Electricity

Induction

3B PHYSICS EXPERIMENT

Transformers

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.

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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
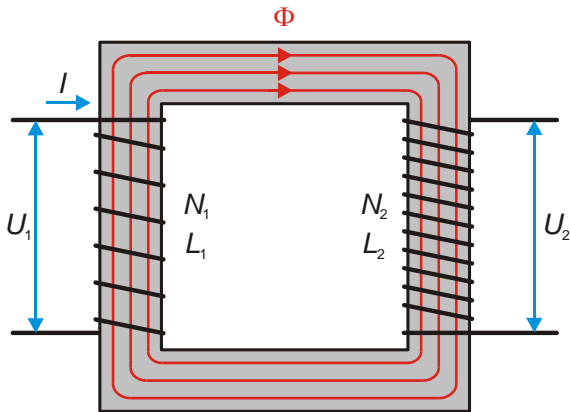Φ: magnetic flux generated by I

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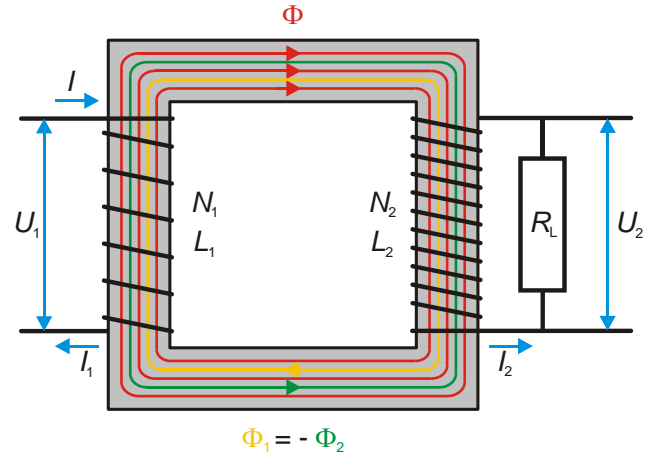

Fig. 3: Schematic of ideal transformer under load with primary and secondary coils wound in the same direction.

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) $U_2 = -N_2 \cdot \dfrac{\mathrm{d}\Phi}{\mathrm{d}t}$.

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

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

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) $\Phi_2 = \mu_0 \cdot \mu_r \cdot N_2 \cdot I_2 \cdot \dfrac{A}{1}$,

μ_0: Magnetic permeability of free space
μ_r: Relative permeability
A: Cross-sectional area of coil
$\ddot{y}$: 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) $\Phi_1 = \mu_0 \cdot \mu_r \cdot N_1 \cdot I_1 \cdot \dfrac{A}{1}$

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) $\dfrac{I_2}{I_1} = -\dfrac{N_1}{N_2}$.

This is because μ_r, A and $\ddot{y}$ 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) $P_1 = U_1 \cdot I_1 = U_2 \cdot I_2 = P_2$.

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 $N_2 / N_1 = 2$.

LIST OF APPARATUS

|		
1	Coil D with 600 Windings	1000988 (U8497430)
1	Coil D with 1200 Windings	1000989 (U8497440)
1	Transformer Core D	1000976 (U8497180)
1	Transformer with Rectifier 1/ 2/ 4/ … 14 V, 5 A @230V	1003558 (U8521112-230)
or		
1	Transformer with Rectifier 1/ 2/ 4/ … 14 V, 5 A @115V	1003557 (U8521112-115)
2	Digital Multimeter P3340	1002785 (U118091)
1	Set of 15 Safety Experiment Leads, 75 cm	1002843 (U138021)
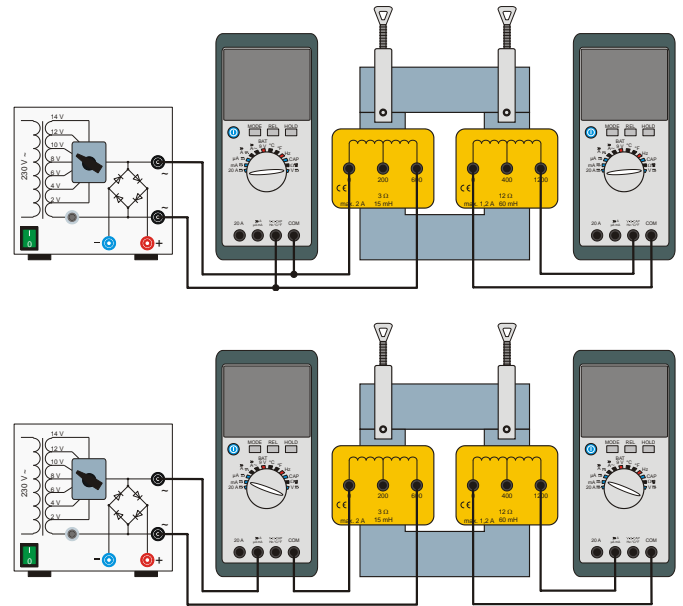
Fig. 4: Experiment set-up for transformer with no load (top) and transformer with load under short-circuit conditions (below).

EXPERIMENT SET-UP AND PROCEDURE

- Set up the experiment as shown in Fig. 4. The multimeter on the primary side coil should be connected in parallel across the primary coil in order to act as a voltmeter. Select the measuring range "V" and mode "AC¨.

- Inputs "COM" and "V" of the multimeter on the secondary side are to be connected to the tap terminals "0" and "1200" on the secondary coil. Select the measuring range "V" and mode "AC¨.

Note

This results in the secondary side being in open circuit ($I_2 = 0$), so open-circuit voltages U_{20} will be measured.

- Turn on the transformer with rectifier and adjust the supply voltages to $U = 2$ V, 4 V, 6 V, 8 V, 10 V, 12 V and 14 V in sequence.

- For each of these supply voltages, read off the primary volt-age and the secondary open-circuit voltage from the multimeters and enter them into Table 1.

- Now reconnect the primary-side multimeter such that it is in series with the primary coil and in a position to measure current. (Fig. 4 below). Select the measuring range "mA" and mode "AC¨.

- Inputs "COM" and "mA" of the multimeter on the secondary side are to be connected to the tap terminals "0" and "1200" on the secondary coil. Select the measuring range "mA" and mode "AC¨.

Note

This results in the secondary side being shorted through the multimeter ($U_2 = 0$), so the meter now measures short-circuit current I_{2C}. The multimeter itself acts as an ohmic load.

- For each of the supply voltages, read off the primary current and the secondary short-circuit current from the multimeters and enter them into Table 2.

SAMPLE MEASUREMENTS

Table 1: Transformer with no load ($I_2 = 0$). Primary voltages U_1 determined by setting supply voltage U and corresponding measurements of open-circuit voltage U_{20}, when $N_1 = 600$ and $N_2 = 1200$.

U_1 / V	U_{20} / V
2.42	4.43
4.74	8.84
6.90	12.92
9.32	17.59
11.37	21.52
13.50	25.63
15.92	30.32

Table 2: Transformer with load under short-circuit conditions ($U_2 = 0$). Primary currents I_1 determined by setting supply voltage U and corresponding measurements of short-circuit current I_{20}, when $N_1 = 600$ and $N_2 = 1200$.

I_1 / mA	I_{2C} / mA
43.6	19.5
86.8	39.6
123.3	56.9
166.0	77.0
200.0	92.0
237.0	109.0
278.0	129.0

EVALUATION

- Plot the open-circuit voltage U_{20} as a function of primary voltage U_1 (Table 1) and short-circuit current I_{2C} as a function of primary current I_1 (Table 2). Fit a straight line which passes through the origin to each graph (Figs. 5, 6).

From equation (3) the magnitude of the voltages would be as follows:

$$U_{20} = \frac{N_2}{N_1} \cdot U_1 .$$

Similarly the short-circuit current values are derived from equation (6):

$$I_{2C} = \frac{N_1}{N_2} \cdot I_1 .$$

This means the gradients of both the lines found in Fig. 5 and Fig. 6 are determined by the ratio of the number of windings $N_2/N_1 = 2$ or $N_1/N_2 = 0.5$. The line fitted to the above results in the no-load case comes out to be $N_2/N_1 = 1.90$ and that for the short-circuited case comes out to be $N_1/N_2 = 0.46$.

The values deviate from the ideal values of 2 and 0.5 because real coils are always subject to loses. These losses consist of so-called iron and copper losses, as well as losses due to scattering of the magnetic flux. Iron losses arise from the hysteresis as the iron core becomes demagnetised and from eddy currents within the core itself. Copper losses arise from ohmic resistance in the copper wires of the coils. Scattering losses are caused because not all of the magnetic flux Φ generated by the current I flowing in the primary coil passes through the secondary coil.
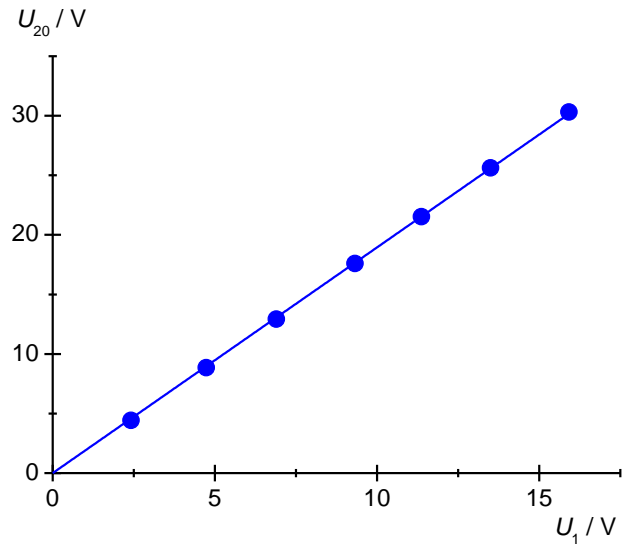

Fig. 5: Transformer without load ($I_2 = 0$). Open-circuit voltage U_{20} as a function of primary voltage U_1, with winding numbers $N_1 = 600$ and $N_2 = 1200$.
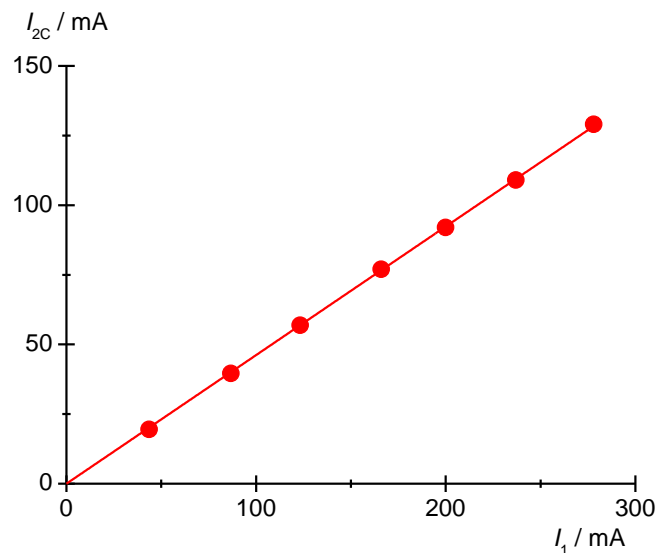

Fig. 6: Transformer with load under short-circuit conditions ($U_2 = 0$). Open-circuit voltage I_{2C} as a function of primary current I_1 with winding numbers $N_1 = 600$ and $N_2 = 1200$.