Lab 3: Inductive Power Transfer

Week 4

In this lab, you will build a resonant inductive coupling mechanism. This will allow you to transfer power wirelessly. In the process, you will use AC analysis and the concepts of impedance matching and resonance. Please answer all lab questions in your report.

1 Inductive Coupling Theory

Inductive power transfer (IPT) is being applied more and more in industry. You can see it in the charging of electric toothbrushes and some cell phones. While the point of consumer products is to make the user think as little as possible about the technology, we are going to do the opposite. In this lab, we will transfer power inductively and light up an LED.

The basic idea behind IPT is based on Faraday's Law and Ampere’s Law. Faraday’s Law states that the induced voltage in a coil is proportional to the rate of change of magnetic flux:

\[ V = -N \frac{d\Phi}{dt}, \]  

(1)

where \( N \) is the number of turns in the coil. Magnetic flux is related to the amount of magnetic field passing perpendicularly through a surface. Thus, in order to induce a current in a remote coil, we need a time-varying magnetic field to go through that coil. We can create such a field using another coil (solenoid) and Amperes Law, which states that the induced magnetic field and the solenoids current are related as:

\[ B = \frac{\mu_0 NI}{l}, \]  

(2)

where \( B \) is the magnetic field magnitude, \( N \) is the number of turns, \( I \) is the current, and \( l \) is the length of the solenoid.

Fig. 1(a) provides a nice visualization of this concept. As alternating current passes through coil 1 (primary), it generates an alternating magnetic field; if the surface formed by coil 2 (secondary) intercepts some of these magnetic field lines, a voltage will appear across its terminals (dictated by eq. (1)).

![Figure 1: (a) Side view of inductive coupling, (b) Simplified model of a transformer.](image-url)
As you can see, not all the lines are passing through coil 2. A common solution to this issue is to use a magnetic core (see Fig. 1(b)) which guides the majority of the magnetic field into the secondary coil; this scheme is used with power transformers, where low energy losses are required. In this lab, our coils will not have cores. It turns out, however, that considerable power can still be transferred.

As (relatively) straightforward as the basic concept is, there are A LOT of variables. For example, how far away can a sufficient current (for a specific task) be induced? How does the orientation of the coils influence the amount of current induced? How many windings are necessary on the primary and secondary? How do we get optimal power transfer?

Let’s explore these questions in the lab.

2 Building the Circuit

2.1 Measuring Coil Inductances

In order to design a functioning circuit, we first have to determine the inductances of the pre-made coils. This can be accomplished using our standard lab equipment (function generator and oscilloscope) and some basic knowledge of AC circuits.

The circuit shown in Fig. 2 depicts the function generator’s alternating voltage source ($V_{Source}$) and internal 50 $\Omega$ resistance. The internal resistance is an inherent property of the function generator, and is not a component that needs to be added explicitly; it is already there. When our inductor is added to the circuit, it will contribute a non-resistive impedance to the flow of AC. This so-called inductive reactance (contrasted with capacitive reactance associated with capacitors) is equal to $j\omega L$. $L$ is the coil inductance (units of Henry), $\omega$ is the angular frequency of the voltage signal ($\omega = 2\pi f$, $f$ = frequency in Hertz), and $j$ is $\sqrt{-1}$.

![Figure 2: Schematic of function generator - inductor circuit.](image)

We now want to measure the value of $L$, and will do so by considering the following. Suppose you want $|V_L|$ to be half of $|V_{Source}|$. What would the relationship need to be between $L$ and $f$? Hint: think of a voltage divider, and don’t worry about the phase of the $V_L$ (although you cannot simply disregard the $j$ during your calculations). If $|V_L|$ is half of $|V_{Source}|$, this means that half of the time-averaged voltage drop occurs across the inductor, while the other half occurs across the
resistor. In such a scenario, what would be the relationship between the magnitude of the resistor’s impedance and the magnitude of the inductor’s impedance?

Connect the function generator to the exposed leads on the primary coil. Start out by generating a 20 kHz sine wave with peak-to-peak value of 1 V. Connect the oscilloscope probes to the same leads (orientation doesn’t matter). Adjust the signal frequency and observe how $|V_L|$ changes. At what driving frequency do you observe $|V_L|$ to be half of $|V_{Source}|$? Using this, calculate $L$.

Use the online inductance calculator (link below) as an alternate way of calculating $L$. Set the relative permeability equal to 1, since our coil has an air core; obtain the remaining values by examining the primary coil. *How does this compare to your first value? Which value do you think is more accurate? Why?* *Hint: read the text on the website. For the purposes of this lab, we will use the first inductance value in our calculations.*

Inductance calculator: http://hyperphysics.phy-astr.gsu.edu/hbase/electric/indsol.html

Repeat the two inductance calculations for the secondary coil. Disconnect the equipment when you are finished.

### 2.2 Choosing Capacitors

Now that we have rough estimates for our inductances, it’s time to pick capacitors. Each circuit needs capacitance in parallel with the inductor to create a resonance condition. The resonant frequency is given by the following formula:

$$f = \frac{1}{2\pi\sqrt{LC}} \text{ (Hz)},$$

where $C$ is the capacitance (units of Farads). By examining your two inductance values, select capacitors such that both primary and secondary circuits resonate at the same frequency. Keep the capacitance of each circuit below 2.2 $\mu$F to facilitate subsequent sections of the lab; provided that you follow this guideline, the frequency you obtain can be arbitrary.

It is likely that your capacitors need to have a ratio that is not formed by any two available capacitors. If you need to combine multiple capacitors, recall the following formulas for equivalent capacitance:

$$C_{eq} = C_1 + C_2 + C_3 + \cdots \text{ (for parallel capacitors)}$$

$$\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \cdots \text{ (for series capacitors)}$$

However, be aware that you do not need to (and likely cannot) achieve a perfect match between the two resonant frequencies. We will explore the consequences of this in a subsequent section.

### 2.3 Assembling Circuits

Using your breadboard, construct the primary and secondary circuits (see Fig. [3]).

- The primary will consist of the primary coil in parallel with your selected capacitors; the function generator will be connected in parallel with all these components.
• The secondary will consist of the secondary coil in parallel with your selected capacitors and a red LED (orientation does not matter); the LED will illuminate when sufficient power is transferred to the secondary coil.

• For both circuits, let the coils lie flat on the table.

• Connect one set of oscilloscope probes to each circuit to measure the primary \( V_p \) and secondary \( V_s \) voltages.

• CAUTION: Unhook 1 lead of the function generator when making circuit adjustments to avoid potential shock.

![Figure 3: Schematic of primary and secondary circuits.](image)

_Tip:_ if you have spare room on your breadboard, consider adding jumper wires so it is easier to connect the function generator and oscilloscope to your circuit. If you try to connect these directly to your capacitors or coil, the leads have a tendency to become disconnected from the breadboard.

3 Testing the Circuit

Before taking measurements, we want to verify that the circuits function properly. Adjust the function generator based on the frequency you chose in section 2.2; start with a peak-to-peak voltage of 1 V.

Place the secondary coil on top of the primary coil such that their centers align. *What do you see on the oscilloscope? Is there a voltage present in your secondary circuit (greater than the value present when the coils are separated)? Try increasing or decreasing the frequency; does the secondary voltage change? Record the frequency that gives the maximum secondary voltage (likely to be different than the resonant frequency you calculated).* At this point, span over a wide range of frequencies to see if you can find another local voltage maximum, which would indicate that the circuits resonate at two different frequencies. *In your lab write-up, be
sure to explain some sources of error in your calculations.* For instance, are the capacitor values exact?

Now, increase the signal voltage until your LED just illuminates. If the room is too bright to tell, cover the LED with your hands and look at it closely from above. Record this minimum voltage. Larger signal voltages will allow you to separate the coils while still powering the LED.

When you perform measurements in sections 4.1 and 4.2, keep your frequency at its ideal value. For all the measurements, keep your signal voltage above the minimum value you just recorded. In terms of the upper voltage limit, choose a value that will allow you to gather sufficient data; increase your voltage if you cannot gather more than several pieces of data per measurement type.

If your LED is illuminated, continue to the section 4.1; otherwise, read through the following troubleshooting tips:

- Ensure that each component is fully inserted into the breadboard. Furthermore, ensure that the leads of components are in the proper rows of the breadboard.

- Ensure that any equipment you may have decided to attach to the coils is attached to the exposed wire ends and not the colored insulation.

- Ensure the function generator is connected to the primary circuit.

- Ensure the frequency you are using does in fact induce the largest voltage in the secondary circuit.

- Ensure you have tried using a 10 V peak-to-peak signal in the primary circuit.

- Ensure you did not make any errors when picking capacitors values

- If you continue to experience difficulties, ask the TA for assistance.

4 Making Measurements

Now that your circuit works, it’s time to obtain some data. *In this part, you will take several point measurements using the oscilloscope, record the results in a table, and plot them. Offer explanations for trends your data exhibits.*

4.1 Voltage as a Function of Distance

Record the voltage received on the secondary coil as a function of distance. The first measurement should be for the orientation described in section 3. Subsequent measurements should be spaced roughly 2 cm apart. Stop measuring once the voltage stops decreasing.

4.2 Voltage as a Function of Secondary Orientation

Record the voltage on the secondary as a function of relative orientation. Start with the coils facing each other (about a diameter apart). Maintaining this distance, rotate the secondary by approximately 15 degrees, and take a measurement. Continue this procedure until you reach 90
degrees (for a total of 7 measurements). *Again, plot the results and offer explanations for trends your data exhibits.*

4.3 Voltage as a Function of Input Frequency

Record the voltage on the secondary as a function of input frequency from the function generator; use the orientation described in section 3. Starting from your ideal frequency, gather 5 data points above and 5 data points below, such that the voltage varies from its maximum value to its minimum value. *Once again, plot your results and offer explanations for trends your data exhibits.*

5 Further Investigations

5.1 Material Interference

Place different materials (hand, book, sheet metal/breadboard, etc.) between coils and record your observations. *Offer possible explanations for what you observe.*

5.2 Successive Coupling

Pair with another group and try to get 2 secondary circuits to illuminate their LEDs. *Did you have to make any adjustments? If so, what were they? Experiment with different orientations and record your observations.*

5.3 Why Does the LED Run on AC?

LED stands for light-emitting diode. In general, diodes only allow current to flow in one direction. *Keeping in mind that your circuits ran on AC, explain why your LED appeared to work normally. What simple test could you have performed (using this lab’s equipment) to verify that the LED is in fact a diode?*

5.4 Reversing Primary and Secondary Circuits

Connect the function generator to the secondary circuit and move the LED to the primary circuit. Compare the relative coil voltages to what you observed with the original setup. *What causes this change? Can you still get your LED to illuminate? If so, is your signal voltage and distance between coils different than with the original setup? In other words, do you have to use a higher voltage or lower voltage? Can your coils be the same distance apart as before?*

5.5 Performance as a Function of Capacitance

Modify your circuits so that you use different capacitor values. *What circuit parameter are you changing? Will it be larger or smaller based on your new capacitors? Comment on any differences you notice in terms of the minimum signal voltage and maximum possible coil distance for the LED to illuminate. For example, does your modified circuit allow you to
separate the coils more (at any voltage)? At a given distance, do you require a higher voltage signal for the LED to illuminate?*

6 Write-Up

In your write-up, answer all the questions posed throughout the lab handout. *In addition, offer suggestions for how to improve the circuit.* Consider efficiency, size, and other applications (more practical than illuminating an LED).

Followup

If you are interested in learning more on this material, look into EECS 224 (Electromagnetics).