CHAPTER TEN
Inductive and Capacitive Reactance

In Chapters Eight and Nine, you learned that the inductance of a circuit acts to oppose any change of current flow in that circuit and that capacitance acts to oppose any change of voltage. These "reactions" are not important in direct current, because they are momentary and occur only when a circuit is first closed or opened. In alternating-current circuits, these effects become very important, because the direction of current flow is reversed many times each second; and the opposition presented by inductance and capacitance is, for practical purposes, constant.

In purely resistive circuits, either a-c or d-c, the term for opposition to current flow is resistance. When the effects of capacitance or inductance are present, as they often are in a-c circuits, the opposition to current flow is called reactance. The total opposition to current flow in circuits that have both resistance and reactance is called impedance.

When you have finished this chapter, you will be able to:

- calculate inductive reactance;
- calculate capacitive reactance;
- describe the phase relationships of resistive, inductive, and capacitive circuits; and,
- calculate impedance.

Calculation of Inductive Reactance

1. You learned in Chapter Eight that inductance generates a self-induced voltage that presents an opposition to the current already flowing in a conductor. This opposition to current flow is called inductive reactance. The amount of reactance depends on the magnitude of the self-induced voltage. For reasons that need not concern you here, this self-induced voltage, E_{ind}, depends on the frequency, f, of the alternating current, the amount of current, I, and a constant, 2π (2 pi). You may know that π represents the circumference of a circle divided by the diameter. It is normally rounded off to 3.14, so $2\pi = 6.28$. Naturally the inductance, L, is also a factor. From Ohm's Law, you know that E = IR. In an inductive

circuit (one that has inductance), E_{ind} is equal to current multiplied by inductive reactance (rather than resistance), because reactance is also an opposition to current flow. Therefore, $E_{ind} = 2\pi fLI$. (The values are switched around because the number usually comes first in a term such as $2\pi fLI$.) Thus, the self-induced voltage E_{ind} is the product of 2π and what other three factors? ____________________

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2. Compare the equations for E in a resistive circuit and E_{ind} in an inductive circuit:

<u>Resistive</u>	<u>Inductive</u>
$E = IR$	$E_{ind} = 2\pi fLI$

E corresponds to E_{ind}; I corresponds to I. R must correspond to what is left in the inductive equation, or __________.

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3. The opposition to current flow in an inductive circuit is <u>inductive reactance</u>, measured in ohms. Its mathematical symbol is X_L (pronounced "X sub L"). R represents resistance, while X represents reactance, whether it is inductive or capacitive. The type of reactance is identified by the subscript, so inductive reactance is X_L, and capacitive reactance (discussed later) is X_C.

Since R corresponds to X_L, the term X_L may be used in an equation for an inductive circuit in the same way that R is used in an equation for a resistive circuit. This does <u>not</u> mean that $R = X_L$. They are merely corresponding terms.

$$R = \frac{E}{I} \qquad X_L = \frac{E_{ind}}{I}$$

Since $E_{ind} = 2\pi fLI$, the term $2\pi fLI$ may be substituted for E_{ind} in any equation.

$$X_L = \frac{E_{ind}}{I} \qquad X_L = \frac{2\pi fLI}{I}$$

The I in the numerator and the I in the denominator of the second equation cancel out, so $X_L =$ __________.

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(Remember, X_L is not equal to R; it is merely the corresponding term.)

4. What is the equation for inductive reactance? ______________________

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5. What number is the constant 2π equal to? __________

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6. Since 2π is a constant equal to 6.28, we can find X_L if we know ________ and ________________________.

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7. In the equation for inductive reactance, X_L, the frequency is always in hertz (Hz), and the inductance is in henries (h). If L is in microhenries or millihenries, the value must be changed to henries in the equation. To convert millihenries to henries, multiply by __________.

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8. The frequency of a circuit is 60 Hz and the inductance is 20 mh. What is X_L? ______________

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Note: If your answer was 1.2, you forgot to multiply by 2π.)

9. L = 10 h and f = 100 Hz.

X_L = __________

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10. L = 4 mh and f = 200 Hz.

X_L = __________

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11. $L = 500\ \mu h$ and $f = 1500$ Hz.

$X_L =$ ________

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(Note: If your decimal was in the wrong place, remember that you have to multiply μh by 0.000001 to get h.)

12. Other values may be found by applying Ohm's Law in the same way you do for resistive circuits. The alternating-current source voltage is 100 v. and the total inductive reactance in a purely inductive circuit is 50Ω. The total current is ________.

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$$\left(I = \frac{E_{ind}}{X_L}\right)$$

13. $X_L = 40\,\Omega$ and $I = 3$ a.

E = ________

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$(E_{ind} = IX_L)$

14. From now on, we will eliminate the subscript "ind" that identifies a voltage as resulting from the inductance in the circuit. Its purpose so far has been to remind you that self-induced voltage as well as source voltage must be taken into account in any circuit that includes inductance. As you will see later, a circuit is likely to include resistance, inductance, and capacitance. Therefore, we will be dealing with both resistance and reactance in the same circuit. The Ohm's Law equation for voltage in a resistive circuit is an old friend: $E = IR$. Its equivalent in an inductive circuit is $E = IX_L$. But you can't use Ohm's Law in an inductive circuit unless you know how to find X_L. What is the equation for X_L? ________

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As we mentioned earlier, reactance may be either inductive (X_L) or capacitive (X_C). We have seen that inductive reactance presents an opposition to current flow in any circuit that includes inductance. If a circuit has capacitance, there is also an opposition to current flow. It is called capacitive reactance, which we will study next.

If you plan to stop pretty soon, this is a good place for a break.

Calculation of Capacitive Reactance

15. Capacitance, like inductance, presents a reactance, or opposition, to current flow. The basic symbol of reactance is X, and the subscript defines the type of reactance. In the symbol for inductive reactance, X_L, the subscript L refers to inductance. Following the same pattern, the symbol for capacitive reactance is __________.

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16. The factors affecting capacitive reactance, X_C, are:

    the same constant, 2π,

    frequency, f, in Hz, and

    capacitance, C, in farads.

However, X_C is a little harder to calculate than X_L, because a reciprocal is involved:

$$X_C = \frac{1}{2\pi fC}$$

What is the capacitive reactance of a circuit operating at a frequency of 60 Hz, if the total capacitance is 133 μf? __________

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(Note: If your answer was 0.050, you forgot to take the reciprocal. If the decimal was in the wrong place, remember that 133 must be multiplied by 0.000001.)

17. C = 50 μf and f = 100 Hz

X_C = __________

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18. The alternating-current source voltage is 120 v. and the total capacitive reactance in a purely capacitive circuit is 40Ω. The total current is __________. (Hint: Apply Ohm's Law, but use capacitive reactance instead of resistance.)

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$\left(I = \frac{E}{X_C}\right)$

19. $X_C = 80\Omega$ and I = 2 a.

E = __________

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(E = IX_C)

20. Of course, there is no such thing as a purely capacitive circuit in the "real" world, because circuits that include capacitors normally include resistors as well. (Even if they didn't, the conductors have resistance, which we usually ignore to simplify the problems in this book.) In fact, many circuits include resistance, inductance, and capacitance. In the next section, we will learn how to calculate the total impedance (that is, the total opposition to current flow) in a circuit that includes resistance, inductive reactance, and capacitive reactance. First, however, let's solve one more problem that involves both the calculation of total capacitance and application of the equation for capacitive reactance.

A circuit operating at a frequency of 100 Hz includes a parallel combination of a 10-microfarad and a 50-microfarad capacitor, and this parallel combination is connected in series with a 30-microfarad capacitor. What is the capacitive reactance of the circuit? (Give your answer to two decimal places.) ____________________

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X_C = Solution: First find the total capacitance, which is 20 μf. (Refer to Chapter Nine if you need to review this.) Then apply the equation for capacitive reactance.

$$X_C = \frac{1}{2\pi fC} = \frac{1}{6.28 \times 100 \times 20 \times 0.000001} = \frac{1}{0.01256} =$$

Phase Relationships of Resistive, Inductive, and Capacitive Circuits

21. In a purely resistive circuit, current rises and falls with voltage; it neither leads nor lags. Therefore, current and voltage are said to be in phase. Current and voltage are not in phase in inductive and capacitive circuits, because occurrences are not quite instantaneous in circuits that have either inductive or capacitive components. So it is time to introduce Eli the Iceman, who will help you to remember the phase relationships.

In the case of an inductor, voltage is first applied to the circuit, then the magnetic field begins to expand, and self-induction causes a "bucking" current to flow in the circuit, opposing the original circuit current. Voltage leads current (ELI) by 90 degrees. (ELI means that voltage, E, comes before current, I, in an inductive, L, circuit.)

When a circuit includes a capacitor, a charge current begins to flow and then a difference in potential appears between the plates of the capacitor. (For simplicity, we say that a voltage appears across the capacitor.) Current leads voltage (ICE) by 90 degrees. The phrase ELI the

ICE man will remind you that in an inductive circuit, voltage leads current by 90 degrees; and in a capacitive circuit, current leads voltage by 90 degrees.

In an inductive circuit, current (leads/lags) ______________ voltage by 90 degrees; in a capacitive circuit, current (leads/lags) ____________ voltage by 90 degrees.

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22. In an inductive circuit, voltage leads current by ________ degrees. In a capacitive circuit, current leads voltage by ________ degrees.

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23. What is the phase relationship between voltage and current in an inductive circuit? ____

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24. What is the phase relationship between current and voltage in a capacitive circuit? ____

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25. What is the phase relationship between current and voltage in a resistive circuit? ____

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26. Disregard the resistance of the coil and connecting wires in View A of Figure 10-1 on the following page. View B shows sine waves for the source voltage E, the current I, and the voltage induced by the coil, E_{ind}. Therefore, you know that the source voltage is a-c. A small sine wave is part of the symbol for an a-c voltage source. Draw the symbol. ____

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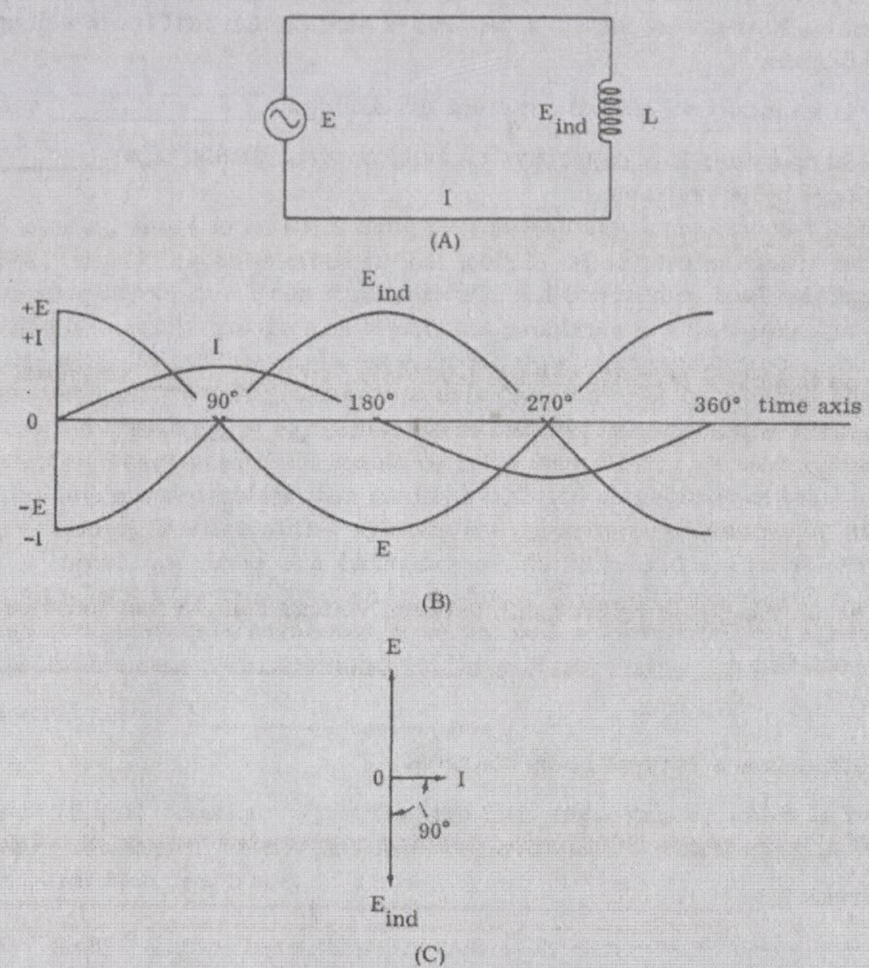

Figure 10-1. Sine waves of voltage, current, and induced voltage in an inductive circuit.

Refer to Figure 10-1 for Frames 26 through 35.

27. When an a-c voltage is applied across the circuit, which in this case includes only a coil, current flows through the coil and a magnetic field begins to expand, inducing a voltage in the coil. Remember from your study of the alternator (another name for an alternating-current generator) that the alternator itself has one or more coils (inductors). The armature cuts the greatest number of lines of force at zero degrees of rotation. Examine the labeled waveforms in View B. The waveforms show that at zero degrees, circuit voltage is maximum (positive/negative) ________________, while circuit current is ________________.

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28. Circuit current reaches its maximum positive value 90 degrees later. At this point, the armature is cutting zero lines of force, and applied voltage (E) is (maximum/zero) ________________.

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29. Remember that the armature rotates counterclockwise, so the vectors representing voltage and current also rotate counterclockwise. View C shows the vectors for applied voltage (E), current (I), and the voltage induced in the coil (E_{ind}). Since voltage leads current in an inductive circuit, the applied voltage in View B reaches its maximum positive value 90 degrees (before/after) ________________ the current.

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30. The vectors in View C show that E (leads/lags) ____________ I by ______ degrees.

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31. The waveforms in View B show that the applied voltage (E) is at maximum positive while the voltage induced in the coil (E_{ind}) is at maximum negative. The vectors for E and E_{ind} in View C show that E leads E_{ind} by how many degrees? __________

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32. When E and E_{ind} are both at maximum (but of opposite polarity) I is at ________________.

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33. The resultant of two vectors that are 180 degrees out of phase is always zero. E and E_{ind} cancel out when both are maximum. Why? __________

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34. What is the phase relationship between the current through the coil and the voltage induced in the coil? ____________________

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35. When we say that voltage leads current by 90 degrees in an inductive circuit, we are referring to (induced/applied) ______________ voltage.

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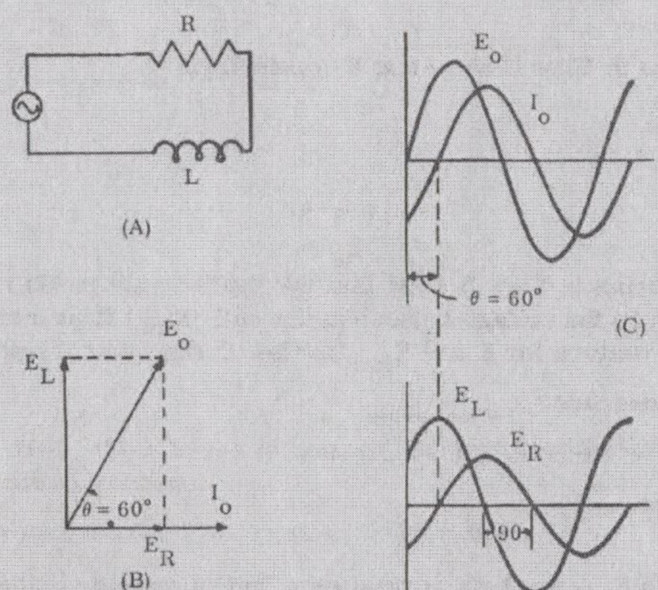

Figure 10-2. Resistance and inductance in series.

Refer to Figure 10-2 for Frames 36 through 39.

36. Because any practical inductor must be wound with wire that has resistance, it is not possible to obtain a coil without some resistance. For the purpose of calculation, this resistance may be considered as a separate resistor, R, in series with an inductor, L, as shown in View A of Figure 10-2. The resistance has been exaggerated in this example to clarify the explanation. In reality it would be comparatively small. The subscript "o", as used in Figure 10-2, means "output." It refers to the output of

the alternator. The alternating current, I_o, flows through both the resistor and the inductor, since they are in series. The voltage dropped across the resistor, E_R, is in phase with the current, but the voltage across the inductor, E_L, leads the current by 90 degrees. The vectors in View B show the relationships of the various phases, which are also represented by the waveforms in View C. What is the phase relationship between E_L and E_R? ____________________

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37. What is the phase relationship between E_R and I_o? ____________________

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38. Angle θ represents the phase relationship between E_o and I_o. E_o leads I_o by how many degrees? ____________

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39. The vectors E_L and E_R are two sides of a right triangle (a triangle that has a 90-degree angle) if the vector E_L is displaced to the position shown by the vertical dashed line in View B. The length of the hypotenuse (in this case, E_o) of a right triangle may be found if the lengths of the other two sides (here, E_L and E_R) are known. While the vectors represent various quantities as problems are solved, it is convenient to label the sides of the right triangle R and X and the hypotenuse Z. (This is easier than learning a different equation for each set of vectors.) In View B, let $R = E_R$, $X = E_L$, and $Z = E_o$. To keep track of the values, write in these labels on the triangle in View B. E_o is the resultant of the voltage drops across R and L. In a resistive circuit, these voltages are merely added; but when the voltages are out of phase, the total (or resultant) must be solved in some other way. One way is the use of the Pythagorean Theorem, which is mathematically stated as

$$Z = \sqrt{R^2 + X^2}$$

Let us assume that the voltage across the resistor, E_R, is 50 volts, and the voltage across the inductor, E_L, is 86.6 volts. We want to solve for the resultant voltage, E_o. The Pythagorean solution is

$$Z = \sqrt{50^2 + 86.6^2} = \sqrt{2500 + 7500} = \sqrt{10,000} = 100.$$

You can see immediately that 86.6^2 is not exactly 7500. It is actually 7499.56, but it is rounded off to 7500, which is close enough. If the specter of finding square roots by longhand (which you probably learned years ago and promptly forgot) bothers you, you should get a slide rule, a table of square roots, or an electronic calculator with a square root function. Anyone seriously interested in solving alternating-current problems should have one of these aids available, to simplify the extraction of square roots. Since you might not have such an aid available now, the problems in this book will involve numbers whose square roots are easy to extract by inspection.

Assign the following values to the vectors in Figure 10-2, View B:

E_L = 44.72 v.; E_R = 40.0 v. E_o = ________

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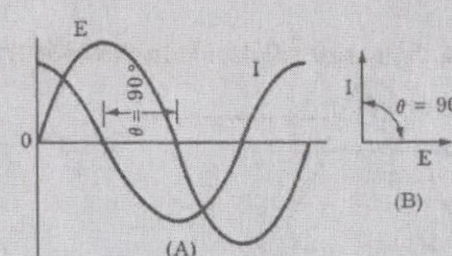

Figure 10-3. Phase relationship between E and I in a capacitive circuit.

Refer to Figure 10-3 for Frames 40 through 43.

40. Figure 10-3 shows the waveforms (View A) and the vectors (View B) for voltage and current in a purely capacitive circuit. It is not at first obvious which leads, current or voltage (although you need to know to follow the discussion). You must pick a point where neither current nor voltage is at a specified level, such as maximum positive, zero, or maximum negative. Then you can see which waveform reaches that point first. For example, choose a point along the time line in View A (which starts at zero and is measured in degrees of rotation of an armature) where neither current nor voltage is at zero amplitude. The waveform that, starting from that point, reaches zero amplitude first is the leading waveform. In View A, which leads, E or I, and by how many degrees?

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41. View B of Figure 10-3 shows the vectors that represent the waveforms shown in View A. Later in this book it will be necessary to know in which direction the vectors rotate. Since you know that current leads voltage by 90 degrees in a capacitive circuit (which we have just reaffirmed), you also know that the vectors in View B rotate (clockwise/counterclockwise) ____________________.

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42. Current leads the voltage across a capacitor by 90 degrees. The connecting wires in a "purely" capacitive circuit have resistance, and current through a resistor is in phase with the voltage dropped across it. If the voltage drop across the resistance was shown in View B, its vector would be superimposed on which vector? ________

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43. Voltage across a resistor (leads/lags) ____________ voltage across a capacitor by 90 degrees.

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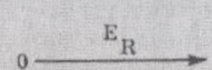
44. In a circuit that includes a capacitor and a resistor, vectors can be drawn to show the phase relationship between E_C, the voltage across the capacitor, and E_R, the voltage across the resistor. The vector for E_R is shown here. Draw in the vector for E_C.



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45. Why was the E_C vector drawn pointing down? ____________________

Why are the vectors at right angles? ____________________

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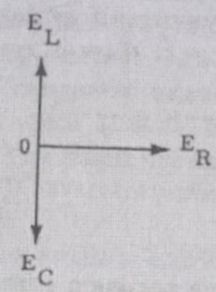
because E_C lags E_R; because the voltages are 90 degrees out of phase (or equivalent)

46. A circuit often includes resistance, inductance, and capacitance. E_L leads E_R, and E_C lags E_R, so all three vectors would look like this:



E_L and E_C are how many degrees out of phase? ___________

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47. When vectors are added, the new vector representing this vectorial sum is called the <u>resultant</u>. If E_L and E_C are equal, they cancel out, because they are 180 degrees out of phase. If E_o, the resultant, or vectorial sum, of all voltages were added to the vectors in Frame 46, its vector would be superimposed on the vector for ________.

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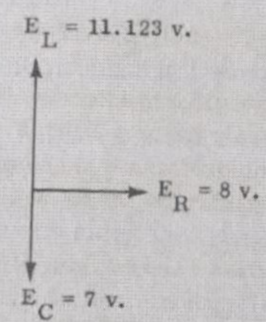
48. E_L and E_C are always 180 degrees out of phase, but they are likely to be unequal, as in this drawing.



In this case, E_C cancels out part, but not all, of E_L. The resultant of E_L and E_C is __________ v.

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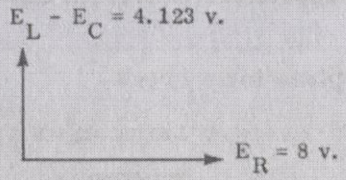
49. E_C cancels out all but 4.123 v. of E_L, so the resultant voltages could be shown as:



Use the Pythagorean Theorem, $Z = \sqrt{R^2 + X^2}$, to find the resultant voltage, E_o. ________

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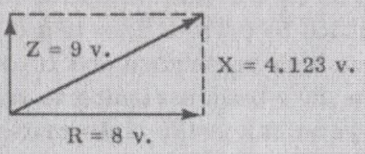

(Note: You can make an approximate check of your answer in such problems if you remember that the value of Z, the hypotenuse of the right triangle, must always be greater than either of the other two sides, but less than their sum.)

50. $E_C = 16.32$ v., $E_L = 10$ v., and $E_R = 3$ v.

$E_o =$ ________

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Earlier in this chapter, we called a circuit inductive if it included only inductance, and capacitive if it included only capacitance. These are theoretical concepts, because any circuit also includes resistance. In the real world, a circuit often includes all three parameters: resistance, inductance, and capacitance. As we have seen, the effects of inductance and capacitance might not be equal. Since the two are always 180 degrees apart, one effect will cancel out part of the effect of the other. Thus, a circuit is:

- capacitive if the effect of capacitance outweighs the effect of inductance;
- inductive if the effect of inductance outweighs the effect of capacitance; and
- resistive if the effects of inductance and capacitance are equal, and therefore cancel out, leaving the effect of resistance only.

Since the phase relationships between voltage and current are always 90 degrees in capacitive or inductive circuits, their vectors form two sides of a right triangle, and the resultant forms the hypotenuse. The side of the right triangle representing resistance is labeled R, that representing reactance (whether inductive or capacitive) is labeled X, and the hypotenuse is labeled Z. Z is the mathematical symbol for impedance, or the total opposition to current flow in a circuit. We will study impedance next.

This is a good place for a break.

Impedance

51. We are more concerned with the <u>reactance</u> of capacitors and inductors than with the voltage drops across them. Since R represents resistance and X (either X_C or X_L) represents reactance, you can see why it is convenient to think of the vectors R, X, and Z. The resultant of X_L, X_C, and R can be found using the same equation as for E_L, E_C, and E_R. The term for <u>all</u> opposition to current flow in a circuit, resistive and reactive, is <u>impedance</u>, since both resistance and reactance impede current flow. From the terms we have been assigning to values in the Pythagorean equation, what do you think is the mathematical symbol for impedance?

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52. $Z = \sqrt{R^2 + X^2}$. If all the reactance in the circuit is inductive,

$Z = \sqrt{R^2 + ?}$ ________

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53. If all the impedance in a circuit is capacitive, the equation for impedance is ____________________.

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54. The phase relationship between X_L and X_C is the same as that between E_L and E_C. Therefore, X_L (leads/lags) ______________ X_C by ________ degrees.

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55. If X represents the resultant (vectorial sum) of X_L and X_C, and X_L is greater than X_C, then $X = X_L - X_C$. Why? ____________________

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56. The net reactance of a circuit that includes both inductive and capacitive reactance is $X_L - X_C$. If X_C is larger than X_L, the net reactance is negative, but this makes no difference in the impedance equation, because the net reactance must be squared. X^2 is positive and $(-X)^2$ is also positive. The value $(X_L - X_C)^2$ is always (positive/negative) ____________.

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57. When the impedance of a circuit includes R, X_L, and X_C, both resistance and net reactance must be taken into account. Write the equation for impedance, and include both X_L and X_C in the equation. ____________

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58. $X_L = 400\Omega$, $X_C = 400\Omega$, and $R = 600\Omega$.

$Z =$ ____________

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59. $X_L = 16\Omega$, $X_C = 10\Omega$, and $R = 8\Omega$.

$Z =$ ____________

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60. $X_L = 30\Omega$, $X_C = 45\Omega$, and $R = 20\Omega$.

$Z =$ ____________

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61. To review, the equation for X_L is ________________________ and the equation for X_C is ________________________.

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X

In this chapter you have learned that voltage and current are in phase in a purely resistive circuit. In an inductive circuit, however, voltage leads current by 90 degrees, while in a capacitive circuit, current leads voltage by 90 degrees. You have seen these relationships in the form of sine waves as well as vectors.

You have seen that the opposition to current flow in alternating-current circuits might be either of two kinds: resistance and reactance. Reactance, in turn, is either inductive (X_L) or capacitive (X_C), depending on whether the opposition to current flow is caused by inductance or capacitance.

The equation for inductive reactance includes frequency and a constant, 2π, as well as inductance. The equation for capacitive reactance includes these same terms in addition to capacitance.

You have learned to solve for impedance (Z) by the use of an equation, $Z = \sqrt{R^2 + X^2}$, which takes into account the phase relationships between current and voltage in capacitive and inductive circuits. When the opposition to current flow includes both X_L and X_C (which are 180 degrees out of phase) in addition to resistance, you must subtract the smaller from the larger value of reactance to arrive at X in the equation.

When you feel you understand the material covered in this chapter, turn to the Self-Test.

Self-Test

The following questions will test your understanding of Chapter Ten. Write your answers on a separate sheet of paper and check them with the answers provided following the test.

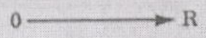
1. What are the factors affecting inductive reactance (in addition to the constant, 2π)?
2. What are the factors affecting capacitive reactance (in addition to the constant, 2π)?
3. A circuit whose frequency is 400 Hz has an inductance of 30 mh. X_L = ?
4. A circuit whose frequency is 100 Hz has a capacitance of 120 μf. X_C = ?
5. What is the phase relationship between voltage and current in a resistive circuit?

6. What is the phase relationship between voltage and current in an inductive circuit?

7. What is the phase relationship between voltage and current in a capacitive circuit?

8. What is the mathematical statement of the Pythagorean Theorem?

9. A circuit includes R, X_L, and X_C. The vector for R is shown below. Disregarding magnitude, complete the diagram by drawing the vectors for X_L and X_C.



10. What is the term for all opposition to current flow? ______________
It includes both ____________________ and net ____________________.

11. Write the equation for Z, including the terms R, X_L, and X_C.

12. $X_L = 27\Omega$, $X_C = 17\Omega$, and $R = 24\Omega$. $Z = ?$

13. $X_L = 12\Omega$, $X_C = 28\Omega$, and $R = 12\Omega$. $Z = ?$

14. What is the impedance of the circuit below?