

## Experiment 3 Inductors and Transformers

**Purpose:** Partly as preparation for the next project and partly to help develop a more complete picture of voltage sources, we will return to considering inductors. The extension we are primarily concerned with is the mutual inductor or transformer. The transformer has three uses: stepping up or down voltages, stepping up or down currents, and transforming impedances. Like other devices we have considered, the transformer does not work in an ideal manner for all circumstances.

Equipment Required:

- HP 34401A Digital Multimeter
- HP 33120A 15 MHz Function / Arbitrary Waveform Generator
- HP 54603B 2 Channel 60 MHz Oscilloscope
- Enameled Magnet Wire
- Iron Ring or Core, Nail, Paper Tube

Helpful links for this experiment can be found on the links page for this course:

<http://hibp.ecse.rpi.edu/~connor/education/EILinks.html#Exp3>

### Part A Making an Inductor

#### Background

*Calculating Inductance:* An inductor consists of a wire of conductive material wound around a (usually) solid object called a core. The inductance of an inductor depends on the material and geometry of both the coil and the core. Inductors have larger values when the core material is a magnetic material like iron. The value of the inductance will also depend on the geometry of the core material. Each physical coil geometry has a unique equation to calculate its inductance. Just for simplicity, we will address only one geometry, the cylindrical core. This produces the kind of inductors we have used in previous experiments. If you do not recall what they look like, get one out and look at it. If the core cylinder has a radius equal to  $r_c$  and we wind a coil  $N$  times around the cylinder to cover a length  $d$ , the inductor will have an inductance equal to:

$$L = \frac{(\mu_0 N^2 \pi r_c^2)}{d} \text{Henries}$$

where  $\mu_0 = 4\pi \times 10^{-7}$  Henries/meter. If the core is not air, but rather some magnetic material, replace  $\mu_0$  with  $\mu$ , that is usually many times larger than  $\mu_0$ . By many times we can mean as much as  $10^5$  times larger. You should know that this formula only works well when the length  $d$  is much larger than the radius  $r_c$ .

What if you have a coil in which  $d$  is not very large compared to  $r_c$ ? This coil would look more like a finger ring and have the shape of a coin. In this case, the above equation would over-estimate the value of the inductance and, thus, it is only useful to find a ballpark number. However, you can use this equation to get a better estimate of the inductance of a ring-shaped coil.

$$L \cong \mu N^2 r_c \left\{ \ln\left(\frac{8r_c}{r_w}\right) - 2 \right\}$$

where  $r_c$  is the major radius of the coil and  $r_w$  is the radius of the wire. A link to calculations (based on this coil shape and others) from the University of Missouri-Rolla Electromagnetic Compatibility Laboratory can be found on the links page. (Electromagnetic Compatibility, or EMC, refers to the ability of a device or system to function without error in its intended electromagnetic environment. Electromagnetic Interference, or EMI, refers to electromagnetic emissions from a device or system that interferes with the

normal operation of another device or system. Both are very big issues indeed in electromechanical systems.)

*Calculating Resistance:* When one makes an inductor, the wires used can have a large variety of cross sectional areas. There are some inductors made with very thick wires, while others are made with very thin wires. Thin wires permit one to wind many more turns of wire around a core and thus increase the inductance. Thick wires have lower resistance for any given length. All wires have a resistance given by

the expression  $R = \frac{l}{\sigma A}$ , where  $l$  is the length of the wire,  $A$  is the cross sectional area of the wire

(thickness), and  $\sigma$  is the conductivity of the wire material. For copper, the conductivity is about  $6 \times 10^7$  Siemens/meter. The unit of Siemens is  $1/\Omega$ . Sea water has a conductivity of 5 Siemens/meter. There are many handbooks like the [CRC Handbook of Chemistry and Physics](#) that have the resistance of different diameter wires per mile (or another unit of distance). It is also quite easy to calculate the resistance of a piece of wire using the formula above. The links page contains several links to tables with conductivity information.

## Experiment

### *Build an Inductor*

In this part of our experiment, we will build an inductor and compare its calculated properties to its measured properties.

- Build an inductor from enameled wire using the following procedure.
  - Build a paper core to wind your coil on. Take a sheet of paper and roll it into a tight cylinder about an inch in diameter. Tape the roll so it does not unwind.
  - Take at least 2 feet of enameled wire. Note the gauge of the wire you are using. Measure its exact length.
  - Remove some of the enamel from the ends of the wire (1/2 to 1 inch). The enamel is the insulation for this type of wire, so you cannot make electrical contact unless it is removed. There should be some sandpaper for this purpose or you can use a knife. You will be provided with wood blocks to do your sanding on. **Please do not sand the table tops when you remove the enamel!**
  - Wrap it tightly *in a single layer* around your roll of paper. Carefully keep track of the number of times you wind the wire around the paper roll. This is the number of turns of your inductor,  $N$ .
  - Leave about 1 inch of wire at each end of the coil so you will have something to connect to. Tape the wire in place.
- Calculate the properties of the inductor
  - Calculate an estimate for the resistance of the wire. Look up the dimensions of the wire in a table of wire properties listed by gauge. Calculate the resistance using the equation.
  - Calculate an estimate for the inductance using the inductor equation for a long, thin coil.
  - Calculate an estimate for the inductance using the inductor equation for a ring-shaped coil.
  - Based on the shape of your coil, which equation should give a closer estimate of the actual inductance?
- Measure the properties of the inductor
  - Measure the resistance using the multimeter. When you measure small resistances, it is *important* to first measure the resistance of the wires you are using to connect the coil to the meter. Then, add the coil and measure again. The resistance of the inductor will be the difference between the resistance of the wires alone and the resistance of the wires with the inductor. Does your measured value agree at least roughly with the calculated value?
  - Measure the inductance of your coil directly with the impedance bridge on the table in the center of the classroom. Which equation gave you a better estimate of the measured value?

## Summary

We can get an approximate expression for the inductance using an equation for an ideal model based on the geometry of the inductor and the materials from which it is made. The ideal model of the cylindrical inductor will generally over-estimate the inductance. We can get a larger inductance and also a more predictable inductance by winding the coil around a piece of iron rather than a paper tube. The permeability of iron is many times larger than that of air. We can also use an equation to estimate resistance.

## Part B Measurement of Inductance

### Background

*Using circuits to estimate inductance:* Now we will use a better method to estimate the inductance of our coil. In the circuit in figure B-1, V1 and R1 represent the function generator, R2 is a 50 ohm load connected to the function generator by a parallel combination of an inductor and a capacitor.

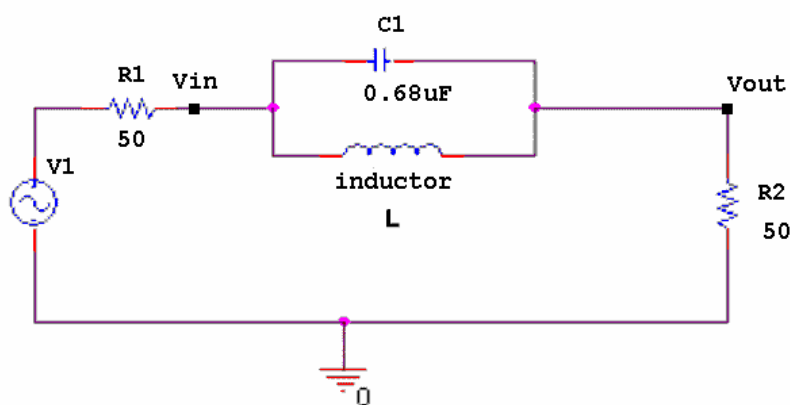


Figure B-1

The inductor will have a positive imaginary impedance given by  $j\omega L$  while the capacitor will have a negative imaginary impedance given by  $\frac{1}{j\omega C}$  or equivalently  $\frac{-j}{\omega C}$ . If we redraw our circuit at low and high frequencies, we can see that at both extremes, the output will be at the center of a voltage divider. Its magnitude should be  $\frac{1}{2}$  the input voltage. At the resonant frequency,  $f_0 = \frac{1}{2\pi\sqrt{L \cdot C1}}$ , the voltage difference across the combination of inductor and capacitor will achieve its most extreme value. We can use this equation and the resonant frequency of a circuit we build to solve for L1.

### Experiment

*The resonant frequency of a circuit can be used to find inductance*

In this experiment, we will build an RLC circuit, find its resonant frequency, and use it to solve for an unknown inductance.

- Find the values for the actual components in your circuit.
  - Measure the capacitance of a 0.68  $\mu\text{F}$  capacitor using the impedance bridge. Do not remove the inductor from the tube. Any changes in the geometry of the inductor changes its inductance. To get the best results, tape it in place.
  - Measure the resistance of a 50 ohm resistor. (The other resistance in the circuit is the 50 ohm impedance of the function generator.)
  - Write down the mathematical value you calculated for the inductance in part A. Use the value from the equation that gave you an amount closest to the measured inductance. We will call

this inductance  $L_c$ . (Remember that we are treating the inductance as unknown, so we *cannot* use the inductance you measured with the impedance bridge.)

- Calculate an estimate for the resonant frequency,  $f_{initial} = \frac{1}{2\pi\sqrt{L_c \cdot C1}}$ , using the capacitance you measured and the inductance you calculated.
- Find the experimental resonant frequency
  - Set up the circuit in figure B-1 on your proto-board. Use the capacitor and resistor you measured and the inductor you built. Be careful to make sure that the inductor is making contact inside the protoboard. Do not remove the inductor from the paper tube.
  - Set the amplitude of your output to 1V. You observe the voltage at  $V_{in}$  on one scope channel and the voltage at  $V_{out}$  on the other channel.
  - Adjust the frequency until the impedance of the LC combination is around the resonant frequency you calculated. Adjust the frequency until the output reaches its most extreme value. Why does the voltage at  $V_{out}$  go down at resonance instead of up? DO NOT ASSUME that the value you measure is exactly the same as  $f_{initial}$ . The calculation for inductance only gives you a rough estimate. Now you are using *the circuit* to get a CLOSER estimate. When you are satisfied you have located the resonant frequency, enter it in the table below. Also list the peak-to-peak values for  $V_{in}$  and  $V_{out}$ .
  - Find a frequency below and above resonance where the LC combination is more-or-less negligible (looks like a short circuit). Enter these frequencies and voltages in the table.
  - Take a picture using the Agilent software of the input and output at the resonant frequency.

	Frequency	$V_{in}$ (peak-to-peak)	$V_{out}$ (peak-to-peak)
Below Resonance			
At Resonance			
Above Resonance			

- Calculate an estimate for the unknown inductance,  $L_{est}$ , using the equation,  $f_{better} = \frac{1}{2\pi\sqrt{L_{est} C1}}$ .

Use the exact resonant frequency you found and the capacitance you measured. What value did you obtain for your unknown inductance? How close is this to the one you measured on the impedance bridge? Is it closer than the estimate you found using the inductance equations?

*Use a simulation to get the best estimate of the unknown inductance*

In this part of the experiment we will use *PSpice* to simulate the circuit we built and get the closest estimate we can to the actual inductance.

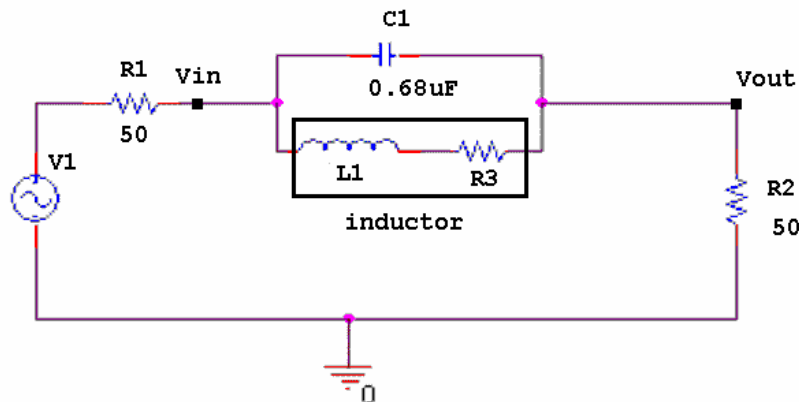


Figure B-2

- Simulate the circuit in figure B-2 in *PSpice*. This is the same circuit as the one pictured in B-1, but the inductor (because it *does not* have an insignificant internal resistance) is more accurately simulated by two components, an inductor and a resistor.
  - Use the measured value for the capacitor and the resistor. Recall that inductors do not have negligible resistance. Therefore, in the *PSpice* model, the inductor you built looks like an inductor and a resistor in series. Use the value you measured for the resistance of the inductor for R3 and the inductance that you just calculated ( $L_{est}$ ) for the L1.
  - Create an AC sweep and determine where the plot reaches a minimum.
  - If the minimum is exactly at the resonant frequency you found for the circuit you built, then your value for L1 is as close as you are going to get to a good theoretical estimate. If it is not, adjust the value of L1 in the circuit until the minimum point in the AC sweep is identical to the resonant frequency you found using the real circuit ( $f_{better}$ ).
- When you have found a good value for L1, print out the plot of the AC sweep. Mark the extreme point. Also write your experimental resonant frequency and the new estimate for L on your plot.

### Summary

In this experiment, you have found an estimate for the impedance of the inductor you built by placing it into a circuit. By finding the resonant frequency of the circuit, you were able to find an estimate for L in two ways: by calculating it using the equation for resonant frequency and by simulating the circuit in *PSpice* and choosing the inductance value such that the resonant frequency matched that of your circuit. How do these two values compare to the inductance you measured using the impedance bridge?

## Part C Transformers

### Background

*Inducing a Current:* Inductors work by creating a magnetic field. When you run a current through an inductor it becomes an electromagnet. The direction of the magnetic field can be found by placing your right hand around the core in the direction of the coil. Your thumb will point in the direction of the magnetic field, as shown in figure C-1.

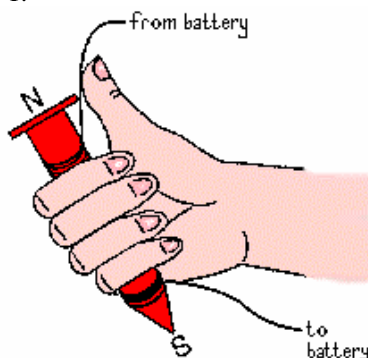


Figure C-1

If one inductor is placed near another inductor, then the magnetic fields of the two inductors will interact with one another. If you have ever built an electromagnet, you will know that the magnets will attract or repel one another if the current in the coil is large enough. Even when we cannot sense that they are interacting, a current in one coil will induce a current in a nearby coil.

*Transformers:* A transformer is a device that takes advantage of the fact that one inductor can induce a current in another inductor. We use it to transform one voltage level into another. A “step up” transformer will make a small voltage larger and a “step down” transformer will make a large voltage smaller. We make transformers by winding coils of wire around some kind of a core material. Sometimes the core

material is just air, as when we wind the wire around a paper tube, for example. Most of the time, the core material is iron or some other magnetic material. To maximize this interaction, we usually wind the coils onto the same core and make them look as similar as possible.

In the transformer circuit in figure C-2, the voltage source ( $V_S$ ) and the 50 ohm resistor ( $R_S$ ) represent a sinusoidal voltage source like the function generator we use in the studio.  $R_L$  is the load on the transformer represented by a single resistance and TX1 is the transformer. The primary (or source) inductor in the transformer,  $L_S$ , draws a current from the source. The magnetic field created by  $L_S$  induces a current in the secondary (or load) inductor,  $L_L$ . This creates a new voltage to power the load,  $R_L$ .

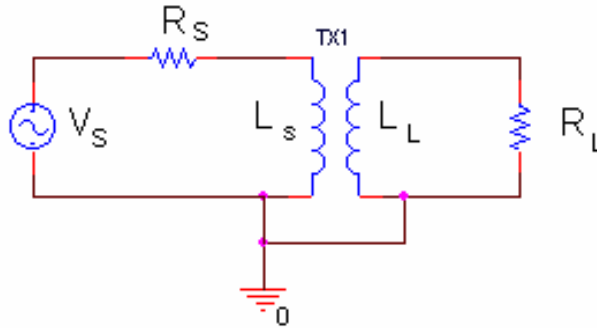


Figure C-2

Transformers only work for time varying currents and voltages. Note that when the coils are as similar as possible, all the geometric terms in the formulas for the inductance will be the same for the primary and the secondary coils. Only the number of turns will be different. We can demonstrate this using our equation for the inductance of a long, thin coil.

$$\frac{L_1}{L_2} = \frac{(\mu_0 N_1^2 \pi r_c^2) / d}{(\mu_0 N_2^2 \pi r_c^2) / d} = \frac{N_1^2}{N_2^2}$$

Since we try to make  $\mu_0$ ,  $r_c$  and  $d$  the same, these terms cancel out and we are left with the ratio of the inductances depending only upon the ratio of the number of turns squared.

*Transformer Analysis:* To analyze just how a transformer works, we have to add an additional kind of inductance, called mutual inductance. If a coil of wire of inductance  $L_1$  is very near another coil of inductance  $L_2$ , there will be a mutual inductance  $M$  between the two coils, where  $M^2 = k^2 L_1 L_2$ . The constant  $k$  is the coupling coefficient. If the coils are perfectly coupled,  $k = 1$ . Usually  $k$  is a little less than 1 in a good transformer.

Referring to figure C-2, the two loop or mesh equations that apply to the two current loops in the transformer circuit are

$$\text{Primary Loop: } V_S = I_S (R_S + j\omega L_S) - I_L (j\omega M)$$

$$\text{Secondary Loop: } 0 = -I_S (j\omega M) + I_L (R_L + j\omega L_L)$$

where  $L_S$  is the inductance of the primary (source) coil and  $L_L$  is the inductance of the secondary (load) coil. By convention, the coil connected to the source is called the primary coil and the coil connected to the load is called the secondary coil. The  $L$  and  $M$  terms have opposite signs because the loop currents go in opposite directions. Thus, the voltage generated by one coil will influence the other in the opposite direction. The input impedance is the impedance across the primary coil,  $L_S$ . Since  $V=IZ$  and the current through all the elements in the primary coil is  $I_S$

$$V_S = I_S R_S + I_S Z_{in} \quad Z_{in} = \frac{V_S}{I_S} - R_S$$

We can solve the primary loop equation for  $Z_{in}$  by solving for  $(V_S/I_S) - R_S$

$$Z_{in} = \frac{V_S}{I_S} - R_S = j\omega L_S - \frac{I_L}{I_S}(j\omega M)$$

If we solve the secondary loop equation for  $I_L/I_S$ , we can then substitute for this ratio in the equation above:

$$\frac{I_L}{I_S} = \frac{j\omega M}{j\omega L_L + R_L}$$

$$Z_{in} = j\omega L_S - \frac{(j\omega M)^2}{j\omega L_L + R_L} = j\omega L_S + \frac{\omega^2 M^2}{j\omega L_L + R_L}$$

We know that by definition,  $M^2 = k^2 L_S L_L$ , and for an ideal transformer, the coupling constant  $k = 1$ , so

$$Z_{in} = j\omega L_S + \frac{\omega^2 k^2 L_S L_L}{j\omega L_L + R_L} = j\omega L_S + \frac{\omega^2 L_S L_L}{j\omega L_L + R_L} = \frac{j\omega L_S R_L}{j\omega L_L + R_L}$$

Now, let both  $L_S$  and  $L_L$  or  $\omega$  become very large (tend to infinity). The  $R_L$  term in the denominator will drop out and

$$Z_{in} = \frac{L_S R_L}{L_L}$$

If we define a constant,  $a$ , that has the following property:  $L_L = a^2 L_S$  then,

$$Z_{in} = R_L/a^2$$

Thus, the transformer transforms the load resistance  $R_L$  by the square of the turns ratio,  $a = N_L/N_S$  where  $N_S$  is the number of turns in the primary coil and  $N_L$  is the number of turns in the secondary coil. This is the first, and most stringent, relationship for an ideal transformer. Remember that  $Z_{in}$  is the ratio of the input voltage to the input current. In any circuit that we build or simulate, we can determine  $Z_{in}$  by finding this ratio.

The relationship between the primary and secondary currents in the transformer can be found from the second loop equation. Solving again for the case where the inductances become very large, we find that

$$a^2 = \frac{L_L}{L_S} \quad a = \sqrt{\frac{L_L}{L_S}} = \frac{N_L}{N_S} = \frac{V_L}{V_S} = \frac{I_S}{I_L}$$

Note that both the voltage and current relationships shown actually contain no sign information. Depending on how the transformer is wired, it is possible for minus signs to appear in these expressions. Thus, you should consider that they hold only for magnitudes. As with  $Z_{in}$ , we can determine these ratios by measuring the voltages and currents separately and then taking their ratios. When we design a particular transformer, we usually have a turns ratio in mind. For example, in the DC power supplies that come with consumer electronics (also called wall worts), there is a step-down transformer that takes the 120 volt line voltage and steps it down to a smaller voltage, like 6 or 12 volts. In such devices,  $N_S/N_L$  is chosen to be 10

or 20, depending upon the desired output voltage. This voltage is then rectified with a full-wave rectifier and sometimes regulated with a zener diode to produce a DC voltage. You will learn more about rectifiers and zener diodes later in this course.

*Working Range of a Transformer:* Although the equations for transformer behavior are quite simple, many assumptions need to be made in order to satisfy them. A transformer will not behave in a circuit according to the equations for all frequencies or load resistances. In order for a transformer to be working properly, the following expressions must all be satisfied when  $a^2 = L_L/L_S$  :

$$Z_{in} = \frac{R_L}{a^2} \quad a = \frac{V_L}{V_S} \quad a = \frac{I_S}{I_L}$$

## Experiment

### Simulation of Transformer

In this section, we will use *PSpice* to create a transformer circuit and find the input frequencies where it is behaving according to the transformer equations.

- Set up the circuit pictured in figure C-3 in *Capture*.
  - For the voltage source  $V_S$ , use VSIN and assume an amplitude of 1 volt, a frequency of 1k, and a DC offset of 0. Also set the AC voltage in the spread sheet to 1 volt.
  - Set the input resistance to 50 ohms (the internal impedance of the function generator) and the load resistance to 50 ohms.
  - For the transformer (XFRM\_LINEAR in the ANALOG library), you need to set the coupling coefficient. Choose 1 for perfect coupling. You also need to set the primary and secondary inductances, L1 and L2. For your first simulation, set L1 and L2 both to 1 mH.

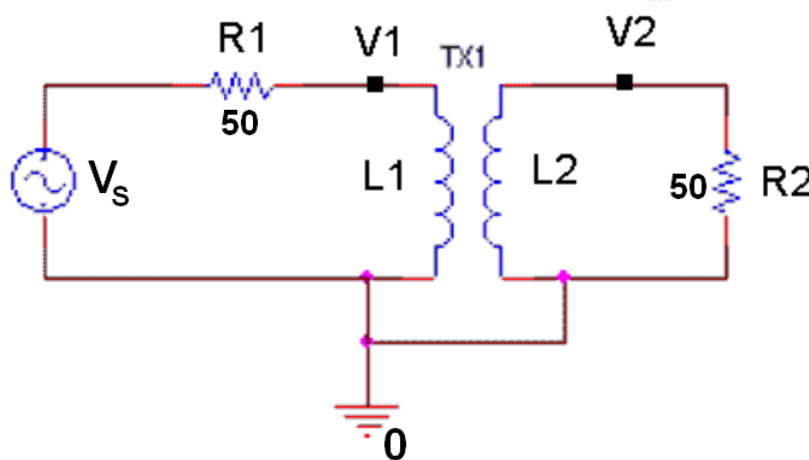


Figure C-3

- Perform an AC sweep from 1 Hz to 10 Meg Hz.
- In order to determine when the transformer is working correctly, we need to determine the frequencies where the relationships for  $Z_{in}$ , V and I are satisfied. Recall this means that  $V_2/V_1$  and  $I_1/I_2$  must be equal to a constant, a. (When R1 is much smaller than R2, we assume that  $V_1=V_S$ ). To find where our transformer works, we can plot the three relationships and determine where all three are satisfied. To avoid dividing by zero current, we will plot  $1/a$ .
  - Find the constant, a, using the ratio of  $\sqrt{L_2}$  to  $\sqrt{L_1}$ . Remember that the ratio of N2 to N1 is determined from the ratio of the square roots of L2 and L1.
  - Add a trace of  $V_1/V_2$ , where V1 is the voltage across the primary coil and V2 is the voltage across the secondary coil.



- Add a trace of  $I_2/I_1$ , where  $I_2$  is the current through the secondary load resistor and  $I_1$  is the current through the resistor in the primary loop. Because *PSpice* is picky about polarities, this ratio may be negative. Multiply it by -1 or change the polarity of one of the resistors to make it positive.
- For the third criteria, we must solve  $Z_{in} = R_2/a^2$  for  $1/a$ . This means  $1/a$  must be equal to  $\sqrt{Z_{in}/R_2}$ .  $Z_{in}$  is the impedance of the primary inductor,  $L_1$ . It is equal to the voltage across  $L_1$  ( $V_1$ ) divided by the current in the source loop ( $I_1$ ). Therefore, to plot  $1/a$ , we must plot  $\sqrt{[(V_1/I_1)/R_2]}$ . Add a trace of  $1/a = \text{SQRT}[(V_1/I_1)/50]$ .
- Print out one plot with all three ratios. Mark the frequency range where all three criteria are satisfied on the plot.
- By trying a variety of values for  $L_1$  and  $L_2$ , find a transformer for which the three relationships are satisfied and  $a=10$  ( $1/a=1/10$ ). In this case, the voltage across the primary coil will be  $1/10$  the voltage across the secondary coil and the other two expressions will also be satisfied. *Use the smallest possible inductances you need to make the transformer work properly at 10K Hz and above.* (To change the effective frequency, you must increase or decrease both  $L_1$  and  $L_2$ , while keeping the ratio of the square roots the same ( $1/10$ )). Write down the values for  $L_1$  and  $L_2$  that you have selected and print your PROBE plot with the three ratios that demonstrate that the transformer works as specified.
- Now repeat the task of the last paragraph for frequencies of 100 Hz and up. Write down the values for  $L_1$  and  $L_2$  that you have selected and print your PROBE plot with the three ratios that demonstrate that the transformer works as specified. What design advantages exist for circuits that are to work at higher frequencies rather than lower frequencies?

### Summary

In this section you learned that the behavior of transformers are governed by simple proportions. However, real transformers only conform to those simple ratios under certain conditions.

### Part D: Making a Transformer

#### Background

*Designing a Transformer:* To design a transformer for which the output voltage is the same as the input voltage, we must have the same number of turns on our output coil as on our input coil. We must also find a range of frequencies for which our transformer actually works as it should. Since you already have one coil, the addition of a second coil will result in a configuration that can be used as a transformer.

#### Experiment

##### *Build a Transformer*

Make a transformer by winding a second coil directly over the inductor you already built.

- Wind a second coil on your paper tube that has exactly the same number of wounds as your first coil. In order to get decent coupling you must try to get the two coils to be as close as possible to one another. Because you have an air core (with a very low permeability), you will need to *wind the second coil directly on top of the first coil*. Be sure that you count the number of turns in both your coils.
- Mark the ends of each coil, so that you know how to hook them up.
- Remove enamel from the ends of your second coil so you can make good electrical contact.
- You have now built a transformer where one of your coils is the primary and one is the secondary.
- Calculate the value of  $a$  using the number of turns in the two coils. How should this value affect the magnitude of your output voltage relative to your input voltage?

Find a frequency where your transformer works

We know from our PSpice simulation that this transformer will only work at certain frequencies.

- Hook one of your two inductors to the function generator. Set the amplitude of the function generator to 1V. Hook the other inductor to a resistance of 50 ohms. Note that the transformer wires don't always contact well with the protoboard. The most reliable way to hook up the transformer is with mini-grabbers and alligator clips.
- Find a frequency for which the voltage ratio of your transformer works more-or-less as expected. This may be very high because your transformer does not have perfect coupling. Note that you will observe a change in amplitude of both the input and the output voltages as you increase the frequency. This is consistent with the behavior of the transformer you used in PSpice.
- Obtain an Agilent plot of the output of your transformer at a frequency for which the voltage ratio equation is satisfied. Be sure that you display the input to the transformer on one scope channel and the output on the other. Print this plot and include it with your report.

### Summary

In a transformer, the time-varying field is produced by an electromagnet with a time-varying current in it (coil #1) and sensed by a similar coil (coil #2). As far as a stationary coil is concerned, it is not possible to tell whether the time-varying magnetic field is produced by a stationary electromagnet or a moving permanent magnet, as long as the field produced oscillates in time. The time-varying magnetic field generates a voltage and current in the second coil. This is the basic principle of electrical generators. Electrical motors are mostly just generators run backwards. In the next project, we will build a motor using a permanent magnet and a coil like the ones you have just wound. You should recall the analysis done here when you do the project so you will be able to figure out the resistance and inductance of your motor coil.

### Report and Conclusions

The following should be included in your report. Everything should be labeled and easy to find. Partial credit will be deducted for poor labeling or unclear presentation.

#### Part A (10 points)

Answer following questions:

1. What value did you calculate for the resistance of the inductor? How did this compare to the measured resistance? (4 pt)
2. What two values did you calculate for the inductance of the inductor? How did these compare to the measured inductance? Which equation worked better? Why? (6 pt)

#### Part B (30 points)

Include Following plots:

1. Agilent plot of the input and output of the RLC circuit at the resonant frequency. (2 pt)
2. PSpice sweep of the AC sweep of your RLC circuit with the value of L that places you closest to the resonant frequency of the circuit you built. (4 pt)

Answer following questions:

1. What are the measured values for the capacitance of your capacitor and the resistance of your resistor? (2 pt)
2. What frequency did you calculate for the expected resonant frequency of your circuit? (2 pt)
3. At what frequency did you actually find the resonance of your circuit? (2 pt)
4. For what range of low frequencies was the influence of the inductor/capacitor combination in the circuit negligible (equivalent to a short)? For what range of high frequencies was the influence of the inductor/capacitor combination in the circuit negligible (equivalent to a short)? (2 pt)
5. What value did you get for  $L_{est}$  using the equation for the resonant frequency? (2 pt)

6. What value of L1 did you get when you adjusted your *Capture* circuit to match the resonant frequency of the circuit you built? (2 pt)
7. Which of the inductances you found was closest to the one measured with the impedance bridge? By what percentage was it off? Why do you think this gave you the best estimate? (3 pt)
8. Find the transfer function of the circuit you used in part B. You do not need to include the resistance of your inductor in the calculations. The function should be in terms of R1, C1, R2 and L. Determine the value of the transfer function at very low frequencies, very high frequencies and the resonant frequency. (5 pt)
9. What effect do you think adding the inductor resistance has on circuit behavior at very low and very high frequencies? (Hint: Draw the circuit with the resistor for the inductance included. Redraw the circuit at very low and very high frequencies by replacing the inductor and the capacitor by shorts or open circuits. Consider the value of the output voltage in each case.) (4 pt)

**Part C (16 points)**

Include Following plots:

1. *PSpice* plot of the initial 3 traces of the ratios for the transformer when L1=1m and L2=1m. (2 pt)
2. *PSpice* plot of the three ratios that prove the transformer works at 10kHz and up. (2 pt)
3. *PSpice* plot of the three ratios that prove the transformer works at 100Hz and up. (2 pt)

Answer Following questions:

1. In what frequency range did the transformer with L1=L2=1mH function as it should? (2 pt)
2. Use your output traces and the three design criteria equations to describe how you know these values satisfy the criteria for an ideal transformer. (2 pt)
3. What are the values of L1 and L2 you chose to obtain correct transformer operation for the range of 10kHz and up? (2 pt)
4. What are the values of L1 and L2 you chose to obtain correct transformer operation for the range of 100Hz and up? (2 pt)
5. What design advantages exist for circuits that are to work at higher frequencies rather than at lower frequencies? (2 pt)

**Part D (12 points)**

Include following plot:

1. Agilent plot with the input and output of your transformer. (2 pt)

Answer following questions:

1. At what frequency did your transformer work as expected? How do you know this? To answer this question, you will need to analyze the voltages observed and show how closely they satisfy the basic formulas for the transformer. (6 pts)
2. List at least 2 things that you could do to the design of your coil to improve your results? (4 pts)

**Summary (12 points)**

1. Summarize key points (8 pts)
2. Discuss mistakes and problems (2 pts)
3. List member responsibilities (2 pts)

**Total: 80 points for write up + 20 for attendance = 100 points**

**Attendance: 3 classes (20 points) 2 classes (10 points) 1 class (0 points) out of 20 possible points  
Minus 5 points for each late.  
No attendance at all = No grade for experiment.**