Faraday’s Law of Induction

Equipment: Function Generator, Oscilloscope.

Supplies: One large and two small (with handles) coils, plastic triangles, T-base BNC connector, graph paper.

A. Objective

The objective of this experiment is to demonstrate the Faraday’s Law of electromagnetic induction.

B. Theory

When current, \( i \), runs through a circular coil with \( N \) turns each of radius, \( r \), a magnetic field is created. Its strength, \( B \), at the center of the coil, is given by the Biot-Savart Law:

\[
B = \frac{N \mu i}{2r},
\]  

(1)

where \( \mu = 4\pi \times 10^{-7} \, \text{T} \cdot \text{m/A} \) is the so-called permeability constant. On the other hand, a changing magnetic flux, \( \Phi \), through a coil of \( N \) turns induces an emf, \( E \), given by the Faraday’s Law:

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

(2)

where \( \Phi = \int B \cdot dA = BA\cos(\theta) \) for a magnetic field \( B \) which is constant over the area \( A \). Here \( \theta \) is the angle between the magnetic field vector and the magnitude of the area vector \( A \). In this experiment we will use a large (field) coil with \( N = 200 \) turns of radius \( r_f \,(\text{approx.})=10.5\, \text{cm} \) to create magnetic field, and two search coils: one with \( N = 400 \) turns and another with \( N = 2000 \) turns, both of radius \( r_s \,(\text{approx.})=1.5\, \text{cm} \), to measure the induced emf. During the experiment, the area of the field and search coils is constant. The current in the field coil, however, oscillates thus creating an oscillatory magnetic field (flux) through the search coil positioned at the center of the field coil. As a result, an average emf is induced in the search coil, given by

\[
E = -NA \frac{\Delta B}{\Delta t},
\]  

(3)

where \( \Delta B/\Delta t \) is the time rate of change (oscillation) of the magnetic field, \( N \) and \( A \) (= \( \pi r_s^2 \) ) are the number of turns and area of the search coil, respectively.
Procedure - Experiment 10

1. Set the Function Generator to produce a triangular wave with amplitude of 5 volts and frequency - 2 KHz.

2. Build the circuit shown below:

Note: the primary side of the circuit includes a 1.2 kΩ resistor, so that the current in the field coil can be calculated from the voltage delivered by the function generator. The resistance and self-inductance of the field coil are small compared to those of the 1.2 kΩ resistor. The 10 kΩ resistor in the secondary(search) coil damps out some of the unwanted oscillations (noise), so a relatively square wave \textit{emf} can be seen on the oscilloscope screen. Position the triangular wave/voltage (generating the oscillatory magnetic field) and the resulting square wave \textit{emf} as shown below to facilitate data reading from the oscilloscope screen. Use both Inputs (#1 and #2) of the scope.
A. Using equation (1) and the known values of the circuit components calculate the strength of the magnetic field at the center of the field coil with $r_f (approx.) = 10.5$ cm.

$$B = \ldots \ldots \ldots \text{[T]}$$

B. Using the computed value of B and equations (2-3) predict the induced emf for the search coils with $N = 400$ and $N = 2000$ turns and radius $r_s (approx.) = 1.5$ cm. Measure those emfs. Compare the predicted and measured values. Comment.

Predicted: $E (400 \text{ turns}) = \ldots \ldots \ldots \text{mV}$

$E (2000 \text{ turns}) = \ldots \ldots \ldots \text{mV}$

Measured: $E (400 \text{ turns}) = \ldots \ldots \ldots \text{mV}$

$E (2000 \text{ turns}) = \ldots \ldots \ldots \text{mV}$

Comments:
C. Measure the emf dependence on the cosine of the angle between the magnetic field vector (B) and the area vector (A). Use the already set triangular wave with amplitude of 5 volts and frequency - 2 KHz, the search coil with 2000 turns and the provided plastic triangles. Plot the data. Comment.

<table>
<thead>
<tr>
<th>θ[deg.]</th>
<th>$s(θ)$</th>
<th>emf [mV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>90</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Comments:

D. Measure the emf dependence on the strength of the magnetic field/flux (at a fixed frequency of 2 kHz). For the purpose, vary the amplitude/voltage of the triangular wave provided by the function generator. Starting amplitude: 0.5 V; step: 0.5 V; end amplitude: 7 V. Use the search coil with 2000 turns. Plot the emf voltage versus the generator (triangular wave) voltage. Comment.

<table>
<thead>
<tr>
<th>Ampl. [V]</th>
<th>emf [mV]</th>
<th>Ampl. [V]</th>
<th>emf [mV]</th>
<th>Amp</th>
<th>1. [V]</th>
<th>emf [mV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td></td>
<td>3</td>
<td></td>
<td></td>
<td>5.5</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>3.5</td>
<td></td>
<td></td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td></td>
<td>4</td>
<td></td>
<td></td>
<td>6.5</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>4.5</td>
<td></td>
<td></td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td></td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
E. Measure the *emf* dependence on the rate of change of the magnetic field/flux (at a fixed generator amplitude of 5 V). For the purpose, vary the frequency of the triangular wave provided by the function generator. Starting frequency: 500 Hz; step: 500 Hz; end frequency: 7.5 kHz. Use the search coil with 2000 turns. Plot the *emf* voltage versus the generator (triangular wave/magnetic field) frequency. Comment.

\[
\begin{array}{|c|c|c|c|c|}
\hline
f [Hz] & \text{emf [mV]} & f [Hz] & \text{emf [mV]} & f [Hz] & \text{emf [mV]} \\
\hline
500 & 3000 & & & 5500 & \\
1000 & 3500 & & & 6000 & \\
1500 & 4000 & & & 6500 & \\
2000 & 4500 & & & 7000 & \\
2500 & 5000 & & & 7500 & \\
\hline
\end{array}
\]

Comments:
F. Measure the *emf* intensity along an axis perpendicular to the field coil, at various distances from the plane of the coil, keeping the generator voltage/triangular wave amplitude (5 V) and frequency (2 kHz) constant. Plot the *emf* voltage versus the distance from the center of the field coil. Comment.

<table>
<thead>
<tr>
<th>Distance [cm]</th>
<th><em>emf</em> [mV]</th>
<th>Distance [cm]</th>
<th><em>emf</em> [mV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Comments: