PHYSICS in Context

An Integrated Approach

Sample Experiment

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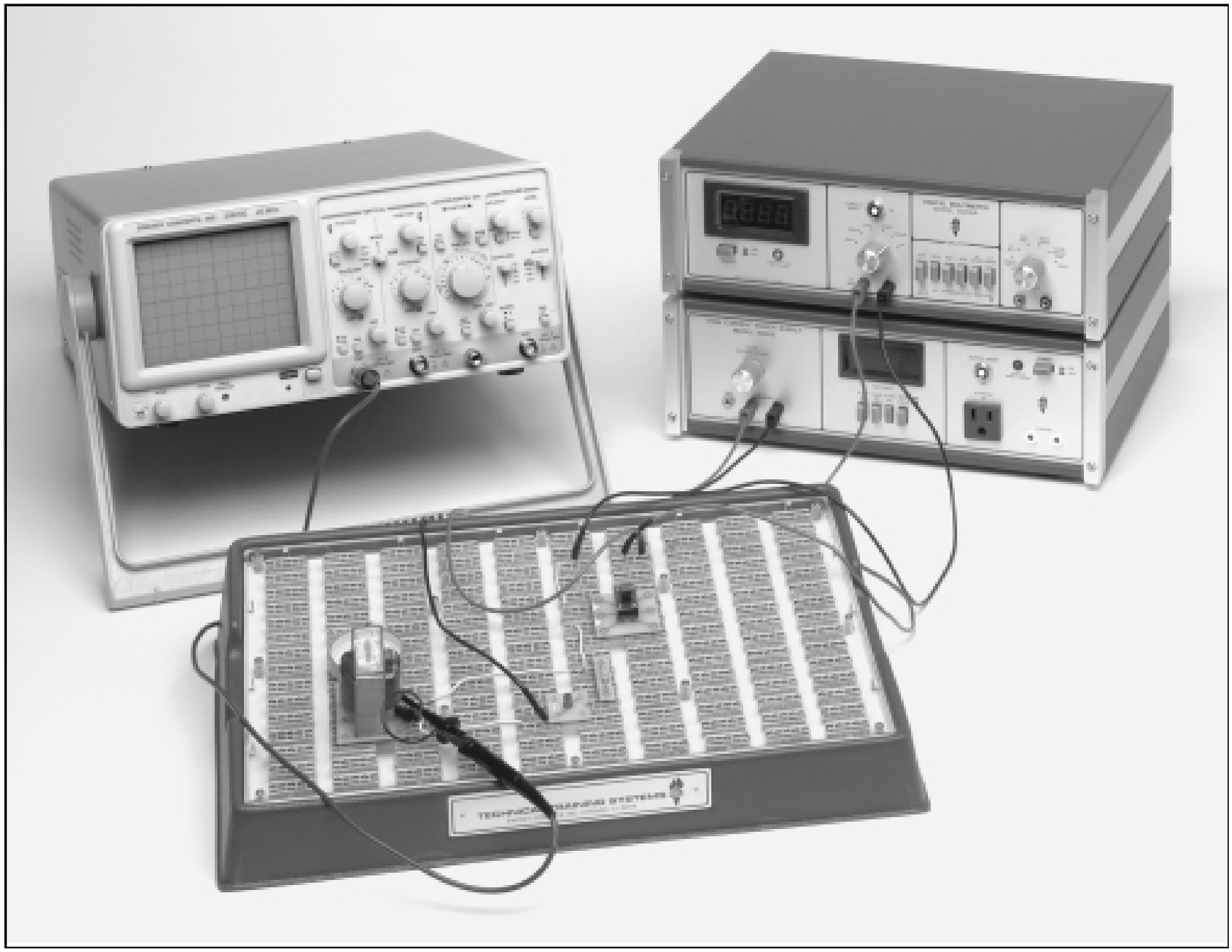
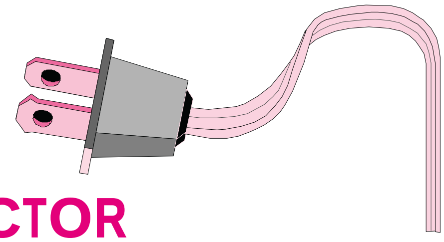


Figure 1
Lab setup for Section 5.3A

5.3A Energy Stored in the Magnetic Field of an Inductor



Experiment Objectives

- Explain how energy is stored in an inductor.
- Determine the amount of potential energy stored in the magnetic field of an inductor.

Laboratory Proficiencies

- Set up an experiment to store and recover energy from an inductor using a DC voltage source.
- Use an oscilloscope to view the voltage waveforms as the magnetic field of an inductor builds and collapses.
- Measure the current through and the voltage across an inductor at steady-state conditions.
- Use a light emitting diode to identify the collapse of the magnetic field around an inductor and the voltage induced by the collapsing field.

Discussion

An **inductor** is an electrical device that stores energy in a magnetic field. A typical inductor consists of wire wrapped in a number of loops. A number of inductors are shown in Figure 2.

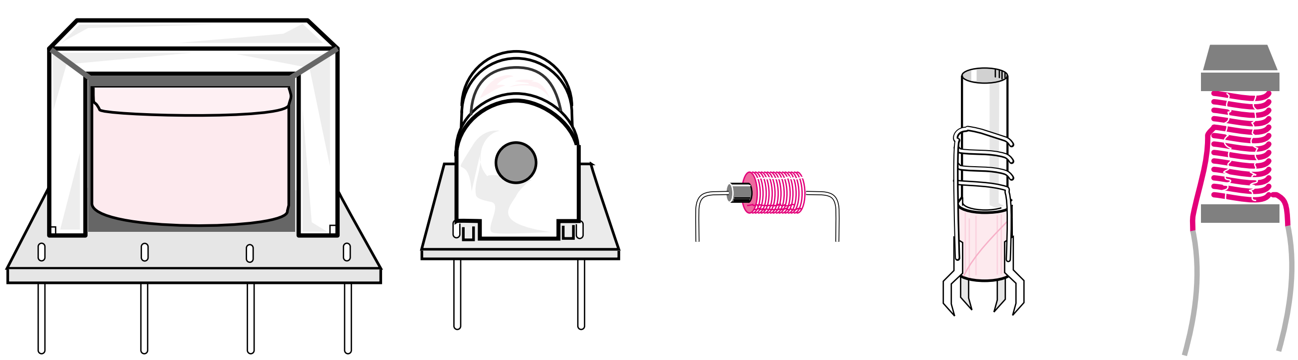


Figure 2
Samples of inductors

Inductor An electrical device, typically consisting of wire wrapped in many loops, that stores energy in a magnetic field.

The center of the loop, called a core, may contain air or other material. If the coil core is iron the inductor has a higher inductance than the same coil with an air core. The inductance of the inductor is a function of its length, cross-sectional area, number of turns and core material. See Figure 3.

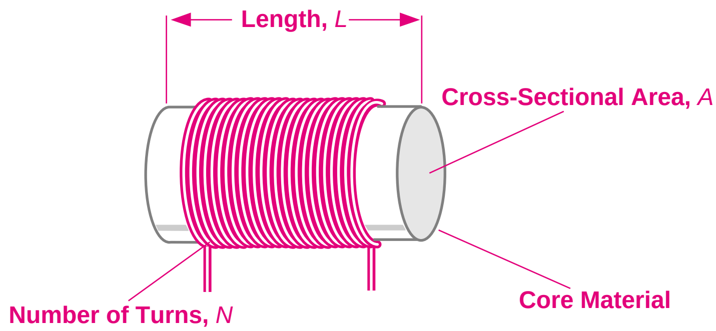


Figure 3
Physical factors determining inductance of a coil

The inductance of an inductor for a given current and core material is greater if the coil has more turns of wire, is larger in diameter, or if the coil is shorter.

Figure 4 shows an inductor circuit containing (1) a DC power supply, (2) an inductor, (3) an ammeter, and (4) a switch. A parallel branch in the circuit contains (5) a **LED (light emitting diode)**, and (6) a carbon resistor.

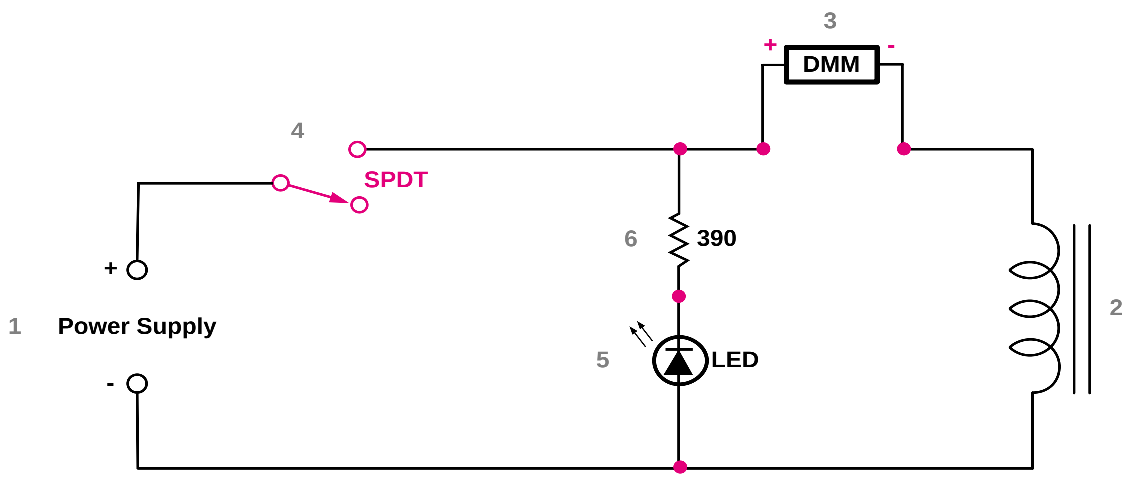


Figure 4
Schematic of circuit in experiment

LED (Light Emitting Diode) A type of diode that emits light when there is forward current.

When the switch is closed, voltage or **EMF (electromotive force)** is applied to the inductor and current begins to flow through the inductor, a magnetic field builds in and around the coil. (Because of the nature of diodes, no current flows through the branch at this time.) See Figure 5.

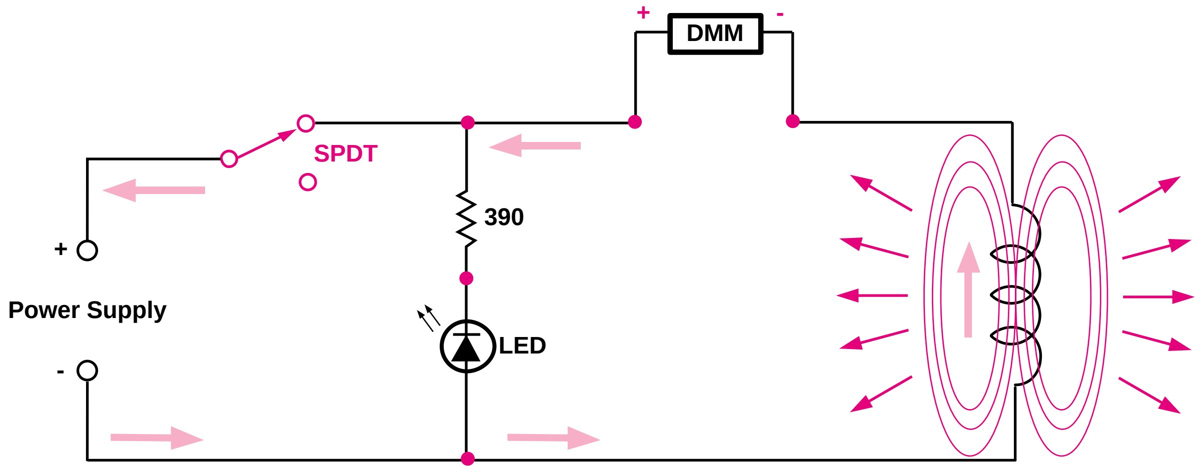


Figure 5
Magnetic field building in and around the inductor

The building magnetic field causes a **back or counter EMF** to form across the inductor. This counter EMF tends to oppose an increase in the current. The power source does work to overcome the counter EMF. The additional work done by the power source is stored in the magnetic field of the inductor.

The work done by the power supply in moving charges through the counter EMF is equal to the product of the charge moved and the counter EMF of the inductor. This is shown below.

$$W = q(V_{EMF}) = {}^{1}/_{2}\, I\, \Delta t\, (V_{EMF})$$

Where

q = Charged moved through V_{EMF}

V_{EMF} = Back EMF of the inductor

I = Current created in inductor

Δt = Time interval for current to move through inductor

W = Work done by the power source

EMF (Electromotive Force) A potential difference or voltage in an electrical circuit
Back or Counter EMF An electromotive force that acts in a direction opposite to the applied electromotive force.

The work done in moving charges through an inductor is stored as potential energy in the magnetic field formed around the inductor.

Energy stored in the magnetic field of an inductor is a function of the inductance of the inductor and the current flow through the inductor.

When the current reaches the maximum value for the circuit, the magnetic field stabilizes and no counter EMF is present. See Figure 6.

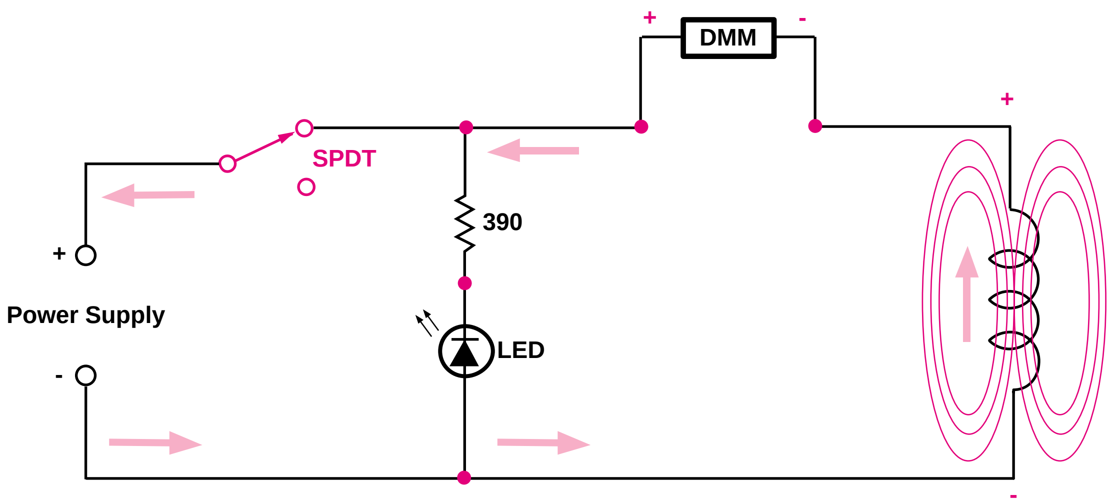


Figure 6
Steady state conditions for circuit

At steady-state current conditions, the potential energy stored in the magnetic field of an inductor may be expressed as:

$$PE = {}^{1}/_{2}\ L\ I^2$$

Where

PE = Potential energy stored in magnetic field (J)

L = Inductance of inductor (H) in **henries**

I = Steady state current (A)

The current in the above equations is a function of the DC resistance of the windings. And as stated earlier, the inductance is a function of the physical makeup of the inductor.

Henry Basic unit of measurement of inductance

When the voltage supplied to the coil is switched off, the current through the inductor diminishes, causing the magnetic field to collapse. See Figure 7.

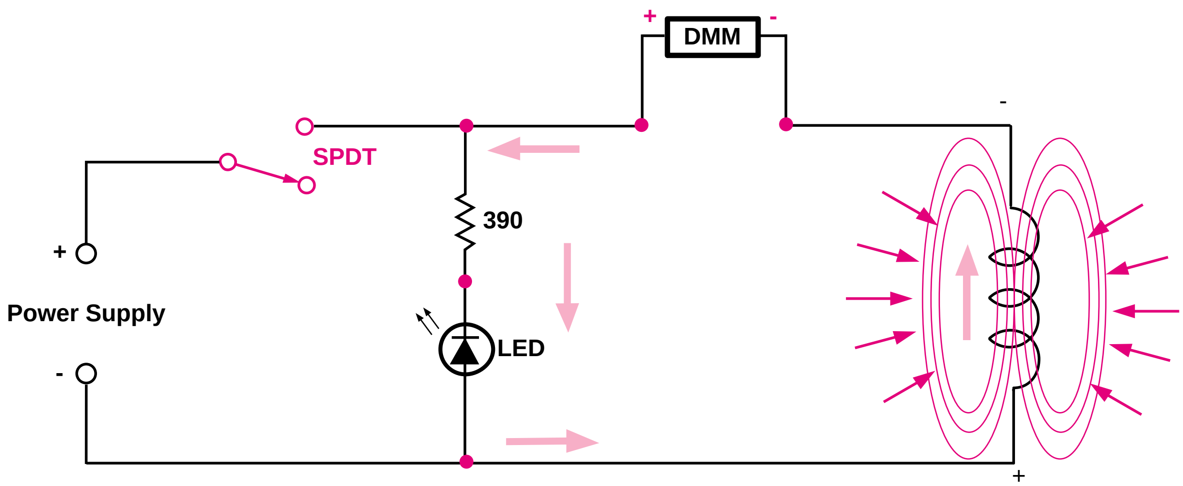


Figure 7
Magnetic field collapses as applied voltage is eliminated

The collapsing magnetic field causes an EMF to form across the inductor. This EMF tends to oppose a change in current and the energy stored in the magnetic field causes a current flow through the inductor.

The collapsing magnetic field causes current to flow through the light emitting diode (LED) branch of the circuit causing the diode to light.

In 60 cycle AC circuits, the applied voltage changes polarity every $^{1}/_{120}{}^{th}$ of a second. The magnetic field around the inductor builds and collapses along with this change in voltage. This causes a similar alternating of the counter EMF in the inductor. The continually changing EMF opposes the applied AC EMF. This results in a lower current flow than when DC current flows through the circuit. In applying Ohm's law to the inductor, the resulting resistance value is larger than the DC resistance of the inductor. This opposition to AC current flow in the inductor is called **impedance**. Impedance is a form of opposition to alternating current measured in ohms. It consists of the DC resistance and the **inductive reactance** of the inductor.

In this experiment you will find the energy stored in the magnetic field of an inductor at steady-state conditions, observe the effects of the magnetic field and the back or counter EMF of an inductor. Finally, you will compare the DC current to the AC current flowing through the inductor when applying comparable AC and DC voltages.

Impedance The total opposition to the alternating current flow in a circuit
Inductive Reactance The opposition an inductor offers to current flow in an AC circuit

Equipment and Materials Needed

- Inductor
- Oscilloscope
- Digital Multimeter
- High Current AC/DC Power Supply
- Resistor (390 Ohm)
- Hook-Up Wire, Stripper, and Spring Tips Set
- Universal Lead Set
- Circuit Panel
- Circuit Panel Easel
- Compass
- SPDT Slide Switch
- LED

Procedure
Part 1

DC Voltage Across an Inductor

The equipment for this experiment is shown in Figure 8. Additional figures will follow as needed.

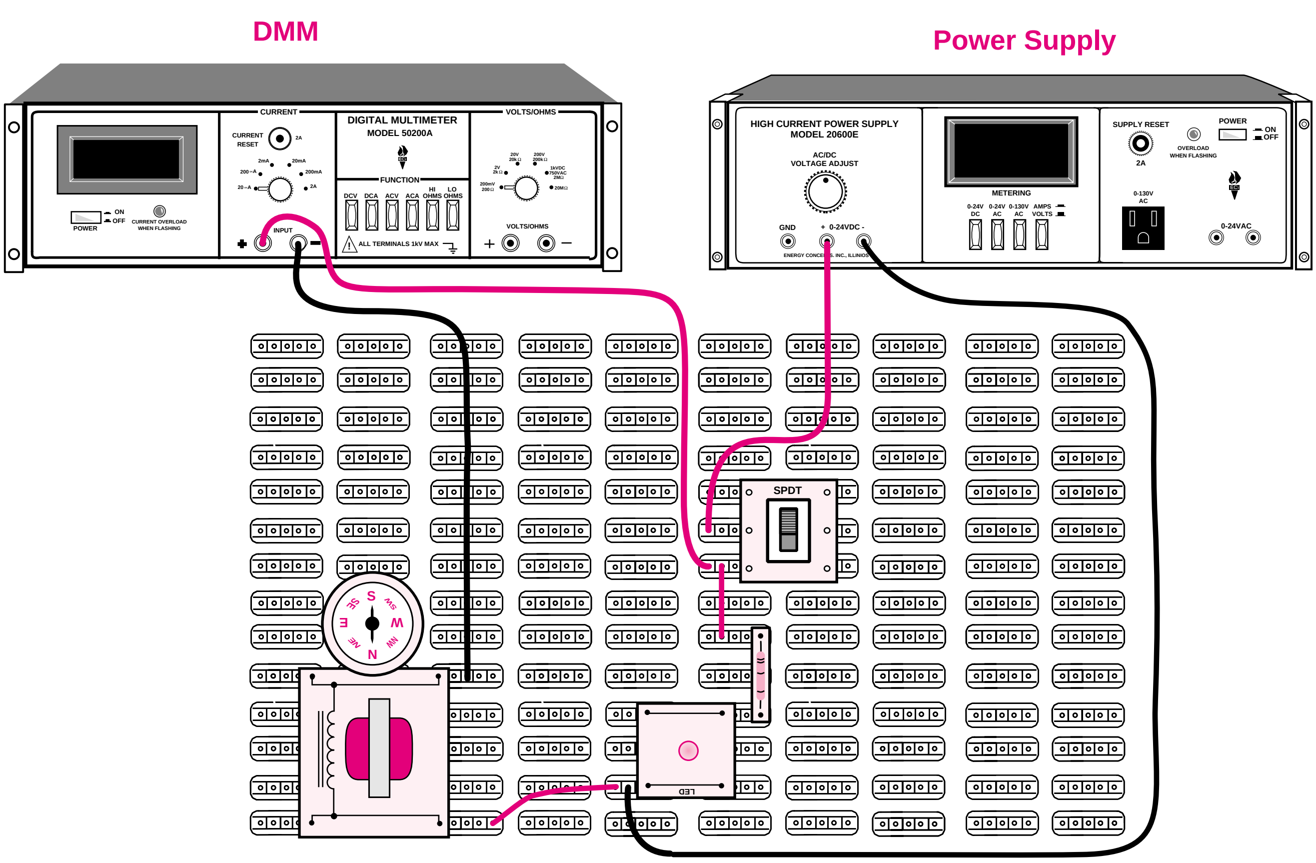


Figure 8
Lab setup for Part 1

❑ 1. Set the DMM function to measure LO ohms. Set the range switch to read 200 ohms. Connect the leads to the volt/ohm terminals of the DMM.

❑ 2. Measure the resistance of the inductor to the nearest ohm. See Figure 9. Record this value as DC resistance of inductor under Observations in Data Table 1 of your Student Journal.

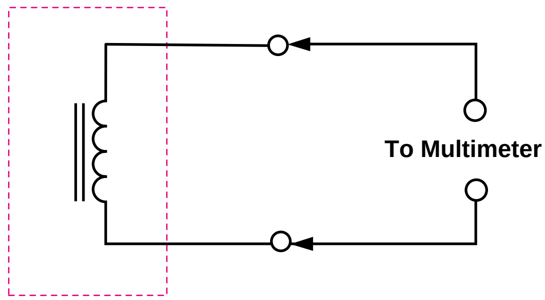


Figure 9
Measuring DC resistance of an inductor

❑ 3. When running this experiment, you will place 5.0 volts DC across the inductor. Record 5.0 DC volts as the theoretical voltage $V_{theoretical}$ under Observations in Data Table 1 of your Student Journal. Use Ohm's law to find the theoretical DC current $I_{theoretical}$ that will flow through the inductor during the experiment.

$$V = IR$$

$$I\ (\text{Amps}) = \frac{V\ (\text{Volts})}{R\ (\text{Ohms})}$$

$$I\ (\text{Amps}) = \frac{5.0\ \text{Volts}}{\_\_\_\ \text{Ohms}}$$

$$I = \_\_\_\_\_\ \text{Amps}$$

Record the theoretical DC current $I_{theoretical}$ that you calculate will flow through the inductor under Observations in Data Table 1 of your Student Journal.

❑ 4. In the discussion you learned that the potential energy stored in the magnetic field of the inductor is equal to

$$PE = {}^{1}/_{2}\, L\, I^2$$

Where

PE = Potential energy stored in the magnetic field

L = Inductance of the inductor

I = Steady-state current flowing through the inductor

The inductance for this inductor is given as 1.5 henries (H).

Use the theoretical current determined in step 3 to find the theoretical potential energy stored in the magnetic field of the inductor. Record this value as $PE_{theoretical}$ under Observations in Data Table 1 of your Student Journal.

❑ 5. Connect the circuit as shown in Figure 10.

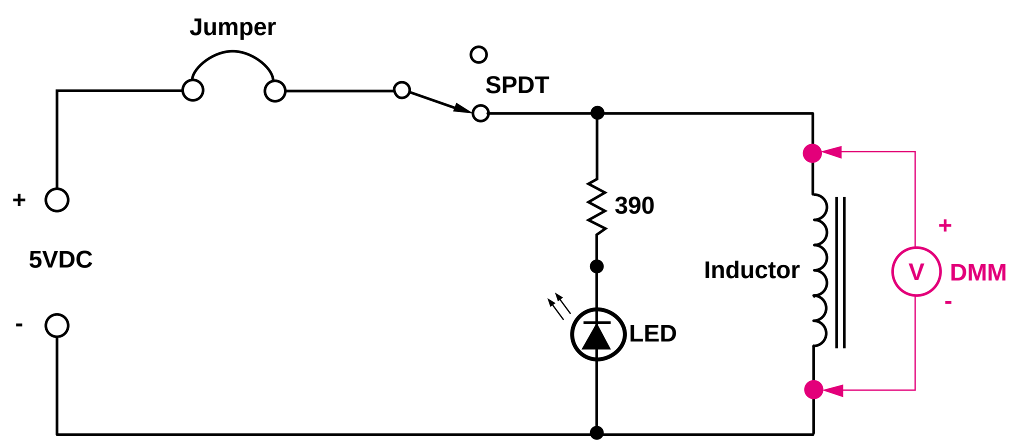


Figure 10
Measuring voltage across an inductor

❑ 6. Set the function switch on the DMM to VDC and the volts/ohms range switch to 20 volts.

❑ 7. Turn on the DMM and the power supply.

❑ 8. Adjust AC/DC voltage/adjust dial of the power supply so that 5.0 volts DC is across the inductor. Record this value as measured applied voltage $V_{measured}$ in Data Table 2 of your Student Journal.

❑ 9. Turn off the power supply using the power button. Do not change the voltage setting.

❑ 10. Set the function switch of the DMM to DCA and the current range switch to 200 MA.

❑ 11. Replace the jumper wire with the leads fitted with spring tips. Connect the other ends of the leads to the current input on the DMM. See Figure 11. Be sure to observe proper polarity.

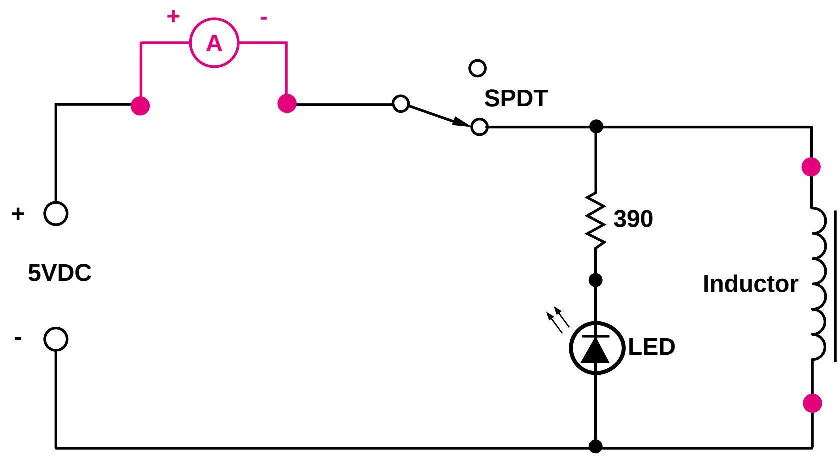


Figure 11
Measuring DC current flow through an inductor

❑ 12. Turn on the power supply.

❑ 13. Read the DC current flowing through the inductor from the display on the DMM. Record this value as measured current $I_{measured}$ under Observations in Data Table 2 of your Student Journal.

❑ 14. Place the compass near the inductor as shown in Figure 12.

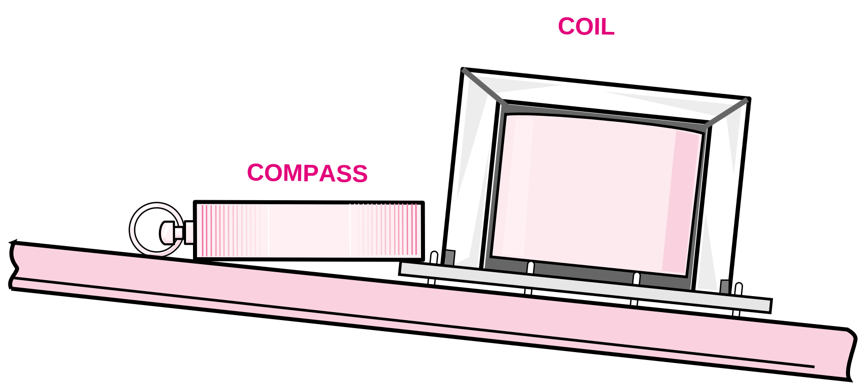


Figure 12
Placement of compass

❑ 15. Again move the switch between closed and open. Observe the behavior of the compass needle. Observe the needle when the switch is closed, then when it is open. Record your observations as step 15 in your Student Journal.

❑ 16. Move the slide switch between its two positions. Notice that the LED flashes in one of the two positions. Is the switch closed or open when the LED lights? Record this answer as step 16 in your Student Journal. Turn off the power supply.

❑ 17. Connect the oscilloscope to the inductor as shown in Figure 13.

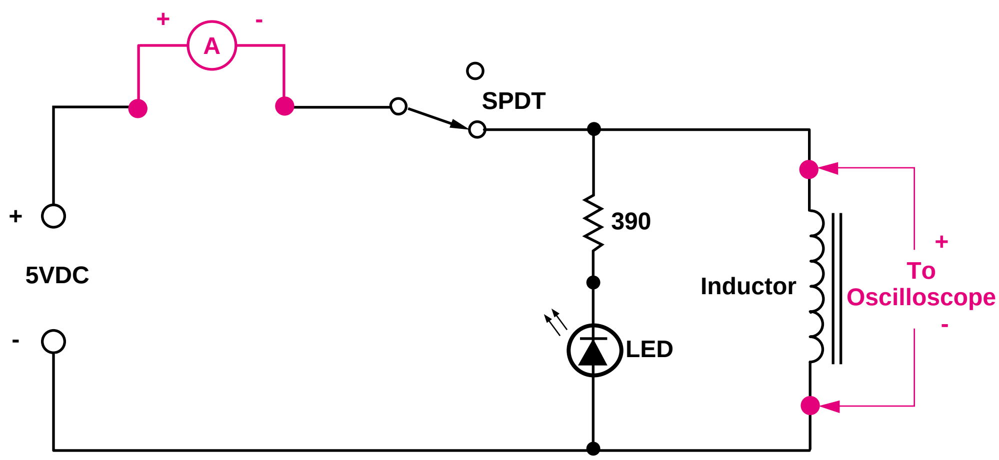


Figure 13
Measuring DC voltage spike and current collapse

Adjust the settings on the front panel of the scope to match the Table 2 below. Be sure to familiarize yourself with proper use of the oscilloscope by reading the instruction manual provided.

Table 2
Oscilloscope Settings

VERNIER	Completely Clockwise
HORIZONTAL TIME/DIV	50 ms
TRIGGER	Auto
TRIGGER SOURCE	Channel 1
TRIGGER HOLDOFF	Normal Lock
TRIGGER SLOPE	Positive
COUPLING (TRIGGER)	Trigger Coupling
VERTICAL MODE	Channel 1
CHANNEL 1 VOLTS/DIV	5 volts
CHANNEL 1 AC/G/DC	DC
PROBE CONNECTION	Channel 1
PROBE SETTING	X 1

❑ 18. Adjust the vertical position of the trace to the second division below the top of the screen. This should be the “zero volt” reading of the trace. Turn on the power supply.

❑ 19. Close the SPDT switch so the DMM indicates that current is flowing through the inductor. Note the position of the trace. Record the number of divisions of this displacement under Observations, step 19a in your Student Journal. Calculate the number of volts represented by this displacement. Using the formula below. Record this value under Observations step 19b.

$$\textbf{Volts} = \textbf{Number of Div} \times \frac{\textbf{Volts}}{\textbf{Div}}$$

$$\textbf{Volts} = \underline{\qquad}\ \textbf{Div} \times \frac{\underline{\quad}\ \textbf{(v)}}{\textbf{(Div)}}$$

$$\textbf{Volts} = \underline{\qquad}$$

❑ 20. Move the slide switch between its open position. Carefully notice the trace on the oscilloscope screen. You may have to repeat opening and closing the switch a few times to observe a representative form of the trace. Allow the current in the inductor to reach steady-state condition between switch positions. Draw a representation of the trace in your Student Journal under Observations, step 20.

❑ 21. Locate the lowest point of the trace on the screen. What voltage does this point represent? Record your answer in your Student Journal under Observations, step 21a. You may have to repeat step 20 a few times to clearly observe the trace pattern. Is the voltage more or less than you applied to the inductor? Explain your answer. Record your answer in your Student Journal under Observations, step 21b.

❑ 22. When moving the switch and observing the trace, you should notice an upward and a downward stroke of the trace pattern. You will need to coordinate the trace with your action on the slide switch to identify the relationship. What does the upward part of the trace represent? Record this answer in your Student Journal under step 22a. What does the downward part of the trace represent? Record this answer in your Student Journal under step 22b.

❑ 23. Turn off the power supply.

❑ 24. Remove the DMM leads from the circuit. Replace the jumper wire in the circuit as shown in Figure 10.

Procedure Part 2

AC Voltage Across the Inductor

In the previous part of this experiment you investigated the interactions of a DC voltage across the inductor. In this part you will look at AC voltage across the inductor.

❑ 25. Move the leads of the power supply from the 0-24 VDC terminals to the 0-24 VAC terminals of the power supply. Remove the LED and the resistor from the circuit.

❑ 26. On the DMM panel, select the ACV function switch. Move the leads to the volts/ohms terminals of the DMM. Connect the leads from the DMM to the circuit as shown in Figure 14.

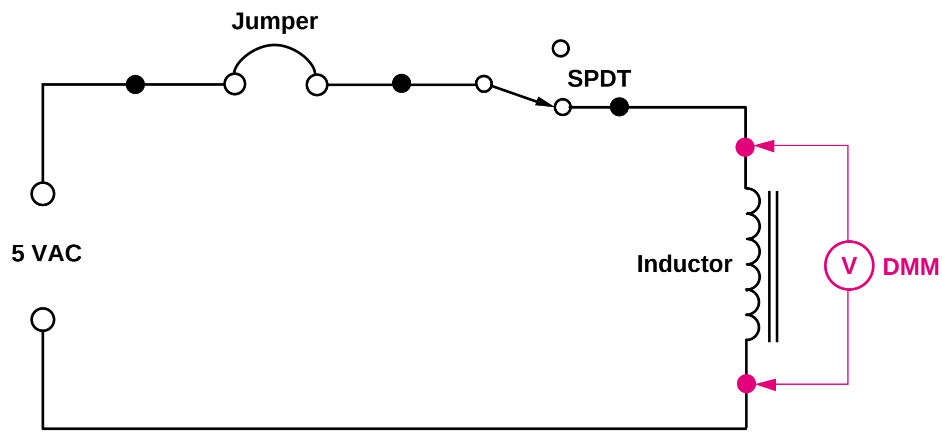


Figure 14
Measuring AC voltage across inductor

❑ 27. Adjust the power supply so the applied voltage is 5.0 volts AC as read by the DMM. Turn off the power supply using the power switch. Do not change the voltage setting.

❑ 28. Remove the leads of the DMM from the circuit. Replace the jumper wires with the leads from the DMM. Move the other end of the leads from the volts/ohms terminals to the current input terminals of the DMM. See Figure 15.

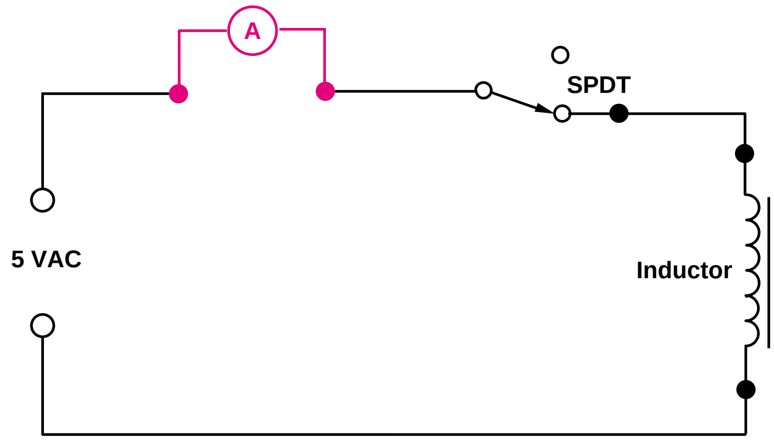


Figure 15
Measuring AC current flow through an inductor

❑ 29. Set the current range switch to 200 MA. And set the function switch to ACA.

❑ 30. Turn on the power supply then slide the slide switch to the closed position. Record the current reading from the panel of the DMM as AC current step 30 under Observations in your Student Journal.

❑ 31. From Ohm's law, the current flow through an electrical component is equal to the voltage across the component divided by the resistance of the component.

$$\frac{\textbf{V (Volts)}}{\textbf{I (Amps)}} = \textbf{R (Ohms)}$$

Since the voltage in part 1 and 2 was 5.0 volts in each case, but the current was different, what can be said about the apparent opposition to current flow of the inductor when used with AC voltage applied? Record your answer as step 31 in your Student Journal.

Calculations

❑ 32. Calculate the measured potential energy stored in the magnetic field of the inductor. From part 1 of this experiment. Use the relationship below:

$$\mathbf{PE = {}^{1}/_{2}\, L\, I^2}$$

Where

PE = Calculated potential energy stored in the magnetic field

L = Inductance of the inductor

I = Measured steady state current flowing through the inductor

Record this value as $PE_{calculated}$ under Observations in Data Table 2 of your Student Journal.

Questions and Interpretations

1. What relationship did this experiment lead you to believe existed between the DC and the AC opposition to current flow in an inductor?

2. From studying the discussion to this experiment, how could you store more potential energy in an inductor?

3. When the switch was closed allowing DC current to flow in the circuit of Figure 7, did the back EMF aid or oppose the applied voltage?

4. In step 16, when the switch was toggled, where did the energy to light the LED come from?

5. When the switch was opened, stopping the flow of DC current in the circuit of Figure 11, was the polarity of the EMF the same as or opposite to the polarity of the applied voltage?