PW n° 2: Study of an electric transformer

I . Apparatus and theoretical description

I.1. General informations

An electric Transformer is a device used to increase or decrease the voltage amplitude of an alternative electric signal. The transformer itself is made of two coils separated electrically but connected together with a ferromagnetic tore. The first (second) coil of self-inductance L_1 (self-inductance L_2) is called the primary (secondary) circuit. One can also use the word winding instead of circuit. The winding traduces the number of loops, n_1 and n_2 that wrap the ferromagnetic material. The latter is called the magnetic circuit.

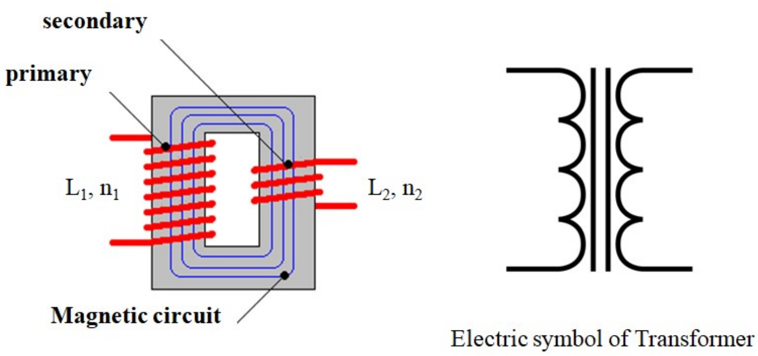

Figure 1.

The transfer of the signal from the primary to the secondary winding is done with the help of the magnetic circuit. The electric current propagating in the first winding generates a magnetic field inside the coil. The use of a ferromagnetic material having stronger magnetic permability $\mu_r \approx 10^5$ compared to non magnetic material $\mu_r \approx 1$ will amplify the magnetic effect leading to a strong magnetic flux ϕ_1 propagating in the magnetic circuit. This flux ϕ_1 will induces an electromotive force (a voltage) in the second coil $e_2 = -\frac{d\phi_1}{dt}$ leading to the creation of a current in the secondary winding. Similarly, the electric current in the secondary winding will induce an electromotive force in the first coil $e_1 = -\frac{d\phi_2}{dt}$. Both circuits are thus connected.

The relation between the voltages and the currents in the primary (U_1, i_1) and in the secondary (U_2, i_2) can be obtained with the Kirchhoff laws applied to the circuit of Figure 2.

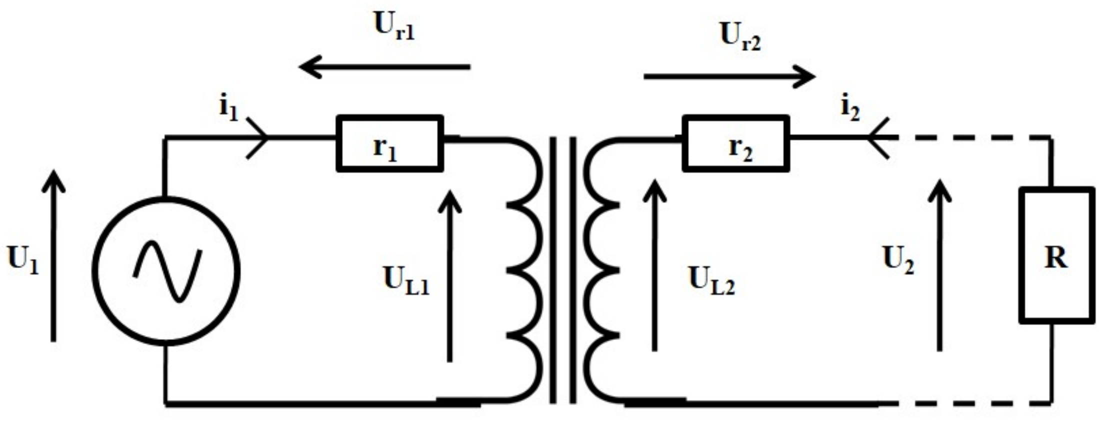

Figure 2.

We assume the primary circuit is connected to an alternative power supply of voltage U_1. The internal resistance of the coil and wires are modeled with the resistance r_1. In the secondary winding, internal resistive elements are modeled with resistance resistance r_2. At the end of the circuit it is possible to add a loading impedance of resistance R or to let the circuit open (without load). The electrical equation are:

$$U_1 = U_{r1} + U_{L1}$$
$$U_2 = U_{r2} + U_{L2}$$

The voltage of the first coil C_1 has two origins. The first one is the self-inductance phenomena. The time-dependent current i_1 generates a magnetic flux Φ_1 inside the coil that will induce an electromotive force (emf) $e_1 = -\frac{d\phi_1}{dt}$. The flux Φ_1 is related to the current i_1 with $\Phi_1 = L_1 i_1$ where L_1 is the proper inductance coefficient of the coil C_1 so that one can write $e_1 = -\frac{d\phi_1}{dt} = -L_1\frac{di_1}{dt}$. According to Lenz law, this emf opposes itself to the time-variation of current i_1 by creating a current in the opposite direction which can be seen as generating a negative voltage in the coil: $-e_1 = L_1\frac{di_1}{dt}$.

The second one is an inductance phenomena produced by the second coil C_2 generating a voltage $-e_2$ where the electromotive force $e_2 = -\frac{d\Phi}{dt}$ is related to the flux Φ created by C_2 and recorded by C_1 after propagating in the magnetic circuit. The flux involves both circuits so that we write $\Phi = Mi_2$ where M (or M_{12}) is the mutual inductance coefficient. The second voltage in the coil C_1 will be $-e_2 = M\frac{di_2}{dt}$. Due to these two effects, the total voltage of the coil C_1 reads:

$$U_{L1} = L_1\frac{di_1}{dt} + M\frac{di_2}{dt}$$

A similar demonstration will gives for the total voltage of the coil C_2 reads:

$$U_{L2} = L_2\frac{di_2}{dt} + M\frac{di_1}{dt}$$

With $U_{r1} = r_1\, i_1$ and $U_{r2} = r_2\, i_2$, the electrical equations obtained from Kirchhoff laws are

$$U_1 = r_1\, i_1 + L_1\frac{di_1}{dt} + M\frac{di_2}{dt}$$
$$U_2 = r_2\, i_2 + L_2\frac{di_2}{dt} + M\frac{di_1}{dt}$$

We can simplify this set of equations by working within the **ideal transformer approximation**, for which the voltages due to the internal resistances can be neglected compared the ones of the coils. Also we assume that all magnetic field lines are kept in the magnetic circuit. The electric scheme is given below in Figure 3.

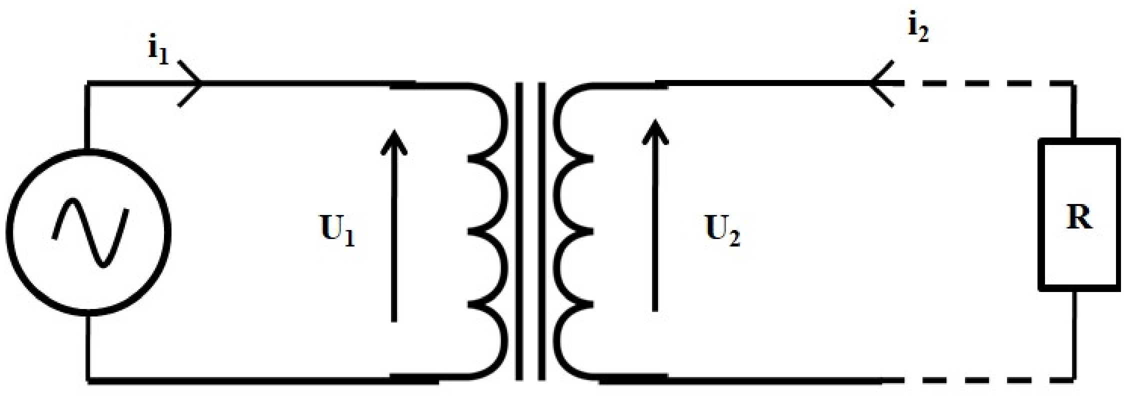

Figure 3. Ideal Transformator

The previous equations are transformed as follows

$$U_1 = L_1 \frac{di_1}{dt} + M \frac{di_2}{dt}$$
$$U_2 = L_2 \frac{di_2}{dt} + M \frac{di_1}{dt}$$

At this step it is interesting to distinguish the functionment with or without charge R. When we do not plug the resistance R, **circuit without load**, the secondary circuit is open and U_2 is the voltage obtained at the terminals of the coils when the current $i_2 = 0$. The time-derivatives involving i_2 are also zeros and we can write $U_1 = L_1 \frac{di_1}{dt}$ and $U_2 = M \frac{di_1}{dt}$ leading directly to

$$\frac{U_2}{U_1} = \frac{M}{L_1}$$

If the coil C_1 is made of n_1 loops, the total flux rigorously reads $n_1\Phi_1 = L_1 i_1$ and for the coil C_2 made of n_2 loops one has $n_2\Phi_2 = M i_1$. In the ideal transformer, the magnetic flux is conserved so that $\Phi_1 = \Phi$. Finally one obtains the turns ratio of the transformer

$$\frac{U_2}{U_1} = \frac{n_2}{n_1}$$

The amplitude of the transformed voltage U_2 is a function of the ratio of the loop number of the two coils $U_2 = \frac{n_2}{n_1} U_1$. If one wants to increase the output voltage one has to chose $n_2 > n_1$.

When we close the secondary circuit with a load of resistance R (**circuit with a load)**, the current i_2 is different than zero and the ratio $\frac{U_2}{U_1}$ can be a bit different, but the principle remains identical. We will accept it at this step of the study. The existence of a current i_2 underlines the transfer of energy in the circuit and we can compare the electrical powers in each circuit $P_1 = U_1 i_1$ and $P_2 = U_2 i_2$ which permits to define the yield of the transformer:

$$\eta = \frac{P_2}{P_1}$$

This yield will depends on the value of the resistance load $\eta = f(R)$. It is thus important to know for which impedance of a load the transformer will give the higher yield. Also, the yield can be reduced due to the losses of energy originating in the Joule effect (copper losses) or in the magnetic circuits (iron losses).

I.2. Preparing the set-up for experimental part

The power supply:

In our experiment, the initial source of voltage U_1 will be an alternating sinusoidal voltage obtained with a wave generator whose frequency will be set to 50 Hz.

The coils:

Indicate the number of loops n_1 and n_2 that is written on the two coils. For one that has only two output, there is only one possible value for n; it will be n_1. For the second coil, there are many outputs. You will select the ones for which n_2 is maximum. Determine the ratio $\frac{n_2}{n_1}$.

The transformer

Prepare the transformer by putting the two coils in the magnetic circuit having the U form and closed it by respecting the directions of the layer constituting the internal structure of the material.

Measurements of voltages and currents

The measurements are performed using numerical multimeters. We will need to measure **i)** the currents in the primary and in the secondary circuits; **ii)** The voltages between the terminals of each coils. Consequently we need four multimeters. We remember that the voltmeter is plugged in parallel to the elements we want to determine the voltage and the amperemeter is set in series in the loop. The voltmeter or amperemeter terminals are indicated in the multimeter, so pay attention to connect correctly the wires to the good functions. In any case, **call the teacher to check your connections before.**

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II. Experimental study

Be sure that the previous steps are clear for you. Plug the cables to be able to measure the voltage and the current with the multimeters like depicted in Figure 5. **Call the teacher to check your connections.**

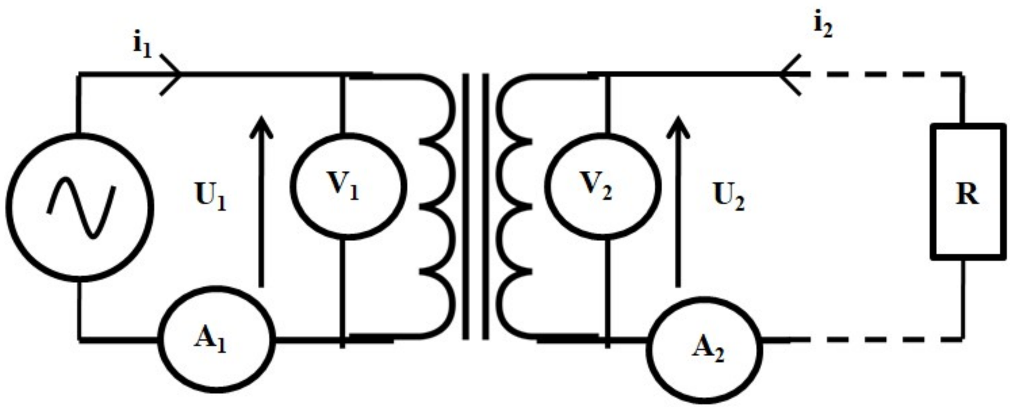

Figure 5. Ideal Transformator including voltmeters and ampermeters

II.1 Study without load

II.1.1. Determination of the turn ratio

- We first open the secondary circuit by do not plugging anything in the terminals of the coil C_2. Consequently, you do not need ampermeter A_2. **Call the teacher to check your connections.**
- Then, turn on the wave generator with the appropriated signal.
- Set up the cursor to 4 V approximately and check the values given by the multimeters. Press the button ACV and ACI respectively in the panel of the voltmeter and the multimeter to ensure a measurement in alternating signal.
- Calculate the ratio U_2/U_1 and compare it to n_2/n_1.

II.1.2) Influence of the value of the input voltage

In that part, we will write all the physical parameters with a **Subscript 0** to underline that we have no load at the end and that the secondary circuit is open. The input voltage U_1 will be depicted as U_{10} as well as for other parameters.

You will measure the following parameters given in the tabular below for different values of the input voltages U_{10} . Starting from U_{10} =1 Volts, take a measurement every 1 volts until 7 Volts.

You may enter also directly your measurements in Origin software as well as to calculate the value of P_{10} and U_2/U_1.

U_{10}	i_{10}	P_{10}	U_{20}	U_2/U_1

Then draw the graphics $U_{10} = f(i_{10})$.

II.2 Study with a load and determination of the yield of the transfomator

We plug now the terminal of the second coil with the variable resistance. The device is pictured in Fig. 6. By moving the cursor you can chose a value of R between 1 and 300 Ω. During all that part we will work at a constant value U_1 fixed around 4 volts for instance.
Plug the cables to be able to measure both voltages and currents in the primary and secondary circuits like depicted in Figure 5.

Figure 6.

Call the teacher to check the electrical connections.

Then, for **a fixed value of U_1** fill the tabular below for different value of R. In the interval [10,60] Ω take a value every 5 Ω. Then, every [60, 140] Ω take a value every 10 Ω.
It is possible that when changing the value of R, the value of U1 changes, to this end adapt the value with the amplitude of the wave generator to read U1= 4 Volt in voltmeter 1. Be sure that U1=4 volts for each measurements.

U_1	i_1	P_1	U_2	i_2	P_2	R

- Enter directly your values in the Origin Software
- Prepare three extra columns for the calculations of P_1, P_2 and η.
- Plot the graphics depicting the yield as a function of the load $\eta = f(R)$ by setting R axis in logarithmic scale.
- Observe the obtained graphics. What can you deduce about the transformer yield?

III. Determination of the losses

III.1. Description

The energy losses in a transformer originate in two main types. We distinguish:

- **The "copper" losses** (or Joule losses) due to the current propagation in the wires and winding elements. The appellation of copper may be used since electric wires are mainly made in copper material.
- **The "iron "losses** are related to the energy losses in the magnetic material. They are of two types. The first one is also a heat effect (Joule) occurring in the magnetic material related to the surface currents induced by the magnetic flux. These currents are located in the different sections of the magnetic material that are perpendicular to the direction of the propagating flux. In France they are

called *Foucault's currents* and *Eddy's current* in England (this mental sickness called nationalism thrives everywhere; and the Germans, maybe because none of them discovered something about it, call them *Wirbelstrom* (vortex current)). The second ones are called hysteresis losses and are related to the magnetization acquired by the material when it is submitted to an external current. At a microscopic level, the magnetization is not uniform and one can distinguish many spatial zones having a different magnetization. When applying the external current these zones will moves in order to give a magnetic contribution in the same direction. During their motions, the walls of one domain can undergo some frictions with the neighboring domains leading to a loss of energy.

In the transformer the copper losses and the iron losses will be determined with the associated electrical power P_{Cu} and P_{Fe}. In what follows we will determine them for a given configuration of current and voltage. To this end we will work in the situation for which the yield is maximal.

- From your previous date, note the values of the U_1, i_1, U_2 and i_2 for which the transformer yield is maximum. Two of them, U_1 and i_2 will be written respectively U_{10} and i_{2sc} . **Subscript 0** will refer to circuit without load and **subscript sc** will refers to short-circuit.
- Unplug the wires of the transformer and measure the internal resistance of the two coils C_1 and C_2 with a multimeter. Note their values depicted as r_1 and r_2 respectively.

III. 2. Determination of Iron losses using secondary circuit without load

- To determined Iron losses we first open the secondary circuit and we plug directly the voltmeter between the terminals of the coil C_2 (similar to figure 5 but without load). There is no current in the secondary circuit, one can not transfer energy and we have $P_2 = P_{20} = 0$. Consequently, all the power P_{10} is given to the Joule effect of the primary circuit equal to $r_1 i_{10}^2$ and to the iron losses P_{Fe}. Consequently we have: $P_{10} = r_1 i_{10}^2 + P_{Fe}$.

  Call the teacher to check your connections.

- Move the cursor of the autotransformer to have the value U_{10} in the voltmeter V1 of the primary circuit. Then measure the value of i_{10} and calculate P_{10}.
- Calculate also the quantity $r_1 i_{10}^2$ in the primary circuit and compare it to P_{10} . Deduce the value of the iron losses P_{Fe}.
- It is possible to show that the iron losses are proportional to the square of the input voltage when working without load: $P_{Fe} = kU_{10}^2$. To check this relation, use your values obtained in II.1.2 and plot the graphics P_{10} as a function of U_{10}^2.

III.3. Determination of all Copper losses: using secondary circuit in short-circuit

- Reset the cursor of the autotransformer to zero. Then connect the amperemeter terminals directly with the ones of the second coil C_2 (see figure 7). The current i_2 circulating in the secondary circuit is called short-circuit current.

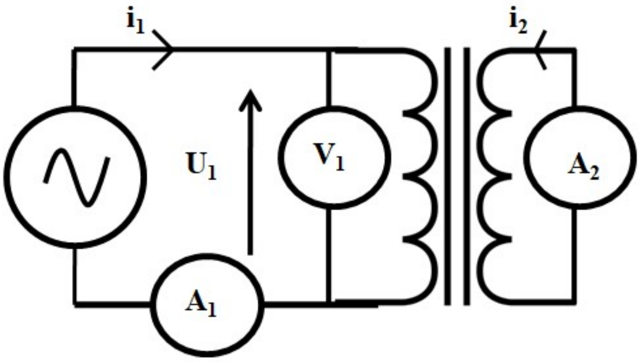

Figure 7.

There is no load and the current in the secondary will be use only to determine the Joule effect (we neglected to this end the internal resistance of the multimeter).

- Move the cursor of the autotransformer to have the value $i_2 = i_{2sc}$ in the ampermeter A2 of the secondary circuit and then measure the values $i_1 = i_{1sc}$, $U_1 = U_{1sc}$.
- Compare the value of i_{1sc} and U_{1s} to the values of i_1 and U_1 taken in III.1.

When working with so small values, we can assume that the iron losses are negligible so that the remaining part of the losses can be attributed to the copper losses $P_{1sc} \approx P_{Cu}$

- Calculate P_{1s} determine the value of the copper losses due to the Joule effect P_{Cu}.
- Take the values of P_2 and P_1 from your measurement giving the maximal yield. Compare the value of P_2 to $P_1 - P_{Fe} - P_{Cu}$. Is the following definition of the yield

$$\eta = \frac{P_2}{P_1} = \frac{P_1 - P_{Fe} - P_{Cu}}{P_1}$$

in good agreement with your results? If not, are the losses too high or to weak compared the energy losses that you can estimate from $\frac{P_2}{P_1}$?