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LABORATORY WORKS

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Укладачі:

Куземко Н. А., канд. техн. наук, доцент;

Котик М. І., асистент.

Рецензент:

Г. М. Осухівська, канд. техн. наук, доцент.

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LABORATORY WORK 1

Investigation

of energy transfer from source to consumer

The purpose of the work. To investigate the energy transfer from source to consumer, electrical source working regimes and to learn practically how to determine the source parameters.

Electrical circuit is the multitude of devices designed for transforming, distribution and conversion of electrical energy, while the processes which are taking places in these devices can be described by the concepts of current, voltage and electromotive force (e.m.f.).

The simplest electrical circuit contains three main elements: electrical source (active element), consumer (passive element) and the wires. Besides, the circuit can have also additional elements: measuring devices, switches, fuses, contactors, etc.

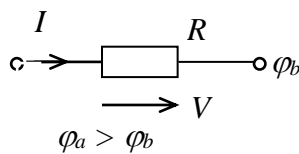


Fig.1.1

Electrical power is transformed into heating, mechanical energy, etc. at the *consumers*. The measure of this transformation is resistance R (fig.1.1). You can see the directions of the electrical values at fig.1.1.

Ohm's law for this element is as follow $V = RI$ or $I = GV$, where R - is resistance, $G = 1/R$ - is conductivity. The power on resistive element is $P = RI^2 = GV^2$.

Heating, mechanical energy, etc. is transformed into electrical power at the *electrical sources*. The measure of this transformation is electromotive force (e.m.f.) E (fig.1.2). You can see the directions of the electrical values at fig.1.2.

The *ideal electrical source* (without losses) is characterized only by E . The

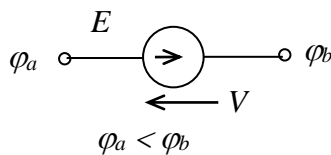


Fig.1.2

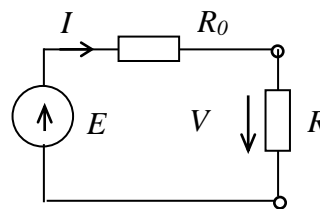


Fig.1.3

power on the electrical source is $P = EI$.

The *real electrical source* has losses and is characterized by E and R_0

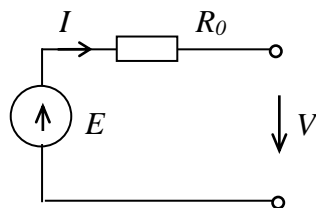


Fig.1.4

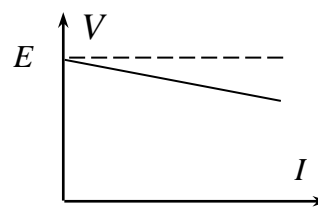


Fig.1.5

(internal resistance), which reflects the losses. The simplest electrical circuit is shown at fig.1.3. For this circuit:

$$I = E / (R_0 + R), \text{ then } V = E - R_0 I, \quad V = RI, \quad R_0 I + RI = E.$$

We can represent real electrical circuit by two substitution schemes: serial (fig. 1.4) and parallel (fig. 1.6). The external volt-ampere characteristic (fig.1.5) $V(I)$ is the main characteristic of the source. Its analytical expression is $V = E - R_0 I$. At fig.1.5 solid line indicates the characteristic of real source, dashed line - the characteristic of ideal source. Boundary points of this characteristic correspond to the source boundary modes – open circuit (idle) mode (without loading), when $I = 0$, $V = E = V_{oc}$ and short circuit mode, when $V = 0$, $I = I_{sc}$. The

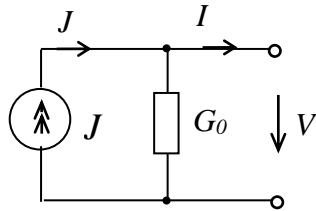


Fig.1.6

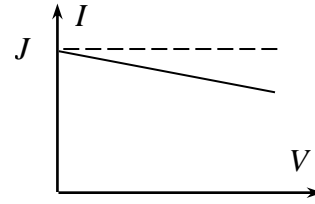


Fig.1.7

external characteristic of ideal source $V = E$ is represented by dashed line at fig. 1.5.

Parallel substitution scheme (fig.1.6) consists of ideal current source J and internal conductivity G_0 , which characterizes the losses. The external characteristic of real source (fig.1.7) is described by the equation $I = J - G_0 U$. The external characteristic of ideal source $I = J$ is represented by dashed line at fig. 1.7.

Serial and parallel schemes are equivalent, it means you can transform one into another using such formulas:

$$E = G_0 J, R_0 = 1/G_0, J = E/R_0, G_0 = 1/R_0.$$

The efficiency factor of the source characterizes the efficiency of energy transforming from the source to consumer:

$$\eta = \frac{P_R}{P_E} = \frac{VI}{EI} = \frac{V}{E}, \quad V = \eta E,$$

where P_R - is a consumer power, P_E - is a source power.

We can also write down the efficiency factor using the elements parameters:

$$\eta = \frac{P_R}{P_R + \Delta P} = \frac{RI^2}{RI^2 + R_0 I^2} = \frac{R}{R_0 + R} = \frac{1}{1 + R_0/R},$$

where ΔP - are power losses.

There are three main *electrical circuit modes*: nominal, operating and boundary.

The nominal mode is the best mode for the working device, the device nominal parameters are shown in its technical passport (I_{NOM} , V_{NOM} , P_{NOM}).

Operating mode is a mode, where the deviation from the nominal parameters is not big.

Boundary modes are: open circuit or idle (non-working) and a short circuit (emergency) modes. For the open circuit (o.c.) mode $R = \infty$, then using the scheme at fig. 1.3, we can write down:

$$I = \frac{E}{R_0 + R} = \frac{E}{R_0 + \infty} = 0, V = E - R_0 I = E, \eta = 1.$$

For short circuit mode (s.c.) $R=0$, then using the scheme at fig.1.3, we can write down:

$$V = RI, V=0, I = E/R_0 = I_{sc}, \eta = 0.$$

The methods of open circuit and short circuit experiments can be used for defining the parameters of the source (E, R_0): $V_{oc} = E, R_0 = E/I_{sc}$. The experiment of s.c. mode is provided at low voltage.

Electrical source operating modes:

- voltage generator, when the voltage at the clamps of the source practically does not depend on the current, thus $V \approx E$, and this mode is close to o.c. In this mode $R_0 I \ll RI$ (fig.1.4), that's why the condition of it is $R_0 \ll R$ and $\eta \approx 1$. This is the main operating mode of electrical engineering devices.

- current generator, when the current at the clamps of the source practically does not depend on the voltage, thus $I \approx J$, and this mode is close to to s.c. In this mode $G_0 U \ll GU$ (fig.1.6), that's why the condition of it is $G_0 \ll G$ ($R_0 \gg R$).

-balanced mode – the maximum power $P = RI^2$ is transferred from the source to the consumer at this mode? $I = E/(R_0 + R)$, and $P = RE^2/(R_0 + R)^2$ at this mode.

The condition of this mode comes out from the expression $dP/dR = 0$, that means $R_0 = R$ and $\eta = 0.5$. This mode is used in electronics.

Homework

At given voltage V , load resistance R , and efficiency factor η of the circuit on fig. 1.8 to define source internal resistance R_0 and electromotive force E , source and consumer powers P_E, P_R . To calculate the efficiency factor when the load will be $R/10$. Tasks variants are listed in the table 1.1.

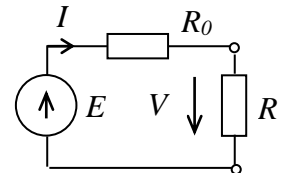


Fig. 1.8

Table 1.1

Var	1	2	3	4	5	6	7	8	9	10
η	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99	1.00
R, Ω	51	62	73	84	95	106	117	128	139	150
V, V	110	120	130	140	150	160	170	180	190	100

Elements of laboratory settings

Laboratory settings consist of the board (fig.1.9), resistances and source of constant control e.m.f. The board includes: ammeter, voltmeter, line resistance simulator, input and 1, 2 and output 3, 4 clamps. The input clamps connect to the source with internal resistance R_0 and output clamps connect to the resistances.

Clamps 3,4 are the clamps of the source (internal resistance of the source includes line resistance $R_0 = R_{\text{line}} + R_{\text{in}}$).

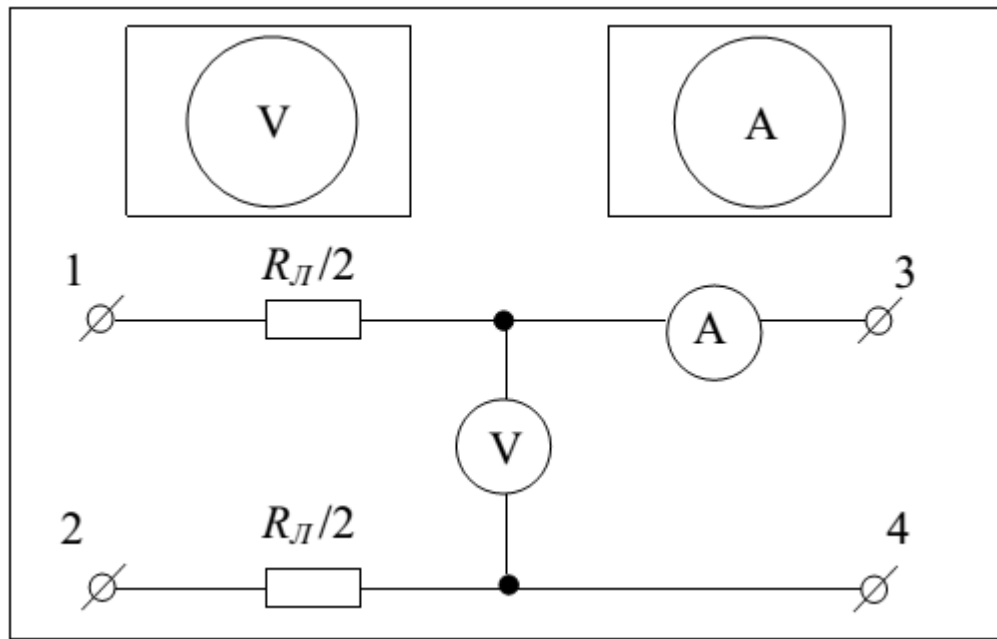


Fig. 1.9

Work execution order

1. Collect the circuit (fig. 1.10).

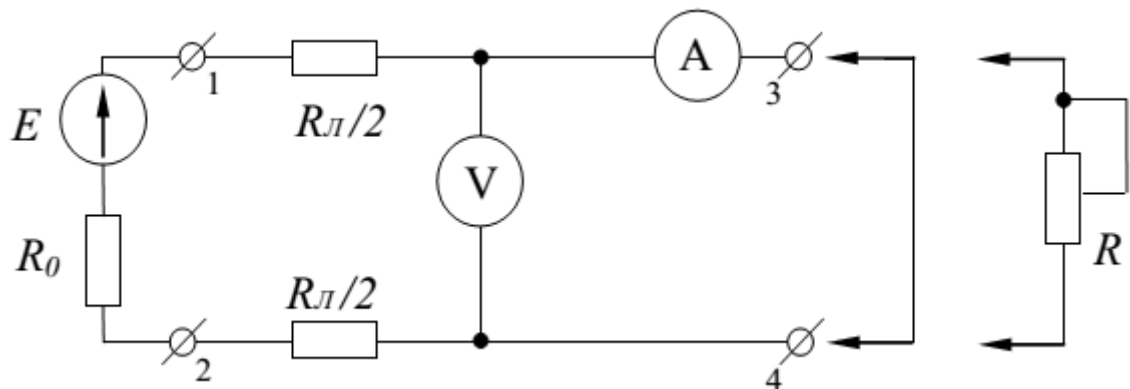


Fig. 1.10

2. Short the clamps 3–4 and set the short circuit current $I_{sc} = 0.1A$. Open the clamps 3–4 and measure the open circuit voltage $E = V_{oc}$. Define the source internal resistance $R_0 = E / I_{sc}$. Write down the results of measuring to the table 1.2.
3. Connect the resistances to the clamps 3,4. The resistances values will be such that I / I_{sc} are $0 \div 1$. Write down the results of measuring voltage and current to the table 1.2.

Table 1.2

I/I_{sc}	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
I, A											
V, V											
R, Ω											
P, W											
P_{sour}, W											
P_0, W											
V_0, V											
η											

4. Calculate (table 1.2): the consumer resistances $R = V / I$, the voltage drops $V_0 = R_0 I$, the source power $P_{sour} = EI$, the consumer power $P = VI$, the power losses $P_0 = R_0 I^2$, the efficiency factor $\eta = P / P_{sour}$. Write down the results of calculations to the table 1.2.

8. Determine the current source parameters J , G_0 for known voltage source parameters E , R_0 . Draw the current source and the voltage source substitutional schemes.

9. Draw graphs: $V(I)$, $V_0(I)$ and $P(I)$, $P_{sour}(I)$, $P_0(I)$, $\eta(I)$ by using the table 1.2.

Make conclusions about electrical source working regimes, the methods of determining the source parameters, the value of losses, the efficiency factor and how the source output voltage change when the load increase.

Report on the work

The name and the purpose of the work. Homework – the calculation of the circuit. The schematic diagram of the investigated circuit (fig 1.10). The table 1.2. The results of calculations of source parameters. The graphs. The conclusions.

Control questions

1. Give the definition of electrical circuit. Draw the simplest electrical circuit and mark the directions of electrical values in it. What are the main and the additional elements of the electrical circuit, what are their purposes?

2. Name and characterize the main circuit working regimes.

3. What devices do we call consumers? What parameter characterizes the measure of energy transfer?

4. Draw the consumer conditional designation and mark the directions of the electrical values in it. Write down the Ohm's law and the power expression for the consumer.

5. What devices do we call the power sources? What parameter characterizes the ideal source?

6. Draw the power source conditional designation and mark the directions of electrical values in it. Write down the power expression for it.
7. How to choose the circuit current direction? What is the condition of generator working regime and consumer working regime of the electrical source?
8. What are the main parameters of the voltage source? What is the difference between real and ideal voltage source?
9. Draw the serial substitution scheme of electrical source. Write down the voltage source equation.
10. Draw the parallel substitution scheme of electrical source. Write down the current source equation.
11. How can we determine the voltage source parameters experimentally? Write down the relevant expressions.
12. Draw the external characteristics of real and ideal voltage source and current source.
13. Describe the work of electrical source in the voltage generator regime. What is the working regime condition?
14. Describe the work of electrical source in the current generator regime. What is the working regime condition?
15. Describe the agreed working regime of the electrical source. What is the working regime condition?
16. Write down the electrical source efficiency factor expression using the parameters of the source and consumer. Analyze the dependence between the source working regime and the efficiency factor.

LABORATORY WORK 1.2

Experimental verification of DC circuits calculation methods

The purpose of the work. To learn different methods of calculation the complex DC circuits. To compare experimental and calculated data.

We can use several methods, which are based on Kirchhoff's laws.

Current law (Kirchhoff's first law) states that the sum of the currents entering the node is equal to the sum of the currents leaving the node $\sum I_n = 0$ (the algebraic sum of the currents in the node is equal to zero).

Voltage law (Kirchhoff's second law) states that the algebraic sum of all voltages across passive elements around a loop is equal the algebraic sum of electro-motive forces around the same loop $\sum R_n I_n = \sum E_n$.

Branch of the circuit is the part of the circuit with the same current, it may be consisted from one or several elements connected in serial.

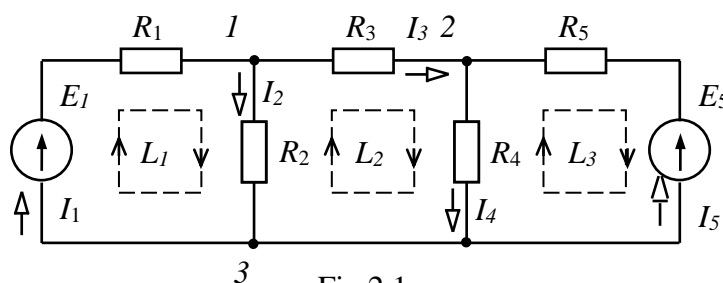


Fig.2.1

Node is the place where three or more branches are connected.

Loop is any closed path around the circuit.

Kirchhoff's laws method.

Let's suppose the circuit has p branches and q nodes. There'll be p unknown currents. We must solve the system of p equations to find them.

First, you have to choose the directions of branch currents arbitrarily and mark them at the scheme, then mark the nodes and the loops. After this, it is necessary to write down $q - 1$ nodes equations according to Current law and $p - q - 1$ loop equations according to the Kirchhoff's second law.

After the system of equations is solved, some currents may have sign “-“, it means that the real directions of that current is opposite to the one we have chosen at the beginning.

Let's write down the system of equations for the scheme at fig.2.1. There are 5 branches $p = 5$ and 3 nodes $q = 3$ here.

The equations according to current law ($q - 1 = 2$) for the nodes 1 and 2:

$$\begin{aligned} \text{“1” } I_1 &= I_2 + I_3 \\ \text{“2” } I_3 + I_5 &= I_4 \end{aligned} \quad (1)$$

The equations according to voltage law ($p - q - 1 = 3$) for the loops L_1, L_2, L_3 (we choose the directions along the loops clockwise, if the directions of our bypass and the voltage or e.m.f. are the same, we denominate it with “+”, if opposite with “-”).

$$\begin{aligned} \text{“L}_1\text{”} \quad & +R_1 I_1 + R_2 I_2 = +E_1 \\ \text{“L}_2\text{”} \quad & -R_2 I_2 + R_3 I_3 + R_4 I_4 = 0 \\ \text{“L}_3\text{”} \quad & -R_4 I_4 - R_5 I_5 = -E_5 \end{aligned} \quad (2)$$

So, the equation system according this method will be:

$$\begin{cases} +I_1 - I_2 - I_3 = 0 \\ +I_3 - I_4 + I_5 = 0 \\ +R_1 I_1 + R_2 I_2 = +E_1 \\ -R_2 I_2 + R_3 I_3 + R_4 I_4 = 0 \\ -R_4 I_4 - R_5 I_5 = -E_5 \end{cases} \quad (3)$$

After solving this system we get the unknown branch currents.

We apply the equation of power balance to verify our calculations: the total power of the sources should be equal to the total power of the consumers $\Sigma P_R = \Sigma P_E$. The total power of the sources $\Sigma P_E = \Sigma E_n I_n = E_1 I_1 + E_5 I_5$. The total power of the consumers $\Sigma P_R = \Sigma R_n I_n^2 = R_1 I_1^2 + R_2 I_2^2 + R_3 I_3^2 + R_4 I_4^2 + R_5 I_5^2$.

Loop currents method.

This method has less equations than previous and is based on the voltage

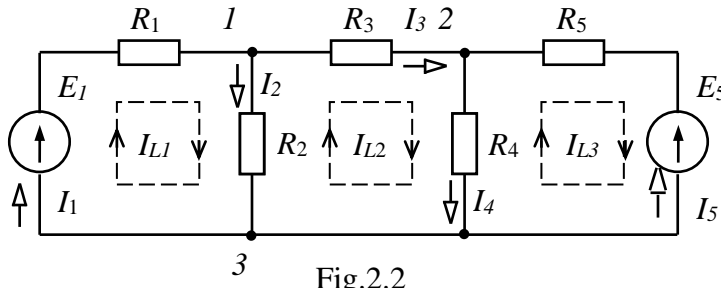


Fig.2.2

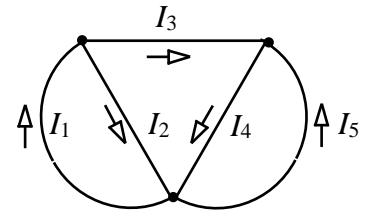


Fig.2.3

law. Let's suppose that we have three loop currents I_{L1}, I_{L2}, I_{L3} at circuit (fig.2.2), the directions of these currents we choose arbitrarily. Then we can write down branch current by using loop currents: $I_1 = I_{L1}$, $I_2 = I_{L1} - I_{L2}$, $I_3 = I_{L2}$, $I_5 = -I_{L3}$, $I_4 = I_{L2} - I_{L3}$.

We have to substitute these expressions in the equations of voltage law:

$$\begin{aligned} \text{“L}_1\text{”} \quad & +R_1 I_1 + R_2 I_2 = +E_1 \\ \text{“L}_2\text{”} \quad & -R_2 I_2 + R_3 I_3 + R_4 I_4 = 0 \\ \text{“L}_3\text{”} \quad & -R_4 I_4 - R_5 I_5 = -E_5 \end{aligned}$$

We get the following:

$$\begin{cases} (R_1 + R_2)I_{L1} - R_2I_{L2} = E_1 \\ -R_2I_{L1} + (R_2 + R_3 + R_4)I_{L2} - R_4I_{L3} = 0 \\ -R_4I_{L2} + (R_4 + R_5)I_{L3} = -E_5 \end{cases} \quad (4)$$

Let's mark:

$R_{11} = R_1 + R_2$, $R_{22} = R_2 + R_3 + R_4$, $R_{33} = R_4 + R_5$ - it'll be individual resistances of the loops, which are equal to the sum of all the resistances of the loop;

$R_{12} = R_{21} = R_2$, $R_{13} = R_{31} = 0$, $R_{23} = R_{32} = R_4$ - mutual resistances of the loops, the resistances of the branches which are mutual for the respective loops;

$E_{L1} = E_1$, $E_{L2} = 0$, $E_{L3} = -E_5$ - loops e.m.f., is equal to the algebraic sum of the electromotive forces of the loops.

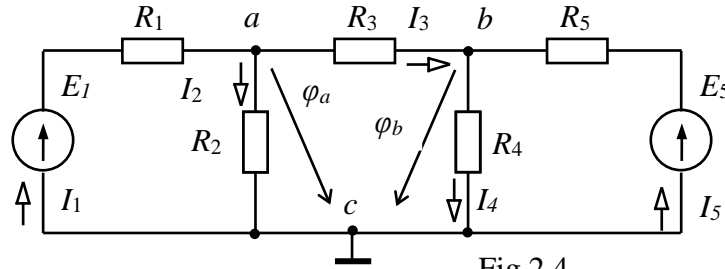
Using these markings, system (4) looks like (5), that can be used for any circuit with three independent loops:

$$\begin{cases} +R_{11}I_{L1} - R_{12}I_{L2} - R_{13}I_{L3} = E_{L1} \\ -R_{21}I_{L1} + R_{22}I_{L2} - R_{23}I_{L3} = E_{L2} \\ -R_{31}I_{L1} - R_{32}I_{L2} + R_{33}I_{L3} = E_{L3} \end{cases} \quad (5)$$

Nodal potential method

This method has less equations than previous one and is based on current law. Let's analyze the circuit on fig.1.19. There are two independent nodes a, b . Try to suppose that the potential of the basic (dependent) node is equal to zero, so the potentials of other nodes are marked at the scheme as φ_a, φ_b (fig.2.4).

We can also write down the branch currents using node potentials:



$$\varphi_a = E_1 - R_1 I_1, \quad I_1 = \frac{(E_1 - \varphi_a)}{R_1} = (E_1 - \varphi_a)G_1,$$

$$\varphi_a = R_2 I_2, \quad I_2 = \frac{\varphi_a}{R_2} = \varphi_a G_2, \quad \varphi_b = R_4 I_4, \quad I_4 = \frac{\varphi_b}{R_4} = \varphi_b G_4,$$

$$\varphi_a - \varphi_b = R_3 I_3, \quad I_3 = \frac{(\varphi_a - \varphi_b)}{R_3} = (\varphi_a - \varphi_b)G_3,$$

$$\varphi_b = E_5 - R_5 I_5, \quad I_5 = \frac{(E_5 - \varphi_b)}{R_5} = (E_5 - \varphi_b)G_5.$$

Let's substitute these expressions into the equations for the nodes a, b

$$\begin{aligned}
& + I_1 - I_2 - I_3 = 0 \\
& + I_3 - I_4 + I_5 = 0, \text{ we get} \\
& \begin{cases} (G_1 + G_2 + G_3)\varphi_a - G_3\varphi_b = G_1 E_1 \\ -G_3\varphi_a + (G_3 + G_4 + G_5)\varphi_b = G_5 E_5 \end{cases}.
\end{aligned} \tag{6}$$

Let's mark:

$G_{11} = G_1 + G_2 + G_3$, $G_{22} = G_3 + G_4 + G_5$ - the individual conductivities of the nodes, it's the sum of the branch conductivities which coming in the node;

$G_{12} = G_{21} = G_3$ - the mutual conductivities of the nodes, the conductivity of the branch, which connects respective nodes;

$J_a = G_1 E_1$, $J_b = G_5 E_5$ - the algebraic sum of the currents of current sources, which are flowing in the respective nodes. If the current J of the source flows in the node, we mark it by the sign "+", when it flows out - with sign "-".

Using these markings, system (6) looks like (7), that can be used for any circuit with two independent nodes:

$$\begin{cases} G_{11}\varphi_a - G_{12}\varphi_b = J_a \\ -G_{12}\varphi_a + G_{22}\varphi_b = J_b \end{cases}. \tag{7}$$

Two nodes method.

This method is used for calculating the circuits with only two nodes and several parallel branches. The example of such circuit is on fig.2.5. This method is also based on the Current

law and is partly the method of nodal potentials. First of all, we calculate the inter-node voltage $V = \Sigma G_n E_n / \Sigma G_n$, where G_n - conductivity of n branch, E_n - e.m.f. of n branch. For the circuit on fig.2.5 it'll be

$$V_{ab} = \frac{G_1 E_1 + G_2 E_2}{G_1 + G_2 + G_3}.$$

Then we calculate the branch currents using such expressions:

$$V_{ab} = R_3 I_3, \quad I_3 = \frac{V_{ab}}{R_3} = V_{ab} G_3,$$

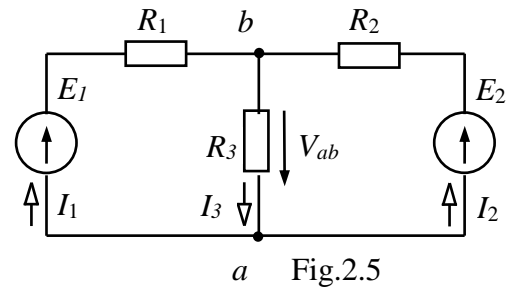
$$V_{ab} = E_1 - R_1 I_1, \quad I_1 = \frac{(E_1 - V_{ab})}{R_1} = (E_1 - V_{ab}) G_1,$$

$$V_{ab} = E_2 - R_2 I_2, \quad I_2 = \frac{(E_2 - V_{ab})}{R_2} = (E_2 - V_{ab}) G_2.$$

The superposition method.

We can use this method when the e.m.f. of one source is changed. The method based on the superposition principle, means that every e.m.f. acts in the circuit independently. So, the calculation of one circuit (fig. 2.5) with two sources, for example, can be reduced to the calculation of two circuits with one source (fig. 2.6, 2.7).

According to this method, we must calculate two partial circuits with partial



currents. We have only e.m.f. E_1 in the first partial circuit (fig. 2.6).

The total resistance of this circuit: $R' = R_1 + \frac{R_2 R_3}{R_2 + R_3}$.

The partial branches currents: $I'_1 = E_1 / R'$, $I'_2 = I'_1 \frac{R_3}{R_2 + R_3}$, $I'_3 = I'_1 \frac{R_2}{R_2 + R_3}$.

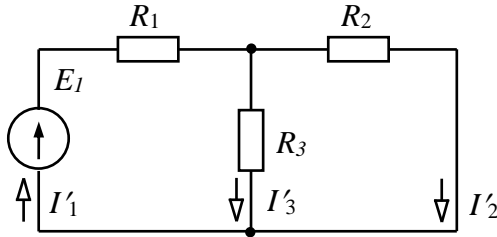


Fig. 2.6

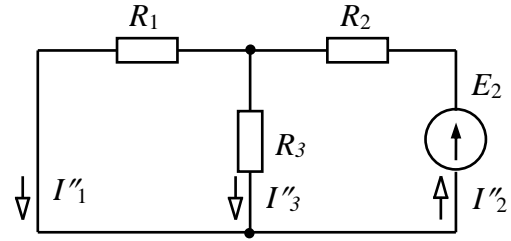


Fig. 2.7

We have only e.m.f. E_2 in the second partial circuit (fig. 2.7).

The total resistance of this circuit: $R'' = R_2 + \frac{R_1 \cdot R_3}{R_1 + R_3}$.

The partial branches currents: $I''_2 = E_2 / R''$, $I''_1 = I''_2 \frac{R_3}{R_2 + R_3}$, $I''_3 = I''_2 \frac{R_1}{R_1 + R_3}$.

Then we have the real branch currents as an algebraic sum of the respective partial currents (fig. 2.5):

$$I_1 = I'_1 - I''_1, \quad I_2 = I''_2 - I'_2, \quad I_3 = I''_3 + I'_3.$$

Equivalent generator method.

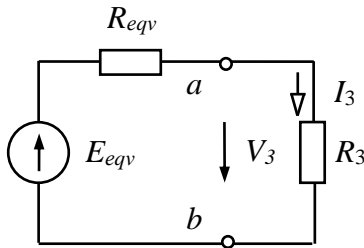


Fig. 2.8

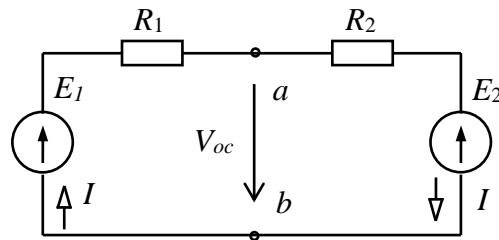


Fig. 2.9

The method is used when it is necessary to calculate the current of only one branch of the circuit (for example it is varying resistor or non-linear element in this branch). We select the branch with unknown current (e.g. I_3) from the circuit on fig. 2.5 and the rest of the circuit is replaced by the equivalent generator (fig.2.8) with parameters E_{eqv} - equivalent e.m.f., which is equal to the open circuit voltage on the clamps of an open branch ab and R_{eqv} - equivalent resistance, which is equal to the input resistance of the circuit in respect to the open branch

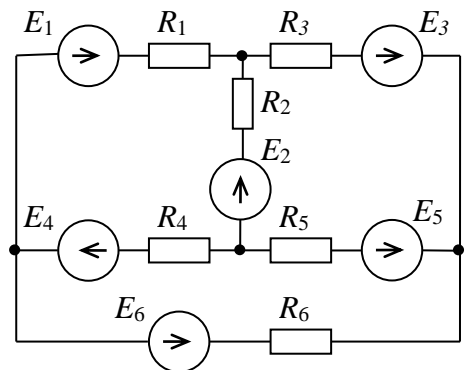


Fig. 2.10

ab. The problem is to calculate the parameters of equivalent generator E_{eqv} and R_{eqv} . For

Table 2.1

Var. №	E_1 V	E_2 V	E_3 V	E_4 V	E_5 V	E_6 V	R_1 Ω	R_2 Ω	R_3 Ω	R_4 Ω	R_5 Ω	R_6 Ω
00	12	15	18	—	—	—	3	4	5	6	7	8
01	—	15	18	21	—	—	4	5	6	7	8	3
02	—	—	18	21	24	—	5	6	7	8	3	4
03	—	—	—	21	24	27	6	7	8	3	4	5
04	15	18	21	—	—	—	7	8	3	4	5	6
05	—	18	21	24	—	—	8	3	4	5	6	7
06	—	—	21	24	27	—	3	4	5	6	7	8
07	—	—	—	24	27	12	4	5	6	7	8	3
08	18	21	24	—	—	—	5	6	7	8	3	4
09	—	21	24	27	—	—	6	7	8	3	4	5
10	—	—	24	27	12	—	7	8	3	4	5	6

the circuit at fig.1.20 $R_{eqv} = \frac{R_1 R_3}{R_1 + R_3}$. Then we can calculate E_{eqv} using fig. 2.9

$$V_{OC} = E_{eqv} = E_1 - R_1 I, \text{ where } I = \frac{E_1 - E_2}{R_1 + R_3}.$$

According to the fig. 2.8 we calculate unknown current $I_3 = E_{eqv} / (R_{eqv} + R_2)$.

Homework

Draw the scheme (fig.2.10) according to your variant in table below. Write down the system of equations according to Kirchhoff's laws.

Elements of laboratory settings

Laboratory settings consists of the test panel (fig. 2.11), a panel of power sources, panel of ammeters and voltmeter.

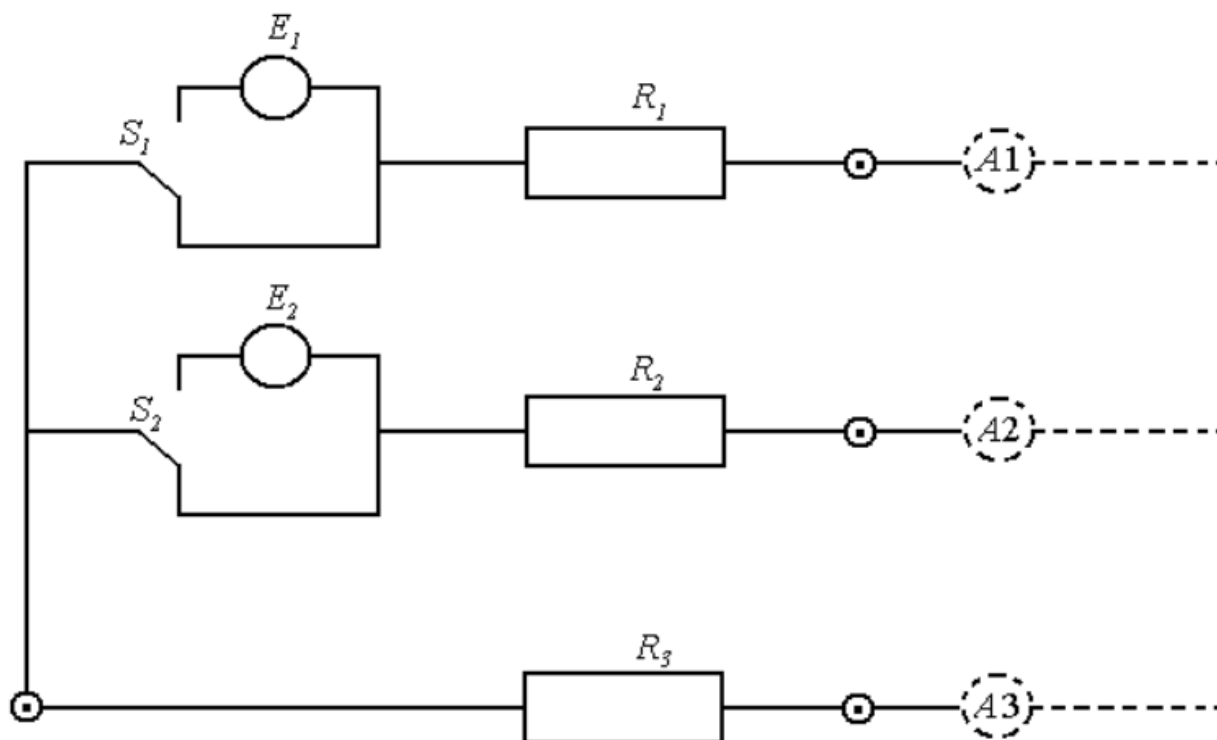


Fig. 2.11 Test panel

The scheme of the circuit is on the front of the tested panel.

The sources of the circuit contain semiconductor diodes rectifiers (nonlinear elements). The internal resistance of such sources depend on the source's current: $R_0 = f(I)$. Therefore, such sources can be considered to be a linear element of the circuit only in the first approximation.

Work execution order

2.1. The tutor gives the values of R_3 , *e.m.f.* and the circuit calculation method.

2.2. Set the value of R_3 and measure values R_1 and R_2 with a multimeter. Connect the multimeter clamps to the clamps 0.3, 0.1 and 0.2 correspondingly. Switches S_1 and S_2 should be in lower position (fig. 2.11). Ammeters A_1 - A_3 should be disconnected.

2.3. Shorten the clamps 1,2,3. Switches S_1 and S_2 should be in upper position (fig.2.11). Connect the e.m.f. sources taking into consideration their polarity. Measure the voltage values on the sources clamps with a multimeter.

2.4. Switch on the power supply. Measure voltages V_1 and V_2 at the clamps of the real sources and on all circuit resistances V_{R1} , V_{R2} , V_{R3} , as well as currents I_1 , I_2 , I_3 in the branches of the circuit.

2.5 Draw the scheme of the circuit (fig. 2.11) without measuring devices and switching elements. Choose arbitrary directions for circuit currents.

2.6. In accordance with measured values of R_1 , R_2 , R_3 and E_1 , E_2 (assuming

that $E_1 \approx V_1$ and $E_2 \approx V_2$) calculate the circuit by given method.

2.7. Switch ammeters A_1 - A_2 in the circuit branches between clamps 1, 2, 3 and measure branch currents (positive current direction should be the same as e.m.f. direction).

2.8. Compare the calculated current values with the measured experimentally ones.

2.9. Verify the calculations of the circuit with the Kirchhoff's laws.

2.10. Make conclusions.

Report on work

The name and purpose of the work. Homework – the calculation of the circuit. The investigated circuit (fig. 2.11). The results of measuring and calculations. Conclusions.

Control questions

1. Describe the main methods of circuits calculation.
2. Write down and explain Kirchhoff's laws.
3. What nodes and loops are called independent? How many equations should be compiled according to the Kirchhoff's laws?
4. Explain the essence of loop current method.
5. Explain the essence of nodal potentials method.
6. Explain the essence of two nodes method.
7. Explain the essence of superposition method.
8. Explain the essence of equivalent generator method.
9. Explain what is two-port networks and its classification.
10. Compare the circuits calculation methods.

LABORATORY WORK 1.3

Investigation

of coil and capacitor serial connection

The purpose of the work is to investigate serial connection of coil and capacitor and the voltage resonance in AC circuit.

Electrical status equations for the circuit (fig.3.1) for voltage instantaneous values and voltage vectors are accordingly:

$$v_R + v_L + v_C = v, \quad \bar{V}_R + \bar{V}_L + \bar{V}_C = \bar{V}.$$

Vector diagram is shown on fig 3.2. The calculated triangles for voltages, resistances and powers (fig.3.3) are obtained from this diagram. Out of those triangles:

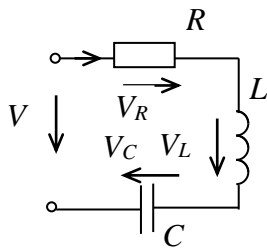


Fig.3.1

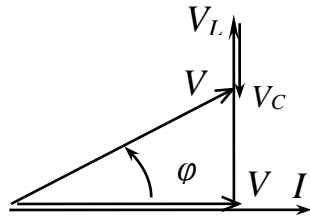


Fig.3.2

$$V = \sqrt{V_R^2 + (V_L - V_C)^2}, \quad \varphi = \arctg(V_L - V_C)/V_R,$$

$$V_R = V \cos \varphi = V_a, \quad V_L - V_C = V \sin \varphi = V_r,$$

-these are active and reactive constituents of the applied voltage V . Therefore circuit impedance makes:

$$Z = \sqrt{R^2 + (X_L - X_C)^2}, \quad \varphi = \arctg((X_L - X_C)/R),$$

$$R = Z \cos \varphi, \quad X = X_L - X_C = Z \sin \varphi -$$

these are resistance and reactance of the circuit.

Total power makes thus:

$$S = \sqrt{P^2 + (Q_L - Q_C)^2} \text{ (VA)}, \quad \varphi = \arctg(Q_L - Q_C)/P,$$

$$P = S \cos \varphi = VI \cos \varphi, \quad Q = Q_L - Q_C = S \sin \varphi = VI \sin \varphi$$

- these are active and reactive powers of the circuit.

Voltage resonance take place at the circuit with serial connection of L, C elements (fig.3.1). $V_L = V_C$ at resonance mode, so the condition of voltage resonance is $X_L = X_C$, it means $\omega_0 L = 1/(\omega_0 C)$.

Thus $\omega_0^2 LC = 1$ and, resonance frequency $\omega_0 = 1/\sqrt{LC}$.

Resonance can be reached by changing C , L or ω_0 .

$\rho = \omega_0 L = 1/(\omega_0 C)$, $\rho = \sqrt{L/C}$ is called wave resistance.

At resonance mode $X = X_L - X_C = 0$, $Z = \sqrt{R^2 + X^2} = R$,

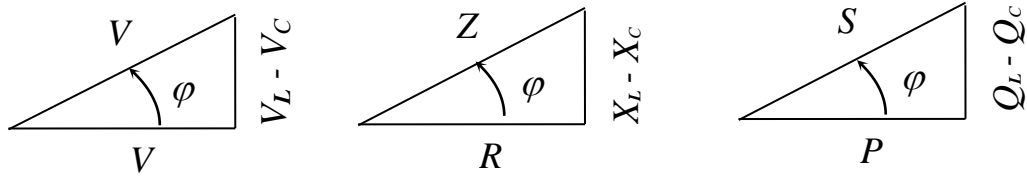


Fig. 3.3

$$Q_L - Q_C = Q = 0, S = \sqrt{P^2 + Q^2} = P, \varphi = 0.$$

Total current $I = V / Z = V / R$ is at maximum, what is an indication of the voltage resonance. Frequency characteristics of the circuit $X_L(\omega) = \omega L$, $X_C(\omega) = 1/(\omega C)$, $X(\omega) = X_L(\omega) - X_C(\omega)$ are shown at fig.3.4. When $\omega < \omega_0$, $X < 0$, $\varphi < 0$, reactance has inductive character. When $\omega > \omega_0$, $X > 0$, $\varphi > 0$ reactance has capacitive character.

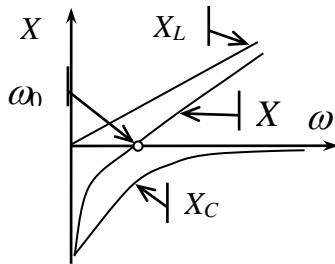


Fig. 3.4

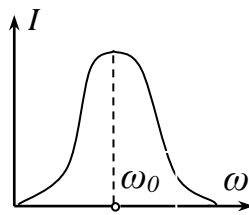


Fig. 3.5

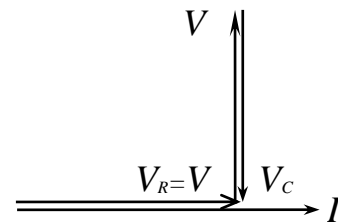


Fig. 3.6

At fig.3.5 resonance curve $I(\omega)$ and at fig.3.6 vector diagram for resonance

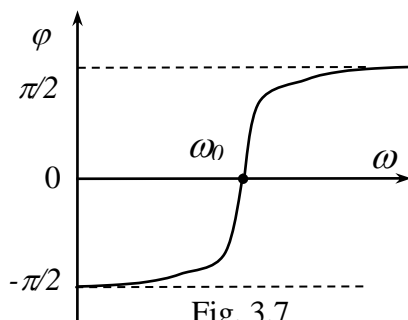


Fig. 3.7

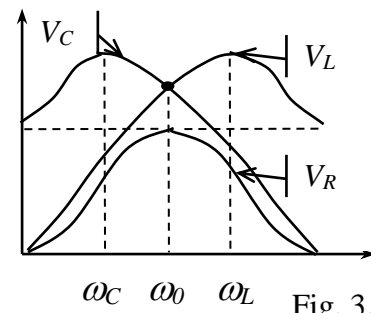


Fig. 3.8

mode are shown. Phase-frequency characteristic $\varphi(\omega) = \arctg \frac{\omega L - 1/(\omega C)}{R}$ is shown at fig.3.7 and the resonance curves of voltages $V_R(\omega)$, $V_L(\omega)$, $V_C(\omega)$ at fig. 3.8 accordingly.

Voltage resonance should be avoided, because the voltage across the elements may several times exceed the nominal value.

Homework

Calculate the input voltage, coil voltage, capacitor voltage active and reactive powers, the resistances of the elements and phase shift angles (fig. 3.9), at given current I , inductivity L , active resistance R , capacitance C .

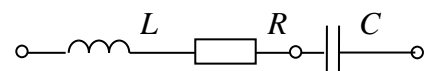


Fig. 3.9

Tasks variants are listed in the table 3.1.

Table 3.1

Var	1	2	3	4	5	6	7	8	9	10
I, mA	180	185	190	195	200	180	185	190	195	200
R, Ω	186	189	187	197	195	186	189	187	197	195
L, H	1.12	1.13	1.15	1.18	1.20	1.12	1.13	1.15	1.18	1.20
$C, \mu F$	3.92	3.76	3.78	3.86	3.87	6.15	6.33	6.02	6.51	6.34

Elements of laboratory settings

Laboratory settings consist of the rheostat with resistance $0-100 \Omega$ for current up to 5 A; capacitors with capacitances $0.5; 1; 2; 4; 8; 16; 32; 64 \mu F$; coil with the core for voltages $127/220 V$, ammeter, limit of measuring $<1A>$, phase meter, voltmeter, limit of measuring $<0 \dots 250 V>$.

Power supply from the controlled transformer with voltmeter, limit of measuring $<0 \dots 250 V>$.

Work execution order

1. Connect the circuit (fig. 3.10). The investigation is assumed to be for the constant frequency and input voltage. A jump-like change of the capacitance should be made twice from $0.5 \mu F$ to $64 \mu F$ which corresponds changing the impedance from active-capacitive character to active-inductive character as well as active character at resonance mode. Move the core inside the coil to reach the resonance. The coil is assumed to be a linear element.

2. Set the circuit voltage as given by tutor ($150 \leq V \leq 200 V$).

3. Reach the minimum of phase shift angle $\varphi = \varphi_V - \varphi_I$, by changing the capacitance.

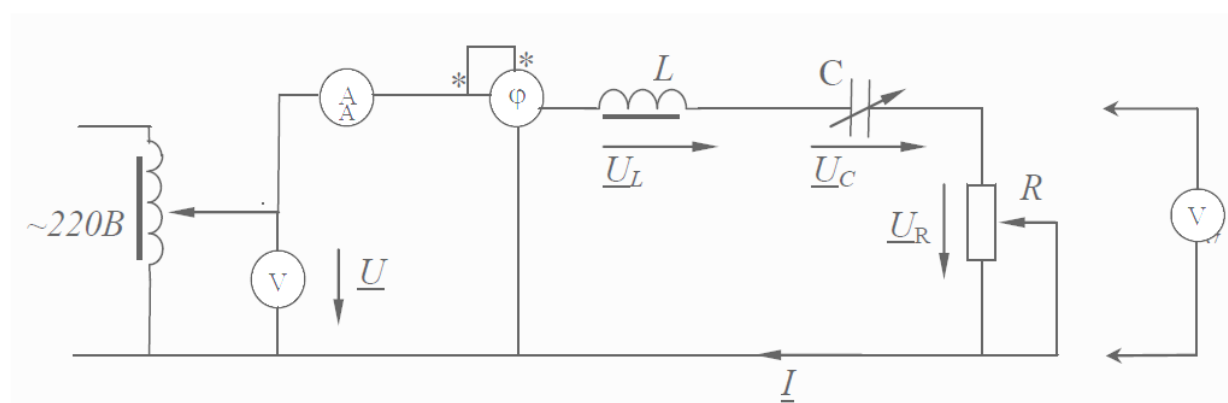


Fig. 3.10

$$C_{res}=4\mu F.$$

Table 3.2

C/C_{res}	$C, \mu F$	V, V	I, A	V_L, V	V_C, V	V_{LC}, V	φ, deg
2^0							
2^1							
2^2							
2^3							
$2^{(-1)}$							
$2^{(-2)}$							
$2^{(-3)}$							

4. Move the core inside the coil or change a little the input voltage to reach the resonance. For resonance mode $\varphi=0$, $X_L=X_C$. Note down the results (voltages and phase shift angle values) to the table 3.2, for the capacitance $C=C_{res}$. Draw the vector diagram according to the results of the experiment. Find the inductance L and coil resistance R_C using the vector diagram.

5. Switch up the capacitance twice for the same value of voltage and rheostat resistance. Note down the results (voltages and phase shift angle values) to the table 3.2.

6. Repeat the same operations as in item 5 for the capacitances less and equal to $64 \mu F$. Then switch the capacitance the same way from $C=C_{res}$ to $0.5 \mu F$.

7. 9. Draw graphs: $V_L(\log_2 C/C_{res})$, $V_C(\log_2 C/C_{res})$, $V_R(\log_2 C/C_{res})$, $V_{LC}(\log_2 C/C_{res})$, $I(\log_2 C/C_{res})$, $\varphi(\log_2 C/C_{res})$ by using the table 3.2. Make conclusions.

Report on work

The name and purpose of the work. Homework – the calculation of the circuit. Schematic diagram of the investigated circuit (fig 3.4). Table 3.2. The vector diagram. The graphs. Conclusions.

Control questions

1. Write down the electrical status equation for the circuit with serial connection of RLC -elements in vector form and draw the vector diagram for this circuit.

2. Draw resistances calculated triangle for the circuit with serial connection of RLC -elements and write down the corresponding relations for it.

3. Explain what is it the active and reactive voltage constituents.

4. Draw powers calculated triangle for the circuit with serial connection of *RLC*-elements and write down the corresponding relations for it.

5. Give the definition of voltage resonance, write down the resonance condition and explain the resonance indication.

6. Give the definition of voltage resonance frequency, circuit wave resistance and explain the ways of resonance reaching.

7. What is the impedance, phase shift factor and total power of the voltage resonance circuit? How voltage resonance is being applied?

8. Draw the voltage resonance circuit frequency characteristics.

9. Draw the resonance curve for the voltage resonance circuit. Explain why the current at resonance is the biggest.

LABORATORY WORK 4

Investigation

of coil and capacitor parallel connection

The purpose of the work is to investigate parallel connection of coil and capacitor and the current resonance in AC circuit.

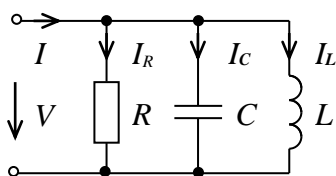


Fig.4.1

Circuit electrical status equations (fig. 4.1) for current instantaneous values and current vectors are accordingly:

$$i_R + i_L + i_C = i, \quad \bar{I}_R + \bar{I}_C + \bar{I}_L = \bar{I}.$$

Vector diagram is shown on fig. 4.2. The calculated triangles of currents and conductivities are obtained from this diagram (fig. 4.3). From those triangles we get subsequently:

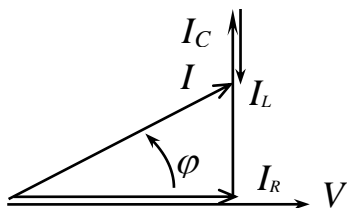


Fig.4.2

$$I = \sqrt{I_R^2 + (I_C - I_L)^2}, \quad \varphi = \arctg((I_C - I_L)/I_R),$$

$I_R = I \cos \varphi = I_a$, $I_C - I_L = I \sin \varphi = I_r$ - these are active and reactive constituents of the current.

Circuit admittance makes:

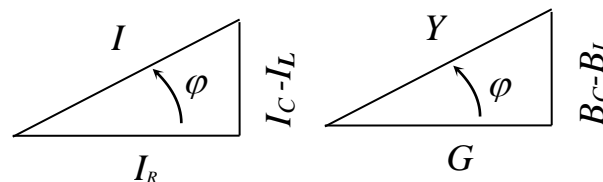


Fig. 4.3

$$Y = \sqrt{G^2 + (B_C - B_L)^2}, \quad \varphi = \arctg \varphi(B_C - B_L)/G,$$

$$G = Y \cos \varphi, \quad B = B_C - B_L = Y \sin \varphi$$

- these are conductance and susceptance of the circuit.

Current resonance takes place at the circuit with parallel connection of *L*, *C* elements (fig.4.4). $I_L = I_C$ at resonance mode, so the condition of voltage

resonance for real circuit is $B_L = B_C$, that means $\omega_0 L / (R^2 + (\omega_0 L)^2) = 1/(\omega_0 C)$.

For ideal circuit ($R=0$) the condition is $\omega_0 L = 1/(\omega_0 C)$.

Thus $\omega_0^2 LC = 1$, resonance frequency $\omega_0 = 1/\sqrt{LC}$.

The resonance can be reached by changing C , L or ω_0 .

At resonance mode $B = B_C - B_L = 0$, $Y = \sqrt{G^2 + B^2} = G$,

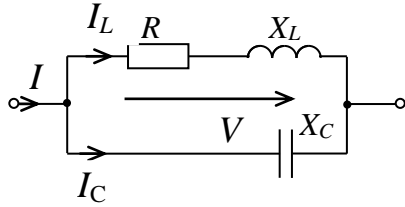


Fig.4.4

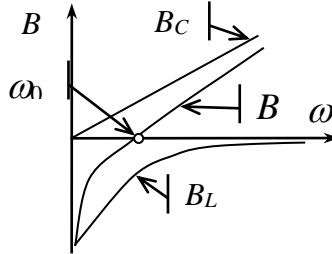


Fig.4.5

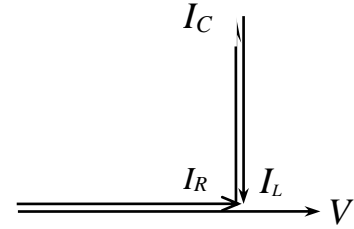


Fig.4.6

$$Q_L - Q_C = Q = 0, S = \sqrt{P^2 + Q^2} = P, \varphi = 0.$$

Total current $I = VY = VG$ is at minimum, what is the indication of the current resonance.

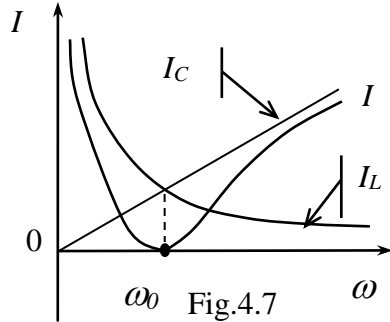


Fig.4.7

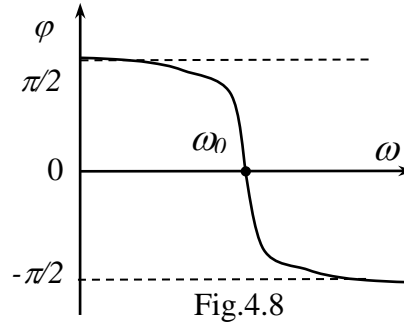


Fig.4.8

Frequency characteristics of the ideal ($R=0$) circuit $B_L(\omega) = 1/(\omega L)$, $B_C(\omega) = \omega C$, $B(\omega) = B_C(\omega) - B_L(\omega)$ are shown at fig.4.5. Susceptance has an inductive character when $\omega < \omega_0$, $B < 0$, $\varphi < 0$. Susceptance has a capacitive character, when $\omega > \omega_0$, $B > 0$, $\varphi > 0$.

Vector diagram for resonance mode is shown at fig.4.6. Resonance curves $I(\omega)$, $I_L(\omega) = B_L V$, $I_C(\omega) = B_C V$ and phase-frequency characteristic $\varphi(\omega)$ are shown at fig.4.7 and 4.8.

Voltage resonance on one hand should be avoided, because the current across the elements may several times exceed the nominal current, but on the other hand the resonance can be applied for rising power factor and as the working mode of some electronic devices.

Homework

Calculate the current in the unforked subcircuit, coil current I_L , capacitor current I_C , active and reactive powers, the conductivities of the elements and phase shift

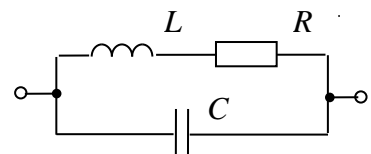


Fig. 4.9

angles in the circuit (fig. 4.9), at given voltage V , inductivity L , active resistance R , capacitances C . Tasks variants are listed in the table 4.1.

Table 4.1

Var	1	2	3	4	5	6	7	8	9	10
V, V	50	55	60	65	70	50	55	60	65	70
R, Ω	186	189	187	197	195	186	189	187	197	195
L, H	1.12	1.13	1.15	1.18	1.20	1.12	1.13	1.15	1.18	1.20
$C, \mu F$	3.99	3.77	3.83	3.82	3.79	4.17	4.15	4.12	4.17	4.11

Elements of laboratory settings

Laboratory settings consist of the power supply, clamps terminal, board (fig.4.10), measuring devices.

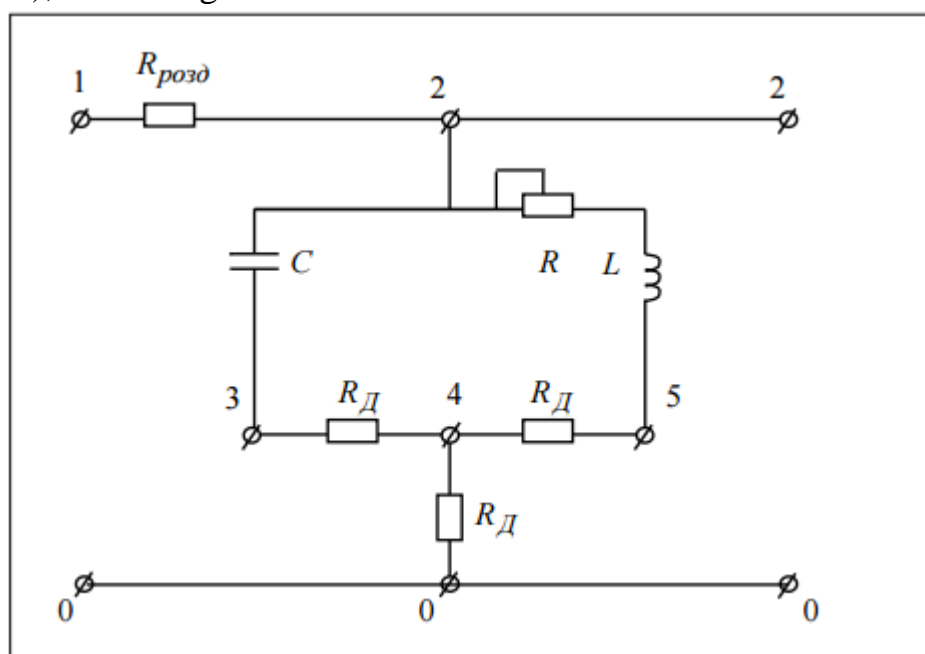


Fig.4.10

Alongside C and coil L the board has a variable resistance $R=0...1K\Omega$ connected serially to L and a calibrated resistances $R_D=1\Omega$. They are to define the currents in the corresponding branches, because $V_D = R_D I$. Resistance R_{PO3D} is for potentials distribution at the clamps of ГЗЧ (sin signal generator) and investigated circuit when the dependence between the circuit voltage and the frequency is investigated. The sin voltage has constant amplitude. Two channel oscilloscope is used to measure voltages and currents.

Use the scheme on fig. 4.11 to investigate the dependence between the currents I_C , I_L and the frequency.

Use the scheme on fig. 4.12 to investigate the dependence between the voltage and the current $I=I_C+I_L$ and the frequency.

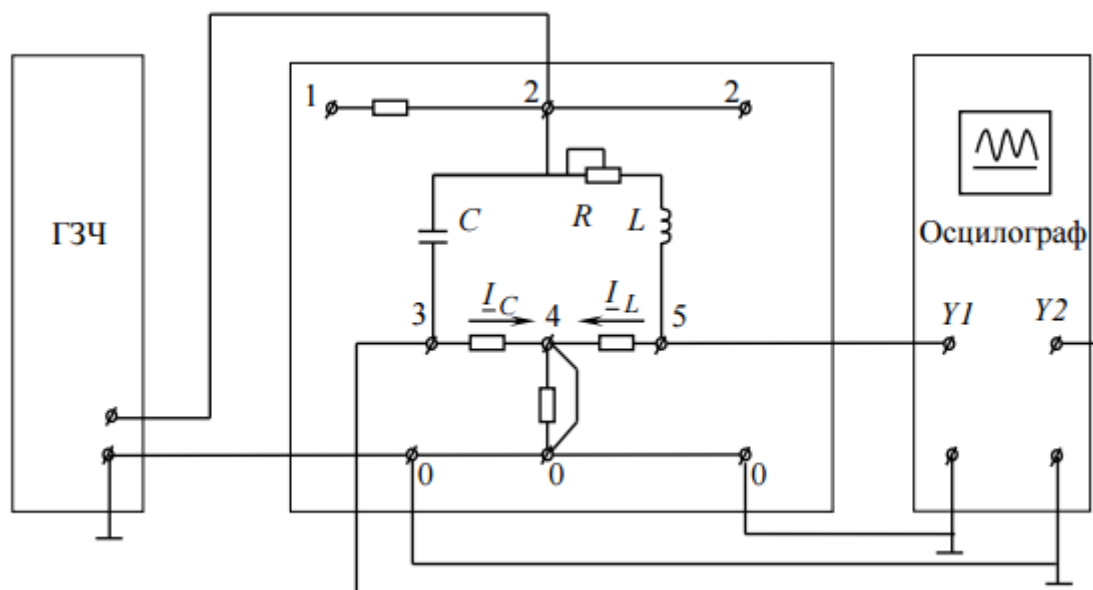


Fig. 4.11

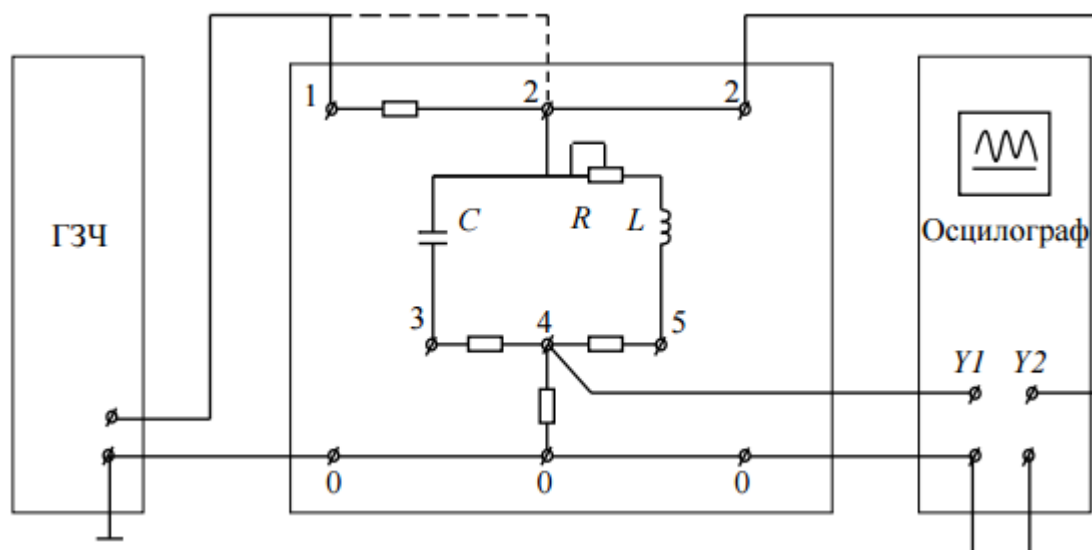


Fig. 4.12

Work execution order

1. Collect the circuit (fig. 4.10). Set the minimum value of resistance R . Switch on the generator and oscilloscope. Set the input circuit voltage within the range of 0-10 V. By changing the voltage frequency within the range of 20Hz-20KHz, define the resonance frequency ω_0 , taking into consideration that the currents in that case have equal magnitudes and opposite phases.

2. Investigate the dependence between the currents I_C , I_L and the frequency. In this case change the generator frequency 1.1: five times for $\omega < \omega_0$ and five times for $\omega > \omega_0$. Note down the results to the table 4.2.

3. Investigate the dependence between the total current I , voltage V and the frequency. In this case change the generator frequency 1.1: five times for $\omega < \omega_0$ and five times for $\omega > \omega_0$. Note down the results to the table 4.3.

Table 4.2

ω , Hz										
I_C, A										
I_L, A										

Draw the graphs $I_C(\omega)$, $I_L(\omega)$.

Table 4.3

ω , Hz										
I, A										
V, V										

Draw the graphs $I(\omega)$, $V(\omega)$.

4. Set the maximum value of resistance R . Investigate the dependence between the currents I_C , I_L and the frequency. In this case change the generator frequency 1.1: five times for $\omega < \omega_0$ and five times for $\omega > \omega_0$. Note down the results to the table 4.4.

Table 4.4

ω , Hz										
I_C, A										
I_L, A										

Draw the graphs $I_C(\omega)$, $I_L(\omega)$.

5. For the maximum value of the resistance R investigate the dependence between the total current I , voltage V and the frequency. In this case change the generator frequency 1.1: five times for $\omega < \omega_0$ and five times for $\omega > \omega_0$. Note down the results to the table 4.5.

Table 4.5

ω , Hz										
I, A										
V, V										

Draw the graphs $I(\omega)$, $V(\omega)$.

6. Draw the vector diagram of the currents using data from table 4.5.

7. Compare the graphs and make the conclusions.

Report on work

The name and purpose of the work. Homework – the calculation of the circuit. Schematic diagrams of the investigated circuit (fig. 4.10). Tables 4.2-4.5. The graphs and vector diagram. Conclusions.

Control questions

1. Write down the electrical status equation for the circuit with parallel

connection of *RLC*-elements in vector form and draw the vector diagram for this circuit.

2. Draw conductivities calculated triangle for the circuit with parallel connection of *RLC*-elements and write down the corresponding expressions for it.

3. Explain what is it the active and reactive current constituents.

4. Draw powers calculated triangle for the circuit with parallel connection of *RLC*-elements and write down the corresponding expressions for it.

5. Give the definition of current resonance, write down the resonance condition and explain the resonance indication.

6. Give the definition of voltage resonance frequency, circuit wave resistance and explain the ways of resonance reaching.

7. What is the admittance of the circuit, phase shift factor and full power of the current resonance circuit? How current resonance is applied?

8. Draw the current resonance circuit frequency and phase characteristics.

9. Draw the resonance curves of currents of the current resonance circuit. Explain why the current at resonance is at minimum.

LABORATORY WORK 5

Transformer

The purpose of the work is to investigate the work of the transformer, define the basic parameters (characteristics) of the transformer by experiments of open and short circuit.

Transformer is a static electromagnetic device that has two (or more) windings inductively connected to each other and is designed to convert primary

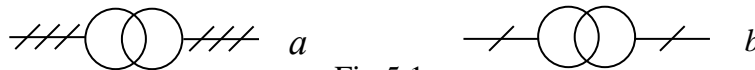


Fig.5.1

parameters AC into secondary ones. A three-phase transformer is shown on fig.5.1a and a single-phase transformer is shown on fig.5.1b. Transformers are used in automatic devices and electrically powered household appliances. There are as well special transformers for converting, welding, measuring and so-called peak transformers.

The transformer's core (fig. 5.2) determines its design. Laminated core is made of insulated electrical steel sheets. Core types like U-and-I (aka core-type) (a), E-and-I (aka shell-type) (b) or toroidal (c) are used in low-power transformers.

Transformer winding is made of insulated copper (aluminum) wire of round or rectangular cross-section. The winding is wound on the frame, which is slid on one of the rods. The principle of the transformer is based on the law of electromagnetic induction. Electromagnetic single-phase transformer circuit is shown on fig. 5.3, and it's schematic diagram on fig. 5.3b. The primary winding w_1 converts electrical energy into magnetic one, whereas the secondary winding w_2 converts the magnetic energy into the electrical one. Magnetic core strengthens the link between the windings. The current i_1 generates an alternating magnetic flux Φ_1 , which closes itself on the core and dissipation magnetic flux Φ_{1d} , which closes itself in the air around the primary winding w_1 . Magnetic flux Φ_1 induces an

electromotive force of self-induction in the transformer primary winding and a mutual electromotive force in the secondary winding. If the secondary winding is connected to the load, the current will flow. The current i_2 generates an alternating magnetic flux Φ_2 , which closes itself on the core and dissipation magnetic flux Φ_{2d} , which closes itself in the air around the secondary winding w_2 .

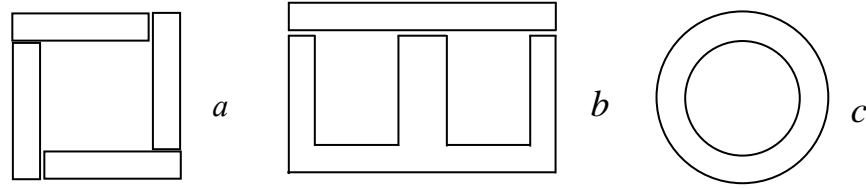


Fig.5.2

Transformer electromotive forces e_1 and e_2 create the resulting magnetic flux in the core.

$$\begin{aligned} e_1 &= -w_1 d\Phi / dt, & E_1 &= \omega w_1 \Phi_m / \sqrt{2}, \\ e_2 &= -w_2 d\Phi / dt, & E_2 &= \omega w_2 \Phi_m / \sqrt{2}, \end{aligned}$$

where $\omega / \sqrt{2} = 2\pi f / \sqrt{2} = 4.44 f$; f – is an AC frequency, Φ_m – is the resulting flux amplitude, w_1 – number of primary winding turns, w_2 – number of secondary winding turns. Induced electromotive force phase lags behind the magnetic flux phase by an angle of $\pi / 2$. The e.m.f. effective values are as follows:

$$E_1 = 4.44 w_1 f \Phi_m, \quad E_2 = 4.44 w_2 f \Phi_m.$$

If $w_1 > w_2$ the transformer is a down transformer and its transformation ratio is $k_{12} = w_1 / w_2 = E_1 / E_2 > 1$. If $w_1 < w_2$ the transformer is an up transformer and its

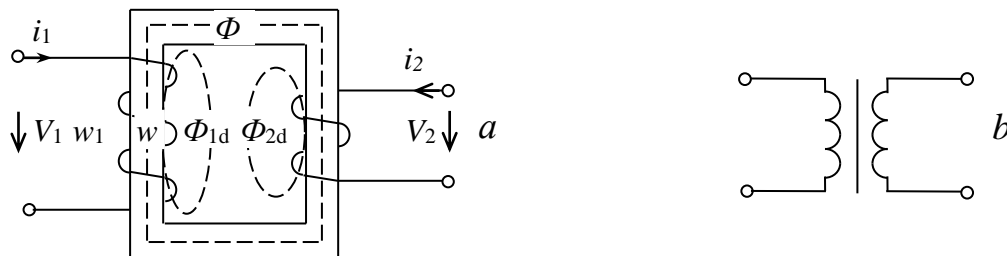


Fig.5.3

transformation ratio is $k_{21} = w_2 / w_1 = E_2 / E_1 > 1$ (i.e. higher than one).

Transformer electromagnetic substitutional scheme (fig.5.4) represents an idealized real transformer, which includes active R_1 R_2 (winding) resistances and (dissipation) reactances X_1, X_2 .

The transformer electrical state equations are (fig. 7.4):

$$\begin{cases} \underline{V}_1 = -\underline{E}_1 + (R_1 + jX_1)\underline{I}_1 = -\underline{E}_1 + \Delta\underline{V}_1 \\ \underline{V}_2 = \underline{E}_2 - (R_2 + jX_2)\underline{I}_2 = \underline{E}_2 - \Delta\underline{V}_2 \end{cases},$$

where $\Delta\underline{V}_1, \Delta\underline{V}_2$ – are accordingly voltage drops across the primary and secondary windings of the transformer. Since $\Delta\underline{V}_1 \approx (0.02 \div 0.05)V_1$, it can be considered $V_1 \approx E_1$. Thus, $V_1 \approx E_1 = 4.44 w_1 f_1 \Phi_m$. When $V_1 = \text{const}$, the magnetic flux is practically independent of the transformer load.

Electrical state equations corresponds to the scheme on fig. 5.5, where E_1 is a receiver of electrical energy (primary winding) and E_2 is an electric energy source (secondary winding).

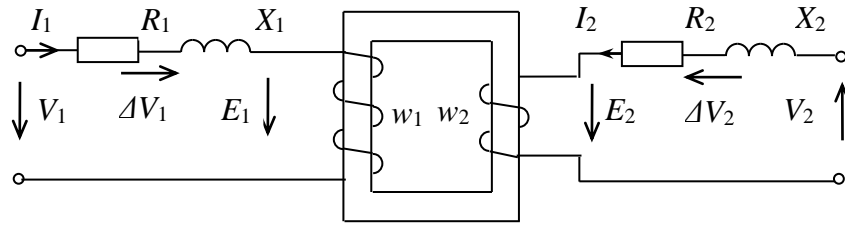


Fig. 5.4

The magnetomotive force of primary winding in idle mode is $w_1 I_{10} = Hl$. It induces the magnetic flux $\Phi = \mu SH$. And magnetic flux of loaded transformer is created by an e.m.f. of primary and secondary windings $w_1 I_1 + w_2 I_2 = Hl$. Taking into consideration that $\Phi \approx const$ and $H \approx const$, transformer magnetic state equation makes:

$$w_1 I_{10} = w_1 I_1 + w_2 I_2.$$

Therefore, the expression for current in the primary winding of the transformer makes:

$$\underline{I}_1 = \underline{I}_{10} - \underline{I}_2 w_2 / w_1 = \underline{I}_1 = \underline{I}_{10} + \underline{I}_2',$$

where $\underline{I}_2' = -\underline{I}_2 w_2 / w_1 = -\underline{I}_2 / k$ is a specific secondary winding current.

Since numbers of turns $w_1 \neq w_2$, then $E_1 \neq E_2$. To simplify the analysis of the transformer, the secondary winding number of turns is reduced to the number

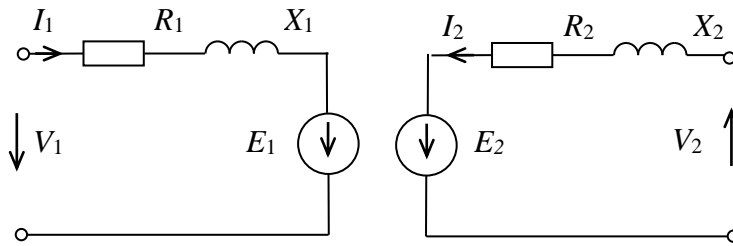


Fig. 5.5

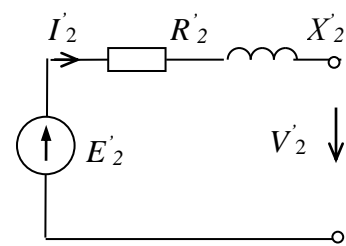


Fig. 5.6

of turns in the primary winding.

The real secondary winding w_2 is replaced by brought-in values $w_2' = w_1$, $w_2' = kw_2 = w_1$. Specific electromotive force makes then $E_2' = kE_2 = E_1$ and specific voltage makes $V_2' = kV_2 = V_1$ accordingly. Specific resistance is defined from the condition $I_2'^2 R_2' = R_2 I_2^2$ as $R_2' = k^2 R_2$ and specific reactance is defined from the condition $\varphi = \arctg(X_2' / R_2') = \arctg(X_2 / R_2)$ as $X_2' = k^2 X_2$. The brought-in

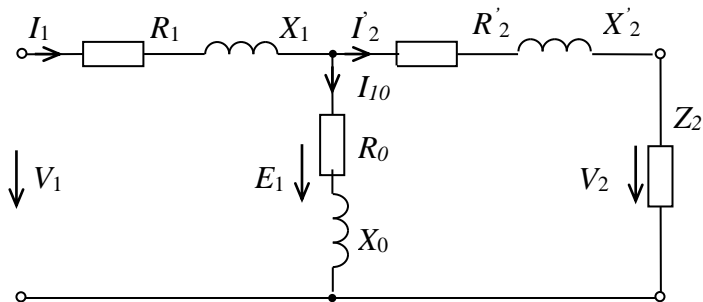


Fig. 5.7

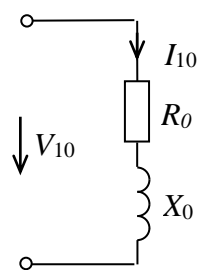


Fig. 5.8

secondary winding elements is applied in fig. 5.6.

T-shaped substitutional scheme is shown on fig. 5.7, where $\underline{E}_1 = R_0 \underline{I}_{10} + jX_0 \underline{I}_{10}$. The scheme elements bear some physical meaning, as such R_0 - are magnetic losses ΔP_M and X_0 - is the main magnetic flux.

Idle mode scheme ($I'_2 = 0$) shown on fig.5.8 is obtained from the scheme 5.7 by neglecting resistances R_1 and X_1 , that are considerably less than R_0 and X_0 . The quality of core steel defines the idle current. Resistance R_0 and impedance $Z_0 = U_{10} / I_{10}$ determine the idle losses: $P_0 = R_0 I_{10}^2$. The transformation ratio makes: $k = w_1 / w_2 = E_1 / E_2 \approx V_{10} / V_{20}$.

The following expressions determines magnetic induction and magnetic flux: $V_{10} \cong E_1 = 4.44 w_1 f_1 \Phi_m$, $\Phi_m = B_m S$.

Transformer magnetic losses are constant and independent from load. Any power consumption in idle mode goes over into transformer magnetic core losses ΔP_M and electrical losses in the primary winding ΔP_{1E} : $P_0 = \Delta P_M + \Delta P_{1E}$. Electrical losses in the transformer primary winding are $\Delta P_{1E} = R_1 I_{10}^2$. They can be neglected because idle state current is smaller than the nominal $I_{1N} \gg I_{10}$ ($I_{10} = (0.04 \div 0.1) I_{1N}$). Thus, $\Delta P_{1E} \ll \Delta P_M$. Consequently, the power consumed by the transformer in the idle mode is almost equal to the magnetic losses $P_0 \approx \Delta P_M$.

The short circuit transformer mode is a wrecking one at nominal voltage

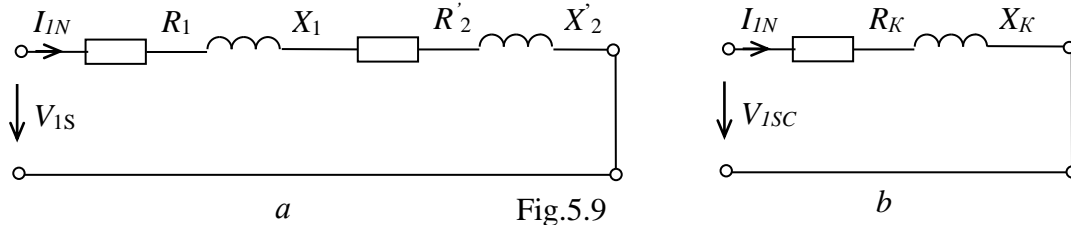


Fig.5.9

V_{1N} , since current makes then $I_{1SC} \approx (10 \div 25) I_{1N}$. Therefore, short circuit mode calculations are done out at nominal current $I_{1SC} = I_{1N}$ and considerably less voltage.

Short circuit transformer mode scheme ($V'_2 = 0$) is shown on fig.5.9. It is obtained from the circuit on fig.5.7 by neglecting R_0, X_0 , which are much less than R'_2, X'_2 and R_1, X_1 . The following elements are used in resulting short circuit scheme (fig.5.9b): $R_1 + R'_2 = R_{SC}$, a $X_1 + X'_2 = X_{SC}$. Voltage, current, R_{SC} and impedance $Z_{SC} = V_{1SC} / I_{1N}$ can be defined, when having short circuit losses $P_{SC} = R_{SC} I_{1N}^2$.

The consumed by transformer power goes over into electrical losses in the windings and magnetic losses in the core. However, short circuit voltage is much less than the nominal $V_{1SC} = (0.05 \div 0.1) V_{1N}$, so the magnetic flux is also much less than at nominal mode. Magnetic losses are proportional to the square of the magnetic induction and

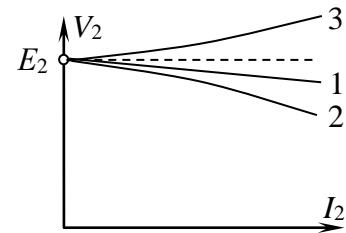


Fig. 5.10

are insignificant. Allowing that $\Delta P_M \ll \Delta P_E$, the consumed by transformer power in the short circuit mode goes over into electrical losses in the windings $P_{SC} \approx \Delta P_E$. These are variable and depend on transformer's load.

External characteristics of the transformer (fig.5.10) is a depending of the voltage from the current at variable load. Active load (curve 1) is at $\cos \varphi_2 < 1$

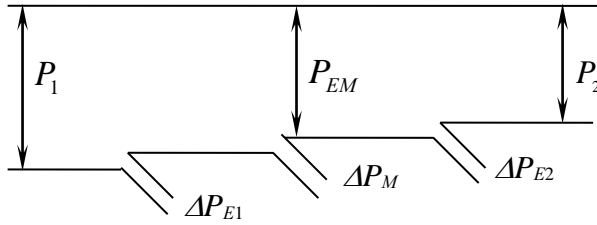


Fig. 5.11

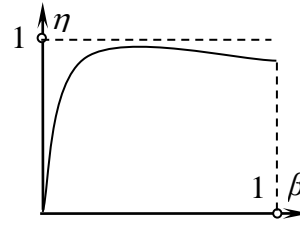


Fig. 5.12

($\varphi_2 > 0$). The active-inductive load (curve 2) is at $\cos \varphi_2 < 1$ ($\varphi_2 > 0$). And active-capacitive load (curve 3) is at $\cos \varphi_2 < 1$ ($\varphi_2 < 0$).

Transformer power diagram is shown on fig.5.11, where input power makes $P_1 = V_1 I_1 \cos \varphi_1$, ΔP_{E1} are electrical losses in the primary winding; $P_{EM} = EI \cos \psi$ - is an electromagnetic power; ΔP_M are magnetic losses in the core; ΔP_{E2} are electrical losses in the secondary winding and $P_2 = V_2 I_2 \cos \varphi_2$ is an output power.

Transformer total power makes $S_1 = S_2 = V_1 I_1 = V_2 I_2$, so $V_1 / V_2 = I_2 / I_1 \approx k$.

The transformer efficiency factor makes:

$$\eta = \frac{P_2}{P_1} = \frac{P_2}{P_2 + \Delta P} = \frac{\beta S_2 \cos \varphi_2}{\beta S_2 \cos \varphi_2 + P_0 + \beta^2 P_{SC}},$$

where $\Delta P = P_0 + \beta^2 P_{SC}$ are the total losses; P_0 are magnetic losses (idle); P_{SC} are short circuit electrical losses; $\Delta P_E = \beta^2 P_{SC}$ are electrical losses, $\beta = I_2 / I_{2N}$ is the transformer load factor.

The dependence of the efficiency factor from the transformer load $\eta(\beta)$ is shown on fig. 5.12. Maximum efficiency factor is at equal electric and magnetic losses, that corresponds to the optimum load. $\eta = (70 \div 95)\%$ is typical for modern transformers.

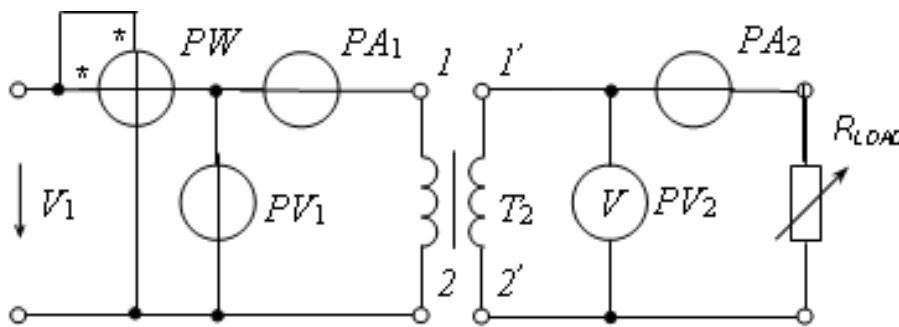


Fig. 5.13.

Homework.

To calculate transformation ratio k , primary and secondary windings currents I_1 , I_2 , primary and secondary windings powers P_1 , P_2 , transformer losses ΔP at given total power S , primary and secondary windings voltages V_1 , V_2 , power factor $\cos \varphi_1$, efficiency factor η , load impedance \underline{Z} . Tasks variants are listed in the table 5.1.

Table. 5.1

Var	1	2	3	4	5	6	7	8	9	10
S, VA	800	850	830	880	900	920	950	980	930	780
V_1, V	220	220	220	220	220	380	380	380	126	126
V_2, V	20	22	11	110	55	20	10	5	42	2
$\cos \varphi_1$	0.7	0.75	0.8	0.73	0.82	0.72	0.71	0.81	0.85	0.83
η	0.9	0.8	0.85	0.95	0.83	0.87	0.93	0.78	0.75	0.78
\underline{Z}, Ω	4+j3	2+j2	5+j8	4-j3	2-j2	5-j8	3+j5	3-j5	6+j9	5-j8

Elements of laboratory settings

Laboratory settings consist of the power supply (220 V, 50 Hz), regulated voltage source (0...36 V, 50 Hz), transformer ($V_{Inom}=220V$, $S_N=0.25kVA$, $f=50$ Hz) measuring devices, resistances, inductances, capacitors.

Work execution order

1. Write down the transformer passport data, define I_{Inom} ($S_{nom} = V_{Inom} I_{Inom}$); Measure the value of R_l (for DC).
2. Collect the electrical circuit (fig. 5.13). Investigate the transformer at open circuit mode (clamps 2-2' open) with a nominal input voltage $V_{Inom}=220V$. Fill in the table 5.2 with results.

Table 5.2

<i>Regimes</i>	<i>Measuring</i>				
	V_1 V	I_1 A	P_1 W	V_2 V	I_2 A
<i>Open circuit</i>					
<i>Nominal</i>					
<i>Short circuit</i>					

3. Collect the electrical circuit (fig. 5.14). Investigate the transformer at short circuit mode with a nominal input current I_{Inom} . Vary the current by changing input voltage. Fill in the table 5.2 with results.
4. Collect the electrical circuit (fig. 5.15). Investigate the transformer at nominal mode with a nominal input voltage $V_{Inom} = 220V$ and a nominal input current I_{Inom} for given load $Z = R + jX$. Fill in the table 5.2 with results.

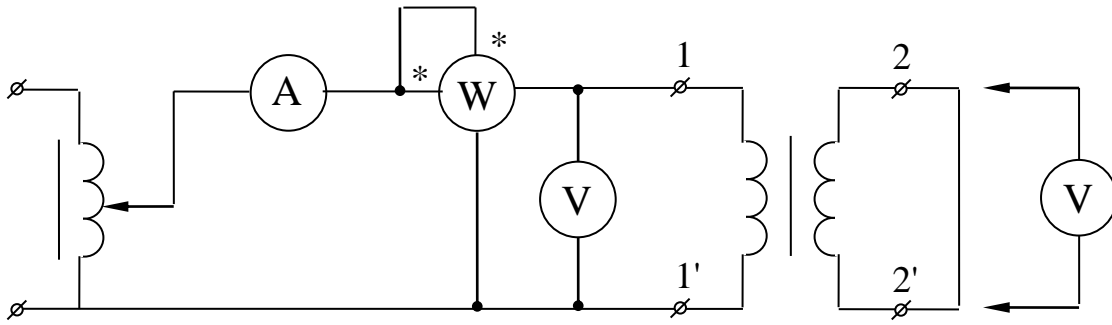


Fig. 5.14

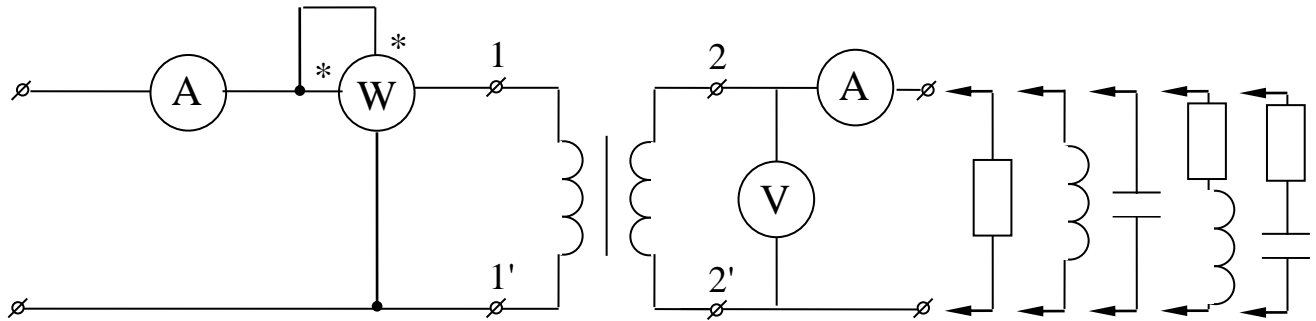


Fig. 5.15

5. Define the transformer parameters from the table 5.2.

$K = V_{1OC} / V_{1nom}$ – transformation ratio;

$\eta_{nom} = P_{2nom} / P_{1nom}$ – efficiency factor;

P_{oc} – open circuit power (magnetic losses); P_{sc} – short circuit power (electrical losses);

$P_{2nom} = V_{2nom} I_{2nom} \cos \varphi_{2nom}$, $\cos \varphi_{2nom} = R / \sqrt{R^2 + X^2}$ – output nominal power;

$\cos \varphi_{1nom} = P_{1nom} / (V_{1nom} I_{1nom})$ – power factor;

$I_{OC}(\%) = (I_{1OC} / I_{1nom}) \cdot 100\%$ – open circuit current;

$V_{SC}(\%) = (V_{1SC} / V_{1nom}) \cdot 100\%$ – short circuit voltage.

6. Define the parameters of transformer T substitutional scheme.

– R_M, X_M from open circuit mode by the following calculations:

$$Z_M = V_{1N} / I_{OC}, P_{OC} = R_M I_{OC}^2, Z_M = \sqrt{R_M^2 + X_M^2}.$$

– R_{SC}, X_{SC} from short circuit mode by the following calculations:

$$Z_{SC} = V_{SC} / I_{1N}, P_{SC} = R_{SC} I_{1N}^2, Z_{SC} = \sqrt{R_{SC}^2 + X_{SC}^2}.$$

– resistances and reactances of the wires by the following calculations:

$$R_1 = R_{SC} / 2, X_1 = X_{SC} / 2, R_2' = R_{SC} / 2, R_2 = R_2' / K^2, X_2' = X_{SC} / 2, X_2 = X_2' / K^2.$$

Compare R_1 calculated and measured.

7. Draw the transformer vector diagram.

8. Make conclusions of the work.

Report on work

The name and purpose of the work. The schematic diagrams of the investigated

circuits (fig 5.13, 5.14, 5.15). The table 5.2. Calculations. Conclusions.

Control questions

1. Draw a conventional graphical representation of transformers and specify their classification.
2. Explain the principle of the transformer and draw its electromagnetic scheme. Explain the role and purpose of the scheme elements.
3. Write the transformer electrical state equation and draw the transformer substitutional scheme.
4. Write the transformer magnetical state equation and write the primary winding current expression.
5. Explain how the transformation ratio is defined.
6. Draw a T-shaped transformer substitutional scheme and explain the physical meaning of its elements.
7. How the parameters of T-shaped transformer substitutional scheme can be defined experimentally?
8. Draw the transformer substitutional scheme for open circuit experiment and explain how the parameters of this scheme are determined.
9. Draw the transformer substitutional scheme for short circuit experiment and explain how the parameters of this scheme are determined.
10. Explain what the specific transformer parameters are.
11. Draw a graph - a dependence of the transformer external characteristics from loading. Why does the voltage increase with the active-capacitive loading?
12. Draw the transformer power diagram and explain its losses.
13. Write down the transformer expressions for power (input, output, losses).
14. Write down the expression for transformer efficiency factor. What is the load factor?
15. Draw and explain the dependence between efficiency factor and transformer loading.

LABORATORY WORK 6

Investigation of „WYE” connection of three-phase circuit

The purpose of the work is to investigate „wye” connection of three phases circuit with balanced and non-balanced loading, to investigate the role of the neutral.

Three-phase electro-motive-force circuit system is the set of three sinusoidal e.m.f. with the same frequency ω and out of phase with each other by $2\pi/3$ (120°). Phase is the part of the circuit with the same current. The amplitudes of e.m.f. are marked accordingly: E_{Am} , E_{Bm} , E_{Cm} , if they are equal, such system is called *balanced*.

The instantaneous values of e.m.f. (fig. 6.1) are:

$$e_A = E_{Am} \sin \omega t, \quad e_B = E_{Bm} \sin(\omega t - 120^\circ), \\ e_C = E_{Cm} \sin(\omega t + 120^\circ).$$

Phase sequence is the time order in which the e.m.f. pass through their respective maximum values (or through zero value).

Phase sequence *ABC* is called positive (fig. 6.1), the reverse phase sequence *ACB* is called negative.

The following requirements are met for three-phase balanced electro-motive force system: $E_A = E_B = E_C = E_{ph}$.

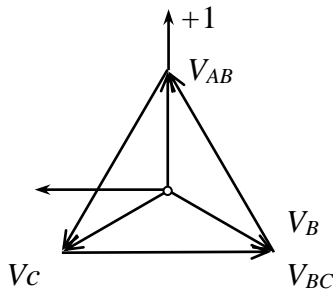


Fig. 6.2

The following expressions are true having disregarded losses at power sources: $E_A = V_A$,

$$E_B = V_B, \quad E_C = V_C,$$

where V_A , V_B , V_C – are *source phase voltages* (between the lines and neutral point N (fig. 6.3)). These voltages in complex form are presented as:

$$\underline{V}_A = V_A e^{j0}, \quad \underline{V}_B = V_B e^{-j120^\circ}, \quad \underline{V}_C = V_C e^{j120^\circ}.$$

Linear voltages (between lines, which connect the sources and the consumers) (fig.6.4) in complex form are:

$$\underline{V}_{AB} = \underline{V}_A - \underline{V}_B = V_{AB} e^{j30^\circ}, \quad \underline{V}_{BC} = \underline{V}_B - \underline{V}_C = V_{BC} e^{-j90^\circ}$$

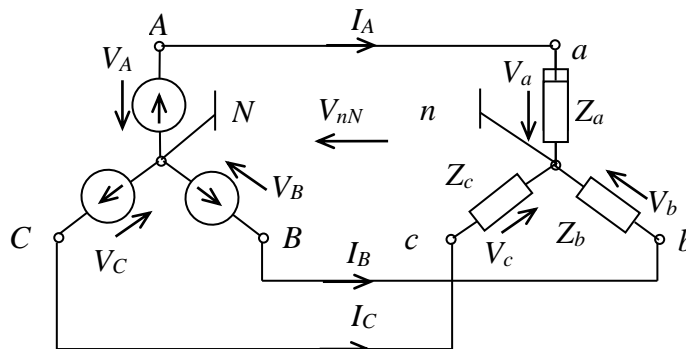


Fig. 6.3

$$\underline{V}_{CA} = \underline{V}_C - \underline{V}_A = V_{CA} e^{j150^\circ}.$$

Linear voltage is equal to the difference between corresponding phase voltages and lead the phase of the first one for 30° (fig. 6.2). Vector diagram (fig. 6.2) illustrates relationship between phase and linear voltages.

Three-phase circuit consists of three-phase electro-motive force system, three-phase loads and connection wires.

The most common types of connection the three-phase sources and consumers are WYE (Y) (fig. 6.3) and DELTA (Δ).

At WYE connection the ends of source phases windings (fig. 6.3) are connected in common neutral point N , and the beginnings of phases A, B, C are connected to the linear wires. The ends of consumer phase windings (fig. 6.3) are connected in common neutral point n , and the beginnings of phases a, b, c are connected to the linear wires.

The consumer phase voltages are called the voltages between phase and neutral point V_A, V_B, V_C , for consumer V_a, V_b, V_c . The source linear voltages are called the voltages between phase points (fig. 6.4) V_{AB}, V_{BC}, V_{CA} , for consumer V_{ab}, V_{bc}, V_{ca} . The directions of these voltages are shown at fig. 6.4. The effective values of phase and linear voltages are related according to the expression $V_L = \sqrt{3} V_{ph}$.

For WYE connection (fig. 6.4) *phase currents* (flowing through the phase)

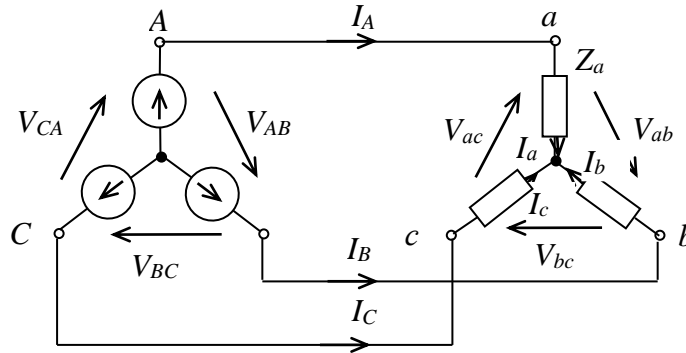


Fig. 6.4

I_{ph} (I_a, I_b, I_c) (fig. 6.4), are equal to the *linear currents* (flowing through the lines connecting the source and the consumer) I_L (I_A, I_B, I_C), $I_{ph} = I_L$. The directions of these currents are shown at fig. 6.4. Balanced load is one in which the phase impedances are equal in magnitude and in phase:

$$\underline{Z}_a = \underline{Z}_b = \underline{Z}_c = \underline{Z}_{ph}.$$

In this case:

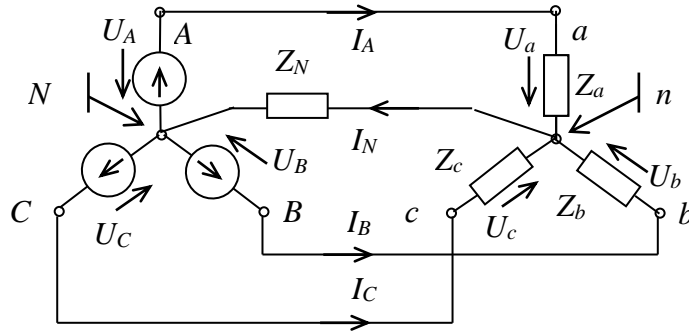


Fig. 6.5

$$V_a = V_A, \quad V_b = V_B, \quad V_c = V_C.$$

$$\underline{I}_A = \underline{V}_a / \underline{Z}_a, \quad \underline{I}_B = \underline{V}_b / \underline{Z}_b, \quad \underline{I}_C = \underline{V}_c / \underline{Z}_c.$$

The effective values of the currents are also equal: $I_A = I_B = I_C = I_{ph} = I_L$.

If the load is unbalanced ($\underline{Z}_a \neq \underline{Z}_b \neq \underline{Z}_c$) the voltage between the neutral points of source and consumer appears – \underline{V}_{nN} (fig. 6.3). This voltage is called the *bias neutral* and can be calculated by using the method of two nodes:

$$\underline{V}_{nN} = \frac{\underline{V}_A \underline{Y}_a + \underline{V}_B \underline{Y}_b + \underline{V}_C \underline{Y}_c}{\underline{Y}_a + \underline{Y}_b + \underline{Y}_c},$$

where $\underline{Y}_a = 1/\underline{Z}_a = I_a/V_a$, $\underline{Y}_b = 1/\underline{Z}_b = I_b/V_b$, $\underline{Y}_c = 1/\underline{Z}_c = I_c/V_c$.

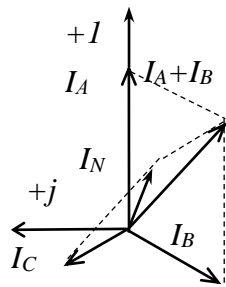


Fig. 6.6

In that case the consumer phase voltages are calculated according to the following expressions:

$$\underline{V}_a = \underline{V}_A - \underline{V}_{nN}, \quad \underline{V}_b = \underline{V}_B - \underline{V}_{nN}, \quad \underline{V}_c = \underline{V}_C - \underline{V}_{nN},$$

Phase currents complexes are:

$$\underline{I}_a = \underline{V}_a / \underline{Z}_a, \quad \underline{I}_b = \underline{V}_b / \underline{Z}_b, \quad \underline{I}_c = \underline{V}_c / \underline{Z}_c.$$

There is also a *neutral wire* at three-phase four-wires circuits, which connects neutral points of source N and consumer n (fig. 6.5). In this case $\underline{V}_{nN} = 0$.

The following is true according to the Kirchhoff's first law for node n :

$$\underline{I}_A + \underline{I}_B + \underline{I}_C = \underline{I}_N.$$

When the load is balanced ($\underline{Z}_a = \underline{Z}_b = \underline{Z}_c$):

$$\underline{I}_A + \underline{I}_B + \underline{I}_C = 0, \quad I_N = 0, \quad \underline{V}_{nN} = 0.$$

The vector diagram of currents for unbalanced load is shown in fig.6.6.

Homework

Write down the phase voltages in complex form for the three-phase power source with linear voltage $V_L = 220 \text{ V}$. To calculate phase active resistances, phase complex currents, neutral complex current for the three-phase consumer (fig.6.7), at given phase powers. Tasks variants are listed in the table 6.1.

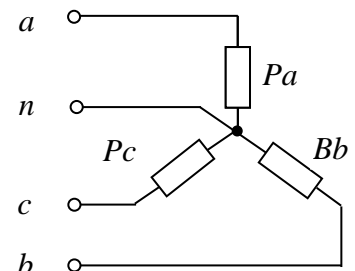


Fig. 6.7

Table. 6.1

<i>Var</i>	1	2	3	4	5	6	7	8	9	10
P_a, W	20	40	60	80	100	20	40	60	80	100
P_b, W	40	60	80	100	20	40	60	80	100	20
P_c, W	60	80	100	20	40	60	80	100	20	40

Elements of laboratory settings

Laboratory set consists of a power supply, a phasemeter, an ammeters and a multimeter.

The investigated circuit has a multimeter on the panel (fig.6.8). Several options of the investigated circuit can be set:

- with an active balanced load $R_A = R_B = R_C$ ($S1$ and $S2$ are closed);
- with an active non-balanced load $R_A \neq R_B \neq R_C$ ($S1$ and $S2$ are open);
- with a non-balanced load (phase A active load R_L , phase B inductive load L , phase C capacitive load C).

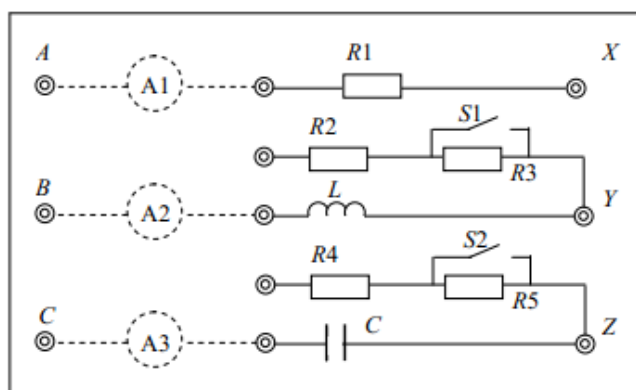


Fig. 6.8

Work execution order

1. Check the balance of a three-phase e.m.f. system. Measure phase and linear voltages (with a voltmeter) and their initial phases with a phasemeter for this purpose. Note the results into the table 6.2. Draw the vector diagram of phase and linear voltages using the data from table 6.2.

Table 6.2

<i>phase voltages</i>	V_A, V	V_B, V	V_C, V	φ_A	φ_B	φ_C
				0°		
<i>linear voltages</i>	V_{AB}, V	V_{BC}, V	V_{CA}, V	φ_{AB}	φ_{BC}	φ_{CA}

2. Measure phase currents, voltages and voltages initial phases for WYE connection without neutral wire for active balanced load ($Z_a = Z_b = Z_c = R = 200 \Omega$, $S1$ and $S2$ are closed). Measure bias voltage V_{nN} . Note the results into the table 6.3 (column № 2).

3. Measure phase currents, voltages and voltages initial phases for WYE connection with neutral wire for active balanced load ($Z_a = Z_b = Z_c = R = 200 \Omega$, $S1$ and $S2$ are closed). Measure neutral current I_N . Note the results into the table 6.3 (column № 3).

4. Measure phase currents, voltages and voltages initial phases for WYE connection without neutral wire for non-balanced load (phase A active load R_L , phase B inductive load L , phase C capacitive load C). Measure bias voltage V_{nN} . Note the results into the table 6.3 (column № 4).

5. Measure phase currents, voltages and voltages initial phases for WYE connection with neutral wire for active non-balanced load ($R_A \neq R_B \neq R_C$, $S1$ and $S2$ are open). Measure neutral current I_N . Note the results into the table 6.3 (column № 5).

6. Measure phase currents, voltages and voltages initial phases for WYE connection without neutral wire for active non-balanced load (phase A active load R_L , phase B inductive load L , phase C capacitive load C). Measure bias voltage V_{nN} . Note the results into the table 6.3 (column № 6).

7. Measure phase currents, voltages and voltages initial phases for WYE connection with neutral wire for non-balanced load (phase A active load R_L , phase B inductive load L , phase C capacitive load C). Measure neutral current I_N . Note the results into the table 6.3 (column № 7).

8. Measure phase currents, voltages and voltages initial phases for WYE connection without neutral wire and open linear wire for non-balanced load (phase A active load R_L , phase B inductive load L , phase C capacitive load C). Measure bias voltage V_{nN} . Note the results into the table 6.3 (column № 8).

9. Measure phase currents, voltages and voltages initial phases for WYE connection with neutral wire and open linear wire for non-balanced load (phase A active load R_L , phase B inductive load L , phase C capacitive load C). Measure neutral current I_N . Note the results into the table 6.3 (column № 8).

10. Draw the vector diagrams of currents and voltages using the data from table 6.3 for every experiment. Make the conclusions.

Table 6.3

<i>Experiment number</i>	<i>№2</i>	<i>№3</i>	<i>№4</i>	<i>№5</i>	<i>№6</i>	<i>№7</i>	<i>№8</i>	<i>№9</i>
<i>Measuring value</i>								
Z_a								
Z_b								
Z_c								
V_a								
V_b								
V_c								
φ_a								
φ_b								
φ_c								
I_a								
I_b								
I_c								
I_N								
V_{nN}								

Report on work

The name and purpose of work. Homework – the calculation of the circuit. Schematic diagram of the investigated circuit (fig. 6.8). Tables 6.2, 6.3. The vector diagrams. Conclusions.

Control questions

1. Give the definition of three-phase electromotive force system. Explain how we can receive it. When the system will be balanced? Draw the vector diagram of three-phases electromotive forces.
2. Explain what is called the order of phase changing and how we can change it. What load we call balanced and write down the condition of balanced load.
3. Write down the expressions of instantaneous phases electromotive forces and their effective value complexes.
4. Explain the main types of source and consumer connection in three-phase system.
5. Write down the expressions of active, reactive and total power of three-phase system using phase voltages and currents and line voltages and currents.
6. Write down the expressions of active, reactive and total power of three-phase system using line voltages and currents.
7. Draw the three-phase source „wye” connection and mark the phases and line voltages and currents.
8. Write down the relationships between effective values of phase and line voltages and currents for „wye” connection.
9. Explain the neutral role in three-phase system. How can the current be defined in it?
10. Write down how we can define the complex line voltages for the known complex phase voltages for the consumers’ „wye” connection.
11. Explain what voltage is called neutral bias voltage and how we can define it.
12. Draw the phase and line voltages for the consumers „wye” connection at vector diagram. What is the phase shift angle for them?
13. Explain how the three-phase circuit with non-balanced „wye” connected load can be calculated.

Attachment

№	<i>Greek letters</i>		
1	<i>A</i>	α	<i>alfa</i>
2	<i>B</i>	β	<i>beta</i>
3	<i>Γ</i>	γ	<i>gamma</i>
4	<i>Δ</i>	δ	<i>delta</i>
5	<i>E</i>	ε	<i>epsilon</i>
6	<i>Z</i>	ζ	<i>dzeta</i>
7	<i>H</i>	η	<i>eta</i>
8	<i>Θ</i>	$\theta,$	<i>teta</i>
9	<i>I</i>	ι	<i>jota</i>
10	<i>K</i>	κ	<i>kapa</i>
11	<i>Λ</i>	λ	<i>lambda</i>
12	<i>M</i>	μ	<i>miu</i>
13	<i>N</i>	ν	<i>niu</i>
14	<i>Ξ</i>	ξ	<i>ksi</i>
15	<i>O</i>	o	<i>micron</i>
16	<i>Π</i>	π	<i>pi</i>
17	<i>P</i>	ρ	<i>ro</i>
18	<i>Σ</i>	σ, ς	<i>sigma</i>
19	<i>T</i>	τ	<i>tau</i>
20	<i>Y</i>	υ	<i>ipsilon</i>
21	<i>Φ</i>	φ	<i>fi</i>
22	<i>X</i>	χ	<i>hi</i>
23	<i>Ψ</i>	ψ	<i>psi</i>
24	<i>Ω</i>	ω	<i>omega</i>

Physical values designation and units

<i>Value</i>	<i>Designation</i>	<i>Dimension</i>
Resistance	R, Ω	<i>Ohm</i>
Reactance	X, Ω	<i>Ohm</i>
Impedance	Z, Ω	<i>Ohm</i>
Conductance	G, Sm	<i>Simens</i>
Susceptance	B, Sm	<i>Simens</i>
Admittance	Y, Sm	<i>Simens</i>
Capacity	C, F	<i>Farada</i>
Inductance	L, H	<i>Henry</i>
Inductance mutual	M, H	<i>Henry</i>
Electromotive force	E, V	<i>Volt</i>
Potential	φ, V	<i>Volt</i>
Voltage	V, V	<i>Volt</i>
Current	I, A	<i>Amper</i>
Active power	P, W	<i>Watt</i>
Reactive power	Q, VAR	<i>Volt-Amper reactive</i>
Total power	S, VA	<i>Volt-Amper</i>
Magnetomotive force	F, A	<i>Amper</i>
Magnetic induction	B, T	<i>Tesla</i>
Magnetic field tension	$H, A/m$	<i>Amper per meter</i>
Magnetic stream	Φ, Wb	<i>Weber</i>
Linkage	ψ, Wb	<i>Weber</i>
Magnetic permeability (absolute)	$\mu_a, \Gamma_{H/M}$	<i>Henry per meter</i>
Magnetic permeability (relative)	μ	
Magnetic constant	$\mu_0, \Gamma_{H/M}$	$4\pi \cdot 10^7$
Frequency	f, Hz	<i>Herz</i>
Angular frequency	$\omega, rad/s$	<i>radian per second</i>
Length	l, m	<i>meter</i>
Hight, depth	h, m	<i>meter</i>
Layer	δ, d, m	<i>meter</i>
Arial	S, m^2	<i>square meter</i>
Magnetic resistance	R_m	
Number of turns	w	
Force	F, N	<i>Newton</i>
Work (energy)	W, J	<i>Joule</i>
Charge	Q, C	<i>Coulomb</i>

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Навчально-методична література

Куземко Н. А., Котик М. І.

Theoretical Fundamentals of Electrical Engineering

LABORATORY WORKS

Part 1

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