Induction - Making a Transformer

1 LEARNING OBJECTIVES

At the conclusion of this activity you should be able to:

- Define Faraday's law of electromagnetic induction.
- Use an oscilloscope to measure a time-dependent potential.
- Describe what an electrical transformer does.
- Construct a transformer.

2 BACKGROUND

2.1 THE MAGNETIC FIELD OF A SOLENOID

A solenoid is a coil of wire that produces a magnetic field when current flows[1]. The magnetic field can be calculated using Ampere's law:

\[ \oint \vec{B} \cdot d\vec{l} = \mu_0 I_{\text{enclosed}}. \] (2.1)

The magnetic field produced by a solenoid is similar to that produced by a bar magnet with north and south poles and looping field lines. Inside the solenoid, the magnetic field is nearly constant. Using Equation 2.1, the magnetic field inside a solenoid can be shown[2][1] to be:

\[ B = \mu_0 nI \] (2.2)

where \( n \) is the number of wire loops per unit length (\( n = N/L \)) and \( I \) is the current.

Outside the solenoid, the magnetic field is weak.

2.2 MAGNETIC FLUX

Magnetic flux \( \Phi_B \) is a measure of the magnetic field passing through a surface \( S \):

\[ \Phi_B = \vec{B} \cdot \vec{S} = |\vec{B}| |\vec{S}| \cos \theta. \] (2.3)

According to Equation 2.3, if the flux is changing with time (\( d\Phi_B/dt \neq 0 \)), then either the magnetic field is changing, the size of the surface is changing, the angle \( \theta \) between the field and surface is changing, or some combination of all three[3].
2.3 Faraday’s Law

Michael Faraday was one of the most influential experimental scientists of all time. He had very little formal education and his mathematical skills never progressed much past basic algebra and trigonometry, but Faraday was an extremely careful experimentalist. His meticulous measurements were used by other scientists to develop the mathematical formalism to explain the phenomena he observed. For example, the physicist James Clerk Maxwell used Faraday’s work to create the mathematical expression that we now know as Faraday’s law of electromagnetic induction:

\[ \varepsilon_{\text{loop}} = -\frac{d\Phi_B}{dt}. \] (2.4)

Faraday’s law states that an electromotive force in a loop of wire (emf), \( \varepsilon_{\text{loop}} \), is equal to the negative change in magnetic flux, \( \Phi_B \), over time. Stated another way, changing magnetic fields give rise to induced electrical fields[4].

2.4 Induction Transformers

A transformer is an electrical device that transfers energy between electrically separate circuits by means of electromagnetic induction. Transformers are typically composed of a driven, primary coil and a secondary coil in which an emf is induced [5].

The primary and secondary coils share the same changing magnetic flux by means of a magnetically soft material that is called a “core”. The core completes the magnetic circuit between the primary and secondary coils.

Since the primary and secondary coils of wire share the same magnetic flux, they also share the same emf per wire loop:

\[ |\varepsilon_{\text{loop}}| = \frac{d\Phi_B}{dt} = \frac{V_{\text{primary}}}{N_{\text{primary}}} = \frac{V_{\text{secondary}}}{N_{\text{secondary}}}, \] (2.5)

where \( V \) is the voltage and \( N \) is the number of wire loops in the respective coils. Rearranging Equation 2.5 we see that the potential on the secondary coil is determined by the ratio of the number of wire loops on the primary and secondary transformer coils:

\[ V_{\text{secondary}} = V_{\text{primary}} \frac{N_{\text{secondary}}}{N_{\text{primary}}}, \] (2.6)
Figure 2.1: A cartoon of a typical transformer. The primary coil shown in red is driven by a time-dependent potential, $V_p$. The resulting time-dependent magnetic flux $\Phi$ induces a potential $V_s$ on the secondary coil (see Equation 2.4). The Transformer core is typically a material, like iron, with high magnetic permeability to efficiently transfer the magnetic flux between the primary and secondary coils. In the figure, the turns on the primary coil are greater than the turns on the secondary: $N_p > N_s$. The induced potential $V_s$ will therefore be less than the driving potential $V_p$ (see Equation 2.6).

Image credit: BillC at the English language Wikipedia [CC-BY-SA-3.0 (http://creativecommons.org/licenses/by-sa/3.0/)], via Wikimedia Commons.
Figure 2.2: A sketch of a Michael Faraday experiment from 1831. Faraday’s experiment moves a magnetic field (produced by the coil labeled “A” powered by a battery) inside a coil (labeled “B”). As coil “A” moves in and out of coil “B”, the magnetic flux changes ($d\Phi_B/dt \neq 0$). The induced current ($\mathcal{E}$) is measured by the galvanometer (labeled “G”).
3 Procedure

3.1 Equipment Introduction

This lab will introduce you to two new pieces of laboratory equipment: the function generator[6] and the oscilloscope[7].

Watch these short videos about each piece of equipment:

• Function Generator Introduction Video.
• Oscilloscope Introduction Video.

You will also be using an air-core solenoid. The air-core solenoid is a tube surrounded by approximately 560 turns of insulated 16 gauge wire.

3.2 Warm-up Exercise: Magnet and Solenoid

This warm-up section is not intended to be written up as part of your Lab Note. These activities will likely be useful as you interpret and discuss your subsequent measurements.

3.2.1 Induction with a Bar Magnet

This is an experiment that is very similar to one that Faraday did that is shown in Figure 2.2.

A solenoid and a magnet will be used to observe electromagnetic induction. Connect the solenoid to the oscilloscope to measure the potential as a function of time. Adjust the volts per division (zoom for the y-axis) and the time scale (zoom for the x-axis) until you get a reading when you move the magnet in and out of the solenoid. On the y-axis, the voltages you will measure are on the order of tens of mV. On the x-axis, the time scale you choose will depend on how quickly you move the magnet in and out of the solenoid.

Try the following:

1. Move the magnet in and out of the solenoid very quickly.
2. Move the magnet in and out of the solenoid very slowly.
3. Stack two magnets on top of one another to create a stronger magnet (stack the magnets north-to-north and south-to-south).

Discuss with your partner how your observations relate to Equations 2.3 and 2.4.

3.3 Build a Transformer: Measure Induction on a Secondary Coil

In this lab you will construct a coaxial transformer.

Use the air-core solenoid as the primary coil. Connect the function generator to the solenoid to provide a time-dependent potential, \( V_p \). Drive the primary coil with a sine wave at a frequency of 1500 Hz. Set the amplitude of the function generator to the maximum “output level”.

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Measure and record the potential on the primary coil $V_p$ with channel 1 (CH 1) of the oscilloscope. You will be measuring a 1.5 kHz signal. Set the oscilloscope time setting (horizontal axis or seconds/division) so that you can clearly observe and measure the signal.

Construct a 10-loop secondary coil by wrapping wire around the short metal rod. Use tape to hold the wire in place on the rod. Connect the secondary coil to channel 2 (CH 2) of the oscilloscope and measure the induced voltage.

Insert the primary coil inside the secondary coil to create a transformer (see Figure 3.1).

Collect data by incrementally reducing the number of turns on the secondary coil. Your goal is to determine the relationship between the voltage induced in the secondary coil and the number of turns on the secondary coil.

3.4 BUILD A 1.0V TRANSFORMER

Using your results from Section 3.3, predict the number of loops on the secondary coil required to produce a 1.0 V output.

Wind the secondary coil according to your prediction. Construct your transformer by placing the secondary coil inside the driven primary coil.

4 LAB NOTE

Write a brief lab note to record and communicate your work. Limit your note to about 1000 words. Your note should be concise and to the point. Bullet points are encouraged.

Please include pictures, figures, diagrams, etc to clearly explain your ideas. Equations can be included using an equation editor or a photo of your handwritten work.
Your note should address the following general ideas:

- **Experiment Purpose (4 points)**
  - In your own words, state the purpose of this experiment.

- **Calculations & Error Propagation (6 points)**
  - Present the equations used to analyze your collected data.
  - Present the equations used to account for and propagate error.

- **Data Collection & Analysis (6 points)**
  - *Briefly describe the method – beyond what was already stated in the assignment – you used to accurately collect your data.*
  - Measured quantities – that do not appear directly in your plot(s) – should be presented in an organized table.
  - Analyze your data using well-formatted plot(s). Clearly show how the plot is used to arrive at your result(s).

- **Results (4 points)**
  - Clearly state the final result(s) of your experiment. Remember to quote your result with units and appropriate significant digits.

- **Discussion**
  - Observations (4 points)
    - What did you observe in your experiment?
    - Relate your observations to your understanding of the underlying physics.
  - Significance (4 points)
    - Compare your measured results to each other and/or to a known/expected value.
    - Choose the best tools for your comparison (*e.g.* plots, pictures, discrepancy, significance, etc).
  - Confidence (8 points)
    - The goal is to communicate to your audience how seriously your result should be taken.
    - Discuss how confident you are in your result.
    - Discuss factors that may be affecting the *accuracy* and *precision* of your result.
    - Suggest improvements to your experiment to address your accuracy and precision.

- **Style (4 points)**
  - Points are allocated to notes that follow the guidelines for the assignment.
  - Examples of things that fall under the “style” category include (but are not limited to): word count, formatting, attention to activity-specific instruction, readability, creativity, etc.
REFERENCES

[1] HyperPhysics entry on Solenoids:  
http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/solenoid.html.


[3] HyperPhysics entry on Magnetic Flux:  
http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/fluxmg.html.


[6] The function generators used in the lab are either B+K Precision 4011 or 4011A devices. User manuals for each can be accessed here:  

[7] The oscilloscopes used in the lab are Tektronix TDS-2002B units. The user manual can be downloaded here:  