 120 V, while the current in the secondary coil is 0.10 A. When 60.0 W of power is being delivered to the circuit attached to the secondary coil, what is the voltage across the secondary coil? Is the transformer a step up or step down unit, and what is its turns ratio? ($6.0 \times 10^2$ V, 1:5)

16. The secondary coil of a transformer provides the voltage that operates an electrostatic air filter. The turns ratio of the transformer is 1:43. The primary coil is plugged into a standard 120 V outlet. The current in the secondary coil is 1.5 mA. Find the power consumed by the air filter. (7.7 W)

17. A generating station is producing 1.2 MW of power that is to be sent to a small town located 7.0 km away. Each of the two wires that comprise the transmission line has a resistance per unit length of 0.050 $\Omega$/km. (a) Find the power lost in heating the wires if the power is transmitted at 1200 V. (b) If a 1:100 step up transformer is used to raise the voltage before the power is transmitted, how much power is now lost in heating the wires? (0.70 MW, 70 W)

18. State 3 reasons why AC is used for large-scale distribution of electrical power instead of DC.

19. Draw a sketch of a transformer and label the three main components. State the function of each component and show which laws of electromagnetic induction govern its operation.

20. Typical hydro-pole transformers reduce voltage from _____ kV to a voltage of _____ V for use in the home.