3.1.2. MAGNETIC INDUCTION

MAIN PRINCIPLE

The induction EMF of a time-varying magnetic field in another coil inside a long coil,

1- Magnetic field as a function of the intensity of $\vec{B}$,

2- Function of the frequency of the magnetic field,

3- Function the number of turns in the coil

4- To study as a function of the diameter of the induction coil.

EQUIPMENT

Power supply, Function Generator, Ammeter, Voltmeter, Coils, Connection cable

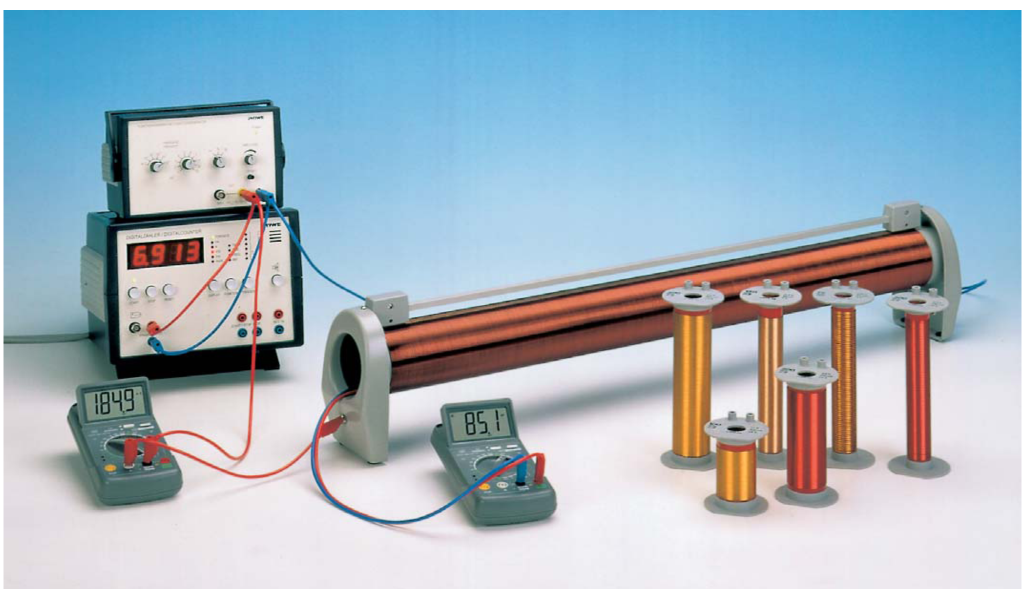

Figure 3.19: Induction Experimental Setup

THEORY

Induction experiments

In the 1830s, Michael Faraday conducted extraordinary experiments at the Smithsonian Institute on the emf produced by magnetic attraction. Figure 3.20 shows one of these experiments. In Figure 3.20-a, a coil of wire is connected to a galvanometer. The galvanometer shows no current when the nearby magnet is stationary. But when the magnet is moved towards or away from the coil, we see current flowing through the galvanometer (Figure 3.20-b). Although no power supply is connected to the circuit, current flows through the circuit.

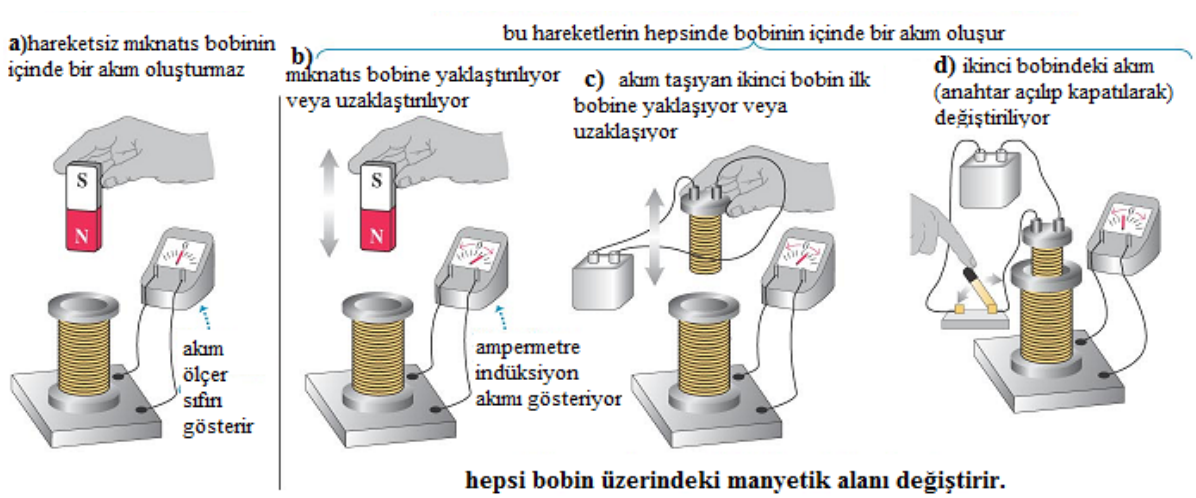

Figure 3.20: Experimentally proving the induction current phenomenon

In Figure 3.20-c, when a second coil carrying current instead of a magnet is moved closer or further away from the coil connected to the galvanometer, the same effect is observed, that is, current passes through the galvanometer. The events in Figure 3.20-b,c are the events in which current passes through the galvanometer only when the magnet or the coil is moved. In Figure 3.20-d, if we place the second coil into the coil connected to the galvanometer and leave it motionless, it is seen that no current passes through the galvanometer. If the current to the first coil is cut off with the help of a switch, it is seen that the current in the galvanometer suddenly increases and reaches zero again, and when the switch is turned on again, this time the current in the galvanometer suddenly changes in the opposite direction to the previous movement and reaches zero again.

The common feature of all these experiments is the changing Φ_B magnetic flux inside the coil connected to the galvanometer. In each case, the magnetic flux in the coil changes as the magnetic field changes with time or as the coil is moved in a non-uniform magnetic field.

Faraday's law

Considering these experiments, Faraday concluded that “the variation of the Φ_B magnetic flux passing through the coil with time releases induction electromotive force (IEMF) in the coil”.

For a very small slice of surface dA in a magnetic field $\vec{B}$, the magnetic flux $d\Phi_B$ passing through this surface;

$$d\Phi_B = \vec{B}.d\vec{A} = B_{\perp}dA = BdA\cos\varphi \tag{3.47}$$

Where $B_{\perp}$ is the component of $\vec{B}$ perpendicular to the surface element and φ is the angle between $\vec{B}$ and $d\vec{A}$. The total magnetic flux Φ_B through the finite surface is equal to the integral of this expression over the surface.

$$\Phi_B = \int \vec{B}.d\vec{A} = \int BdA\cos\varphi \tag{3.48}$$

In the final form of Faraday's law of induction, "**the induction emf in a closed circuit is equal to the negative of the rate of change with time of the magnetic flux passing through this circuit.**"

$$\varepsilon = -\frac{d\Phi_B}{dt}, \qquad (Faraday's\ induction\ rule) \tag{3.49}$$

Lenz's law

H.F.E. Lenz, a Russian scientist, independently repeated many of the phenomena discovered by Faraday and Henry. He presented a method that makes it easy to find the direction of the induction current or emf. Accordingly, he expressed Lenz's law as "**the direction of any magnetic induction event is opposite to that of the effect which produced it**". This is the meaning of the minus sign in Faraday's law.

A long, thin cross-sectional area A and a conductor with a number of n turns are wound in a ring. A current I in the solenoid turns causes a magnetic field $\vec{B}$ along the solenoid axis. The magnitude of this field was calculated in the theoretical information as $B = \mu_0 nI$. Let us have a second ring with n_1 turns that we will put inside this ring. If we choose the surface vector $\vec{A}$ in the direction of $\vec{B}$, the Φ_B flux through the ring,

$$\Phi_B = BA = \mu_0 nIA \tag{3.50}$$

is found. When the flux I of the solenoid changes with time, the Φ_B magnetic flux also changes and according to Faraday's law, the induction emf in the second loop is expressed as follows.

$$\varepsilon = -n_1\frac{d\Phi_B}{dt} = -\mu_0 nA\frac{dl}{dt} \tag{3.51}$$

Since the current I flowing through the solenoid varies with time if the expression $I = I_0\sin\omega t$ is substituted equation above,

$$\varepsilon = -\mu_0 nn_1 A\omega I_0\cos\omega t \tag{3.52}$$

is found. This expression gives the induction voltage of the small coil inside the coil.

SETUP AND PROCEDURE

PART I:

Determination of the induction EMF of a time-varying magnetic field in another coil inside a long coil as a function of the magnetic field B.

1- Set up the experimental setup in Figure 3.19. Measure the primary coil's alternative current and induction voltage with a multimeter.

2- Insert the induction coil with $n = 300$ turns and $d = 41\ mm$ diameter into the first long coil as a secondary coil.

3- Fix the current frequency of the primary coil at $10\ kHz$.

4- Measure the induction voltage of the secondary coil for the magnitudes of the current values of the primary coil in the table below and record them in Table 3.3.

Table 3.3: $\boldsymbol{f = 10KHz}$, $\boldsymbol{n = 300\ turns}$ **and** $\boldsymbol{d = 41\ mm}$

$I_0\ (mA)$	$\varepsilon\ (mV)$
2.0	
5.0	
10.0	
15.0	
20.0	
25.0	

5- Draw the graph of the change in $\varepsilon(I_0)$ using $\log \varepsilon$ and $\log I_0$. Explain what the slope of the line you found means to you.

$$\varepsilon = -\mu_0 n n_1 A \omega I_0 \cos \omega t \tag{3.53}$$

$$\varepsilon = k{I_0}^m \Rightarrow \log \varepsilon = \log k + m \log I_0 \tag{3.54}$$

PART II:

Determination of the induction voltage as a function of the number of turns of the induction coil.

1- Set up the experimental setup in Figure 3.19. Keep the current passing through the primary coil as $I_0 = 25\,mA$, the frequency is fixed at $10\,kHz$ and measure the induction voltages using secondary coils with a radius of $41\,mm$ and turns $n = 300, 200, 100$ and record them in Table 3.4 below.

Table 3.4: $\boldsymbol{I_0 = 25\,mA, f = 10\,kHz}$ and $\boldsymbol{d = 41\,mm}$

$\boldsymbol{n}$	$\boldsymbol{\varepsilon\ (mV)}$
300	
200	
100	

2- Draw the graph expressing the change in $\varepsilon(n)$ using $\log \varepsilon$ and $\log n$ values. Explain what the slope of the line means to you.

$$\varepsilon = -\mu_0 n n_1 A \omega I_0 \cos \omega t \tag{3.55}$$

$$\varepsilon = k n^m \Rightarrow \log \varepsilon = \log k + m \log n \tag{3.56}$$

PART III:

Determination of the induction voltage as a function of the diameter of the induction coil.

1- Set up the experimental setup in Figure 3.19. Keep the current passing through the primary coil constant at I0=25mA and the frequency fixed at 10 kHz and measure the induction voltages using secondary coils of different diameters, each with 300 turns, and record them in Table-III below.

Table 3.5: $\boldsymbol{I_0 = 25\,mA, f = 10\,kHz}$ and $\boldsymbol{n = 300}$

$\boldsymbol{n}$	$\boldsymbol{\varepsilon\ (mV)}$
300	
200	
100	

2- Using $\log \varepsilon$ and $\log d$ values, draw the graph expressing the change in $\varepsilon(d)$ using the data in Table 3.5. Explain what the slope of the line means to you.

$$A = \frac{\pi d^2}{4} \tag{3.57}$$

$$\varepsilon = -\mu_0 n n_1 A \omega I_0 \cos \omega t \tag{3.58}$$

$$\varepsilon = k d^m \Rightarrow \log \varepsilon = \log k + m \log d \tag{3.59}$$

Note: In all three experiments, the graphs we want will not be linear. Therefore, read the explanations below carefully.

In experiments, the resulting formulas are not always in the form of the typical line equation. For example, It can be of the form

$v^2 = v_0^2 - 2ax$

or

$I = kv^n$

In this case, the correct equation can be obtained by transferring to new variables. Taking $v^2 = y$, $v_0^2 = b$ and $2a = m$ in the first expression above, or taking the logarithm of the second expression,

$\log I = \log k + n \log v$

$\log I = y,\ \log k = b\ ,\ m = n,\ \log v = x$

linear graphs can be drawn.