Electricity
Electromagnetic induction
*Induction by means of a variable magnetic field*

Measuring the induction voltage in a conductor loop for a variable magnetic field - with Power-CASSY as variable source of current

**Description from CASSY Lab 2**

For loading examples and settings, please use the CASSY Lab 2 help.
Induction in a variable magnetic field

Experiment description

Voltages and currents which are produced as a result of variations in magnetic fields are called induction voltages and currents, and the phenomenon itself is referred to as electromagnetic induction. When a conductor loop is placed within a magnetic field $B$, the magnetic flux permeating the loop is determined by the integral of the conductor loop area:

$$\Phi = \int_A B \cdot dA$$
If instead of a conductor loop we use a coil with \( N_1 \) turns, all perpendicular to the magnetic field, \( \Phi \) increases correspondingly to

\[ \Phi = B \cdot A \cdot N_1. \]

If the magnetic field \( B \) does not vary, the magnetic flux \( \Phi \) remains constant. When the magnetic field, and thus the magnetic flux through the area of the coil, changes over time, a voltage and consequently a current as well are induced in the coil; their magnitude and direction depend on how the field varies. Faraday's law of induction applies:

\[ U = -\frac{d\Phi}{dt} \]

and thus

\[ U = -\frac{dB}{dt} \cdot A \cdot N_1. \]

Conversely, an electric current generates a magnetic field, e.g. when a current \( I \) flows through a coil. For the magnetic field inside a large cylindrical coil with the length \( L \) and the number of turns \( N_2 \), the following applies:

\[ B = \mu_0 \frac{N_2}{L} I \]

where \( \mu_0 = 4\pi \cdot 10^{-7} \text{Vs/Am} \) (magnetic field constant).

This experiment uses a large cylindrical coil as a field coil through which a varying current \( I(t) \) flows, which generates a varying magnetic field \( B(t) \) within the coil. Rectangular induction coils having different cross-sections (areas) \( A \) and numbers of turns \( N_1 \) are placed inside this field coil. A voltage \( U \) is induced in these coils, which can be calculated as:

\[ U = -\frac{dI}{dt} \cdot \mu_0 \cdot A \cdot \frac{N_2}{L} \cdot N_1 \]

This experiment verifies the proportionality between the induced voltage \( U \) and the change over time \( dI/dt \) of the field-coil current \( I \), the area \( A \) of the induction coils and the number of turns \( N_1 \) of the induction coils. Power-CASSY (524 011) or the triangular wave form power supply (521 56) are particularly suitable for this experiment, as the output current \( I \) over time can be controlled so that the slope \( |dI/dt| \) is constant. The slope \( |dI/dt| \) is continuously adjustable from 0.2 A/s to 2.2 A/s. Three induction coils are also provided, with \( N_1 = 300 \) turns each. Coil 1 has the cross-section \( A = 50 \times 50 \text{mm}^2 \), coil 2 \( A = 30 \times 50 \text{mm}^2 \) and coil 3 \( A = 20 \times 50 \text{mm}^2 \). Coil 1 is also provided with additional taps at \( N_1 = 100 \) and \( N_1 = 200 \) turns.

**Equipment list**

1. Sensor-CASSY
2. Power-CASSY
3. CASSY Lab 2
4. \( \mu \text{V} \) box
5. Field coil, \( d = 120 \text{mm} \)
6. Stand for tubes and coils
7. Set of induction coils
8. Connecting leads, 100 cm, red
9. Connecting leads, 100 cm, blue
10. PC with Windows XP/Vista/7/8

Alternatively (without Power-CASSY)

1. Sensor-CASSY
2. CASSY Lab 2
3. \( \mu \text{V} \) box
4. 30-A box
5. Field coil, \( d = 120 \text{mm} \)
6. Stand for tubes and coils
7. Set of induction coils
8. Triangular wave form power supply
9. Connecting lead, 50 cm, blue
10. Connecting leads, 100 cm, red
11. Connecting leads, 100 cm, blue
12. PC with Windows XP/Vista/7/8
Experiment setup (see drawing)
The large coil is supplied with a constant $|\frac{dI}{dt}|$ using either Power-CASSY or the triangular wave form power supply. In the latter case, the flowing current must be measured at input $A$ of Sensor-CASSY using the 30 A box. The induced voltage of the induction coils is measured using the µV box at input $B$.

Carrying out the experiment

a) Measuring the induction voltage $U$ as a function of the area (cross-section) $A$ of the induction coils

- **Load settings**
  - Place coil 1 ($A = 0.0025 \text{ m}^2$, $N_1 = 300$ turns) in the large field coil and connect it to the µV box.
  - Execute the measurement with $\triangle$. Repeat the measurement with $\triangle$. $N_1 = 300$ turns of coil 1.

b) Measuring the induction voltage $U$ as a function of the number of turns $N_1$ of the coils

- **Load settings**
  - Connect coil 1 ($N_1 = 100$ turns) in the large field coil to the µV box.
  - Execute the measurement with $\triangle$. Repeat the measurement with $\triangle$. $N_1 = 200$ and $N_1 = 300$ of coil 1.

c) Measuring the induction voltage $U$ as a function of $\frac{dI}{dt}$

- **Load settings**
  - Connect coil 1 ($N_1 = 300$ turns) in the large field coil to the µV box.
  - Execute the measurement with $\triangle$. Repeat the measurement with the reduced maximum current $I_{\text{max}}$ or $\frac{dI}{dt}$ respectively; to do this, move the pointer of the display instrument to the desired position using the mouse.

Alternatively (without Power-CASSY)

a) Measuring the induction voltage $U$ as a function of the area (cross-section) $A$ of the induction coils

- **Load settings**
  - Place coil 1 ($A = 0.0025 \text{ m}^2$, $N_1 = 300$ turns) in the large field coil and connect it to the µV box.
  - Turn the voltage knob on the triangular wave form power supply all the way to the right, and turn up the current knob until the power limiting (LED $P_{\text{max}}$) is just below the cut-in threshold.
  - Choose the middle setting for $\frac{dI}{dt}$ and press the key to activate triangle mode.
  - Start the measurement with $\triangle$ (the measurement begins with a rising edge of the induction voltage $U_{B1}$; you may need to deactivate the trigger).
  - Stop the measurement with $\triangle$ after a few current periods.
  - Repeat the measurement with coils 2 ($A = 0.0015 \text{ m}^2$) and 3 ($A = 0.0010 \text{ m}^2$).

b) Measuring the induction voltage $U$ as a function of the number of turns $N_1$ of the coils

- **Load settings**
  - Connect coil 1 ($N_1 = 100$ turns) in the large field coil to the µV box.
  - Turn the voltage knob on the triangular wave form power supply all the way to the right, and turn up the current knob until the power limiting (LED $P_{\text{max}}$) is just below the cut-in threshold.
  - Choose the middle setting for $\frac{dI}{dt}$ and press the key to activate triangle mode.
  - Start the measurement with $\triangle$ (the measurement begins with a rising edge of the induction voltage $U_{B1}$; you may need to deactivate the trigger).
  - Stop the measurement with $\triangle$ after a few current periods.
  - Repeat the measurement with $N_1 = 200$ and $N_1 = 300$ of coil 1.

c) Measuring the induction voltage $U$ as a function of the frequency of the excitation field

- **Load settings**
  - Connect coil 1 ($N_1 = 300$ turns) in the large field coil to the µV box.
  - Turn the voltage knob on the triangular wave form power supply all the way to the right, and turn up the current knob until the power limiting (LED $P_{\text{max}}$) is just below the cut-in threshold.
  - Choose the middle setting for $\frac{dI}{dt}$ and press the key to activate triangle mode.
  - Start the measurement with $\triangle$ (the measurement begins with a rising edge of the induction voltage $U_{B1}$; you may need to deactivate the trigger).
  - During the measurement increase $\frac{dI}{dt}$ in steps of about 0.4 A/s.
  - Stop the measurement with $\triangle$. 

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Evaluation

Depending on the experiment section, activate the appropriate display (click on Area, Number of Turns or dI/dt) with the mouse. A further table is filled out in which the induction voltage is determined for the respective parameter A, N₁ or dI/dt (by entering via the keyboard; dI/dt can be determined by fitting a straight line). You can find the induction voltage U e.g. by determining the mean value. You can then use the mouse to drag this value from the status line and drop it into the table (drag & drop). The desired diagram is generated as you enter the values.

All three diagrams confirm the proportionalities between the induction voltage U and the area A, number of turns N₁ and dI/dt.

In this example, we obtain the proportionality factor \( \frac{U}{A} = 101 \text{ mV/m}^2 \) (or 129 mV/m² without Power-CASSY) between the induction voltage U and the coil cross-section A. Theory expects the proportionality factor

\[
\frac{U}{A} = - \frac{dI}{dt} \cdot \mu_0 \cdot \frac{N_2}{L} \cdot N_1.
\]

By comparison, the number of turns of the induction coil N₁ = 300 and N₂ = 120 of the air coil, the air coil length L = 0.41 m, the calculated current increase dI/dt = 1.00 A/s (resp. 1.19 A/s) and the magnetic field constant \( \mu_0 = 4\pi \cdot 10^{-7} \text{Vs/Am} \) taken together give us the proportionality factor \( \frac{U}{A} = -110 \text{ mV/m}^2 \) (resp. -131 mV/m²), which agrees with the experiment result. The sign depends on the direction of the turns and the connection to the \( \mu \text{V} \) box.

Notes

The \( \mu \text{V} \) box may have a slight offset, which can be corrected in Settings by selecting Correct, setting value 0 mV and choosing Correct Offset; be sure to interrupt the circuit of the air coil first.

Power-CASSY can also output a significantly higher frequency, and thus make the \( \mu \text{V} \) box unnecessary. However, note that in this case the current regulation of Power-CASSY tends to slight overshoots at higher frequencies and inductive loads, which negatively affect the induced voltage (1st derivation of the current). You can resolve this by connecting a resistor of around 10 Ω in series.