Challenges of Online Laboratory Electrical Engineering Exercises

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***Abstract*— This paper presents some of difficulties that the professors of the Department of Theoretical Electrical Engineering have with the laboratory exercises teaching in online environment. During pandemic and spread of COVID -19 everyone's life has changed and nothing is as the same as before. This change also reflects on the way of teaching not only of the theoretical material – lectures and tutorials, but also the acquisition to the practical skills in distance teaching.**

Keywords—laboratory exercises, electrical engineering, learning in distance.

I. Introduction

The main goal of this work is to show the substitute students' practical knowledge in their training about the nature of the processes, by means of modern, advanced and interesting methods. For this purpose, video clips of laboratory exercises are done. They allow visualizing the power supply devices, the measuring equipment and the loads that are used. The teacher can make video clips pauses that allows to make specific audio explanations of electrical connections and measurements.

II. The Goals

In these days, with fast technical developing, our society is obliged to upgrade its knowledge and skills. It is also happened in the different way of presenting the study material, especially the laboratory exercises.

The aim of laboratory exercises is to consolidate the knowledge acquired by students in the theoretical course and to build practical skills in the engineering profession in distance teaching. Each exercise contains a theoretical statement on the topic, a description of the experimental one, performance tasks and control questions. In order to facilitate the work in the laboratories in distance teaching, for each exercise has been made video and the recommendations and sequences of actions is given from the teacher.

Laboratory measurements are made and recorded in six themes [1, 2]:

- Linear circuits in sinusoidal steady–state.
- Series resonance.
- Parallel resonance.
- Magnetically coupled liner electric circuits.
- Two-ports.
- Transients in linear circuits.

In each of the laboratory exercises, one to five schemes are connected. For every one of them, separate video clips with different duration have been made depending on its complexity.

A. Linear Circuits in Sinusoidal Steady-State

In this exercise students are acquainted with the correspondence of the ideal passive and active electrical elements of the circuits in their actual connection in the real electrical circuits shown in Fig. 1.

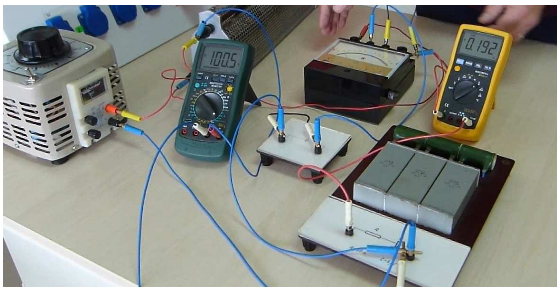

Fig. 1 Real connected circuit

The aim of the exercise is to create technical skills of students to recognize and measure the basic electrical parameters. This experiment has to confirm some dependencies and theorems used in the analysis of electrical circuits. A voltmeter, ammeter and wattmeter are required for the experimental determination of the complex resistance. The multimeters measure the effective (RMS) values of voltage, current and the active power in one-port circuit.

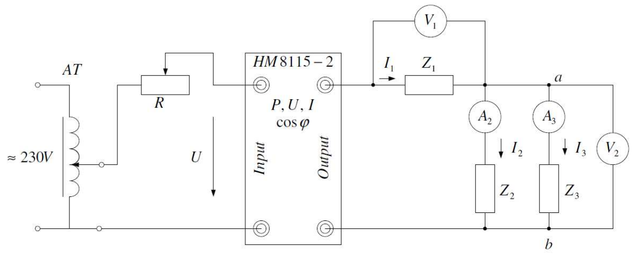

Fig. 2 Schema of investigated circuit

Their connection scheme (V-A or A-V) depends on the magnitude of the measured resistance and the internal resistances of the non-ideal devices. The goal is to minimize systematic measurement error. In the exercise, large resistors

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values are measured and V-A type connection scheme is suitable.

RMS values of the voltages are measured by voltmeters and effective values of the currents - by ammeters that are shown in Fig. 2.

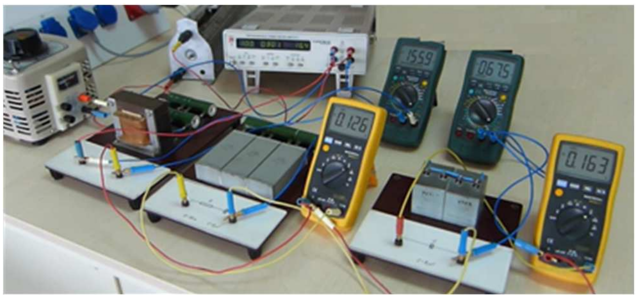

Fig. 3 Circuit of Tevenen's and Norton's theorems

$$U_V = Mod\left[\dot{U}\right]; \quad I_A = Mod\left[\dot{I}\right]. \qquad (1)$$

Performance tasks for students are to determine experimentally the complex resistances of one port, to measure the RMS values of currents, voltages (Fig. 3) and the active power. At the end, they compare the calculation results with the measured ones.

Tevenen's and Norton's theorems are proved for the third branch of the Fig.2.

$$\dot{I}_3 = \frac{U_0}{Z_e + Z_3}; \quad \dot{I}_3 = \dot{I}_k \frac{Z_e}{Z_e + Z_3}. \qquad (2)$$

They make it possible to determine the current in a particular branch of an electrical circuit, considering the rest of the circuit as an active one-port.

B. Series resonance

The students study the resonant properties and frequency characteristics of RLC series circuit (Fig. 4) in this laboratory exercise (Fig. 5).

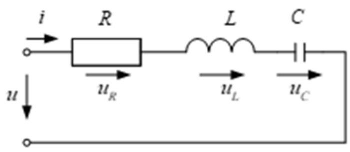

Fig. 4 Schema of RLC series circuit

This resonance is observed in circuit consisting of a resistor, an inductor and a capacitor connected in series.

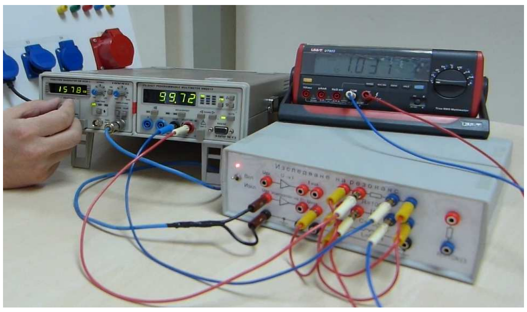

Fig. 5 High frequency generator with resonance model

If the circuit is considered as a series one-port with equivalent complex resistance:

$$Z_e = R_e + jX_e \qquad (3)$$

then the condition for series resonance $\varphi_e = 0$ has to be observed. The equivalent reactance in the circuit is zero $X_e = 0$.

$$X_e(\omega_p) = \omega_p L - \frac{1}{\omega_p C} = 0 \qquad (4)$$

The voltage and current are in phase at the input passive one-port containing resistors, coils and capacitors in sinusoidal state [1].

Resonance phenomena have an important part in communication and electronic techniques. Some of their important applications are:

- obtaining an ideal active load and transmitting maximum power in it;
- receiving voltage or current amplification;
-obtaining resonance in frequency-selective circuits – in some filters.

C. Parallel resonance

The goal of this experiment is to investigate parallel resonance phenomena (Fig. 6). Branch currents of a parallel one-port are measured indirectly.

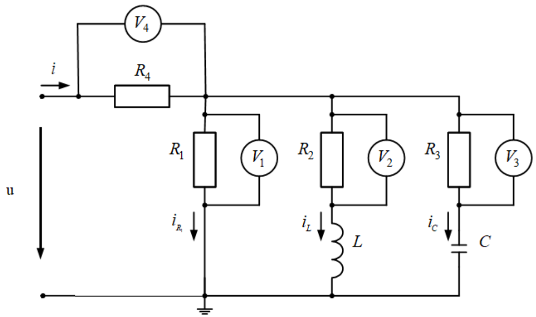

Fig. 6 Schema of investigated circuit

Fig. 7 High frequency generator with resonance model

A laboratory model (Fig. 7) is used and additional resistors and voltmeters are connected instead of ammeters. The readings of the voltmeters and theoretical explanations of different resonance characteristics connected with voltages and currents give students the opportunity to better understand these characteristics.

Performance tasks for students are to determine dependencies and draw characteristics of $I(f)$, $U_{R1}(f)$, $I_{R1}(f)$, $I_L(f)$, $I_C(f)$ if $I=const$ and $U=const$.

Physical meanings of both a quality factor and a resonant frequency are explained by corresponding algebraic equations. In addition, these quantities, received by measurements and calculations are compared.

D. Magnetically coupled liner electric circuit

The parameters L_1, L_2 and M are given. Given also are the currents $i_1(t)$ and $i_2(t)$, their directions and the dotted terminals are shown in Fig. 8.

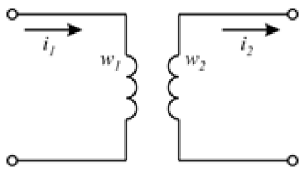

Fig. 8 Inductively connected windings

The exercise provides student opportunity to comprehend in more details the physical part of the phenomenon - mutual induction. For this purpose, the influence of the inductive connection type on the parameters that are replaced with sections of series or parallel connection of magnetically coupled coils is investigated [3].

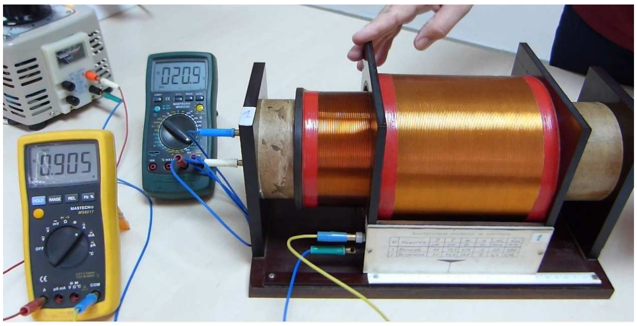

Fig. 9 The laboratory model

The laboratory model (Fig. 9) consists of two concentric solenoid copper windings. They are inductively connected when each of them is located in the magnetic flux excited by the current of the other. These windings cover both their own full magnetic flux and each other's full magnetic flux. The medium is linear, that is the magnetic permeability μ is a constant quantity μ = const.

It is necessary to find the voltages $u_1(t)$ and $u_2(t)$. At the

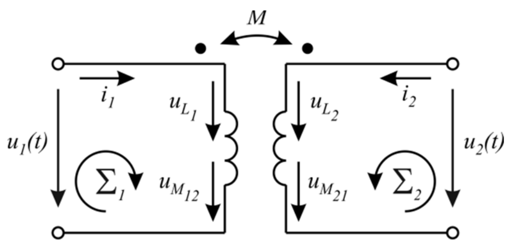

Fig. 10 Investigated schema

beginning, it has to assign direction of the self-inductive voltages $u_{L_1}(t)$ and $u_{L_2}(t)$ that are shown in Fig. 10. The signs are always positive (they coincide with current). The signs of mutual inductive voltages $u_{M_{12}}(t)$ and $u_{M_{21}}(t)$ depend on the direction of the currents $i_1(t)$ and $i_2(t)$ with respect to the dots: if both currents leave or enter the dots, the signs are plus, otherwise – minus [1].

The following equations can be written according to Kirchhoff's voltage low (KVL):

$$\left| \begin{aligned} u_1(t) &= \frac{d\Psi_1}{dt} = \frac{d}{dt}(L_1 i_1 \pm M i_2) = L_1\frac{di_1}{dt} \pm M\frac{di_2}{dt} = u_{L_1}(t) \pm u_{M_{12}}(t) \\ u_2(t) &= \frac{d\Psi_2}{dt} = \frac{d}{dt}(L_2 i_2 \pm M i_1) = L_2\frac{di_2}{dt} \pm M\frac{di_1}{dt} = u_{L_2}(t) \pm u_{M_{21}}(t) \end{aligned} \right. \qquad (5)$$

If the quantities are sinusoids we can introduce the phasors of the *AC* steady state:

$$\left| \begin{aligned} \dot{U}_1 &= \dot{U}_{L_1} \pm \dot{U}_{M_{12}} = j\omega L_1 \dot{I}_1 \pm j\omega M \dot{I}_2 = j\omega L_1 \dot{I}_1 \pm Z_M \dot{I}_2 \\ \dot{U}_2 &= \dot{U}_{L_2} \pm \dot{U}_{M_{21}} = j\omega L_2 \dot{I}_2 \pm j\omega M \dot{I}_1 = j\omega L_2 \dot{I}_2 \pm Z_M \dot{I}_1 \end{aligned} \right. \qquad (6)$$

where $\omega M = X_M$ is a mutual inductive reactance and $Z_M = j\omega M = jX_M$ is a mutual inductive impedance. The positive signs for the inductive voltages are when the current $\dot{I}_1$ and $\dot{I}_2$ have the same directions with respect to the beginning of the inputs [1].

The active power transmitted by induction is determined by the mutual magnetic field between the coils. The theoretical and experimental results are compared.

E. Two-ports

The aim of this laboratory work is to experimentally determine the coefficients A, B, C and D of the equivalent two-port. It is obtained by series, parallel and chain connection of two passive two-ports.

The two-port is a device with two pairs of terminals - input and output terminals. There is no external electrical connection between them. The passive two-port is composed of passive elements only - resistors, coils and capacitors. In our laboratory exercise this type of two-port is used.

Suppose the parameters of a two-port are known: either analytically calculated or experimentally measured. There are two basic equivalent circuits: "T" and "Π" circuits [1].

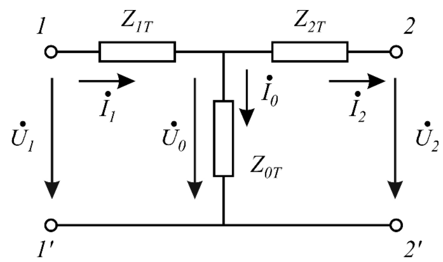

Fig. 11 Equivalent "T" circuit of a two-port

Equivalent "T" circuit of a two-port is shown in Fig. 11. In this case have to be expressed the impedances Z_{1T}, Z_{2T} and Z_{0T} in terms of the coefficient *A*, *B*, *C* and *D*.
The *A*-system is:

$$\left| \begin{aligned} \dot{U}_1 &= A\dot{U}_2 + B\dot{I}_2 \\ \dot{I}_1 &= C\dot{U}_2 + D\dot{I}_2 \end{aligned} \right. \qquad (7)$$

so the voltage $\dot{U}_1$ and current $\dot{I}_1$ must be represented as functions of the voltage $\dot{U}_2$ and current $\dot{I}_2$.

Applying Kirchhoff's and Ohm's law for the circuit of Fig. 11 we receive the equations:

$$\dot{U}_1 = Z_{1T}\dot{I}_1 + Z_{2T}\dot{I}_2 + \dot{U}_2 \quad (8)$$

$$\dot{I}_1 = \dot{I}_2 + \dot{I}_0 = \dot{I}_2 + \frac{\dot{U}_0}{Z_{0T}} = \frac{1}{Z_{0T}}\dot{U}_2 + \left(1 + \frac{Z_{2T}}{Z_{0T}}\right)\dot{I}_2 \quad (9)$$

$$\dot{U}_1 = Z_{1T}\left[\frac{1}{Z_{0T}}\dot{U}_2 + \left(1 + \frac{Z_{2T}}{Z_{0T}}\right)\dot{I}_2\right] + Z_{2T}\dot{I}_2 + \dot{U}_2 = \\ = \left(1 + \frac{Z_{1T}}{Z_{0T}}\right)\dot{U}_2 + \left(Z_{1T} + Z_{2T} + \frac{Z_{1T}Z_{2T}}{Z_{0T}}\right)\dot{I}_2. \quad (10)$$

The coefficients of two-ports are:

$$A = 1 + \frac{Z_{1T}}{Z_{0T}};\ B = Z_{1T} + Z_{2T} + \frac{Z_{1T}Z_{2T}}{Z_{0T}}; \\ C = \frac{1}{Z_{0T}};\qquad D = 1 + \frac{Z_{2T}}{Z_{0T}}. \quad (11)$$

If the coefficients have been determined, it could be find the impedances of the "T" equivalent circuit using the relations:

$$Z_{0T} = \frac{1}{C}\qquad Z_{1T} = \frac{A-1}{C}\qquad Z_{2T} = \frac{D-1}{C} \quad (12)$$

Equivalent "П" - circuit of a two-port is shown in Fig. 12.

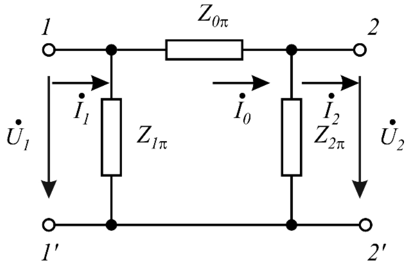

Fig. 12 Equivalent "П" circuit of a two-port

In this case have to find the connections between $\dot{U}_1$ and $\dot{I}_1$ on one hand and $\dot{U}_2$ and $\dot{I}_2$ on the other hand.

Applying KVL, KCL and Ohm's law the following equations are written for the assumed directions of the voltages and currents:

$$\dot{I}_0 = \dot{I}_2 + \frac{\dot{U}_2}{Z_{2\pi}} \quad (13)$$

$$\dot{U}_1 = Z_{0\pi}\dot{I}_0 + \dot{U}_2 = Z_{0\pi}\left(\dot{I}_2 + \frac{\dot{U}_2}{Z_{2\pi}}\right) + \dot{U}_2 = \left(1 + \frac{Z_{0\pi}}{Z_{2\pi}}\right)\dot{U}_2 + \\ + Z_{0\pi}\dot{I}_2 \quad (14)$$

$$\dot{I}_1 = \frac{\dot{U}_1}{Z_{1\pi}} + \dot{I}_0 = \frac{\left[\left(1 + \frac{Z_{0\pi}}{Z_{2\pi}}\right)\dot{U}_2 + Z_{0\pi}\dot{I}_2\right]}{Z_{1\pi}} + \dot{I}_0 \\ = \left(\frac{1}{Z_{1\pi}} + \frac{1}{Z_{2\pi}} + \frac{Z_{0\pi}}{Z_{1\pi}Z_{2\pi}}\right)\dot{U}_2 + \left(1 + \frac{Z_{0\pi}}{Z_{1\pi}}\right)\dot{I}_2. \quad (15)$$

The coefficients of equivalent "П" two-ports are:

$$A = 1 + \frac{Z_{0\pi}}{Z_{2\pi}},\quad B = Z_{0\pi}, \\ C = \frac{1}{Z_{1\pi}} + \frac{1}{Z_{2\pi}} + \frac{Z_{0\pi}}{Z_{1\pi}Z_{2\pi}},\quad D = 1 + \frac{Z_{0\pi}}{Z_{1\pi}}. \quad (16)$$

It is possible to determine the impedance of the "П"– equivalent circuit expressed by *A*, *B*, *C* and *D:*

$$Z_{0\pi} = B;\qquad Z_{1\pi} = \frac{B}{D-1};\qquad Z_{2\pi} = \frac{B}{A-1} \quad (17)$$

In analyzing electric circuits, it is usually necessary to replace a device with an equivalent two-port containing only three impedances.

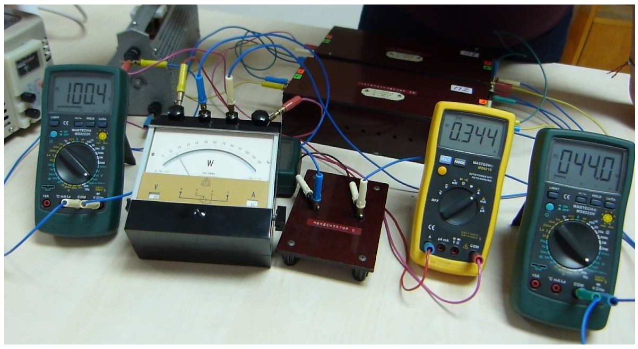

Fig. 13 The two-port circuit

Laboratory models are shown in Fig. 13.

F. Transients in linear circuit

This laboratory exercise is made in order to visualize the results of transients in linear electric circuits of the first and second order.

The influence of elements' values in the circuits is established on the character and the rate of transient processes.

Transients in electric circuits occur whenever its steady state is changing i.e. these are processes that occur and develop in transition of the electrical circuit from one steady state to another. The cause of this change and the subsequent transition can be changes in the topology or in the parameters of the circuit, as well as changing the value of power sources. The steady state cannot change instantaneously after switching. Theoretically, the process is infinitely long. Practically it is very quick - fractions of a second and rarely a few seconds [3].

The processes in the circuit during the transients can be described by system of differential equations, written according Kirchhoff's laws for the circuit after commutation. In general, transient response in electric circuit consists of two components: steady-state response and source free response. For example:

$$x(t) = x_s(t) + x_f(t) \quad (18)$$

The steady-state response corresponds to stationary process that is established in the circuit after the changes have already been completed. The source free response corresponds to the change processes, taking place due to the difference between stored in inductors and capacitors energy before and after commutation.

The laboratory module consists of a coil *L*, a decade capacitor C_d and a decade resistor R_d. The circuit is shown in Fig. 14. The repeatability of transient process is provided by an electrical relay with a frequency switch. The aim of the electrical relay is to switch a decade capacitor from power supply to the external circuit and back.

Fig. 14 The transient in RLC circuit

The different steady state types of transition processes should be done with appropriate value combinations of C_d and R_d. To observe the transient voltage response of an RLC circuit and to estimate the time constant, the electrical oscilloscope is connected to the R_d. The data is received by students from the screen of oscilloscope

At the end of each exercise there is a protocol, which students must fill in with the results of measurements and calculations.

III. Conclusions

Online learning has certain advantages and significant disadvantages when laboratory exercises in the discipline are included.

The most important advantage of video clips is to provide the learning process and allows to finish the semester successfully. In this way, all type of classes - lectures, tutorials, course work and labs are implemented according to curriculum.

Disadvantages of online training are lack of practical skills to:

- connect electrical circuits;
- correct connection of measuring devices in the circuits;
- visual recognition of the basic elements (resistors, coils and capacitors) in the circuit;
- measure the data of devices;
- proper arrangement of models, devices, electrical conductors for easy manipulation (switching, reports, etc.).

Acknowledgment

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