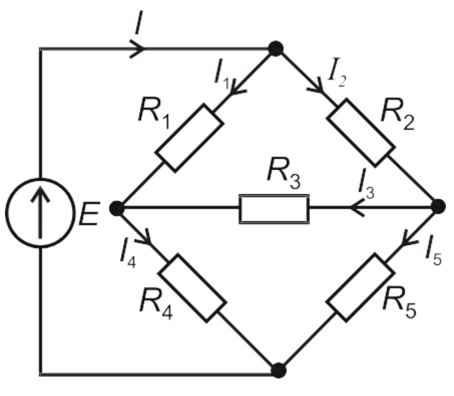
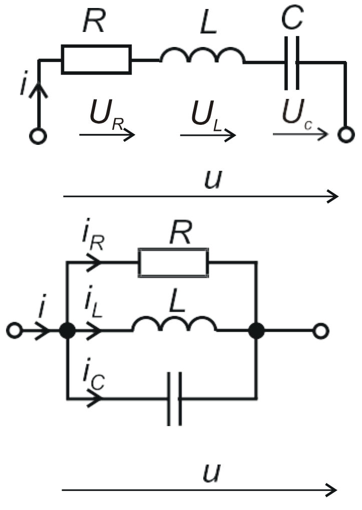
EDUCATION AND SCIENCE MINISTRY OF UKRAINE

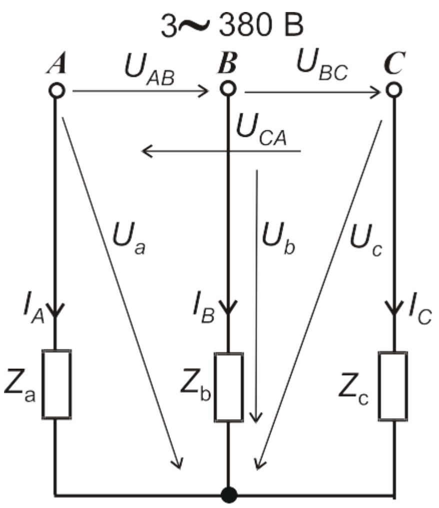
NATIONAL TECHNICAL UNIVERSITY
«KHARKIV POLYTECHNIC INSTITUTE»

E L E C T R I C C I R C U I T S

LABORATORY WORKS
ON ELECTRICAL ENGINEERING







Kharkiv 2022

EDUCATION AND SCIENCE MINISTRY OF UKRAINE

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ELECTRIC CIRCUITS

LABORATORY WORKS
ON ELECTRICAL ENGINEERING
In three parts
Part I

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Electric circuits: meth. instructions for laboratory works on electrical engineering. In three parts. P. I/ V. F. Boliukh, E. V. Honcharov, K. V. Korytchenko and others., – Kharkiv, NTU“KhPI”, 2022. – 46 p.

ISBN

The course of five laboratory works in the section "Electrical Circuits" of the discipline "Electrical Engineering, Electronics and Microprocessor Engineering" and others taught by the Department of Applied Electrical Engineering in NTU "KhPI" for full-time and part-time students of non-electrical specialties in the form of complex independent work has been given. Theoretical material, methods of calculation of electric circuits and principles of drawing of phasor diagrams are also presented.

It has been designed for an independent work of students in the preparation and implementation of laboratory, calculation and graphic work, preparation for tests and exams.

Figures 21. Tables 19. Bibliography :12 titles.

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INTRODUCTION

Proposed handbook is an integral part of the learning process and is intended for full-time students.

This handbook provides for the consistent study related to the research and calculation of electrical circuits and for laboratory work on electrical and electronic devices.

The guidelines provide safety rules for laboratory work, the order of their execution, the design and content of the report, and element symbols on the circuits of electrical and electronic devices.

The purpose of laboratory studies is to gain theoretical knowledge and acquire practical skills in electrical circuit design, measuring currents, voltage, powers, rotation speed of electric machines, as well as working out practical skills of experimental study on parameters and characteristics of various semiconductor devices and construction of semiconductor electronics devices on its basis.

Calculations of electric circuits, calculations of parameters, draw of characteristics of electrical and electronic devices and the analysis of study results are carried out on the basis of these studies.

DESCRIPTION OF THE UNIVERSAL LABORATORY BENCH FOR LABORATORY WORKS ON ELECTRICAL ENGINEERING

The universal laboratory bench is intended for conducting laboratory works at the “Electrical engineering” course by the frontal method.

The laboratory bench includes:

- an assembly bench with electrical measuring devices and electrotechnical elements;
- an electric machine bench, which contains electric machines of direct and alternating current, mechanical brakes of electric machines, loading rheostat R_{H}.

The placement of devices and outputs of the main devices on the front pannel of the assembly bench is shown in Fig. 1.

Buttons for magnetic starters and terminals of the following electrical supply sources that are located in the lower part of the bench are:

- a three-phase current of 220/380 V (phase and line value);
- a direct current of 230 V;
- a single-phase alternating current with voltage of 127 V;
- a regulated variable voltage up to 250 V with the help of a laboratory autotransformer (LATR) T1, and also a constant - up to 250 V, which is formed by means of rectifier *VA*;
- a three-phase voltage source of 22/36V (phase and line values).

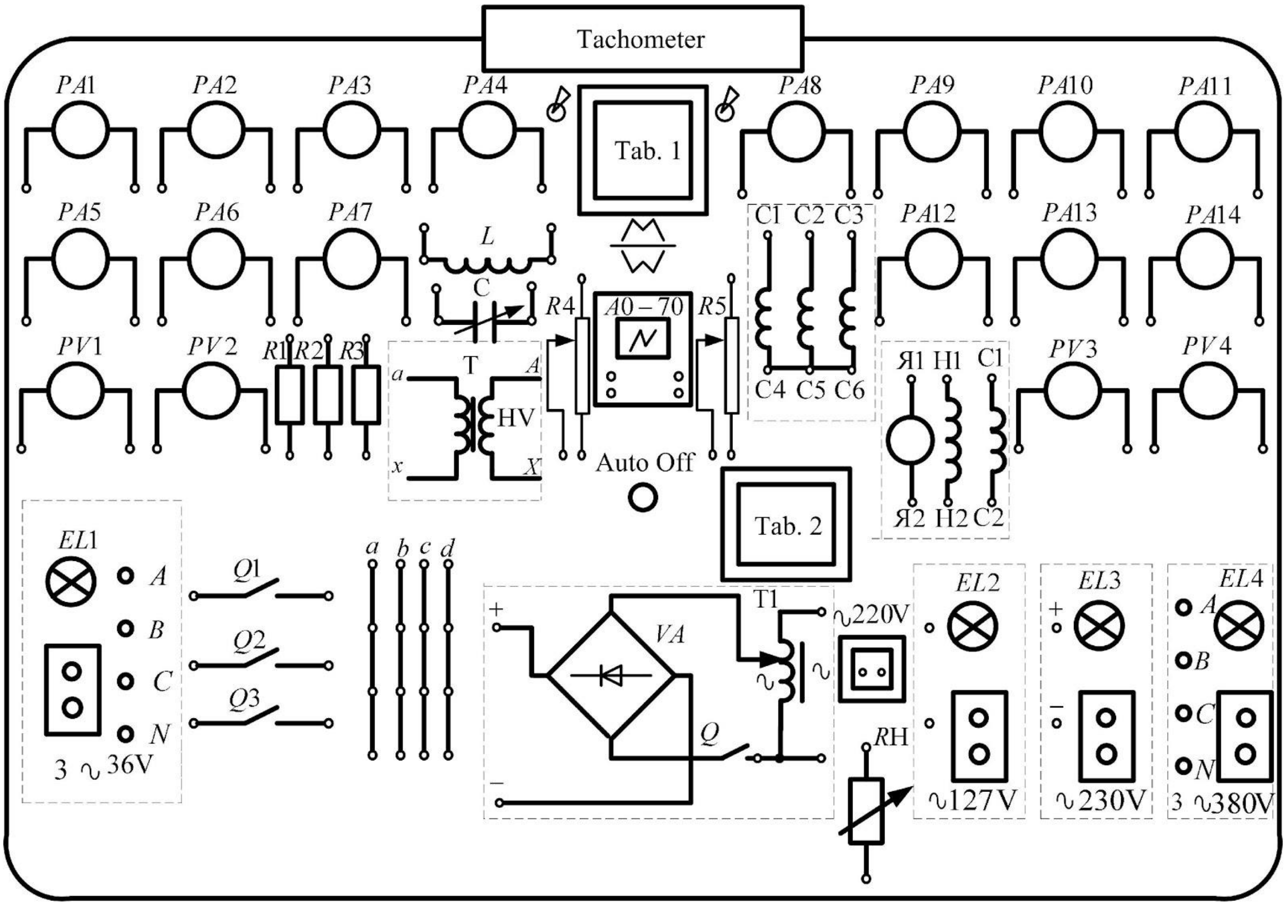

Figure 1

On the bench there are:

- electrical measuring devices: ammeters *PA*1–*PA*14 and voltmeters *PV*1-*PV*4 of direct and alternating current;
- fixed resistors *R*1, *R*2, *R*3;
- rheostats *R*4, *R*5 (with regulated resistance);
- coil inductor *L*;
- capacitor *C*;
- single-phase transformer T;
- electron-beam oscilloscope type “ЛО–70”;
- outputs of stator winding of the asynchronous electric motor C1-C6;
- outputs of direct current machine windings: of armature Я1–Я2; of independent excitation H1-H2; of sequential excitation C1-C2;
- outputs of the loading rheostat $R_{\text{Н}}$;
- four connection terminals *a*, *b*, *c*, *d* – four clips in each for convenient collection of experimental schemes;
- keys *Q*1, *Q*2, *Q*3;
- an emergency button for removing all types of voltage from the clamps of the bench –“Auto Off” (“АВАРИЙНОЕ ВЫКЛЮЧЕНИЕ”);
- signal lights of supply sources *EL*1-*EL*4;
- AC power outlet 220V;
- digital tachometer for measuring the frequency of electric machine rotation.

Additionally, portable phasometers, watt-meters, ammeters and voltmeters can be located on the table.

On the bench (Fig. 1) there are plates with rules on the basics of electrical measurements (Table 1), as well as with the rated parameters of electrical equipment (Table 2).

SAFETY RULES DURING LABORATORY WORKS

Laboratory benches are operating electrical and electromechanical installations, which under certain conditions can become sources of electric shock. To create safe conditions for laboratory work and prevent the possibility of damage to electrical equipment, students must know and strictly follow the rules:

1. Before starting work, it must be ensured that all sources of voltage are in the ("OFF") position, and the auto-transformer slider is set to zero.
2. It is strictly forbidden to touch uninsulated wires, connecting clamps and other parts of the electric circuits under voltage.
3. Installation of the electrical circuit and any re-connections should be carried out with switched-off all the voltage sources.
4. It is strictly forbidden to enable the installation without conducting a circuit check by the lecturer.
5. If the applied voltage disappears during operation, immediately turn off the laboratory installation and place the autotransformer slider in a position that corresponds to the minimum voltage.
6. Disassembling of the circuit should be only performed with permission of the lecturer.
7. If any malfunction is detected in an electrical device under voltage, it is necessary to immediately switch off the bench from the network with the emergency shut-off button. This case should be immediately reported to the class lecturer.

LABORATORY WORK PROCEDURE

For laboratory work, academic groups of students are divided into subgroup of 2-4 students. Laboratory works are carried out by the frontal method, that is, all the students simultaneously perform the same work, but at different benchs.

To perform laboratory work, one preliminary test report (draft) must be prepared for each student, it must contain the electrical scheme of the experiment and the measurement tables. Before starting the experiments, the subgroup should get acquainted with the workplace that contains the experimental installation, supply sources used, loads of electrical energy and devices.

When assembling a circuit, it is first recommended to make the main circuit with the loads to be studied and the current circuits of ammeters, wattmeters and phase meters.

Then you can connect circuits of voltmeters, wattmeters and phase meters, which are connected in parallel with loads. It is necessary to remember the rule that terminals of devices are used only for their connection to the circuit. Nothing else can be connected to these terminals, and all additional connections are performed with free terminals on the bench panel.

Completed circuit must be shown for verification; voltage sources should be turned on only by the permission of the lecturer.

Results of all primary observations, measurements and calculations should be recorded in pre-prepared tables.

After the experiment, the power sources should be turned off, and the measurement results should be given to the lecturer for verification.

If the results of the experiment are recognized as correct by the lecturer, the electric circuit should be disassembled and passed for the assembly of the following circuit. After completing the research, the work place should be organized, the conductors and the equipment should be transferred to the place of their storage.

EXPECTED WORK REPORT CONTENT

The report on laboratory work is completed by each student individually and must be neat, executed according to the established form.

The report begins with a title page, a sample of which is given in Fig. 2. On the following pages, please indicate:

- an electric circuit of the experiment;
- rated data of researched devices, necessary for the report;
- formulae and dependency graphs used for calculations;
- observation data tables and results of calculations in accordance with the requirements presented in the guide for each laboratory work;
- graphic material (graphs, diagrams, drawings).

Students draw the circuits using tools according to Ukrainian State Standard. Legend of typical elements and their sizes is given in Table 1.

Resulting dependency graphs should be drawn on the millimeter paper, indicating standard letter designations of values and measurement units on the axes.

Phasor diagrams should be built on the selected scale.

The report is received by the lecturer on the day the next work is carried out. During this, the student must analyze the results, answer the control questions and solve the exercises on the topic of the work.

Ministry of Education and Science of Ukraine

National Technical University
«Kharkiv Polytechnic Institute»

Department of Applied Electrical Engineering

Laboratory report №

____

(full title of the work)

Work was performed by:
student ______________; group ___________; __________________________
(surname, initials) (index) (execution date)

The report was accepted on____________ Lecturer___________________
(date) (position, surname, initials)

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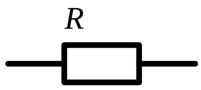
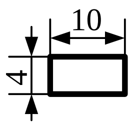
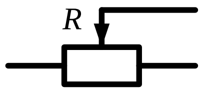
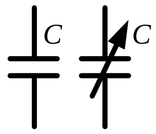
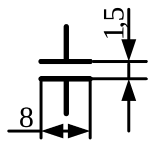
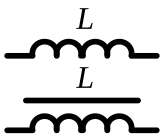
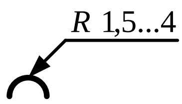
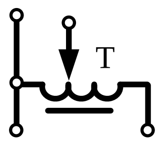
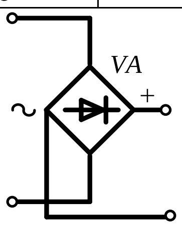
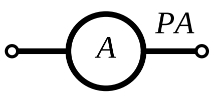
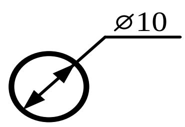
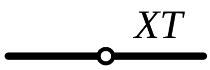
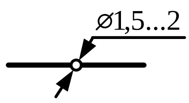
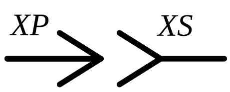
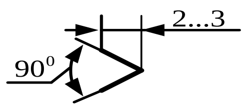
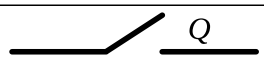
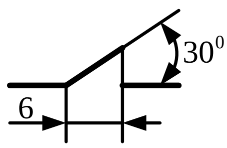
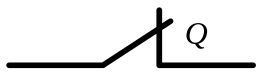
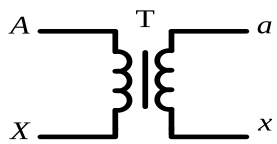
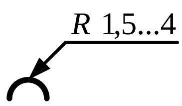
Figure 2

Table 1 – Legend of functional elements in electrical circuit

Element name		Symbol	Dimensions, mm
Resistor	Constant		
	Variable		
Capacitor of constant and variable capacitance			
Inductance coil (inductor) Air cored inductor Iron-core inductor			
Adjustable autotransformer			
Single-phase semiconductor bridge rectifier			
Electrical meters: *PA* – ammeter; *PV* – voltmeter; *PW* – wattmeter; P_{φ} – phase meter			
Joints	separable		
	non-separable		
Contacts of detachable connection (male connector – *XP* and female connector – *XS*)			
Contacts of switching equipment (*Q* – in the power circuits; *S* – control, alarm system)	locking		
	breakable		
Current	direct		
	alternating		
Single-phase double-winding transformer			

L a b o r a t o r y   w o r k 1

STUDY OF SIMPLE CIRCUITS OF A DIRECT CURRENT

The purpose of the work is to gain theoretical knowledge and develop practical skills in the design and experimental study of simple electric circuits of direct current with one source of energy in the case of series, parallel and mixed connection of electric energy loads.

1.1. Problem Statement

Read safety rules, organization and procedure for the laboratory work. Learn the structure of a universal laboratory bench. Determine the resistance of the resistors by measuring the currents and voltages that are applied to them. Study electric circuits in the case of series, parallel and mixed connection of loads by measuring currents, voltages and powers.

1.2. Theoretical thesis

Electric circuit is a set of devices and objects that form the path for electric current and intended for receiving, transmitting and converting electric energy. The electric circuit is characterized by following parameters: current, voltage, electromotive force (EMF), power.

Branch is a section of an electric circle in which all the elements are connected in series and the same current flows through them.

Node is a point of an electric circle in which at least three branches converge. The node is indicated by a dot in the electric. A node is called “independant” if it connects at least one new branch.

The current, unchanged in magnitude and direction, is called *a direct current*. Constant electric values of an electric circuit are denoted by upper case letters: current I (measured in amperes (A)), EMF E (measured in volts (V)), voltage U (measured in volts (V)), power P (measured in watts (W)).

Ohm’s law: the electric current on the passive part of the electric circuit (without EMF) is directly proportional to the voltage U and inversely proportional to the resistance R

$$I = \frac{U}{R}.$$

In general, Ohm’s law for a segment of a circuit with EMF can be represented as

$$I = \frac{E \pm U}{R},$$

where E – EMF power supply; R – total resistance of the circuit.

Kirchhoff's Current Law (law for a node): the algebraic sum of currents in the node is zero (the sum of the currents entering the node is equal to the sum of currents coming out of the node)

$$\sum_{k=1}^{n} I_k = 0.$$

Kirchhoff's Votage Law (law for a loop): the algebraic sum of all EMF acting in the loop is equal to the algebraic sum of the voltage drops on the loads in that loop

$$\sum_{k=1}^{n} E_k = \sum_{k=1}^{m} I_k R_k \; .$$

The EMFs are taken with the "+" sign if the direction of bypass loop matches the direction of the EMF and with the sign "-" if they are opposite.

Voltages in the loop are taken with the "+" sign, if the direction of voltage coincides with the direction of bypass loop, and with the sign "-" if they are opposite.

The connection of elements that are part of a single branch and in which the same current flows, is called *series connection*. The connection of elements that are under the same voltage is called *parallel*. A *mixed connection* of the elements consists of series and parallel connections of the elements (*series-parallel connection*).

Equivalent transformations are the replacement of the resistance group with one resistance or another resistance group in such a way that the voltages and currents in the places of group connections remain unchanged.

At a *series* connection of resistors their equivalent resistance is

$$R_{\text{e}} = R_1 + R_2 + ... + R_n = \sum_{1}^{n} R_k \; .$$

At a *parallel* connection of resistors their equivalent resistance is

$$\frac{1}{R_{\text{e}}} = \frac{1}{R_1} + \frac{1}{R_2} + ... + \frac{1}{R_n} = \frac{1}{\sum_{1}^{n} \frac{1}{R_k}} \; .$$

For two resistors in a *parallel* connection their equivalent resistance is

$$R_{12} = \frac{R_1 \cdot R_2}{R_1 + R_2} \; .$$

For three resistors in a *parallel* connection their equivalent resistance is

$$R_{123} = \frac{R_1 \cdot R_2 \cdot R_3}{R_1 R_2 + R_2 R_3 + R_1 R_3} \; .$$

Power balance: the algebraic sum of the power of all energy sources is equal to the arithmetic sum of capacities of all loads. Equation for power balance is

$$\sum_{k=1}^{n} E_k I_k = \sum_{k=1}^{m} I_k^2 R_k \ .$$

where $P = I_k^2 R_k$ – power consumed by the load – resistance R_k (by the law of Joule-Lenz);

$P = E_k I_k$ – power of the source.

The Joule-Lenz law: the amount of electrical energy W, which is converted into the heat on the circuit part with the resisatance R is equals to

$$W = R \cdot I^2 t$$

1.3. Object of study

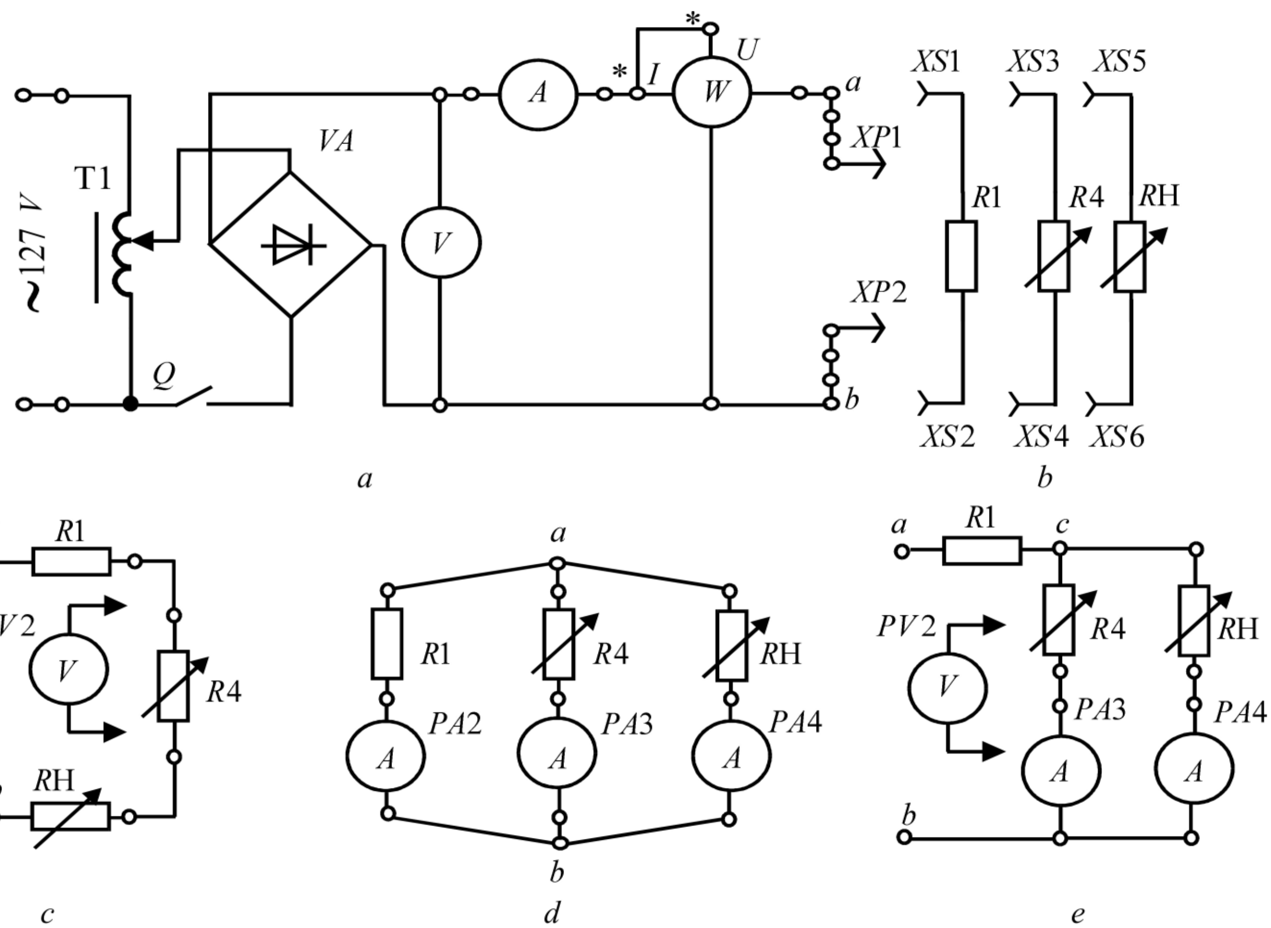


Figure 1.1

The electrical circuit of the experiment is shown in Fig. 1.1. It consists of the base part and the circuits under study. The base part of the circuit (Fig. 1.1, *a*) contains a power supply, an autotransformer "LATR T1", by which the voltage applied to the circuit is slowly regulated, the *VA* rectifier that rectifies this voltage and the measuring devices required for conducting an experiment. The basic part of the circuit ends with the terminal assemblies ***a*** and ***b***, from which portable pins *XP*1 and *XP*2 are derived.

The objects of research are separately taken resistors R_1, R_4 and R_H (Fig. 1.1, *b*), as well as circuits with series, parallel and mixed connections (Fig. 1.1, *c*, *d*, *e*). To connect the basic part of the circuit with the object of study, the pins *XP*1 and *XP*2 are inserted into the corresponding slots *XSk* (where *k* is the number of the slot) according to Fig. 1.1, *b*.

1.4. The order of the experiment execution

1.4.1. Indirectly determine the resistance of the resistors.

Assemble a basic part of the circuit (Fig. 1.1, *a*). Insert the male connectors *XP*1 and *XP*2, respectively, into the female connectors *XS*1 and *XS*2, *XS*3 and *XS*4, *XS*5 and *XS*6, which are the input terminals of the R_1, R_4 and R_H resistors (Fig. 1.1, *b*).

Set autotransformer *T*1 to zero before each turning on and off.

Apply voltage from the power supply and use “ЛАТР Т1” to increase it each time to the required value, referring to the following.

When measuring resistor R_1 resistance, set the current value to $I = 1$ A and measure the according voltage *U*.

In rheostats R_4 and R_H in their initial positions, it is necessary to provide maximum resistance, then it is necessary to set the resistance provided by the lecturer.

To do this, you must first bring the voltage *U* to the value, numerically equal to the resistance, and then move the slider of the rheostat to set the value of the current $I = 1$ A. Before the end of the work, the obtained positions of the rheostat sliders should remain unchanged. Measurement data should be included in Table 1.1.

Table 1.1

Measured		Calculated
U, V	*I*, A	Resistance , Ohm
		R_1 = R_4 = R_H =

1.4.2. Conduct a study of the electric circuit with series resistor connection.

Connect the area of the circuit (Fig. 1.1, *c*) to the terminals ***a*** and ***b*** of the basic part of the circuit (Fig. 1.1, *a*).

Set the voltage *U* at the inlet as directed by the lecturer (100–120 V is recommended).

Measure current *I* and power *P*, as well as voltage drops U_1, U_4, and U_H on resistors R_1, R_4 and R_H using a portable voltmeter PV2. Measurement data should be included in Table 1.2.

Table 1.2

Given	Measured					Calculated	
U	I	P	U_1	U_4	$U_н$	$U_1+U_4+U_н$	P
V	A	W	V	V	V	V	W

1.4.3. Conduct a study of the electric circuit with parallel resistor connection.

Connect the area of the circuit (Fig. 1.1, *d*) to the terminals ***a*** and ***b*** of the basic part of the circuit (Fig. 1.1, *a*).

Set the voltage U at the inlet as directed by the lecturer (50 V recommended).

Measure currents I, I_1, I_4 and $I_н$, as well as the power P. Measurement data should be included in Table 1.3.

Table 1.3

Given	Measured					Calculated	
U	I	P	I_1	I_4	$I_н$	$I_1+I_4+I_н$	P
V	A	W	A	A	A	A	W

1.4.4. Conduct a study of the electric circuit with mixed resistor connection.

Connect the area of the circuit (Fig. 1.1, *e*) to the terminals ***a*** and ***b*** of the basic part of the circuit (Fig. 1.1, *a*).

Set the voltage U at the inlet as directed by the lecturer (100 V ia recommended).

Measure currents I_1, I_4, $I_н$, and power P, as well as voltages U_1, U_4, and U_H on resistors R_1, R_4 and R_H using a portable voltmeter PV2. Measurement data should be included in Table 1.4.

Table 1.4

Given	Measured						Calculated		
U	I_1	P	U_1	$U_4=U_н$	I_4	$I_н$	U_1+U_4	$I_4+I_н$	P
V	A	W	V	V	A	A	V	A	W

1.4.5. According to the results of the experiments, check the implementation of Kirchhoff's laws.

1.5. Processing the results of the experiment

1.5.1. Based on the results of the measurements in Table 1.1, calculate the resistor resistance values using Ohm's law, namely $R = U / I$.

1.5.2. Based on the results of the measurements in Table 1.2–1.4, calculate the specified amounts of the load voltages and currents based on Kirchhoff's laws and compare the results with the corresponding values which are coming from the source.

Also calculate according to the measured voltage and current of the voltage source, power of which derives from it according to the formula $P = UI$. Compare the results with the measured power values.

1.5.3. With the given voltage of the power supply (from Table 1.2–1.4) and the resistor resistances (from Table 1.1), calculate the currents, voltages and capacities for the series, parallel and mixed connections of the resistors in accordance with Figure 1.1, *c*, *g*, *d* and corresponding calculation diagrams in Figure 1.2, *a*, *b*, *c*.

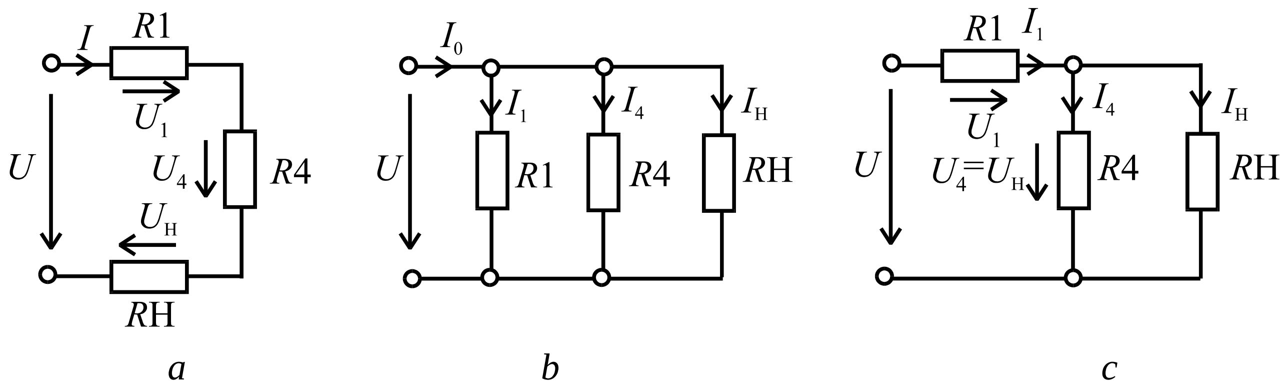


Figure 1.2

Calculate data in Table 1.5.

For series connection of loads, the equivalent circuit resistance is defined as

$$R_{eq} = R_1 + R_4 + R_н .$$

Thus, the current in the circuit is $I = \frac{U}{R_{eq}}$.

Power consumed in a circuit is defined as

$$P_1 = R_1 I^2; \; P_4 = R_4 I^2; \; P_н = R_н I^2 .$$

For a case with a parallel connection of the resistors:

$$I_1 = \frac{U}{R_1}; \; I_4 = \frac{U}{R_4}; \; I_н = \frac{U}{R_н};$$

$$P_1 = R_1 I_1^2; \; P_4 = R_4 I_4^2; \; P_н = R_н I_н^2 .$$

For the case with mixed resistor connection

$$I_1 = \frac{U}{R_{\text{eq}}},$$

where the equivalent resistance of the circuit is defined as $R_{\text{н}} = R_1 + \dfrac{R_4 R_{\text{н}}}{R_4 + R_{\text{н}}}$.

Thus, calculate the voltages, currents and powers as:

$$U_4 = U_{\text{н}} = \frac{R_4 R_{\text{н}}}{R_4 + R_{\text{н}}} I_1; \quad I_4 = \frac{U_4}{R_4}; \quad I_{\text{н}} = \frac{U_{\text{н}}}{R_{\text{н}}};$$

$$P_1 = R_1 I_1^2; \;\; P_4 = R_4 I_4^2; \;\; P_{\text{н}} = R_{\text{н}} I_{\text{н}}^2.$$

Check the results of calculations according to the Kirchhoff laws, as well as the balance of power equation.

Compare the results of the experiment (see Table 1.2–1.4) with the results of calculations (Table 1.5). Formulate the main conclusions of the work.

1.5.4. Make work report according to the rules. The report must contain the title page, experimental schemes (Fig. 1.1), Tables 1.1–1.5, calculation procedure.

Table 1.5

Connection diagram of loads	Given				Calculated									
	U	R_1	R_4	$R_{\text{н}}$	U_1	U_4	$U_{\text{н}}$	I_1	I_4	$I_{\text{н}}$	P_1	P_4	$P_{\text{н}}$	P
R_1, R_4, R_{H}	V	Ohm	Ohm	Ohm	V	V	V	A	A	A	W	W	W	W
Series														
Parallel														
Mixed														

Control questions

1. What is called a branch and a node in an electric circuit?
2. What kind of connection of elements is called series, parallel, mixed?
3. How the equivalent resistance of a circuit is determined in a series, parallel and mixed connections of loads?
4. State Kirchhoff’s laws.
5. Write the equation of the power balance.
6. Explain the principle of turning on the electrical measuring devices: ammeter, voltmeter, wattmeter.
7. How to determine scale divisions of electrical measuring instruments: ammeter, voltmeter, wattmeter?
8. How to determine a resistance using an ammeter-voltmeter method?

L a b o r a t o r y   w o r k 2

STUDY OF CIRCUITS OF A DIRECT CURRENT WITH THE BRIDGE CIRCUIT

The purpose of the work is to consolidate theoretical knowledge and develop practical skills in the design and experimental study of the bridge electric circuits of a direct current with one power supply.

2.1. Formulation of the problem

By direct measurements, determine the distribution of currents in the branches and voltages across the parts of a direct current circuit with a single source of power, compiled according to the bridge scheme, and then check the results obtained by calculation.

2.2. Theoretical thesis

Equivalent transformation is the replacement of the resistance of resistors group with one resistance or another resistance group in such a way that the voltages and currents in the places of joining the group remain unchanged.

Connection of three elements of a circuit R_{ab}, R_{ac}, R_{cb}, forming the sides of a closed triangle, is called a delta (Δ) connection (Fig. 2.1, *a*). Connection of three elements of a circuit R_a, R_b and R_c, which have the form of a three-beam star with a common node *O* in the center, is called a star (wye, Y) connection (Fig. 2.1, *b*).

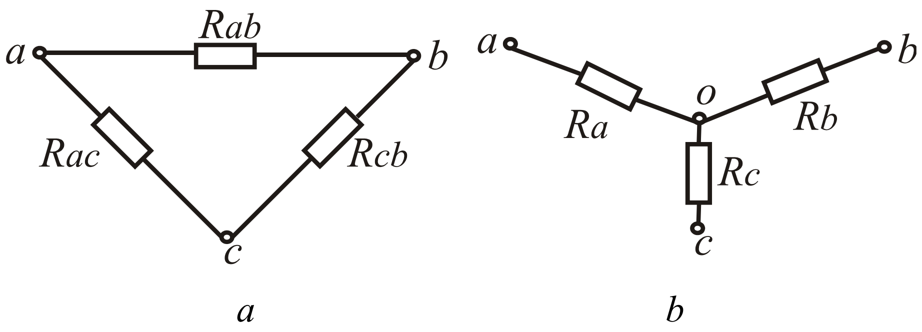


Figure 2.1

Transform the delta (Δ) connection of resistors R_{ab}, R_{ac}, R_{cb} in the equivalent wye (Y) connection with resistances R_a, R_b and R_c, is executed with the following expressions:

$$R_a = \frac{R_{ab}R_{ac}}{R_{ab} + R_{ac} + R_{cb}} \; ;$$

$$R_c = \frac{R_{ac}R_{cb}}{R_{ab} + R_{ac} + R_{cb}} \; ; \quad R_b = \frac{R_{ab}R_{cb}}{R_{ab} + R_{ac} + R_{cb}} \; .$$

Thus, the resistance of any branch of the equivalent wye is equal to the product of two resistances of the delta adjacent to the same node, divided by the sum of all three resistances of the delta.

Transform the wye connection of resistors with the resistance R_a, R_b and R_c, in an equivalent delta connection with resistors R_{ab}, R_{ac}, R_{cb}, where their resistances are:

$$R_{cb} = R_c + R_b + \frac{R_c R_b}{R_a}\ ;\ R_{ab} = R_a + R_b + \frac{R_a R_b}{R_c}\ ;\ R_{ac} = R_a + R_c + \frac{R_a R_c}{R_b}\ .$$

The bridge circuit of a direct current in which current in a diagonal of the bridge is equal to zero is called *balanced*. If the current in the diagonal of the bridge circuit differs from zero, then such a circuit is called *unbalanced*. The current in the diagonal of the bridge circuit will be zero, provided the next relationship between the resistances of this circuit

$$\frac{R_1}{R_4} = \frac{R_3}{R_5}.$$

2.3. Object of study

The scheme of an electric circuit is given on Fig. 2.2. A DC power supply is carried out from the AC network via the autotransformer *T*1 and the rectifier *VA*. The resistors *R*1, *R*2, *R*3 and rheostats *R*4 and *R*5 are used as the loads in the circuit.

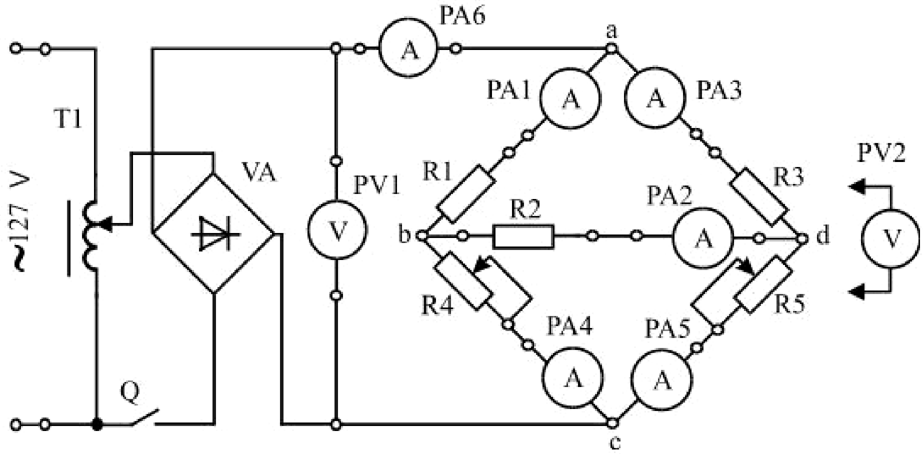


Figure 2.2

2.4. The order of the experiment execution

2.4.1. Assemble an electric circuit according to a schematic diagram (Fig. 2.2). The nodes of the circuit ***a***, ***b***, ***c***, ***d*** are placed on the terminals assemblies, respectively, *a*, *b*, *c*, *d*. Set the *T*1 autotransformer to the zero position before turning on the power source.

2.4.2. Supply voltage from the power source.

Using the autotransformer *T*1, set the input voltage U_0 set by the lecturer at the input of the circle (100 V is recommended).

2.4.3. Unbalance the circuit by changing the resistance of the rheostats *R*4 and *R*5 so that the current I_2 comparable to the currents in other parts of the circuit, and make the measurements. Measure with the help of ammeters the currents of the branches, and using a portable voltmeter PV2 – the voltage between the nodes: U_{ad}, U_{dc}, U_{ab}, U_{bc}, U_{db}. Write down the results of the measurements in the corresponding column "Measured" in Table 2.1.

Table 2.1

Bridge circuit		Parameters											
		U_0	I_0	U_{ad}	U_{dc}	U_{ab}	U_{bc}	U_{db}	I_1	I_2	I_3	I_4	I_5
		V	A	V	V	V	V	V	A	A	A	A	A
Unbalanced	Measured												
	Calculated												

2.4.4. Use Kirchoff's laws to check the results. In case of data differences (more than 5 %) it is necessary to achieve more correct measurement results.

2.5. Processing the results of the experiment

2.5.1. For a number of freely chosen loops and nodes (Fig. 2.2), write down the Kirchhoff's laws equations and check the implementation of these laws according to the experimental data (Table 2.1).

2.5.2. According to the measurements (Table 2.1), calculate resistances of the resistors in the circuit as:

$$R_1 = \frac{U_{ab}}{I_1}; \quad R_2 = \frac{U_{db}}{I_2}; \quad R_3 = \frac{U_{ad}}{I_3}; \quad R_4 = \frac{U_{bc}}{I_4}; \quad R_5 = \frac{U_{dc}}{I_5}.$$

and write the results in Table 2.2.

2.5.3. For two states of the electric circuit at a given voltage source U_0 (Table 2.1) and calculated circuit parameters (R_1, R_2, R_3, R_4, R_5 from Table 2.2). Calculate the currents and voltages in all branches by the method of equivalent transformations (including, using transformation of the "Δ" connection to the "Y" connection). The transformation of the "Δ" to the "Y" is shown in Fig. 2.3. Write down the calculation data in the appropriate "Calculated" graphs of Table 2.1.

Table 2.2

Circuit state	Resistors impedance, Ohm				
	R_1	R_2	R_3	R_4	R_5
Unbalanced					

The calculation order must be done as shown below:

$$R_b = \frac{R_2 \cdot R_4}{R_2 + R_4 + R_5}; \; R_c = \frac{R_5 \cdot R_4}{R_2 + R_4 + R_5}; \; R_d = \frac{R_2 \cdot R_5}{R_2 + R_4 + R_5};$$

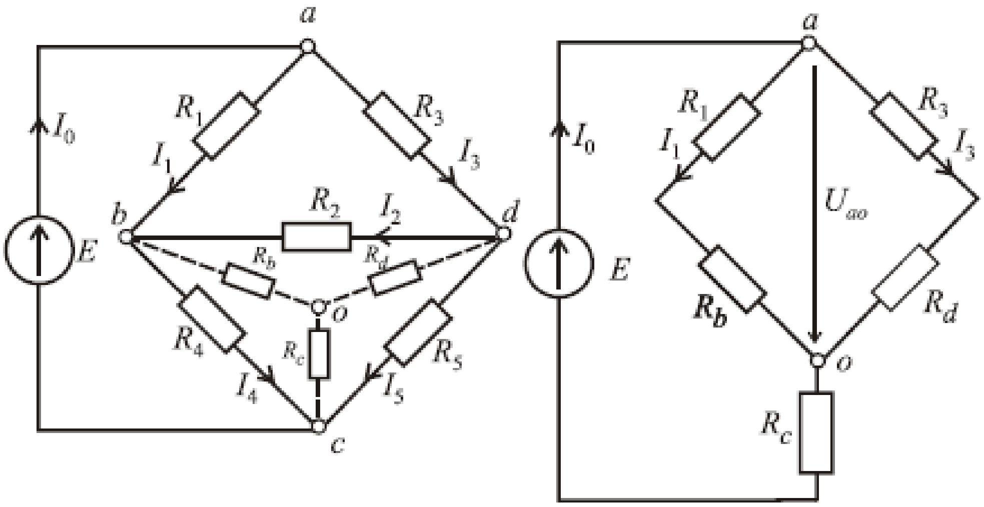


Figure 2.3

$$R_{oa} = \frac{(R_1 + R_b)\cdot(R_3 + R_d)}{R_1 + R_b + R_3 + R_d}; \; R_e = R_{oa} + R_c;$$

$$I_0 = \frac{U_0}{R_å}; \; U_{oa} = I_o \cdot R_{oa}; \; I_1 = \frac{U_{oa}}{R_1 + R_b}; \; I_3 = \frac{U_{oa}}{R_3 + R_d};$$

$$I_3 R_3 + I_2 R_2 - I_1 R_1 = 0 \; ; \; I_2 = \frac{I_1 R_1 - I_3 R_3}{R_2};$$

$$I_4 = I_1 + I_2; \; I_5 = I_3 - I_2.$$

2.5.4. Check with the balance of power equation

$$U_0 I_0 = I_1^2 R_1 + I_2^2 R_2 + I_3^2 R_3 + I_4^2 R_4 + I_5^2 R_5.$$

2.5.5. Compare the results of the experiment with the calculated data and make the appropriate conclusions.

Control questions

1. State Kirchhoff laws.
2. State equivalence conditions for the combination of “Y” and “Δ”.
3. What is the essence of the method of equivalent transformations?
4. Give the formulas of the equivalent transformation “Δ” – “Y”.
5. Give formulas equivalent to the transformation of “Y” – “Δ”.
6. What is a balanced and unbalanced bridge circuit? Provide bridge conditions.
7. Write down the balance of power equation.

L a b o r a t o r y   w o r k 3

STUDY OF A SINUSOIDAL CURRENT ELECTRIC CIRCUIT IN THE CASE OF SERIES CONNECTION OF LOADS

The purpose of the work is to gain theoretical knowledge and practical skills in the design and experimental study of a sinusoidal current electric circuit in the case of a series connection of loads.

3.1. Problem Statement

Using a sinusoidal voltage source, conduct a study of:

a) electric loads: resistor, induction coil and capacitor by determining the parameters of their equivalent circuits;

b) an electric circuit with a series connection of loads.

3.2. Theoretical thesis

Alternating current (AC) is a current, the value and direction of which periodically change. The most common form of AC is sinusoidal. The main source of a sinusoidal alternating current is alternators.

A sinusoidal voltage, a sinusoidal current and a sinusoidal EMF in the analytical form are:

$$u = U_m \sin(\omega t + \psi_u);\; i = I_m \sin(\omega t + \psi_i);\; e = E_m \sin(\omega t + \psi_e).$$

where *u, i, e* – instantaneous values of a sinusoidal voltage, a current, and an EMF;
$U_m,\ I_m,\ E_m$ – amplitude (peak or maximum) value of a sinusoidal voltage, a current and an EMF;
$\omega t + \psi_u$, $\omega t + \psi_i$, $\omega t + \psi_e$ – phase of a sinusoidal voltage, current and EMF correspondingly;
ψ_u, ψ_i, ψ_e – initial phases of voltage, current and EMF correspondingly.

Voltage and current sinewaves are shown in Fig. 3.1.

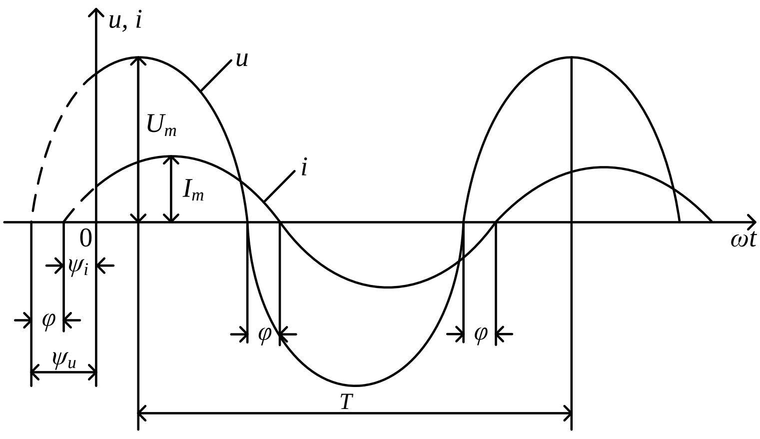


Figure 3.1

Period T – time interval for which a complete cycle of sinusoidal function change occurs. *Current frequency* $f = \frac{1}{T}$ – number of periods per unit of time (per second). Angular frequency is determined as follows $\omega = \frac{2\pi}{T} = 2\pi f$.

The difference between the initial phases of a sinusoidal voltage and a sinusoidal current is called *phase difference angle or a displacement angle* φ

$$\varphi = \psi_u - \psi_i .$$

Depending on load of an electric circuit, phase displacement angle values of the sinusoidal current are as follows:

– $\varphi = 0°$ – resistance;
– $\varphi = +90°$ – inductive;
– $\varphi = -90°$ – capacitive;
– $0° < \varphi < +90°$ – resistance-inductive;
– $-90° < \varphi < 0°$ – resistance-capacitive.

Resistance R, *reactance* $X = X_L - X_C$, (X_L – *inductive reactance*, X_C – *capacitive reactance*); *impedance Z* of an AC circuit are:

$$X_L = \omega L; \quad X_C = \frac{1}{\omega C};$$

$$Z = \sqrt{R^2 + X^2} = \sqrt{R^2 + (X_L - X_C)^2} ;$$

$$R = Z \cdot \cos\varphi; \quad X = Z \cdot \sin\varphi .$$

Resistance, reactance and impedance are measured in ohms.

The root mean square or RMS value of the sinusoidal AC is equal to the value of the direct current, the energy effect of which is equal to the energy of the alternating current. The RMS values of sinusoidal current, a voltage and an EMF are correspongingly equal to:

$$I = \frac{I_m}{\sqrt{2}}; \quad U = \frac{U_m}{\sqrt{2}}, \quad E = \frac{E_m}{\sqrt{2}} .$$

Ohm’s law for circuits of sinusoidal current states the RMS current value is directly proportional to the RMS value *U* of the applied voltage and inversely proportional to the circuit element impedance *Z*

$$I = \frac{U}{Z} .$$

Kirchhoff's current law for circuits of sinusoidal current: the algebraic sum of instanteneous current values in the node is zero

$$\sum_{k=1}^{n} i_k = 0.$$

Kirchhoff's voltage law for circuits of a sinusoidal current: the algebraic sum of instanteneous values of EMF in a loop is equal to the algebraic sum of the instanteneous values of the voltage drops across elements of this loop

$$\sum_{k=1}^{n} e_k = \sum_{k=1}^{m} i_k Z_k .$$

Active power P is measured in watts [W], *reactive power Q* – in volt-amperes reactive [var], *apparent* (*total*) *power S* – in volt-amperes [V·A]. Powers are respectively determined by the following formulae:

$$P = I^2 R \ ; \quad Q = I^2 X; \quad S = I^2 Z = \sqrt{P^2 + Q^2} .$$

For an electric circuit with a series connection of elements *R*, *L*, *C*, according to Kirchhoff's voltage law, the voltage relationship is

$$\underline{U} = \underline{U}_R + \underline{U}_L + \underline{U}_C$$

The phasor diagram of the voltagea across elements *R*, *L*, *C* in the case of a series connection of the elements is shown in Fig. 3.2.

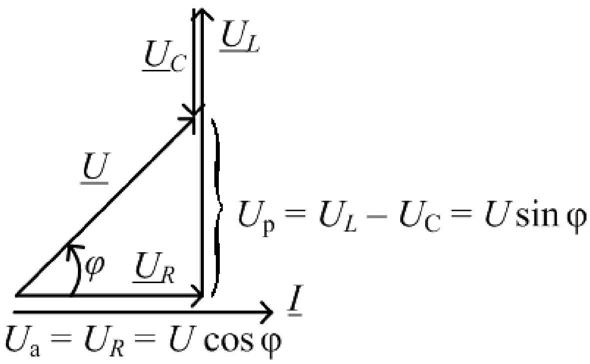


Figure 3.2.

In a circuit of a sinusoidal current with a series connection of elements *R*, *L*, *C*, a voltage resonance may occur. Necessary and sufficient condition for a voltage resonance is the equation $X_L = X_C$. The impedance of the circuit is equal to *R* ($Z = R$). The relationship between the voltages across the ideal reactive elements is $U_L = U_C$. The phase difference angle in the case of a resonance is zero $\varphi = 0$. The phasor diagram of a voltage resonance is shown in Fig. 3.3.

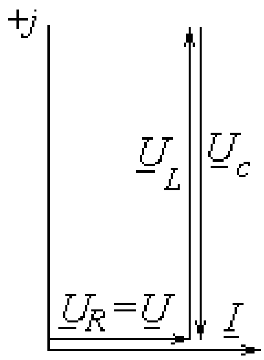


Figure 3.3

3.3. Object of study

In all the experiments being carried out, the basic part of the circuit with power supply and electric meters is used (Fig. 3.4, *a*). As a regulating source of an alternating voltage, a laboratory autotransformer T1 (LATR) is used, which is connected to the circuit of an alternating voltage of 127 V. From the outlet of the LATR voltage is applied to the terminals ***a*** and ***b***, to which portable pins *XR*1 and *XR*2 are connected.

The objects of research are separate loads: resistor R_1, inductor *L* and capacitor *C* with regulated capacitance, shown in Fig. 3.4, *b*, as well as electric circuit formed by their series connection in accordance with Fig. 3.4, *c*. To connect the base part of the circuit with a specific object of study, the pins *XP*1 and *XP*2 are inserted into the corresponding slots XS_k (where *k* is the slot number) according to Fig. 3.4, *b*, *c*.

3.4. The order of the experiment execution

3.4.1. Assemble a basic part of the scheme (Fig. 3.4, *a*). Set LATR *T*1 to zero.

3.4.2. Conduct an individual study of electric loads. To do this, when the power source is off, insert male connectors *XR*1 and *XR*2 (see Fig. 3.4, *a*) into the *XS*1, *XS*2 load female connectors shown in Fig. 3.4, *b*.

3.4.3. Conduct an individual study of electric loads.

Table 3.1

Load's name		Measured			Calculated		
		U	*I*	φ	*Z*	*R*	*X*
		V	A	deg	Ohm	Ohm	Ohm
Resistor *R*1							
Inductor *L*							
Capacitor *C* (position *n*)	position *C* №1						
	position *C* №2						

Use LATR to bring a source voltage *U* to the set value (100 V is recommended), measure a current *I* and phase difference between the current and the voltage. Record the results in Table 3.1.

The capacitor is tested in two positions of the switch, which are recorded in Table 3.1 (recommended positions are 2 and 6, if there are no additional lecturer's instructions).

3.4.4. Study the series connection of the loads: the resistor *R*1, the inductor *L* and the capacitor *C*. Connect them according to Fig. 3.4, *c*: the male connectors *XP1* and *XP2* of the base part of the circuit to the female connectors of the studied circuit *XS3*, *XS4*. An optional *PV2* voltmeter with portable terminals *XP*3 and *XP*4 is also used here.

The test is carried out twice (according to the lecturer's instruction) at the switch positions of the capacitor *C*, that were recorded in Table 3.1. Changes in the switch positions are carried out when the voltage is turned off.

Set the U_0 voltage according to the lecturer's instruction (100 V is recommended) and measure the current I_0 and the phase shift φ_0 and record the results in Table 3.2. Measure the voltages across separate loads (U_{R1} – across the resistor, U_{co} – across the inductor, U_C – across the capacitor) with voltmeter *PV2*.

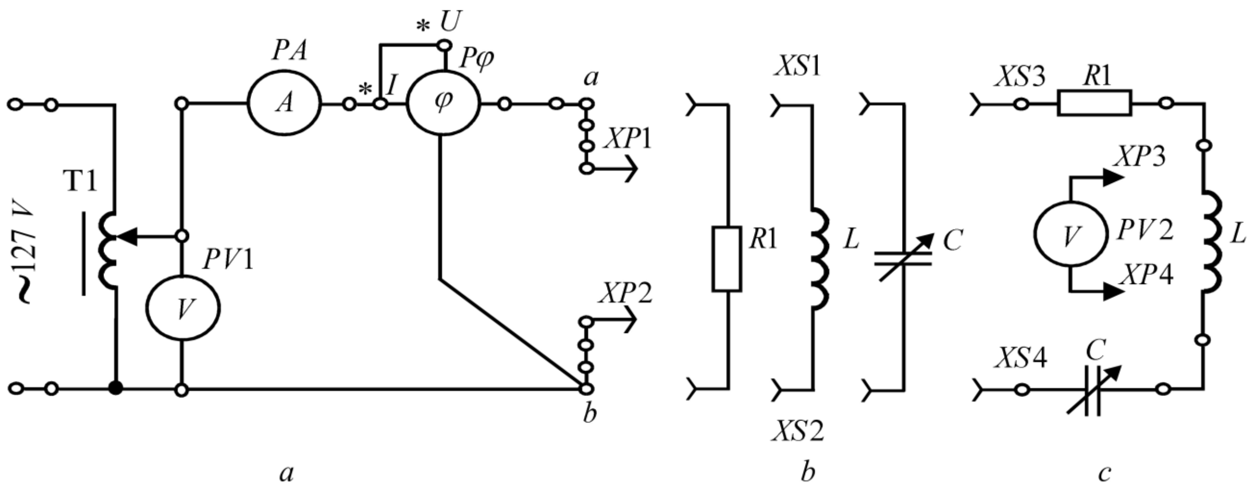


Figure 3.4

Table 3.2

The loads are connected in series at different capacitor positions *C*	Measured					
	U	I	φ	U_{R_1}	U_{Co}	U_C
	V	A	deg	V	V	V
R_1, *L*, *C* №....						
R_1, *L*, *C* №....						

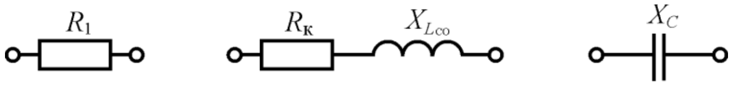
3.5. Processing the results of the experiment

3.5.1. Use the measurement data from Table 3.1 and determine the impedance *Z*, resistance *R* and reactance *X* of the tested loads:

$$Z = U / I; \qquad R = Z\cos\varphi; \qquad X = Z\sin\varphi; \qquad X_C = |Z\sin\varphi|.$$

On this basis, depict the replacement schemes of these loads. If one of the two values of *R* or *X* is infinitely smaller than the second, then the smaller one can be neglected.

The typical replacement schemes for of a resistor, a inductor and a capacitor are shown in Fig. 3.5, *a*, *b*, *c*, respectively.



a *b* *c*

Figure 3.5

3.5.2. Use equivalent circuit of load to depict the circuit for replacement of the electric circuit with series connection of the loads.

By the given input voltage of the circuit U_0 from Table 3.2, as well as the impedance of the ideal load elements from Table 3.1, calculate the circuit with the series connection of the loads for one used position *n* of the capacitor *C*.

Enter the results in Table 3.3, where, along with previously noted values, the following are defined:

R_1 – resistance of the resistor R_1;

R_{co}, X_{Lco} – resistance and inductive reactance of the industor *L*;

X_C – capacitance of the capacitor *C*, and capacitive reactance $X_C = -X$;

R_0, X_0, Z_0 – resistance, reactance and impedance of the whole circuit;

U_{Rco}, U_{Lco} – active and reactive components of the coil voltage, that are defined as the voltage drop across it;

P_0, Q_0 – active and reactive power of the entire circuit.

Table 3.3

Given						Calculated											
Positions *C*	U_0	R_1	R_{co}	X_{Lco}	X_C	R_0	X_0	Z_0	I_0	φ_0	U_{R1}	U_{Rco}	U_{Lco}	U_{co}	U_C	P_0	Q_0
	V	Ohm	Ohm	Ohm	Ohm	Ohm	Ohm	Ohm	A	deg	V	V	V	V	V	W	var
№…																	
№…																	

Resistance, reactance and impedance are determined as:

$$R_0 = R_1 + R_{co}; \quad X_0 = X_{Lco} - X_C; \quad Z_0 = \sqrt{R_0^2 + X_0^2}.$$

Then the RMS value of the current in the circuit is equal according to the Ohm's law

$$I_0 = U / Z_0.$$

The phase difference angle between the source voltage and the current in degrees is

$$\varphi_0 = \text{arctg}\frac{X_0}{R_0}.$$

The RMS values of the voltages on the elements of the circuit will be determined as:

$$U_{R_1} = I_0 R_1;\ U_{Rco} = I_0 R_{co};\ U_{Lco} = I_0 X_{co}; U_{co} = \sqrt{U_{Lco}^2 + U_{Rco}^2};\ U_C = I_0 X_C.$$

Active and reactive powers are: $P_0 = I_0^2 R_0; \quad Q_0 = I_0^2 X_0$.

Compare the calculation data (Table 3.3) and measurements (Table 3.2). If they are close enough, the work is done right.

3.5.3. Draw a phasor diagram of electrical quantities on a scale for the circuit with a series connection of loads according to Table 3.3. An example of such are the diagrams that are shown in Fig. 3.6, the resistance-inductive (phase difference angle $\varphi > 0$, Fig. 3.6, *a*) and the resistance-capacitive (phase difference angle $\varphi < 0$, Fig. 3.3, *b*).

Build a phasor diagram for the case of a voltage resonance.

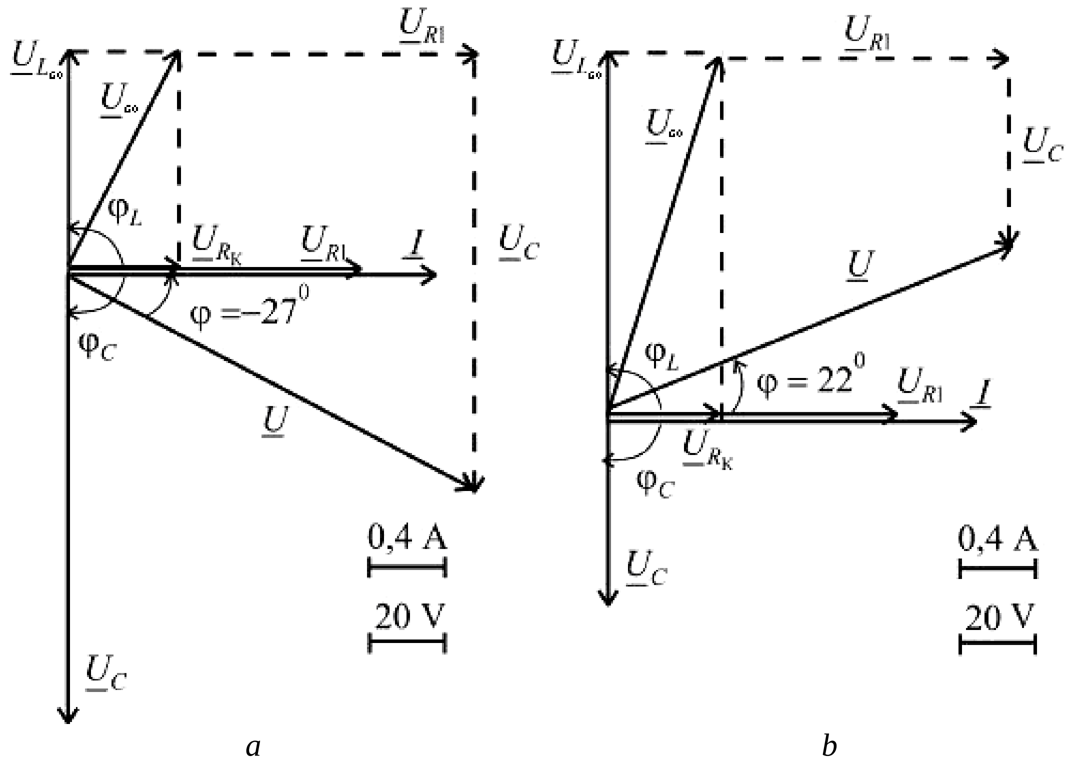


Figure 3.6

Control questions

1. What quantities are sinusoidal current and voltage characterized by?

2. What do periodic electric quantities mean and how RMS values of sinusoidal current and voltage are determined?

3. State Kirchhoff's laws for sinusoidal circuits.

4. What are the ideal elements used for the replacement schemes of real loads?

5. How do the ideal elements replace electric loads and how are the parameters of these elements determined?

6. Write down the Ohm's law for RMS values of current and voltage across the ideal elements *R*, *L*, *C*, and for the circuit with a series connection of these elements.

7. What powers characterized energy processes in electric circuits of sinusoidal current and how are these powers determined? How do they relate to each other?

8. What are the conditions for the voltage resonance and what are the rationships of the main electrical quantities in this mode?

9. How to draw phasor diagrams when calculating electric circuits with a series connection of loads?

Laboratory work 4

STUDY OF A SINUSOIDAL CURRENT ELECTRIC CIRCUIT IN THE CASE OF A PARALLEL CONNECTION OF LOADS

The purpose of the work is to consolidate theoretical knowledge and develop practical skills in the design and experimental study of electric loads and the electric circle of sinusoidal current in the case of their parallel connection.

4.1. Formulation of the problem

Use a source of sinusoidal voltage and conduct a study:

a) electric loads: a resistor, an inductor and a capacitor in their individual switching on in order to determine the parameters of the equivalent schemes;

b) an electric circuit with a parallel connection of loads.

4.2. Theoretical thesis

Conductance, inductive susceptance and capacitive susceptance are determined by the formulae respectively:

$G = \frac{1}{R}$; $B_L = \frac{1}{X_L}$; $B_C = \frac{1}{X_C}$; $B = B_L - B_C$; $Y = \frac{1}{Z}$ are measured in siemens [S].

Impedance *Z*, resistance *R* and loads succeptance are determined by the formulae:

$$Z = U / I; \quad R = P / I^2; \quad X = \sqrt{Z^2 - R^2},$$

admittance *Y*, conductance *G* and reactive *B* loads conductivity are determined by the formulae

$$Y = I / U; \quad G = P / U^2; \quad B = \sqrt{Y^2 - G^2}.$$

If under these conditions one of the two values of *R* or *X*, *G* or *B* is immensely smaller than the other, then the smaller one can be neglected.

The phase difference angle φ between a voltage and a current for each load is determined by resistance and reactance or conductance and susceptances:

$$\varphi = \text{arctg}\left[(X_L - X_C) / R\right] \text{ or } \varphi = \text{arctg}\left[(B_L - B_C) / G\right],$$

where (X_L and B_L – inductive reactance and susceptance; X_C and B_C – capacitive reactance and susceptance).

The mode of resonance of currents will occur provided that the inductive susceptance of the branch with a coil will be equal to the capacitive susceptance of the branch with a capacitor $B_L = B_C$.

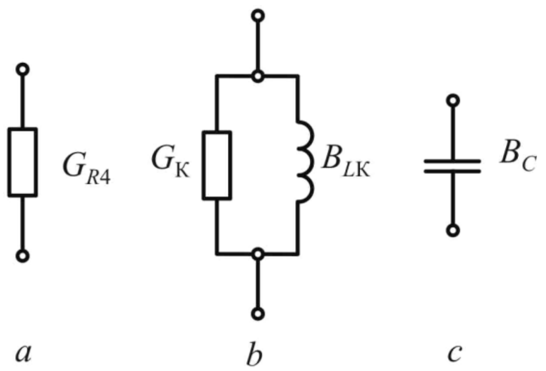


Figure 4.1

Inductive susceptance of a branch with a inductor equals $B_{L_К} = \frac{X_{L_К}}{Z_К^2} = \frac{X_{L_К}}{R_К^2 + X_{L_К}^2}$, and capacitive conductivity of a branch with a capacitor, in case of neglect by resistance ($R_C = 0$) – $B_C = \frac{X_C}{Z_C^2} = \frac{X_C}{R_C^2 + X_C^2} = \frac{X_C}{X_C^2} = \frac{1}{X_C}$. Total reactive susceptance of two parallel branches in one of which a inductor is switched on, and in the second – a capacitor will be equal $B_0 = B_L - B_C$. The conductance of the branch is equal to $G = \frac{R}{Z^2} = \frac{R}{R^2 + X^2} = \frac{R}{R^2 + (X_L - X_C)^2}$. Admittance of parallel branches is equal $Y_0 = \sqrt{B_0{}^2 + G_0{}^2}$.

The phasor diagram of resonance of currents is given in Fig. 4.2.

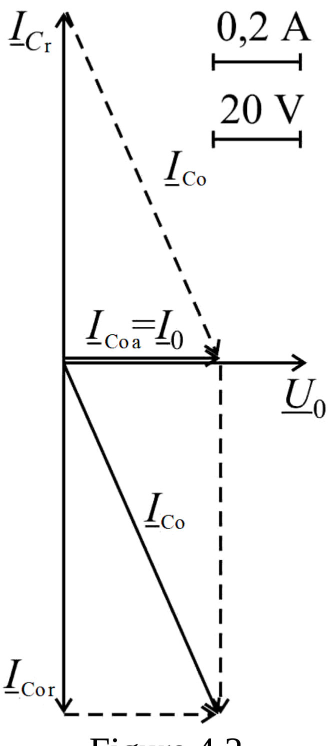


Figure 4.2.

4.3. Object of study

In all experiments, a circuit with electrometer-based devices is used, which is shown in Fig. 4.3. As the voltage regulating source, the laboratory autotransformer *T*1 (LATR) is used, which is activated in the network of the voltage variable ~ 127 V. From the output of the LATR voltage is applied to the terminals of the assembly ***a*** and ***b***, to which the branches with the loads are connected.

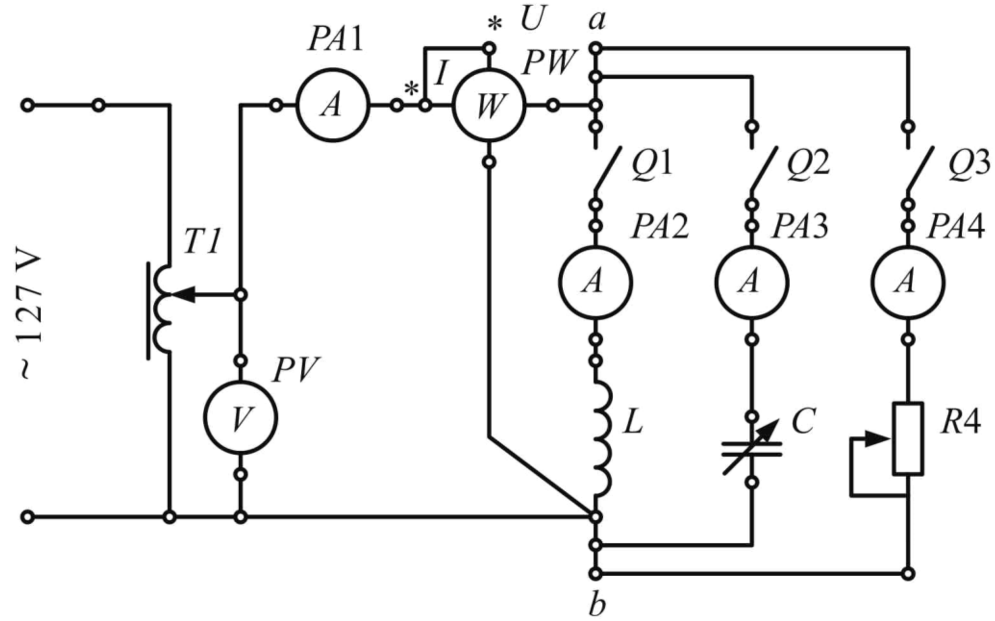


Figure 4.3

The objects of research are separately taken loads: the rheostat *R*4, the coil of inductance *L* and the capacitor *C* with the regulating capacity, as well as the electric circle, which is formed by their parallel connection. Required circle options are provided by switching the keys *Q*1, *Q*2 and *Q*3.

4.4. The order of the experiment execution

4.4.1. Assemble a circuit as shown in Fig. 4.1 set LATR *T*1 to zero.

4.4.2. Conduct an individual study of electric loads in turn. To do this, leave the locked key only to the load that is being investigated.

With LATR, bring the voltage *U* to the set value (100 V is recommended) and measure the current *I* and the active power *R*.

Record results in Table 4.1.

Table 4.1

The name of the electric load		Measured			Calculated						
		U	*I*	*P*	*Z*	*R*	*X*	*Y*	*G*	*B*	φ
		V	A	W	Ohm	Ohm	Ohm	S	S	S	deg
Inductor *L*											
Capacitor	position *C* №…										
	position *C* №…										
Rheostat *R*4											

The capacitor will test in two positions of the switch, which are recorded in the Table. 4.1 (It is not recommended to choose the average position of the switch of the condenser switch).

When testing the rheostat *R*4, set its slider to the current of 30–50 % less than the value obtained for the inductance coil (the position of the slider is further stored).

4.4.3. Explore the parallel connection of loads for those variants from the Table. 4.2, which will be given by the lecturer. The specific variant is obtained by appropriate switching of the keys *Q*1-*Q*3 according to the citcuit in Fig. 4.3.

In each variant, the trial is conducted twice using the positions of the switch C, which were recorded in the Table. 4.1.

Set the voltage U_0 according to the lecturer's instruction (100 V recommended).

Conduct measurements according to the scheme of Fig. 4.3 and record the results in the Table 4.2, where U_0, I_0, P_0 is the total voltage, current and active power received from the source; I_{Co}, I_C, I_{R4} – coil, capacitor and resistor currents correspondingly.

Table 4.2

In parallel, loads are connected at different stages C_n	Measured					
	U_0	I_0	P_0	I_{Co}	I_C	I_{R4}
	V	A	W	A	A	A
L, *C* №…, *R*4						
L, *C* №…, *R*4						

4.5. Processing the results of the experiment

4.5.1. According to the circuit diagrams of the loads, depict a common circuit for replacing the electric circuit in the case of the parallel connection of these loads. According to the input voltage circle U_0, which is given from Table 4.2, and parameters of the ideal elements of loads from the Table 4.1 calculate the circle with the parallel connection of loads for those variants from the Table 4.2, which were investigated experimentally. Make the calculation of results in Table 4.3, where, along with the already mentioned previously defined:

R_{Co}, $X_{L\,Co}$, Z_{Co}, φ_{Co} – resistance, inductive reactance, impedance and phase difference angle of the coil *L*;

X_C – capacitive reactance of capacitor *C*;

R_4 – resistance of resistor *R*4;

φ_0 – phase difference angle between voltage U_0 and current I_0;

S_0, P_0, Q_0 – apparent (total), active and reactive powers of the whole electrical circuit.

$$Z_{Co} = \sqrt{R_{Co}^2 + X_{LCo}{}^2}\ ;\ \varphi_{Co} = \text{arctg}\frac{X_{L_{Co}}}{R_{Co}}\ ;$$

$$I_{Co} = \frac{U_0}{Z_{Co}}\ ;\ I_C = \frac{U_0}{X_C}\ ;\ I_{R_4} = \frac{U_0}{R_4}\ ;$$

$$\psi_{i_{Co}} = -\varphi_{Co};$$

$$I_{Co\text{a}} = I_{Co}\cos\psi_{i_{Co}};\ I_{Cor} = I_{Co}\sin\psi_{i_{Co}};$$

Active component of current I_0

$$I_{0\text{a}} = I_{R_4\text{a}} + I_{Co\text{a}};$$

The reactive component of the current I_0:

$$I_{0\text{r}} = I_{Co\text{r}} + I_{C\text{r}};$$

RMS values of current source:

$$I_0 = \sqrt{I_{0\text{a}}^2 + I_{0\text{r}}^2};$$

$$\psi_{i_0} = \text{arctg}\frac{I_{0\text{r}}}{I_{0\text{a}}};$$

$$\varphi_0 = -\psi_{i_0};$$

$$S_0 = U_0 \cdot I_0;\ P_0 = S_0\cos\varphi_0;$$

$$Q_0 = S_0\sin\varphi_0.$$

In calculations, it is also possible to use the admittance, conductance and reactance of the corresponding loads in Table 4.1:

$$I_{Co} = U_0 Y_{Co};\ I_C = U_0 B_C;\ I_{R4} = U_0 G_{R4};$$

$$I_0 = U_0 Y_0;\ Y_0 = \sqrt{(G_{R4} + G_{Co})^2 + \left(B_{L_{Co}} - B_C\right)^2};$$

$$\varphi_0 = \text{arctg}\frac{B_0}{G_0} = \text{arctg}\frac{B_{L_{Co}} - B_C}{G_{R4} + G_{R_{Co}}};$$

$$S_0 = U_0 \cdot I_0;\ P_0 = S_0\cos\varphi_0;$$

$$Q_0 = S_0\sin\varphi_0.$$

Table 4.3

Given						Calculated									
Position of C	U_0	R_K	X_{LCo}	X_C	R_4	Z_{Co}	φ_{Co}	I_{Co}	I_C	I_{R4}	I_0	φ_0	S_0	P_0	Q_0
	V	Ohm	Ohm	Ohm	Ohm	Ohm	deg	A	A	A	A	deg	VA	W	var
№1															
№2															

Compare the calculations from Table 4.3 and measurement data from Table 4.2 and make sure the research has been conducted.

4.5.2. Draw phasor diagrams of electric quantities for a circuit with a parallel load connection for $B_{LCo} > B_C$ and $B_{LCo} < B_C$ (Fig. 4.4 *a*, *b*).

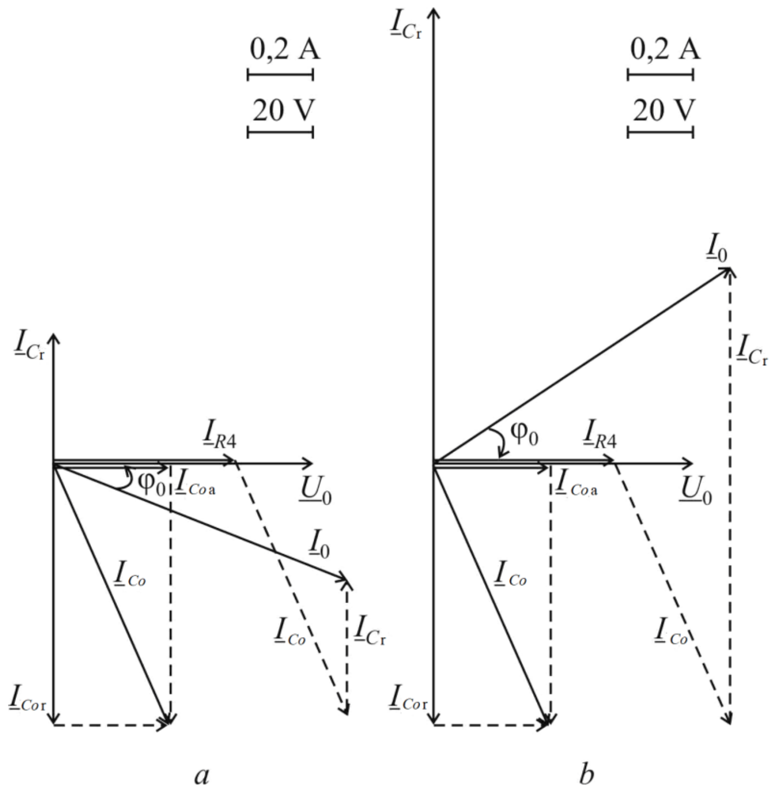


Figure 4.4.

Table 4.4

Given					Calculated										
Position of *C*	U_0	G_{Co}	B_{LCo}	B_C	Y_{Co}	φ_{Co}	I_{Co}	φ_C	I_C	Y_0	I_0	φ_0	S_0	P_0	Q_0
	V	S	S	S	S	deg	A	deg	A	S	A	deg	V·A	V	var
№1															
№2															

Control questions

1. How are the parameters of the circuit of replacing electric loads based on the results of measurement of voltage, current and active power?
2. What is the calculation of a circuit of sinusoidal current in the case of parallel connection of loads?
3. How determine conductance, reactance and admittance of the electric load, if we know resistance, reactance and impedance of the load?
4. What is the order of drawning of a phasor diagram for a sinusoidal current with a parallel connection of loads?
5. What are the conditions for the resonance of currents and what are the relationships of the main electrical quantities in this mode?

L a b o r a t o r y   w o r k 5

STUDY OF THREE-PHASE CIRCUITS OF ALTERNATING SINUSOIDAL CURRENT

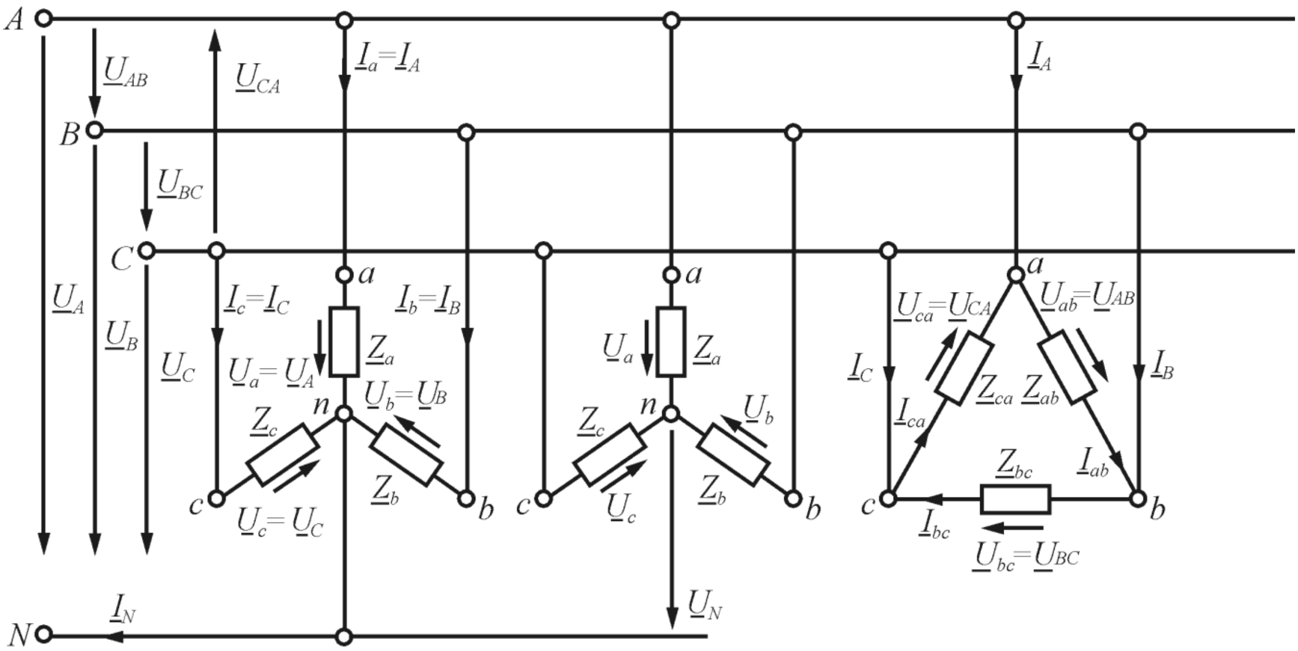
The purpose of the work is to consolidate theoretical knowledge about the operation of three-phase circuits of sinusoidal current, to obtain practical skills in measuring currents, voltages, powers in a three-phase circuit in the case of connecting the loads with a wye (Y) connection and a delta (Δ) connection.

5.1. Formulation of the problem

Learn how to form three-phase circuits and measure them in phase and line currents and voltages as well as active power. Experimentally check the basic ratios of phase and line currents and voltages in the case of a balanced load. Check the implementation of Kirchhoff's laws in three-phase circuits.

5.2. Theoretical thesis

In Fig. 5.1 a circuit is shown of a three-phase electrically connected in which the source phase is connected in wye (star, Y) scheme, and the load in wye (Y) (Fig. 5.1, *a*, *b*) or indelta (Δ) (Fig. 5.1, *c*). The source and loads are connected by a three-phase power transmission line formed by three line wires (*A*-*a*, *B*-*b*, *C*-*c*) and a neutral (*N*-*n*) wire (Fig. 5.1).



a   *b*   *c*

Figure 5.1

There are also a line phase current and voltage. The voltages between line wires (U_{AB}, U_{BC}, U_{CA}) are called line, but between line wires and neutral ***N*** (U_A, U_B, U_C) – the phase voltages.

The phase voltages of the source forms a three-phase symmetric system:

$$\underline{U}_A = U_{\text{Ph}} \cdot e^{j0^\circ};\ \underline{U}_B = U_{\text{Ph}} \cdot e^{-j120^\circ};\ \underline{U}_C = U_{\text{Ph}} \cdot e^{j120^\circ},$$

i.e. have the same active value U_{Ph} and the phase shifted relative to each other in one third of the period T an angle of $120°$, as shown in Fig. 5.2.

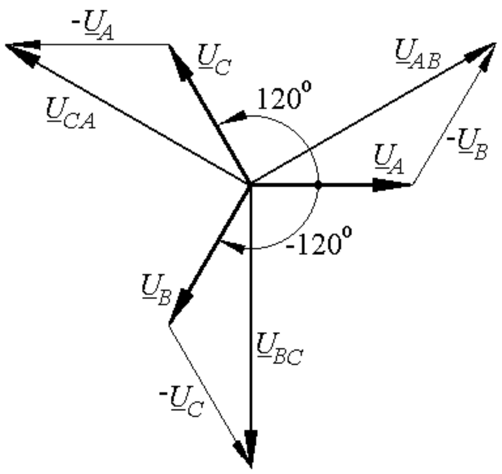


Figure 5.2

The line voltages of the source are related to the phase voltages on the basis of Kirchhoff’s voltage law:

$$\underline{U}_{AB} = \underline{U}_A - \underline{U}_B;$$

$$\underline{U}_{BC} = \underline{U}_B - \underline{U}_C;$$

$$\underline{U}_{CA} = \underline{U}_C - \underline{U}_A,$$

and form their symmetric system with the effective value of U_{L}. This system is also shown in Fig. 5.2 and shifted by phase relative to the system of phase voltage on 30º. From the phasor diagram, the relationship is obtained geometrically $U_{\text{L}} = \sqrt{3} \cdot U_{\text{Ph}}$ or $U_{\text{Ph}} = U_{\text{L}} / \sqrt{3}$. The system of the phase voltage of the source is always symmetric.

Three-phase loads can be connected in the following ways:

- Y with neutral – wye (Y) with the neutral wire (Fig. 5.1, *a*);
- Y – wye (Y) without the neutral wire (Fig. 5.1, *b*);
- Δ – delta (Δ) (Fig. 5.1, *c*).

In Fig. 5.1 the integrated resistances of the phases of the loads are marked: $\underline{Z}_a$, $\underline{Z}_b$, $\underline{Z}_c$ – when connected in Y (with neutral) and Y, $\underline{Z}_{ab}$, $\underline{Z}_{bc}$, $\underline{Z}_{ca}$ – when connected in Δ.

In general, for phase load $\underline{Z}_{\text{Ph}} = Z_{\text{Ph}} \cdot e^{j\varphi_{\text{Ph}}}$, where Z_{Ph} – impedance of the phase load, and φ_{Ph} – phase difference angle between a phase of the load voltage U_{Ph} and a phase of the load current I_{Ph}. The biasing angle determines the character of the load in the phase.

In Fig. 5.1 the following system of citation marks is adopted:

$\underline{I}_a$, $\underline{I}_b$, $\underline{I}_c$ – phase currents when connected in “Y” ($\underline{I}_{\text{PhY}}$);

$\underline{I}_{ab}$, $\underline{I}_{bc}$, $\underline{I}_{ca}$ – phase currents when connected in “Δ” ($\underline{I}_{\text{Ph}\Delta}$);

$\underline{I}_N$ – current in the neutral wire;

$\underline{I}_A$, $\underline{I}_B$, $\underline{I}_C$ – line currents with any method of load connection ($\underline{I}_{\text{LY}}$ or $\underline{I}_{\text{L}\Delta}$).

When a connection in Y between the neutral point of the load ***n*** and the neutral conductor ***N*** can occur, the neutral bias voltage $\underline{U}_N$.

On loads phase voltage is established (U_{PL}):

$\underline{U}_a$, $\underline{U}_b$, $\underline{U}_c$ or U_{PhY} – for connections in Y and Y;

$\underline{U}_{ab}$, $\underline{U}_{bc}$, $\underline{U}_{ca}$ or $U_{\text{Ph}\Delta}$ – for connection in Δ.

This voltage should not be confused with the already mentioned a phase voltage of the source. Specific voltage relatonships can be set by Fig. 5.3, namely:

$$\underline{U}_a = \underline{U}_A,\ \underline{U}_b = \underline{U}_B,\ \underline{U}_c = \underline{U}_C \ \text{– for Y}; \qquad (5.1)$$

$$\underline{U}_a = \underline{U}_A - \underline{U}_N,\ \underline{U}_b = \underline{U}_B - \underline{U}_N,\ \underline{U}_c = \underline{U}_C - \underline{U}_N \ \text{– for Y}; \qquad (5.2)$$

$$\underline{U}_{ab} = \underline{U}_{AB};\ \underline{U}_{bc} = \underline{U}_{BC};\ \underline{U}_{ca} = \underline{U}_{CA} \ \text{– for } \Delta. \qquad (5.3)$$

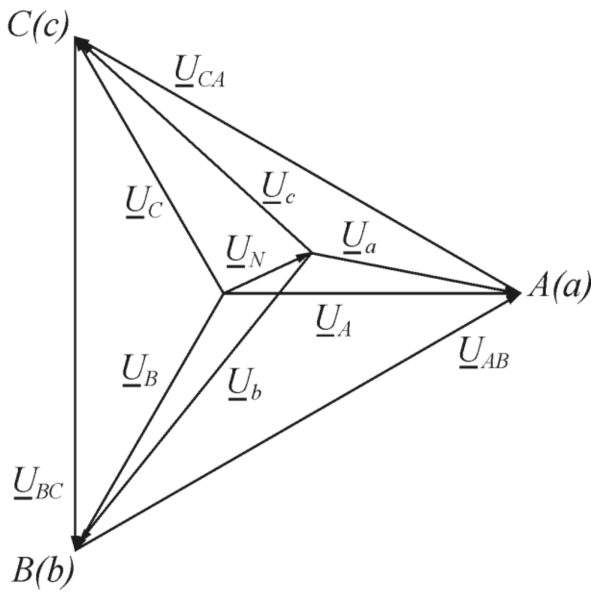


Figure 5.3

When connecting the load to Y and Δ its phase voltages, which form their phase and line voltage sources, respectively (see Fig. 5.2), are symmetric systems. When connected in the general case without the neutral wire and neutral bias voltage U_N is not equal to zero $\underline{U}_N \neq 0$., then three-phase load voltages are unbalanced, as shown in Fig. 5.3.

The active power of the three-phase load consists of active phase powers. For each phase of the load power is determined by a known expression

$$P_{\text{Ph}} = U_{\text{Ph}} \cdot I_{\text{Ph}} \cdot \cos \varphi_{\text{Ph}}.$$

5.2.1. Balanced load

If the complex resistances of the phases of loads are equal, then the load in this case will be symmetric. That is, there should be levels and modules of phase resistances Z_{Ph} and angles of phase shift φ_{Ph}, which determine the nature of the load in each phase.

$\underline{Z}_{\text{Ph}} = Z_{\text{Ph}} \cdot e^{j\varphi_{\text{Ph}}} = \underline{Z}_a = \underline{Z}_b = \underline{Z}_c$ – for connection in Y and Y;

$\underline{Z}_{\text{Ph}} = Z_{\text{Ph}} \cdot e^{j\varphi_{\text{Ph}}} = \underline{Z}_{ab} = \underline{Z}_{bc} = \underline{Z}_{ca}$ – for connection in **Δ.**

In this case, the acting values of phase currents are also equal, respectively, equal to each other and the effective values of line currents. Consequently, the calculation is enough to conduct only one of the phases. Between line voltages and phase currents and voltage and phase currents of the load, the following relationships are established:
when combined with a "Y" (with a neutral with and without a wire) based on formulas (5.1), (5.2) and taking into account $U_N = 0$

$$U_{\text{PhY}} = \frac{U_{\text{L}}}{\sqrt{3}}; \quad I_{\text{LY}} = I_{\text{PY}} = \frac{U_{\text{PhY}}}{Z_{\text{Ph}}} = \frac{U_{\text{L}}}{\sqrt{3} \cdot Z_{\text{Ph}}}, \tag{5.4}$$

when connected by a "Δ" based on the formula (5.3)

$$U_{\text{Ph}\Delta} = U_{\text{L}}; \quad I_{\text{L}\Delta} = \sqrt{3} \cdot I_{\text{Ph}\Delta} = \sqrt{3}\frac{U_{\text{Ph}\Delta}}{Z_{\text{Ph}}} = \frac{\sqrt{3} \cdot U_{\text{L}}}{Z_{\text{Ph}}} \tag{5.5}$$

Consequently, when re-coupling the load from the "Y" to the "Δ", the line currents and the power consumption increases three-fold:

$$P_{\Delta} = 3 \cdot P_{\text{Ph}\Delta} = 3 \cdot U_{\text{Ph}\Delta} \cdot I_{\text{Ph}\Delta} \cdot \cos\varphi_{\text{Ph}} = 3 \cdot U_{\text{L}} \frac{U_{\text{L}}}{Z_{\text{Ph}}} \cdot \cos\varphi_{\text{Ph}} = 3\frac{U_{\text{L}}^2}{Z_{\text{Ph}}} \cdot \cos\varphi_{\text{Ph}}.$$

5.2.2. Unbalanced load

If the phase impedances of the load are not equal to each other, then the load is unbalanced, that is

$\underline{Z}_a \neq \underline{Z}_b \neq \underline{Z}_c$ – when connected in "Y",

$\underline{Z}_{ab} \neq \underline{Z}_{bc} \neq \underline{Z}_{ca}$ – when connected in "Δ".

In the case of connecting the phases of the load in "Y" without a neutral wire, the phase voltage on the load changes with respect to the voltage of the source, since there is a bias voltage of the neutral wire, which is determined by the formula

$$\underline{U}_N = \frac{\underline{Y}_a \cdot \underline{U}_A + \underline{Y}_b \cdot \underline{U}_B + \underline{Y}_c \cdot \underline{U}_C}{\underline{Y}_a + \underline{Y}_b + \underline{Y}_c}, \tag{5.6}$$

where $\underline{Y}_a = \frac{1}{\underline{Z}_a}$, $\underline{Y}_b = \frac{1}{\underline{Z}_b}$, $\underline{Y}_c = \frac{1}{\underline{Z}_c}$ – complex admittance of the load phases. In the case of connecting the phases of the load to the "Y" with a neutral conductor, or in the "Δ", the asymmetry of the load on the phase voltage does not affect.

The phase current is determined by the Ohm law for the AC circuit

$$\underline{I}_{\text{Ph}} = \frac{\underline{U}_{\text{Ph}}}{\underline{Z}_{\text{Ph}}}, \tag{5.7}$$

where $\underline{U}_{\text{Ph}}$ – the voltage applied to the load phase, which is determined depending on the method of connecting the phases and the presence of asymmetry in accordance with (5.1), (5.2) or (5.3). Addition of phase currents for the determination of the line current, as well as the current in the neutral wire, is carried out in a phasor or complex form taking into account the received direction of currents.

When connected in "Y":

$$\underline{I}_A = \underline{I}_a,\ \underline{I}_B = \underline{I}_b,\ \underline{I}_C = \underline{I}_c,$$

and the current in the neutral wire $\underline{I}_N = \underline{I}_A + \underline{I}_B + \underline{I}_C$, (5.8)

when connected in "Δ", the line currents relationships with phases on the basis of Kirchhoff's first law are

$$\underline{I}_A = \underline{I}_{ab} - \underline{I}_{ca},\ \underline{I}_B = \underline{I}_{bc} - \underline{I}_{ab},\ \underline{I}_C = \underline{I}_{ca} - \underline{I}_{bc}. \tag{5.9}$$

With unbalanced load, the power of each phase is determined in accordance with its phase voltage, currents and load factors. The power consumed by the three-phase network is equal to the sum of phase powers.

when connected in "Y"

$$P_Y = U_a \cdot I_a \cdot \cos\varphi_a + U_b \cdot I_b \cdot \cos\varphi_b + U_c \cdot I_c \cdot \cos\varphi_c;$$

when connected in "Δ"

$$P_\Delta = U_{ab} \cdot I_{ab} \cdot \cos\varphi_{ab} + U_{bc} \cdot I_{bc} \cdot \cos\varphi_{bc} + U_{ca} \cdot I_{ca} \cdot \cos\varphi_{ca}.$$

5.3. Object of study

The diagram of the electric circuit in the case of connecting loads in "Δ" is shown in Fig. 5.4. Resistors *R*1, *R*2, *R*3 are used as loads. The investigated circuit is switched on to the three-phase network *A*, *B*, *C*, *N* with a line voltage of 36 *V*. The voltage measurement is carried out using a portable voltmeter *PV*.

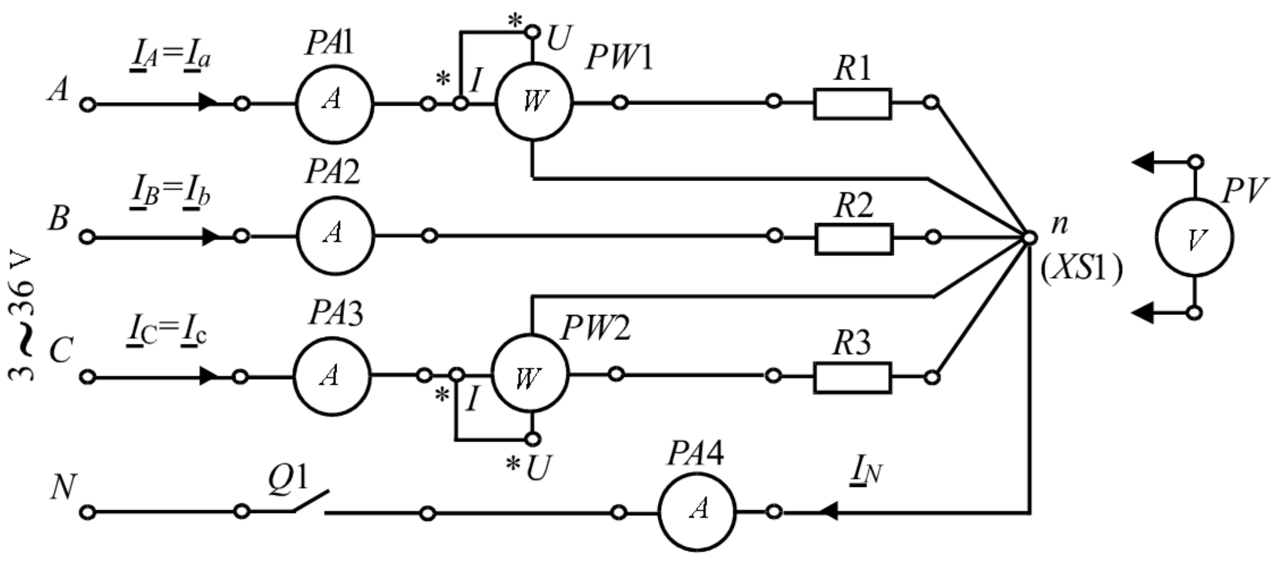


Figure 5.4

Voltages: U_{AB}, U_{BC}, U_{CA} line (between corresponding lines A, B and C); U_A, U_B, U_C phase in the network (between A, B and C and the neutral wire N); U_a, U_b, U_c phase on the load (between the phases A, B, C and the neutral point of loading $\boldsymbol{n}$); U_N the bias voltage of the neutral (between the points $\boldsymbol{N}$ and $\boldsymbol{n}$).

When connecting the load according to the "Y" scheme, the line currents I_A, I_B, I_C are equal to the corresponding phase currents I_a, I_b, I_c. Therefore, line and phase currents are measured by the *PA*1, *PA*2, and *PA*3 ammeter. Ammeter *PA*4 – current I_N in the neutral wire.

Wattmeter *PW*1 and *PW*2 measure the active powers of phases A and C – P_a and P_c. In the case of a balanced load, the power of all phases should be the same and equal to the power P_{Ph}, which is consumed by any phase load. Therefore, the active power of the three-phase balanced load is $P_S = 3P_{\text{Ph}}$.

In the case of connecting the loads in "Δ" circuit diagram of the electric circuit is given in Fig. 5.5. Here as well as loads of electric energy resistors *R*1, *R*2, *R*3 are used. Resistors *R*1, *R*2, *R*3 form a balanced load. The circuit is connected to a three-phase balanced network *A*, *B*, *C*, *N* with a line voltage of 36 *V*.

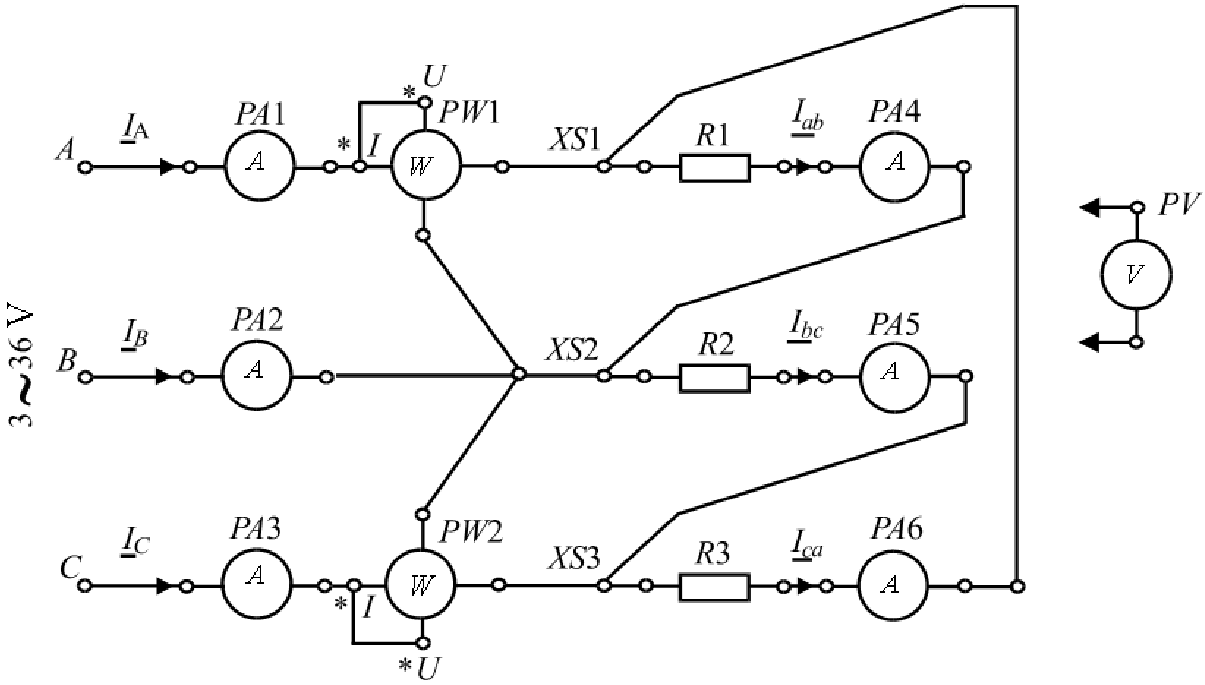


Figure 5.5

The measurement of line voltages of U_{AB}, U_{BC}, U_{CA} is carried out using a portable *PV* voltmeter (between the corresponding lines *A*, *B* and *C*). When connecting a three-phase load according to the "Δ" scheme, these same voltages are simultaneously phase-dependent and are denoted U_{ab}, U_{bc}, U_{ca}.

Line I_A, I_B, I_C and phase I_{ab}, I_{bc}, I_{ca} currents are measured by the corresponding ammeter *PA*1-*PA*6.

Watthmeters *PW*1 and *PW*2 according to the scheme shown in Fig. 5.2, measure the active power of the three-phase load in general, i.e. $P_S = P_1 + P_2$.

5.4. The order of the experiment execution

5.4.1. Measure the line and phase voltage of the source. Enter the results of measurements in Table 5.1.

Table 5.1

Voltage source, V								Correlation voltages (Line/Phase)
Measured						Average values		
U_{AB}	U_{BC}	U_{CA}	U_A	U_B	U_C	U_{L}	U_{Ph}	$U_{\mathrm{L\ mid}}/U_{\mathrm{Ph\ mid}}$
V	V	V	V	V	V	V	V	–

5.4.2. Assemble the electric circuit in accordance with Fig. 5.4. Place a neutral loading point ***n*** on terminal assembly *XS*1.

5.4.3. Conduct a balanced load test without a neutral conductor (in the phase the identical resistors *R*1, *R*2 and *R*3 are switched on, and the key *Q*1 must be in the open state). Measure the phase voltages U_a, U_b, U_c of the loads *R*1, *R*2, *R*3 and make sure that they are equal to the corresponding phase voltages of the source U_A, U_B, U_C, and the neutral bias voltage U_N is zero. These data, as well as the measured currents and power, are recorded in Table 5.2.

5.4.4. Conduct a balanced load test with a neutral wire (in the phase the identical resistors *R*1, *R*2 and *R*3 are switched on and the key *Q*1 must be in the closed state). It is necessary to carry out the same measurements as in the previous paragraph and to make sure that in the case of balanced load, the neutral wire does not make any changes (any changes are possible due to asymmetry of the voltage in the power supply). Enter the results in Table 5.2.

Table 5.2

Given		Measured												Calculated		
Character of the load	Connection method	Voltage, V				Current, A				Power, W				Phase impedance, Ohm		
		U_a	U_b	U_c	U_N	I_a	I_b	I_c	I_N	P_a	P_b	P_c	P_S	Z_a	Z_b	Z_c
Balanced *R*1, *R*2, *R*3	Y															
	Y̶															

5.4.5. Assemble an electric circuit in the case of connecting loads to a “Δ” in accordance with Fig. 5.2.

5.4.6. Conduct research of a three-phase circuit with a balanced load. To do this, measure the values given in Table 5.3 and record the results.

Table 5.3

Given	Measured											Calculated			
The character of the three-phase load	Voltage, V			Current, A						Power, W			Phase impedance, Ohm		
	U_{AB}	U_{BC}	U_{CA}	I_A	I_B	I_C	I_{ab}	I_{bc}	I_{ca}	P_1	P_2	P_S	Z_{ab}	Z_{bc}	Z_{ca}
*R*1, *R*2, *R*3															

5.5. Processing the results of the experiment and design work

5.5.1. Calculate the average values of the line and phase voltages of the source U_{Lmid} and U_{Pmid} and their ratios according to tab. 5.3 and compare with the theoretical value.

5.5.2. According to Table 5.2, calculate the Z_a, Z_b, Z_c phase resistance of Ohm's law for phase impedance $Z_{\text{Ph}} = U_{\text{Ph}} / I_{\text{Ph}}$, where U_{Ph}, I_{Ph} are phase voltages and currents on the load of the corresponding phases. Next, consider that in all cases resistors $Z_{\text{Ph}} = R_{\text{Ph}}$ (resistance).

5.5.3. According to the results of measurements, calculate the total active power of the three-phase circuit – P_S (Table 5.2).

5.5.4. Draw on a scale of the research data a phasor diagram of voltages and currents for the balanced load in the case of connecting loads in "Y" in accordance with Fig. 5.1.

5.5.5. Calculate the average values of line and phase currents in the case of balanced load and their ratios $I_{\text{L}} / I_{\text{P}}$ according to Table 5.3 and compare with the theoretical value $\sqrt{3}$.

5.5.6. According to Table 5.3, calculate the three-phase load Z_{ab}, Z_{bc}, Z_{ca} of the Ohm's law: phase impedance $Z_{\text{Ph}} = U_{\text{Ph}} / I_{\text{Ph}}$, where U_{Ph}, I_{Ph} are phase voltages and currents on the load of the corresponding phases, because in all cases for resistors $Z_{\text{Ph}} = R_{\text{Ph}}$ (resistance).

5.5.7. By the results of measurements, calculate the total power of the three-phase circuit P_S (Table 5.3).

5.5.8. Draw on a scale of the experimental data a phasor diagrams and currents for the balanced load in the case of connection of the loads in "Δ" according to Fig. 5.6.

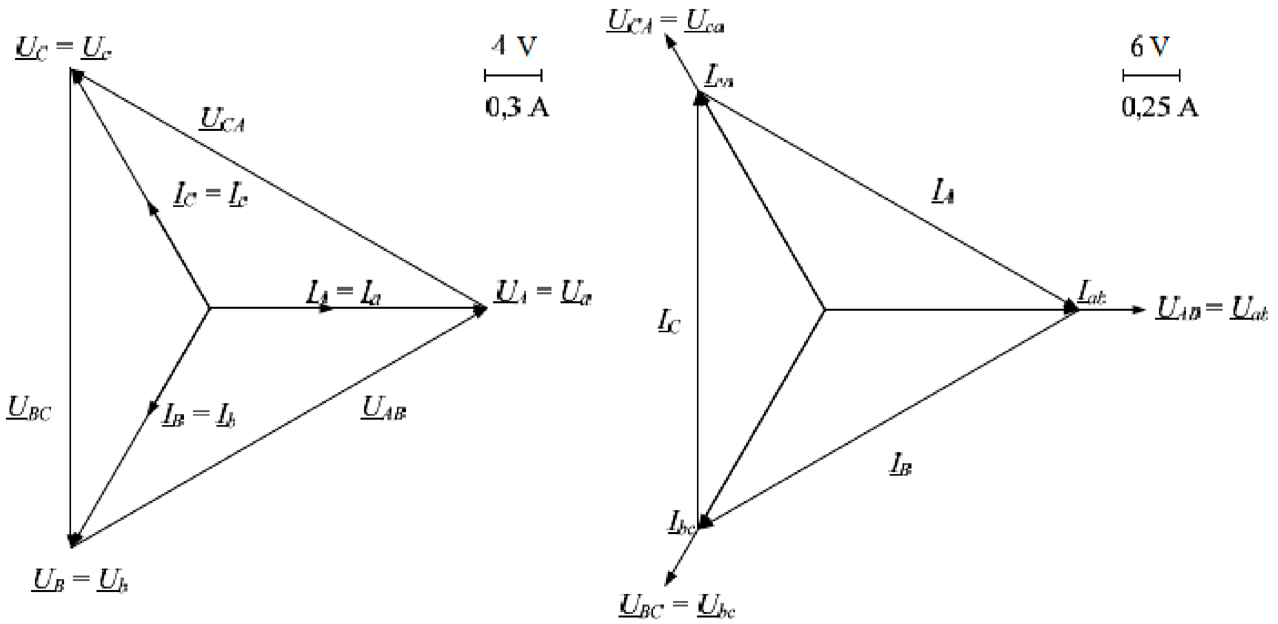


Figure 5.6

Control questions

1. What is the load of a three-phase circuit calledbalanced, and which one calledunbalanced?

2. How to combine three single-phase loads with “Y” or “Δ” connections?

3. What voltages and currents are called phase, line and where are they in a circuit?

4. What are the dependencies between the current values of line and phase voltages and currents in the case of a balanced load when the loads are connected in “Y”?

5. What is the relationship between line and phase currents and voltages in the case of balanced load when the phases are connected in “Δ”?

6. What is the order of building phasor diagrams for different conections of the three-phase load, which is connected according in “Y” scheme?

7. What role does the neutral wire play?

8. What is a neutral bias; in what cases it appears and how to calculate it?

9. How do you determine the phase difference angle between the load currents and voltages?

10. How is active power measured in a three-phase network?

11. How can you build a phasor diagram of voltages and currents when connecting a three-phase load in “Δ”?

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для студентів неелектротехнічних спеціальностей
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