University of Salahaddin / Collage of Basic Education

Department of General Science:

Second: stage

Experiments: Electric and magnetism

Second Course: 2023-2024

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Ohm’s Law (1)

VERIFICATION OF OHM’S LAW.

- Verification of Ohm’s law for a constantan wire and a brass wire.
- Verification of Ohm’s law for constantan wires of various lengths.
- Verification of Ohm’s law for constantan wires of various thickness.

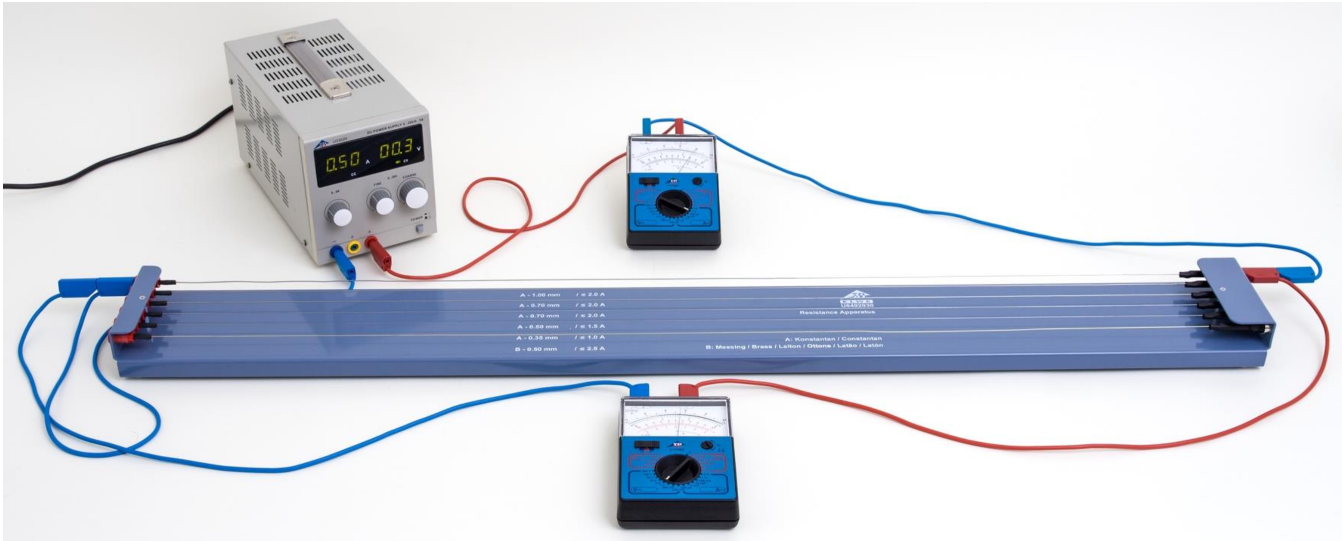


Fig. 1: Experiment set-up

BASIC PRINCIPLES

***Georg Simon Ohm* was the first in 1825 to show that the current flowing through a simple conductor is proportional to the voltage applied.**

This means that Ohm’s law applies:

(1) $U = R \cdot I$

The constant of proportionality R is the resistance of the conductor. For a metal wire of length x and cross-sectional area A, the resistance R is given by the following formula:

(2) $R = \rho \cdot \frac{x}{A}$.

The specific resistivity ρ depends on the material of which the wire is made.

In order to verify this fundamental relationship, an experiment is to be carried out to investigate the proportionality between current and voltage for metal wires of varying thickness, length and material. The resistivity will also be determined and compared with values quoted in literature.

LIST OF EQUIPMENT

1	Resistance Apparatus	1009949 (U8492030)
1	DC Power Supply 0-20 V, 0-5 A @230 V	1003312 (U33020-230)
or		
1	DC Power Supply0-20 V, 0-5 A @115 V	1003311 (U33020-115)
2	Analogue Multimeter AM50	1003073 (U17450)
1	Set of 15 Safety Experiment Leads, 75 cm	1002843 (U138021)

SET-UP AND PROCEDURE

- Set up the equipment as shown in Fig. 1. Connect the "+/–" sockets of the power supply to the sockets at the ends of the wires to be measured. Connect a multimeter between them to measure the current. The other multimeter should be connected in parallel with the sockets at the ends of the wire being measured in order to measure the voltage.

All the wires are of length x = 1 m.

- For measurements using wires made of various materials, connect the fourth wire from the top (constantan, d = 0.5 mm) or the sixth wire from the top (brass, d = 0.5 mm) as described above.
- For measurements with wires of length x = 1 m, connect the second (or third) wire from the top (constantan, d = 0.7 mm) as described above. For measurements with wires of length x = 2 m, first connect the "–" socket of the power supply to the left-hand end of the second wire from the top. Then connect the socket at the right-hand end of the second wire from the top to the socket at the left hand end of the third wire from the top. Finally, connect the socket at the right-hand end of the third wire from the top (via the ammeter) to the "+" socket of the power supply. This series connection of the two constantan wires of the same thickness d = 0.7 mm and length x = 1 m is equivalent to a single wire of thickness d = 0.7 mm which is double the length, x = 2 m.
- For measurements on wires of different thickness, connect the first, second (or third), fourth and fifth wires from the top (constantan with d = 1, 0.7, 0.5, 0.35 mm) as described above.
- For all three sets of measurements, set the voltage in suitable steps and measure the current until the maximum permissible current level is reached (2 A for constantan with d = 1 mm or 0.7 mm, 1.5 A for constantan with d = 0.,5 mm, 1 A for constantan with d = 0.35 mm and 2.5 A for brass with d = 0.5 mm). Make a note of all the values (Tables 1 – 3).

SAMPLE MEASUREMENT

Wires of differing materials

Table 1: Measurements for a constantan wire and a brass wire of length x = 1 m and thickness d = 0.5 mm.

Constantan		Brass	
U / V	I / A	U / V	I / A

Wires of differing length

Table 2: Measurements for constantan wires of differing lengths x but constant thickness d = 0.7 mm.

x = 1 m		x = 2 m	
U / V	I / A	U / V	I / A

Wires of differing thickness

The cross-sectional area A is calculated from the thickness of the wire d as follows:

$$(3) \quad A = \frac{\pi}{4} \cdot d^2$$

Table 3: Measurements for constantan wires of differing thickness d and cross-sectional area A, all of length x = 1 m.

d = 1 mm A = 0.79 mm²		d = 0.7 mm A = 0.38 mm²		d = 0.5 mm A = 0.2 mm²		d = 0.35 mm A = 0.1 mm²	
U / V	I / A	U / V	I / A	U / V	I / A	U / V	I / A

EVALUATION

- For each of the various parameters, ρ, x and d, plot the measurements in a graph of U against I (Figs. 2, 3, 5).
- In each case, match straight lines to the measured values $U(I)$. The ohmic resistance R can then be found in each case by using Equation (1) (Tables 4, 6, 7).
- In the case of measuring wires made of different materials (2), calculate the resistivity ρ from the known values of length x and thickness d (Table 5).
- In the case of measuring wires of different lengths and thicknesses/cross-sections, plot the values of the resistance against the lengths x or the inverse of the cross-sectional area A, draw a straight line through the points (Figs. 4, 6). The gradient of the line can be used to calculate the resistivity ρ from the known values of thickness d and length x, as shown in Equation (2).

Wires of differing materials

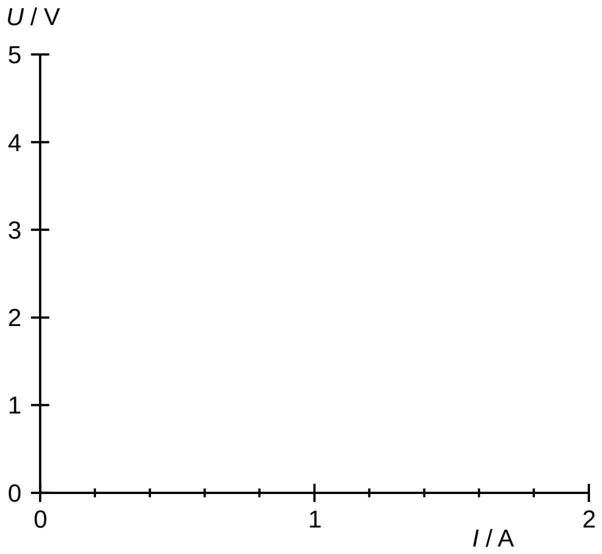


Fig. 2: Graph of U against I for constantan wire (blue) and brass wire (red), length $x = 1$ m and thickness $d = 0.5$ mm.

Table 4: Ohmic resistance of a constantan wire and a brass wire of length $x = 1$ m and thickness $d = 0.5$ mm determined from the gradient of the straight lines through the points in Fig. 2.

Material	R / Ω
Constantan	
Brass	

From (2) the following is true:

$$(4) \quad R = \rho \cdot \frac{x}{A} \Rightarrow \rho = R \cdot \frac{A}{x} .$$

Table 5: Resistivity ρ of constantan and brass as determined from (4) and compared with values quoted in literature.

Material	ρ / (Ω·mm²·m⁻¹)	
	Measurement	Literature
Constantan		
Brass		

The values determined by measurement are well in agreement with those quoted in literature.

Wires of differing length

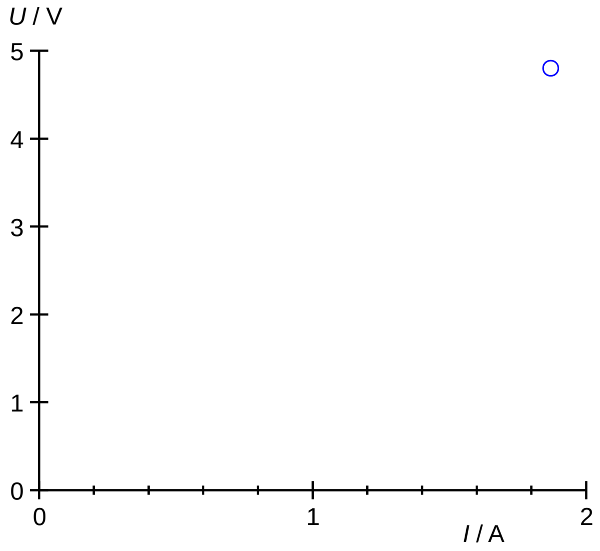


Fig. 3: Graph of U against I for constantan wires of various lengths x and thickness $d = 0.7$ mm.

Table 6: Ohmic resistance of constantan wires of differing length x but constant thickness $d = 0.7$ mm determined from the gradient of the straight lines through the points in Fig. 3.

x / m	R / Ω

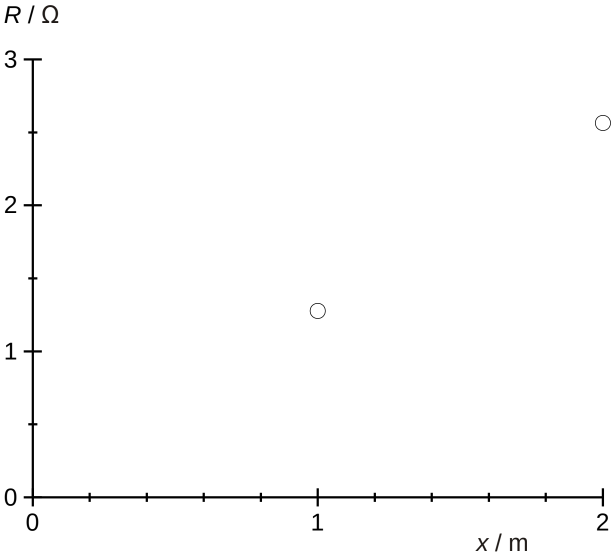


Fig. 4: Resistance R as a function of length x.

- Determine the resistivity ρ from the gradient a of a straight line through the measurement points $R(x)$:

(5) $R = \rho \cdot \frac{x}{A} = \frac{\rho}{A} \cdot x = a \cdot x$ where $a = \frac{\rho}{A}$

(6) $a = \frac{\rho}{A} \Leftrightarrow$

$a \cdot A$ ^{2} ______ ^{2}

The value determined by measurement is well in agreement with the value for constantan quoted in tables, $\rho = 0.49\ \Omega \cdot mm^2 \cdot m^{-1}$.

Wires of differing thickness

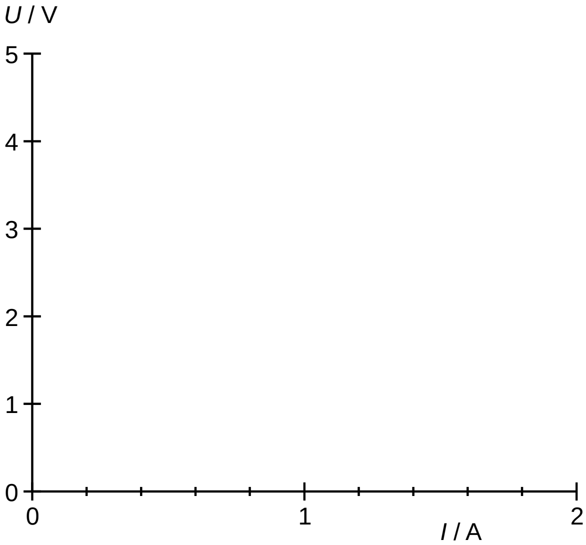


Fig. 5: Graph of U against I for constantan wires of various thickness d and length x = 1 m

Table 7: Ohmic resistance of constantan wires of various thicknesses d and cross section A but the same length x = 1 m, as determined from the gradient of the straight lines through the points in Fig. 5.

d / mm	A / mm²	R / Ω

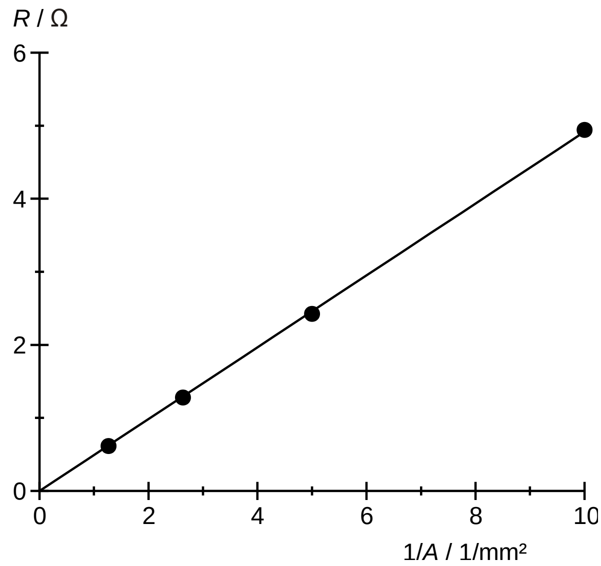


Fig. 6: Resistance R as a function of the inverse of the cross-sectional area A

- Determine the resistivity ρ from the gradient b of a straight line through the measurement points $R(1/A)$:

(7) $R = \rho \cdot \frac{x}{A} = \rho \cdot x \cdot \frac{1}{A} = b \cdot \frac{1}{A}$ where $b = \rho \cdot x$

(8) $b = \rho \cdot x \Leftrightarrow \rho = \frac{b}{x} =$ ______ ^{2} ______ ^{2}

The value determined by measurement is well in agreement with the value for constantan quoted in tables, $\rho = 0.49\ \Omega \cdot mm^2 \cdot m^{-1}$.

ELECTRICAL CONDUCTORS (2)

EXPERIMENT PROCEDURE

- Measure voltage drop *U* as a function of distance *d* between contact points at a constant current *I*.
- Measure voltage drop *U* as a function of current *I* for a fixed distance *d* between contact points.
- Determine the electrical conductivity of copper and aluminum and make a comparison with values quoted in literature.

OBJECTIVE

Determine the electrical conductivity of copper and aluminum

SUMMARY

Electrical conductivity of a material is highly dependent on the nature of the material. It is defined as the constant of proportionality between the current density and the electric field in the material under investigation. In this experiment, four-terminal sensing is used to measure current and voltage in metal bars of known cross section and length.

REQUIRED APPARATUS

Quantity	Description	Item Number
1	Heat Conducting Rod Al	1017331
1	Heat Conducting Rod Cu	1017330
1	DC Power Supply 1 - 32 V, 0-20 A (230 V, 50/60 Hz)	1012857 or
	DC Power Supply 0 - 40 V, 0-40 A (115 V, 50/60 Hz)	1022289
1	Measurement Amplifier U (230 V, 50/60 Hz)	1020742 or
	Measurement Amplifier U (115 V, 50/60 Hz)	1020744
2	Digital Multimeter E	1018832
1	Set of 15 Experiment Leads, 75 cm, 2.5 mm^2	1002841

PHYSICS EXPERIMENT

Electrical Conductors (2)

DETERMINE THE ELECTRICAL CONDUCTIVITY OF COPPER AND ALUMINIUM

- **Measure voltage drop *U* as a function of distance d between contact points at a constant current *I*.**
- **Measure voltage drop U as a function of current *I* for a fixed distance *d* between contact points.**
- **Determine the electrical conductivity of copper and aluminium and make a comparison with values quoted in literature.**

Fig. 1: Experiment set-up

GENERAL PRINCIPLES

Electrical conductivity of a material is highly dependent on the nature of the material. It is defined as the constant of proportionality between the current density and the electric field in the respective material. In metals it is determined by the number density and mobility of electrons in the conduction band and is also dependent on temperature.

For a long metal conductor of cross-sectional area *A* and length *d*, a relationship between current *I* through the conductor and the voltage *U* which drops over a distance *d* along it can be deduced from the following formula:

(1) $j = \sigma \cdot E$

j: current density, *E*: electric field

That relationship is as follows:

(2) $I = j \cdot A = A \cdot \sigma \cdot \frac{U}{d}$

In the experiment, this relationship is used to determine the conductivity of metal bars using four-terminal sensing (Fig. 2). This involves feeding in a current *I* through two wires and measuring the drop in voltage *U* between two contact locations separated by a distance *d*. Since the area of the cross section *A* is known, it is possible to calculate the conductivity σ.

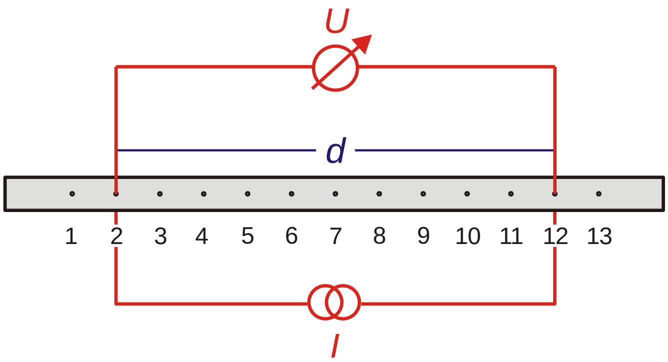


Fig. 2: Schematic of four-terminal sensing measurement

LIST OF EQUIPMENT

1 Heat Conducting Rod Al 1017331 (U8498292)

1 Heat Conducting Rod Cu 1017330 (U8498291)

1 DC Power Supply
1 - 32 V, 0 – 20 A @230V 1012857 (U11827-230)

or

1 DC Power Supply
1 – 32 V, 0 – 20 A @115V 1012858 (U11827-115)

1 Microvoltmeter @230V 1001016 (U8530501-230)

or

1 Microvoltmeter @115V 1001015 (U8530501-115)

1 Digital Multimeter E 1006809 (U8531050)

1 Set of 15 Experiment Leads
2.5 mm² 1002841 (U13801)

SET-UP

- Put the copper or aluminium heat conducting rod on an insulated surface.
- Connect the "–" output socket on the back of the power supply to the hole in the side of the conducting rod level with the second measuring point (Fig. 2). Connect the "+" output socket on the back of the power supply to the hole in the side of the conducting rod level with the twelfth measuring point. Connect the digital multimeter in series between them for the purpose of measuring voltage.
- Short the input to the microvoltmeter and calibrate the display to 0 with the help of the DC offset knob. Check the zero calibration regularly in the course of your measurements.
- Connect two measuring probes to the 4-mm safety sockets of the microvoltmeter.
- Set the upper limit of the frequency on the microvoltmeter to "OFF" by means of the "Filter Hz" knob and select a measuring of up to 200 μV DC.

EXPERIMENT PROCEDURE

Notes:
Take care not to exceed the maximum current capacity of the power supply, 20 A.

Thermo-electric voltages at the measurement points could restrict the accuracy of the measurements.

The relative distance between adjacent measurement points is $d_{N+1} – d_N$ = 4 cm, i.e. $d_{N+k} – d_N = k \cdot 4$ cm.

Dependence on distance

- Set up the power supply such that a current *I* of about 10 A flows through the conduction rod. Read off the value from the multimeter and write it down.
- Make contact between the measuring probe connected to the ground socket of the microvoltmeter and the second measurement point (*N* = 2).
- Use the other probe to make contact with the third to twelfth measurement points in sequence, read off the voltage *U* for each one and enter the results into Table 1.

Dependence on current

- Use the power supply to increase the current from 1 A to 10 A in steps of 1 A. Read off the current values for each step from the multimeter and enter them into Table 2.
- At each step, measure the voltage between the 2nd and 12th measurement points (*d* = 40 cm) with the measuring probes (take care with the polarity). Read off the values from the microvoltmeter and enter them into Table 2.

SAMPLE MEASUREMENT

Table 1: Voltages measured as a function of the distance between measurement points, *I* = 9.92 A (copper) and 9.90 A (aluminium).

N	$d = d_N – d_2$	*U* / μV	
		Copper	Aluminium
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			

Table 2: Voltage measured as a function of current, *d* = 40 cm.

Copper		Aluminium	
I / A	*U* / μV	*I* / A	*U* / μV
9,91			

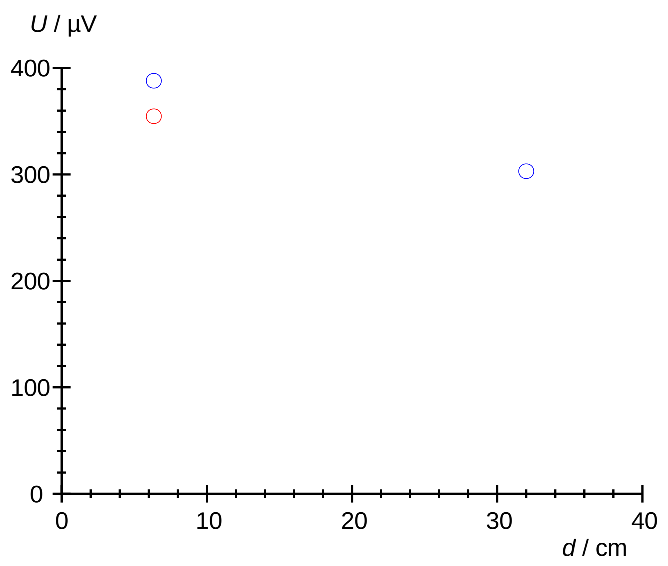


Fig. 3: Plot of *U* against *d* for copper and aluminium

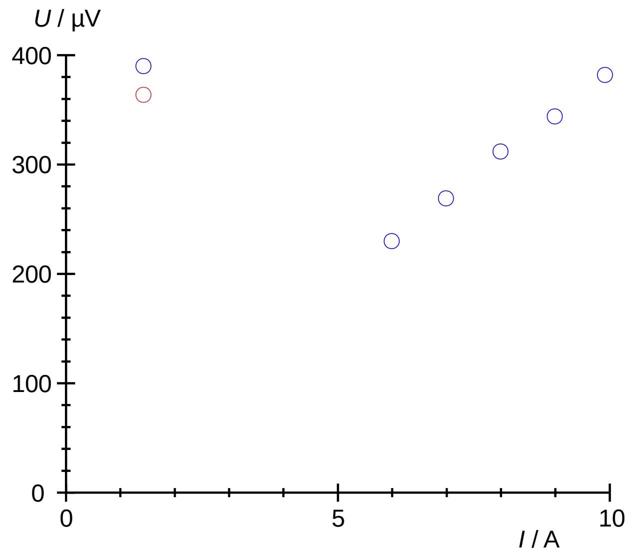


Fig. 4: Plot of *U* against *I* for copper and aluminium

EVALUATION

Dependence on distance

- Plot the voltages *U* measured as a function of distance *d* (Tab. 1) for the copper and aluminium rods on one graph (Fig. 3) and fit a straight line through the origin to each set of points.

NOTE:
Contact voltages between the measurement probes and the metal bar may become apparent by causing the straight lines to be shifted away from the origin.

According to equation (2), the following is true

$$(3)\quad \alpha = \frac{I}{A\cdot\sigma}\,.$$

Since *I* and *A* are known, it is possible to calculate the conductivity:

$$(4)\quad \sigma = \frac{I}{A\cdot\alpha} = \begin{cases} \dfrac{\qquad}{\quad{}^{2}\qquad\underline{\qquad}} = & \text{(Cu)} \\[2ex] \dfrac{\qquad}{\quad{}^{2}\qquad\underline{\qquad}} = & \text{(Al)} \end{cases}$$

Dependence on current

- Plot the voltages *U* (Tab. 2) measured as a function of current *I* for the copper and aluminium rods on one graph (Fig. 4) and fit a straight line through the origin to each set of points.

NOTE:
Contact voltages between the measurement probes and the metal bar may become apparent by causing the straight lines to be shifted away from the origin.

According to equation (2), the following is true

$$(5)\quad \beta = \frac{d}{A\cdot\sigma}$$

Since *d* and *A* are known, it is possible to calculate the conductivity:

$$(6)\quad \sigma = \frac{d}{A\cdot\beta} = \begin{cases} \dfrac{\qquad}{\quad{}^{2}\qquad\underline{\qquad}} = & \text{(Cu)} \\[2ex] \dfrac{\qquad}{\quad{}^{2}\qquad\underline{\qquad}} = & \text{(Al)} \end{cases}$$

The result for copper is in good agreement with the value stated in literature for pure copper $\sigma = 58\cdot10^{6}$ S/m. Comparison of the measured value for aluminium with that quoted in literature for pure aluminium $\sigma = 37\cdot10^{6}$ S/m indicates that the heat conduction rod used here is not made of pure aluminium but is an alloy of it.

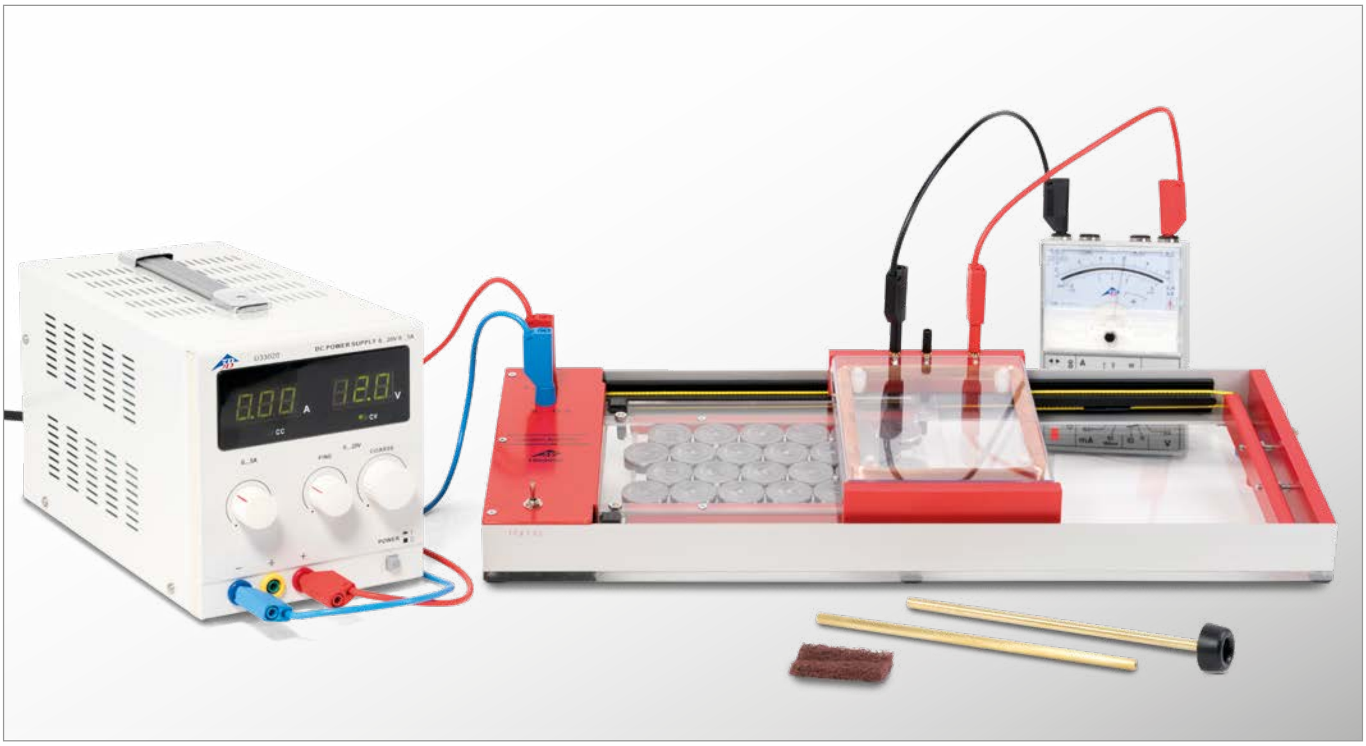
NOTE:
The experiment uses the same metal bars investigated in the experiment on heat conduction, UE2020100. Two measurement probes are used to measure the voltage drop between the contact points, which can also be used to measure temperature along the bars.

By comparing the measurements with the heat conductivity values obtained in experiment UE2020100 it is possible to verify the Wiedemann-Franz law. This states that thermal conductivity λ is proportional to electrical conductivity σ in metals and the factor is a universal value temperature-dependent coefficient *L* (Lorenz coefficient):

$$(7)\quad \frac{\lambda}{\sigma} = L(T)\cdot T\,.$$

T: temperature

INDUCTION IN A MOVING CONDUCTOR LOOP **(3)**



EXPERIMENT PROCEDURE

- Measure the induced voltage as a function of the velocity of the conductor loop.
- Measure the induced voltage as a function of the number of turns in the conductor loop.
- Compare the sign of the induced voltage when moving the conductor loop into the field or out of it.
- Compare the sign of the induced voltage when the direction of motion is changed.
- Measure the induced voltage in a conductor loop with a single turn of variable area.

OBJECTIVE

Measure the induced voltage in a conductor made into a loop as it moves through a magnetic field

SUMMARY

The change in magnetic flux that is needed to induce a voltage in a conductor loop can be caused by a movement of the loop. Such a situation results, for example, when a conductor loop orientated with its plane perpendicular to a homogeneous magnetic field is moved into the magnetic field or withdrawn from it at a constant velocity. In the first case the magnetic flux increases at a rate determined by the relevant parameters, whereas in the second case it decreases in a similar way. Therefore the induced voltages are of opposite signs.

REQUIRED APPARATUS

Quantity	Description	Item Number
1	Induction Apparatus	1000968
1	DC Power Supply 0 – 20 V, 0 – 5 A (230 V, 50/60 Hz)	1003312 or
	DC Power Supply 0 – 20 V, 0 – 5 A (115 V, 50/60 Hz)	1003311
1	Analogue Multimeter ESCOLA 100	1013527
1	Set of 15 Safety Experiment Leads, 75 cm	1002843
1	Mechanical Cumulative Stopwatch	1002810
Additionally recommended		
1	Measurement Amplifier U (230 V, 50/60 Hz)	1020742 or
	Measurement Amplifier U (115 V, 50/60 Hz)	1020744

BASIC PRINCIPLES

The term electromagnetic induction refers to the process whereby an electric voltage is generated around a conductor loop when the magnetic flux passing through the loop is changed. Such a change in flux can result from a change in the magnetic field strength or from movement of the conductor loop.

To describe the relationships involved, a U-shaped conductor loop with a moveable crossbar is often considered. The plane of this loop is aligned perpendicular to a homogeneous magnetic field of flux density *B* (see Fig. 1). The magnetic flux through the area limited by the cross-bar is

(1) $$\Phi = B \cdot a \cdot b$$

a: Width, *b*: Length of the loop.

If the cross-bar is moved with a velocity *v*, the flux changes, since the length of the loop is changed. The rate of change of the flux is

(2) $$\frac{\mathrm{d}\Phi}{\mathrm{d}t} = B \cdot a \cdot v$$

and in the experiment it is observed as a voltage

(3) $$U = -B \cdot a \cdot v$$

which is in the order of microvolts but can be measured using the amplifier that is recommended as additional equipment.

A much greater induced voltage is obtained if a conducting loop with multiple turns on a rigid frame is moved through the magnetic field. When the frame is only partly projecting into the magnetic field, the situation is as shown schematically in Figure 1. The movement of the loop into the magnetic field results in a change of flux at the following rate

(4) $$\frac{\mathrm{d}\Phi_1}{\mathrm{d}t} = B \cdot N \cdot a \cdot v$$

N: Number of turns,

and this can be measured as an induced voltage.

(5) $$U_1 = -B \cdot N \cdot a \cdot v$$

As soon as the conductor loop is completely in the magnetic field, the induced voltage returns to zero. No further change occurs until the loop begins to move out of the magnetic field. Now the magnetic flux is decreasing and the induced voltage is of opposite sign compared to the initial situation. A change of sign also occurs if the direction of motion of the loop is reversed.

In this experiment, the voltage driving an electric motor used to pull the conductor loop along is varied. This provides a range of different constant velocities. The direction of rotation of the motor can also be reversed. The coil provided also has an intermediate tapping point, so that the induced voltage can be measured for three different values of *N*, the number of turns.

EVALUATION

Calculate the velocity from the time *t* required for the conductor loop to move completely through the magnetic field and the corresponding distance *L*

$$v = \frac{L}{t}$$

Then draw a graph of the induced voltage *U* as a function of the velocity *v*. The data will be found to lie on a straight line through the origin (see Fig. 2).

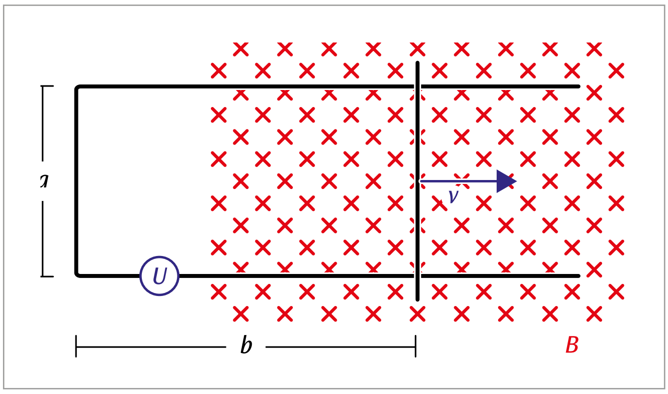


Fig. 1: The change of the magnetic flux through the conducting loop when its area is altered

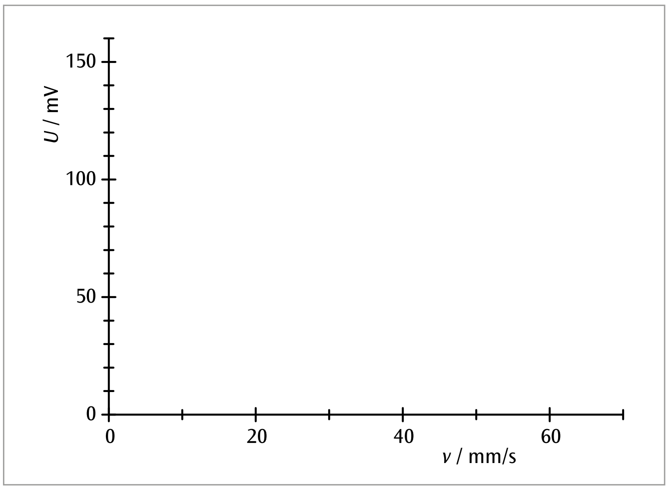


Fig. 2: Induced voltage as a function of the velocity of the conducting loop

PHYSICS EXPERIMENT

Magnetic Field of the Earth (4)

DETERMINE THE HORIZONTAL AND VERTICAL COMPONENTS OF THE EARTH'S MAGNETIC FIELD.

- Measure the angle of rotation of a compass needle initially aligned parallel with the horizontal component of earth's magnetic field when a second horizontal magnetic field is superimposed with the help of a pair of Helmholtz coils.
- Determine the horizontal component of the earth's magnetic field.
- Measure the inclination and vertical component and calculate the overall magnitude of the earth's magnetic field.

Fig. 1: Measurement set-up.

GENERAL PRINCIPLES

The earth is surrounded by a magnetic field generated by a so-called geo-dynamo effect. Close to the surface of the earth, this field resembles that of a magnetic dipole with field lines emerging from the South Pole of the planet and circling back towards the North Pole. The angle between the actual magnetic field of the earth and the horizontal at a given point on the surface is called the inclination. The horizontal component of the Earth's field roughly follows a line running between geographical north and south. Because the earth's crust exhibits magnetism itself, there are localised differences which are characterised by the term declination.

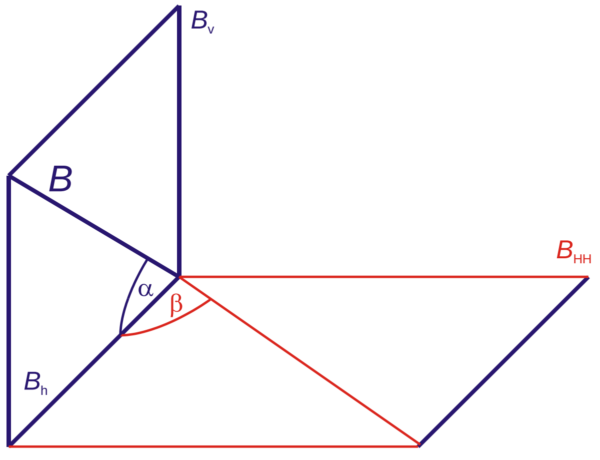


Fig. 2: Diagram of components of the magnetic fields observed in the experiment and definition of the corresponding angles.

This experiment involves measuring the inclination and the absolute magnitude of the Earth's magnetic field along with the horizontal and vertical components of it at the point where the measurement is made.

The following relationships apply (Fig. 2):

(1) $B_v = B_h \cdot \tan\alpha$

α: inclination
B_h: horizontal component
B_v: vertical component

and

(2) $B = \sqrt{B_h^2 + B_v^2}$.

It is therefore sufficient to determine the values B_h and α, since the other values can simply be calculated.

The inclination α is determined with the aid of an dip needle. In order to obtain the horizontal component B_h, the dip needle is aligned in horizontal plane in such a way that its needle points to 0° when parallel to the horizontal component 0°. An additional horizontal magnetic field B_{HH}, which is perpendicular to B_h, is generated by a pair of Helmholtz coils and this field causes the compass needle to turn by an angle β. According to Fig. 2 the following is then true:

(3) $\frac{B_{HH}}{B_h} = \tan\beta$

In order to improve the accuracy, this measurement is carried out for a variety of angles β.

LIST OF EQUIPMENT

1	Helmholtz Coils 300 mm	1000906 (U8481500)
1	DC Power Supply 0-20 V, 0-5 A @230V	1003312 (U33020-230)
or		
1	DC Power Supply 0-20 V, 0-5 A @115V	1003311 (U33020-115)
1	Digital Multimeter P1035	1002781 (U11806)
1	Inclination Instrument E	1006799 (U8495258)
1	Rheostat 100 Ω	1003066 (U17354)
1	Set of 15 Safety Experiment Leads, 75 cm	1002843 (U138021)

SET-UP AND PROCEDURE

Note:
Set up the experiment on a flat, horizontal surface at a location which is not affected by any interfering magnetic fields from the environment.

Determining the horizontal component B_h

- Turn the hand wheel on the inclination instrument such that the plane of the ring scale and the compass needle are situated parallel to the work surface.

This ensures the compass needle is always aligned along the horizontal component of the Earth's magnetic field.

- Turn the inclination instrument at its base until the 0°-marking of the ring scale aligns with the direction of the compass needle.
- Shift the Helmholtz coils using the inclination instrument such that it is positioned in the middle between the two coils (Fig. 1) and the axis of the Helmholtz coils is oriented perpendicular to the direction of the compass needle.
- Connect the Helmholtz coils, the digital multimeter and the rheostat in series to the power supply unit (Fig. 1).
- Set the rheostat to 100 Ω.
- Switch on the DC power supply and increase the current by raising the voltage with the fine adjustment controller of the DC voltage until the direction pointed to by the compass needle aligns with the 5° marking of the ring scale. Enter the deflection angle β = 5° into Tab. 1. Take the current reading on the multimeter and enter this value into Tab. 1 as well.
- Gradually increase the current incrementally until the deflection angle goes up to β = 75° in 5° steps. Enter each deflection angle and current value into Table 1. If fine adjustment controller for DC voltage reaches limit stop, continue to increase the current by reducing the resistance on the rheostat.

Determining inclination α

- Turn the hand wheel on the inclination instrument such that the plane of the ring scale and the compass needle are parallel to the work surface.

This ensures the compass needle is always aligned along the horizontal component of the Earth's magnetic field.

- Turn the inclination instrument at its base until the 0°-marking of the ring scale aligns with the direction of the compass needle.
- Turn the hand wheel on the inclination instrument so that the plane of the ring scale and the compass needle are perpendicular to the work surface.
- Wait unit the compass needle is steady.
- Take a reading of the inclination angle α_1 on the ring scale of the inclination instrument and enter the value into Tab. 2.
- Turn the inclination instrument by 180 ° by turning the hand wheel.
- Wait until the compass needle is steady.
- Take a reading of the inclination angle α_2 on the ring scale of the inclination instrument and enter it into Tab. 2.

SAMPLE MEASUREMENT AND EVALUATION

Tab. 1: Deflection angle β, set currents I and calculated magnetic fields B_{HH} of the Helmholtz coils in accordance with Equation (5).

β	I / mA	B_{HH} / µT
5°		
10°		
15°		
20°		
25°		
30°		
35°		
40°		
45°		
50°		
55°		
60°		
65°		
70°		
75°		

Tab. 2: Determine the inclination α based on the average value of the two measured values α_1 and α_2.

α_1	α_2	$\alpha = \frac{\alpha_1 + \alpha_2}{2}$

Determining the horizontal component B_h

From equation (3) the following can be deduced:

(4) $B_{HH} = B_h \cdot \tan\beta$

The horizontal component B_h is therefore equivalent to the gradient of a line through points plotted on a graph of B_{HH} against $\tan\alpha$.

The magnetic field of the Helmholtz coils B_{HH} can be determined easily. Inside the pair of coils it is highly uniform and is proportional to the current I through either of the coils:

(5) $B_{HH} = k \cdot I$ where

$$k = \left(\frac{4}{5}\right)^{\frac{3}{2}} \cdot 4\pi \cdot 10^{-7}\,\frac{\text{Vs}}{\text{Am}} \cdot \frac{N}{R}$$

N = 124: number of windings
R = 147.5 mm: radius

- Compute the magnetic field B_{HH} of the Helmholtz coil pairs for all set currents I (Tab. 1) in accordance with Equation (5) and enter the results in Tab. 1.

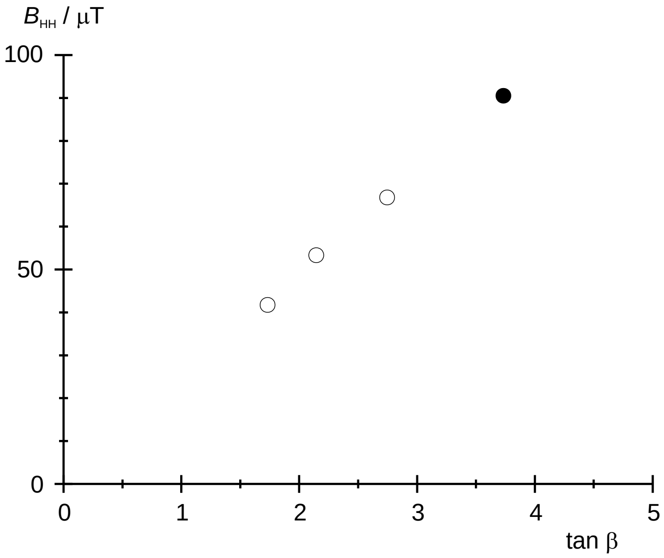


Fig. 3: B_{HH} – $\tan\alpha$ - Graph to determine the horizontal component of the earth's magnetic field.

- Plot the magnetic filed B_{HH} versus $\tan\beta$ in a graph and fit a straight line (Fig. 2).
- Deduce the horizontal component B_h directly from the slope of the line.

  (6) $B_h = 23\ \mu\text{T}$

Determining the vertical component B_v from the inclination α

- Determine the inclination α from the average value of the two measured values α_1 and α_2 (Tab. 2) and enter the results into Tab. 2.
- Use Equation (1) to determine the vertical component.

  (7) $B_v = B_h \cdot \tan =$

Determine the overall magnetic field

- Determine the overall magnitude of the Earth's magnetic field B with the aid of Equation (2).

  (8) $B = \sqrt{(\qquad\qquad)}$

The values for the horizontal and vertical components determined from the measurement are in very good agreement with the values found in the literature for Central Europe B_h = 20 µT and B_v = 44 µT.

Transformers (5)

MAKE MEASUREMENTS ON A TRANSFORMER WITH AND WITHOUT LOAD

- **Measure the open-circuit voltage as a function of the primary voltage for fixed numbers of windings.**
- **Measure the open-circuit voltage as a function of the primary voltage for fixed numbers of windings.**

Fig. 1: Set-up for measuring open-circuit voltage as a function of primary voltage.

BASIC PRINCIPLES

Transformers are devices based on Faraday's law of induction which are used for converting voltages. One major use is for the transmission of electrical power over large distances, whereby power losses can be minimised by converting the voltage up to the highest possible levels thus reducing the current to a minimum.

The simplest form of transformer consists of two coils coupled together, a primary coil with N_1 winding turns and a secondary coil with N_2 winding turns, both of which are wound around a common iron core. The following treatment considers an ideal, i.e. loss-free, transformer.

As long as there is no load on the transformer, no current can flow in the secondary circuit, i.e. $I_2 = 0$. If an alternating voltage U_1 is applied to the primary coil, it will act purely as an inductive resistance because, in the case of an ideal coil, the normal, ohmic resistance can be neglected. Then a current of I will flow in the primary circuit and will generate a magnetic flux Φ Fig. 2), thereby inducing a voltage of U_{ind}. This induced voltage is equal and opposite to U_1 due to Kirchhoff's second (voltage) law, $U_1 + U_{ind} = 0$:

$$(1) \quad U_{ind} = -L_1 \cdot \frac{dI}{dt} = -N_1 \cdot \frac{d\Phi}{dt} = -U_1 .$$

L_1: inductance of primary coil
Φ: magnetic flux generated by I

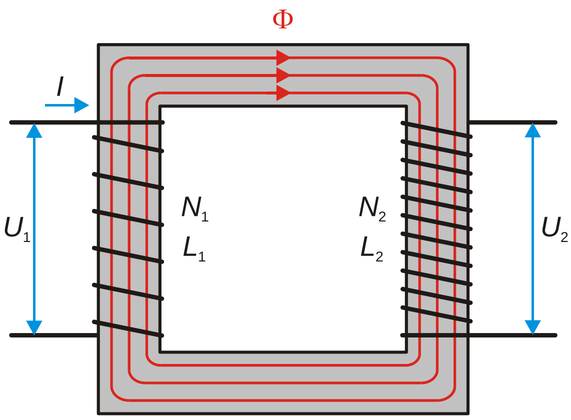


Fig. 2: Schematic of ideal transformer under no load with primary and secondary coils wound in the same direction.

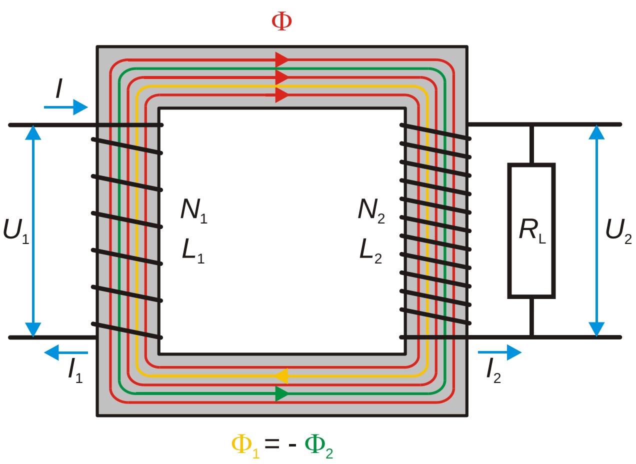


Fig. 3: Schematic of ideal transformer under load with primary and secondary coils wound in the same direction.

The current I corresponds to a purely reactive current since the voltage and current across an inductive resistance are phase-shifted by $\varphi = 90°$ with respect to one another (current lags the voltage by 90°).

Since the magnetic flux Φ would have a full effect on the secondary coil under ideal conditions, the following voltage would be induced in it:

$$(2) \quad U_2 = -N_2 \cdot \frac{d\Phi}{dt}.$$

From equations (1) and (2) the following relationship between the voltage and winding ratios can be deduced:

$$(3) \quad \frac{U_2}{U_1} = -\frac{N_2}{N_1}.$$

The negative sign indicates that U_1 and U_2 would be phase-shifted by 180° if the windings are wound in the same direction (Fig. 2). If they were wound in opposing directions, U_1 and U_2 would be in phase.

When there is a load on the transformer, the current flowing in the secondary coil will be $I_2 = U_2 / R_L$, where R_L is the ohmic resistance, e.g. of a consumer or appliance (Fig. 3). This secondary current is purely active since, in the case of an ohmic resistance, the voltage and current will be in phase ($\varphi_2 = 0°$). In this situation, a magnetic flux is generated which, in the ideal case, takes full effect on the primary coil and, as predicted by Lenz's law, opposes the magnetic flux φ generated in the primary coil by the current I. The magnitude of this secondary flux is as follows

$$(4) \quad \Phi_2 = \mu_0 \cdot \mu_r \cdot N_2 \cdot I_2 \cdot \frac{A}{l},$$

μ_0: Magnetic permeability of free space
μ_r: Relative permeability
A: Cross-sectional area of coil
ÿ: Length of coil

Thus the primary reactive current I has an active current I_1 superimposed on it which is in phase with the primary voltage ($\varphi_1 = 0°$) and which generates the following additional magnetic flux

$$(5) \quad \Phi_1 = \mu_0 \cdot \mu_r \cdot N_1 \cdot I_1 \cdot \frac{A}{l}$$

Since the magnetic flux Φ remains the same, the magnetic fluxes Φ_1 and Φ_2 must cancel out, i.e. $\Phi_1 + \Phi_2 = 0$. Thus, from equations (4) and (5) we may deduce the following:

$$(6) \quad \frac{I_2}{I_1} = -\frac{N_1}{N_2}.$$

This is because μ_r, A and ÿ are the same for both coils. From equations (3) and (6) it may be concluded that the active power generated in the primary and secondary coils must be equal:

$$(7) \quad P_1 = U_1 \cdot I_1 = U_2 \cdot I_2 = P_2.$$

Equation (3) also applies in the case of ideal transformers under load. By looking at the impedance values, we may conclude that the voltage ratio in the case of an ideal transformer is independent of the resistance value of the ohmic load.

For a transformer under load, though, two limiting conditions emerge. In the limiting case where $R_L \to \infty$ ($I_2 = 0$) the secondary side of the transformer is effectively open. Equation (3) is then applicable for determining the open-circuit voltage U_{20}. In the other limiting case where $R_L = 0$ ($U_2 = 0$), the secondary side of the transformer is shorted out and equation (6) applies for the short-circuit current I_{2C}.

In this experiment, measurements are to be made of the open-circuit voltage U_{20} as a function of the primary current U_1 and of the short-circuit current I_{2C} as a function of the primary current I_1 when there is a fixed ratio between the number of windings $N_2 / N_1 = 2$.