Lesson Y2SG03
Inductance

Objectives

Some inductance is present in all electrical circuits. The inductance of most power system circuit wiring is small and generally only important in calculating available fault current. However, voltage and current relationships in AC circuits are affected by inductive loads such as discharge lamp ballasts, transformers, and motors, and often must be considered in making circuit calculations. When you have completed this lesson you should be able to accomplish the following:

- Explain what inductive reactance is
- Explain how inductance affects electrical circuits and equipment
- Calculate inductance
- Calculate inductive reactance
- Calculate the equivalent inductance of series connected inductors
- Calculate the equivalent inductance of parallel inductors
- Calculate the quality (Q) of a coil
- Calculate voltage in R-L series circuits
- Calculate current in R-L series circuits
- Calculate apparent power in R-L series circuits
- Calculate reactive power in R-L series circuits
- Calculate resistance in R-L series circuits
- Calculate inductive reactance in R-L series circuits
- Calculate true power in R-L series circuits
- Calculate impedance in R-L series circuits
- Calculate power factor in R-L series circuits
- Calculate the phase angle of current and voltage in R-L series circuits
- Calculate voltage in R-L parallel circuits
- Calculate current in R-L parallel circuits
- Calculate apparent power in R-L parallel circuits
- Calculate reactive power in R-L parallel circuits
- Calculate resistance in R-L parallel circuits
- Calculate inductive reactance in R-L parallel circuits
- Calculate true power in R-L parallel circuits
- Calculate impedance in R-L parallel circuits
- Calculate power factor in R-L parallel circuits
- Calculate the phase angle of current and voltage in R-L parallel circuits

The outline of this lesson is not intended to replace a thorough review of the reading materials and any referenced Code sections. The outline is designed to be supplemental material highlighting certain parts of the indicated reading materials and NEC® Article. Students must carefully review any of the reading materials and any referenced Code sections in the 2005 NEC® in addition to the lesson outline. Review questions, exercises and quiz questions will reference the outline, reading materials and the actual 2005 NEC® section(s).

Study either of the following reading material:

– Herman, Delmar's Standard Textbook of Electricity 3rd Edition, Units 16, 17, 18
– Herman, Delmar's Standard Textbook of Electricity 2nd Edition, pp. 434-511

Study Suggestions

The introduction to this course contains important study suggestions. If you are not familiar with that material, please study it before continuing with this lesson.

Delmar Learning can provide a e.resource disk for Delmar's Standard TextBook of Electricity. The e.resource includes: PowerPoint Presentations, Computerized Test Bank, Image Library, Video Clips, Solution to Lab-Volt Lab Manual and Instructor's Guide. Delmar Learning also can provide the Training with Mastery Advntage CD, AC Theory and DC Theory. The Inductance in AC Circuits Section of the AC Theory CD is recommend for this lesson.

Lesson Y2SG03 Outline

Find answers to the review questions in this outline as they are presented. Check your answers against those in the *Solutions to Review Questions* in the back of this lesson. If you find that you do not understand a particular topic, review it, and if necessary, ask your leader for help.

Inductance

Herman, Delmar's Standard Textbook of Electricity 3rd Edition, pp. 460-463 or 2nd Edition, pp. 434-437

Inductance (L): The property of an electrical circuit that tends to oppose any change in current.

A primary type of load: Circuits that have coils in them will have inductance. These types of circuits could contain motors, transformers or lighting ballasts.

Basic facts:
- When a magnetic line of flux cuts through a coil, a voltage is induced in the coil
- The induced voltage is opposite in polarity to the applied voltage. This is called counter–electromotive force (CEMF)
- The amount of induced voltage is proportional to the rate of change of current
- An inductor opposes a change in current

Induced voltage:
- Is 180 degrees out of phase with the applied voltage (See *Figure 3-1*)
- Since the induced voltage is always in opposition to the applied voltage, the effective applied voltage is reduced by the induced voltage

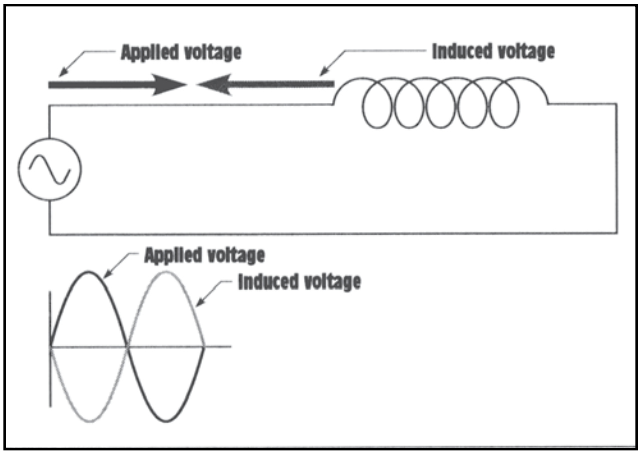


Fig. 3-1. The applied and induced voltages are 180 degrees out of phase with each other. Courtesy of Delmar Learning. Delmar's Standard Textbook of Electricity 3rd Ed pg 462

Computing the induced voltage:

The amount of induced voltage in an inductor can be computed if you know:

1. The voltage applied to the coil
2. The resistances of the wire in the coil
3. The amount of current flowing through the coil

Simply use Ohm's law to compute the voltage needed to overcome the resistance of the wire.

E (voltage needed to overcome resistance of wire) **= I** (current flowing through the inductor) × **R** (resistance of the wire)

Now, to determine the CEMF, use the Pythagorean Theorem to subtract the voltage needed to overcome the resistance of the wire from the voltage applied to the coil.

Inductive Reactance

Herman, Delmar's Standard Textbook of Electricity 3rd Edition, pp. 463-467 or 2nd Edition, pp. 437-441

Definition of Inductive Reactance (X_L): The current limiting property of an inductor in an AC circuit.

- It is measured in ohms
- Symbolized by: X_L
- Formula: $X_L = 2\pi fL$
  - X_L = Inductive reactance
  - $\pi = 3.1416$
  - $2\pi = 6.2832$ = the number of radians in a circle. (The radian is another unit for measuring angles. One radian equals approximately 57.3 degrees: the length of the arc of one radian is the radius of the circle).
  - **f** = Frequency in hertz (Hz)
  - **L** = Inductance in henrys (H)

Inductive reactance is proportional to:

- Number of turns of wire – more wire, more inductance
- Strength of the magnetic field – the stronger the field, the more inductance
- Relative motion of the inductor and the magnetic lines of flux – the faster the motion, the more inductance

Examples

- Calculate current in a circuit with a coil
- Calculate inductance in a circuit
- Explain how current is changed by increasing frequency

Schematic Symbols

Herman, Delmar's Standard Textbook of Electricity 3rd Edition, pp. 467-468 or 2nd Edition, pp.441-442

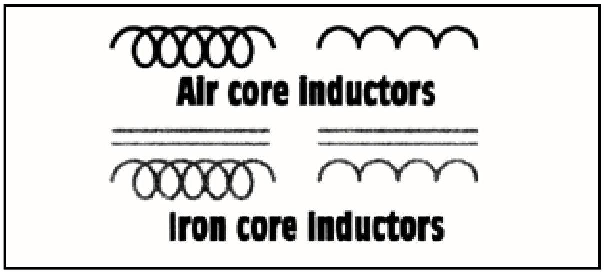


Fig. 3-2. Schematic symbols for inductors. Courtesy of Delmar Learning. Delmar's Standard Textbook of Electricity 3rd Ed pg 468

Inductors Connected in Series

Herman, Delmar's Standard Textbook of Electricity 3rd Edition, pp. 468-469 or 2nd Edition, pp. 442-443

Total inductance equals the sum of the inductances of all the inductors

$$L_T = L_1 + L_2 + L_3$$

Total inductive reactance of inductors equals the sum of the inductances

$$X_{LT} = X_{L1} + X_{L2} + X_{L3}$$

Examples

- Total inductance of three inductors in series
- Calculate total inductive reactance of a circuit

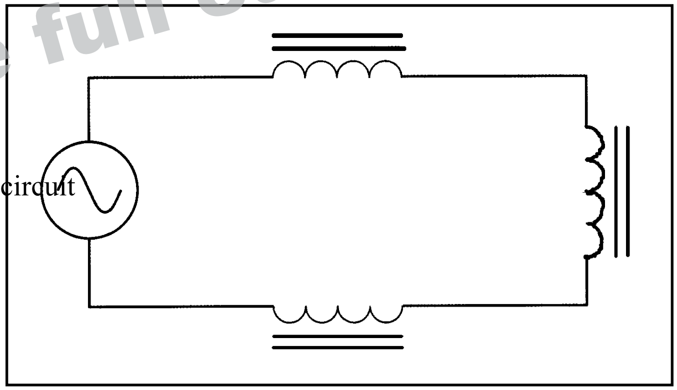


Fig. 3-3. Inductors connected in series. Courtesy of Delmar Learning. Delmar's Standard Textbook of Electricity 3rd Ed pg 468.

Inductors Connected in Parallel

Herman, Delmar's Standard Textbook of Electricity 3rd Edition, pp. 469-471 or 2nd Edition, pp. 443-444

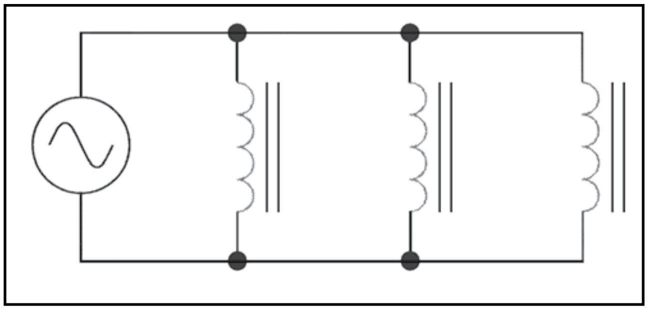


Fig. 3-4. Inductors connected in parallel. Courtesy of Delmar Learning. Delmar's Standard Textbook of Electricity 3rd Ed pg 470

$$\frac{1}{L_T} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} \qquad L_T = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3}}$$

Product over sum formulas:

$$L_T = \frac{L_1 \times L_2}{L_1 + L_2} \qquad L_T = \frac{L}{n}$$ (inductances of same values only)

Total inductive reactance formulas - inductors connected in parallel:

$$\frac{1}{X_{LT}} = \frac{1}{X_{L1}} + \frac{1}{X_{L2}} + \frac{1}{X_{L3}} \qquad X_{LT} = \frac{1}{\frac{1}{X_{L1}} + \frac{1}{X_{L2}} + \frac{1}{X_{L3}}}$$

$$X_{LT} = \frac{X_{L1} \times X_{L2}}{X_{L1} + X_{L2}} \qquad X_{LT} = \frac{X_L}{n}$$ (Where all X_L **are equal**)

Example

- Calculate the total inductance of three inductors connected in parallel.

Voltage and Current Relationships in an Inductive Circuit

Herman, Delmar's Standard Textbook of Electricity 3rd Edition, pp. 471-472 or 2nd Edition, pp. 445-446

In a purely inductive circuit the current lags the voltage by 90 degrees.

Power in an Inductive Circuit

Herman, Delmar's Standard Textbook of Electricity 3rd Edition, pp. 472-474 or 2nd Edition, pp. 446-447
In a purely resistive circuit, the power is a product of the voltage and the current and will always have a positive value. In a purely inductive circuit, the power is still a product of the voltage and current, however, twice each cycle there will be positive and negative value for power. When the power is positive it is being used by the circuit. When it is negative it is being given back to the systems.

Reactive Power

Herman, Delmar's Standard Textbook of Electricity 3rd Edition, pg. 474 or 2nd Edition, pp. 447-448

Reactive power is that portion of the Apparent Power that is caused by inductors and capacitors. No work is performed by Reactive Power. The power is stored in the capacitor or inductor and then returned to the circuit.

Volt-amps-reactive (VAR)

$$\mathbf{VAR} = \frac{E_L}{X_L} \times E_L \qquad \mathbf{VAR} = E_L \times I_L \qquad \mathbf{VAR} = I_L^2 \times X_L$$

Q of an Inductor

Herman, Delmar's Standard Textbook of Electricity 3rd Edition, pp. 474-477 or 2nd Edition, pp. 448-449

The Q of an inductor describes the amount of resistance compared with inductive reactance of the coil or circuit.

- Q = quality
- Higher ratio of inductive reactance to resistance = higher quality
- Inductors with higher Q are considered to be more pure inductors
- Large wire coils = higher Q
- Many turns of smaller wire = lower Q

$$Q = \frac{X_L}{R}$$

Impedance (Z) of an Inductor

Impedance (Z) = Vector sum of inductive reactance (X_L) + resistance (R) of the inductor. It represents the total opposition to current flow presented by an inductor at a given frequency.

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

Review Questions

1. How many degrees are the current and voltage out of phase with each other in a pure resistive circuit?

2. How many degrees are the current and voltage out of phase with each other in a pure inductive circuit?

3. To what is the inductive reactance proportional?

4. Four inductors, each having an inductance of 0.6 H, are connected in series. What is the total inductance of the circuit?

5. Three inductors are connected in parallel. Inductor 1 has an inductance of 0.06 H; inductor 2 has an inductance of 0.05 H; and inductor 3 has an inductance of 0.1 H. What is the total inductance of this circuit?

6. If the three inductors in question 5 were connected in series to a 60-Hz circuit, what would be their combined inductive reactance?

7. The current through an inductor connected to a 240-V, 1000-Hz line is 0.6 A.

What is the inductance of the inductor?

8. An inductor with an inductance of 3.6 H is connected to a 480-V, 60-Hz line. How much current will flow in the circuit?

9. If the frequency in question 8 is reduced to 50 Hz, how much current will flow in the circuit?

10. An inductor has an inductive reactance of 250 Ω, when connected to a 60-Hz line. What will be the inductive reactance if the inductor is connected to a 400-Hz line?

R-L Series Circuits

Herman, Delmar's Standard Textbook of Electricity 3rd Edition, pp. 481-483 or 2nd Edition, pp. 456-458

- In AC circuits with pure resistive loads, voltage and current are in phase.
- In AC circuits with pure inductive loads, voltage and current are 90° out of phase.
- In AC circuits with both resistance and inductance, voltage and current are out of phase by some amount between 0° and 90°.

Impedance (Z) in R-L Circuits

Herman, Delmar's Standard Textbook of Electricity 3rd Edition, pp. 483-485 or 2nd Edition, pp. 467-468

- Impedance (Z) is the total opposition to the flow of current in an AC circuit

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

Total Current

Herman, Delmar's Standard Textbook of Electricity 3rd Edition, pp. 485-486 or 2nd Edition, pp. 467-468

- The total circuit current (**I_T**) can be computed by dividing the total applied voltage by the total current-limiting factor; impedance (Z).

$$\mathbf{I_T = \frac{E_T}{Z}}$$

Voltage Drop Across the Resistor

Herman, Delmar's Standard Textbook of Electricity 3rd Edition, pp. 486-487 or 2nd Edition, pp. 469-470

- Uses quantities pertaining to the resistive part of the circuit.

$$\mathbf{E_R = I_R \times R}$$

- If impedance and inductance of a circuit are known, you can find circuit resistance by rearranging the impedance formula:

$$R = \sqrt{Z^2 - X_L{}^2}$$

Watts

Herman, Delmar's Standard Textbook of Electricity 3rd Edition, pp. 487-488 or 2nd Edition, pp. 469-470

True power (P): Computed by:

- Multiplying the voltage drop across a resistor by current flow through it
  Power = voltage times current (P = EI)
- Dividing the square of the voltage drop across a resistor by its resistance
  Power = voltage squared divided by the resistance
- Multiplying the square of the current through a resistor by its resistance
  Power = current squared times resistance
- In R-L series circuits only the resistive parts of the circuit consume power (watts). See page 487 of Delmar's Standard Textbook of Electricity 3rd ed.
  $\mathbf{P = E_R \times I_R}$

Computing Inductance

Herman, Delmar's Standard Textbook of Electricity 3rd Edition, pg. 488 or 2nd Edition, pg. 470

$$\mathbf{L = \frac{X_L}{2\pi f}}$$

Voltage Drop Across the Inductor

Herman, Delmar's Standard Textbook of Electricity 3rd Edition, pg. 488 or 2nd Edition, pg. 470

$\mathbf{E_L = I_L \times X_L}$

Total Voltage

Herman, Delmar's Standard Textbook of Electricity 3rd Edition, pp. 489-490 or 2nd Edition, pp. 470-472

- The total voltage (E_T) can be found by using the Pythagorean Theorem in the following formula:
  $$E_T = \sqrt{E_R{}^2 + E_L{}^2}$$

Computing the Reactive Power

Herman, Delmar's Standard Textbook of Electricity 3rd Edition, pg. 490 or 2nd Edition, pg. 473

- Reactive power (VARs) in the circuit is a product of the voltage across the inductor multiplied by the current through the inductor. VAR's are often referred to as Quadrature power or Wattless power. Some formulas for calculating VARs are:
  $\mathbf{VAR = E_L \times I_L}$ **or**
  $\mathbf{VAR = I_L{}^2 \times X_L}$

Computing the Apparent Power

Herman, Delmar's Standard Textbook of Electricity 3rd Edition, pp. 491-493 or 2nd Edition, pp.473-475

- Volt-amperes (VA) is the apparent power in the circuit. It is a product of the Voltage Applied (E_T) multiplied by the Current Total (I_T).
  $\mathbf{VA = E_T \times I_T}$

VA can also be calculated using the following formula:

$$\mathrm{VA} = \sqrt{\mathrm{P}^2 + \mathrm{VAR}^2}$$

Knowing any two values of VA, Power or VARs, the formula can be rearranged to find the unknown values using the following formulas:

$$\mathrm{P} = \sqrt{\mathrm{VA}^2 - \mathrm{VAR}^2} \qquad \mathrm{VARs} = \sqrt{\mathrm{VA}^2 - \mathrm{P}^2}$$

Power Factor

Herman, Delmar's Standard Textbook of Electricity 3rd Edition, pp. 493-494 or 2nd Edition, pp. 475-476

Power Factor is the ratio of true power to apparent power. Some of the formulas that can be used to calculate Power Factor are:

$$\mathrm{PF} = \frac{E_R}{E_T} \qquad \mathrm{PF} = \frac{R}{Z} \qquad \mathrm{PF} = \frac{P}{VA} \qquad \mathrm{PF} = \frac{W}{VA}$$

Note that the above formulas express power factor as a decimal. In the electrical power field, it is often expressed as a percentage. Decimal values of power factor are converted to percentage values simply by multiplying the decimal value by 100 (decimal point moved two places to the right). Conversely, percentage values are converted to decimal values by dividing the percentage value by 100 (decimal point moved two places to the left).

Angle Theta (θ)

Herman, Delmar's Standard Textbook of Electricity 3rd Edition, pp. 494-499 or 2nd Edition, pp. 476-478

Angular displacement by which voltage and current are out of phase is called the Angle Theta. Some common formulas for calculating the Angle Theta include:

$$\cos\theta = \mathbf{PF} \qquad \sin\theta = \frac{\mathbf{VARs}}{\mathbf{VA}} \qquad \tan\theta = \frac{\mathbf{VARs}}{\mathbf{Watts}}$$

Example 17.1 from textbook

- Apparent power
- Total circuit current
- Other circuit values
- Impedance
- Power factor
- Phase angle

Notes

Review Questions

1. What is the relationship of voltage and current phase angles in a pure resistive circuit?

2. What is the relationship of voltage and current phase angles in a pure inductive circuit?

3. What is the power factor of a circuit?

4. A circuit supplied by a 60-Hz power source contains a 20-ohm resistor and an inductor with an inductance of 0.093 henrys. What is the total impedance of the circuit?

5. An R-L series circuit has a power factor of 86%. How many degrees are the voltage and current out of phase with each other?

6. An R-L series circuit has an apparent power of 230 VA and a true power of 180 W. What is the reactive power?

7. The resistor in an R-L series circuit has a voltage drop of 53 V, and the inductor has a voltage drop of 28 V. What is the applied voltage of the circuit?

8. An R-L series circuit has a reactive power of 1234 VAR and an apparent power of 4329 VA. How many degrees are the voltage and current out of phase with each other?

9. An R-L series circuit containing a 6.5 ohm resistor and an inductor is connected to a 120-volt source and has a current flow of 12 amperes. What is the inductive reactance of this circuit?

10. What is the voltage drop across the resistor in the circuit in question 9?

Resistive-Inductive Parallel Circuits

Herman, Delmar's Standard Textbook of Electricity 3rd Edition, pp. 509-510 or 2nd Edition, p. 492

- Voltage applied to a resistor and inductor connected in parallel has the same magnitude and phase across each component.
- Current flow through the inductor is 90 degrees out of phase with the applied voltage.
- Current flow through the resistor is in phase with the applied voltage.
- The phase angle difference between current flow through a pure inductive load and a pure resistive load is 90 degrees.
- The phase angle shift between the total circuit current and the applied voltage is determined by the ratio of the resistance to the inductive reactance.

Computing Circuit Values

Herman, Delmar's Standard Textbook of Electricity 3rd Edition, pp. 510-524 or 2nd Edition, pp. 492-508

The following are some formulas that are useful in solving circuits with resistors and inductors in parallel:

Resistive current: $I_R = \frac{E}{R}$

Watts: $P = E_R \times I_R$

Inductive current: $I_L = \frac{E}{X_L}$

Reactive power: $VAR = E_L \times I_L$

Inductance: $L = \frac{X_L}{2\pi f}$

Total current: $I_T = \sqrt{{I_R}^2 + {I_L}^2}$

Impedance: $Z = \frac{E}{I_T}$

Apparent power: $VA = E_T \times I_T$

Power factor: $PF = I_R/I_T$ or Z/R

Phase angle: $\cos\theta = PF$

Example 18.1 from the textbook
- Finding values in a circuit

Review Questions

1. When an inductor and resistor are connected in parallel, how many degrees out of phase are the current flow through the resistor and the inductor?
2. A 0.2-henry inductor and 50-ohm resistor are connected in parallel to a 120-V, 60-Hz line. What is the total current flow through the circuit?
3. What is the impedance of the circuit in question 2?
4. What is the power factor of the circuit in question 2?
5. How many degrees out of phase are the current and voltage in question 2?
6. In the circuit shown in *Figure 18-1* (Delmar's Standard Textbook of Electricity), the resistor has a current flow of 6.5 A, and the inductor has a current flow of 8 A. What is the total current in this circuit?

7. A 24-ohm resistor and inductor with an inductive reactance of 20 ohms are connected in parallel. What is the impedance of this circuit?

8. The R-L parallel circuit shown in *Figure 18-1* has an apparent power of 325 VA. The circuit power factor is 66%. What is the true power in this circuit?

9. The R-L parallel circuit shown in *Figure 18-1* has an apparent power of 465 VA and a true power of 320 W. What is the reactive power?

10. How many degrees out of phase are the current and voltage in question 9?

Resistive-Inductive Circuits

Discussion
Inductance (**L**) is easily determined indirectly by measuring the effect that it has on a circuit. In this exercise, the value of an inductor in a series R-L circuit is determined by analyzing the voltage drops across a resistance and an inductor. You begin this experiment by constructing a circuit consisting of a potentiometer and an inductor in series. You adjust the potentiometer until the voltage drop across it ($\mathbf{V_R}$) equals the voltage drop across an inductor ($\mathbf{V_L}$). When these voltages are equal, the resistance of the potentiometer is equal to the inductive reactance ($\mathbf{X_L}$) of the coil. By measuring the resistance of the potentiometer, you will be able to determine the reactance of the coil at that particular frequency. You will then calculate the inductance of the coil by solving the equation for **L**.

You will repeat this procedure for three different frequencies and observe the effect changes in frequency have on the inductive reactance of the coil. You will compare the average value of the calculated inductance for each of the three frequencies with the nominal inductance of the coil. You will also find the impedance (**Z**), phase angle, and power factor of the circuit at different frequencies.

Procedure

1. Turn the signal generator on and adjust the frequency to 2 kHz. Check the frequency with the oscilloscope (sweep time is 0.2 ms at 2 kHz). Turn the signal generator off.
2. Construct the circuit in *Figure 3-5* and connect it to the signal generator.
3. Turn the signal generator on, close S_1 and adjust the potentiometer (R_1) until the voltage on R_1 equals the voltage on the inductor (L_1).

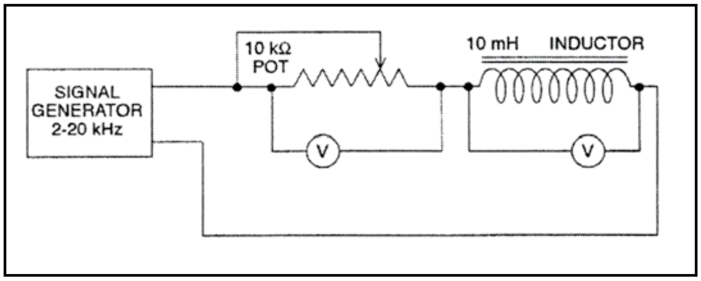


Fig. 3-5. When XL equals R, the two voltage drops are equal. Courtesy of Delmar Learning.

Applied Voltage _____ VAC
Voltage across L_1 = ______VAC
Voltage across R_1 = ______VAC

4. Turn the power off and open S_1.
5. Without changing the adjustment of R_1, read its resistance. R_1 = _____

6. Using the formula for inductive reactance (X_L), calculate the inductance of the coil.
   $X_L = 2\pi fL$ or $X_L = 2\pi \times$ Frequency × Inductance (in henrys)

   $V_{XL} = V_{R1}$, therefore $X_L = R_1$ X_L = _______

   $L = X_L \div 2\pi f$ L = _________

7. Turn the signal generator on and adjust to 10 kHz. Check the frequency with the oscilloscope (sweep time at 10 kHz is 0.1 ms).

8. Repeat steps 3-6 using 10 kHz.
   Voltage on L_1 = ______ V
   Voltage on R_1 = ______ V
   Resistance of R_1 = ______ ohms
   X_L = ______ohms
   L = _______ henrys

9. Turn the signal generator on and adjust to 20 kHz (sweep time at 20 kHz is 50 microseconds).

10. Repeat steps 3-6 using 20 kHz.
    Voltage on L_1 = ______ V
    Voltage on R_1 = ______ V
    Resistance of R_1 = ______ ohms
    X_L = ______ ohms
    L = _______ henrys

11. Calculate the average value of inductance for each of the three frequencies.
    L (2 kHz) = _____ L (10 kHz) = _______
    L (20 kHz) = _____ Average = _______

    The inductance of the coil does not change with frequency. If values for inductance vary significantly for any of the frequencies, this indicates an error in your procedure or in your meter readings. Repeat that section of the experiment.

12. How does the rated value or the inductor you are using compare with your findings?

Notes

13. How do you explain any difference between your findings and the rated value of the inductor?

14. Draw a voltage triangle, using V_{XL} and V_{R1} from step 3. Calculate the applied voltage and the phase angle.

How does the calculated applied voltage compare to the measured applied voltage in step 3?

Phase angle = ____degrees

Cosine of phase angle = ______

The cosine of the angular difference between voltage and current is the power factor.

Explain why the sum of V_{XL} and V_{R1}, is greater than V applied.

15. Draw an impedance triangle using the X_L and R_1 values obtained when you were using 2 kHz (in step 3 above). Calculate Z (impedance) and the phase angle for this triangle.
Z = _______ ohms
Phase Angle = _______ degrees

How does the angle of this triangle compare with the angle in the voltage triangle calculated in question 14 above? ___________________________

Explain the similarity (or difference) in the angles.

16. Draw an impedance triangle for the circuit using the data obtained at 10 kHz.

    What is the impedance of the circuit?

    What is the phase angle?

    Why are the impedance (Z) and/or the phase angle for this triangle different from the triangle you drew for question 15 using the data at 2 kHz?

Observations

1. How does increasing the frequency affect the inductive reactance of a coil?

2. What causes the inductive reactance of a coil to change with a change in frequency?

3. How would you expect an increase in frequency to affect the amount of current flowing in a coil if the voltage is constant?

4. Does changing the applied frequency change the inductance of a coil?

5. Name four factors that determine the inductance of a coil or choke.

6. What effect would operating a 240-VAC, 60-Hz motor at 240 VAC 50 Hz have on the following?

   The inductive reactance of the motor: ___________________________
   The input amperes at the motor’s rated horsepower: ________________

Inductive Reactance

Discussion

This exercise demonstrates the effects of AC and DC voltage on inductive devices by operating the same devices with both AC and DC power sources. The effect that the inductance of a device has on a circuit is demonstrated by changing two physical properties of the coil:

- The number of turns of wire
- The permeability of the core

Changing these properties modifies the coil's inductance, which in turn affects the inductive reactance of the coil. You will use two different coils from solenoids as inductors. You begin by removing the iron core of the 120-VAC solenoid, and will later use the core to change the permeability of the magnetic path of the coils. You will also observe the high-voltage "inductive kick" that occurs when current through the coil changes abruptly.

Procedure

1. Remove the iron core from the 120-VAC solenoid, and measure and record the resistance of the coil.
   120-VAC coil resistance = _____ohms

2. Connect the circuit shown in *Figure 3-6* using the 120-VAC solenoid coil with the iron core removed.

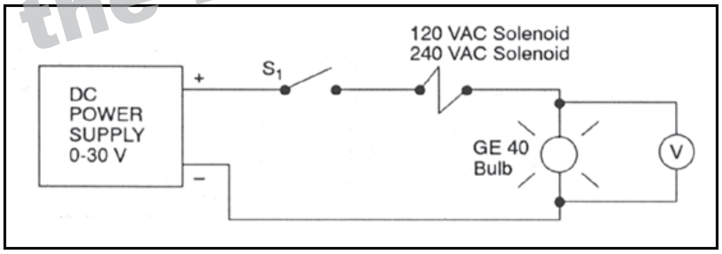


Fig. 3-6. Inductance in a DC circuit. Courtesy of Delmar Learning.

3. Turn the DC power supply on and close switch S_1. Adjust to 6 VDC across the lamp.

   Did the lamp light at normal brightness?

   What is the voltage on the coil?

4. Insert the iron core in the coil. Can you feel the pull of the magnetic field on the core as you inserted it?

   Does the coil vibrate or hum?

   Did the lamp dim when you inserted the core?

   What is the voltage on the lamp with the core in the coil?

5. Slide the iron core in and out of the coil while observing the lamp. Does the brightness of the lamp change as you move the core?
6. Return the voltage to zero, open S_1, and turn the power supply off.
7. Measure the resistance of the 240-VAC coil. Resistance = _________
8. Remove the 120-VAC coil from the circuit and replace it with the 240 VAC coil.
9. Repeat steps 1-6 using the 240-VAC coil. Note that you are still applying 6 VDC to the lamp.

   Did changing the coil affect the brightness of the lamp?

   Does using the 240-VAC coil and/or moving the iron core affect the lamp's bright-ness?

10. Push the core into the coil against the springs until the magnetic field grabs the core. Observe the lamp while you pull the core until it breaks free from the magnetic field. Was it more difficult to remove the core from this coil than from the 120-VAC coil?

    Did the lamp flash momentarily when you pulled the core out of the grip of the magnetic field?

11. Turn the power to zero, open switch S_1 and turn the power supply off. Remove the 240- VAC coil from the circuit and replace it with the 120-VAC coil.
12. Construct the circuit in *Figure 3-7* using the 120-VAC coil and the variable AC 60-Hz power supply.

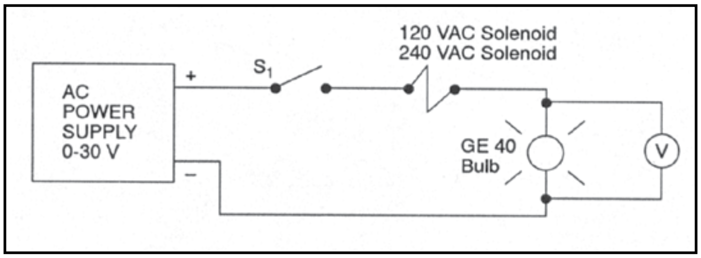


Fig. 3-7. Inductance in a AC circuit. Courtesy of Delmar Learning.

13. Close S_1, and adjust AC supply to 6 VAC across the lamp.
    Does the lamp light?
    Does it appear to be as bright as when you were using 6 VDC?

14. Insert the iron core.
    Does the magnetic field pull on the core as strongly as it did with DC?

    Did the lamp dim when you inserted the core?

    With the core inserted, what is the voltage on the lamp?

    What is the voltage on the coil?

15. Turn the voltage to zero, open switch S_1 and turn the power off.
16. Remove the 120-VAC coil and replace it with the 240-VAC coil with the core removed.
17. Close S_1 and adjust the voltage to 6 VAC across the lamp.
18. Observe the lamp and the voltage on the 240-VAC coil.
    Did changing the coil change the brightness of the lamp?

19. Slide the core in and out several times while observing the lamp and the voltmeters.
    Did inserting the core make the lamp dimmer?

    When was the lamp brightest?

20. Record the voltage on the lamp and coil when the lamp is brightest.
    Voltage on lamp = _____ Voltage on coil = _____

21. Record the voltages when lamp is dimmest.
    Voltage on lamp = _____ Voltage on coil = _____

22. Turn the voltage to zero, open switch S_1 and turn the power supply off.
    Disassemble the circuit and replace the armatures in the coils.

23. Calculate the current that would flow through this coil with 6 V applied if the resistance of the wire were the only factor limiting current. Use the resistance as measured in question 7.
    I = ____

24. Using the 240-VAC coil and the DC power supply, construct the circuit in *Figure 3-8*. Turn the power supply on and adjust voltage to 6 VDC. Close switch S_1.

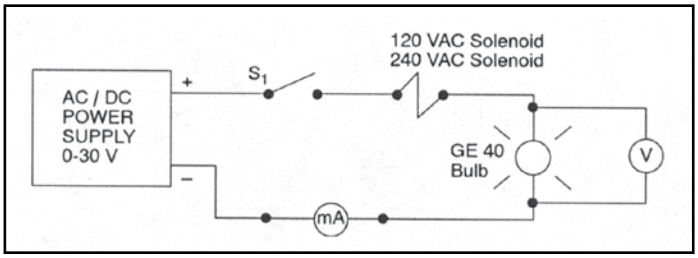


Fig. 3-8. Current in inductive DC and AC circuits. Courtesy of Delmar Learning.

25. Measure the current flowing through the coil.
I = ________

26. Open switch S_1, adjust the voltage to zero, and turn the power off.

27. Connect the same circuit (See *Figure 3-8*) to the 60-Hz variable AC power supply. Turn the supply on and adjust to 6 VAC. Close switch S_1. Note that the magnetic field is not strong enough to pull the core completely into the body of the solenoid. Manually push the core fully into the coil (against the springs). You will see the current drop when the core is fully inserted.

28. Measure the current. I = __________ amperes

29. Does more current flow in the coil with 6 VAC or 6 VDC?

Why?

30. Turn voltage adjustment to zero and turn the supply off.

31. Construct the circuit in *Figure 3-9*, and connect it to the DC power supply.

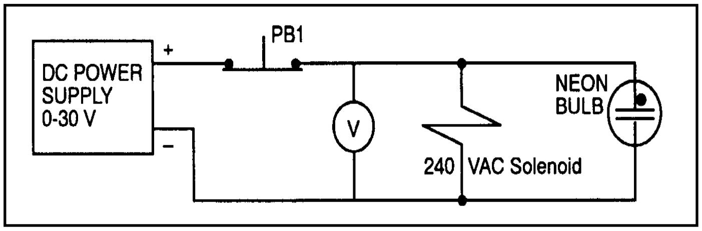


Fig. 3-9. Collapse of the magnetic field in an inductive device produces a voltage. Courtesy of Delmar Learning.

32. Turn the power supply on and adjust to 20 VDC on the coil. Does the neon bulb light with 20 volts applied?

33. With the voltage set at 20 VDC, observe the neon lamp as you disconnect the circuit from the power supply by depressing the normally closed push button.

Did the lamp fire when you opened the circuit?

34. Turn the power off, insert the core into a coil, and repeat steps 33 and 34.

    Was the neon bulb brighter with the core inserted?

    What is the source of the energy that fires the neon bulb when you disconnect the circuit from the power supply by pressing the push button?

35. Adjust the voltage to zero and turn the power supply off.

Observations

1. Write the formula for inductive reactance (X_L):

2. Using this formula, what is X_L for DC?

3. Did DC or AC seem to produce a stronger magnetic field in the coils? How could you tell?

4. Did changing from AC to DC affect the response when you inserted the iron core?

5. Why did the lamp become dimmer when you inserted the iron core into the coil?

6. When you were using DC, which coil seemed to have the strongest magnetic field?

7. Can you tell whether the 120-volt or 240-volt coil has more turns in its windings by measuring their resistances? Why?

8. Why does inserting the iron core into the coil change the brightness of the lamp?

9. Explain how your observations confirm or contradict the following formula for the inductance of a coil:

$$L = \frac{N^2 \times A \times P}{\text{length}}$$

Where:

L = Inductance in Henrys
A = Cross section of core in square meters
N = Number of turns in coil
A = Area of core in square meters
P = Permeability of core
Length = Length of coil in meters

10. Why does increasing the number of turns of wire in a coil affect its inductive reactance?

11. Why does increasing the permeability of the core affect the inductive reactance of a coil?

12. What is the source of the energy that generates the EMF required to make the neon lamp flash the moment power is removed from the coil?

Inductance

1. 0°; Current and voltage are in phase.
2. 90°
3. Inductance of the inductor and the frequency
4. 2.44 H = .6 H + .6 H + .6 H + .6 H
5. 0.0214 H = 1/(1/.06 H + 1/.05 H + 1/.1 H)
6. 79.12 ohms $2 \times \pi \times 60\ H_Z \times (.06\ H + .05\ H + .1\ H)$
7. 0.064 henrys: $X_L = 240\ V/0.6\ A = 400\ \Omega$; $L = 400/(2 \times 3.14 \times 1000\ H_Z) = .064$ henrys
8. 0.354 A: $X_L = 2 \times \pi \times 60\ H_Z\ 3.6\ H = 1356.48$ ohms; I = 480 V/1356.48 ohms = 0.354 A
9. 0.425A: $X_L = 2 \times \pi \times 50\ H_Z \times 3.6\ H = 1130.4$ ohms; 480 V/1130.4 ohms = 0.425 A
10. 1,666.7 ohms: $L = 250/(2 \times \pi \times 60\ H_Z) = 0.663\ H$; $X_L = 2 \times \pi \times 400 \times 0.663\ H$

R-L Series Circuits

1. The voltage and current are in phase with each other.
2. The current lags the voltage by 90 degrees.
3. The power factor of a circuit is the ratio of the true power to the apparent power.
4. 40.35 ohms; $X_L = 2 \times \pi \times 60 \times .093 = 35.04$ ohms

$$Z = \sqrt{20^2 + 35.04^2} = 40.35 \text{ ohms}$$

5. $\cos^{-1} .86 = 30.68$ degrees
6. $$\text{VARs} = \sqrt{230\text{VA}^2 - 180\text{W}^2} = 143.18 \text{ VARs}$$
7. $$E_T = \sqrt{28^2 + 53^2} = 59.94\,\text{V}$$
8. Angle Theta = $\sin^{-1}$ (VARs/VA) = $\sin^{-1}$ (1234 VARs/4329 VA) = 16.65 degrees
9. $$Z = 120\,\text{V} / 12\ \text{A} = 10 \text{ ohms}$$

$$X_L = \sqrt{10^2 - 6.5^2} = 7.6 \text{ ohms}$$

10. 78 volts: $E_R = 6.5$ ohms × 12 A

Resistive-Inductive Parallel Circuits

1. 90 degrees
2. 2.88A:

$X_L = 2 \times 3.14 \times 60\ Hz \times 0.2\ H = 75.36$ ohms
$I_L = 120\ V/75.36$ ohms = 1.59 A
$I_R = 120\ V/50$ ohms = 2.4 A

$$\begin{aligned} I_T &= \sqrt{I_L{}^2 + I_R{}^2} = \sqrt{(1.59\text{A})^2 + (2.4\text{A})^2} \\ &= \sqrt{2.5281\ \text{A}^2 + 5.76\ \text{A}^2} \\ &= \sqrt{8.2881\ \text{A}^2} \\ &= 2.88\,\text{A} \end{aligned}$$

Resistive-Inductive Parallel Circuits

3. 41.67 ohms; $Z = E_T/I_T$ = 120 V/2.88 A

4. PF = Z/R = 41.67 ohms/50 ohms × 100 = 83.3%

5. $\cos^{-1}$ PF = $\cos^{-1}$ .833

6. $$I_T = \sqrt{I_R{}^2 + I_L{}^2} = \sqrt{(8\,\text{A})^2 + (6.5\,\text{A})^2} = \sqrt{64\,\text{A}^2 + 42.25\,\text{A}^2} = \sqrt{106.25} = 10.3\,\text{A}$$

7. $$Z = \frac{1}{\sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_L}\right)^2}} = \frac{1}{\sqrt{\left(\frac{1}{24}\right)^2 + \left(\frac{1}{20}\right)^2}} = 15.36\ \text{ohms}$$

8. 214.5 W: PT = PF × PA = .66 × 325 VA

9. $$\begin{aligned} \text{VARs} &= \sqrt{\text{VA}^2 - \text{P}^2} \\ &= \sqrt{(465\ \text{VA})^2 - (320\ \text{W})^2} \\ &= \sqrt{216{,}225\ \text{VA}^2 - 102{,}400\ \text{W}^2} \\ &= \sqrt{113{,}825} = 337.38\ \text{VARs} \end{aligned}$$

10. 45.4 degrees: PF = PT/PA= 320 W/456 VA = .7017; $\cos^{-1}$ PF = Angle Theta = $\cos^{-1}$ .7017

Resistive-Inductive Circuits

3. Applied Voltage 3.11 VAC
   Voltage across L_1 = 2.2 VAC
   Voltage across R_1 = 2.2 VAC
   Answers: $V_{applied} = 2.2 \div \cos 45°$; $V_{applied}$ = 3.11 VAC

5. $R_1 = 140\ \Omega$

6. X_L = 140 ohms L = 0.011 H

8. Voltage on L_1 = ______ V
   Voltage on R_1 = ______ V
   Resistance of R_1 = ______ ohms
   X_L = ______ohms
   L = _______ henrys
   $X_L = R_1$ $X_L = 710$
   $L = X_L \div 2\pi f$ $L = 710 \div (2 \times \pi \times 10000)$ L = 0.011

10. Repeat steps 3-6 using 20 kHz.
    Voltage on L_1 = ______ V
    Voltage on R_1 = ______ V
    Resistance of R_1 = ______ ohms
    X_L = ______ ohms
    L = _______ henrys
    $X_L = R_1$ X_L = 1.47 k
    $L = X_L \div 2\pi f$ $L = 1470 \div (2 \times \pi \times 20000)$ L = 0.011

11. L (2 kHz) = 11 mH L (10 kHz) = 11 mH
    L (20 kHz) = 11mH Average = 11 mH

12. Measurements will vary depending on the components used. In the above example, the manufacturer's rating was 10 mH; its actual value was 11 mH.

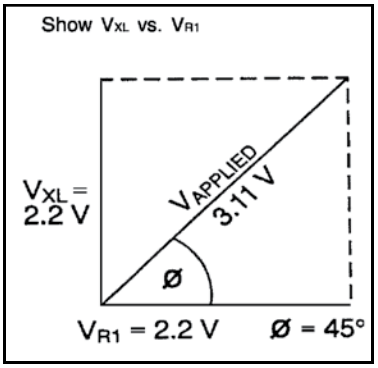
13. Minor differences can be attributed to tolerances in components used, meter error, and errors in the reading of meters and/or an oscilloscope.

14. The calculated voltage should be approximately the same as the applied voltage. The experiment requires that the voltages be set to equal values.
    Phase angle = 45 degrees
    This results in an isosceles triangle with 45° angles. Thus, the phase angle is 45° angles. Thus, the phase angle is 45°.

    The cosine of 45° is 0.707.

    The cosine of the angular difference between voltage and current is the power factor.

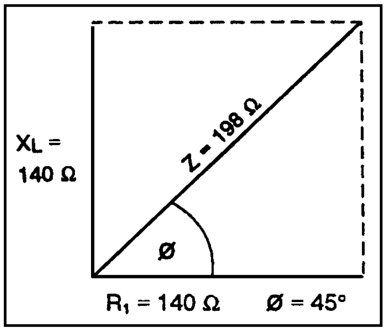
    Current and voltage are not in phase; consequently, the voltage drops must be added with vectors or by using trigonometry;
    $V_{applied} = V_{R1} \div \cos 45°$ (or because they are equal, V_{XL})



Step 14

15. Z = 198 ohms
    Phase angle = 45°

    The angles are similar because in each case the vectors making the voltage and impedance triangles are of equal value, respectively.

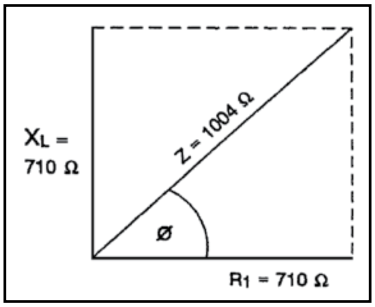


Step 15

16. 1004.2 ohms

    45 degrees

    The two triangles are similar because the phase angles are the same. The impedance is different because the triangles are based on different data.



Step 16

Observations - Resistive-Inductive Circuits

1. The higher the frequency, the higher the inductive reactance. Inductive reactance and frequency are directly proportional.

2. The higher frequency will cause a larger CEMF which will increase the inductive reactance.

3. An increase in frequency will increase inductive reactance causing the current to decrease. Frequency and current flow are inversely proportional.

4. No, changing the frequency does not change the inductance (L).

5. Number of turns in coil, cross sectional area of core, area of core, length of coil

6. Inductive reactance will decrease.

   Current will increase.

Procedure - Inductive Reactance

1. 3 ohms

3. The lamp appears as bright as it normally would.

   Voltage on the coil is approximately 0.5 VDC.

4. No, the coil does not appear to pull the core.
   There is no hum.
   The lamp does not change noticeably.
   Voltage on the lamp = 6 VDC.

5. Moving the core has no obvious effect on the lamp.

7. 18 ohms

9. Changing the coil had no effect on the brightness of the lamp.
   When the core is put into the coil, there is a momentary dimming of the lamp before it returns to its normal condition.

10. The coil pulls the core and holds it when the core is inserted. It is difficult to remove the core.
    The lamp flashes momentarily when the core is removed.

13. The lamp is ON.
    It appears to be normal.

14. The 120-VAC coil does not pull the core noticeably.
    Fully inserting the core causes the lamp to dim.
    Voltage on the lamp = 4.5 VAC
    Voltage on the coil = 10.5 VAC

18. Changing to the 240-VAC coil does not have much effect on the lamp.

19. Inserting the core causes the lamp to be very, very dim.
    The lamp is bright when the core is removed from the coil.

20. 6 VAC, 3.3 VAC

21. 1 VAC, 23.43 VAC

23. I = .33 A
    6 V/18 Ω = .33 A

25. I = Approximately .33 A

28. I = Varies depends on components’ amperes

29. Because with AC inductive reactance decreases the current

32. No

33. Yes

34. Yes
    Source is collapsing magnetic field

Observations - Inductive Reactance

1. $X_L = 2\pi fL$

2. Zero ohms

3. DC

   The core was harder to pull out.

4. YES

5. Inductance was increased, increasing X_L, causing a reduced voltage available for the lamp.

6. 240-VAC coil

7. Possibly

   Depends on sensitivity of ohm meter. The 240-VAC coil should have more turns of wire.

8. Inductance was increased, increasing X_L, causing a reduced voltage available for the lamp.

9. When the number of windings in the coil was increased, the inductance increased which increased the inductive reactance. When the permeability of the core was increased, the inductance increased which increased the inductive reactance.

10. Increasing the number of turns provides more CEMF which increases the inductive reactance.

11. Increasing the permeability of the core focuses the magnetic lines of flux causing a greater CEMF.

12. The collapsing magnetic field cutting across the turns of wire in the coil.