PHYS 1444 – Section 003
Lecture #11

Wednesday, Oct. 5, 2005
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- Alternating Current (AC)
- Power in AC
- Microscopic view of current
- Superconductivity
- Electric shock hazards
- EMF and Terminal Voltage
Announcements

• Homework due has been changed to noon Tuesdays starting #6
• First term exam next Wednesday, Oct. 12
  – Time: 1 – 2:20 pm
  – Location: SH103
  – Coverage: CH. 21 – 25
• Reading Assignments
  – CH25 – 9
  – CH25 – 10
• There will be a workshop 1 – 5pm this Saturday in SH103 for construction of the World’s Largest Cloud Chamber
  – Food from 12:30pm
Alternating Current

• Does the direction of the flow of current change when a battery is connected to a circuit?
  – No. Why?
    • Because its source of potential difference stays put.
    – This kind of current is called the Direct Current (DC), and it does not change its direction of flow.
      • How would DC look as a function of time?
        – A straight line

• Electric generators at electric power plant produce alternating current (AC)
  – AC reverses direction many times a second
  – AC is sinusoidal as a function of time

• Most the currents supplied to homes and business are AC.
Alternating Current

- The voltage produced by an AC electric generator is sinusoidal
  - This is why the current is sinusoidal
- Voltage produced can be written as
  \[ V = V_0 \sin 2\pi f t = V_0 \sin \omega t \]
- What are the maximum and minimum voltages?
  - \( V_0 \) and \(-V_0\)
  - The potential oscillates between \(+V_0\) and \(-V_0\), the peak voltages or amplitude
  - What is \( f \)?
    - The frequency, the number of complete oscillations made per second. What is the unit of \( f \)? What is the normal size of \( f \) in the US?
      - \( f=60\text{Hz} \) in the US and Canada.
      - Many European countries have \( f=50\text{Hz} \).
    - \( \omega=2\pi f \)
Alternating Current

• Since $V=IR$, if a voltage $V$ exists across a resistance $R$, the current $I$ is

$$I = \frac{V}{R} = \frac{V_0}{R} \sin 2\pi ft = I_0 \sin \omega t$$

What is this?

• What are the maximum and minimum currents?
  – $I_0$ and $-I_0$
  – The current oscillates between $+I_0$ and $-I_0$, the peak currents or amplitude. The current is positive when electron flows to one direction and negative when they flow opposite.
  – AC is as many times positive as negative. What’s the average current?
    • Zero. So there is no power and no heat is produced in a heater?
      – Yes, the electrons actually flow back and forth and power is delivered.
Power Delivered by Alternating Current

- AC power delivered to a resistance is:
  \[ P = I^2 R = I_0^2 R \sin^2 \omega t \]
  - Since the current is squared, the power is always positive

- The average power delivered is
  \[ \bar{P} = \frac{1}{2} I_0^2 R \]

- Since the power is also \( P = V^2 / R \), we can obtain
  \[ \bar{P} = \frac{1}{2} \left( \frac{V_0^2}{R} \right) \]

- The average of the square of current and voltage are important in calculating power:
  \[ \bar{I^2} = \frac{1}{2} I_0^2 \]
  \[ \bar{V^2} = \frac{1}{2} V_0^2 \]
Power Delivered by Alternating Current

• The square root of each of these are called root-mean-square, or rms:
  \[ I_{\text{rms}} = \sqrt{I^2} = \frac{I_0}{\sqrt{2}} = 0.707I_0 \]
  \[ V_{\text{rms}} = \sqrt{V^2} = \frac{V_0}{\sqrt{2}} = 0.707V_0 \]

• rms values are sometimes called effective values
  – These are useful quantities since they can substitute current and voltage directly in power, as if they are in DC
  \[ P = \frac{1}{2} I_0^2 R = I_{\text{rms}}^2 R \]
  \[ P = \frac{1}{2} \frac{V_0^2}{R} = \frac{V_{\text{rms}}^2}{R} \]
  \[ \bar{P} = I_{\text{rms}} V_{\text{rms}} \]
  – In other words, an AC of peak voltage \( V_0 \) or peak current \( I_0 \) produces as much power as DC voltage of \( V_{\text{rms}} \) or DC current \( I_{\text{rms}} \).
  – So normally, rms values are specified in AC are specified or measured.

• US uses 115V rms voltage. What is the peak voltage?
  \[ V_0 = \sqrt{2}V_{\text{rms}} = \sqrt{2} \cdot 115V = 162.6V \]
• Europe uses 240V
  \[ V_0 = \sqrt{2}V_{\text{rms}} = \sqrt{2} \cdot 240V = 340V \]
Example 25 – 11

Hair Dryer. (a) Calculate the resistance and the peak current in a 1000-W hair dryer connected to a 120-V line. (b) What happens if it is connected to a 240-V line in Britain?

The rms current is: \[ I_{rms} = \frac{\bar{P}}{V_{rms}} = \frac{1000W}{120V} = 8.33A \]

The peak current is: \[ I_0 = \sqrt{2}I_{rms} = \sqrt{2} \cdot 8.33A = 11.8A \]

Thus the resistance is: \[ R = \frac{\bar{P}}{I_{rms}^2} = \frac{1000W}{(8.33A)^2} = 14.4\Omega \]

(b) If connected to 240V in Britain …

The average power provide by the AC in UK is \[ \bar{P} = \frac{V_{rms}^2}{R} = \frac{(240V)^2}{14.4\Omega} = 4000W \]

So? The heating coils in the dryer will melt!
Microscopic View of Electric Current

• When a potential difference is applied to the two ends of a wire of uniform cross-section, the direction of electric field is parallel to the walls of the wire, this is possible since the charges are moving, electrodynamics

• Let’s define a microscopic vector quantity, the current density, \( j \), the electric current per unit cross-sectional area
  
  – \( j = I/A \) or \( I = jA \) if the current density is uniform
  – If not uniform \( I = \int j \cdot dA \)
  – The direction of \( j \) is the direction a positive charge would move when placed at that position, generally the same as \( E \)

• The current density exists on any point in space while the current \( I \) refers to a conductor as a whole so a macroscopic
Microscopic View of Electric Current

• The direction of j is the direction of a positive charge. So in a conductor, since negatively charged electrons move, the direction is \(-j\).

• Let’s think about the current in a microscopic view again:
  – When voltage is applied to the end of a wire
  – Electric field is generated by the potential difference
  – Electrons feel force and get accelerated
  – Electrons soon reach to a steady average speed due to collisions with atoms in the wire, called drift velocity, \(v_d\)
  – The drift velocity is normally much smaller than electrons’ average random speed.
Microscopic View of Electric Current

• How do we relate \( v_d \) with the macroscopic current \( I \)?
  – In time \( \Delta t \), the electrons travel \( l = v_d \Delta t \) on average.
  – If wire’s x-sectional area is \( A \), in time \( \Delta t \) electrons in a volume \( V = lA = Av_d \Delta t \) will pass through the area \( A \).
  – If there are \( n \) free electrons (of charge \( -e \)) per unit volume, the total charge \( \Delta Q \) that pass through \( A \) in time \( \Delta t \) is
    \[
    \Delta Q = \text{(total number of charge, } N) \times \text{(charge per particle)} = (nV)(-e) = -(nAv_d \Delta t e)
    \]
  – The current \( I \) in the wire is
    \[
    I = \frac{\Delta Q}{\Delta t} = -neAv_d
    \]
  – The density in vector form is
    \[
    \vec{j} = \frac{I}{A} = -ne \vec{v}_d
    \]
  – For any types of charge:
    \[
    I = \sum_i n_i q_i v_{di} A \quad \quad \quad \quad \quad \vec{j} = \sum_i n_i q_i \vec{v}_{di}
    \]
Microscopic View of Electric Current

- The drift velocity of electrons in a wire is only about 0.05mm/s. How could we get light turned on immediately then?

  - While the electrons in a wire travels slow, the electric field travels essentially at the speed of light. Then what is all the talk about electrons flowing through?

    - It is just like water. When you turn on the facet, water flows right off the facet despite the fact that the water travels slow.
    
    - Electricity is the same. Electrons fill the conductor wire and when the switch is flipped on or a potential difference is applied, the electrons closed to the positive terminal flows.

    - Interesting, isn’t it? Why is the field travel at the speed of light then?
Ohm’s Law in Microscopic View

- Ohm’s law can be written in microscopic quantities.
  - Resistance in terms of resistivity is \( R = \rho \frac{l}{A} \)
  - We can rewrite \( V \) and \( I \) as: \( I = jA \), \( V = E \ell \)
  - If electric field is uniform, from \( V = IR \), we obtain
    - \( V = IR \)
    - \( El = (jA)(\rho \frac{l}{A}) = j \rho l \)
    - So \( j = \frac{E}{\rho} = \sigma E \)
    - In a metal conductor, \( \rho \) or \( \sigma \) does not depend on \( V \), thus, the current density \( j \) is proportional to the electric field \( E \)

Microscopic statement of Ohm’s Law

- In vector form, the density \( j \) is \( \vec{j} = \frac{\vec{E}}{\rho} = \sigma \vec{E} \)
Superconductivity

• At the temperature near absolute 0K, resistivity of certain material becomes 0.
  – This state is called the “superconducting” state.
  – Observed in 1911 by H. K. Onnes when he cooled mercury to 4.2K (-269°C).
    • Resistance of mercury suddenly dropped to 0.
  – In general superconducting materials become superconducting below a transition temperature.
  – The highest temperature superconductivity seen is 160K
    • First observation above the boiling temperature of liquid nitrogen is in 1987 at 90k observed from a compound of yttrium, barium, copper and oxygen.

• Since much smaller amount of material can carry just as much current more efficiently, superconductivity can make electric cars more practical, computers faster, and capacitors store higher energy
Electric Hazards: Leakage Currents

• How does one feel shock by electricity?
  – Electric current stimulates nerves and muscles, and we feel a shock
  – The severity of the shock depends on the amount of current, how long it acts and through what part of the body it passes
  – Electric current heats tissues and can cause burns

• Currents above 70mA on a torso for a second or more is fatal, causing heart to function irregularly, “ventricular fibrillation”

• A dry human body between two points on opposite side of the body is about $10^4$ to $10^6 \, \Omega$.

• When wet, it could be $10^3\Omega$.

• A person in good contact with the ground who touches 120V DC line with wet hands can get the current:
  – Could be lethal

$$I = \frac{V}{R} = \frac{120V}{1000\Omega} = 120mA$$