Lab 10: Faraday's Law

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Introduction

Magnetic induction is a core principle in electronics, especially in electricity generation and transformers. Faraday's law of induction, $\mathcal{E} = -N\frac{d\Phi_B}{dt}$, describes how a changing magnetic field induces an electromotive force in a conductor (N is normally 1 but represents the number of turns of a coil). This principle is what allows generators to create a voltage from mechanical rotation caused by steam, wind, water, and other natural forces. Transformers use this principle to transform electricity between high and low voltage, while not wasting power like a resistor, since the current adjusts to preserve the expression $P = VI$. Induction is used extensively in power generation and delivery making it essential for a functioning electrical grid.

Problem 1: Induction and the AC Question

Materials: Magnet, coil, Galvanometer.

Methods: Assemble Galvanometer–coil circuit, move bar magnet through the coil, take note of galvanometer reading as magnet is moved. The coil should be coiled counterclockwise when viewed from the top.

Results: As the south pole of the magnet is inserted into the top of the coil, the reading on the galvanometer jumps to the negative side. As the south pole is removed, the galvanometer jumps to the positive side. The opposite occurs when the North pole is used.

Analysis: To produce a constant e.m.f. of positive 10 V, the change in magnetic flux would have to be constant. This could be achieved by rotating the magnet at a constant velocity. To get the largest deflection of the needle, you would need to get the largest change in magnetic flux, which is simply done by moving the magnet as fast as possible. When the magnet spins instead of moving in and out, the direction of the change in magnetic flux alternatives, which in term creates an alternating e.m.f., which creates an alternating (AC) current.

Problem 2: Coils and Coils

Materials: 2 coils with different numbers of loops, an iron core, the Galvanometer, 10 V AC power supply.

Methods: Assemble the two coils on the iron core, and connect these to both the galvanometer and the power supply. Power up the power supply and take note of the behavior of the galvanometer.

Results: Upon powering up the coils with a DC current, the galvanometer immediately jumps to one side (the positive one in our case although it depends on how it is wired, then falls back to zero). Upon turning off the DC current, the galvanometer jumped in the other direction, negative, before falling back to zero.

Applying an AC current to the coils will cause the needle on the galvanometer to rapidly alternate between the positive and negative. Having a smaller number of turns hooked up to the AC than the galvanometer creates a larger impulse while the opposite ratio creates a smaller movement. Having a larger ratio between the number of turns on each coil increases this effect.

When the top of the iron core was removed with the current on, it rattled and shook. Upon turning off the power supply, the top was difficult to remove as it had been magnetized to the rest of the core. When replacing the galvanometer for a multimeter set to measure voltage for alternating current, the resulting voltage is the ratio of turns on the coils times the voltage of the attached power supply.

Analysis: Transformers work using magnetization and induction on two sets of coils connected by a ferrous core. The first coil creates a changing magnetic flux in the core as its current alternates. The changing magnetic flux then induces a current in the second coil which creates another alternating current. This can be shown like so, with two coils (a) and (b):

$$V_A = -N_A \frac{d\Phi_B}{dt} \qquad V_B = -N_B \frac{d\Phi_B}{dt}$$

Since the magnetic flux is carryed through the core, it can be assumed equal at each coil. Solving for the flux and substituting:

$$\frac{V_A}{N_A} = \frac{V_B}{N_B}$$

$$\frac{V_A}{V_B} = \frac{N_A}{N_B}$$

The ratio of the voltages between the coils is directly proportional to the ratio of the number of turns. Since power is also conserved (there is no resistor to disipate power as heat), the ratio of currents in each coil is:

$$P = V_A I_A = V_B I_B \implies \boxed{\frac{V_A}{V_B} = \frac{N_A}{N_B} = \frac{I_B}{I_A}}$$

Moreover, the reason the top part of the iron core stays magnetized and attracts the bottom part is because it's field lines (the magnetic flux) form North and South poles, which attract the opposite poles of the two connecting portions of the magnetized "U-shaped" bottom part.

Problem 3: The AM Radio

Materials: 200 turn coil, 800 turn coil, multimeter, 10 V AC power supply.

Methods: Connect the 200 turn coil to the power supply, and the 800 turn coil to the multimeter. Power up the power supply and move the coils around each other. Take note of the resultant voltage. Take the top of the iron core and place it within the 200 turn coil, Take note of the resultant voltage as it is moved around.

Results: When the 200 and 800 turn coils were put side by side, oriented the same way, a 0.4 V voltage was detected on the voltmeter. When they were oriented in opposite directions a 0.3 V was detected. When they were stacked in the same orientation a 1.1 V was detected. When they were stacked in opposite directions, a 0.9 V was detected. After the iron core was inserted into the 800 turn coil, all the voltages were much larger. Side by side with the same orientation was 2.2 V while opposite was 1.9 V. Vertically stacked with the same orientation was 15 V while the opposite orientation was also 15 V.

Analysis: The reason that the two coils sensed each other without the magnetized iron cores connecting them was due to the propagation of magnetic fields in free space (air). The orientation mattered because the strength of the magnetic field differs at different points relative to the source coil (200 turns). The antenna (800 turns) was able to sense the AM radio because when the switching current in the source induces a switching magnetic field, this creates a change in magnetic flux which creates an electric field and therefore a current and voltage in the antenna as dictated by Maxwell's Laws, specifically the Maxwell–Faraday Law of Induction: $\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$ The iron core increased the sensing dramatically because the magnetic field magnetized the core which increases the change in magnetic flux which in turn increases the electric field which increases the current and therefore the voltage.

Conclusion

Electromagnetic induction is a prime example demonstrating the interconnectedness between electricity and magnetism, the experiments we ran helped us to understand this relationship in further detail. We started by understanding that magnets can induce a current when moved through a coil. In experiment two we determined that a transformer acts almost as an electrical gearbox, with a relationship that follows $\frac{N_2}{N_1}V_S = V_R$. We finally experimented with interacting magnetic fields between two coils, and by adding the iron core to the coil, we ended up with an amplifier, showing a massive increase in voltage, for example when vertically stacked inline, the measured voltage went from 1.1V to 15V, and when inline and side by side, the voltage went from 0.4V to 2.2V. These concepts are essential in electrical generation/transmission and communications, where induction is either the driving principle or a significant component of the concepts at play. Being able to step between voltages is essential as the extreme voltages generated would easily fry most consumer electronics almost instantly.