CHAPTER 18

Electric Currents

Charges in motion are called **electric currents.**

The Electric Battery

Alessandro Volta ranked the relative potential differences produced by combining pairs of metals, and he created the first **battery** using zinc and silver discs within an acidic solution.

The metals of a simple battery (or **electric cell**) are called **electrodes,** and the medium in which they rest is called an **electrolyte.** The exposed parts of the metals are called **terminals.**

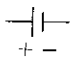
In operation, the electrolyte dissolves one terminal, whose ions enter the electrolyte and leave electrons behind on that terminal, which is now negatively charged. These ions cause the electrolyte to become positively charged, and this causes electrons of the other terminal to flow into the electrolyte, leaving *that* terminal with a positive charge. The difference in charges of the terminals causes a potential difference, and so chemical energy is made available as electrical energy.

Battery voltage is additive when the batteries are arranged in series.

Electric Current

A conducting pathway between battery terminals creates a **circuit,** where charge flows to create an **electric current.** Conventional current flows from the positive terminal through the pathway to the negative terminal.

In diagrams, a battery is expressed through the symbol shown below. The longer line represents the positive terminal.



Current is the amount of charge that passes per unit of time at a point along the pathway, $I = \Delta Q/\Delta t$, whose units C/s are called **amperes.**

Electron flow is in the opposite direction from the conventional current described above.

Ohm's Law: Resistance and Resistors

Electric current (I) is proportional to the potential difference (V) that causes it. This forms the basis of **Ohm's law,** $V = IR$ where R is the resistance encountered along the pathway.

A resistor is a device used in a circuit to reduce the amount of a current. In diagrams, a resistor is expressed through the symbol shown below.

The units of resistance are ohms, symbolized by Ω, which is equivalent to voltage per ampere.

Resistivity

The resistance of a wire is proportional to its length, and it is inversely proportional to the cross section of the wire's area, such that $R = \rho L/A$.

ρ is a constant of proportionality, called the **resistivity,** which depends on the composition of the material.
Resistance is also a function of temperature, and resistivity usually increases with temperature. In equation form, $\rho_T = \rho_0[1 + \alpha(T - T_0)]$, where ρ_0 represents the resistivity at a temperature T_0 and α is the temperature coefficient of resistivity.

Electric Power

Electric energy can be converted into mechanical work, thermal energy, or light.

The power transferred by an electrical device is equal to the rate of energy transferred, which is given by the product of current and voltage, $P = IV$.
Rather than J/s, the unit of electrical power is equivalently expressed as the **watt.** In practice, kilowatts are often used.
The relationship between electrical power, electrical current, and resistance is given by $P = I^2R$.
The relationship between electrical power, potential difference, and resistance is given by $P = V^2/R$.
The quantity of energy produced is the product of power and the time period.
The kilowatt-hour is a common unit of energy, equal to the 3.6×10^6 J.

Power in Household Circuits

Fuses and circuit breakers are designed to prevent overloading circuits. Fuses have a maximum ampere rating. If more than the maximum current flows through the fuse, an element inside the fuse will melt to break the pathway and stop the flow of current.

Alternating Current

Electric currents flowing in a single direction are called **direct currents.** Common household currents are **alternating currents,** so named due to the periodic changes in current direction.

The magnitude of voltage in alternating currents also changes as a function of time, t, and the frequency of oscillation per second, f, such that $V = V_0 \sin 2\pi ft$, where V_0 represents the **peak voltage** the current can attain.

Combined with Ohm's law, $I = (V_0 \sin 2\pi ft)/R = I_0 \sin 2\pi ft$, where $I_0 = V_0/R$, is called the **peak current.** Thus, the current changes also as a function of time and of the frequency of oscillation.
Combined with the definition of power, $P = I_0^2 R \sin^2 2\pi ft$.
The **root-mean-square current,** called the effective current, is given by $I_{rms} = 0.707\ I_0$.
The **root-mean-square voltage,** called the effective voltage, $V_{rms} = 0.707\ V_0$.
For common household circuits, $V_{rms} = 120$ volts.

For Additional Review

Study all equivalent units for new terms presented in this section in terms of units presented in previous chapters.

Multiple-Choice Questions

1. How long will it take for a 1500 C charge to pass through a circuit at 325 A?
   (A) 4.6 seconds
   (B) 11 seconds
   (C) 23 seconds
   (D) 45 seconds
   (E) 1 minute 21 seconds

2. What is the current in a wire attached to a 3.5 Ω resistor with a 9 V battery?
   (A) 0.13 A (D) 7.3 A
   (B) 0.64 A (E) 11.1 A
   (C) 2.6 A

3. What is the current in a 1 m tungsten wire of 1 mm diameter when attached to a 1.5 V battery, if tungsten has a resistivity of $5.6 \times 10^{-8}\ \Omega\cdot$m?
   (A) 21 A (D) 99 A
   (B) 57 A (E) 142 A
   (C) 72 A

4. Find the current in a gold wire of length 75 cm and radius 2 cm connected to a 6 V battery at 100°C. The resistivity of the wire at 20°C is $2.44 \times 10^{-8}\ \Omega\cdot$m with a temperature coefficient of $0.0034\ (\text{C}°)^{-1}$.
   (A) 3.2×10^5 A
   (B) 7.1×10^5 A
   (C) 1.5×10^6 A
   (D) 6.4×10^6 A
   (E) 8.9×10^6 A

5. What is the power transferred to a 4.0 Ω resistor in a circuit connected to a 5.7 V battery?
   (A) 1.1 W (D) 7.2 W
   (B) 4.4 W (E) 8.1 W
   (C) 6.1 W

6. If the cost of energy is 9 cents per kilowatt hour, what will it cost to run a 0.75 A current continuously on a standard 120-V line per year?
   (A) \$51 (D) \$71
   (B) \$59 (E) \$82
   (C) \$66

7. In one household circuit, what is the maximum number of 60-watt light bulbs that can be connected to a 25-amp fuse without overloading it?
   (A) Up to 7
   (B) Up to 19
   (C) Up to 31
   (D) Up to 50
   (E) Up to 76

8. What is the peak current in a 60 W bulb in a circuit to a standard 120-V line?
   (A) 0.41 A (D) 2.4 A
   (B) 0.71 A (E) 4.1 A
   (C) 1.2 A

9. What is the peak voltage in a standard 120-V line?
   (A) 60 V
   (B) 120 V
   (C) 170 V
   (D) 220 V
   (E) 240 V

10. What is the average current in an AC circuit of 240-volt line?
   (A) 0 A
   (B) 15 A
   (C) 30 A
   (D) 60 A
   (E) 120 A

Free-Response Questions

1. Power can be quantitatively described in several equivalent ways.
   (a) Combine Ohm's law with the relationship between power, current, and voltage to develop two other equations for power.
   (b) Detail the differences between the output of alternating and direct currents.
   (c) How does this difference relate to the concepts of root-mean-square current and peak current?

2. Electrical currents are influenced by the qualities of the material through which they travel.
   (a) Define resistivity.
   (b) Explain how an increased resistivity affects a current.
   (c) List potential causes for an increased resistivity.

ANSWERS AND EXPLANATIONS

Multiple-Choice Questions

1. (A) is correct. The relationship between current, time, and charge is given by $I = \Delta Q/\Delta t$ so $\Delta t = \Delta Q/I =$ 1500 C/325 A = 4.6 seconds.
2. (C) is correct. Ohm's law provides the relationship between voltage, resistance, and current by $V = IR$ so $I = V/R = 9\text{ V}/3.5\ \Omega = 2.6$ A.
3. (A) is the correct answer. Rearranging Ohm's law, $I = V/R$ where $R = \rho L/A$. Thus, $I = V/(\rho L/A)$
$= (1.5\text{ V})/(5.6 \times 10^{-8}\ \Omega\cdot\text{m})(1\text{ m})/\pi(0.5 \times 10^{-3}\text{ m})^2$
$= 1.5\text{ V}/7.1 \times 10^{-2} = 21$ A.
4. (A) is correct. The relationship between resistivity and temperature is given by $\rho_T = \rho_0[1 + \alpha(T - T_0)] = (2.44 \times 10^{-8}\ \Omega\cdot\text{m})[1 + 0.0034\ (\text{C}°)^{-1}(80\ \text{C}°)] = 3.1 \times 10^{-8}\ \Omega\cdot\text{m}$. $R = \rho L/A = (3.1 \times 10^{-8}\ \Omega\cdot\text{m})(0.75\text{ m})/\pi(2.0 \times 10^{-2})^2 = 1.9 \times 10^{-5}\ \Omega$. Applying Ohm's law, $I = V/R = 6\text{ V}/1.9 \times 10^{-5}\ \Omega = 3.2 \times 10^5$ A.
5. (E) is the correct answer. The relationship between power, voltage, and resistance is given by $P = V^2/R = (5.7\text{ V})^2/4.0\ \Omega = 8.1$ W.
6. (D) is correct. $P = IV = (0.75\text{ A})(120\text{ V}) = 90\text{ W} = 0.090$ kW. At 9 cents per kilowatt hour, (0.090 kW)(9 cents/kilowatt-hour) = 0.81 cents per hour. Then cost = (0.81 cents/hour)(24 hours/day)(365 days/year)
= 7100 cents/year or $71.

7. **(D) is correct.** The relationship between current, power, and voltage is given by $I = P/V$. Here 25 A = n60 W/120 V, where n is the number of light bulbs. There could be up to 50 light bulbs.

8. **(B) is correct.** The root-mean-square current is given by $I_{rms} = P/V_{rms}$ = 60 W/120 V = 0.5 A. Since $I_{rms} = 0.707\ I_0$, peak current is I_0 = 0.5 A/0.707 = 0.71 A.

9. **(C) is correct.** Standard voltage represents the root-mean-square voltage. The relationship between peak voltage and root-mean-square voltage is given by $V_0 = \sqrt{2}V_{rms}$ = 170 V.

10. **(A) is correct.** Without computation, the alternation of current is regular, and the current is as often positive as it is negative. The average current is zero.

Free-Response Questions

1. (a) Ohm's law states $V = IR$ while the relationship between power, current, and voltage is $P = IV$. Combining these equations, $P = IV$ where $V = IR$ so $P = I(IR) = I^2V$. Also, $I = V/R$, so $P = V(V/R) = V^2/R$. (Equivalent rearrangements are acceptable.)
   (b) A direct-current circuit has a constant current in terms of magnitude and direction, whereas the magnitude of an alternating current follows a sinusoidal current flow (alternating direction) as a function of time and frequency. Alternating current is also the predominantly utilized circuit.
   (c) The concepts of root-mean-square current and peak current apply to alternating currents. The root-mean-square current represents the average current, and the peak current represents the highest value of current the circuit achieves. For direct currents, these values are the same.

   This would be considered an optimal response. In the response to part a, the laws are correctly stated, and the mathematical derivations requested are presented clearly. In the response to part b, the major differences are correctly highlighted. While "alternating current is also the predominantly utilized circuit" is true and shows a thorough understanding of the material, this fact would not be necessary for full credit. In the response to part c, the differences for root-mean-square current and peak current are explained as particular to alternating currents.

2. (a) Resistivity is a constant of proportionality unique to a substance that affects its electrical resistance. Its relationship to resistance is given by $R = \rho L/A$.
   (b) As resistivity increases, resistance increases, and in a circuit with a constant voltage, Ohm' law ($I = V/R$) predicts that the current would decrease.
   (c) Depending on the material, resistivity can be a function of temperature, $\rho_T = \rho_0[1 + \alpha(T - T_0)]$, where α is a value that depends on the material, typically relating a base resistivity to 20°C.

   This response includes all relevant equations, as well as a full definition in parts a and b, as well as their logical consequences. In the response to part c, the actual equation is not necessary, although its implications would have to be presented—that increased temperature means increased resistivity, and that it has a constant of proportionality dependant on the substance.