TFEE-2

MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE

Dnipro University of Technology

Department of Electrical Engineering

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Guidelines to laboratory works on discipline
THEORETICAL FUNDAMENTALS OF ELECTRICAL ENGINEERING

For full-time students' education in academic discipline 141"Electric Power, Electrical Engineering and Electromechanics"

Part 1
THREE–PHASE CIRCUITS, POLYHARMONIC VOLTAGES AND CURRENTS IN CIRCUITS
and
TRANSIENT ANALYSIS OF LINEAR CIRCUITS

Dnipro
2021

Рекомендовано до видання навчально-методичним відділом (протокол № від за поданням науково-методичної комісії зі спеціальності 141 – Електроенергетика, електротехніка та електромеханіка (протокол № 21/22-01 від 30.08.2021 р.)

Методичні вказівки англійською мовою до лабораторних робіт з дисципліни «Теоретичні основи електротехніки», частина 2 (розділи: «Трифазні електричні кола. Вищі гармоніки у електричних колах» та «Перехідні процеси в лінійних електричних колах» для студентів спеціальності 141 – Електроенергетика, електротехніка та електромеханіка / В.С. Хілов; Нац. техн. ун-т. «Дніпровська політехніка» – Д.: НТУ "ДП", 2021. – 52 с.

Методичні вказівки англійською мовою призначено для виконання лабораторних робіт з дисципліни «Теоретичні основи електротехніки», частина 2 (розділи: «Трифазні електричні кола. Вищі гармоніки у електричних колах» та «Перехідні процеси в лінійних електричних колах» В інструкціях до виконання лабораторних робіт наведено основний матеріал, який викладається на протязі двох чвертей семестру та відповідає затвердженій програмі. Кожна лабораторна робота складається з назви, мети, програми та етапів виконання, методичних вказівок, контрольних запитань.

Друкується в редакції автора.

Introduction

One of the most important types of classes in the course "Theoretical fundamentals of electrical engineering" is the performance of laboratory work. To increase the efficiency of the laboratory practicum, these methodical instructions have been developed.

Methodical instructions are intended for laboratory work in the discipline "Theoretical fundamentals of electrical engineering" (part 2, modules 3, 4 " Three-phase Circuits, Poliharmonic Voltages and Currents" and "Transient Analysis of Linear Circuits") for full-time students education in academic discipline: 141"Electric Power, Electrical Engineering and Electromechanics".

These laboratory works contain all the basic material, which is taught during two quarters of the semester and corresponds to the approved program.

Each laboratory work consists of the name, objective, program and stages of work execution, guidelines, control questions.

Duration of laboratory work is two academic hours; independent preparation for work - one hour; report - one hour.

The objective of laboratory classes is to consolidate the theoretical knowledge gained in lectures, and the acquisition of skills in experimental research of electrical circuits.

The process of laboratory work is designed for four stages: independent preparation for laboratory classes; experimental research on the stand; registration of research results; obtain the credit for laboratory work.

Independent preparation for the laboratory lesson is carried out in accordance with the topic and objective of the work. This is an in-depth study of the relevant sections of the TFEE course, the selection of individual parameters of the schemes, recording the necessary analytical relationships, drawings of schematic diagrams and tables for experimental results, answers to questions posed in the task.

The report is compiled by each student independently and is the main document in the performance and defense of laboratory work, which is drawn up in a separate notebook (18 sheets). Graphs and vector diagrams are built at scale. The report on each laboratory work should contain the main items: 1. Number and title of the work; 2. Objective of work; 3. Program of work c; 4. Analysis of results; 5. Conclusions on the performed calculations and their experimental verification. In addition to the main points, the report should contain additional points that are listed in each paper.

Experimental research is conducted at the training and research stand by teams of 2-3 students. The team receives permission to draw up an electrical circuit only after an interview with the tutor.

The student during the laboratory work must:

• follow the rules of electrical safety, which are given in the guidelines for laboratory work;

• perform laboratory work according to the appropriate method;

• make a report on the performance of laboratory work;

• protect the results of previous laboratory work;

• to receive an assessment for a laboratory module through a certain form of modular control (protection of reports on laboratory work).

BASIC SAFETY RULES
WHEN PERFORMED A LABORATORY PRACTICUM

1. Only students who are acquainted with the rules of safety in the electrical laboratories of the university are allowed to take the laboratory practicum.
2. Before passing the next cycle of the laboratory practicum in the electrical laboratories of the university, students must study the safety instructions and receive additional instruction before starting work in each subsequent laboratory. Students, after getting acquainted with the rules of safety and instructed, must sign the logbook for compliance with safety rules and liability for violation.
3. During work in electric laboratories it is forbidden to switch on laboratory stands under voltage, to make any switching on or switching in the main distribution cabinet, to change safety locks, and after automatic switching off by the protective equipment to do switching on again without the permission of the tutor conducting laboratory practicum.
4. Drawing up of electric schemes and all changes in electric schemes should be carried out at the switched-off voltage. It is impossible to switch in the scheme in work before check of its serviceability.
5. It is forbidden to leave current conductors with or without voltage in the passages between workplaces. It is forbidden to make any switches in the power supply circuits of the research stands.
6. It is possible to use conductors for drawing up schemes only on condition of sufficient area of their section by the provided value of currents. Conductors must be intact insulation and lugs. Particular care should be taken when studying circuits with series connections of inductors and capacitors, as resonant overvoltage’s are possible in such circuits.
7. Keep in mind that a disconnected capacitor can retain a dangerous residual charge, so it must be discharged before connecting to the circuit. Do not touch uninsulated current-carrying parts of electrical circuits that are or may be with voltage.
8. If during the laboratory work on the stand there is a characteristic smell of burnt plastic, strong buzzing of electrical equipment, smoke, or a sudden movement of the arrows off-scale of measuring instruments, you must immediately turn off the voltage and notify of the tutor.
9. In the event of an emergency (may be a person under voltage, a short circuit on the lab stand, breakage of current-carrying wires, fire etc.) first of all with the switch turns off the lab stand from the power supply, and if necessary, the button "Off 95 "the power supply of the classroom is disconnected. Button "Off. 95 "is in the distribution cabinet.
10. The fire is extinguished by a carbon dioxide fire extinguisher located at the workplace of the duty laboratory assistant. There is also a first aid kit with medicines for first aid.

Laboratory Work TFEE – 2/1

EXPERIMENTAL STUDY OF THREE PHASE CIRCUITS POWERED BY SYMMETRICAL EMF SUPPLY AND WYE-CONNECTED LOAD

Objective

Analysis three- and four-wires systems operating modes when the load is wye-connected and symmetrical power source.

Program of Work

1. Assemble three-phase symmetrical power unit by the symmetrical wye circuit.
2. Assemble three-phase load by wye connection for next cases:
- symmetrical homogeneous without neutral wire (three-wire system);
- symmetrical homogeneous with neutral wire (four-wire system);
- asymmetrical homogeneous without neutral wire (three-wire system);
- asymmetrical homogeneous with neutral wire (four-wire system);
- asymmetrical non-homogeneous without neutral wire (three-wire system);
- asymmetrical non-homogeneous with neutral wire (four-wire system);
- asymmetrical non-homogeneous without a zero wire when the load phase A interruption;
- asymmetrical non-homogeneous with a zero wire when the load phase A interruption.
3. Experimental study the three phases circuits when three- and four-wires systems and load assembled in wye-connection.
4. Plotting phasore diagrams for three-phase load connecting by wye circuit, with and without a neutral wire.
5. Analysis of results. Summarizing.

Work stages

Stage 1. Assemble three-phase symmetrical power unit by the wye circuit.

Assemble the electrical circuit of the power supply, which is shown in Fig. 1.1. Single-phase sources from a three-phase unit are used as the main elements of the circuit.

The measured line and phase voltages of the power supply and the results obtained are entered in table. 1.1.

The load of the three-phase voltage block is shown in the form of a passive two-port circuit (Fig. 1.1). At the first stage of the work, the load is not switched on.

Stage 2. Assemble of a three-phase load by the wye connection.

2.1. Next elements are used as phase impedances:

as impedance $\underline{Z}_A$ in all connection circuits, the resistance R_1 is taken from the block of fixed resistances;

as impedance $\underline{Z}_B$ in all homogeneous balanced and unbalanced connection circuits, the resistance R_2 is taken from the block of fixed resistances; in non-homogeneous connection circuits, the C_2 capacitance is taken from the block of fixed capacities;

as $\underline{Z}_C$ in homogeneous balanced and unbalanced circuits of connection is taken resistance R_3 from the block of adjustable resistances; in non-homogeneous connection circuits, the inductance L_2 is taken from the block of fixed inductances (the resistance of the coil is measured with a multimeter before connecting the coil to the circuit).

The value of phase impedances its need be recorded in in table 1.2.

2.2. Assemble the electrical circuit of the three-phase source, which is shown in Fig. 1.2. Symmetrical three-phase power supply is represented by an active two-port circuit, which is assembled according to the circuit of Fig. 1.1.

2.3. After checking the electrical circuit by the tutor, the power supply is turned on.

Stage 3. Experimental study the three phases circuits when three- and four-wires systems and load assembled in wye-connection.

3.1. Measure the voltages across the phases of the load U_A, U_B, U_C, line voltages U_{AB}, U_{BC}, U_{CA}, the voltage between neutral points $U_{00'}$. The finding voltage values its need record in table 1.2.

3.2. Measure the currents in the electrical circuit, Fig. 1.2, by swithing on milliammeter one-by-one in line wires. Record the currents in Table 1.2.

Stage 4. Plotting phasor diagrams for three-phase load connecting by wye circuit, with and without a neutral wire.

According to table 1.1, 1.2 in the selected scale its need plot combined phasor diagrams of electric currents and voltages when load is connected in wye circuits for the next cases:

- symmetrical homogeneous without neutral wire (three-wire system);
- symmetrical homogeneous with neutral wire (four-wire system);
- asymmetrical homogeneous without neutral wire (three-wire system);
- asymmetrical homogeneous with neutral wire (four-wire system);
- asymmetrical non-homogeneous without neutral wire (three-wire system);
- asymmetrical non-homogeneous with neutral wire (four-wire system);
- asymmetrical non-homogeneous without a zero wire when the load phase A interruption;
- asymmetrical non-homogeneous with a zero wire when the load phase A interruption.

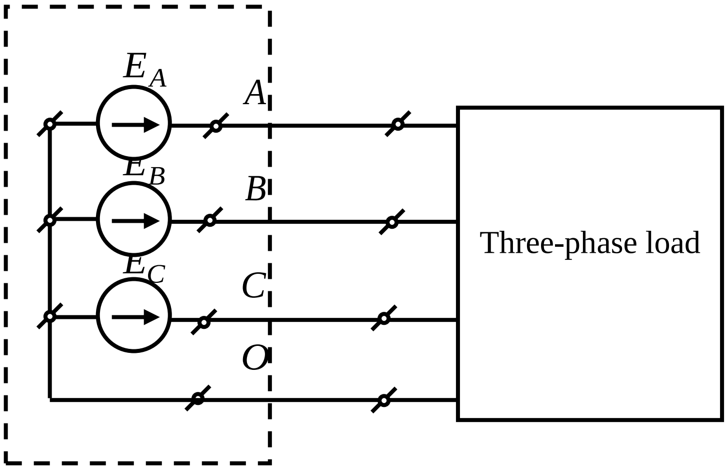

Figure 1.1. – Four-wired three-phase circuit

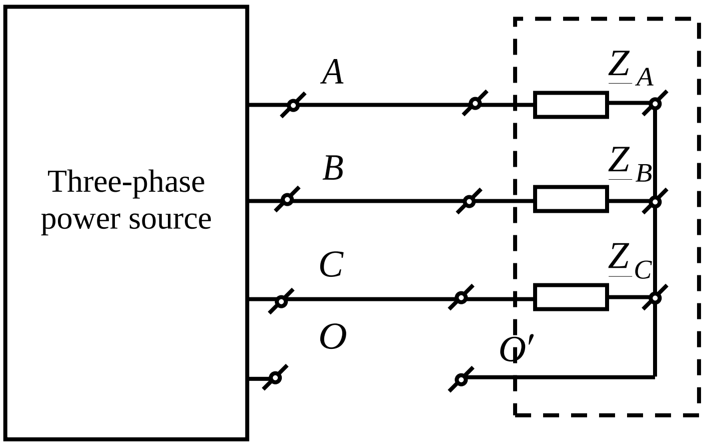

Figure 1.1. – Three-wired three-phase circuit

Table 1.1.

Measured parameters of a symmetrical three-phase power supply

E_A	E_B	E_C	U_{AB}	U_{BC}	U_{CA}
V	V	V	V	V	V

Table 1.2.

Values of phase resistances and measured values of voltages and currents at Wye Connection

Load Character	Power System	Phase Resistance						Load Across Voltage							Currents Through the Load Phases			
		R_A	X_A	R_B	X_B	R_C	X_C	U_A	U_B	U_C	U_{AB}	U_{BC}	U_{CA}	$U_{00'}$	I_A	I_B	I_C	I_N
		Ω	Ω	Ω	Ω	Ω	Ω	V	V	V	V	V	V	V	A	A	A	A
Symmetrical Homogeneous	3-wire																	
	4-wire																	
Asymmetrical Homogeneous	3-wire																	
	4-wire																	
Asymmetrical Non-homogeneous	3-wire																	
	4-wire																	
Asymmetrical Non-homogeneous (load phase A interruption)	3-wire																	
	4-wire																	

The Report must contain

1. The number and title of the laboratory work.
2. The Objective.
3. The Program of work.
4. Figures 1.1, 1.2.
5. Tables 1.1, 1.2.
6. Calculated ratios.
7. Phasor diagrams according to Table 1.2.
8. The conclusions of the laboratory work

Methodical Instruction

To the Stage 1. In order to assemble a symmetrical three-phase power source, it is necessary and sufficient to fulfill two conditions: the equality of the phase (or line) voltage modules and the shift angles between the phase (or line) voltages must be equal to $2 \cdot \pi / 3$.

To fulfill the first condition before switching on the circuit of loading by the multimeter values of phase EMF of power supplies are checked and voltages of the order of 20 V are established by decade switches.

By connecting the terminals of single-phase power supplies the same named (seen on the stand *) into a common point, the second condition is fulfilled. Then you need to measure the line voltages of the power supply. If the power supply is symmetrical, then the modules of the line voltages are equal to one another.

Phase voltages are measured between a common point and a phase terminal, and line voltages are measured between the terminals of the corresponding phases.

To the Stage 2. When the inductance L of the coil and the capacity C of the capacitor are known, then the inductive x_L and the capacity x_C reactance are defined like this:

$$x_L = 2 \cdot \pi \cdot f \cdot L; \quad x_C = 1/(2 \cdot \pi \cdot f \cdot C),$$

where f – industrial cyclic frequency of supply voltage, Hz; L – inductance, H; C – capacity, F.

To the Stage 4. It is recommended to plot vector diagrams starting with the phase and line voltages of the power supply.

4.1. Phasor diagrams of an electric load wye-connected without a neutral wire.

With a mathematical compass on the scale of voltages, it is necessary to make marks that are equal to the load phase voltages U_A, U_B, U_C, and the ends of these vectors should be connect with the ends of the same named vectors of phase voltages of the power source. The marks by mathematical compasses outline a geometric place (a triangle with sides in the form of arcs). The geometric center of the found triangle is the potential of the load common point O' relative to the power source common point O. By connecting the points O' and O, one can find the neutral displacement voltage vector $U_{OO'}$. Then by connecting the geometric center of the triangle O' with the points A, B, C on the vector diagram, we determine the vectors of the phase voltages on the load.

Phase currents on a phasor diagram by phases are shifted relative to the corresponding phase voltage.

When ohmic resistance, the current and voltage coincided in the phase, and when a active - reactive impedance, there occur phase displacement

$$\varphi = arctg(x / R),$$

where x – reactance; R – phase ohmic resistance.

4.2. Phasor diagram plotting for load connected by wye with a neutral wire.

In this case, the displacement voltage of the neutral between the points O and O' absent since the potentials between the neutral points are equalized by the neutral wire.

The phase voltages at the load are equal to the phase voltages at the power supply. The phase currents of the load are shifted by the phase relative to the phase voltages and the current through the neutral wire is located as the geometric sum of the phase currents.

Questions for check knowledge

1. Under what conditions will the three-phase EMF system be symmetric?
2. How is a symmetrical three-phase power source wye assembled?
3. What is the relationship between line and phase voltages when symmetrical wye-connected power source?
4. What is the displacement neutral voltage and how it affects the mode of operation of the thee-phase load?
5. Why switch on the neutral wire?
6. What is equal the sum of the vectors of the phase currents when wye-connected load?
7. How to calculate the voltage between the neutral points of the power supply and the load in case of phase interruption A?
8. How is defined the average power of a symmetrical three-phase circuit wye-connected?
9. How and in what cases are the phase voltages at the source and receiver different when wye-connected?
10. Do it need a neutral wire in a symmetrical load wye-connected?

Laboratory Research TFEE – 2/2

EXPERIMENTAL STUDY OF THREE-PHASE CIRCUITS WHEN DELTA CONNECTED LOAD AND SYMMETRICAL POWER SOURCE

Objective

Three-phase circuits operation modes analysis when connected the load by delta and a symmetrical power supply.

Program of Work

1. Assemble three-phase symmetrical power unit by the symmetrical wye circuit.
2. Assemble of a three-phase load according to the delta circuit for next cases:
- symmetrical homogeneous;
- asymmetrical homogeneous;
- non-homogeneous;
- non-homogeneous when load AB-phase interruption;
- non-homogeneous when source A-phase interruption.
3. The three-phase circuit experimental research when load connected by delta circuit.
4. Plotting phasor diagrams for the studied three-phase circuits when connecting the load by delta circuit.
5. Analysis of results. Conclusions.

Stages of operation

Stage 1. Assemble of a three-phase symmetrical power supply unit by the wye circuit.

Assemble the electrical circuit of the power supply, which is shown in Fig. 2.1. Single-phase sources from the three-phase block are used as the main elements of the circuit.

The measured line and phase voltages of the power supply and the obtained results are entered in Table 2.1.

Table 2.1.

Measured voltages of a symmetric three-phase energy source

E_A	E_B	E_C	U_{AB}	U_{BC}	U_{CA}
V	V	V	V	V	V

The load of the three-phase voltage block is shown in the form of a passive two-port circuit (Fig. 2.1). The load is not switched on at the first operation stage.

Stage 2. Assemble of a three-phase load by delta circuit.

2.1. Elements are used as phase impedances:

– in all connection circuits the ohmic resistance R_2 is taken from the block of fixed resistances;

–in homogeneous symmetrical and asymmetrical connection circuits the ohmic resistance R_2 from the block of fixed resistances is used; in inhomogeneous connection circuits the capacity C_2 from the block of fixed capacitors is taken;

– in homogeneous symmetrical and asymmetrical connection circuits, the ohmic resistance R_4 is used from the block of adjustable resistances; in non-homogeneous connection circuits, the inductance L_4 is taken from the block of adjustable inductances (the ohmic resistance of the coil is measured with a multimeter before the coil is connected to the electrical circuit).

The values of the phase resistances are record in Table. 2.2.

2.2. Assemble the electrical circuit of the three-phase load showing in Fig. 2.2.

The symmetrical three-phase power supply is shown by an active two-port circuit, which is assembled according to the circuit shown in Fig. 2.1.

2.3. After checking the electrical circuit by the tutor, turn on the power supplies.

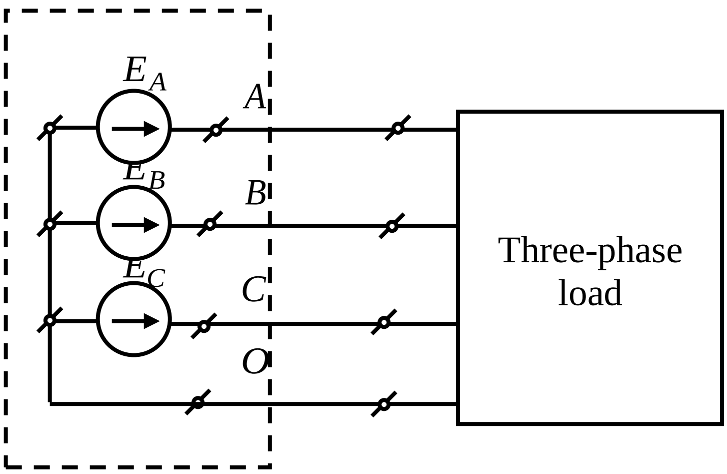

Figure 2.1. – Four-wired three-phase network

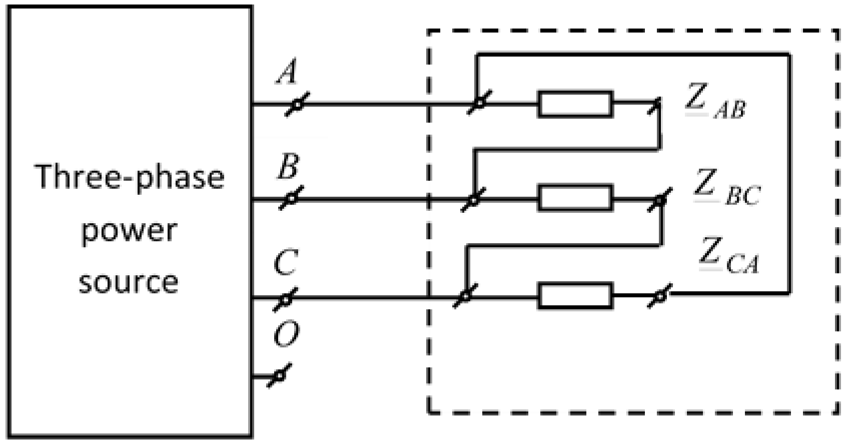

Figure 2.2. – Three-wired three-phase network

<u>**Stage 3.** Experimental study of a three-phase circuit when load connecting by delta circuit</u>.

3.1 Measure phase (line) voltages of the load U_{AB}, U_{BC}, U_{CA}. Record the found values in the Table. 2.2.

3.2. Measure currents through the branches of a three-phase circle (Fig. 2.2), switching on a milliammeter alternately in the line and phase wires. Record the values of the currents in Table. 2.2.

<u>**Stage 4**</u>**.** <u>Plotting of phasor diagrams for the studied three-phase circuits when the load connected by delta circuit.</u>

In the convenient selected scale according to data of the Table. 2.1, 2.2 construct combined phasor diagrams of electric currents and voltages when the load delta connecting for the next cases:

- symmetrical homogeneous;
- asymmetrical homogeneous;
- symmetrical non-homogeneous;
    - non-homogeneous when load AB-phase interruption;
    - non-homogeneous when source A-phase interruption.

The Report must contain

1. The number and title of the laboratory work.
2. The Objective.
3. The Program of Work.
4. Figures 2.1, 2.2.

5. Tables 2.1, 2.2.
6. Calculated ratios.
7. Phasor diagrams according to Table 2.2.
8. The conclusions of the laboratory work.

Questions for check knowledge

1. Is the sum of instantaneous values of linear currents equal to zero?
2. Is the geometric sum of the vectors of linear currents equal to zero?
3. What is the relationship between line and phase currents with a symmetrical load connected in delta?
4. How will the linear current change if at first the load phase resistances were the same and then the phase circuit was broken?
5. How is related linear and phase currents under asymmetric load? Are these ratios valid under symmetrical loading or not?
6. How will the phasor diagram change under asymmetric loading, if the capacitive resistance in phase is replaced by a perfectly inductive resistance equal to its value?
7. How to calculate the average power with a symmetrical load connected by delta through linear current and voltage?
8. How to calculate the reactive power when asymmetric and symmetric loads connected by a delta?
9. How to calculate the total power of a circuit when connected by a delta and a symmetrical load?
10. How to calculate the total power of a circuit when connected by a delta and an asymmetric load?

Laboratory Research TFEE – 2/3

EXPERIMENTAL RESEARCH OF THREE-PHASE CIRCUITS WHEN WYE-CONNECTED LOAD AND ASYMMETRICAL POWER SOURCE

Objective

Research three-phase circuits asymmetric operation modes by the method of symmetrical components.

Program of Work

1. Assembly of a three-phase asymmetric power supply.
2. To the asymmetric three phase power supply unit join symmetrical three-phase load when wye connection without zero wire.

3. The phase currents measurement when the symmetric three-phase load connected wye-circuit without neutral wire.
4. To the asymmetric three phase power supply unit join symmetrical three-phase load when wye connection with zero wire.
5. The phase currents and currents through the neutral wire measurement when the symmetric three-phase load connected wye-circuit with neutral wire.
6. To the asymmetric three phase power supply unit join asymmetrical three-phase load when wye connection with zero wire.
7. The phase currents and currents through the neutral wire measurement when the asymmetric three-phase load connected wye-circuit with neutral wire.
8. Calculation currents in a three-phase circuit with asymmetric power supply unit and wye connected load.
9. Plotting phasor diagrams.
10. Analysis of results. Conclusions.

Stages of operation

Stage 1. Assemble of a three-phase asymmetrical power supply unit by the wye circuit.

1.1. Using three EMF sources from the three-phase voltage block, assemble a symmetrical three-phase voltage source (U_{ph}= 20 V) according to the wye circuit, fig.1.

1.2. By changed the start and finish of any phase of a symmetric three-phase power supply (for example in B phase), obtain an asymmetric power source according to the wye circuit. Measure the phase and line voltages, enter this data in table. 1.

Stage 2. To the asymmetric three phase power supply unit join symmetrical three-phase load when wye connection without zero wire.

Using fixed resistors of the block of active resistances, assemble the symmetrical three-phase load according to the wye circuit without a zero wire, Fig. 3.2. Check the symmetry of the phase resistors with a multimeter operating in the resistance measurement mode. The resistance values must not differ from each other by more than 5%, otherwise the by using an additional resistances are equalized the resistance values. Write down the phase resistances values.

Stage 3. The phase currents measurement when the symmetric three-phase load connected wye-circuit without neutral wire.

Switching on the milliammeter in turn in the linear wires, measure the currents of the lines I_A, I_B, I_C and enter their values in Table.3.2.

Table 3.1.

Measured voltages of an asymmetric three-phase energy source

E_A	E_B	E_C	U_{AB}	U_{BC}	U_{CA}
V	V	V	V	V	V

<u>Stage 4.</u> <u>To the asymmetric three phase power supply unit join symmetrical three-phase load when wye connection with zero wire.</u>

Without changing the circuit drawn up in Stage 2 (Fig. 3.2), connect the zero points of the power supply O and load O'.

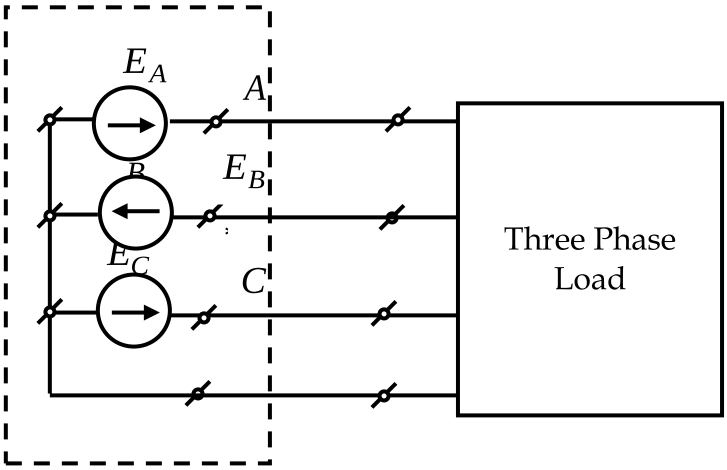

Figure 3.1. – Four wired network with asymmetric three-phase power supply

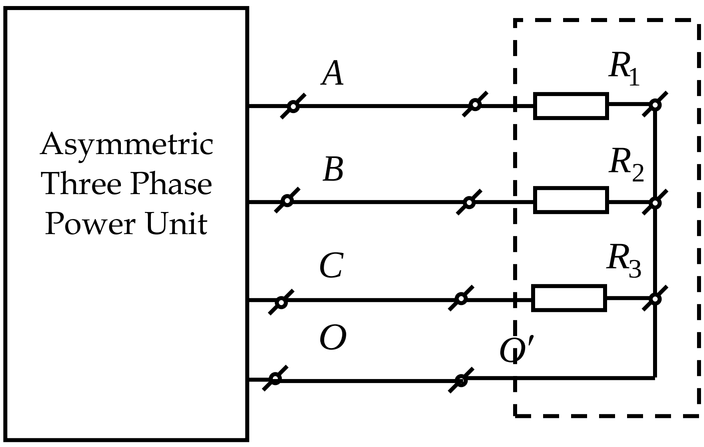

Figure 3.2. – Four-wired network with asymmetric three-phase power supply and symmetrical active load

<u>Stage 5</u>. <u>The phase currents and currents through the neutral wire measurement when the symmetric three-phase load connected wye-circuit with neutral wire.</u>

Use a milliammeter to measuring the line currents I_A, I_B, I_C and through neutral wire I_N. Record the obtained data in Tabl 3.2.

<u>Stage 6</u>. <u>To the asymmetric three phase power supply unit join asymmetrical three-phase load when wye connection with zero wire.</u>

Table 3.2.

Calculated and measured parameters of a three-phase network with an asymmetric power supply

Load Circuit	Measured				Calculated									
	I_A	I_B	I_C	I_N	E_{A1}	E_{A2}	E_{A0}	I_{A1}	I_{A2}	I_{A0}	I_A	I_B	I_C	I_N
	A	A	A	A	V	V	V	V	V	V	A	A	A	A
Symmetrical wye-connection without zero wire														
Symmetrical wye-connection with zero wire														
Asymmetrical wye-connection with zero wire														

In the circuit was assembled in Stage 4, increase the value of one of the phase resistors (approximately in twice). Write down the values of phase resistances.

Stage 7. The phase currents and currents through the neutral wire measurement when the asymmetric three-phase load connected wye-circuit with neutral wire.

Measure the currents by swithing on the milliammeter into the line and the neutral wires. Record the obtained data in Tabl 3.2.

Stage 8. Calculation currents in a three-phase circuit with asymmetric power supply unit and wye connected load.

8.1. Calculate the symmetrical components: zero, positive and negative sequences of an asymmetric three-phase power supply. The initial data are the values of the phase voltages summarized in Table 3.1.

The found values of the positive $\underline{E}_{A1}$, negative $\underline{E}_{A2}$ and zero $\underline{E}_{A2}$ sequences of the phase EMFs to entered in Table 3.2.

8.2. According to the found symmetrical components of phase EMFs, symmetrical components of phase currents and zero-sequence current are calculated when:

– symmetrical load without neutral wire;
– symmetrical load with neutral wire;
– asymmetrical load without neutral wire.

The results of the calculation are entered in Table 3.2.

8.3. From the obtained symmetric components find the phase currents and the current in the neutral wire. Record the obtained data in Table 3.2. Calculation is performing for a symmetrical load with zero wire.

Stage 9. Plotting phasor diagrams.

In the convenient selected scale according to data of the Table 3.1, 3.2 construct combined phasor diagrams of electric currents and voltages when the load wye connecting for the next cases:

– symmetrical load without neutral wire;
– symmetrical load with neutral wire;
– asymmetrical load without neutral wire.

The Report must contain

1. The number and title of the laboratory work.
2. The Objective.
3. The Program of Work.
4. Figures 3.1, 3.2.
5. Tables 3.1, 3.2.
6. Calculated ratios.
7. Phasor diagrams according to Table 3.2.
8. The conclusions of the laboratory work.

Methodical Instruction

To Stage 1. In order for a three-phase power supply to be symmetrical, two conditions must be met:

– the same values of the modules of phase (line) voltages;

– equal shift angle between phase vectors.

If in the symmetrical three-phase power supply the start and finish of any phase to change places, then with the same values of the phase voltage modules, the linear voltage modules and the shift angle between the phase voltage vectors will be unequal.

Changing the start and finish of the phase leads to rotates the phase EMF vector by an angle of 180˚.

To Stage 8. Calculation currents in a three-phase circuit with asymmetric power supply unit and wye connected load.

Load symmetrical wye connection without neutral wire.

The line currents are found along the components of the positive and negative sequences:

$$\begin{cases} \underline{I}_A = \underline{I}_{A1} + \underline{I}_{A2}; \\ \underline{I}_B = \underline{I}_{B1} + \underline{I}_{B2} = a^2 \cdot \underline{I}_{A1} + a \cdot \underline{I}_{A2}; \\ \dot{I}_C = \underline{I}_{C1} + \underline{I}_{C2} = a \cdot \underline{I}_{A1} + a^2 \cdot \underline{I}_{A2}, \end{cases}$$

where a – rotation multiplier with a single module $a = 1 \cdot e^{j120^0}$; $\underline{I}_{A1}, \underline{I}_{A2}$ – components of positive and negative current sequences $\underline{I}_{A1} = \underline{E}_{A1} / \underline{Z}_{ф}$, $\underline{I}_{A2} = \underline{E}_{A2} / \underline{Z}_{ф}$; $\underline{E}_{A1}, \underline{E}_{A2}$ – components of the positive and negative sequences of the EMF source of three-phase voltage $\underline{E}_{A2} = \left(\underline{U}_A + a^2 \cdot \underline{U}_B + a \cdot \underline{U}_C\right)/3$, $\underline{E}_{A1} = \left(\underline{U}_A + \underline{U}_B + \underline{U}_C\right)/3$; U_A, U_B, U_C – voltage of the phases of the power supply, the modules of which are taken according to table 1, and the initial phases are found relative to the phases of symmetrical power supply with a rotation of 180˚ of the phase, in which the start and finish change.

8.2. Load connection by a symmetrical wye with a neutral wire.

The phase currents and through the neutral wire are found according to the components:

$$\begin{cases} \underline{I}_A = \underline{I}_{A1} + \underline{I}_{A2} + \underline{I}_{A0}; \\ \underline{I}_B = \underline{I}_{B1} + \underline{I}_{B2} + \underline{I}_{B0} = a^2 \cdot \underline{I}_{A1} + a \cdot \underline{I}_{A2} + \underline{I}_{A0}; \\ \underline{I}_C = \underline{I}_{C1} + \underline{I}_{C2} + \underline{I}_{C0} = a \cdot \underline{I}_{A1} + a^2 \cdot \underline{I}_{A2} + \underline{I}_{A0}; \\ \underline{I}_N = \underline{I}_{A0} + \underline{I}_{B0} + \underline{I}_{C0} = 3 \cdot \underline{I}_{A0}, \end{cases}$$

where the components of the zero, positive and negative sequences, respectively

$\underline{I}_{A1} = \underline{E}_{A1} / \underline{Z}_{ф}$, $\underline{I}_{A0} = \underline{E}_{A0} / \left(\underline{Z}_{ф} + 3 \cdot \underline{Z}_{N}\right)$, $\underline{I}_{A2} = \underline{E}_{A2} / \underline{Z}_{ф}$,
$\underline{E}_{A0} = \left(\underline{U}_{A} + \underline{U}_{B} + \underline{U}_{C}\right)/3$,
in the calculation $\underline{E}_{A0}$ voltage vectors are used $\underline{U}_{A}, \underline{U}_{B}, \underline{U}_{C}$ as in the calculation of the components $\underline{E}_{A1}$, $\underline{E}_{A2}$.

8.3. Load connection by a asymmetrical wye with a neutral wire.

The components of the forward, inverse and zero sequences of the phase *A* current are found from the solution of the system of equations:

$$\begin{cases} \underline{E}_{A0} = \underline{I}_{A1} \cdot \underline{Z}_{1}^{'} + \underline{I}_{A2} \cdot \underline{Z}_{2}^{'} + \underline{I}_{A0} \cdot \underline{Z}_{0}^{'}; \\ \underline{E}_{A1} = \underline{I}_{A1} \cdot \underline{Z}_{0}^{'} + \underline{I}_{A2} \cdot \underline{Z}_{1}^{'} + \underline{I}_{A0} \cdot \underline{Z}_{2}^{'}; \\ \underline{E}_{A2} = \underline{I}_{A1} \cdot \underline{Z}_{2}^{'} + \underline{I}_{A2} \cdot \underline{Z}_{0}^{'} + \underline{I}_{A0} \cdot \underline{Z}_{1}^{'}, \end{cases}$$

where the impedances are calculated by the ratios:

$$\underline{Z}_{0}^{'} = \left(\underline{Z}_{A} + \underline{Z}_{B} + \underline{Z}_{C}\right)/3;$$
$$\underline{Z}_{1}^{'} = \left(\underline{Z}_{A} + a^{2} \cdot \underline{Z}_{B} + a \cdot \underline{Z}_{C}\right)/3;$$
$$\underline{Z}_{2}^{'} = \left(\underline{Z}_{A} + a \cdot \underline{Z}_{B} + a^{2} \cdot \underline{Z}_{C}\right)/3.$$

According to the symmetrical components of the currents $\underline{I}_{A0}, \underline{I}_{A1}, \underline{I}_{A2}$ the vectors of the currents are found:

$$\begin{cases} \underline{I}_{A} = \underline{I}_{A1} + \underline{I}_{A2} + \underline{I}_{A0}; \\ \underline{I}_{B} = a^{2} \cdot \underline{I}_{A1} + a \cdot \underline{I}_{A2} + \underline{I}_{A0}; \\ \underline{I}_{C} = a \cdot \underline{I}_{A1} + a^{2} \cdot \underline{I}_{A2} + \underline{I}_{A0}; \\ \underline{I}_{N} = \underline{I}_{A} + \underline{I}_{B} + \underline{I}_{C} = 3 \cdot \underline{I}_{A0}. \end{cases}$$

To Stage 9. Knowing the modules and phases of voltages and currents, build in scale on a complex plane combined vector diagrams:

– symmetrical load without neutral wire;
– symmetrical load with neutral wire;
– asymmetrical load without neutral wire.

Questions for check knowledge

1. Give analytical relations for the calculation of zero, positive and negative sequences, if the original asymmetric three-phase voltage system is known.
2. Formulate the necessary and sufficient conditions under which the three-phase system of voltage (current) vectors will be symmetric.

3. Using the known vectors $\underline{U}_{A0}, \underline{U}_{A1}, \underline{U}_{A2}$ build the phase voltage vectors $\underline{U}_{A}, \underline{U}_{B}, \underline{U}_{C}$.
4. Draw and explain single-phase equivalent circuits for the zero components of currents with a symmetrical load in a wye circuit without a neutral wire.
5. Draw and explain single-phase equivalent circuit for phase currents under symmetrical load according to the wye connection without neutral wire.
6. Write down the system of equations in which the symmetrical components of the current of phase *A* are found with an asymmetrical three-phase load and an asymmetric power supply.
7. How will the system of equations, written in accordance with the initial data of the sixth control question, change in the presence of resistances in the neutral wire?
8. Calculate the degree of unbalance of the research three-phase system.
9. Calculate the power consumed in a balanced load with an unbalanced power supply.
10. Why, when a symmetrical load, zero component currents flow in the neutral wire?

Laboratory Research TFEE – 2/4

EXPERIMENTAL RESEARCH OF HIGHER HARMONIC IN SINGLE-PHASE CIRCUITS

Objective

Harmonic analysis and calculation of single-phase circuit currents when non-sinusoidal input voltage.

Program of Work

1. Assembly of the research electrical circuit.
2. Oscillography and measurement of non-sinusoidal voltages and currents of a single-phase circuit sections. Measurement of active power of an electric circuit.
3. Determination of the harmonic composition of the input voltage.
4. Calculation of circuit currents and plot of calculated currents.
5. Calculation of the average power of the electrical circuit.
6. Analysis of results. Conclusions.

Stages of operation

Stage 1. Assembly of the research electrical circuit.

1.1. Assemble an electrical circuit shown in Fig. 4.1. The main elements of the circuit are:

power source $e(t)$– EMF of one phase from a three-phase voltage unit (20 V, 50 Hz);
semiconductor diode *VD* – converter of the input EMF harmonic components;
resistors for measuring currents (R_m=1…2 ohms);
resistive element of the electric circuit R =75…100 ohms;
coil L_2 – fixed inductance from the inductor block.

The inductance values L_k are given on the front panel of the stand. Before connecting the inductance to the electrical circuit, the internal resistance of the coil R_k is measured by the multimeter. Coil parameters are recorded.

1.2. After checking the electrical circuit by the tutor, one can the power supply switching on.

Stage 2. Oscillography and measurement of non-sinusoidal voltages and currents of a single-phase circuit sections. Measurement of active power of an electric circuit.

2.1. Switching on the oscilloscope power supply and connect the measurement cable to the input connector of the oscilloscope. Connect the test leads of the cable between themselves. The input switch “ $\overline{\sim}$ $\sim$ ” must be in the position “ $\overline{\sim}$ ” (open input).

Achieve the zero line a stable image in the middle of oscilloscope screen.

2.2. The measurement leads of the oscilloscope must be connected in parallel with the resistance. To achieve a convenient scale for the vertical deflection of the beam and once again check the zero line on the oscilloscope screen along the time axis. After that, transfer the supply voltage curve from the oscilloscope screen to tracing paper (voltage across the resistance *R*) or photograph it. Record the time and vertical deviation scales in the laboratory report.

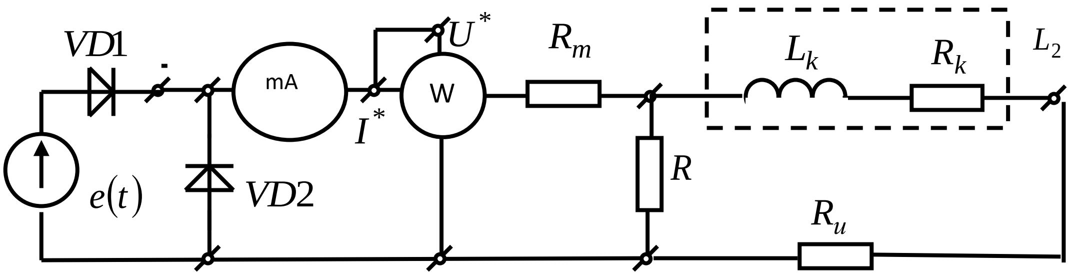

Figure 4.1. – Circuit of experimental study of higher harmonics in a single-phase circuit

2.3. Leaving the measuring leads of the oscilloscope on the resistance, switch the input switch from position “$\overline{\sim}$” (open input) to position “$\sim$” (closed input). The shift of the voltage curve along the vertical axis gives a zero (constant) voltage of the power supply. Write down the value of zero voltage.

2.4. Use a voltmeter of the electromagnetic system to measure the voltage at the output of the power supply. Record the results in Table 4.1.

2.5. Measure the currents in the branches with a milliammeter of the electromagnetic system and enter the data in Table 4.1.

2.6. Connect the measuring terminals of the oscilloscope to the resistors R_m of the input branch and in the branch with the coil. In these branches draw (photograph) waveforms of currents in the input switch in position “ ∼ ”).

Table 4.1.

Measured and calculated values of higher harmonics in a single-phase circuit

Brach	Measured				Calculated						
	$U_{(0)}$, V	U, V	$I_{(0)}$, mA	I, mA	$U_{(0)}$, V	U, V	$I_{(0)}$, mA	$I_{(1)}$, mA	$I_{(2)}$, mA	$I_{(3)}$, mA	I, mA
Input											
Resistive											
Resistive-inductive											

2.7. By moving the input switch of the oscilloscope from the open position to the closed input position by the vertical shift of the current curves to find a direct current in the branches. Enter the numerical values of the constant currents in table 1.
2.8. According to the readings of the wattmeter, find the value of the consumed active power.

Stage 3. Determination the input voltage of harmonic composition.
Using the Perry graph-analytical method, find the amplitudes and initial phases of the harmonics for the oscillogram of non-sinusoidal voltage (Fourier series coefficients). Calculate the zero, first, second and third harmonics. The obtained data are entered in Table 4.1.

Stage 4. Calculation of circuit currents and plotting it over time.
4.1. Calculate the impedance of the branches for the harmonics of the supply voltage.
4.2. Calculate the currents in the branches of an electric circuit from all voltage harmonics. The found values of currents to enter in Table 4.1.
4.3. According to the calculated data, plot a current graph of the input branch as a function of time.

Stage 5. Calculation of active power of an electric circuit.
According to the obtained values of voltages and currents of the branches to find the lost active power of the electrical circuit.

The Report must contain

1. The number and title of the laboratory work.
2. The Objective.
3. The Program of operation.
4. Figures 4.1.

5. Table 4.1.
6. Oscillograms:
– supply voltage;
 – current of input branche;
 – current of branch with ohmic resistance R;
 – current of branch with inductance coil L;
7. Calculation of Fourier series coefficients for supply voltage and branch currents.
8. The constructed graph of current through input branch graph
9. The conclusions of the laboratory work.

Methodical Instruction

To Stage 2. The oscilloscope input switch “ ” ” “ in position “ ”(open input) transmits a signal to the attenuator input (frequency-compensated voltage divider) directly, and in position“ ” (closed input) - through the divider.
The scale of the current m_u and value of measurement resistor R_u, i.e.

$$m_i = m_u / R_u .$$

Voltmeter, milliammeter of the electromagnetic system measure the effective value of non-sunosoidal voltage and current.
Constant components of voltages and currents can also be measured with a voltmeter and milliamperes of the magnetic-electric system.

To stage 3. Determination of the harmonic composition of the input voltage.
The Fourier series with respect to the output voltage of a non-sinusoidal power supply is as follows:

$$U(\omega \cdot t) = U_{(0)} + \sum_{k=1}^{3} U_{(k)m} \sin(k \cdot \omega \cdot t + \varphi_k),$$

where $U_{(0)}$ – constant component; k – the number of the harmonic; $U_{(k)m}$ – the number of the k-th harmonic; φ_k – the initial phase of the k-th harmonic.

The relations for calculating the parameters of the second form of the Fourier series are given below:

$$U_{(0)} = \frac{1}{N} \cdot \sum_{p=1}^{N} U(x); \qquad U_{(k)m} = \sqrt{(U'_{(k)m})^2 + (U''_{(k)m})^2} ;$$

$$U'_{(k)m} = \frac{2}{N} \sum_{p=1}^{N} U(x) \sin(kx); \qquad U''_{(k)m} = \frac{2}{N} \sum_{p=1}^{N} U(x) \cos(kx);$$

Table 4.2.

Calculation of the higher harmonics components

Ordinates (N=24)	$k=1$					$k=2$					$k=3$				
	x	Sin(x)	Cos(x)	upSin(x)	upCos(x)	2x	Sin(2x)	Cos(2x)	upSin(2x)	upCos(2x)	3x	Sin(3x)	Cos(3x)	upSin(3x)	upCos(3x)
u_1															
u_2															
u_3															
u_4															
u_5															
u_6															
u_7															
u_8															
u_9															
u_{10}															
u_{11}															
…															
u_{22}															
u_{23}															
u_{24}															

$$\varphi_k = arctg\frac{U''_{(k)m}}{U'_{(k)m}}; \qquad x = (p-0{,}5)\cdot 2\cdot\pi/N; k = 1,2,3,\ldots,$$

where N – the number of the period breakdown intervals (it is recommended for the studied form of voltage to take N=24); p – current interval number; $x = p\cdot\Delta t$ – discrete time.

The value $U(x)$ must be taken for the middle of the interval, which reduces the calculation error of the initial phase φ_k.

To facilitate the calculations, it is recommended to use Table 4.2.

<u>To Stage 4</u>. Calculation of circuit currents, plot of calculated currents.
Calculate the currents for the zero, first, second and third harmonics. Thus, for a branch with active-inductive load, the instantaneous value of current

$$i(\omega\cdot t) = I_{(0)} + I_{(1)m}\sin(\omega\cdot t + \psi_1 - \varphi_1) +$$
$$+ I_{(2)m}\sin(2\cdot\omega\cdot t + \psi_2 - \varphi_2) + I_{(3)m}\sin(3\cdot\omega\cdot t + \psi_3 - \varphi_3) + \ldots$$

де $I_{(0)} = U_0/R_k$; $I_{(1)m} = U_{(1)m}/\sqrt{R_k^2 + (\omega\cdot L_k)^2}$;

$$I_{(2)m} = U_{(2)m}/\sqrt{R_k^2 + (2\cdot\omega\cdot L_k)^2}; I_{(3)m} = U_{(3)m}/\sqrt{R_k^2 + (3\cdot\omega\cdot L_k)^2};$$

$U_{(1)m}, U_{(2)m}, U_{(3)m}, \varphi_1, \varphi_2, \varphi_3$ – voltage harmonics amplitudes and initial values of the phase: $\varphi_1 = arctg(\omega\cdot L_k/R_k)$; $\omega = 314$ rad/s.
The effective value of non-sinusoidal voltage and current of this branch, respectively:

$$U = \sqrt{U_{(0)}^2 + U_{(1)}^2 + U_{(2)}^2 + U_{(3)}^2}; \; I = \sqrt{I_{(0)}^2 + I_{(1)}^2 + I_{(2)}^2 + I_{(3)}^2},$$

where $U_{(0)}$, $U_{(1)}$, $U_{(2)}$, $U_{(3)}$ – effective values of voltage harmonics; $I_{(0)}$, $I_{(1)}$, $I_{(3)}$, $I_{(2)}$ – effective values of current harmonics. When plotting time diagrams of current harmonics, the scale along the ordinate axis m_i should be taken to be the same for all harmonics, and the scale along the abscissa axis $m_{\omega\cdot t}$ should be taken equal $m_{\omega\cdot t}\cdot k$ (k – harmonic number).

<u>To Stage 5.</u> Calculation of the average power of the electrical circuit.
The active power consumed in this electrical circuit is defined as the sum of the active powers of the harmonics:

$$P = \sum_{k=0}^{3}(P_{(k)L} + P_{(k)R}),$$

where k – harmonic number; $P_{(k)L}$ – active power for the k-th harmonic in the branch with resistive-inductive load; $P_{(k)R}$ – active power for the k – th harmonic in the branch with resistive load. The consumption of active power in the measuring resistors is neglected.

Questions for check knowledge

1. Give the main cases of periodic functions symmetry and their influence on the coefficients of the Fourier series.
2. Write formulas for calculating the constant component of the Fourier series.
3. Write the basic formulas for calculating currents in a linear circuit at non-sinusoidal voltage of the source.
4.Is it possible arises at the same time voltages and currents resonances phenomena when R, L, C elements are connected mixed and powered by non-sinusoidal voltage?
5. Write expressions to calculate the current values of currents and voltages.
6. What is the difference between the average modulus value and the DC component of the current?
7. Which the system of devices can measure the constant component?
8. How does the shape of the current curve change from the load R, L, C?
9. What coefficients can characterize non-sinusoidal periodic curves?
10. On what principle is based the method of calculating currents in linear circuits when powered by a non-sinusoidal voltage source?

Laboratory Research TFEE – 2/5

EXPERIMENTAL RESEARCH OF HIGHER HARMONIC IN THREE-PHASE CIRCUITS

Objective

Harmonic analysis voltages and currents in three-phase circuit powered by non-sinusoidal source

Program of Work

1. Assembly of a three-phase non-sinusoidal power supply.
2. Oscillography of linear and phase voltages of a three-phase non-sinusoidal power supply.
3. Connection to a three-phase non-sinusoidal power supply of the load according to the circuit of a symmetrical wye without a zero wire.
4. Research of the voltages and currents harmonic composition in a three-phase circuit.
5. Connection to a three-phase non-sinusoidal power supply of the load according to the circuit of a symmetrical wye with a zero wire.
6. Research of the harmonic composition of voltages in a three-phase four-wire circuit.
7. Analysis of results. Conclusions.

Stages of operation

Stage 1. Assembly of the three-phase non-sinusoidal power source.

1.1. Assemble the electrical circuit, which is given in Fig. 5.1. As the main elements of the circuit are used: single-phase power sources $\underline{E}_A, \underline{E}_B, \underline{E}_C$ – from the three-phase voltage unit ($E_A = E_B = E_C$=30 V);

1.2. Single-phase transformers 1, 2, 3 – are at the bottom of the interconnection board.

1.3. After checking the electrical circuit of three-phase source by the tutor, one can the power supply switching on.

Stage 2. Oscillography of linear and phase voltages of a three-phase non-sinusoidal power supply.

2.1. The electronic oscilloscope switches on into an electrical network.

2.2. By connecting the measuring terminals of the oscilloscope first to the phase voltages ($u_A(\omega t)$, $u_B(\omega t)$, $u_C(\omega t)$), and then to the line voltages ($u_{AB}(\omega t)$, $u_{BC}(\omega t)$, $u_{CA}(\omega t)$), of the three-phase asymmetric power supply obtane a stable image on the screen.

2.3. Draw on tracing paper (or photograph) the phase and line voltages of three-phase non-sinusoidal power supplies from the oscilloscope screen.

2.4. Make a visual harmonic analysis based on the shape of the voltages curves. Record the obtained analysis results in Table 5.1. If there is a harmonic in the researching curve, put sign “+” in the table; in its absence, put in the table sign “–“.

Stage 3. Connection to a three-phase non-sinusoidal power supply of the load according to the circuit of a symmetrical wye without a zero wire.

3.1. Assemble the electrical circuit, which is shown in Fig. 5.2. The main elements of the circuit are:

– three-phase non-sinusoidal power supply, which is made at the first stage of work;

– phase impedance $\underline{Z}_1, \underline{Z}_2, \underline{Z}_3$– ohmic resistances from the block of adjustable resistances $(\underline{Z} = R_1 = R_2 = R_3)$.

3.2. After checking the electrical circuit by the tutor, one can the power supply switching on.

Stage 4. Research of the voltages and currents harmonic composition in a three-phase circuit.

4.1. Connect the measuring terminals of the oscilloscope first to the phase voltages and then to the line voltages of the load.

Based on the forms of voltage curves make a visually harmonic analysis, and the results are recorded in Table 5.1.

Table 5.1.

Visual harmonic analysis.

Harmonic number	Presence of a harmonic in the voltages							
	Power supply		Three-wire load			Four-wire load		
	U_L	U_{PH}	U_L	U_{PH}	U_N	U_L	U_{PH}	I_N
1								
3								
5								
9								

4.3. Connect the measuring terminals of the oscilloscope between the neutral points of the power supply and the receiver. In the Table 5.1 enter the harmonic composition of the neutral displacement voltage U_N.

4.4. Using an electromagnetic voltmeter, measure RMS values of the line and phase voltages at the source and receiver in a three-wire electrical circuit.

4.5. Measure the RMS value of currents in a three-phase circuit with an electromagnetic milliammeter. Write this data to the Table 5.2.

Stage 5. Connection to a three-phase non-sinusoidal power supply of the load according to the circuit of a symmetrical wye with a zero wire.

In the circuit drawn up at the third stage (Fig. 5.2), connect points O and O' through measurement resistance (shunt) R_m=1…2 ohms.

Stage 6. Research of the harmonic composition of voltages in a three-phase four-wire circuit.

Table 5.2.

Measured currents of a three-phase circuit

Power supply		Three-wire load				Four-wire load			
U_L,V	U_{PH},V	U_L,V	U_{PH}, V	U_N, V	I_{PH}, μA	U_{PH}, V	I_N,A	U_L,B	I_{PH}, μA

6.1. Connect the measuring terminals of the oscilloscope to the phase, line voltages of the load, and then to the measuring resistance between the neutral points of the source and load.

6.2. On the basis of visual harmonic analysis fill in the correspond rows in table1.

6.3. Use an electromagnetic voltmeter to measure the line and phase voltages at the load. Enter the values of voltages in Table 5.2.

6.4. Measure the currents of a three-phase circuit by an electromagnetic milliammeter. The value enters in Table 5.2.

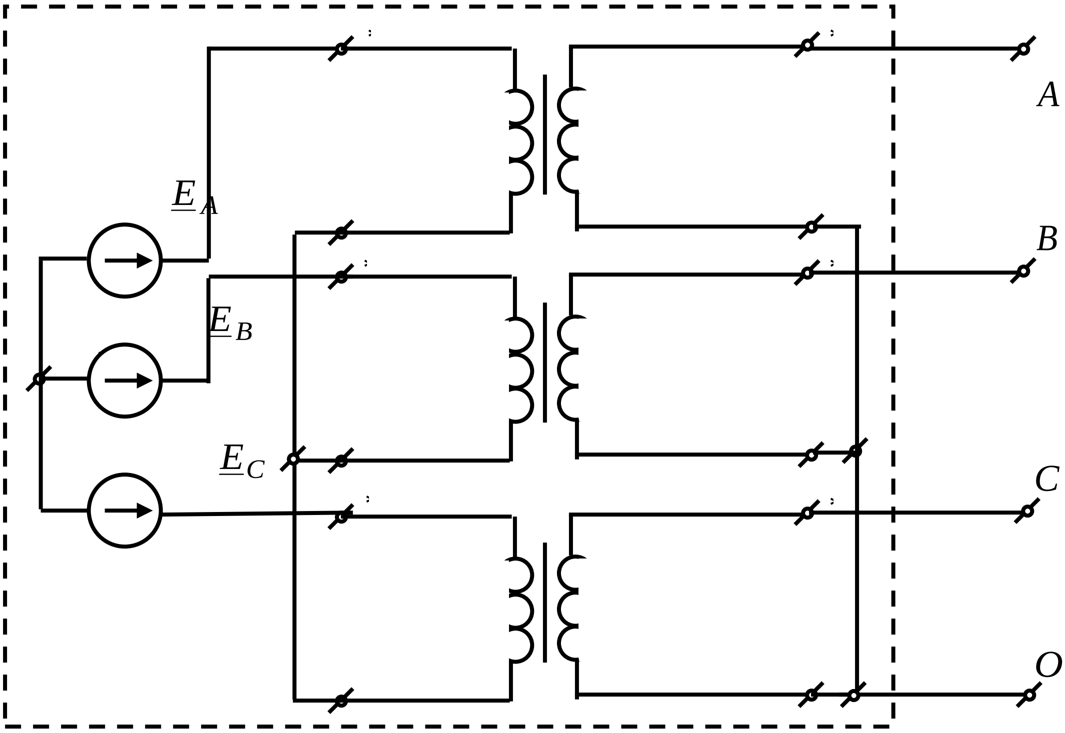

Figure 5.1 – Three-phase non-sinusoidal power supply

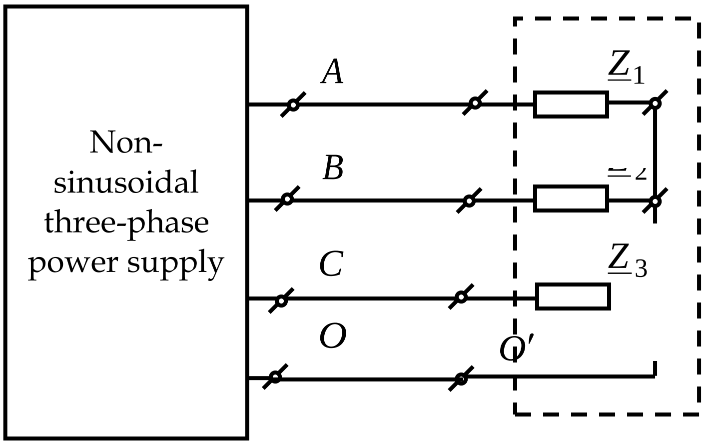

Figure 5.2 – Three-phase four-wired non-sinusoidal network

The Report must contain

1. The number and title of the laboratory work.
2. The Objective.
3. The Program of Work.
4. Figures 5.1, 5.2.
5. Tables 5.1, 5.2.
6. Oscillograms of phase and line voltages of three-phase non-sinusoidal power supply.
7. Calculated ratios.
8. The conclusions of the laboratory work.

Methodical Instruction

<u>To Stage 1</u>. The appearance of harmonics in the EMF curves of transformers secondary windings is due to the nonlinearity of the ferromagnetic magnetic circuit. The physical basis of this phenomenon is studied in the section "Nonlinear electric circuits at alternating currents".

In a three-phase non-sinusoidal power supply, the phase EMFs are repeated in shape with a shift of one third of the oscillation period.

Since the phase EMF curve is symmetric about the time axis, there will be only odd non-sinusoidal components when decomposed into a Fourier series. Given the fact that as the number of harmonics increases, its specific weight decreases rapidly, then in the study of a three-phase electric circuit without much error it is enough to consider only the first, third, fifth and ninth sinusoidal components.

<u>To Stage 4</u>. When connecting a three-phase source according to the wye circuit, the line voltages are equal to the difference of the corresponding phase EMF or voltages. Due to the fact that the third and multiples of the three harmonics of the EMF (voltages) coincide in phase, their difference is zero. Thus, there are no third and multiples of three harmonics in the line voltage.

The effective value of the line voltage

$$U_L = \sqrt{3}\sqrt{U_1^2 + U_5^2 + \ldots} \ .$$

The effective value of the phase voltage

$$U_{PH} = \sqrt{U_1^2 + U_3^2 + U_5^2 + \ldots} \ .$$

Their ratio

$$\frac{U_L}{U_{PH}} = \frac{\sqrt{3}\sqrt{U_1^2 + U_5^2 + \ldots.}}{\sqrt{U_1^2 + U_3^2 + U_5^2 \ldots.}} < \sqrt{3} \ .$$

Since the harmonic composition of non-sinusoidal line and phase voltages is different the shape of the curves of line and phase voltages is also different.

The voltage between the neutral points is equal to the difference between the phase voltages of the source and load. Thus, the voltage between the neutral points is equal to the third harmonic of the source phase voltage.

To Stage 6. Since the phase EMF sources have the same harmonic composition as in three-wire circuits, the phase and line voltages of the source differ in the third harmonics.

For currents of a four-wire circuit there is a relation

$$i_A + i_B + i_C - i_N = 0$$

or

$$i_{A1} + i_{A3} + i_{A5} + i_{A9} + i_{B1} + i_{B3} + i_{B5} + i_{B9} + i_{C1} + i_{C3} + i_{C5} + i_{C9} - i_N = 0 .$$

The first (fifth) harmonics of currents form a symmetrical system of positive (negative) sequence, therefore

$$i_{A1} + i_{B1} + i_{C1} = 0,\ i_{A5} + i_{B5} + i_{C5} = 0,$$

from this $$i_{A3} + i_{B3} + i_{C3} = i_{N3},\ i_{A9} + i_{B9} + i_{C9} = i_{N9}.$$

The current effective value

$$I_N = 3 \cdot \sqrt{I_3^2 + I_5^2} ,$$

where I_3, I_5 – effective values of the line current third and fifth harmonic.

The phase voltages of the load are non-sinusoidal and coincide with the phase voltages of the source. The voltage between the neutral points of the source and load is zero.

Questions for check knowledge

1. Why harmonics of non-sinusoidal currents three-phase system, which are multiples of three, form three-phase systems of zero sequence?
2. What sequences form harmonics that are not multiples of three?
3. Why do the line currents of a three-wire three-phase circuit not contain harmonics multiples of three?
4. Why do the line currents of a four-wire three-phase circuit contain harmonics multiples of three?
5. What harmonics will the line voltages have if the phase voltages of the source contain the first, third, and fifth harmonics?
6. Why does the voltage U_N not contain the first harmonics?
7. What harmonics will contain current if the phase resistances of the load are different?

8. How do phase and line voltages relate when non-sinusoidal three-phase power supply?
9. How to calculate the phase currents of the load when a non-sinusoidal three-phase power supply?
10. How to calculate the neutral wire current when a non-sinusoidal three-phase power supply?

Laboratory Work TFEE – 2/6

EXPERIMENTAL STUDY OF TRANSIENT WHEN CONNECT A CIRCUIT WITH INDUCTANCE COIL TO DC SOURCE

Objective

Experimental check of the switching first law

Program of Work

1. Calculation of time constants values of the transient.
2. Assembly of the rectangular pulses generator.
3. Oscillography of the rectangular pulses source output signal.
4. Connection of inductive-resistive circuit to the source of rectangular pulses.
5. Oscillography of transients in a circuit with inductive-resistive elements.
6. Analysis of results. Conclusions.

Work Stages

Stage 1. Calculation of time constants values of the transient.

Based on the restriction that the duration of the transient process should not exceed half the period of the frequency of industrial voltage and knowing the dependence of the time constant on the value of active resistance calculate the values of additional resistances R_4.

Stage 2. Assembly of the rectangular pulses generator.

Assemble electric circuit shown in Fig.1. As the main elements are used:
- unregulated DC source from DC voltage unit;
- limiting resistor R_{lim} is taken to be about 100 Ω;
- normally open contact *S* is taken from the electronic switches unit.

Switch on the power supply of laboratory stent УИЛС, power supply of the DC voltage unit, the electronic switches unit, and switch the "electronic switch synchronization" toggle switch to the "internal synchronization" position.

Step 3. Oscillography of the output signal of the rectangular pulses source.

3.1. Switch on of the oscilloscope toggle “сеть” (“main”) and give to warm up for oscilloscope till the appearance of stabile horizontal line on a screen.

3.2. Connect the measuring cable of the oscilloscope to the output voltage of the generator of rectangular pulses and observe the pulses on the screen.
3.3. Use the voltage divider "amplifier Y" (“усилитель Y”) to set a convenient scale on the ordinate axis, and by the switch of “horizontal sweep” (“развертка”) along of the abscissa axis.

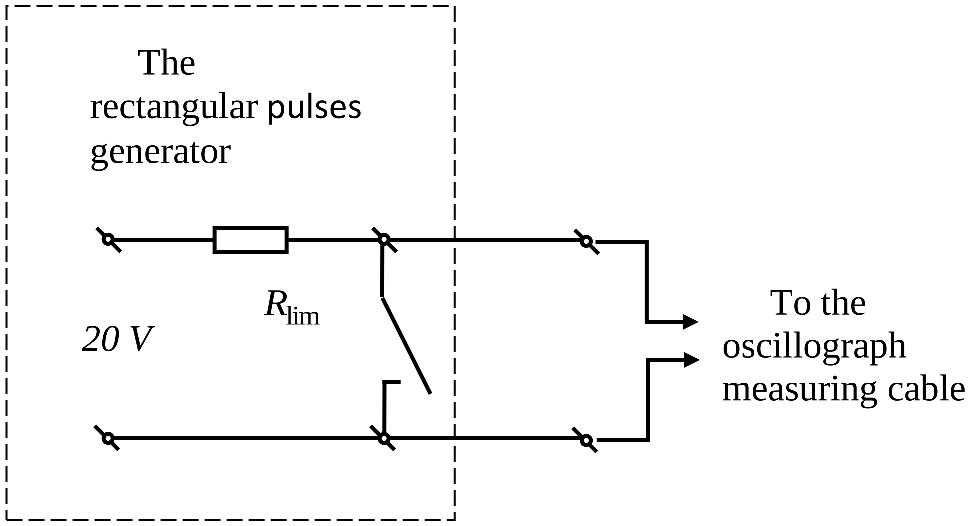

Figure 6.1. - Circuit of the rectangular pulses source

3.4. By turning handle “level” (“уровень”) clockwise to the stop, and then the by handle “stabilization” (“Стаб”) to achieve the disappearance of the signal from the oscilloscope screen. Then turning the handle “level” (“уровень”) counterclockwise to achieve a clear, synchronized image of the signal under study.
Attach a tracing paper to the oscilloscope screen and capture an image or take a picture. Write the scales along the ordinate and abscissa.

<u>Stage 4.</u> <u>Connection of inductive-resistive circuit to the source of rectangular pulses.</u>

Assemble electric circuit shown in Fig.6.2. As the main elements to use:

- regulated resistor R_4 from ohmic resistors unit;
- inductance coil L_1 from inductance unit;
- measuring resistor R_m for current curve oscillography (R_m=1 .. .2 Ω).

Set the value of the calculated resistance R_4 by decade switches.

<u>Stage 5.</u> <u>Oscillography of transients in a circuit with inductive-resistive elements.</u>

Connect the oscilloscope measuring cable parallel to coil L_1 and remove the voltage oscillogram on the coil. To select convenient signal scales on the oscilloscope screen, perform the actions of points 3.3, 3.4.

Connect the measuring cable of the oscilloscope parallel to the resistor R_m. Remove the voltage oscillogram. Since the current and voltage coincide in phase on the resistor, the recorded oscillogram in the current scale is an oscillogram of the current. The current scale is defined as the result of dividing the voltage scale by the value of the measuring resistor. Scaling and synchronization of the signal is done in accordance with points 3.3, 3.4. Write the scales on the axes of ordinate and abscissa.

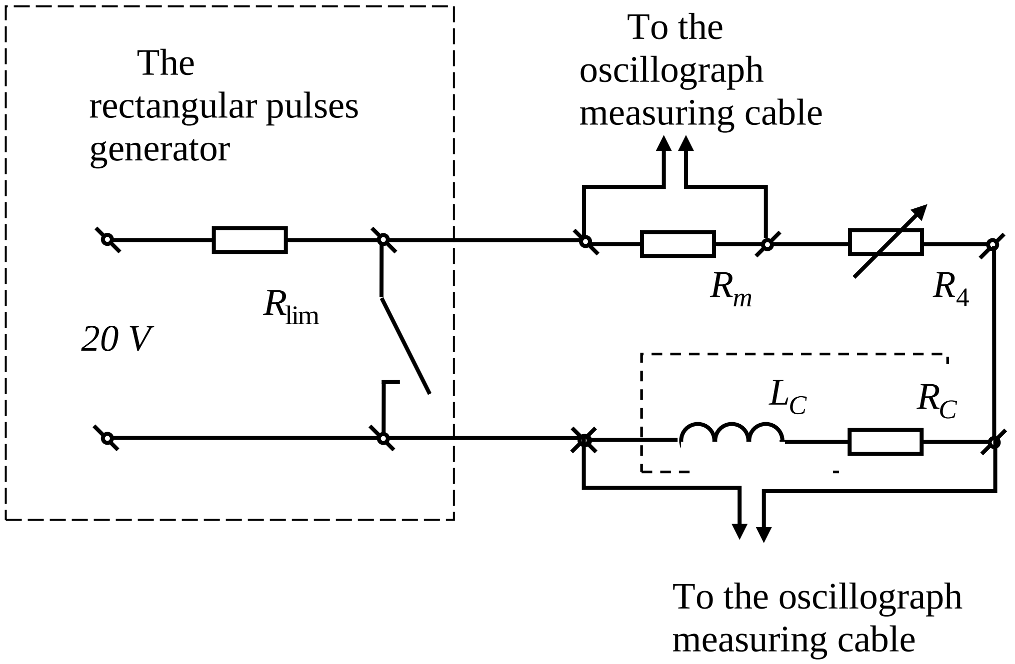

Figure 6.2. - The experiment circuit

To disconnect study inductance from the source of rectangular impulses and measure its ohmic resistance R_C by multimeter.

Stage 6. Analysis of the results.

In a circuit containing a resistor and an inductor connected in series, the transient current when the switch *S* is opened and the zero initial conditions is determined by the dependence

$$i(t) = I_0(1 - e^{-t/\tau_1}),$$

where $I_0 = U_0/(R_4 + R_C + R_m + R_{lim})$ – steady-state current value; U_0 – DC supply voltage; $\tau_1 = L_C/(R_4 + R_C + R_m + R_{lim})$ – the time constant of transient.

When the switch S is closed and the non-zero initial conditions the current is determined by the dependence

$$i(t) = I_0 e^{-t/\tau_2},$$

where $I_0 = U_0/(R_4 + R_C + R_m + R_{lim})$ – current initial value; $\tau_2 = L_C/(R_4 + R_C + R_m)$ – the time constant of transient.

The time constant of the transition process can be determined from the graphs of the transition functions as the length of the tangent, expressed in time scale.

The Report must contain

1. The number and title of the laboratory work.
2. The objective.
3. The work program.
4. Scheme of study circuit.
5. Calculation of the resistor value R_4.
6. The transient oscillograms: the source rectangular voltage pulses, voltages across ohmic resistor and inductance coil.
7. The conclusions of the laboratory work.

Methodical Instruction

To the Stage 1. Calculation of time constants values of the transient.

The switch *S* switches synchronously with frequency (main) industrial circuits. The time of the closed and open state of the key *S* of the rectangular pulses source (Fig.1) is 1/50=0, 01 s. When the swich S is closed, the output of the rectangular pulses unit, the voltage is equal to zero, and when the key S is opened, a voltage of 20 V appears at the output (Fig. 6.3).

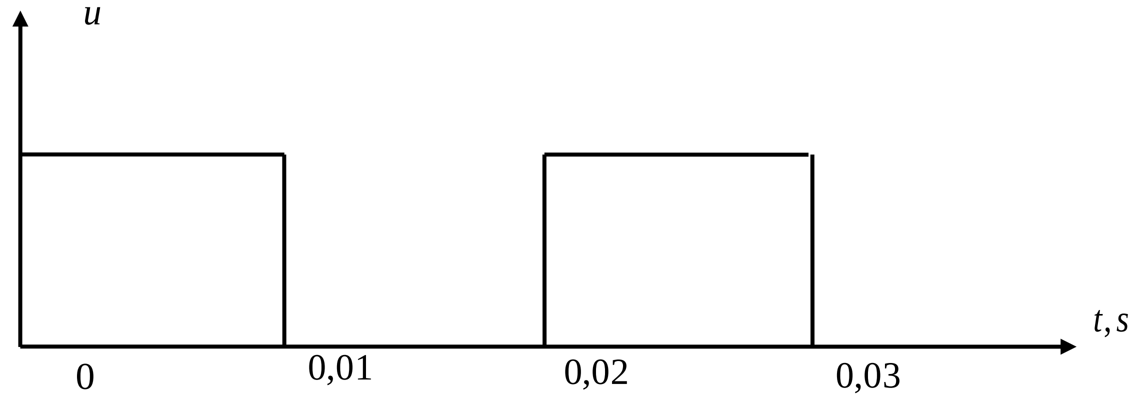

Figure 6.3. - Output signal of the rectangular pulse generator

We choose the load parameters and the source of rectangular pulses parameters (Fig. 6.2, 6.3) from that calculation that the transient is copmleted in 0.01 s.

Inductance-resistance load (Fig.6.2, Fig. 6.4)

$$R_4 = \frac{5 \cdot L_C}{0{,}01} - R_C - R_m = 500 L_C - R_C - R_m, \ \Omega$$

where L_C - coil induction, H.

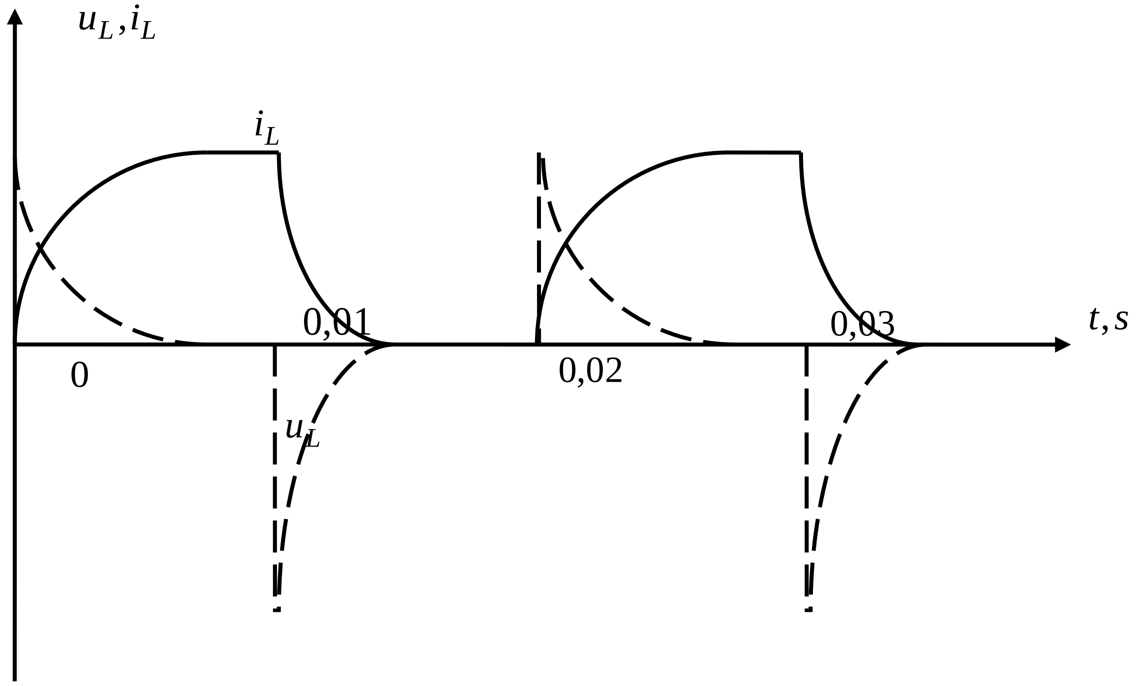

Figure 6.4. - Transient current and voltage in the R-L circuit.

Questions for check knowledge

1. Formulate the first law of switching.
2. How to calculate the independent initial conditions in the presence of inductance in the circuit?
3. How are the dependent initial conditions calculated in the presence of inductance in the circuit?
4. Formulate a rule for finding the roots of a characteristic equation.
5. How to analytically determine the time constant of the transition process?
6. Why the current in the branches with inductance does not change by a jump?
7. How is the time constant of the transition calculated?
8. How long does the transition process take?
9. How do changes in the parameters of the scheme affect the duration of the transient process?
10. Formulate the order of calculation of transients by the classical method.

Laboratory Work TFEE – 2/7

EXPERIMENTAL STUDY OF TRANSIENT WHEN CONNECT A CIRCUIT WITH CAPASITOR TO DC SOURCE

Objective

Experimental check of the swiching second law

Program of Work

1. The calculation of the time constant values of transient.
2. Assembling of the rectangular pulses generator.
3. The output signal of the rectangular pulses source oscillography.
4. Capacitance-resistance circuit connection to the source of rectangular pulses.
5. Oscillography of transients in a circuit with capacitive-resistive elements.
6. Analysis results. Summary.

Work Stages

Stage 1. The calculation of the time constant values of transient.

On the basis of limitation that duration of transient process should not exceed the halves of the period of the frequency of industrial voltage and knowing the dependence of time constant from the significance of ohmic resistance to calculate values of the extra resister R_4..

Stage 2. Assembling of the rectangular pulses generator.

Assemble electric circuit shown in Fig.7.1. As the main elements are used:

- unregulated DC source from DC voltage unit;
- limiting resistor R_{lim} is taken to be about 100 Ω;
- normally open contact *S* is taken from the electronic switches unit.

Switch on the power supply of laboratory stent УИЛС, power supply of the DC voltage unit, the electronic switches unit, and switch the "electronic switch synchronization" toggle switch to the "internal synchronization" position.

Stage 3. The output signal of the rectangular pulses source oscillography.

3.1. Switch on of the oscilloscope toggle “сеть” (“main”) and give to warm up for oscilloscope till the appearance of stabile horizontal line on a screen.

3.2. Connect the measuring cable of the oscilloscope to the output voltage of the generator of rectangular pulses and observe the pulses on the screen.

3.3. Use the voltage divider "amplifier Y" (“усилитель Y”) to set a convenient scale on the ordinate axis, and by the switch of “horizontal sweep” (“развертка”) along of the abscissa axis.

3.4. By turning handle “level” (“уровень”) clockwise to the stop, and then the by handle “stabilization” (“Стаб”) to achieve the disappearance of the signal from the

oscilloscope screen. Then turning the handle “level” (“уровень”) counterclockwise to achieve a clear, synchronized image of the signal under study.
Attach a tracing paper to the oscilloscope screen and capture an image or take a picture. Write the scales along the ordinate and abscissa.

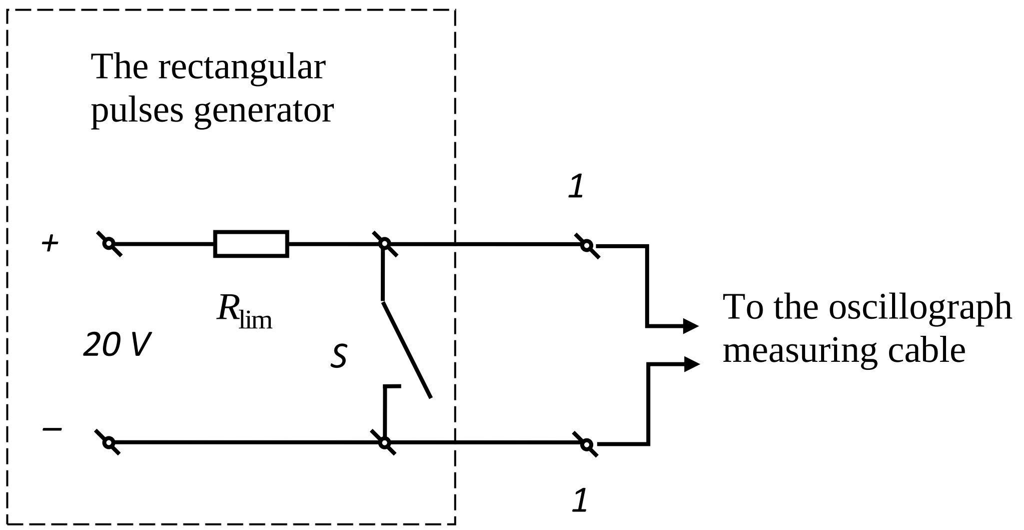

Figure 7.1. - Rectangular pulse generator circuit

Stage 4. Capacitance-resistance circuit connection to the source of rectangular pulses.
Assemble electric circuit shown in Fig.7.2. As the main elements to use:

- regulated resistor R_4 from ohmic resistors unit;
- capacitor C_1 from capacitance unit;
- measuring resistor R_m for current curve oscillography (R_m=1 .. .2 Ω).

Set the value of the calculated resistance R_4 by decade switches.
Stage 5. Oscillography of transients in a circuit with capacitive-resistive elements.
Connect the oscilloscope measuring cable parallel to condencer C_1 and remove the voltage oscillogram on the condencer. To select convenient signal scales on the oscilloscope screen, perform the actions of points 3.3, 3.4.
Connect the measuring cable of the oscilloscope parallel to the resistor R_m. Remove the voltage oscillogram. Since the current and voltage coincide in phase on the resistor, the recorded oscillogram in the current scale is an oscillogram of the current. The current scale is defined as the result of dividing the voltage scale by the value of the measuring resistor. Scaling and synchronization of the signal is done in accordance with points 3.3, 3.4. Write the scales on the axes of ordinate and abscissa.

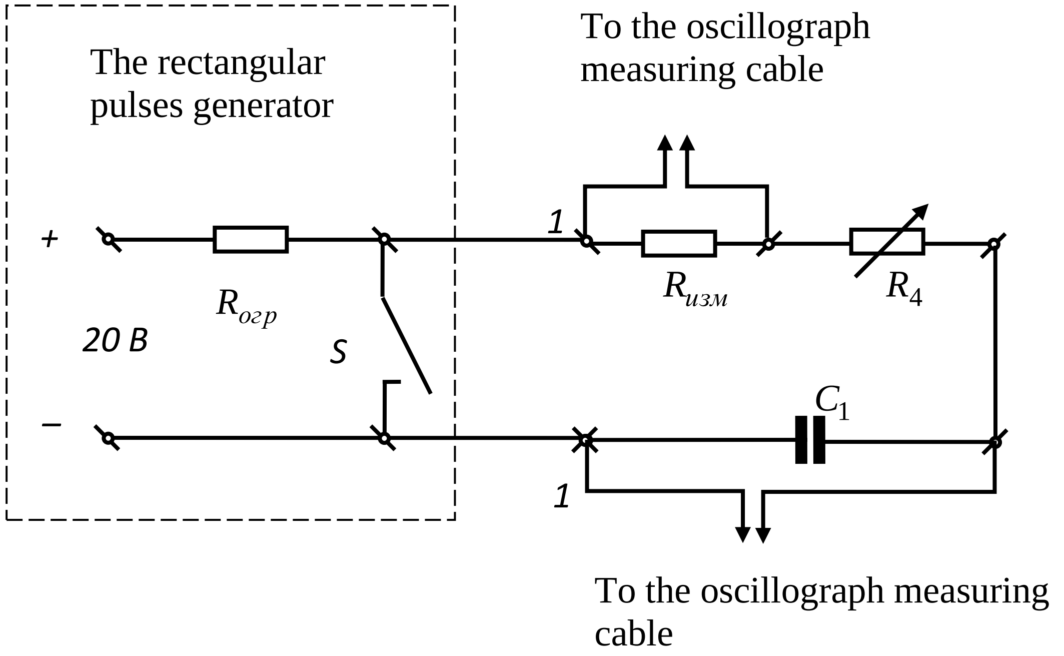

Figure 7.2. – The study circuit of the transients in the R-C circle

Stage 6. The analysis results.
In a circuit containing a resistor and an capacitor connected in series, the transient voltage when the switch *S* is opened and the zero initial conditions is determined by the dependence

$$u_c(t) = U_0(1 - e^{-t/\tau_3}),$$

where $\tau_3 = C_1(R_4 + R_m + R_{\lim})$ – the time constant of transient process.
When the switch *S* is closed and the non-zero initial conditions the voltage is determined by the dependence

$$u_c(t) = U_0 e^{-t/\tau_4},$$

where $\tau_4 = C_1(R_4 + R_m)$ – the time constant of transient process.

The time constant of the transition process can be determined from the graphs of the transition functions as the length of the tangent, expressed in time scale.
.

The Report must contain

1. The number and title of the laboratory work.
2. The work program.
3. Scheme of probe circuit.
4. Calculation of the time constant.
5. The transient process oscillograms: the source rectangular voltage pulses, voltages on ohmic resistance and capacitor.
6. The conclusions of the laboratory work.

Methodical Instruction

To the Stage 1. The calculation the time constant of transient.

The switch *S* switches synchronously with frequency (main) industrial circuits. The time of the closed and open state of the key *S* of the rectangular pulses source (Fig.1) is 1/50=0, 01 s. When the switch S is closed, the output of the rectangular pulses unit, the voltage is equal to zero, and when the key S is opened, a voltage of 20 V appears at the output (Fig. 7.3).

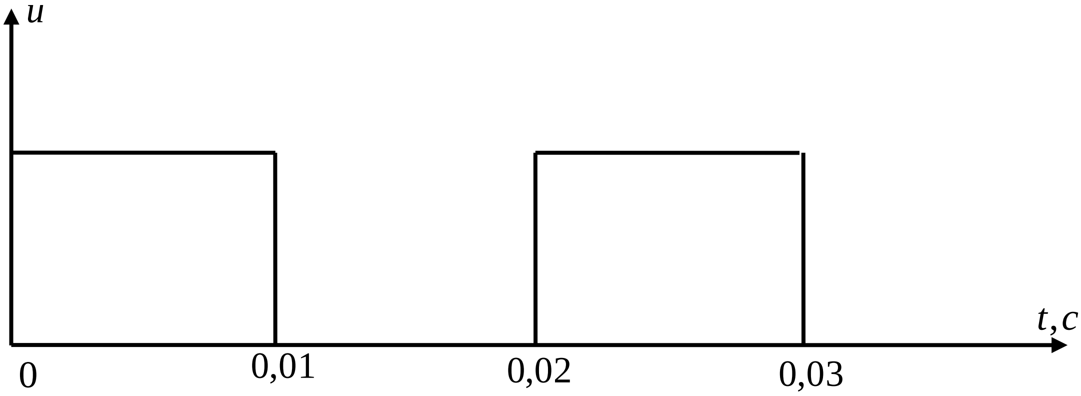

Figure 7.3. - Output voltage of the pulse generato

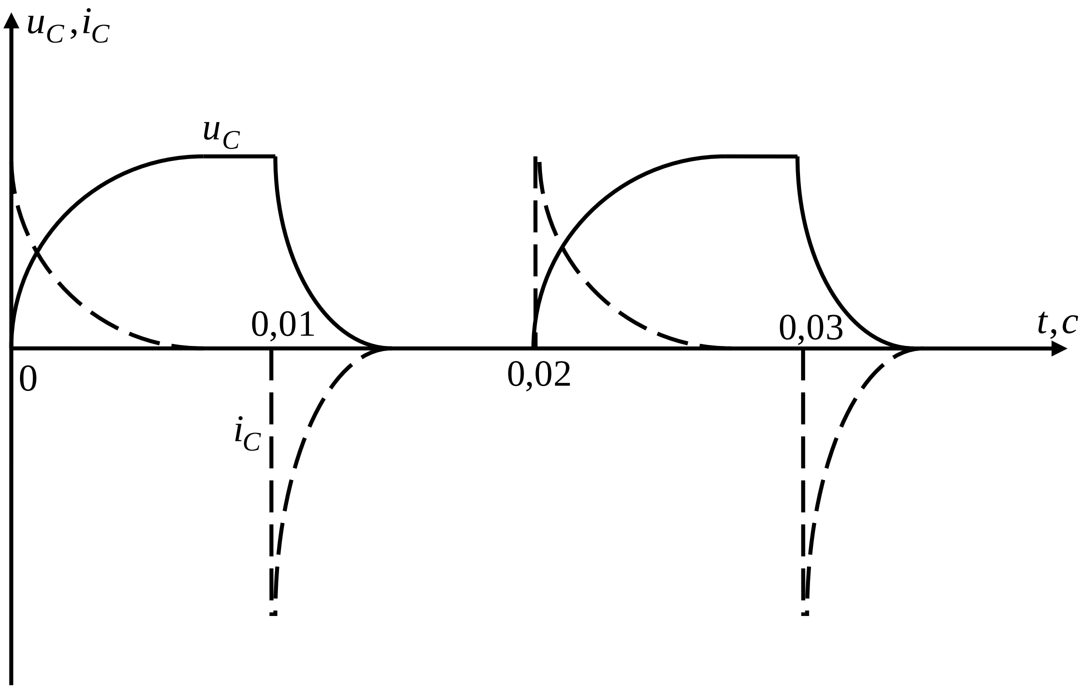

Figure 7.4. - Graphs of transient voltage and current in the R-C circuit

We choose the load parameters and the source of rectangular pulses parameters (Fig. 7.2, 7.3) from that calculation that the transient is copmleted in 0.01 s.

Capacitance-resistance load (Fig.7.3, Fig.7. 4)

$$R_4 = \frac{0,01}{5 \cdot C_1} = \frac{0,02}{C_1},\ \Omega$$

where C_1 - capacity of capacitor, F.

Questions for check knowledge

1. Formulate the second law of switching.
2. How to calculate the independent initial conditions in the presence of capacitor in the circuit?
3. How are the dependent initial conditions calculated in the presence of capacitor in the circuit?
4. Formulate a rule for finding the roots of a characteristic equation.
5. How to analytically determine the time constant of the transition?
6. Why the voltage in the branches with a capacitive stepwise does not change?
7. How is the time constant of the transition calculated?
8. How long does the transition continue?
9. How do changes in circuit parameters affect the duration of the transition process?
10. Formulate the procedure for calculating transients by the operator method

Laboratory Work TFEE – 2/8

EXPERIMENTAL STUDY OF CAPASITOR CHARGE AND DISCHARGE THROUGH INDUCTIVE-RESISTIVE CIRCUIT

Objective

Experimental check of the switching laws

Program of Work

1. Assembly of the rectangular pulses generator.
2. The output signal of the rectangular pulses source oscillography.
3. Capacitance-inductance-resistance circuit connection to the source of the rectangular pulses.
4. Tuning the oscillation transient in the circuit.
5. Oscillography of the oscillation transient current curve in capacitance-inductance-resistance circuit.
6. Tuning the boundary aperiodic transient process in the circuit.
7. Oscillography of the boundary aperiodic transient current curve in the capacitance-inductance-resistance circuit oscillography.
8. Tuning the aperiodic transient process in the circuit.
9. Oscillography of the aperiodic transient current curve in capacitance-inductance-resistance circuit.

10. Analysis results. Summary.

Work Stages

Stage 1. Assembly of the rectangular pulses generator.

1.1. Assemble electric circuit shown in Fig.8.1. As the main elements using:
- source of nonregulated voltage from DC voltage unit;
- limitation resistance R_{lim} is taken on a value about 100 Ω;
- normally open contact S is taken from the bloc of electronic switches unit.

1.2. Switch on the power supply of laboratory stent УИЛС, power supply of the DC voltage unit, the electronic switches unit, and switch the "electronic switch synchronization" toggle switch to the "internal synchronization" position.

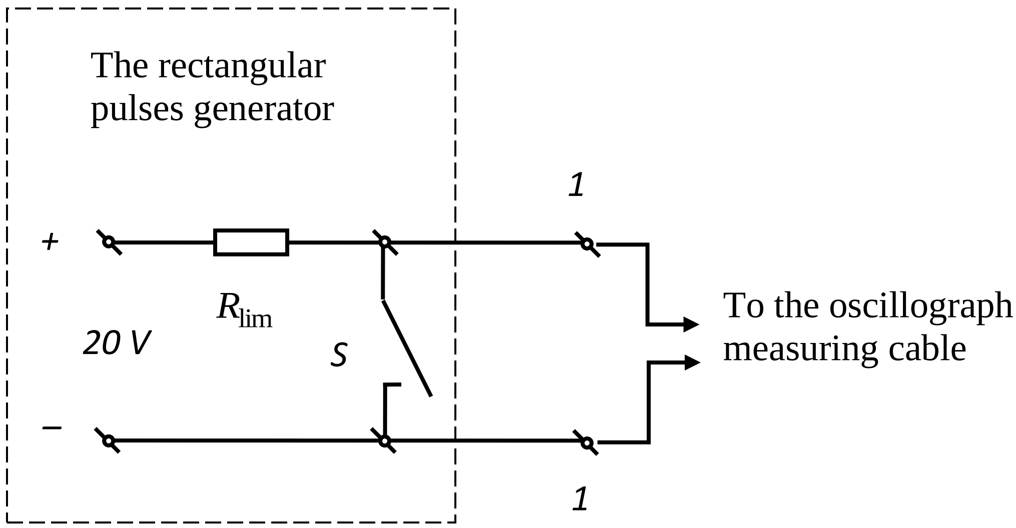

Figure 8.1. - Rectangular pulse generator circuit

Stage 2. Oscillography of the output signal of the rectangular pulses source.

2.1. Switch on of the oscilloscope toggle “сеть” (“main”) and give to warm up for oscilloscope till the appearance of stabile horizontal line on a screen.

2.2. Connect the measuring cable of the oscilloscope to the output voltage of the generator of rectangular pulses and observe the pulses on the screen.

2.3. Use the voltage divider "amplifier Y" (“усилитель Y”) to set a convenient scale on the ordinate axis, and by the switch of “horizontal sweep” (“развертка”) along of the abscissa axis.

2.4. By turning handle “level” (“уровень”) clockwise to the stop, and then the by handle “stabilization” (“Стаб”) to achieve the disappearance of the signal from the oscilloscope screen. Then turning the handle “level” (“уровень”) counterclockwise to achieve a clear, synchronized image of the signal under study.

Attach a tracing paper to the oscilloscope screen and capture an image or take a picture. Write the scales along the ordinate and abscissa.

Stage 3. Capacitance-inductance-resistance circuit connection to the source of rectangular pulses.

3.1. Assemble electric circuit shown in Fig.8.2. As the main elements using:

- feed source – the source of nonregulated voltage from DC voltage unit;
- limitation resistance R_{lim} is taken on a value about 100 Ω;
- parameters of circuit elements L_4 and C_4 from Table 8.1 chosen according to a team number;
- L_4 element is chosen from inductances unit and set by decade switches;
- C_4 element is chosen from capacitances unit and set by decade switches;
- regulated resistor R_4 is chosen from ohmic resistances unit and set by decade switches;
- measuring resistor R_m for current curve oscillography (R_m=1 .. .2 Ω).

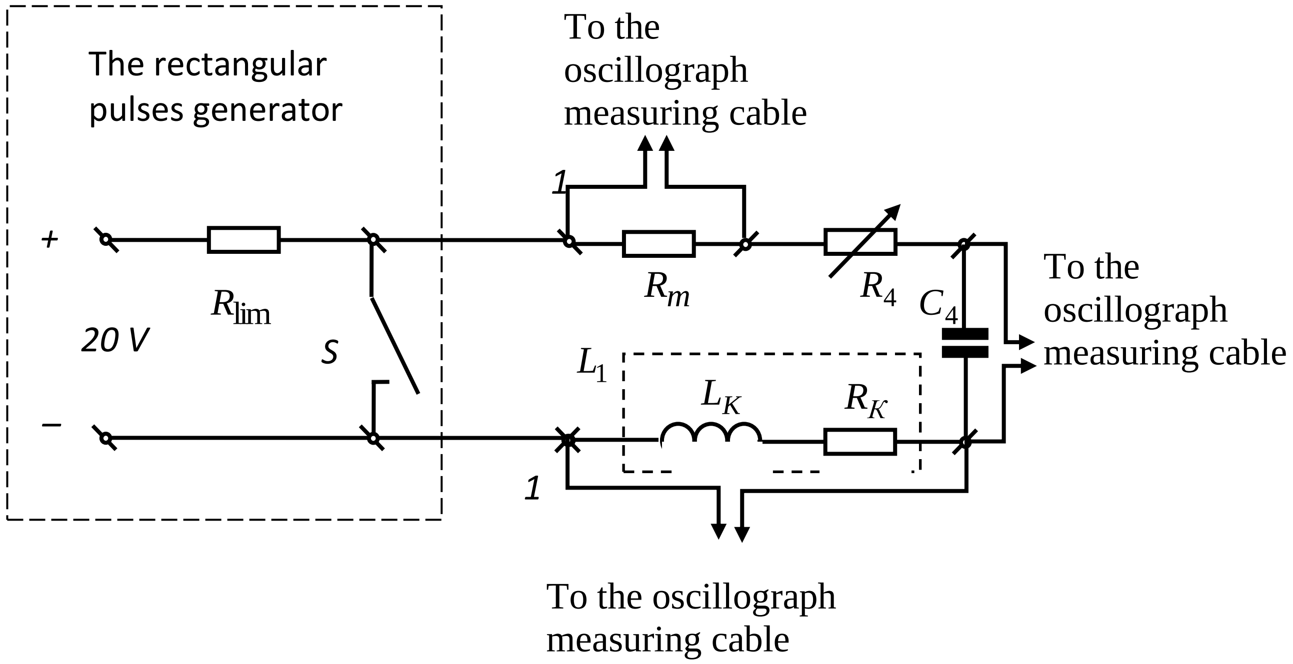

Figure 8.2. – The circuit of experimental study of transients in the second order

Table 8.1.

Initial values of the reactive elements of the second order circle

№ team	1	2	3	4	5	6
L_4 , mH	90	90	80	80	90	80
C_4, μF	1,0	0,5	0,513	1,0	0,25	0,25

Before the element L_4 is connected in the circuit, the internal ohmic resistance R_K is measured with a multimeter. Record the measured value in the report to the laboratory work.

After checking the electrical circuit, switch on the power supply.

Stage 4. Tuning the oscillation transient in the circuit.

Reducing the dissipative losses in the circuit by reducing the ohmic resistance R_4 to achieve a stable oscillatory transient both during charging and discharge of the capacitor through the resistive-inductive circuit. Under the oscillating transient process, we understand the process in which there is a change in the sign of the polarity of the voltage of the capacitor in the process of charging and discharging the capacitor through a resistive-inductive circuit.

Stage 5. Oscillography of the oscillation transient current curve in capacitance-inductance-resistance circuit.

Put a tracing paper to the oscilloscope screen and capture an image or take a picture. Write the scales along the ordinate and abscissa.

Stage 6. Tuning the boundary aperiodic transient process in the circuit.

Increasing the dissipative losses in the circuit by increasing the ohmic resistance R_4 to achieve the boundary aperiodic transient process both when charging and when discharging the capacitor through the resistive-inductive circuit. Under the boundary aperiodic transient we mean the boudary transient between oscillatory and aperiodic transients.

Stage 7. Oscillography of the boundary aperiodic transient current curve in capacitance-inductance-resistance circuit.

Put a tracing paper to the oscilloscope screen and capture an image or take a picture. Write the scales along the ordinate and abscissa.

Stage 8. Tuning the aperiodic transient process in the circuit.

Further increasing the dissipative losses in the circuit by increasing the ohmic resistance R_4 achieve an aperiodic transient process both when charging and when discharging the capacitor through a resistive-inductive circuit. By aperiodic transient we mean a transient in which a capacitor is discharged or charged only once through a resistive-inductive circuit.

Stage 9. Oscillography of the aperiodic transient current curve in capacitance-inductance-resistance circuit.

Put a tracing paper to the oscilloscope screen and capture an image or take a picture. Write the scales along the ordinate and abscissa.

The Report must contain

1. The number and title of the laboratory work.
2. The work program.
3. Scheme of probe circuit.
4. The transient process oscillograms: the source rectangular voltage pulses, voltages on ohmic resistance, inductance and capacitance.
5. Calculation of the critical resistance, characteristic resistance, own angular frequency undamped oscillation.
6. The conclusions of the laboratory work.

Methodical Instruction

The electronic switch *S* during internal synchronization is switching by the mains voltage with a frequency of 50 Hz, so at the output of the generator of rectangular pulses there is a unipolar rectangular voltage with the frequency of 50 Hz, the amplitude equal to the DC voltage.

When the switch *S* is opened, the capacitor is charged through a resistive-inductive circuit, and when it is closed, the capacitor discharged through this circuit. Moreover, the parameters of the circuit are selected so that the transient process from the previous pulse ended earlier than the transient process from the next pulse. In this case, the transients of the discharge and charge of the capacitor are not superimposed on each other and are considered separately.

By changing the value of the ohmic resistance R_4, we change the losses in the circuit containing two energy storage devices. At small losses in the circuit there are several periods of recharging of the capacitor during one operation period of the electronic switch (Fig. 8.3, a). The roots of the characteristic equation in the oscillatory transition are complex - conjugated. The current curve is described by the equation

$$i = Be^{\delta t}\sin(\omega_0 t + \beta),$$

where B and β – are integrating constants.

Increasing the losses in the circuit by increasing the ohmic resistance R_4 at the beginning we obtain the boundary aperiodic process (Fig. 8.3, b), and then aperiodic (Fig. 8.3, c). At the boundary aperiodic transient, the roots of the characteristic equation are real and equal, and at the aperiodic - real and different. Current curves are described by the equations:

- boundary aperiodic transient

$$i = A_1 e^{p_1 t} t;$$

– aperiodic transient process

$$i = A_2 e^{p_2 t} + A_3 e^{p_3 t},$$

where A_1, A_2, A_3 – integrating constants; p_1, p_2, p_3 – the characteristic equation real roots.

The angular frequency value of oscillation transient process is determined experimentally from received oscillogram

$$\omega' = 2\pi f n,$$

where n – the number of periods of discharge of the capacitor, which are within one period of a rectangular voltage pulse; *f* – the frequency of pulses.

The damping decrement of the oscillatory transient is determined from experimental data as the ratio of two adjacent amplitudes of oscillations of one sign.

From the initial values of inductance and capacitance, you can calculate the critical resistance of the circuit with two energy storage devices

$$R_{cr} = 2\sqrt{L_4 / C_4}.$$

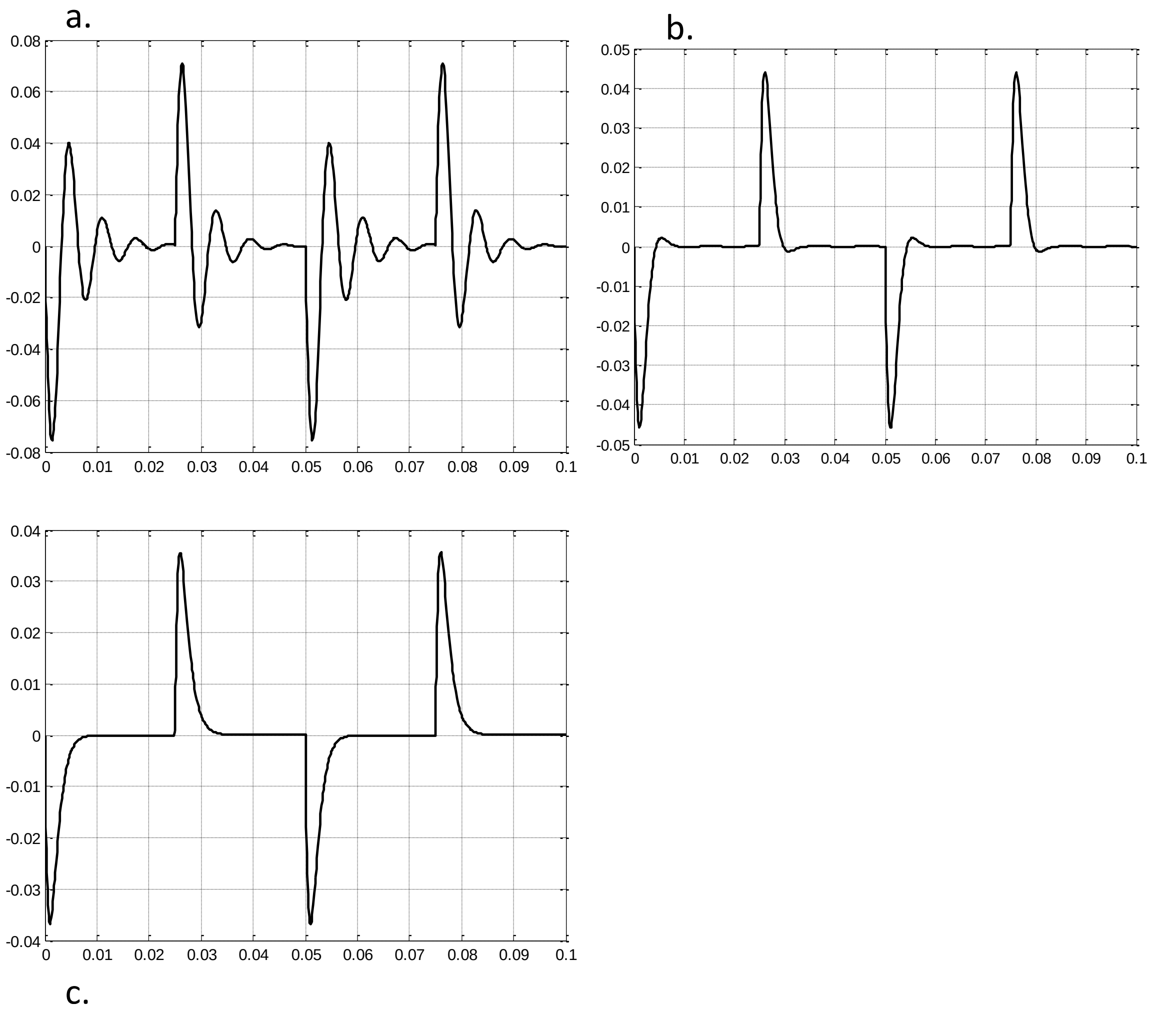

Figure 8.3. - Oscillograms of current in a circuit with two energy storage devices

The wave (matched or characteristic) resistance of loop is calculate as to basic data circuit

$$\rho = R_c = \sqrt{L_4 / C_4}\ .$$

Own angular frequency undamped oscillation

$$\omega_0 = 1/\sqrt{L_4 C_4}\ .$$

Questions for check knowledge

1. Formulate the first and second law of switching.
2. How to calculate the independent initial conditions in the presence of capacitance and inductance in the circuit?
3. How are the dependent initial conditions calculated in the presence of capacitance and inductance in the circuit?
4. Formulate a rule for finding the roots of a characteristic equation.
5. How to analytically determine the time constant of the transition process?
6. Why the voltage in the branches with capacitance and the current in the branches with inductance stepwise does not change?

7. Where is the energy stored in the reactive element spent on when its shunted by jumper?
8. How long does the transition process take?
9. How do changes in the parameters of the circuit affect the duration of the transient process?
10. Formulate the order of calculation of transients by classical and operator methods.

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CONTENT

Автор

Хілов Віктор Сергійович

Методичні вказівки англійскою мовою до лабораторних робіт з дисципліни
ТЕОРЕТИЧНІ ОСНОВИ ЕЛЕКТРОТЕХНІКИ, ЧАСТИНА 1
(розділи: розділи: «Трифазні електричні кола. Вищі гармоніки у електричних колах» та «Перехідні процеси в лінійних електричних колах»
для студентів спеціальності
141 – Електроенергетика, електротехніка та електромеханіка

Друкується в редакції автора.

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у Національному технічному університеті
«Дніпровська політехніка».
Свідоцтво про внесення до Державного реєстру ДК № 1842

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