Electricity

Electromagnetic induction
Transformer

Physics Leaflets

P3.4.5.2

Voltage transformation with a transformer under load

Objects of the experiment

- Measuring the secondary voltage and current of a ‘soft’ and a ‘hard’ transformer as function of the load
- Determination of the output power of a transformer under load as function of the current in the secondary coil.
- Investigation of the lines of the magnetic flux in a ‘soft’ and a ‘hard’ transformer

Principles

A transformer usually consists of two coils which are inductively coupled by an iron core. They are used to change alternating currents. The frequency is not changed by the voltage conversion.

The relationship between the input voltage U_1 and the output voltage U_2 of a transformer depends on the ratio of the number of turns N_1:N_2. The voltage transformation without load and the current transformation of a transformer under full load (short-circuited operation) is investigated in the related experiment P3.4.5.1.

On the other hand the output voltage (secondary voltage) of a transformer depends on the load. The output voltage U_2 decreases with increasing current I_2 in the secondary coil due to an increasing voltage drop across the internal resistance of this power source (i.e. the secondary coil).

Further, the current-voltage characteristic of a transformer under load depends also on the physical design of the transformer. In this experiment the relationship between the secondary voltage U_2 and the secondary current I_2 of a loaded transformer is investigated when the primary and secondary windings

a) are distributed symmetrically on both limbs of the iron core (fixed-ratio or ‘hard’ transformer) and

b) are wound separately on each limb of the iron core (high-reactance or ‘soft’ transformer).

In both cases the lines of the magnetic flux of the transformer are investigated by using iron filings on a transparent plate placed on top of the transformer.

The output power P of the two transformer types can be determined by using the relation (assuming low losses):

$$P_2 = U_2 \cdot I_2 \qquad \text{(I)}$$

Thus the current-power characteristic is obtained from which the maximum attainable output power can be determined.

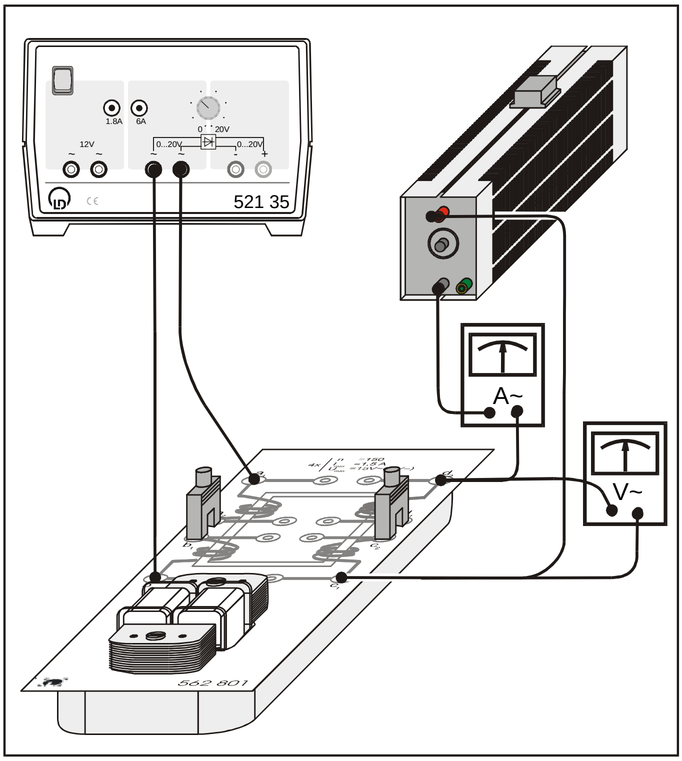

Fig. 1: Experimental setup to investigate the current-voltage characteristic of a transformation with load.

Bi 1006

Apparatus

1 Transformer for student's experiments 562 801
1 Variable extra low-voltage transformer S 521 35
1 Rheostat 100 Ohm 537 34
2 Multimeter LDanalog 20 .... 531 120
1 Acrylic glass screen on rod 459 23
1 Shaker for iron filings 514 72
1 Iron filings 514 73
7 Connecting Lead 100 cm Black 500 444

Setup

a) current-voltage characteristic of a 'soft' transformer

The setup for measuring the output voltage and output current of a 'soft' transformer (primary and secondary coils on separate limbs) under load is shown in Fig. 1. The variable low voltage power supply is connected to the primary coils. The ammeter is connected in series with the load to the secondary coils. The output voltage of the transformer is measured with the voltmeter (Fig. 2).

b) current-voltage characteristic of a 'hard' transformer

The setup for measuring the output voltage and output current of a 'hard' transformer (primary and secondary coils on the same limbs) under load is shown in Fig. 3. The variable low voltage power supply is connected to the primary coils. The ammeter is connected in series with the load to the secondary coils. The output voltage of the transformer is measured with the voltmeter.

c) magnetic field of a 'soft' and a 'hard' transformer

A schematic representation of the setup for revealing the lines of magnetic flux of a loaded soft transformer is schematically depicted in Fig. 4.

Safety notes

Increase AC voltages on the transformer only gradually; do not apply higher voltages directly! (danger of damage to connected measuring instruments due to high currents – 100-fold excess currents).

Avoid overheating of the transformer – Mind the maximum applied voltages and currents listed in the instruction sheet 562 801 of the transformer for student's experiments.

- Maximum permissible AC voltage per winding 15 V AC.
- Maximum permissible power consumption 40 W.

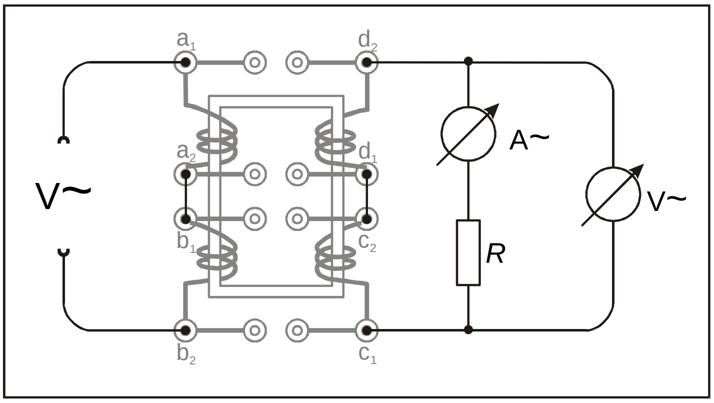

Fig. 2: Experimental setup to measure the current-voltage characteristic of a 'soft' transformer under load. Primary side: coils a and b connected in series, secondary side: coils d and c connected in series, $N_1 : N_2 = 300 : 300$.

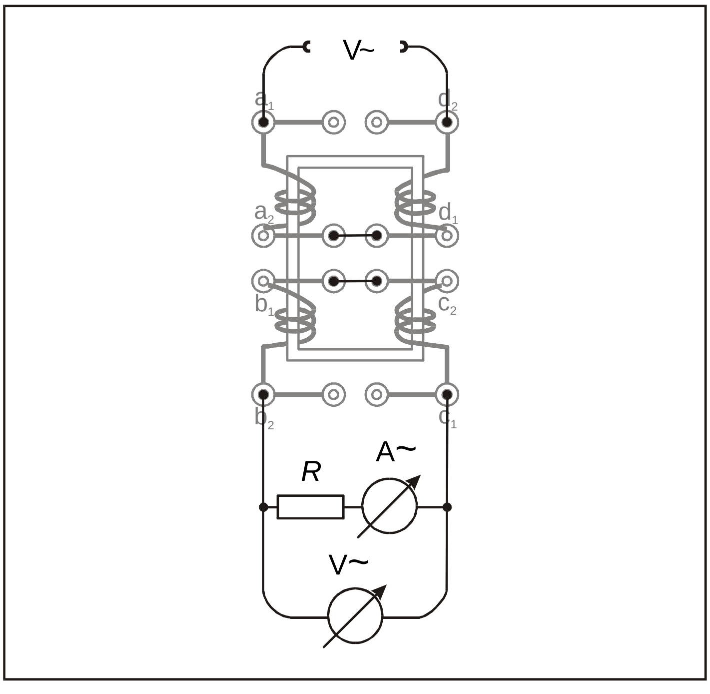

Fig. 3: Experimental setup to measure the current-voltage characteristic of a 'hard' transformer under load. Primary side: coils a and d connected in series, secondary side: coils b and c connected in series, $N_1 : N_2 = 300 : 300$.

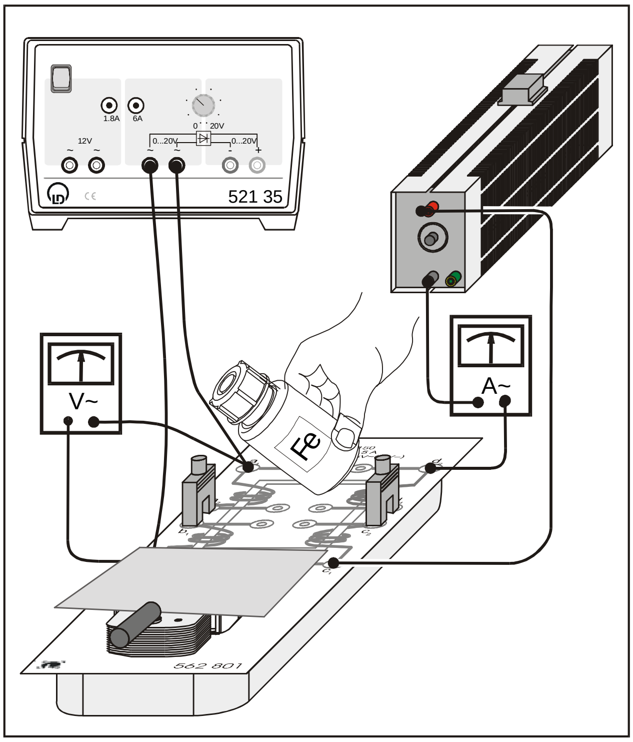

Fig. 4: Schematic representation of the experimental setup to reveal the lines of the magnetic flux using iron filings on a transparent plate on top of the 'soft' transformer under load.

Carrying out the experiment

a) current-voltage characteristic of a 'soft' transformer

- Connect the low voltage power supply, Rheostat (i.e. the load), the ammeter and the voltmeters to the Transformer for student's experiments as shown in Fig. 1. To realize a symmetrical transformer design choose the ratio $N_1 : N_2$ of 300 : 300 as depicted in Fig. 2.
- Set the voltage U_1 to 4 V.
- Measure the voltage U_2 and the current I_2 by varying the load.

b) current-voltage characteristic of a 'hard' transformer

- Connect the low voltage power supply, Rheostat (i.e. the load), the ammeter and the voltmeters to the Transformer for student's experiments as shown in Fig. 3. To realize a symmetrical transformer design the ratio $N_1 : N_2$ is be chosen to 300 : 300.
- Set the voltage U_1 to 4 V.
- Measure the voltage U_2 and the current I_2 by varying the load.

c) magnetic field of a 'soft' and a 'hard' transformer

- Setup the 'soft' transformer with load according Fig. 4.
- Place the Acrylic glass screen on rod on top of the transformer (Fig. 4.)
- Using the shaker, spread a thin uniform layer of iron filings on the Acrylic glass.
- Set the current I_2 to 1.5 A by adjusting the load or the applied voltage U_1 and observe the resulting pattern. It might be necessary to tap gently the glass plate.
- Repeat this experiment for the 'hard' transformer.

Measuring example

a) current-voltage characteristic of a 'soft' transformer

Table. 1: Voltage U_2 as function of current I_2.

$\frac{I_2}{A}$	$\frac{U_2}{V}$
0.00	4.0
0.04	3.8
0.08	3.6
0.13	3.4
0.17	3.2
0.22	3.0
0.26	2.8
0.30	2.6
0.33	2.4
0.36	2.2
0.40	2.0
0.42	1.8
0.45	1.6
0.48	1.4
0.50	1.2
0.53	1.0
0.55	0.8
0.59	0.4
0.63	0.0

b) current-voltage characteristic of a 'hard' transformer

Table. 2: Voltage U_2 as function of current I_2.

$\frac{I_2}{A}$	$\frac{U_2}{V}$
0.00	4.0
0.10	3.8
0.16	3.6
0.22	3.4
0.28	3.2
0.34	3.0
0.40	2.8
0.45	2.6
0.53	2.4
0.58	2.2
0.62	2.0
0.70	1.8
0.75	1.6
0.80	1.4
0.86	1.2
0.93	1.0
0.95	0.8
1.00	0.6
1.05	0.3
1.15	0.0

c) magnetic field of a 'soft' and a 'hard' transformer

A schematic sketch of magnetic field of the 'soft' transformer is depicted in Fig. 5. For the 'hard' transformer no field lines are observed.

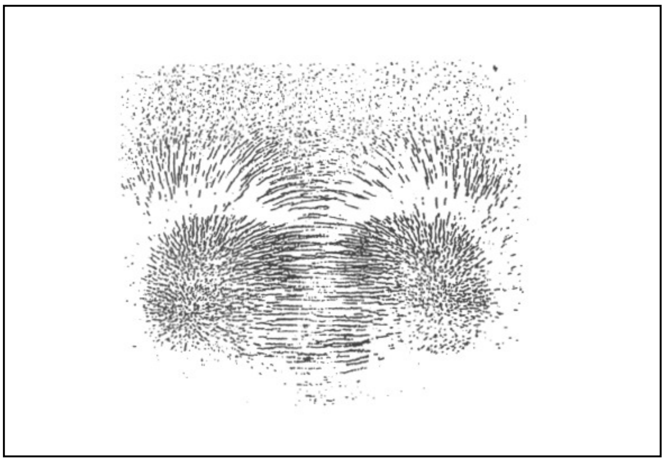

Fig. 5: Schematic sketch of the observed magnetic flux lines of a 'soft' transformer under load.

Evaluation and results

a) current-voltage characteristic of a 'soft' transformer

Fig. 6 summarizes the results of the table 1 and 2. The output voltage (secondary voltage) U_2 falls from its maximum value, i.e. off-load voltage ($R \to \infty$), with increasing current in the secondary coils. U_2 reaches zero at a maximum load (short-circuit operation: $R = 0$).

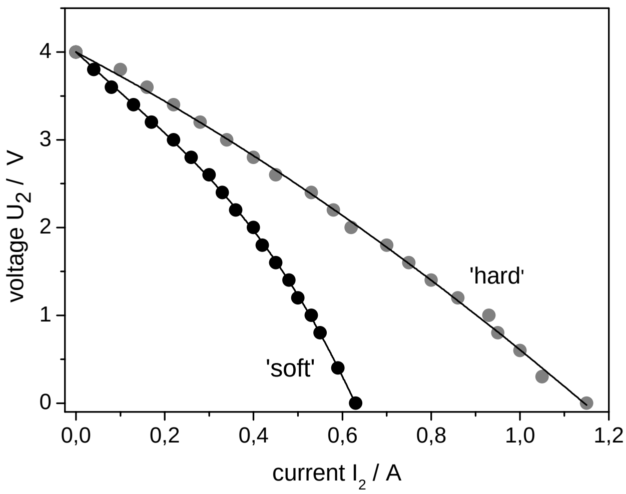

Fig. 6: Output voltage U_2 as function of the output current I_2 of 'soft' (black) and 'hard' (grey) transformer under load ($N_1 : N_2 = 300:300$). The solid lines are guides to the eye.

Using equation (I) the power P_2 can be calculated from the measured output voltage U_2 and the current I_2. Plotting P_2 as function of I_2 gives the current power characteristic of the transformers (Fig. 7). The power produced at the secondary side is zero where the transformer is operated with no load; in short-circuited operation the power output is zero again due to the breakdown of voltage. The maximum value is reached approximately in the middle between these extreme values. From Fig. 7 follows that the maximum output power of a 'hard' transformer is larger than for the 'soft' transformer.

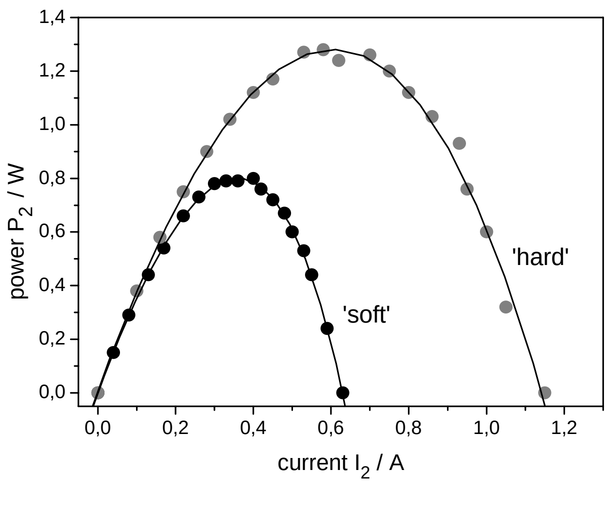

Fig. 7: Output power P_2 as function of the current I_2 of 'soft' (black) and 'hard' transformer (grey) under load ($N_1 : N_2 = 300:300$). The solid lines are guides to the eye.

b) current-voltage characteristic of a 'hard' transformer

The current-voltage characteristic of the 'hard' transformer is compared in Fig. 6 with the 'soft' transformer.

For the 'hard' transformer the losses are mainly due to the internal resistance of the secondary coil. Since the primary and secondary windings are distributed symmetrically on both limbs of the core the other losses (i.e. due a stray field) are largely eliminated. As a result this type of transformer possesses a relatively high electric strength. Therefore this type of transformer is named 'hard' transformer or 'fixed-ratio' transformer.

In contrast to the 'hard' transformer the losses of the 'soft' transformer are larger for the same ratio of the number of turns $N_1 : N_2$. The reason for this behaviour can be found in the design of this transformer where the primary and secondary windings are on different limbs of the iron core. As a result, a strong magnetic stray field is produced (Fig. 5). This stray field causes heat and magnetization losses which are added to the voltage drop across the internal resistance of the secondary coils. Therefore, due to this 'soft' voltage behaviour, this type of transformer is named 'soft' transformer or 'high-reactance' transformer.

c) magnetic field of a 'soft' and a 'hard' transformer

The field pattern depicted in Fig. 5 shows a magnetic field around the 'soft' or 'high-reactance' transformer. The energy of this magnetic field is lost with respect to the power balance between primary and secondary coils of the transformer (i.e. so-called stray field losses).

No magnetic field can be observed around the 'hard' or 'fixed-ratio' transformer. Losses due to a stray field are therefore largely eliminated for this type of transformer.

Supplementary information

The disadvantage of the 'hard' transformer is its high short-circuit current which may damage the windings under certain circumstances.

The advantage of the 'soft' transformer (high-reactance transformer) is its low short-circuit current. This is exploited, e.g. for bell or toy transformers, which require short-circuit resistance.

In experiment P3.4.5.1 the voltage and the current transformation of a isolating transformer and an autotransformer have been investigated. The isolated transformer investigated in this experiment corresponds to the 'soft' transformer and, thus, it has a 'soft' voltage behaviour.

On the other hand, the autotransformer has a current-voltage characteristic of a 'hard' transformer as can be seen in Fig. 8.

Note: The measurement of the current-voltage characteristic of the autotransformer in Fig. 8 was limited by the maximum admissible current $I_2 = 1.5$ A of the Transformer for student's experiments, i.e. the short-circuit operation could not be reached for the initial off-load voltage $U_2 \approx 2.7$ V.

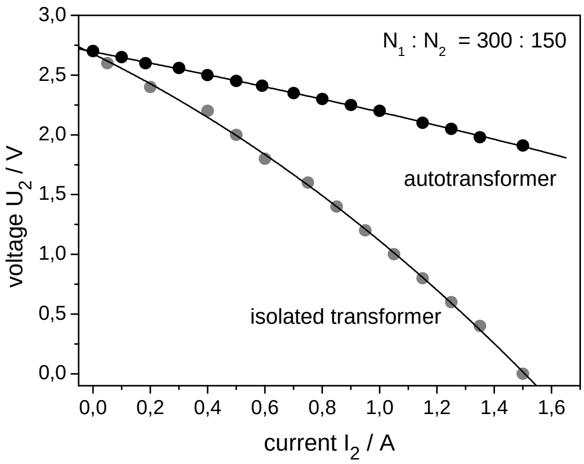

Fig. 8: Output voltage U_2 as function of the output current I_2 of the autotransformer (black) and the isolated transformer (grey) under load ($N_1 : N_2 = 300:150$). The solid lines are guides to the eye.