21

Alternating Current Circuits and Electromagnetic Waves

Clicker Questions

Question O1.01

Description: Relating object color to the wave nature of light.

Question

A particular object appears to be red. The reason it appears red is:

1. It absorbs **only red** frequencies as they hit.
2. It reflects **only red** frequencies as they hit.
3. It absorbs **red** frequencies **more** than other frequencies.
4. It reflects **red** frequencies **more** than other frequencies.
5. It emits **red** frequencies **more** than other frequencies.
6. Not enough information.

Commentary

Purpose: To hone the concept of "color" as a property of an object.

Discussion: If an object appears red when you look at it, the light emanating from it and reaching your eye must be predominantly red in frequency. Physically, answers (2), (4), and (5) are all possible. Case (5) would describe a glowing object such as a neon sign or red LED. Most common objects, however, do not emit light, but rather reflect some of the light striking them. A real red object will reflect predominantly red frequencies of light, but will not perfectly absorb all other frequencies. Thus, (4) is a better answer than (2).

If you interpret "a particular object" as a typical non-luminous object, (4) would be the best answer. However, (6) — not enough information — is defensible, since you were not told whether the object is luminous, which would make (5) accurate.

Key Points:

- The apparent color of an object is determined by the mix of frequencies in the light traveling from it to the observer; the light from a red object will be dominated by light in the red portion of the spectrum.
- An object may emit light if it is luminous (glowing), but most objects merely reflect some of the light incident upon them.

For Instructors Only

Questions that may support productive discussion: "What will you see if you look at a red object through a piece of red-tinted glass? How about through blue-tinted glass? If you shine red light on it? Or blue light? How does an RGB monitor display millions of different colors?"

Question O1.02

Description: Linking optics to real-world experience of color.

Question

The Sun appears to be yellow when overhead because:

1. The human eye is most sensitive to yellow.
2. Yellow frequencies are transmitted better through the atmosphere.
3. Air does not absorb yellow frequencies.
4. The temperature of the Sun is 6000 K.
5. More than one of the above.
6. None of the above.

Commentary

Purpose: To probe your understanding of the colors of glowing objects, and to connect physics processes to your everyday experience.

Discussion: Hot matter emits photons of many frequencies, but more of some frequencies than others. The higher the temperature of the matter, the more high-frequency photons are emitted. If the temperature high enough, the emitted light will be visible (have enough photons in the visible part of the spectrum), the color will be determined by the mix of photon frequencies. The higher the temperature, the closer to the blue end of the spectrum the radiated light will appear.

At a temperature of about 6000 K, the mix of radiated photon frequencies is such that the object will appear to glow yellow. This accounts for the sun's color when overhead. Other stars, having different surface temperatures, have different colors: there are red stars, blue stars, etc.

Key Points:

- Objects glow when hot enough. The mix of photon frequencies emitted, and thus the color, depends on the temperature of the object.
- The sun's surface temperature is approximately 6000 K, resulting in its yellow color.

For Instructors Only

This question is most effectively used *before* covering the relevant material on light and black-body radiation, to elicit student's preconceptions and motivate learning of the material.

Question O1.03

Description: Linking optics to real-world experience of color.

Question

The sky appears to be blue during the day because:

1. Air absorbs blue light less than other frequencies (i.e., acts like a blue filter).
2. Air molecules emit blue light after being struck by sunlight.

3. The sky reflects blue light from the oceans.
4. The temperature high in the Earth's upper atmosphere is 1000 K.
5. None of the above.

Commentary

Purpose: To connect physics processes to your everyday experience.

Discussion: When light travels through the atmosphere, some of the photons collide with air molecules and change directions (a process called "scattering"), and most travels through unscattered. Some photons are more likely to be scattered than others, however; photons toward the blue end of the visible spectrum are far, far more likely to scatter than those near the red end. Thus, when sunlight travels through the atmosphere, much of the blue light scatters off in various directions. An observer looking at the sun sees photons of all colors traveling directly without scattering; an observer looking elsewhere in the sky sees photons that have reached her after scattering off an air molecule, and these are predominantly blue.

Thus, the proper answer to "Why is the sky blue?" is that "Blue photons are much more likely to scatter from air molecules than photons of other colors." This is not on the list, so "none of the above" (5) is the best choice.

Key Points:

- When light travels through air, some of the photons collide with air molecules and scatter off in different directions.
- The frequency (color) of a photon strongly affects how likely it is to scatter off of an air molecule. The closer to the blue end of the visible spectrum, the more likely scattering is.
- The sky's color is due to photons that reach the observer after scattering from an air molecule.

For Instructors Only

This also is a good question to ask before students should "know" the right answer, to elicit preconceptions, stimulate discussion, and motivate subsequent learning.

Depending on your students' mathematical sophistication, they may appreciate knowing that the scattering probability of a photon from an air molecule goes as the fourth power of the frequency. This is not because blue molecules are "bigger," but rather because of the quantum-mechanical nature of the scattering interaction.

Discussion of the sky's color near sunrise and sunset has been omitted here, as that subject is taken up in Question O1.04 (which makes a good follow-up to this one).

We do want students to take "none of the above" answers seriously.

Question O1.04

Description: Linking optics to real-world experience of color.

Question

The Sun appears to be red as it sets because:

1. Air absorbs red light less than other frequencies (i.e., acts like a red filter).
2. The sunlight has a red-shift when you're moving fastest away from it.

3. The Sun cools down to 5000 K each evening.
4. Light is refracted as it enters the atmosphere.
5. The Sun dies in a glorious fireball each evening and is reborn each morning.
6. None of the above.

Commentary

Purpose: To connect physics processes to your everyday experience.

Discussion: When light travels through the atmosphere, some of the photons collide with air molecules and change directions (a process called "scattering"), and most travels through unscattered. Some photons are more likely to be scattered than others, however; photons toward the blue end of the visible spectrum are far, far more likely to scatter than those near the red end. Thus, when sunlight travels through the atmosphere, much of the blue light scatters off in various directions.

At sunset, light from the sun skims along the Earth's surface before reaching an observer, traveling through much more air than it does at midday. This means each photon has many more chances to scatter off in another direction, and by the time the sunlight has reached the observer, enough of the blue light has been scattered away that the remaining light looks reddish. This explanation does not appear among the listed answers, so "none of the above" is the best choice.

Light does refract upon entering the atmosphere, but only slightly, about half a degree. Although refraction will cause separation of colors because of frequency dependence of the index of refraction, refraction is not the cause of the red light at sunset.

At midday, more blue light scatters away than for other colors, but enough remains that the sun's color is not significantly altered from its original yellowish-white color.

Key Points:

- When light travels through air, some of the photons collide with air molecules and scatter off in different directions.
- The frequency (color) of a photon strongly affects how likely it is to scatter off of an air molecule. The closer to the blue end of the visible spectrum, the more likely scattering is.
- As blue photons are disproportionately scattered out of the sun's light, the remaining light is increasingly reddish in appearance.

For Instructors Only

This question makes a good follow-up to Question O1.03: it requires the same principles as discussed there, but asks students to reason further with them. This checks how well they grasp those principles (as opposed to just memorizing the answer) and helps them solidify the ideas.

QUICK QUIZZES

1. (c). The average power is proportional to the rms current, which is nonzero even though the average current is zero. (a) is only valid for an open circuit, for which $R \to \infty$. (b) and (d) can never be true because $i_{av} = 0$ for AC currents.

2. (b). Choices (a) and (c) are incorrect because the unaligned sine curves in Figure 21.9 mean the voltages are out of phase, and so we cannot simply add the maximum (or rms) voltages across the elements. (In other words, $\Delta V \neq \Delta V_R + \Delta V_L + \Delta V_C$ even though $\Delta v = \Delta v_R + \Delta v_L + \Delta v_C$.)

3. (b). Closing switch A replaces a single resistor with a parallel combination of two resistors. Since the equivalent resistance of a parallel combination is always less than the lowest resistance in the combination, the total resistance of the circuit decreases, which causes the impedance $Z = \sqrt{R_{\text{total}}^2 + (X_L - X_C)^2}$ to decrease.

4. (a). Closing switch A replaces a single resistor with a parallel combination of two resistors. Since the equivalent resistance of a parallel combination is always less than the lowest resistance in the combination, the total resistance of the circuit decreases, which causes the phase angle, $\phi = \tan^{-1}\left[(X_L - X_C)/R\right]$, to increase.

5. (a). Closing switch B replaces a single capacitor with a parallel combination of two capacitors. Since the equivalent capacitance of a parallel combination is greater than that of either of the individual capacitors, the total capacitance increases, which causes the capacitive reactance $X_C = 1/2\pi fC$ to decrease. Thus, the net reactance, $X_L - X_C$, increases causing the phase angle, $\phi = \tan^{-1}\left[(X_L - X_C)/R\right]$, to increase.

6. (b). Inserting an iron core in the inductor increases both the self-inductance and the inductive reactance, $X_L = 2\pi fL$. This means the net reactance, $X_L - X_C$, and hence the impedance, $Z = \sqrt{R_{\text{total}}^2 + (X_L - X_C)^2}$, increases, causing the current (and therefore, the bulb's brightness) to decrease.

7. (b), (c). Since pressure is *force per unit area,* changing the size of the area without altering the intensity of the radiation striking that area will not cause a change in radiation pressure. In (b), the smaller disk absorbs less radiation, resulting in a smaller force. For the same reason, the momentum in (c) is reduced.

8. (b), (d). The frequency and wavelength of light waves are related by the equation $\lambda f = v$ or $f = v/\lambda$, where the speed of light v is a constant within a given medium. Thus, the frequency and wavelength are inversely proportional to each other, when one increases the other must decrease.

ANSWERS TO MULTIPLE CHOICE QUESTIONS

1. $\Delta V_{\text{rms}} = \dfrac{\Delta V_{\max}}{\sqrt{2}} = \dfrac{170\text{ V}}{\sqrt{2}} = 120\text{ V}$, so (c) is the correct choice.

2. When the frequency doubles, the rms current $I_{\text{rms}} = \Delta V_{L,\text{rms}}/X_L = \Delta V_{L,\text{rms}}/2\pi fL$ is cut in half. Thus, the new current is $I_{\text{rms}} = 3.0\text{ A}/2 = 1.5\text{ A}$ and (e) is the correct answer.

3. $\Delta V_{C,\text{rms}} = I_{\text{rms}} X_C = \dfrac{I_{\text{rms}}}{2\pi fC} = \dfrac{1.00\times 10^{-3}\text{ A}}{2\pi(60.0\text{ Hz})\left[(1.00/2\pi)\times 10^{-6}\text{ F}\right]} = 16.7\text{ V}$, so choice (a) is correct.

4. $\Delta V_{L,\text{rms}} = I_{\text{rms}} X_L = I_{\text{rms}}(2\pi fL) = (2.0\text{ A})2\pi(60.0\text{ Hz})\left[(1.0/2\pi)\text{H}\right] = 120\text{ V}$, and the correct answer is choice (c).

5. At the resonance frequency, $X_L = X_C$ and the impedance is $Z = \sqrt{R^2 + (X_L - X_C)^2} = R$. Thus, the rms current is $I_{\text{rms}} = \Delta V_{\text{rms}}/Z = (120\text{ V})/(20\ \Omega) = 6.0\text{ A}$, and (b) is the correct choice.

6. The battery produces a constant current in the primary coil, which generates a constant flux through the secondary coil. With no change in flux through the secondary coil, there is no induced voltage across the secondary coil, and choice (e) is the correct answer.

7. The peak values of the electric and magnetic field components of an electromagnetic wave are related by $E_{max}/B_{max} = c$, where c is the speed of light in vacuum. Thus,

$$E_{max} = cB_{max} = \left(3.0 \times 10^{8}\ \text{m/s}\right)\left(1.5 \times 10^{-7}\ \text{T}\right) = 45\ \text{N/C}$$

which is choice (d).

8. When a power source, AC or DC, is first connected to a *RL* combination, the presence of the inductor impedes the buildup of a current in the circuit. The value of the current starts at zero and increases as the back emf induced across the inductor decreases somewhat in magnitude. Thus, the correct choice is (c).

9. The voltage across the capacitor is proportional to the stored charge. This charge, and hence the voltage Δv_C, is a maximum when the current has zero value and is in the process of reversing direction after having been flowing in one direction for a half cycle. Thus, the voltage across the capacitor lags behind the current by 90°, and (a) is the correct choice.

10. In an *RLC* circuit, the instantaneous voltages Δv_R, Δv_L, and Δv_C (across the resistance, inductance, and capacitance, respectively) are not in phase with each other. The instantaneous voltage Δv_R is in phase with the current, Δv_L leads the current by 90°, while Δv_C lags behind the current by 90°. The instantaneous values of these three voltages do add algebraically to give the instantaneous voltages across the *RLC* combination, but the rms voltages across these components do not add algebraically. The rms voltages across the three components must be added as vectors (or phasors) to obtain the correct rms voltage across the *RLC* combination. Among the listed choices, choice (e) is the *false* statement.

11. In an AC circuit, both an inductor and a capacitor store energy for one-half of the cycle of the current, and return that energy to the circuit during the other half of the cycle. On the other hand, a resistor converts electrical potential energy into thermal energy during all parts of the cycle of the current. Thus, only the resistor has a nonzero average power loss. The power delivered to a circuit by a generator is given by $\mathcal{P}_{av} = I_{rms}\Delta V_{rms}\cos\phi$, where ϕ is the phase difference between the generator voltage and the current. Among the listed choices, the only *true* statement is choice (c).

12. If the voltage is a maximum when the current is zero, the voltage is either leading or lagging the current by 90° (or a quarter cycle) in phase. Thus, the element could be *either* an inductor or a capacitor. It could not be a resistor since the voltage across a resistor is always in phase with the current. If the current and voltage were out of phase by 180°, one would be a maximum in one direction when the other was a maximum value in the opposite direction. The correct choice for this question is (d).

13. At resonance, $X_L = X_C$, and the phase difference between the current and the applied voltage is

$$\phi = \tan^{-1}\left[\left(X_L - X_C\right)/R\right] = \tan^{-1}\left(0\right) = 0°$$

The correct answer is choice (c).

14. At a frequency of $f = 5.0 \times 10^2$ Hz, the inductive reactance, capacitive reactance, and impedance are $X_L = 2\pi fL$, $X_C = \dfrac{1}{2\pi f C}$, and $Z = \sqrt{R^2 + (X_L - X_C)^2}$. This yields

$$Z = \sqrt{(20.0\ \Omega)^2 + \left[2\pi(5.0 \times 10^2\ \text{Hz})(0.120\ \text{H}) - \frac{1}{2\pi(5.0 \times 10^2\ \text{Hz})(0.75 \times 10^{-6}\ \text{F})}\right]^2} = 51\ \Omega,$$

and $I_{\text{rms}} = \dfrac{\Delta V_{\text{rms}}}{Z} = \dfrac{120\ \text{V}}{51\ \Omega} = 2.3$ A. Choice (a) is the correct answer.

ANSWERS TO EVEN NUMBERED CONCEPTUAL QUESTIONS

2. At resonance, $X_L = X_C$. This means that the impedance $Z = \sqrt{R^2 + (X_L - X_C)^2}$ reduces to $Z = R$.

4. The fundamental source of an electromagnetic wave is a moving charge. For example, in a transmitting antenna of a radio station, charges are caused to move up and down at the frequency of the radio station. These moving charges set up electric and magnetic fields, the electromagnetic wave, in the space around the antenna.

6. Energy moves. No matter moves. You could say that electric and magnetic fields move, but it is nicer to say that the fields stay at that point and oscillate. The fields vary in time, like sports fans in the grandstand when the crowd does the wave. The fields constitute the medium for the wave, and energy moves.

8. The average value of an alternating current is zero because its direction is positive as often as it is negative, and its time average is zero. The average value of the square of the current is not zero, however, since the squares of positive and negative values are always positive and cannot cancel.

10. The brightest portion of your face shows where you radiate the most. Your nostrils and the openings of your ear canals are particularly bright. Brighter still are the pupils of your eyes.

12. The changing magnetic field of the solenoid induces eddy currents in the conducting core. This is accompanied by I^2R conversion of electrically transmitted energy into internal energy in the conductor.

14. The voltages are not added in a scalar form, but in a vector form, as shown in the phasor diagrams throughout the chapter. Kirchhoff's loop rule is true at any instant, but the voltages across different circuit elements are not simultaneously at their maximum values. Do not forget that an inductor can induce an emf in itself and that the voltage across it is 90° *ahead* of the current in the circuit in phase.

PROBLEM SOLUTIONS

21.1 (a) $\Delta V_{R,\text{rms}} = I_{\text{rms}} R = (8.00\ \text{A})(12.0\ \Omega) = \boxed{96.0\ \text{V}}$

(b) $\Delta V_{R,\max} = \sqrt{2}(\Delta V_{R,\text{rms}}) = \sqrt{2}(96.0\ \text{V}) = \boxed{136\ \text{V}}$

(c) $I_{\max} = \sqrt{2} I_{\text{rms}} = \sqrt{2}(8.00\ \text{A}) = \boxed{11.3\ \text{A}}$

(d) $\mathcal{P}_{\text{av}} = I_{\text{rms}}^2 R = (8.00\ \text{A})^2(12.0\ \Omega) = \boxed{768\ \text{W}}$

21.2 (a) $\Delta V_{R,\max} = \sqrt{2}\left(\Delta V_{R,\mathrm{rms}}\right) = \sqrt{2}\left(1.20\times 10^{2}\ \mathrm{V}\right) = \boxed{1.70\times 10^{2}\ \mathrm{V}}$

(b) $\mathcal{P}_{\mathrm{av}} = I_{\mathrm{rms}}^2 R = \dfrac{\Delta V_{\mathrm{rms}}^2}{R} \;\Rightarrow\; R = \dfrac{\Delta V_{\mathrm{rms}}^2}{\mathcal{P}_{\mathrm{av}}} = \dfrac{\left(1.20\times 10^{2}\ \mathrm{V}\right)^2}{60.0\ \mathrm{W}} = \boxed{2.40\times 10^{2}\ \Omega}$

(c) Because $R = \dfrac{\Delta V_{\mathrm{rms}}^2}{\mathcal{P}_{\mathrm{av}}}$ (see above), if the bulbs are designed to operate at the same voltage, $\boxed{\text{the } 1.00\times 10^{2}\ \text{W will have the lower resistance}}$.

21.3 The meters measure the rms values of potential difference and current. These are

$$\Delta V_{\mathrm{rms}} = \frac{\Delta V_{\max}}{\sqrt{2}} = \frac{100\ \mathrm{V}}{\sqrt{2}} = \boxed{70.7\ \mathrm{V}}, \text{ and } I_{\mathrm{rms}} = \frac{\Delta V_{\mathrm{rms}}}{R} = \frac{70.7\ \mathrm{V}}{24.0\ \Omega} = \boxed{2.95\ \mathrm{A}}$$

21.4 All lamps are connected in parallel with the voltage source, so $\Delta V_{\mathrm{rms}} = 120\ \mathrm{V}$ for each lamp. Also, the current is $I_{\mathrm{rms}} = \mathcal{P}_{\mathrm{av}}/\Delta V_{\mathrm{rms}}$ and the resistance is $R = \Delta V_{\mathrm{rms}}/I_{\mathrm{rms}}$.

$$I_{1,\ \mathrm{rms}} = I_{2,\ \mathrm{rms}} = \frac{150\ \mathrm{W}}{120\ \mathrm{V}} = \boxed{1.25\ \mathrm{A}} \text{ and } R_1 = R_2 = \frac{120\ \mathrm{V}}{1.25\ \mathrm{A}} = \boxed{96.0\ \Omega}$$

$$I_{3,\ \mathrm{rms}} = \frac{100\ \mathrm{W}}{120\ \mathrm{V}} = \boxed{0.833\ \mathrm{A}} \text{ and } R_3 = \frac{120\ \mathrm{V}}{0.833\ \mathrm{A}} = \boxed{144\ \Omega}$$

21.5 The total resistance (series connection) is $R_{eq} = R_1 + R_2 = 8.20\ \Omega + 10.4\ \Omega = 18.6\ \Omega$, so the current in the circuit is

$$I_{\mathrm{rms}} = \frac{\Delta V_{\mathrm{rms}}}{R_{eq}} = \frac{15.0\ \mathrm{V}}{18.6\ \Omega} = 0.806\ \mathrm{A}$$

The power to the speaker is then $\mathcal{P}_{\mathrm{av}} = I_{\mathrm{rms}}^2 R_{speaker} = (0.806\ \mathrm{A})^2(10.4\ \Omega) = \boxed{6.76\ \mathrm{W}}$

21.6 The general form of the generator voltage is $\Delta v = (\Delta V_{\max})\sin(\omega t)$, so by inspection

(a) $\Delta V_{R,\max} = \boxed{170\ \mathrm{V}}$ and (b) $f = \dfrac{\omega}{2\pi} = \dfrac{60\pi\ \mathrm{rad/s}}{2\pi\ \mathrm{rad}} = \boxed{30.0\ \mathrm{Hz}}$

(c) $\Delta V_{R,\mathrm{rms}} = \dfrac{\Delta V_{R,\max}}{\sqrt{2}} = \dfrac{170\ \mathrm{V}}{\sqrt{2}} = \boxed{120\ \mathrm{V}}$

(d) $I_{\mathrm{rms}} = \dfrac{\Delta V_{R,\mathrm{rms}}}{R} = \dfrac{120\ \mathrm{V}}{20.0\ \Omega} = \boxed{6.00\ \mathrm{A}}$

(e) $I_{\max} = \sqrt{2} I_{\mathrm{rms}} = \sqrt{2}(6.00\ \mathrm{A}) = \boxed{8.49\ \mathrm{A}}$

(f) $\mathcal{P}_{\mathrm{av}} = I_{\mathrm{rms}}^2 R = (6.00\ \mathrm{A})^2(20.0\ \Omega) = \boxed{720\ \mathrm{W}}$

(g) The argument of the sine function has units of $[\omega t] = (\mathrm{rad/s})(\mathrm{s}) = \boxed{\text{radians}}$.
At $t = 0.005\,0\ \mathrm{s}$, the instantaneous current is

$$i = \frac{\Delta v}{R} = \frac{(170\ \mathrm{V})}{20.0\ \Omega}\sin\left[(60\pi\ \mathrm{rad/s})(0.005\,0\ \mathrm{s})\right] = \frac{(170\ \mathrm{V})}{20.0\ \Omega}\sin(0.94\ \mathrm{rad}) = \boxed{6.9\ \mathrm{A}}$$

21.7 $X_C = \dfrac{1}{2\pi fC}$, so its units are

$$\frac{1}{(1/\text{Sec})\text{Farad}} = \frac{1}{(1/\text{Sec})(\text{Coulomb}/\text{Volt})} = \frac{\text{Volt}}{\text{Coulomb}/\text{Sec}} = \frac{\text{Volt}}{\text{Amp}} = \text{Ohm}$$

21.8 $I_{\max} = \sqrt{2}\,I_{\text{rms}} = \dfrac{\sqrt{2}\left(\Delta V_{\text{rms}}\right)}{X_C} = \sqrt{2}\left(\Delta V_{\text{rms}}\right)2\pi f C$

(a) $I_{\max} = \sqrt{2}(120\text{ V})2\pi(60.0\text{ Hz})\left(2.20\times10^{-6}\text{ C/V}\right) = 0.141\text{ A} = \boxed{141\text{ mA}}$

(b) $I_{\max} = \sqrt{2}(240\text{ V})2\pi(50.0\text{ Hz})\left(2.20\times10^{-6}\text{ C/V}\right) = 0.235\text{ A} = \boxed{235\text{ mA}}$

21.9 $I_{\text{rms}} = \dfrac{\Delta V_{\text{rms}}}{X_C} = 2\pi f C\left(\Delta V_{\text{rms}}\right)$, so

$$f = \frac{I_{\text{rms}}}{2\pi C\left(\Delta V_{\text{rms}}\right)} = \frac{0.30\text{ A}}{2\pi\left(4.0\times10^{-6}\text{ F}\right)(30\text{ V})} = \boxed{4.0\times10^{2}\text{ Hz}}$$

21.10 (a) $X_C = \dfrac{1}{2\pi fC} = \dfrac{1}{2\pi(60.0\text{ Hz})\left(12.0\times10^{-6}\text{ F}\right)} = \boxed{221\ \Omega}$

(b) $I_{\text{rms}} = \dfrac{\Delta V_{C,\text{rms}}}{X_C} = \dfrac{36.0\text{ V}}{221\ \Omega} = \boxed{0.163\text{ A}}$

(c) $I_{\max} = \sqrt{2}\,I_{\text{rms}} = \sqrt{2}(0.163\text{ A}) = \boxed{0.231\text{ A}}$

(d) $\boxed{\text{No.}}$ The current reaches its maximum value one-quarter cycle before the voltage reaches its maximum value. From the definition of capacitance, the capacitor reaches its maximum charge when the voltage across it is also a maximum. Consequently, the maximum charge and the maximum current do not occur at the same time.

21.11 $I_{\text{rms}} = \dfrac{\Delta V_{\text{rms}}}{X_C} = 2\pi f C\left(\dfrac{\Delta V_{\max}}{\sqrt{2}}\right) = \pi f C\left(\Delta V_{\max}\right)\sqrt{2}$

so $C = \dfrac{I}{\pi f\left(\Delta V_{\max}\right)\sqrt{2}} = \dfrac{0.75\text{ A}}{\pi(60\text{ Hz})(170\text{ V})\sqrt{2}} = 1.7\times10^{-5}\text{ F} = \boxed{17\ \mu\text{F}}$

21.12 (a) By inspection, $\Delta V_{C,\max} = 98.0$ V, so $\Delta V_{C,\text{rms}} = \dfrac{\Delta V_{C,\max}}{\sqrt{2}} = \dfrac{98.0\text{ V}}{\sqrt{2}} = \boxed{69.3\text{ V}}$

(b) Also by inspection, $\omega = 80\pi$ rad/s, so $f = \dfrac{\omega}{2\pi} = \dfrac{80\pi\text{ rad/s}}{2\pi\text{ rad}} = \boxed{40.0\text{ Hz}}$

(c) $I_{\text{rms}} = \dfrac{I_{\max}}{\sqrt{2}} = \dfrac{0.500\text{ A}}{\sqrt{2}} = \boxed{0.354\text{ A}}$

(d) $X_C = \dfrac{\Delta V_{C,\max}}{I_{\max}} = \dfrac{98.0\text{ V}}{0.500\text{ A}} = \boxed{196\ \Omega}$

(e) $X_C = \dfrac{1}{2\pi fC} = \dfrac{1}{\omega C}$, so $C = \dfrac{1}{\omega X_C} = \dfrac{1}{(80\pi\text{ rad/s})(196\ \Omega)} = 2.03\times10^{-5}\text{ F} = \boxed{20.3\ \mu\text{F}}$

21.13 $X_L = 2\pi f L$, and from $|\mathcal{E}| = L\left(\frac{\Delta I}{\Delta t}\right)$, we have $L = \frac{|\mathcal{E}|(\Delta t)}{\Delta I}$. The units of self inductance are then $[L] = \frac{[\mathcal{E}][\Delta t]}{[\Delta I]} = \frac{\text{Volt}\cdot\text{sec}}{\text{amp}}$. The units of inductive reactance are given by

$$[X_L] = [f][L] = \left(\frac{1}{\text{sec}}\right)\left(\frac{\text{Volt}\cdot\text{sec}}{\text{Amp}}\right) = \frac{\text{Volt}}{\text{Amp}} = \text{Ohm}$$

21.14 (a) $X_L = 2\pi f L = 2\pi(80.0 \text{ Hz})(25.0\times10^{-3} \text{ H}) = \boxed{12.6\ \Omega}$

(b) $I_{\text{rms}} = \frac{\Delta V_{L,\text{rms}}}{X_L} = \frac{78.0 \text{ V}}{12.6\ \Omega} = \boxed{6.19 \text{ A}}$

(c) $I_{\max} = \sqrt{2}\, I_{\text{rms}} = \sqrt{2}(6.19 \text{ A}) = \boxed{8.75 \text{ A}}$

21.15 The required inductive reactance is $X_L = \frac{\Delta V_{L,\max}}{I_{\max}} = \frac{\Delta V_{L,\max}}{\sqrt{2}\, I_{\text{rms}}}$ and the needed inductance is

$$L = \frac{X_L}{2\pi f} = \frac{\Delta V_{L,\max}}{\sqrt{2}(2\pi f) I_{\text{rms}}} \geq \frac{4.00 \text{ V}}{\sqrt{2}(2\pi)(300.0 \text{ Hz})(2.00\times10^{-3} \text{ A})} = \boxed{0.750 \text{ H}}$$

21.16 Given: $v_L = (1.20\times10^2 \text{ V})\sin(30\pi t)$ and $L = 0.500$ H

(a) By inspection, $\omega = 30\pi$ rad/s, so $f = \frac{\omega}{2\pi} = \frac{30\pi \text{ rad/s}}{2\pi} = \boxed{15.0 \text{ Hz}}$

(b) Also by inspection, $\Delta V_{L,\max} = 1.20\times10^2$ V, so that

$$\Delta V_{L,\text{rms}} = \frac{\Delta V_{L,\max}}{\sqrt{2}} = \frac{1.20\times10^2 \text{ V}}{\sqrt{2}} = \boxed{84.9 \text{ V}}$$

(c) $X_L = 2\pi f L = \omega L = (30\pi \text{ rad/s})(0.500 \text{ H}) = \boxed{47.1\ \Omega}$

(d) $I_{\text{rms}} = \frac{\Delta V_{L,\text{rms}}}{X_L} = \frac{84.9 \text{ V}}{47.1\ \Omega} = \boxed{1.80 \text{ A}}$

(e) $I_{\max} = \sqrt{2}\, I_{\text{rms}} = \sqrt{2}(1.80 \text{ A}) = \boxed{2.55 \text{ A}}$

(f) The phase difference between the voltage across an inductor and the current through the inductor is $\phi_L = 90°$, so the average power delivered to the inductor is

$$\mathcal{P}_{L,\text{av}} = I_{\text{rms}}\Delta V_{L,\text{rms}}\cos\phi_L = I_{\text{rms}}\Delta V_{L,\text{rms}}\cos(90°) = \boxed{0}$$

(g) When a sinusoidal voltage with a peak value $\Delta V_{L,\max}$ is applied to an inductor, the current through the inductor also varies sinusoidally in time, with the same frequency as the applied voltage, and has a maximum value of $I_{\max} = \Delta V_{L,\max}/X_L$. However, the current lags behind the voltage in phase by a quarter-cycle or $\pi/2$ radians. Thus, if the voltage is given by $\Delta v_L = \Delta V_{L,\max}\sin(\omega t)$, the current as a function of time is $i = I_{\max}\sin(\omega t - \pi/2)$. In the case of the given inductor, the current through it will be $\boxed{i = (2.55 \text{ A})\sin(30\pi t - \pi/2)}$.

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(h) When $i = +1.00$ A, we have: $\sin(30\pi t - \pi/2) = (1.00 \text{ A}/2.55 \text{ A})$, or

$$30\pi t - \pi/2 = \sin^{-1}(1.00 \text{ A}/2.55 \text{ A}) = \sin^{-1}(0.392) = 0.403 \text{ rad}$$

and $$t = \frac{\pi/2 \text{ rad} + 0.403 \text{ rad}}{30\pi \text{ rad/s}} = 2.09 \times 10^{-2} \text{ s} = \boxed{20.9 \text{ ms}}$$

21.17 From $L = N\Phi_B/I$ (see Section 20.6 in the textbook), the total flux through the coil is $\Phi_{B,\text{ total}} = N\Phi_B = L \cdot I$, where Φ_B is the flux through a single turn on the coil. Thus,

$$\left(\Phi_{B,\text{total}}\right)_{\max} = L \cdot I_{\max} = L \cdot \left[\frac{\Delta V_{\max}}{X_L}\right]$$
$$= L\frac{\sqrt{2}(\Delta V_{\text{rms}})}{2\pi f L} = \frac{\sqrt{2}(120 \text{ V})}{2\pi(60.0 \text{ Hz})} = \boxed{0.450 \text{ T}\cdot\text{m}^2}$$

21.18 (a) The applied voltage is $\Delta v = \Delta V_{\max}\sin(\omega t) = (80.0 \text{ V})\sin(150t)$, so we have that $\Delta V_{\max} = 80.0$ V and $\omega = 2\pi f = 150$ rad/s. The impedance for the circuit is

$$Z = \sqrt{R^2 + (X_L - X_C)^2} = \sqrt{R^2 + (2\pi f L - 1/2\pi f C)^2} = \sqrt{R^2 + (\omega L - 1/\omega C)^2}$$

or $$Z = \sqrt{(40.0\ \Omega)^2 + \left[(150 \text{ rad/s})(80.0 \times 10^{-3} \text{ H}) - \frac{1}{(150 \text{ rad/s})(125 \times 10^{-6} \text{ F})}\right]^2} = \boxed{57.5\ \Omega}$$

(b) $$I_{\max} = \frac{\Delta V_{\max}}{Z} = \frac{80.0 \text{ V}}{57.5\ \Omega} = \boxed{1.39 \text{ A}}$$

21.19 $$X_C = \frac{1}{2\pi f C} = \frac{1}{2\pi(60.0 \text{ Hz})(40.0 \times 10^{-6} \text{ F})} = 66.3\ \Omega$$

$$Z = \sqrt{R^2 + (X_L - X_C)^2} = \sqrt{(50.0\ \Omega)^2 + (0 - 66.3\ \Omega)^2} = 83.0\ \Omega$$

(a) $$I_{\text{rms}} = \frac{\Delta V_{\text{rms}}}{Z} = \frac{30.0 \text{ V}}{83.0\ \Omega} = \boxed{0.361 \text{ A}}$$

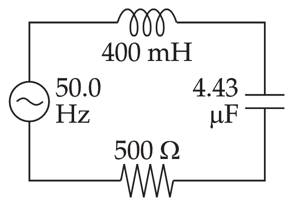
(b) $$\Delta V_{R,\text{ rms}} = I_{\text{rms}} R = (0.361 \text{ A})(50.0\ \Omega) = \boxed{18.1 \text{ V}}$$

(c) $$\Delta V_{C,\text{ rms}} = I_{\text{rms}} X_C = (0.361 \text{ A})(66.3\ \Omega) = \boxed{23.9 \text{ V}}$$

(d) $$\phi = \tan^{-1}\left(\frac{X_L - X_C}{R}\right) = \tan^{-1}\left(\frac{0 - 66.3\ \Omega}{50.0\ \Omega}\right) = -53.0°$$

so, $\boxed{\text{the voltage lags behind the current by } 53°}$

21.20 (a) $X_L = 2\pi f L = 2\pi(50.0\text{ Hz})(400\times10^{-3}\text{ H}) = 126\ \Omega$



$$X_C = \frac{1}{2\pi f C} = \frac{1}{2\pi(50.0\text{ Hz})(4.43\times10^{-6}\text{ F})} = 719\ \Omega$$

$$Z = \sqrt{R^2 + (X_L - X_C)^2} = \sqrt{(500\ \Omega)^2 + (126\ \Omega - 719\ \Omega)^2} = 776\ \Omega$$

$$\Delta V_{\max} = I_{\max} Z = (0.250\text{ A})(776\ \Omega) = \boxed{194\text{ V}}$$

(b) $\phi = \tan^{-1}\left(\dfrac{X_L - X_C}{R}\right) = \tan^{-1}\left(\dfrac{126\ \Omega - 719\ \Omega}{500\ \Omega}\right) = -49.9°$

Thus, $\boxed{\text{the current leads the voltage by } 49.9°}$.

21.21 (a) $X_L = 2\pi f L = 2\pi(240\text{ Hz})(2.50\text{ H}) = 3.77\times10^3\ \Omega$

$$X_C = \frac{1}{2\pi f C} = \frac{1}{2\pi(240\text{ Hz})(0.250\times10^{-6}\text{ F})} = 2.65\times10^3\ \Omega$$

$$Z = \sqrt{R^2 + (X_L - X_C)^2} = \sqrt{(900\ \Omega)^2 + \left[(3.77 - 2.65)\times10^3\ \Omega\right]^2} = \boxed{1.44\text{ k}\Omega}$$

(b) $I_{\max} = \dfrac{\Delta V_{\max}}{Z} = \dfrac{140\text{ V}}{1.44\times10^3\ \Omega} = \boxed{0.097\,2\text{ A}}$

(c) $\phi = \tan^{-1}\left(\dfrac{X_L - X_C}{R}\right) = \tan^{-1}\left[\dfrac{(3.77 - 2.65)\times10^3\ \Omega}{900\ \Omega}\right] = \boxed{51.2°}$

(d) $\phi > 0$, so $\boxed{\text{the voltage leads the current}}$

21.22 $X_L = 2\pi f L = 2\pi(60.0\text{ Hz})(0.100\text{ H}) = 37.7\ \Omega$

$$X_C = \frac{1}{2\pi f C} = \frac{1}{2\pi(60.0\text{ Hz})(10.0\times10^{-6}\text{ F})} = 265\ \Omega$$

$$Z = \sqrt{R^2 + (X_L - X_C)^2} = \sqrt{(50.0\ \Omega)^2 + (37.7\ \Omega - 265\ \Omega)^2} = 233\ \Omega$$

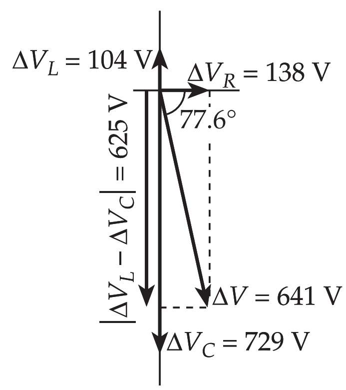
(a) $\Delta V_{R,\text{rms}} = I_{\text{rms}} R = (2.75\text{ A})(50.0\ \Omega) = \boxed{138\text{ V}}$

(b) $\Delta V_{L,\text{rms}} = I_{\text{rms}} X_L = (2.75\text{ A})(37.7\ \Omega) = \boxed{104\text{ V}}$

(c) $\Delta V_C = I_{\text{rms}} X_C = (2.75\text{ A})(265\ \Omega) = \boxed{729\text{ V}}$

(d) $\Delta V_{\text{rms}} = I_{\text{rms}} Z = (2.75\text{ A})(233\ \Omega) = \boxed{641\ \Omega}$

(e)



21.23 $X_L = 2\pi f L = 2\pi(60.0\text{ Hz})(0.400\text{ H}) = 151\ \Omega$

$$X_C = \frac{1}{2\pi f C} = \frac{1}{2\pi(60.0\text{ Hz})(3.00\times10^{-6}\text{ F})} = 884\ \Omega$$

$$Z_{RLC} = \sqrt{R^2 + (X_L - X_C)^2} = \sqrt{(60.0\ \Omega)^2 + (151\ \Omega - 884\ \Omega)^2} = 735\ \Omega$$

and $I_{\text{rms}} = \dfrac{\Delta V_{\text{rms}}}{Z_{RLC}}$

(a) $Z_{LC} = \sqrt{0 + (X_L - X_C)^2} = |X_L - X_C| = 733\ \Omega$

$$\Delta V_{LC,\text{ rms}} = I_{\text{rms}} \cdot Z_{LC} = \left(\frac{\Delta V_{\text{rms}}}{Z_{RLC}}\right) Z_{LC} = \left(\frac{90.0\text{ V}}{735\ \Omega}\right)(733\ \Omega) = \boxed{89.8\text{ V}}$$

(b) $Z_{RC} = \sqrt{R^2 + (0 - X_C)^2} = \sqrt{(60.0\ \Omega)^2 + (884\ \Omega)^2} = 886\ \Omega$

$$\Delta V_{RC,\text{ rms}} = I_{\text{rms}} \cdot Z_{RC} = \left(\frac{\Delta V_{\text{rms}}}{Z_{RLC}}\right) Z_{RC} = \left(\frac{90.0\text{ V}}{735\ \Omega}\right)(886\ \Omega) = \boxed{108\text{ V}}$$

21.24 $X_L = 2\pi f L = 2\pi(60\text{ Hz})(2.8\text{ H}) = 1.1\times10^3\ \Omega$

$$Z = \sqrt{R^2 + (X_L - X_C)^2} = \sqrt{(1.2\times10^3\ \Omega)^2 + (1.1\times10^3\ \Omega - 0)^2} = 1.6\times10^3\ \Omega$$

(a) $I_{\max} = \dfrac{\Delta V_{\max}}{Z} = \dfrac{170\text{ V}}{1.6\times10^3\ \Omega} = \boxed{0.11\text{ A}}$

(b) $\Delta V_{R,\max} = I_{\max} R = (0.11\text{ A})(1.2\times10^3\ \Omega) = \boxed{1.3\times10^2\text{ V}}$

$\Delta V_{L,\max} = I_{\max} X_L = (0.11\text{ A})(1.1\times10^3\ \Omega) = \boxed{1.2\times10^2\text{ V}}$

(c) When the instantaneous current is a maximum $(i = I_{\max})$, the instantaneous voltage across the resistor is $\Delta v_R = iR = I_{\max} R = \Delta V_{R,\max} = \boxed{1.3\times10^2\text{ V}}$. The instantaneous voltage across an inductor is always 90° or a quarter cycle out of phase with the instantaneous current. Thus, when $i = I_{\max}$, $\Delta v_L = \boxed{0}$.

Kirchhoff's loop rule always applies to the instantaneous voltages around a closed path. Thus, for this series circuit, $\Delta v_{\text{source}} = \Delta v_R + \Delta v_L$ and at this instant when $i = I_{\max}$ we have $\Delta v_{\text{source}} = I_{\max} R + 0 = \boxed{1.3\times10^2\text{ V}}$.

(d) When the instantaneous current i is zero, the instantaneous voltage across the resistor is $\Delta v_R = iR = \boxed{0}$. Again, the instantaneous voltage across an inductor is a quarter cycle out of phase with the current. Thus, when $i = 0$, we must have $\Delta v_L = \Delta V_{L,\max} = \boxed{1.2\times10^2\text{ V}}$. Then, applying Kirchhoff's loop rule to the instantaneous voltages around the series circuit at the instant when $i = 0$ gives $\Delta v_{\text{source}} = \Delta v_R + \Delta v_L = 0 + \Delta V_{L,\max} = \boxed{1.2\times10^2\text{ V}}$.

21.25

$$X_C = \frac{1}{2\pi f C} = \frac{1}{2\pi(60.0\text{ Hz})(20.0\times10^{-12}\text{ F})} = 1.33\times10^{8}\ \Omega$$

$$Z_{RC} = \sqrt{R^2 + X_C^2} = \sqrt{(50.0\times10^{3}\ \Omega)^2 + (1.33\times10^{8}\ \Omega)^2} = 1.33\times10^{8}\ \Omega$$

and $I_{\text{rms}} = \dfrac{(\Delta V_{\text{secondary}})_{\text{rms}}}{Z_{RC}} = \dfrac{5\ 000\text{ V}}{1.33\times10^{8}\ \Omega} = 3.76\times10^{-5}\text{ A}$

Therefore, $\Delta V_{b,\text{ rms}} = I_{\text{rms}}R_b = (3.76\times10^{-5}\text{ A})(50.0\times10^{3}\ \Omega) = \boxed{1.88\text{ V}}$

21.26 (a) $X_C = \dfrac{1}{2\pi f C} = \dfrac{1}{2\pi(60.0\text{ Hz})(30.0\times10^{-6}\text{ F})} = \boxed{88.4\ \Omega}$

(b) $Z = \sqrt{R^2 + (0 - X_C)^2} = \sqrt{R^2 + X_C^2} = \sqrt{(60.0\ \Omega)^2 + (88.4\ \Omega)^2} = \boxed{107\ \Omega}$

(c) $I_{\max} = \dfrac{\Delta V_{\max}}{Z} = \dfrac{1.20\times10^{2}\text{ V}}{107\ \Omega} = \boxed{1.12\text{ A}}$

(d) The phase angle in this *RC* circuit is

$$\phi = \tan^{-1}\left(\frac{X_L - X_C}{R}\right) = \tan^{-1}\left(\frac{0 - 88.4\ \Omega}{60.0\Omega}\right) = -55.8^\circ$$

Since $\phi < 0$, $\boxed{\text{the voltage lags behind the current by } 55.8^\circ}$. Adding an inductor will change the impedance and hence the current in the circuit.

21.27 (a) $X_L = 2\pi f L = 2\pi(50.0\text{ Hz})(0.250\text{ H}) = \boxed{78.5\ \Omega}$

(b) $X_C = \dfrac{1}{2\pi f C} = \dfrac{1}{2\pi(50.0\text{ Hz})(2.00\times10^{-6}\text{ F})} = 1.59\times10^{3}\ \Omega = \boxed{1.59\text{ k}\Omega}$

(c) $Z = \sqrt{R^2 + (X_L - X_C)^2} = \sqrt{(150\ \Omega)^2 + (78.5\ \Omega - 1590\ \Omega)^2} = 1.52\times10^{3}\ \Omega = \boxed{1.52\text{ k}\Omega}$

(d) $I_{\max} = \dfrac{\Delta V_{\max}}{Z} = \dfrac{2.10\times10^{2}\text{ V}}{1.52\times10^{3}\ \Omega} = 0.138\text{ A} = \boxed{138\text{ mA}}$

(e) $\phi = \tan^{-1}\left(\dfrac{X_L - X_C}{R}\right) = \tan^{-1}\left(\dfrac{78.5\ \Omega - 1590\ \Omega}{150\ \Omega}\right) = \boxed{-84.3^\circ}$

(f) $\Delta V_{R,\max} = I_{\max}R = (0.138\text{ A})(150\ \Omega) = \boxed{20.7\text{ V}}$

$\Delta V_{L,\max} = I_{\max}X_L = (0.138\text{ A})(78.5\ \Omega) = \boxed{10.8\text{ V}}$

$\Delta V_{C,\max} = I_{\max}X_C = (0.138\text{ A})(1.59\times10^{3}\ \Omega) = \boxed{219\text{ V}}$

21.28 The voltage across the resistor is a maximum when the current is a maximum, and the maximum value of the current occurs when the argument of the sine function is $\pi/2$. The voltage across the capacitor lags the current by 90° or $\pi/2$ radians, which corresponds to an argument of 0 in the sine function and a voltage of $\boxed{v_C = 0}$. Similarly, the voltage across the inductor leads the current by 90° or $\pi/2$ radians, corresponding to an argument in the sine function of π radians or 180°, giving a voltage of $\boxed{v_L = 0}$.

21.29

$$X_L = 2\pi f L = 2\pi(50.0\text{ Hz})(0.185\text{ H}) = 58.1\ \Omega$$

$$X_C = \frac{1}{2\pi f C} = \frac{1}{2\pi(50.0\text{ Hz})(65.0\times10^{-6}\text{ F})} = 49.0\ \Omega$$

$$Z_{ad} = \sqrt{R^2 + (X_L - X_C)^2} = \sqrt{(40.0\ \Omega)^2 + (58.1\ \Omega - 49.0\ \Omega)^2} = 41.0\ \Omega$$

and $$I_{\text{rms}} = \frac{\Delta V_{\text{rms}}}{Z_{ad}} = \frac{(\Delta V_{\text{max}}/\sqrt{2})}{Z_{ad}} = \frac{150\text{ V}}{(41.0\ \Omega)\sqrt{2}} = 2.59\text{ A}$$

(a) $Z_{ab} = R = 40.0\ \Omega$, so $(\Delta V_{\text{rms}})_{ab} = I_{\text{rms}} Z_{ab} = (2.59\text{ A})(40.0\ \Omega) = \boxed{104\text{ V}}$

(b) $Z_{bc} = X_L = 58.1\ \Omega$, and $(\Delta V_{\text{rms}})_{bc} = I_{\text{rms}} Z_{bc} = (2.59\text{ A})(58.1\ \Omega) = \boxed{150\text{ V}}$

(c) $Z_{cd} = X_C = 49.0\ \Omega$, and $(\Delta V_{\text{rms}})_{cd} = I_{\text{rms}} Z_{cd} = (2.59\text{ A})(49.0\ \Omega) = \boxed{127\text{ V}}$

(d) $Z_{bd} = |X_L - X_C| = 9.10\ \Omega$, so $(\Delta V_{\text{rms}})_{bd} = I_{\text{rms}} Z_{bd} = (2.59\text{ A})(9.10\ \Omega) = \boxed{23.6\text{ V}}$

21.30 $$X_C = \frac{1}{2\pi fC} = \frac{1}{2\pi(60\text{ Hz})(2.5\times10^{-6}\text{ F})} = 1.1\times10^3\ \Omega$$

$$Z = \sqrt{R^2 + (X_L - X_C)^2} = \sqrt{(1.2\times10^3\ \Omega)^2 + (0 - 1.1\times10^3\ \Omega)^2} = 1.6\times10^3\ \Omega$$

(a) $$I_{\text{max}} = \frac{\Delta V_{\text{max}}}{Z} = \frac{170\text{ V}}{1.6\times10^3\ \Omega} = \boxed{0.11\text{ A}}$$

(b) $$\Delta V_{R,\text{ max}} = I_{\text{max}} R = (0.11\text{ A})(1.2\times10^3\ \Omega) = \boxed{1.3\times10^2\text{ V}}$$

$$\Delta V_{C,\text{ max}} = I_{\text{max}} X_C = (0.11\text{ A})(1.1\times10^3\ \Omega) = \boxed{1.2\times10^2\text{ V}}$$

(c) When the instantaneous current i is zero, the instantaneous voltage across the resistor is $|\Delta v_R| = iR = \boxed{0}$. The instantaneous voltage across a capacitor is always 90° or a quarter cycle out of phase with the instantaneous current. Thus, when $i = 0$,

$$|\Delta v_C| = \Delta V_{C,\text{ max}} = \boxed{1.2\times10^2\text{ V}}$$

and $$q_C = C(\Delta v_C) = (2.5\times10^{-6}\text{ F})(1.2\times10^2\text{ V}) = 3.0\times10^{-4}\text{ C} = \boxed{300\ \mu\text{C}}$$

Kirchhoff's loop rule always applies to the instantaneous voltages around a closed path. Thus, for this series circuit, $\Delta v_{\text{source}} + \Delta v_R + \Delta v_C = 0$, and at this instant when $i = 0$, we have $|\Delta v_{\text{source}}| = 0 + |\Delta v_C| = \Delta V_{C,\text{ max}} = \boxed{1.2\times10^2\text{ V}}$.

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(d) When the instantaneous current is a maximum $(i = I_{\max})$, the instantaneous voltage across the resistor is $|\Delta v_R| = |iR| = I_{\max}R = \Delta V_{R,\max} = \boxed{1.3\times10^2 \text{ V}}$. Again, the instantaneous voltage across a capacitor is a quarter cycle out of phase with the current. Thus, when $i = I_{\max}$, we must have $|\Delta v_C| = \boxed{0}$ and $q_C = C|\Delta v_C| = \boxed{0}$. Then, applying Kirchhoff's loop rule to the instantaneous voltages around the series circuit at the instant when $i = I_{\max}$ and $|\Delta v_C| = 0$ gives

$$\Delta v_{\text{source}} + \Delta v_R + \Delta v_C = 0 \quad \Rightarrow \quad |\Delta v_{\text{source}}| = |\Delta v_R| = \Delta V_{R,\max} = \boxed{1.3\times10^2 \text{ V}}$$

21.31 (a) $Z = \dfrac{\Delta V_{\text{rms}}}{I_{\text{rms}}} = \dfrac{104 \text{ V}}{0.500 \text{ A}} = \boxed{208\ \Omega}$

(b) $\mathcal{P}_{\text{av}} = I_{\text{rms}}^2 R$ gives $R = \dfrac{\mathcal{P}_{\text{av}}}{I_{\text{rms}}^2} = \dfrac{10.0 \text{ W}}{(0.500 \text{ A})^2} = \boxed{40.0\ \Omega}$

(c) $Z = \sqrt{R^2 + X_L^2}$, so $X_L = \sqrt{Z^2 - R^2} = \sqrt{(208\ \Omega)^2 - (40.0\ \Omega)^2} = 204\ \Omega$

and $L = \dfrac{X_L}{2\pi f} = \dfrac{204\ \Omega}{2\pi(60.0 \text{ Hz})} = \boxed{0.541 \text{ H}}$

21.32 Given $v = \Delta V_{\max}\sin(\omega t) = (90.0 \text{ V})\sin(350t)$, observe that $\Delta V_{\max} = 90.0 \text{ V}$ and $\omega = 350 \text{ rad/s}$. Also, the net reactance is $X_L - X_C = 2\pi fL - 1/2\pi fC = \omega L - 1/\omega C$.

(a) $X_L - X_C = \omega L - \dfrac{1}{\omega C} = (350 \text{ rad/s})(0.200 \text{ H}) - \dfrac{1}{(350 \text{ rad/s})(25.0\times10^{-6} \text{ F})} = -44.3\ \Omega$

so the impedance is $Z = \sqrt{R^2 (X_L - X_C)^2} = \sqrt{(50.0\ \Omega)^2 + (-44.3\ \Omega)^2} = \boxed{66.8\ \Omega}$

(b) $I_{\text{rms}} = \dfrac{\Delta V_{\text{rms}}}{Z} = \dfrac{\Delta V_{\max}/\sqrt{2}}{Z} = \dfrac{90.0 \text{ V}}{\sqrt{2}(66.8\ \Omega)} = \boxed{0.953 \text{ A}}$

(c) The phase difference between the applied voltage and the current is

$$\phi = \tan^{-1}\left(\frac{X_L - X_C}{R}\right) = \tan^{-1}\left(\frac{-44.3\ \Omega}{50.0\ \Omega}\right) = -41.5^\circ$$

so the average power delivered to the circuit is

$$\mathcal{P}_{\text{av}} = I_{\text{rms}}\Delta V_{\text{rms}}\cos\phi = I_{\text{rms}}\left(\frac{\Delta V_{\max}}{\sqrt{2}}\right)\cos\phi = (0.953 \text{ A})\left(\frac{90.0 \text{ V}}{\sqrt{2}}\right)\cos(-41.5^\circ) = \boxed{45.4 \text{ W}}$$

21.33 Please see the textbook for the statement of Problem 21.21 and the answers for that problem. There, you should find that $\Delta V_{\max} = 140 \text{ V}$, $I_{\max} = 0.097\,2 \text{ A}$, and $\phi = 51.2^\circ$. The average power delivered to the circuit is then

$$\mathcal{P}_{\text{av}} = I_{\text{rms}}\Delta V_{\text{rms}}\cos\phi = \left(\frac{I_{\max}}{\sqrt{2}}\right)\left(\frac{\Delta V_{\max}}{\sqrt{2}}\right)\cos\phi = \frac{(0.097\,2 \text{ A})(140 \text{ V})}{2}\cos(51.2^\circ) = \boxed{4.26 \text{ W}}$$

21.34 The rms current in the circuit is

$$I_{\text{rms}} = \frac{\Delta V_{\text{rms}}}{Z} = \frac{160 \text{ V}}{80.0\ \Omega} = 2.00 \text{ A}$$

and the average power delivered to the circuit is

$$\mathcal{P}_{\text{av}} = I_{\text{rms}}(\Delta V_{\text{rms}}\cos\phi) = I_{\text{rms}}\Delta V_{R,\text{rms}} = I_{\text{rms}}(I_{\text{rms}}R) = I_{\text{rms}}^2 R = (2.00 \text{ A})^2(22.0\ \Omega) = \boxed{88.0 \text{ W}}$$

21.35 (a) $\mathcal{P}_{av} = I_{rms}^2 R = I_{rms}\left(I_{rms} R\right) = I_{rms}\left(\Delta V_{R,\,rms}\right)$, so $I_{rms} = \dfrac{\mathcal{P}_{av}}{\Delta V_{R,\,rms}} = \dfrac{14\ \text{W}}{50\ \text{V}} = 0.28\ \text{A}$

Thus, $R = \dfrac{\Delta V_{R,\,rms}}{I_{rms}} = \dfrac{50\ \text{V}}{0.28\ \text{A}} = \boxed{1.8\times10^2\ \Omega}$

(b) $Z = \sqrt{R^2 + X_L^2}$, which yields

$$X_L = \sqrt{Z^2 - R^2} = \sqrt{\left(\frac{\Delta V_{rms}}{I_{rms}}\right)^2 - R^2} = \sqrt{\left(\frac{90\ \text{V}}{0.28\ \text{A}}\right)^2 - \left(1.8\times10^2\ \Omega\right)^2} = 2.7\times10^2\ \Omega$$

and $L = \dfrac{X_L}{2\pi f} = \dfrac{2.7\times10^2\ \Omega}{2\pi\left(60\ \text{Hz}\right)} = \boxed{0.72\ \text{H}}$

21.36 $X_L = 2\pi fL = 2\pi\left(600\ \text{Hz}\right)\left(6.0\times10^{-3}\ \text{H}\right) = 23\ \Omega$

$$X_C = \frac{1}{2\pi fC} = \frac{1}{2\pi\left(600\ \text{Hz}\right)\left(25\times10^{-6}\ \text{F}\right)} = 11\ \Omega$$

$$Z = \sqrt{R^2 + \left(X_L - X_C\right)^2} = \sqrt{\left(25\ \Omega\right)^2 + \left(23\ \Omega - 11\ \Omega\right)^2} = 28\ \Omega$$

(a) $\Delta V_{R,\,rms} = I_{rms} R = \left(\dfrac{\Delta V_{rms}}{Z}\right) R = \left(\dfrac{10\ \text{V}}{28\ \Omega}\right)\left(25\ \Omega\right) = 8.9\ \text{V}$

$\Delta V_{L,\,rms} = I_{rms} X_L = \left(\dfrac{\Delta V_{rms}}{Z}\right) X_L = \left(\dfrac{10\ \text{V}}{28\ \Omega}\right)\left(23\ \Omega\right) = 8.2\ \text{V}$

$\Delta V_{C,\,rms} = I_{rms} X_C = \left(\dfrac{\Delta V_{rms}}{Z}\right) X_C = \left(\dfrac{10\ \text{V}}{28\ \Omega}\right)\left(11\ \Omega\right) = 3.9\ \text{V}$

$\boxed{\text{No}}$, $\Delta V_{R,\,rms} + \Delta V_{L,\,rms} + \Delta V_{C,\,rms} = 9.0\ \text{V} + 8.2\ \text{V} + 3.8\ \text{V} = 21\ \text{V} \neq 10\ \text{V}$

(b) The $\boxed{\text{power delivered to the resistor}}$ is the greatest. No power losses occur in an ideal capacitor or inductor.

(c) $\mathcal{P}_{av} = I_{rms}^2 R = \left(\dfrac{\Delta V_{rms}}{Z}\right)^2 R = \left(\dfrac{10\ \text{V}}{28\ \Omega}\right)^2 \left(25\ \Omega\right) = \boxed{3.2\ \text{W}}$

21.37 (a) The frequency of the station should match the resonance frequency of the tuning circuit. At resonance, $X_L = X_C$ or $2\pi f_0 L = 1/2\pi f_0 C$, which gives $f_0^2 = 1/4\pi^2 LC$ or

$$f_0 = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{\left(3.00\times10^{-6}\ \text{H}\right)\left(2.50\times10^{-12}\ \text{F}\right)}} = \boxed{5.81\times10^7\ \text{Hz}} = \boxed{58.1\ \text{MHz}}$$

(b) $\boxed{\text{Yes, the resistance is not needed.}}$ The resonance frequency is found by simply equating the inductive reactance to the capacitive reactance, which leads to Equation (21.19) as shown above.

21.38 (a) The resonance frequency of an *RLC* circuit is $f_0 = 1/2\pi\sqrt{LC}$. Thus, the inductance is

$$L = \frac{1}{4\pi^2 f_0^2 C} = \frac{1}{4\pi^2\left(9.00\times10^9 \text{ Hz}\right)^2\left(2.00\times10^{-12} \text{ F}\right)} = 1.56\times10^{-10} \text{ H} = \boxed{156 \text{ pH}}$$

(b) $X_L = 2\pi f_0 L = 2\pi\left(9.00\times10^9 \text{ Hz}\right)\left(1.56\times10^{-10} \text{ H}\right) = \boxed{8.82\ \Omega}$

21.39 $f_0 = \dfrac{1}{2\pi\sqrt{LC}}$, so $C = \dfrac{1}{4\pi^2 f_0^2 L}$

For $f_0 = \left(f_0\right)_{\text{min}} = 500 \text{ kHz} = 5.00\times10^5 \text{ Hz}$

$$C = C_{\text{max}} = \frac{1}{4\pi^2\left(5.00\times10^5 \text{ Hz}\right)^2\left(2.0\times10^{-6} \text{ H}\right)} = 5.1\times10^{-8} \text{ F} = \boxed{51 \text{ nF}}$$

For $f_0 = \left(f_0\right)_{\text{max}} = 1600 \text{ kHz} = 1.60\times10^6 \text{ Hz}$

$$C = C_{\text{min}} = \frac{1}{4\pi^2\left(1.60\times10^6 \text{ Hz}\right)^2\left(2.0\times10^{-6} \text{ H}\right)} = 4.9\times10^{-9} \text{ F} = \boxed{4.9 \text{ nF}}$$

21.40 (a) At resonance, $X_L = X_C$ so the impedance will be

$$Z = \sqrt{R^2 + \left(X_L - X_C\right)^2} = \sqrt{R^2 + 0} = R = \boxed{15\ \Omega}$$

(b) When $X_L = X_C$, we have $2\pi fL = \dfrac{1}{2\pi fC}$, which yields

$$f = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{\left(0.20 \text{ H}\right)\left(75\times10^{-6} \text{ F}\right)}} = \boxed{41 \text{ Hz}}$$

(c) The current is a maximum $\boxed{\text{at resonance}}$ where the impedance has its minimum value of $Z = R$.

(d) At $f = 60$ Hz, $X_L = 2\pi\left(60 \text{ Hz}\right)\left(0.20 \text{ H}\right) = 75\ \Omega$, $X_C = \dfrac{1}{2\pi\left(60 \text{ Hz}\right)\left(75\times10^{-6} \text{ F}\right)} = 35\ \Omega$,

and $Z = \sqrt{\left(15\ \Omega\right)^2 + \left(75\ \Omega - 35\ \Omega\right)^2} = 43\ \Omega$

Thus, $I_{\text{rms}} = \dfrac{\Delta V_{\text{rms}}}{Z} = \dfrac{\left(\Delta V_{\text{max}}/\sqrt{2}\right)}{Z} = \dfrac{150 \text{ V}}{\sqrt{2}\left(43\ \Omega\right)} = \boxed{2.5 \text{ A}}$

21.41 $\omega_0 = 2\pi f_0 = \dfrac{1}{\sqrt{LC}} = \dfrac{1}{\sqrt{(10.0\times 10^{-3}\text{ H})(100\times 10^{-6}\text{ F})}} = 1\,000\text{ rad/s}$

Thus, $\omega = 2\omega_0 = 2\,000\text{ rad/s}$

$$X_L = \omega L = (2\,000\text{ rad/s})(10.0\times 10^{-3}\text{ H}) = 20.0\ \Omega$$

$$X_C = \frac{1}{\omega C} = \frac{1}{(2\,000\text{ rad/s})(100\times 10^{-6}\text{ F})} = 5.00\ \Omega$$

$$Z = \sqrt{R^2 + (X_L - X_C)^2} = \sqrt{(10.0\ \Omega)^2 + (20.0\ \Omega - 5.00\ \Omega)^2} = 18.0\ \Omega$$

$$I_{\text{rms}} = \frac{\Delta V_{\text{rms}}}{Z} = \frac{50.0\text{ V}}{18.0\ \Omega} = 2.78\text{ A}$$

The average power is $\mathcal{P}_{\text{av}} = I_{\text{rms}}^2 R = (2.78\text{ A})^2(10.0\ \Omega) = 77.3\text{ W}$ and the energy converted in one period is

$$E = \mathcal{P}_{\text{av}}\cdot T = \mathcal{P}_{\text{av}}\cdot\left(\frac{2\pi}{\omega}\right) = \left(77.3\ \frac{\text{J}}{\text{s}}\right)\cdot\left(\frac{2\pi}{2\,000\text{ rad/s}}\right) = \boxed{0.243\text{ J}}$$

21.42 The resonance frequency is $\omega_0 = 2\pi f_0 = \dfrac{1}{\sqrt{LC}}$

Also, $X_L = \omega L$ and $X_C = \dfrac{1}{\omega C}$

(a) At resonance, $X_C = X_L = \omega_0 L = \left(\dfrac{1}{\sqrt{LC}}\right)L = \sqrt{\dfrac{L}{C}} = \sqrt{\dfrac{3.00\text{ H}}{3.00\times 10^{-6}\text{ F}}} = 1\,000\ \Omega$

Thus, $Z = \sqrt{R^2 + 0^2} = R$, $I_{\text{rms}} = \dfrac{\Delta V_{\text{rms}}}{Z} = \dfrac{120\text{ V}}{30.0\ \Omega} = 4.00\text{ A}$

and $\mathcal{P}_{\text{av}} = I_{\text{rms}}^2 R = (4.00\text{ A})^2(30.0\ \Omega) = \boxed{480\text{ W}}$

(b) At $\omega = \dfrac{1}{2}\omega_0$; $X_L = \dfrac{1}{2}\left(X_L\big|_{\omega_0}\right) = 500\ \Omega$, $X_C = 2\left(X_C\big|_{\omega_0}\right) = 2\,000\ \Omega$

$$Z = \sqrt{R^2 + (X_L - X_C)^2} = \sqrt{(30.0\ \Omega)^2 + (500\ \Omega - 2\,000\ \Omega)^2} = 1\,500\ \Omega$$

and $I_{\text{rms}} = \dfrac{120\text{ V}}{1\,500\ \Omega} = 0.080\,0\text{ A}$

so $\mathcal{P}_{\text{av}} = I_{\text{rms}}^2 R = (0.080\,0\text{ A})^2(30.0\ \Omega) = \boxed{0.192\text{ W}}$

(c) At $\omega = \dfrac{1}{4}\omega_0$; $X_L = \dfrac{1}{4}\left(X_L\big|_{\omega_0}\right) = 250\ \Omega$, $X_C = 4\left(X_C\big|_{\omega_0}\right) = 4\,000\ \Omega$

$Z = 3\,750\ \Omega$, and $I_{\text{rms}} = \dfrac{120\text{ V}}{3\,750\ \Omega} = 0.032\,0\text{ A}$

so $\mathcal{P}_{\text{av}} = I_{\text{rms}}^2 R = (0.032\,0\text{ A})^2(30.0\ \Omega) = 3.07\times 10^{-2}\text{ W} = \boxed{30.7\text{ mW}}$

continued on next page

(d) At $\omega = 2\omega_0$; $X_L = 2\left(X_L\big|_{\omega_0}\right) = 2\ 000\ \Omega$, $X_C = \frac{1}{2}\left(X_C\big|_{\omega_0}\right) = 500\ \Omega$

$$Z = 1\ 500\ \Omega\text{, and } I_{\text{rms}} = \frac{120\text{ V}}{1\ 500\ \Omega} = 0.080\ 0\text{ A}$$

so $\mathcal{P}_{\text{av}} = I_{\text{rms}}^2 R = (0.080\ 0\text{ A})^2(30.0\ \Omega) = \boxed{0.192\text{ W}}$

(e) At $\omega = 4\omega_0$; $X_L = 4\left(X_L\big|_{\omega_0}\right) = 4\ 000\ \Omega$, $X_C = \frac{1}{4}\left(X_C\big|_{\omega_0}\right) = 250\ \Omega$

$$Z = 3\ 750\ \Omega\text{, and } I_{\text{rms}} = \frac{120\text{ V}}{3\ 750\ \Omega} = 0.032\ 0\text{ A}$$

so $\mathcal{P}_{\text{av}} = I_{\text{rms}}^2 R = (0.032\ 0\text{ A})^2(30.0\ \Omega) = 3.07\times10^{-2}\text{ W} = \boxed{30.7\text{ mW}}$

The power delivered to the circuit is a maximum when the rms current is a maximum. This occurs when the frequency of the source is equal to the resonance frequency of the circuit.

21.43 The maximum output voltage $(\Delta V_{\text{max}})_2$ is related to the maximum input voltage $(\Delta V_{\text{max}})_1$ by the expression $(\Delta V_{\text{max}})_2 = \frac{N_2}{N_1}(\Delta V_{\text{max}})_1$, where N_1 and N_2 are the number of turns on the primary coil and the secondary coil respectively. Thus, for the given transformer,

$$(\Delta V_{\text{max}})_2 = \frac{1\ 500}{250}(170\text{ V}) = 1.02\times10^3\text{ V}$$

and the rms voltage across the secondary is $(\Delta V_{\text{rms}})_2 = \frac{(\Delta V_{\text{max}})_2}{\sqrt{2}} = \frac{1.02\times10^3\text{ V}}{\sqrt{2}} = \boxed{721\text{ V}}$.

21.44 (a) The output voltage of the transformer is

$$\Delta V_{2,\text{rms}} = \left(\frac{N_2}{N_1}\right)\Delta V_{1,\text{rms}} = \left(\frac{1}{13}\right)(120\text{ V}) = \boxed{9.23\text{ V}}$$

(b) Assuming an ideal transformer, $\mathcal{P}_{output} = \mathcal{P}_{input}$, and the power delivered to the CD player is

$$(\mathcal{P}_{\text{av}})_2 = (\mathcal{P}_{\text{av}})_1 = I_{1,\text{rms}}(\Delta V_{1,\text{rms}}) = (0.250\text{ A})(120\text{ V}) = \boxed{30.0\text{ W}}$$

21.45 The power input to the transformer is

$$(\mathcal{P}_{\text{av}})_{\text{input}} = (\Delta V_{1,\text{ rms}})I_{1,\text{ rms}} = (3\ 600\text{ V})(50\text{ A}) = 1.8\times10^5\text{ W}$$

For an ideal transformer, $(\mathcal{P}_{\text{av}})_{\text{ouput}} = (\Delta V_{2,\text{ rms}})I_{2,\text{ rms}} = (\mathcal{P}_{\text{av}})_{\text{input}}$ so the current in the long-distance power line is

$$I_{2,\text{ rms}} = \frac{(\mathcal{P}_{\text{av}})_{\text{input}}}{(\Delta V_{2,\text{ rms}})} = \frac{1.8\times10^5\text{ W}}{100\ 000\text{ V}} = 1.8\text{ A}$$

The power dissipated as heat in the line is then

$$\mathcal{P}_{\text{lost}} = I_{2,\text{ rms}}^2 R_{\text{line}} = (1.8\text{ A})^2(100\ \Omega) = 3.2\times10^2\text{ W}$$

The percentage of the power delivered by the generator that is lost in the line is

$$\%\text{ Lost} = \frac{\mathcal{P}_{\text{lost}}}{\mathcal{P}_{\text{input}}}\times100\% = \left(\frac{3.2\times10^2\text{ W}}{1.8\times10^5\text{ W}}\right)\times100\% = \boxed{0.18\%}$$

21.46 (a) Since the transformer is to step the voltage *down* from 120 volts to 6.0 volts, the secondary must have $\boxed{\text{fewer turns}}$ than the primary.

(b) For an ideal transformer, $(\mathcal{P}_{av})_{input} = (\mathcal{P}_{av})_{ouput}$ or $(\Delta V_{1,\,rms})I_{1,\,rms} = (\Delta V_{2,\,rms})I_{2,\,rms}$ so the current in the primary will be

$$I_{1,\,rms} = \frac{(\Delta V_{2,\,rms})I_{2,\,rms}}{\Delta V_{1,\,rms}} = \frac{(6.0\text{ V})(500\text{ mA})}{120\text{ V}} = \boxed{25\text{ mA}}$$

(c) The ratio of the secondary to primary voltages is the same as the ratio of the number of turns on the secondary and primary coils, $\Delta V_2/\Delta V_1 = N_2/N_1$. Thus, the number of turns needed on the secondary coil of this step down transformer is

$$N_2 = N_1\left(\frac{\Delta V_2}{\Delta V_1}\right) = (400)\left(\frac{6.0\text{ V}}{120\text{ V}}\right) = \boxed{20\text{ turns}}$$

21.47 (a) At 90% efficiency, $(\mathcal{P}_{av})_{output} = 0.90(\mathcal{P}_{av})_{input}$

Thus, if $(\mathcal{P}_{av})_{output} = 1\,000\text{ kW}$

the input power to the primary is $(\mathcal{P}_{av})_{input} = \dfrac{(\mathcal{P}_{av})_{output}}{0.90} = \dfrac{1\,000\text{ kW}}{0.90} = \boxed{1.1\times 10^3\text{ kW}}$

(b) $$I_{1,\,rms} = \frac{(\mathcal{P}_{av})_{input}}{\Delta V_{1,\,rms}} = \frac{1.1\times 10^3\text{ kW}}{\Delta V_{1,\,rms}} = \frac{1.1\times 10^6\text{ W}}{3\,600\text{ V}} = \boxed{3.1\times 10^2\text{ A}}$$

(c) $$I_{2,\,rms} = \frac{(\mathcal{P}_{av})_{output}}{\Delta V_{2,\,rms}} = \frac{1\,000\text{ kW}}{\Delta V_{1,\,rms}} = \frac{1.0\times 10^6\text{ W}}{120\text{ V}} = \boxed{8.3\times 10^3\text{ A}}$$

21.48 $R_{line} = (4.50\times 10^{-4}\ \Omega/\text{m})(6.44\times 10^5\text{ m}) = 290\ \Omega$

(a) The power transmitted is $(\mathcal{P}_{av})_{transmitted} = (\Delta V_{rms})I_{rms}$

so $I_{rms} = \dfrac{(\mathcal{P}_{av})_{transmitted}}{\Delta V_{rms}} = \dfrac{5.00\times 10^6\text{ W}}{500\times 10^3\text{ V}} = 10.0\text{ A}$

Thus, $(\mathcal{P}_{av})_{loss} = I_{rms}^2 R_{line} = (10.0\text{ A})^2(290\ \Omega) = 2.90\times 10^4\text{ W} = \boxed{29.0\text{ kW}}$

(b) The power input to the line is

$$(\mathcal{P}_{av})_{input} = (\mathcal{P}_{av})_{transmitted} + (\mathcal{P}_{av})_{loss} = 5.00\times 10^6\text{ W} + 2.90\times 10^4\text{ W} = 5.03\times 10^6\text{ W}$$

and the fraction of input power lost during transmission is

$$\textit{fraction} = \frac{(\mathcal{P}_{av})_{loss}}{(\mathcal{P}_{av})_{input}} = \frac{2.90\times 10^4\text{ W}}{5.03\times 10^6\text{ W}} = \boxed{0.005\,77\text{ or }0.577\%}$$

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(c) It is impossible to deliver the needed power with an input voltage of 4.50 kV. The maximum line current with an input voltage of 4.50 kV occurs when the line is shorted out at the customer's end, and this current is

$$\left(I_{\text{rms}}\right)_{\max} = \frac{\Delta V_{\text{rms}}}{R_{\text{line}}} = \frac{4\ 500\ \text{V}}{290\ \Omega} = 15.5\ \text{A}$$

The maximum input power is then

$$\left(\mathcal{P}_{\text{input}}\right)_{\max} = \left(\Delta V_{\text{rms}}\right)\left(I_{\text{rms}}\right)_{\max}$$

$$= \left(4.50\times 10^{3}\ \text{V}\right)\left(15.5\ \text{A}\right) = 6.98\times 10^{4}\ \text{W} = 6.98\ \text{kW}$$

This is far short of meeting the customer's request, and all of this power is lost in the transmission line.

21.49 From $v = \lambda f$, the wavelength is

$$\lambda = \frac{v}{f} = \frac{3.00\times 10^{8}\ \text{m/s}}{75\ \text{Hz}} = 4.00\times 10^{6}\ \text{m} = 4\ 000\ \text{km}$$

The required length of the antenna is then

$L = \lambda/4 = \boxed{1\ 000\ \text{km}}$, or about 621 miles. Not very practical at all.

21.50 (a) $$t = \frac{d}{c} = \frac{6.44\times 10^{18}\ \text{m}}{3.00\times 10^{8}\ \text{m/s}}\left(\frac{1\ \text{y}}{3.156\times 10^{7}\ \text{s}}\right) = \boxed{6.80\times 10^{2}\ \text{y}}$$

(b) From Table C.4 (in Appendix C of the textbook), the average Earth-Sun distance is $d = 1.496\times 10^{11}$ m, giving the transit time as

$$t = \frac{d}{c} = \frac{1.496\times 10^{11}\ \text{m}}{3.00\times 10^{8}\ \text{m/s}}\left(\frac{1\ \text{min}}{60\ \text{s}}\right) = \boxed{8.31\ \text{min}}$$

(c) Also from Table C.4, the average Earth-Moon distance is $d = 3.84\times 10^{8}$ m, giving the time for the round trip as

$$t = \frac{2d}{c} = \frac{2\left(3.84\times 10^{8}\ \text{m}\right)}{3.00\times 10^{8}\ \text{m/s}} = \boxed{2.56\ \text{s}}$$

21.51 The amplitudes of the electric and magnetic components of an electromagnetic wave are related by the expression $E_{\max}/B_{\max} = c$; thus the amplitude of the magnetic field is

$$B_{\max} = \frac{E_{\max}}{c} = \frac{330\ \text{V/m}}{3.00\times 10^{8}\ \text{m/s}} = \boxed{1.10\times 10^{-6}\ \text{T}}$$

21.52 $$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}} = \frac{1}{\sqrt{\left(4\pi\times 10^{-7}\ \text{N}\cdot\text{s}^2/\text{C}^2\right)\left(8.854\times 10^{-12}\ \text{C}^2/\text{N}\cdot\text{m}^2\right)}}$$

or $c = \boxed{2.998\times 10^{8}\ \text{m/s}}$

21.53 (a) The frequency of an electromagnetic wave is $f = c/\lambda$, where c is the speed of light and λ is the wavelength of the wave. The frequencies of the two light sources are then

$$\text{Red:}\quad f_{\text{red}} = \frac{c}{\lambda_{\text{red}}} = \frac{3.00\times10^{8}\ \text{m/s}}{660\times10^{-9}\ \text{m}} = \boxed{4.55\times10^{14}\ \text{Hz}}$$

and

$$\text{Infrared:}\quad f_{\text{IR}} = \frac{c}{\lambda_{\text{IR}}} = \frac{3.00\times10^{8}\ \text{m/s}}{940\times10^{-9}\ \text{m}} = \boxed{3.19\times10^{14}\ \text{Hz}}$$

(b) The intensity of an electromagnetic wave is proportional to the square of its amplitude. If 67% of the incident intensity of the red light is absorbed, then the intensity of the emerging wave is $(100\% - 67\%) = 33\%$ of the incident intensity, or $I_f = 0.33I_i$. Hence, we must have

$$\frac{E_{\max,\,f}}{E_{\max,\,i}} = \sqrt{\frac{I_f}{I_i}} = \sqrt{0.33} = \boxed{0.57}$$

21.54 If I_0 is the incident intensity of a light beam, and I is the intensity of the beam after passing through length L of a fluid having concentration C of absorbing molecules, the Beer-Lambert law states that $\log_{10}(I/I_0) = -\mathcal{E}CL$ where $\mathcal{E}$ is a constant.

For 660-nm light, the absorbing molecules are oxygenated hemoglobin. Thus, if 33% of this wavelength light is transmitted through blood, the concentration of oxygenated hemoglobin in the blood is

$$C_{\text{HBO2}} = \frac{-\log_{10}(0.33)}{\mathcal{E}L} \qquad \textbf{[1]}$$

The absorbing molecules for 940-nm light are deoxygenated hemoglobin, so if 76% of this light is transmitted through the blood, the concentration of these molecules in the blood is

$$C_{\text{HB}} = \frac{-\log_{10}(0.76)}{\mathcal{E}L} \qquad \textbf{[2]}$$

Dividing equation [2] by equation [1] gives the ratio of deoxygenated hemoglobin to oxygenated hemoglobin in the blood as

$$\frac{C_{\text{HB}}}{C_{\text{HBO2}}} = \frac{\log_{10}(0.76)}{\log_{10}(0.33)} = 0.25 \quad \text{or} \quad C_{\text{HB}} = 0.25C_{\text{HBO2}}$$

Since all the hemoglobin in the blood is either oxygenated or deoxygenated, it is necessary that $C_{\text{HB}} + C_{\text{HBO2}} = 1.00$, and we now have $0.25C_{\text{HBO2}} + C_{\text{HBO2}} = 1.0$. The fraction of hemoglobin that is oxygenated in this blood is then

$$C_{\text{HBO2}} = \frac{1.0}{1.0 + 0.25} = 0.80 \quad \text{or} \quad \boxed{80\%}$$

Someone with only 80% oxygenated hemoglobin in the blood is probably in serious trouble, needing supplemental oxygen immediately.

21.55 From $\mathit{Intensity} = \dfrac{E_{\max}B_{\max}}{2\mu_0}$ and $\dfrac{E_{\max}}{B_{\max}} = c$, we find $\mathit{Intensity} = \dfrac{cB_{\max}^2}{2\mu_0}$

Thus,

$$B_{\max} = \sqrt{\frac{2\mu_0}{c}(\mathit{Intensity})} = \sqrt{\frac{2\left(4\pi\times10^{-7}\ \text{T}\cdot\text{m/A}\right)}{3.00\times10^{8}\ \text{m/s}}\left(1\,340\ \text{W/m}^2\right)} = \boxed{3.35\times10^{-6}\ \text{T}}$$

and $E_{\max} = B_{\max}c = \left(3.35\times10^{-6}\ \text{T}\right)\left(3.00\times10^{8}\ \text{m/s}\right) = \boxed{1.01\times10^{3}\ \text{V/m}}$

21.56 (a) To exert an upward force on the disk, the laser beam should be aimed vertically upward, striking the lower surface of the disk. To just levitate the disk, the upward force exerted on the disk by the beam should equal the weight of the disk.

The momentum that electromagnetic radiation of intensity I, incident normally on a perfectly reflecting surface of area A, delivers to that surface in time Δt is given by Equation (21.30) as $\Delta p = 2U/c = 2(IA\Delta t)/c$. Thus, from the impulse-momentum theorem, the average force exerted on the reflecting surface is $F = \Delta p/\Delta t = 2IA/c$. Then, to just levitate the surface, $F = 2IA/c = mg$ and the required intensity of the incident radiation is $\boxed{I = mgc/2A}$.

(b) $$I = \frac{mgc}{2A} = \frac{mgc}{2\pi r^2} = \frac{(5.00\times10^{-3}\text{ kg})(9.80\text{ m/s}^2)(3.00\times10^{8}\text{ m/s})}{2\pi(4.00\times10^{-2}\text{ m})^2} = \boxed{1.46\times10^{9}\text{ W/m}^2}$$

(c) Propulsion by light pressure in a significant gravity field is impractical because of the enormous power requirements. In addition, no material is perfectly reflecting, so the absorbed energy would melt the reflecting surface.

21.57 The distance between adjacent antinodes in a standing wave is $\lambda/2$.

Thus, $\lambda = 2(6.00\text{ cm}) = 12.0\text{ cm} = 0.120\text{ m}$, and

$$c = \lambda f = (0.120\text{ m})(2.45\times10^{9}\text{ Hz}) = \boxed{2.94\times10^{8}\text{ m/s}}$$

21.58 At Earth's location, the wave fronts of the solar radiation are spheres whose radius is the Sun-Earth distance. Thus, from $Intensity = \dfrac{\mathcal{P}_{av}}{A} = \dfrac{\mathcal{P}_{av}}{4\pi r^2}$, the total power is

$$\mathcal{P}_{av} = (Intensity)(4\pi r^2) = \left(1\,340\ \frac{\text{W}}{\text{m}^2}\right)\left[4\pi(1.49\times10^{11}\text{ m})^2\right] = \boxed{3.74\times10^{26}\text{ W}}$$

21.59 From $\lambda f = c$, we find $f = \dfrac{c}{\lambda} = \dfrac{3.00\times10^{8}\text{ m/s}}{5.50\times10^{-7}\text{ m}} = \boxed{5.45\times10^{14}\text{ Hz}}$

21.60 $\lambda = \dfrac{c}{f} = \dfrac{3.00\times10^{8}\text{ m/s}}{27.33\times10^{6}\text{ Hz}} = \boxed{11.0\text{ m}}$

21.61 (a) For the AM band,

$$\lambda_{min} = \frac{c}{f_{max}} = \frac{3.00\times10^{8}\text{ m/s}}{1\,600\times10^{3}\text{ Hz}} = \boxed{188\text{ m}}$$

$$\lambda_{max} = \frac{c}{f_{min}} = \frac{3.00\times10^{8}\text{ m/s}}{540\times10^{3}\text{ Hz}} = \boxed{556\text{ m}}$$

(b) For the FM band,

$$\lambda_{min} = \frac{c}{f_{max}} = \frac{3.00\times10^{8}\text{ m/s}}{108\times10^{6}\text{ Hz}} = \boxed{2.78\text{ m}}$$

$$\lambda_{max} = \frac{c}{f_{min}} = \frac{3.00\times10^{8}\text{ m/s}}{88\times10^{6}\text{ Hz}} = \boxed{3.4\text{ m}}$$

21.62 The transit time for the radio wave is

$$t_R = \frac{d_R}{c} = \frac{100\times10^3 \text{ m}}{3.00\times10^8 \text{ m/s}} = 3.33\times10^{-4} \text{ s} = 0.333 \text{ ms}$$

and that for the sound wave is

$$t_s = \frac{d_s}{v_{\text{sound}}} = \frac{3.0 \text{ m}}{343 \text{ m/s}} = 8.7\times10^{-3} \text{ s} = 8.7 \text{ ms}$$

Thus, $\boxed{\text{the radio listeners hear the news 8.4 ms before the studio audience}}$ because radio waves travel so much faster than sound waves.

21.63 If an object of mass *m* is attached to a spring of spring constant *k*, the natural frequency of vibration of that system is $f = \sqrt{k/m}/2\pi$. Thus, the resonance frequency of the C=O double bond will be

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m_{\substack{\text{oxygen}\\\text{atom}}}}} = \frac{1}{2\pi}\sqrt{\frac{2\,800 \text{ N/m}}{2.66\times10^{-26} \text{ kg}}} = \boxed{5.2\times10^{13} \text{ Hz}}$$

and the light with this frequency has wavelength

$$\lambda = \frac{c}{f} = \frac{3.00\times10^8 \text{ m/s}}{5.2\times10^{13} \text{ Hz}} = 5.8\times10^{-6} \text{ m} = \boxed{5.8\ \mu\text{m}}$$

The infrared region of the electromagnetic spectrum ranges from $\lambda_{\text{max}} \approx 1$ mm down to $\lambda_{\text{min}} = 700 \text{ nm} = 0.7\ \mu\text{m}$. Thus, the $\boxed{\text{required wavelength falls within the infrared region}}$.

21.64 Since the space station and the ship are moving toward one another, the frequency after being Doppler shifted is $f_O = f_S(1+u/c)$, so the change in frequency is

$$\Delta f = f_O - f_S = f_S\left(\frac{u}{c}\right) = \left(6.0\times10^{14} \text{ Hz}\right)\left(\frac{1.8\times10^5 \text{ m/s}}{3.0\times10^8 \text{ m/s}}\right) = \boxed{3.6\times10^{11} \text{ Hz}}$$

and the frequency observed on the spaceship is

$$f_O = f_S + \Delta f = 6.0\times10^{14} \text{ Hz} + 3.6\times10^{11} \text{ Hz} = \boxed{6.003\,6\times10^{14} \text{ Hz}}$$

21.65 Since you and the car ahead of you are moving away from each other (getting farther apart) at a rate of $u = 120 \text{ km/h} - 80 \text{ km/h} = 40 \text{ km/h}$, the Doppler shifted frequency you will detect is $f_O = f_S(1-u/c)$, and the change in frequency is

$$\Delta f = f_O - f_S = -f_S\left(\frac{u}{c}\right) = -\left(4.3\times10^{14} \text{ Hz}\right)\left(\frac{40 \text{ km/h}}{3.0\times10^8 \text{ m/s}}\right)\left(\frac{0.278 \text{ m/s}}{1 \text{ km/h}}\right) = \boxed{-1.6\times10^7 \text{ Hz}}$$

The frequency you will detect will be

$$f_O = f_S + \Delta f = 4.3\times10^{14} \text{ Hz} - 1.6\times10^7 \text{ Hz} = \boxed{4.299\,999\,84\times10^{14} \text{ Hz}}$$

21.66 The driver was driving toward the warning lights, so the correct form of the Doppler shift equation is $f_O = f_S\left(1+u/c\right)$. The frequency emitted by the yellow warning light is

$$f_S = \frac{c}{\lambda_S} = \frac{3.00\times10^{8}\ \text{m/s}}{580\times10^{-9}\ \text{m}} = 5.17\times10^{14}\ \text{Hz}$$

and the frequency the driver claims that she observed is

$$f_O = \frac{c}{\lambda_O} = \frac{3.00\times10^{8}\ \text{m/s}}{560\times10^{-9}\ \text{m}} = 5.36\times10^{14}\ \text{Hz}$$

The speed with which she would have to approach the light for the Doppler effect to yield this claimed shift is

$$u = c\left(\frac{f_O}{f_S}-1\right) = \left(3.00\times10^{8}\ \text{m/s}\right)\left(\frac{5.36\times10^{14}\ \text{Hz}}{5.17\times10^{14}\ \text{Hz}}-1\right) = \boxed{1.1\times10^{7}\ \text{m/s}}$$

21.67 (a) At $f = 60.0$ Hz, the reactance of a $15.0\text{-}\mu\text{F}$ capacitor is

$$X_C = \frac{1}{2\pi fC} = \frac{1}{2\pi\left(60.0\ \text{Hz}\right)\left(15.0\times10^{-6}\ \text{F}\right)} = 177\ \Omega$$

and the impedance of this *RC* circuit is

$$Z = \sqrt{R^2+X_C^2} = \sqrt{\left(50.0\ \Omega\right)^2+\left(177\ \Omega\right)^2} = \boxed{184\ \Omega}$$

(b) $$I_{\text{rms}} = \frac{\Delta V_{\text{rms}}}{Z} = \frac{1.20\times10^{2}\ \text{V}}{184\ \Omega} = 0.652\ \text{A} = \boxed{652\ \text{mA}}$$

(c) After addition of an inductor in series with the resistor and capacitor, the impedance of the circuit is $Z' = \sqrt{R^2+\left(X_L-X_C\right)^2} = \sqrt{\left(50.0\ \Omega\right)^2+\left(2\pi fL-177\ \Omega\right)^2}$. To reduce the current to one-half the value found above, the impedance of the circuit must be doubled to a value of $Z' = 2\left(184\ \Omega\right) = 368\ \Omega$. Thus,

$$\left(50.0\ \Omega\right)^2+\left(2\pi fL-177\ \Omega\right)^2 = \left(368\ \Omega\right)^2$$

or $$2\pi fL = 177\ \Omega \pm \sqrt{\left(368\ \Omega\right)^2-\left(50.0\ \Omega\right)^2} = 177\ \Omega \pm 365\ \Omega$$

Since the inductance cannot be negative, the potential solution associated with the lower sign must be discarded, leaving

$$L = \frac{177\ \Omega+365\ \Omega}{2\pi\left(60.0\ \text{Hz}\right)} = \boxed{1.44\ \text{H}}$$

21.68 Suppose you cover a 1.7 m-by-0.3 m section of beach blanket. Suppose the elevation angle of the Sun is 60°. Then the target area you fill in the Sun's field of view is $(1.7\text{ m})(0.3\text{ m})\cos 30° = 0.4\text{ m}^2$.

The intensity the radiation at Earth's surface is $I_{\text{surface}} = 0.6\, I_{\text{incoming}}$ and only 50% of this is absorbed. Since $I = \dfrac{\mathcal{P}_{\text{av}}}{A} = \dfrac{(\Delta E/\Delta t)}{A}$, the absorbed energy is

$$\Delta E = (0.5\, I_{\text{surface}})A(\Delta t) = \left[0.5(0.6\, I_{\text{incoming}})\right]A(\Delta t)$$

$$= (0.5)(0.6)(1\,340\text{ W/m}^2)(0.4\text{ m}^2)(3\,600\text{ s}) = 6\times10^5\text{ J} \quad\text{or}\quad \boxed{\sim 10^6\text{ J}}$$

21.69 $$Z = \sqrt{R^2 + (X_C)^2} = \sqrt{R^2 + (2\pi f C)^{-2}}$$

$$= \sqrt{(200\ \Omega)^2 + \left[2\pi(60\text{ Hz})(5.0\times10^{-6}\text{ F})\right]^{-2}} = 5.7\times10^2\ \Omega$$

Thus, $\mathcal{P}_{\text{av}} = I_{\text{rms}}^2 R = \left(\dfrac{\Delta V_{\text{rms}}}{Z}\right)^2 R = \left(\dfrac{120\text{ V}}{5.7\times10^2\ \Omega}\right)^2 (200\ \Omega) = 8.9\text{ W} = 8.9\times10^{-3}\text{ kW}$

and $\quad cost = \Delta E\cdot(rate) = \mathcal{P}_{\text{av}}\cdot\Delta t\cdot(rate)$

$$= (8.9\times10^{-3}\text{ kW})(24\text{ h})(8.0\text{ cents/kWh}) = \boxed{1.7\text{ cents}}$$

21.70 $X_L = \omega L$, so $\omega = X_L/L$

Then, $X_C = \dfrac{1}{\omega C} = \dfrac{1}{C(X_L/L)}$, which gives

$$L = (X_L\cdot X_C)C = \left[(12\ \Omega)(8.0\ \Omega)\right]C \text{ or } L = (96\ \Omega^2)C \qquad \textbf{[1]}$$

From $\omega_0 = 2\pi f_0 = \dfrac{1}{\sqrt{LC}}$, we obtain $LC = \dfrac{1}{(2\pi f_0)^2}$

Substituting from Equation [1], this becomes $(96\ \Omega^2)C^2 = \dfrac{1}{(2\pi f_0)^2}$

or $\quad C = \dfrac{1}{(2\pi f_0)\sqrt{96\ \Omega^2}} = \dfrac{1}{\left[2\pi(2\,000/\pi\text{ Hz})\right]\sqrt{96\ \Omega^2}} = 2.6\times10^{-5}\text{ F} = \boxed{26\ \mu\text{F}}$

Then, from Equation [1],

$$L = (96\ \Omega^2)(2.6\times10^{-5}\text{ F}) = 2.5\times10^{-3}\text{ H} = \boxed{2.5\text{ mH}}$$

21.71 $$R = \frac{(\Delta V)_{\text{DC}}}{I_{\text{DC}}} = \frac{12.0\text{ V}}{0.630\text{ A}} = 19.0\ \Omega$$

$$Z = \sqrt{R^2 + (2\pi f L)^2} = \frac{\Delta V_{\text{rms}}}{I_{\text{rms}}} = \frac{24.0\text{ V}}{0.570\text{ A}} = 42.1\ \Omega$$

Thus, $L = \dfrac{\sqrt{Z^2 - R^2}}{2\pi f} = \dfrac{\sqrt{(42.1\ \Omega)^2 - (19.0\ \Omega)^2}}{2\pi(60.0\text{ Hz})} = 9.97\times10^{-2}\text{ H} = \boxed{99.7\text{ mH}}$

21.72 (a) The required frequency is $f = \dfrac{c}{\lambda} = \dfrac{3.00\times10^{8}\ \text{m/s}}{3.00\times10^{-2}\ \text{m}} = 1.0\times10^{10}\ \text{Hz}$. Therefore, the resonance frequency of the circuit is $f_0 = \dfrac{1}{2\pi\sqrt{LC}} = 1.0\times10^{10}\ \text{Hz}$, giving

$$C = \frac{1}{(2\pi f_0)^2 L} = \frac{1}{(2\pi\times10^{10}\ \text{Hz})^2(400\times10^{-12}\ \text{H})} = 6.3\times10^{-13}\ \text{F} = \boxed{0.63\ \text{pF}}$$

(b) $C = \dfrac{\epsilon_0 A}{d} = \dfrac{\epsilon_0 \ell^2}{d}$, so

$$\ell = \sqrt{\frac{C\cdot d}{\epsilon_0}} = \sqrt{\frac{(6.3\times10^{-13}\ \text{F})(1.0\times10^{-3}\ \text{m})}{8.85\times10^{-12}\ \text{C}^2/\text{N}\cdot\text{m}}} = 8.4\times10^{-3}\ \text{m} = \boxed{8.4\ \text{mm}}$$

(c) $X_C = X_L = (2\pi f_0)L = 2\pi(1.0\times10^{10}\ \text{Hz})(400\times10^{-12}\ \text{H}) = \boxed{25\ \Omega}$

21.73 (a) $\dfrac{E_{\max}}{B_{\max}} = c$, so

$$B_{\max} = \frac{E_{\max}}{c} = \frac{0.20\times10^{-6}\ \text{V/m}}{3.00\times10^{8}\ \text{m/s}} = \boxed{6.7\times10^{-16}\ \text{T}}$$

(b) $$\textit{Intensity} = \frac{E_{\max}B_{\max}}{2\mu_0} = \frac{(0.20\times10^{-6}\ \text{V/m})(6.7\times10^{-16}\ \text{T})}{2(4\pi\times10^{-7}\ \text{T}\cdot\text{m/A})} = \boxed{5.3\times10^{-17}\ \text{W/m}^2}$$

(c) $$\mathcal{P}_{\text{av}} = (\textit{Intensity})\cdot A = (\textit{Intensity})\left[\frac{\pi d^2}{4}\right]$$

$$= (5.3\times10^{-17}\ \text{W/m}^2)\left[\frac{\pi(20.0\ \text{m})^2}{4}\right] = \boxed{1.7\times10^{-14}\ \text{W}}$$

21.74 (a) $$Z = \frac{\Delta V_{\text{rms}}}{I_{\text{rms}}} = \frac{12\ \text{V}}{2.0\ \text{A}} = \boxed{6.0\ \Omega}$$

(b) $$R = \frac{\Delta V_{\text{DC}}}{I_{\text{DC}}} = \frac{12\ \text{V}}{3.0\ \text{A}} = 4.0\ \Omega$$

From $Z = \sqrt{R^2 + X_L^2} = \sqrt{R^2 + (2\pi f L)^2}$, we find

$$L = \frac{\sqrt{Z^2 - R^2}}{2\pi f} = \frac{\sqrt{(6.0\ \Omega)^2 - (4.0\ \Omega)^2}}{2\pi(60\ \text{Hz})} = 1.2\times10^{-2}\ \text{H} = \boxed{12\ \text{mH}}$$

21.75 (a) From Equation (21.30), the momentum imparted in time Δt to a perfectly reflecting sail of area A by normally incident radiation of intensity I is $\Delta p = 2U/c = 2(IA\Delta t)/c$.

From the impulse-momentum theorem, the average force exerted on the sail is then

$$F_{av} = \frac{\Delta p}{\Delta t} = \frac{2(IA\Delta t)/c}{\Delta t} = \frac{2IA}{c} = \frac{2(1\,340\ \text{W/m}^2)(6.00\times10^4\ \text{m}^2)}{3.00\times10^8\ \text{m/s}} = \boxed{0.536\ \text{N}}$$

(b) $a_{av} = \dfrac{F_{av}}{m} = \dfrac{0.536\ \text{N}}{6\,000\ \text{kg}} = \boxed{8.93\times10^{-5}\ \text{m/s}^2}$

(c) From $\Delta x = v_0 t + \frac{1}{2}at^2$, with $v_0 = 0$, the time is

$$t = \sqrt{\frac{2(\Delta x)}{a_{av}}} = \sqrt{\frac{2(3.84\times10^8\ \text{m})}{8.93\times10^{-5}\ \text{m/s}^2}} = (2.93\times10^6\ \text{s})\left(\frac{1\ \text{d}}{8.64\times10^4\ \text{s}}\right) = \boxed{33.9\ \text{d}}$$

21.76 (a) The intensity of radiation at distance r from a point source, which radiates total power $\mathcal{P}$, is $I = \mathcal{P}/A = \mathcal{P}/4\pi r^2$. Thus, at distance $r = 2.0$ in from a cell phone radiating a total power of $\mathcal{P} = 2.0\ \text{W} = 2.0\times10^3\ \text{mW}$, the intensity is

$$I = \frac{2.0\times10^3\ \text{mW}}{4\pi\left[(2.0\ \text{in})(2.54\ \text{cm/1 in})\right]^2} = \boxed{6.2\ \text{mW/cm}^2}$$

$\boxed{\text{This intensity is 24\% higher than the maximum allowed leakage from a microwave}}$

at this distance of 2.0 inches.

(b) If when using a Blue toothheadset (emitting 2.5 mW of power) in the ear at distance $r_h = 2.0\ \text{in} = 5.1\ \text{cm}$ from center of the brain, the cell phone (emitting 2.0 W of power) is located in the pocket at distance $r_p = 1.0\ \text{m} = 1.0\times10^2\ \text{cm}$ from the brain, the total radiation intensity at the brain is

$$I_{total} = I_{phone} + I_{headset} = \frac{2.0\times10^3\ \text{mW}}{4\pi(1.0\times10^2\ \text{cm})^2} + \frac{2.5\ \text{mW}}{4\pi(5.1\ \text{cm})^2} = 1.6\times10^{-2}\ \frac{\text{mW}}{\text{cm}^2} + 7.6\times10^{-3}\ \frac{\text{mW}}{\text{cm}^2}$$

or $$I_{total} = 1.6\times10^{-2}\ \frac{\text{mW}}{\text{cm}^2} + 7.6\times10^{-3}\ \frac{\text{mW}}{\text{cm}^2} = 2.4\times10^{-2}\ \frac{\text{mW}}{\text{cm}^2} = \boxed{0.024\ \text{mW/cm}^2}$$