Faraday's Law Demonstration

Jin Shi, R. E. DuBroff, and J. L. Drewniak
UMR EMC Laboratory

1. OBJECTIVES

To investigate Faraday's and Lenz's law
To determine the emf induced in various linked paths

2. EQUIPMENT

The equipment required for this experiment consists of a signal generator capable of producing a 10 to 20 V sinusoidal signal at frequencies the 10-100 kHz range; a digital multimeter; and an electrical circuit as shown in the following diagram

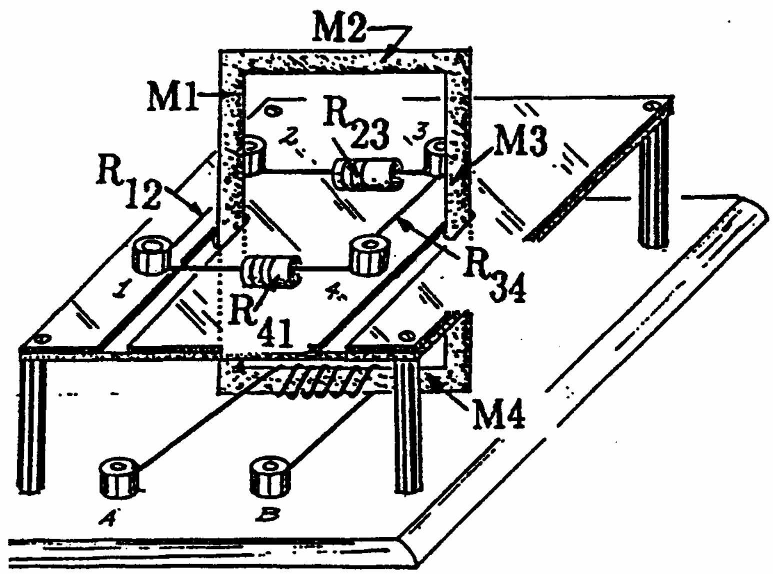

Figure 1: Electrical Circuit to demonstrate Faraday's law

This circuit, in turn, consists of a magnetic core having segments M1, M2, M3, and M4. The magnetic core in this case came from an old TV flyback transformer. Banana jacks (labeled 1, 2, 3, and 4) are mounted on a plexiglass sheet. R41 is a nominal 2kΩ resistor soldered between jacks 1 and 4. R23 is a nominal 1 kΩ resistor soldered between jacks 2 and 3. R34 is simply a piece of wire soldered between jacks 3 and 4. Note that R34 passes through the magnetic core. Finally, R12 is a removable jumper with banana plugs at each end. The magnetic field in the core is produced by approximately 20 to 30 turns of wire winding around segment M4. Terminals A and B are used to provide current to the winding. These terminals are mounted in a wooden base. A photograph of this circuit is provided below

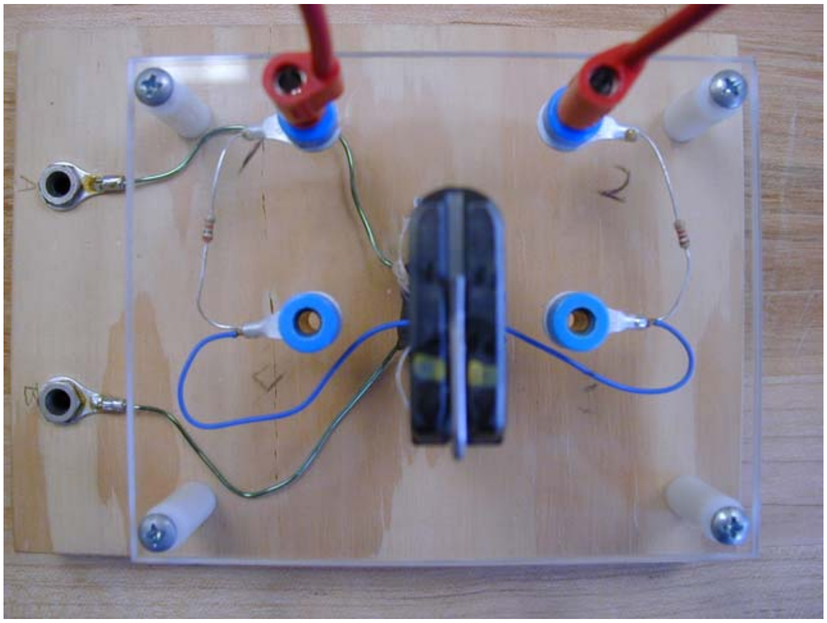

Figure 2: Top view of the electrical circuit shown in Figure 1, including the jumper wire connected between jacks 1 and 2.

3. PROCEDURE

a. Measure and record the resistances of resistors R23 and R41 using the digital multimeter. After measuring the resistances, connect a jumper wire (with banana plugs at both ends) between jacks 1 and 2. Make sure that the jumper DOES NOT pass through the magnetic core.
b. Connect terminals A and B to the signal generator. Adjust the signal generator to produce a 10 to 20 V (approximately) peak to peak sinusoidal signal at a frequency somewhere between 10 and 20 kHz. Measure and record the RMS voltage across AB
c. Use the digital multimeter to measure the rms voltages between terminal pairs 1-2, 2-3, 3-4, and 4-1. The multimeter should be connected so that the loop formed by the multimeter leads and the component connected between the terminals DOES NOT pass through the magnetic core. Figures showing the connections to make these measurements are shown below:

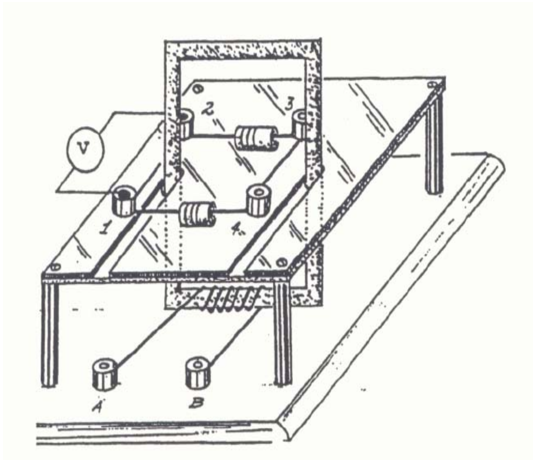

Figure 2(a) Measurement of V_{21}

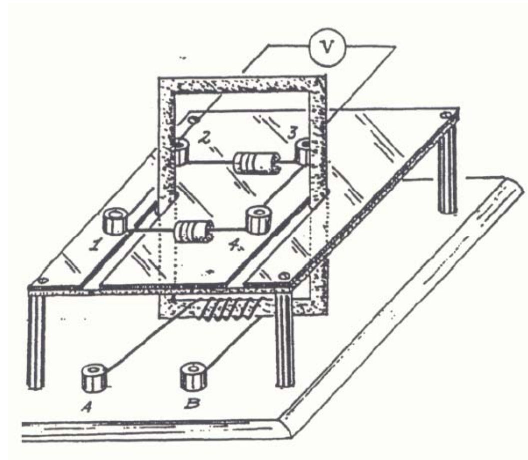

Figure 2(b) Measurement of V_{32}

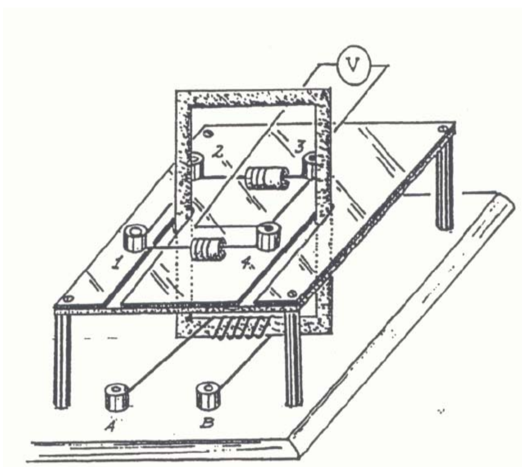

Figure 2(c) Measurement of V_{43}

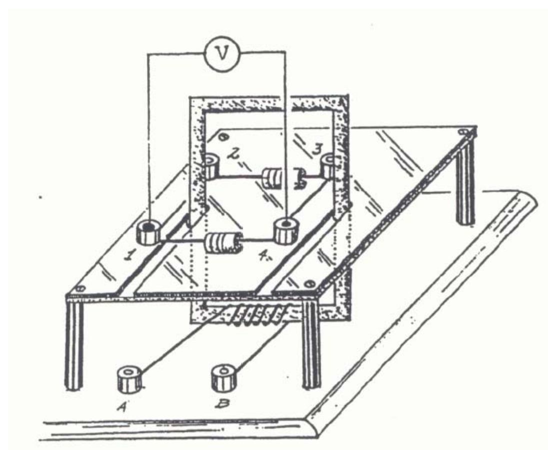

Figure 2(d) Measurement of V_{14}

Record these voltages. Is there any way that Kirchhoff's voltage law could be satisfied with these four measurements? If not, assume that the four voltages measured are exactly in phase. Then consider the following equivalent circuit which now includes an independent voltage source:

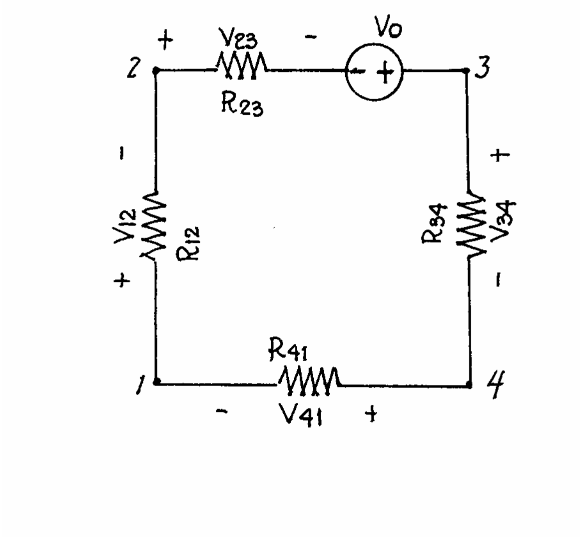

Figure 3: An equivalent circuit to account for the discrepancy in Kirchhoff's voltage source.

Using the rms voltages you found for V_{21}, V_{32}, V_{43}, and V_{14}, calculate the rms voltage V_0 of the equivalent voltage source shown in Figure 3. Using this value of V_0 together with the previous measurement of the rms voltage between terminals A and B determine the number of turns of wire wound around section M4 of the magnetic core.

d. The voltage source V_0 results from the induced voltage in the resistive loop circuit formed by nodes 1, 2, 3 and 4. Remove the jumper (R12) and replace it with a nominal 1 kΩ resistor. Re-measure the voltages V_{21}, V_{32}, V_{43}, and V_{14}. Recalculate the value of V_0. Does the value of V_0 change significantly when compared to the value it had when R12 was a jumper.?

e. Remove the 1 kΩ resistor connected between terminals 1 and 2. Replace this 1 kΩ resistor with the jumper used previously. Now consider the following set of figures:

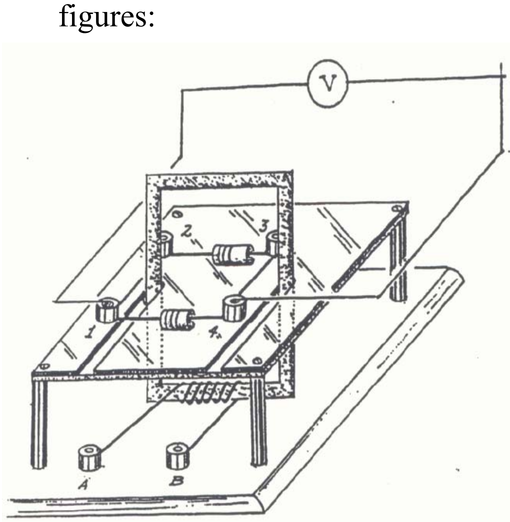

Figure 3(a) Measuring V_{14}, Configuration A

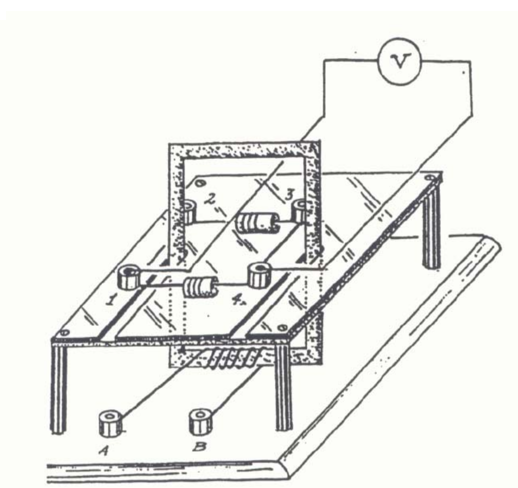

Figure 3(b) Measuring V_{14}, Configuration B

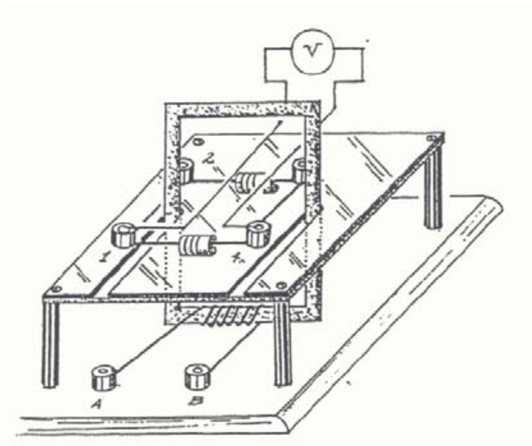

Figure 3(c) Measuring V_{14}
Configuration C

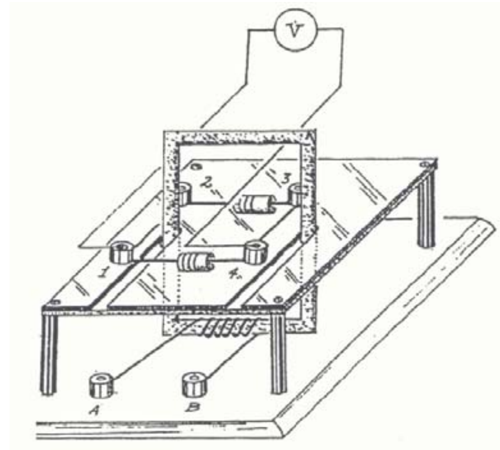

Figure 3(d) Measuring V_{14}
Configuration D

In the first case (configuration A) the measurement loop, consisting of the multimeter leads and R41, does not link the loop formed by the magnetic core. In fact, configuration A is essentially the same as the measurement shown in Figure 2d. Configuration B shows the measurement loop linking the right side of the magnetic core. Configuration C shows the measurement loop linking neither side of the magnetic core. Configuration D shows the measurement loop linking the left side of the magnetic core. Using Lenz's law and Faraday's law, together with some of the measurements and calculations in part c, it should be possible to calculate the rms voltages in each of the four configurations shown above. Perform these calculations and compare them with measurements of V_{14} in each of these four configurations.

4. THEORY & DISCUSSION

Note: the four configurations listed above can be represented schematically as

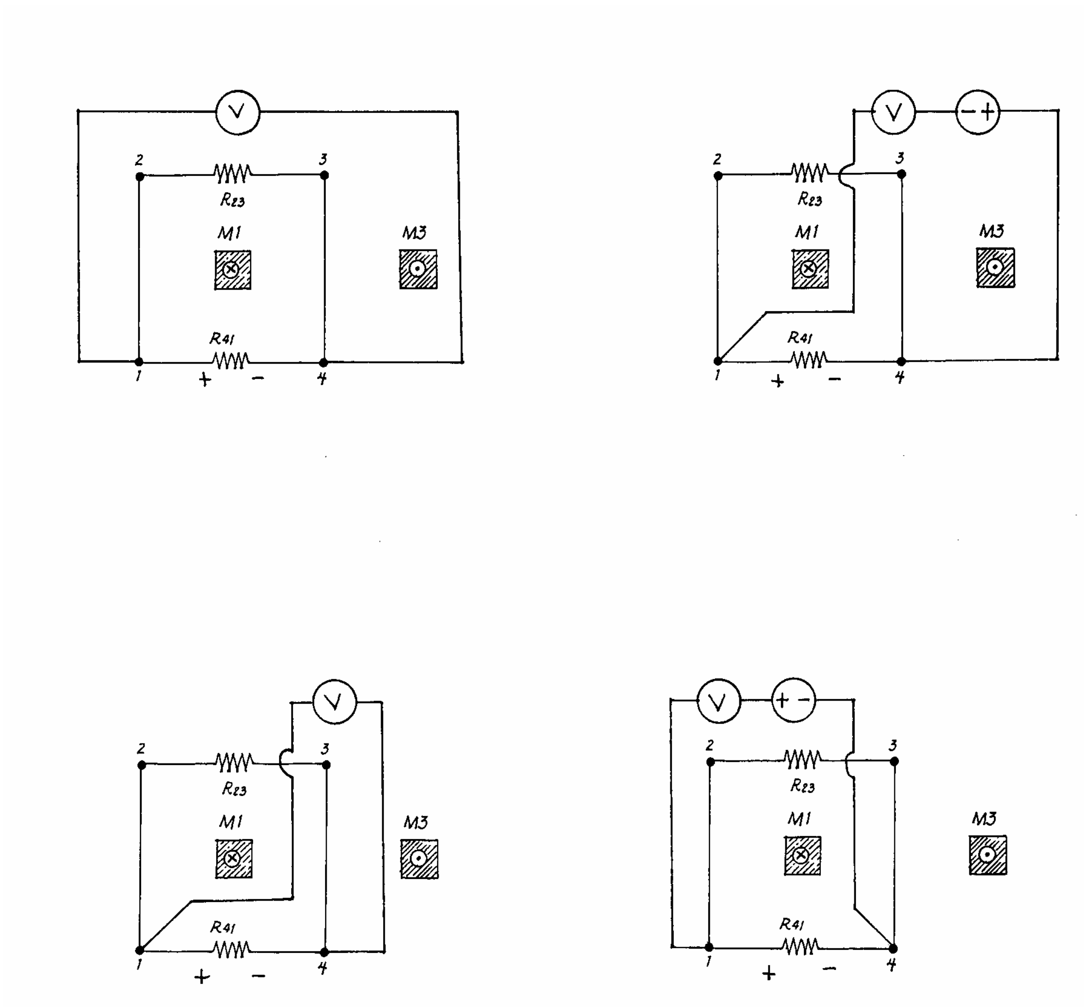

Figure 4: Equivalent circuits for configurations A, B, C, and D.

The upper left hand corner shows an equivalent circuit for configuration A. The resistor loop circuit, having nodes shown as 1, 2, 3, and 4 encircles segment M1 of the magnetic core. At some instant of time magnetic flux in segment M1 will be increasing in the downward direction as indicated by the cross. At this instant, current will flow around the resistor loop circuit to oppose the increase in magnetic flux. This means current will have to flow in the counterclockwise direction. Counterclockwise current flow causes the voltage across R41 to have the polarity shown in the figure. The loop consisting of the digital multimeter, its leads, and R41 does not encircle any net time varying magnetic flux. The magnetic flux in segment M1 is cancelled by the magnetic flux in segment M3. Thus the digital multimeter will read the IR drop across R41. A similar result would be expected in configuration C (lower left figure). However, in the case of configuration B (upper right corner) an additional emf source will be induced in the multimeter loop circuit because this circuit now encircles segment M3. When the magnetic flux in M1 is increasing in the downward direction, the magnetic flux in M3 must be increasing in the upward direction. By Lenz’s law, any current flowing in the multimeter loop would then have to flow in the clockwise direction. Therefore the induced emf source must have a polarity that would drive current in the clockwise direction. The polarity of this induced emf source is the same as the polarity of the IR drop across R41. Thus the multimeter reading in configuration B must be higher than the reading in either configurations A or C. In configuration D the induced emf source has a polarity opposing the IR drop across R41. Thus configuration D should correspond to the lowest multimeter reading.

5. SUMMARY & CONCLUSIONS

Although the equipment is fairly simple and the procedure is not complicated, the results are somewhat counter-intuitive unless one takes the concept of an induced emf into account. Specifically R23 and R41 appear to be in parallel yet unless the voltage is measured in the "right" way, the measured voltages across these components are not equal. It is also possible to loop one or more of the voltmeter leads multiple times around the magnetic core and produce different measurements as well.

6. APPENDIX

Sample measurements

3a.

R23 = 0.991 kΩ	R41 = 2.016 kΩ

3b.

VAB = 2.857 Volts

3c.

Voltage	V21	V32	V43	V14
Measurement	0.669	35.921	4.563	71.158

Note all of these voltages are in millivolts

V21+V32+V43+V14 = 112 mV
N = 2.857/0.112 = 25 turns (approximately)

3e.

Voltage	V14A	V14B	V14C	V14D
Measurement	72.093	180.07	73.832	32.582