TOMSK POLYTECHNIC UNIVERSITY

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ELECTRICAL SUPPLY OF INDUSTRIAL ENTERPRISES

Laboratory course

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In the laboratory course the main issues, previously studied in the course "Electrical supply of industrial enterprises", have been considered. A detailed description of the elements which are a part of a laboratory bench of power systems, their parameters and methods of power supply system control in the process of carrying out the laboratory work have been described. The structure and procedure of laboratory works involve feedback of the previous works. A list of problems and tasks aimed at work preparation, processing and data analysis has been provided.

The laboratory course is designed for students of 140400 "Power and Electrical Engineering".

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INTRODUCTION

The laboratory course “Electrical supply of industrial enterprises” includes 7 laboratory works grouped by a shared objective: effective operation of electrical facilities of industrial enterprises.

The laboratory work consists of five identical laboratory installations; each represents a mathematical model of a typical system of an electric supply of the enterprise. Students carry out all laboratory works on the same laboratory installation fixed for a cycle of works. Topics for laboratory works and procedure of their performance provide complex study of operating modes of a typical electrical supply system. Feedback of previous works is used at carrying out of the subsequent ones.

Each laboratory installation models a daily cycle of operation of an electrical supply system. Laboratory installations differ only by load curves that provide individuality for students work and variety of results. A set of system elements of an electrical supply, their parameters, and also their control is stated in the description of the laboratory installation.

DESCRIPTION OF THE LABORATORY INSTALLATION

The laboratory installation is a mathematical system model which provides electrical supply of industrial enterprises (ESIE) and is intended for educational purposes. The installation models a daily cycle of typical ESIE operation.

A symbolic circuit of the installation is shown on its front plate; it includes the following elements that are typical of ESIE (fig. 1):

1. The main step-down substation (SDS) 110/10 kilovolt, it consists of transformers T1, T2 with rated power of 10000 kilovolt and a switchgear (SG) 10 kV. There is a possibility of manual or automatic control of switching transformer T2;
2. A shop transformer substation 10/0,4 kilovolt, it consists of transformers T3 and T4 with rated power of 1000 kilovolt. A transformer T4 is equipped with a switching device – tap without excitation (TWE);
3. A synchronous motor (SM) type СДН-10-1250, it has manual and automatic excitation adjustments provided every hour by the daily schedule;
4. Batteries of power capacitors with rated voltage of 10,5 kV (BC1 and BC2) and voltage 0,4 kV (BC3 and BC4). There is a possibility of manual or automatic batteries switch-off. Battery capacity is set by pressing buttons “more”, “less”, located next to their mnemonic symbols on the scheme, or automatically according to the program;

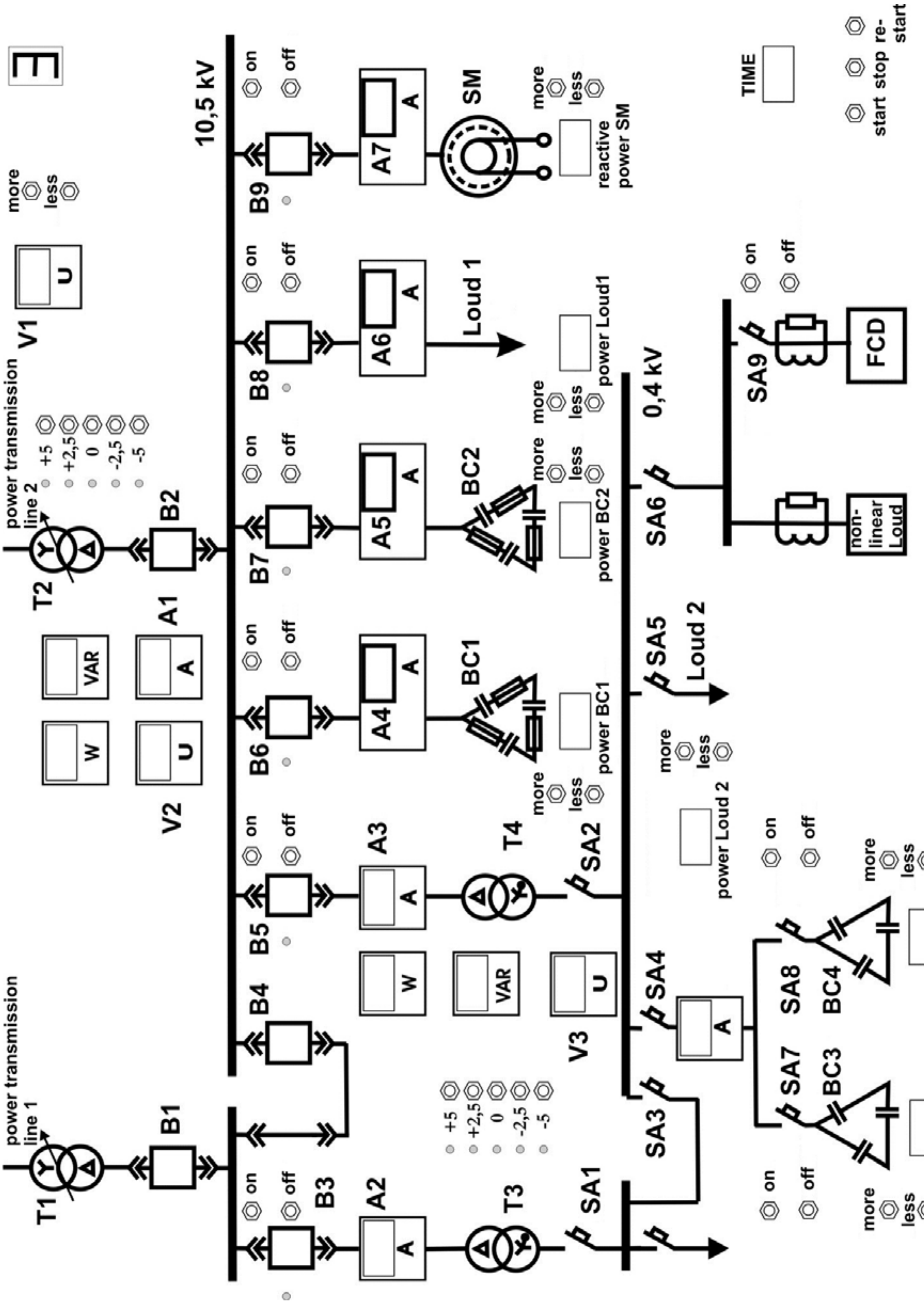


Fig. 1. A symbolic circuit of the installation

5. A power unit (PU) in a shop network of 380/220V. A nonlinear load (NL) is connected to it and causes occurrence of higher voltage harmonics on buses of PU;

6. A filter compensating device (FCD) is intended for reduction of higher harmonics levels on tires of PU.

The following measuring devices are placed on a symbolic circuit:

V1 – A panel board kilovoltmeter for voltage measurement from the high party of a transformer SDS T2;

V2 – A kilovoltmeter for voltage control on SG buses 10 kV;

V3 – A voltmeter for voltage control on SG buses 380/220 in a shop transformer substation;

A1-A8 – Panel board ampermeters aimed at current control of the modeled network. Parameters of modeled elements are shown in Tab. 1.

Table 1

Parameters of elements of the electrical supply system modeled on a laboratory installation

Designation on a mimic scheme (fig. 1)	Type	Rated voltage, kV	Parameters
T1, T2	ТДН 10000/110	115/11	S_r = 10000 kVA, ΔP_{nl} = 27 kW, ΔP_{sc} = 74 kW, u_f = 10,5 %, I_{nl} = 0,9 %
T3, T4	ТМЗ 1000/10	10/0,4	S_r = 1000 kVA, ΔP_{nl} = 2,4 kW, ΔP_{sc} = 12,2 kW, u_f = 5,5 %, I_{nl} = 2 %
BC1, BC2		10,5	Q_r = 8 x 105 = 840 kVAr, ΔP_o = 0,0025 kW/ kVAr
BC3, BC4	УКЛ-0,38	0,4	Q_r = 3 x 105 = 315 kVAr, ΔP_o = 0,0045 kW/ kVAr
Cable feeder T4	АСБ 10(3x50)	10	I_{cc} = 140 A, R_o = 0,62 Ohm/km, X_o = 0,04 Ohm/km, L = 1 km
SM	СДН-10-1250	10	P_r = 1250 kW, cos φ_r = 0,9, K_1 = 0,8, D_1 = 6,77 kW, D_2 = 6,98 kW
FCD		0,4	

Load diagram S2 of a shop transformer substation (STS) is modeled close to the real one. It is programmatically set and always the same for a particular group of students.

The others (in relation to a symbolic circuit of STS shown in the diagram) consumers 10 kV SDS are presented by a generalized loading S1 which load diagram is also set by the program. Load of a synchronous motor, connected to tires 10 kV SDS, is invariable in time.

In a modeled network 0,4/0,23 kV one of the PP with a single-phase nonlinear load which causes presence of higher voltage harmonics on tires of the PP is shown on a symbolic circuit. For compensation of these harmonics a FCD is established, its connection and switch-off is provided by the buttons located on the front plate. Voltage can be studied from the image on the monitor.

All installation controls are located on the front plate. In the bottom left corner of the panel an automatic installation switch-on is established.

At the stand, about the image of switching devices, switch-on and switch-off buttons of these devices are established. Alarm lamps indicate a condition of the switching device. The measuring devices are placed on the front plate, they are aimed at lines current measurement and voltage on tires 10,5 кV and 0,4 kV. Active and reactive capacity in circuits T2 and T4 are measured by the gages established in the stand. Transformer and alarm lamps are located next to mnemosymbols of transformers T2 and T4 switching buttons.

Buttons "Power BC" and "Reactive power SM" are intended for a value assignment of generated reactive power of capacity batteries and the synchronous motor accordingly (power is specified in kVAr). On the right bottom part of the obverse panel controls for operating modes of the whole installation are located: button "Start-up" – for installation start; button "Dump/Reset" – for installation return to an initial condition; button "Stop" – for fixation of any installation mode; a digital board – for control of modeling time. The laboratory installation provides an automatic switch of T2 transformer, and also switch-on and switch-off of T3 transformer and BC1, BC2, BC3 and BC4capacity batteries.

Laboratory installation has two operating modes:

1. A preparation mode (an initial mode) which is started at a switch-on. In this mode entry conditions (switch-on and switch-off of corresponding system elements) are set; a work program according to time of days of РПН device of T2 and T3 transformers is set, condenser batteries BC1, BC2, BC3 and BC4 are established. Required measuring devices are connected and adjusted, and also readiness of installation for a "pass" of a daily cycle is checked.

2. A process of loads modeling of a daily cycle is switched on by clicking "Start-up". On a digital board figure 01 lights up and power is on.

Modeling time of days per hour is shown on a digital board.

Upon the end of a daily cycle installation automatically returns to an initial mode. If necessary it is possible to return installation compulsorily to an initial mode by clicking "Dump/Reset". By clicking "Stop" the program of modeling of a daily cycle stops, readout of time stops and the account of power consumption ends up. The program can be run again by clicking “Start-up”.

Scales of all ampermeters and voltmeters on the obverse panel of the stand gauged in valid sizes. These devices are used for visual control and record of parameters of an operating mode of modeled system.

At performance of some measurements the additional equipment (an oscillograph, a measuring instrument of nonlinear distortions, etc.) is used. The device and work of this equipment are studied by carrying out of corresponding laboratory works.

In most cases at carrying out of laboratory works it is more convenient to operate not with the buttons located on the stand, but by means of the tool panel of the program “Workbench”. This method will be considered in more details.

IMPLEMENTATION OF THE “WORKBENCH” PROGRAM

All laboratory works provided in the course are carried out by means of the program “Workbench”. The tool panel of the program which is highlighted on the monitor after computer switching-on serves for performance of necessary operations at carrying out laboratory works. The kind of tool panel with the name of buttons is shown in the figure 2.

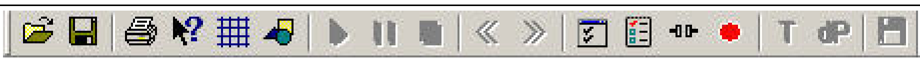
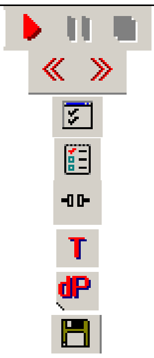
	
Buttons	
	“Run task”, “Pause task”, “Stop task” “Back” and “Next” for a step-by-step task performance “Stand Options” “Select (edit) versions of tasks” “Connect to the stand” “The graph of cable temperature change” “The graph of power losses” “Save graphics”

Fig. 2. The tool panel of the program

Consider functions which are carried out by the program by clicking this or that button on the panel of tools.

Work begins with the button “Select (edit) versions of tasks”. In a pop-up window it is necessary to allocate the required version of the task and to confirm it by “OK”. Then the button “Run task” is activated. By clicking it the automatic “pass” of the daily production schedule with indication at the stand

and the monitor of parameters of loading on each hour of days are started. “Pass” end is displayed by a stop of indications change and indication of a 24-th hour of a day. If necessary program execution can be suspended by clicking “Pause task”. By the subsequent clicking “Run task” tasks will be carried on. If “Stop task” is clicked, the program stops further work and by clicking “Start task” the process of the schedule “pass” starts with the 1st hour of a day.

The program allows us to see load parameters in the electrical supply system at any hour of a day. For this purpose buttons “Back” and “Next” are provided. By clicking “Next” load parameters indicate the hour which is shown on the watch. In order to see data of next hour it is necessary to click “Next” repeatedly. There is a step-by-step indication of all parameters. By clicking “Back” indication of a load condition occurs inversely (from the end of the graph).

The button “Stand Options” allows us to see the set parameters of the program. After clicking on it it is possible to change necessary parameters in a pop-up window. It allows choosing optimum time of “prorace” for faultless fixing and logging of all indications of devices at each step of the production schedule.

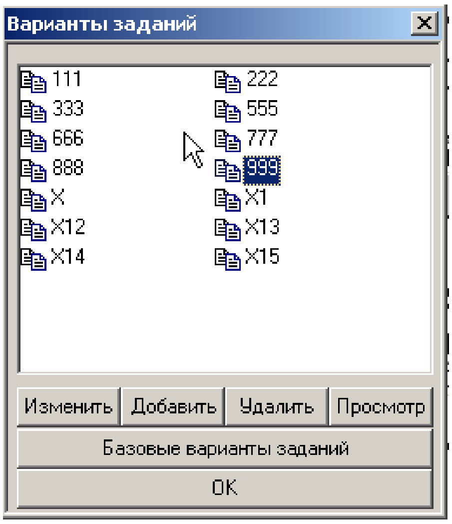


Fig. 3. Variants of tasks

The choice of the set variant is made by means of the button “Choice (editing) of variants of tasks”. By clicking it there will be a window with variants of tasks (fig. 3). In the pop-up window it is necessary to allocate the variant. The further actions depend on the allocation purpose. If it is necessary to banish the daily production schedule it is necessary to click consistently buttons “Apply”, “OK” and “Start the task”. Updating of the chosen variant of the task during the laboratory works can be done in two ways.

The first method. Click “Change”. Make changes of load settings in each day hour from the initial value till 24 o'clock in a pop-up window (fig. 4). Transition in time of the day is carried out by clicking “Forward” and “Back”.

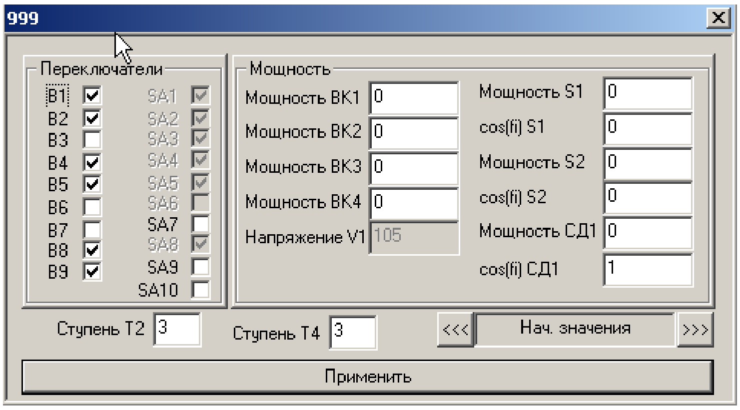
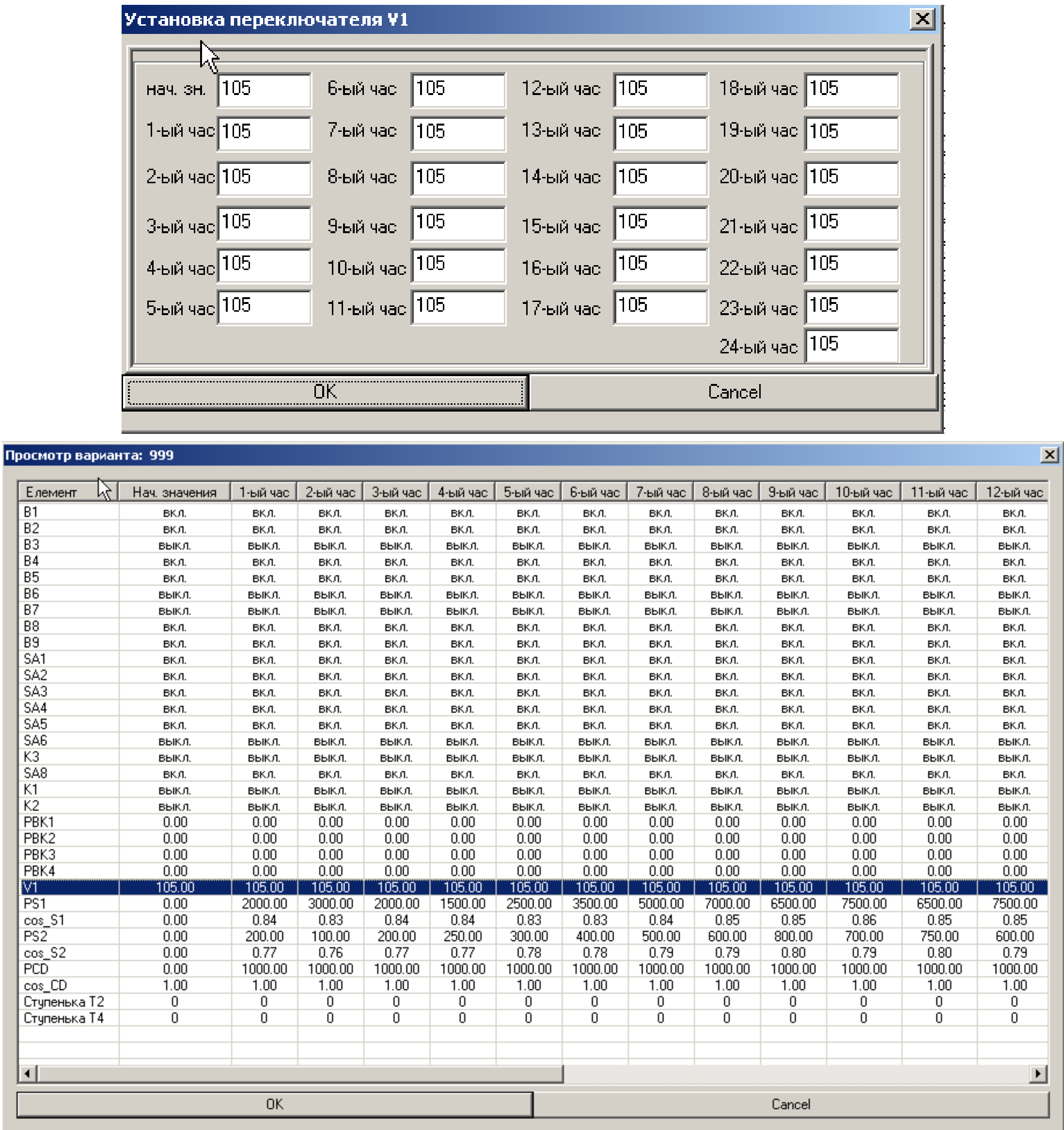


Fig. 4. Editing of the chosen variant



a

Елемент	Нач. значения	1-ый час	2-ый час	3-ый час	4-ый час	5-ый час	6-ый час	7-ый час	8-ый час	9-ый час	10-ый час	11-ый час	12-ый час
B1	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.
B2	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.
B3	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.
B4	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.
B5	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.
B6	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.
B7	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.
B8	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.
B9	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.
SA1	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.
SA2	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.
SA3	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.
SA4	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.
SA5	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.
SA6	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.
K3	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.
SA8	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.	вкл.
K1	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.
K2	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.	выкл.
PBK1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PBK2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PBK3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PBK4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
V1	105.00	105.00	105.00	105.00	105.00	105.00	105.00	105.00	105.00	105.00	105.00	105.00	105.00
PS1	0.00	2000.00	3000.00	2000.00	1500.00	2500.00	3500.00	5000.00	7000.00	6500.00	7500.00	6500.00	7500.00
cos_S1	0.00	0.84	0.83	0.84	0.84	0.83	0.83	0.84	0.85	0.85	0.86	0.85	0.85
PS2	0.00	200.00	100.00	200.00	250.00	300.00	400.00	500.00	600.00	800.00	700.00	750.00	600.00
cos_S2	0.00	0.77	0.76	0.77	0.77	0.78	0.78	0.79	0.79	0.80	0.79	0.80	0.79
PCD	0.00	1000.00	1000.00	1000.00	1000.00	1000.00	1000.00	1000.00	1000.00	1000.00	1000.00	1000.00	1000.00
cos_CD	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Ступенька Т2	0	0	0	0	0	0	0	0	0	0	0	0	0
Ступенька Т4	0	0	0	0	0	0	0	0	0	0	0	0	0

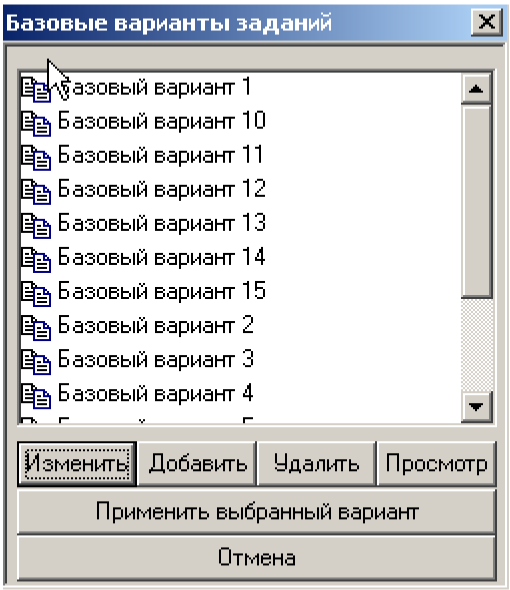
b

Fig. 5. The second method of a daily mode assignment

The second method. Click “Review”. Double click on an element which is necessary to edit in a pop-up window (fig. 5, *a*). Enter all parameter values in a daily interval or only updated ones in a new window (fig. 5, *b*).

Creation of a new task variant is carried out in the following order. Click “Choice of the task variants”, then click on “Basic task variants” in a pop-up window (fig. 3). A new window will appear (fig. 6, *a*) where it is necessary to single out a required basic variant and click “Apply”. As a result there will be a new window (fig. 6, *b*) where the name of the variant (a surname, a set of figures or letters as a name of a new variant) is entered. Click “Apply” and a new variant under this name will appear in the window of the variant choice (fig. 3). The further work is done as usual.

To supervise processes of a daily load curve and reading the instruments it is possible to use a mimic diagram of the panel. For this purpose the button “Connect to the panel” is installed. By clicking it, the panel is connected to the computer and duplicates instrument readings on the monitor. By repeated clicking, the panel will be disconnected.



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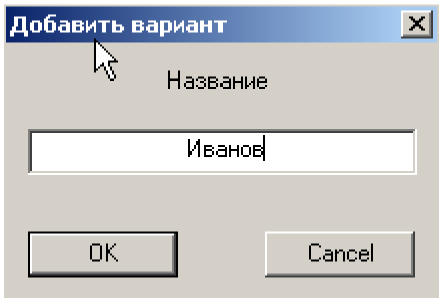

b

Fig. 6. Creation of task variants

When current flows in a communication cable from the main step-down substation up to the shop transformer T4 the cable is heated. By means of a temperature-sensitive element the temperature of the cable overheating is read and is recorded as a graph. For viewing and analyzing the graph of overheating temperature, it is necessary to click “The graph of the cable heating temperature change”. After these actions a necessary graph will appear on the screen.

By researching parallel operation of shop transformers it is possible to look at the graph of power losses of one and two transformers operating in parallel at the same load. For this purpose there is a button "The graph of power losses". By clicking it, graphs of power losses appear on the monitor screen which should be compared with the design graphs.

After "run" of a daily load curve of the given variant it is possible to see the graphs of an element load parameter of the power supply system. For this purpose it is necessary to double click on the chosen element. The example is shown in fig. 7.

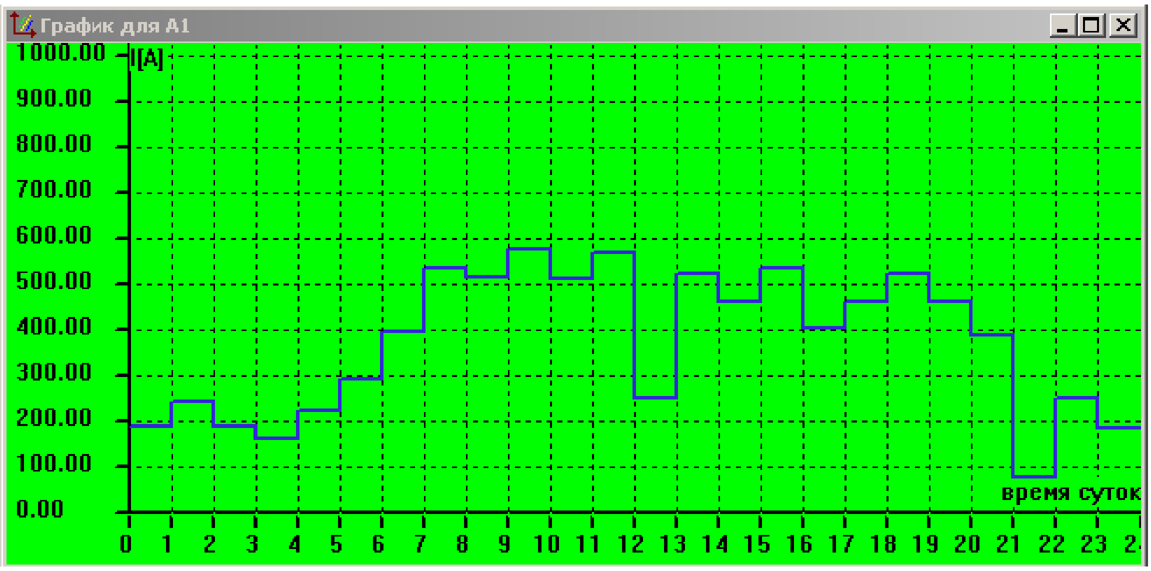

Fig.7. A daily load curve of the element A1

If it is necessary to save graphs for further work the button "Save graphs to disk" should be clicked. The graphs will be saved under a working variant name (the task variant).

LABORATORY WORK № 1

STUDY OF INSTALLATION DESIGN AND SETUP MODES MODELED BY SAPP

1. Purpose

The purpose of the work is to study the laboratory unit design, its operation principle and simulated element parameters of the power supply system of industrial enterprises. The work is focused on the operating mode investigation of the power supply system of industrial enterprises at day time interval and characterization of the mode parameters.

2. Introduction

The basic rated simulated element parameters of the power supply system of industrial enterprises are given in the table 1. For three-phase power transformers in L-shaped single-line equivalent circuit the following parameters are used:

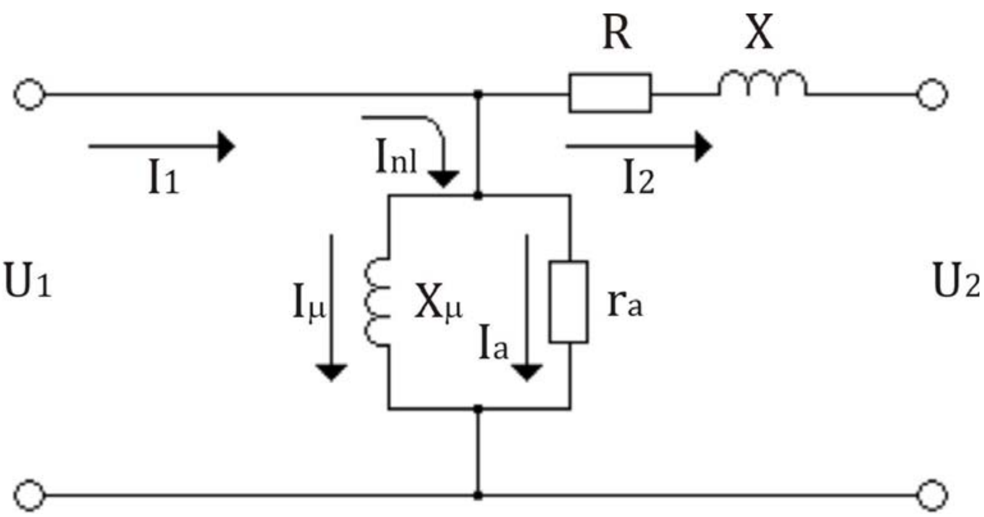

Fig. 8. L-shaped single-line equivalent circuit of a three-phase transformer

U_1, U_2 – phase-to-phase voltage reduced to one voltage level;
I_1, I_2 – currents of the transformer primary and secondary windings;
$I_{nl} = I_a - jI_{re}$ – no-load transformer current;
$X_\mu = \frac{\sqrt{3}U_1^2}{\Delta Q_{nl}}$ – induction resistance component of the magnetizing branch (U_1 – phase-to-phase voltage) ;
$r_a = \frac{\sqrt{3}U_1^2}{\Delta P_{nl}}$ – active resistance component of the magnetizing branch;
$R = \frac{\Delta P_{sc}}{3I_r^2} = \frac{\Delta P_{sc} \cdot U_r^2}{S_r^2}$ – transformer resistance;
$x = \frac{\sqrt{\left(\frac{u_f \cdot U_r}{100}\right)^2 - \left(I_r R\right)^2}}{\sqrt{3}I_r}$ – transformer inductance;
$\Delta \dot{S} = 3I_2^2 R - j3I_2^2 x = \Delta P_{sc} \cdot K_1^2 - j\Delta Q_{sc} \cdot K_1^2$ – transformer load losses ($K_1 = \frac{I_2}{I_r}$ – the load factor);
$\Delta \dot{U} = \dot{I}_2 R + j\dot{I}_2 x$ – transformer voltage losses.

The basic feature of operating modes of the power supply system of industrial enterprises over long time periods (day, week, year) is their variability which is caused by variability of electric loads. Modes of the power supply system of industrial enterprises in time T are characterized by parameters of two kinds: current parameter and integral parameter. Current parameters are values of currents, voltage, power in network nodes which can change in time. Integral parameters in time T are average values of currents, voltage, power, their dispersion, electric power losses, etc.

At day time intervals the mode parameter values of the power supply system of industrial enterprises can be represented in the form of daily graphs (current, voltage, power, etc.) of their average values in sequential intervals Θ (Θ= 30 or 60 minutes).

Integral parameters for the graph of current are:

$$I_a = \frac{1}{n}\sum_{i=1}^{n} I_i; \quad \sigma_I^2 = \frac{1}{n}\sum_{1}^{n}(I_i - I_a)^2 = \frac{1}{n}\sum_{1}^{n} I_i^2 - I_a^2 = I_{ms}^2 - I_a^2,$$

where n – the interval number Θ in the daily graph of current; I_{ms} – the mean square value of the graph of current.

Electric power losses in the line with resistance R and during time T:

$$\Delta W = \Delta P_{nl} T + \left(\frac{I_a}{I_r}\right)^2 \Delta P_{sc} T + \frac{\sigma_i^2}{I_r^2}\Delta P_{sc} T = \Delta P_{nl} T + \Theta \sum_{1}^{n}\left(\frac{I_i}{I_r}\right)^2 \Delta P_{sc}.$$

Losses in the transformer during time T:

$$\Delta W = \Delta P_{sc} T + \left(\frac{I_a}{I_r}\right)^2 \Delta P_{sc} T + \frac{\sigma_i^2}{I_r^2}\Delta P_{sc} T = \Delta P_{nl} T + \Theta \sum_{1}^{n}\left(\frac{I_i}{I_r}\right)^2 \Delta P_{sc}.$$

3. Work procedure (task)

3.1. Study the laboratory unit design. Calculate the equivalent circuit resistances for the transformers T2, T4.

3.2. Be ready for recording active and reactive load curves – make table 2 in duplicate (for the transformers T2 and T4 separately).

3.3. Set up the unit for recording the operating mode parameters of the simulated power supply system of industrial enterprises at day time interval: turn on the computer and the panel; connect the panel to the computer, turn on a T4 transformer and generalized load S1 at 10,5 kV buses of the main step-down substation, synchronous electric motor; turn off a T3 transformer and capacitor banks BK1, BK2, BK3 and BK4, a power filter of the filter compensating device; put on-load tap changer of the transformer T2 and off-circuit tap-changer of the transformer T4 in zero position.

3.4. Set up the unit by clicking "Start the task" or "Start" and record active and reactive power transformer loads (the transformers T2 and T4). Record the instrument readings in Table 2 (column 2,3). Record the current value of the transformer load (the transformers T2 and T4) (column 4) using ammeters.

3.5. Calculate the graphs of total power. Calculate average values and mean square deviation of the load curve. For self-check it is recommended to compare the received current values with the values calculated for total power.

3.6. Calculate electric power losses during a day in the transformers T2, T4 and in a cable line (in watt-hours and in percentage terms). Single out a component caused by variation of the load curves in the losses value.

3.7. Prepare a report on the laboratory work which should contain:

- mimic diagram of the unit, a brief description and the simulated element parameters of the typical power supply system of industrial enterprises, purpose;
- calculation of the equivalent circuit resistances;
- results of recording and calculation of load curves and their parameters for the transformers T2 and T4 (table. 2);

Table 2

Actual and rated mode parameters of the power supply system of industrial enterprises at day time interval for the transformer T2 (T4)

Day hour	Load curves				Rated data			
	Active power, kW	Reactive power, kVAr	Current, A	Voltage, kV	Total power, kVA	Rated current, A	tg φ	cos φ
1	2	3	4	5	6	7	8	9
1 2 3 . . 24								
Average current value I_a = . Mean square deviation σ_y = .								

Load curves T2 and T4 (active power, reactive power, total power and current);

- calculation of electric power losses in the transformers T2, T4 and in the cable line feeding the transformer T4;
- conclusions and answers to test questions.

Calculation of I_a and σ_y is necessary to give design equations and to show the figures used.

4. Preparation

Self-preparation for the laboratory work includes:

1) study theoretical material of the course “Power supply of industrial enterprises”, section “Modes of power consumption of industrial enterprises”;
2) complete points 3.1 and 3.2 of the task.

5. Test questions

1. Give reasons of operating mode parameter variability of the power supply system of industrial enterprises in time.
2. What losses can occur in transformers and what do they depend on?
3. How can electric power losses in industrial power supply networks be characterized?
4. Is variation of power consumption modes complicated? Does it make operation of electric power systems worse? Why?

LABORATORY WORK № 2

RESEARCH AND REGULATION OF VOLTAGE LEVELS IN INDUSTRIAL NETWORKS

1. Purpose

The purpose of the work is to study estimation technique of voltage levels in networks and ways of their improvement at day time interval.

2. Introduction

There are two major factors causing voltage variability in electric networks: load variability causing fluctuation of voltage losses, and voltage regulation for keeping it in the prescribed limits.

It is accepted to estimate voltage levels by deviations of voltage from nominal V, which values are time variables.

From technical and economic efficiency point of view, the best voltage at electric receiver terminals is $U(t) = U_r = \text{const}$, i.e. $V = 0$. Supply of such voltage mode for all electric receivers in the network is practically impossible, therefore $V \neq 0$. The more value *of* V, the worse voltage. There is a number of exceptions from this rule, for example, for poorly loaded asynchronous electric motor the best voltage is lower than the nominal one. Allowed values of V are normed by the State Standard [2] as a whole for electrical networks depending on their voltage. The most rigid requirements to value V are imposed on the electric networks feeding a great bulk of electric receivers (up to 1000 V).

For electric networks of voltage up to 1000 V with 0,95 cumulative probability voltage deviations are allowed that equal ±5 %. If cumulative probability is 0,05, greater deviations are allowed, but they should not exceed ±10 %.

Table 3

Allowed values of voltage deviations according to State Standard 13109–97

Voltage of the electric network	Allowed values	
	normal	maximum
Up to 1 kV	± 5 %	± 10 %
6…20 kV	—	± 10 %
35 kV and above	—	—

Estimation of the maximum voltage deviations is usually made for maximum and minimum load modes by means of the diagram of voltage deviations in the network. For a simulated network a design diagram and diagram V is shown in fig. 9. In this figure:

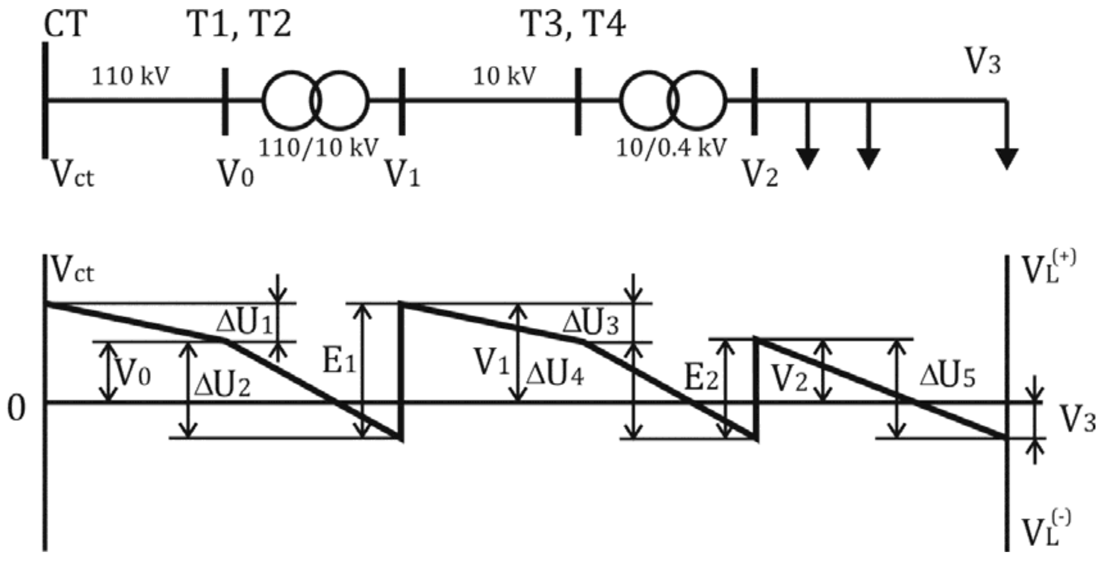

Fig.9. Design diagram and diagram of voltage deviation

V_{ct} –voltage deviation in the center of supply;
ΔU_1 – voltage loss in 110 kV overhead power line feeding the transformer at the main step-down substation;
V_0 – voltage deviation at the balance inventory boundary of the power supply company networks and electric power consumer networks.

V_1 – voltage deviation of 10 kV switchgear buses at the main step-down substation;
ΔU_2 – voltage losses in the transformer at the main step-down substation;
E_1 – addition of voltage in the transformer at the main step-down substation;
ΔU_3 – voltage loss in the cable line feeding the transformer T4 at the shop transformer substation;
E_2 – additional voltage to the transformer at the shop transformer substation;
V_2 – voltage deviation of 380/220 V switchgear buses at the shop transformer substation;
ΔU_4 – voltage loss in the shop transformer;
V_3 – voltage deviation in the network in the connection point of the farthest electric receiver;
ΔU_5 – voltage losses in the shop network (for example, in a bus trunk SHM).

Under operating conditions all consumers calculate demanded values of V_0 for modes of maximum and minimum loads in view of voltage regulation means. If a power supply company does not maintain these values it is subjected to economic penalties. As a result the performance of the given laboratory work is focused on the investigation of voltage deviations in the industrial electrical network by calculating demanded values of V_0 for modes of maximum and minimum loads.

Voltage losses in the network element with resistance $Z = R + jx$ and current $\dot{I} = I' - jI''$ are defined by the equation

$$\Delta U = \frac{I'R + I''x}{U\text{r}}, \quad (1)$$

where I' и I'' – active and reactive current components in the circuit.

All necessary element parameters in the simulated network are given in table 1. The parameters of the transformers T2 and T4 are calculated in item 3.1. of the laboratory work №1.

3. Work procedure (task)

3.1. Process results of voltage measurements according to the data of the laboratory work № 1:

1) plot graphs $V(t)$ for 10 kV busses of the main step-down substation and 380/220V buses of the shop transformer substation;
2) plot bar charts of voltage deviations and calculate their average values and dispersions.

3.2. Analyze the received results, determine optimal off-circuit tap-changer step of the transformer T4 and design a graph of tap switching of the transformer T2. An opportunity of voltage regulation by means of capacitor banks is not considered in the given work.

3.3. Set up the unit: turn on the computer and the panel, connect the panel to the computer, turn on the transformer T4, turn off the transformer T3, connect the generalized load to10 kV buses $S1$, turn on the synchronous motor, disconnect the capacitor banks BC1, BC2, BC3, BC4 and the filter compensating device.

3.4. According to bar charts and conclusions edit the off-circuit tap-changer step of the transformer T4 and set tap switching program of on-load tap changer of the transformer T2 during a day.

3.5. Launch the unit and record voltages in a daily cycle similarly to the laboratory work № 1.

3.6. Process measurement results according to item 3.1 and estimate conformance of voltage in the simulated network to requirements of State Standard [2].

3.7. According to the results received in item 3.6 plot diagrams of voltage deviations for the simulated network (similarly to fig. 9) for modes of maximum and minimum loads. Deviations of V_1 and V_2 are determined experimentally, deviations of V_0 are determined by the equation (1). Due to the fact that 380/220 V shop network is not presented (SHM in fig. 9), losses in this network (ΔU_5) are calculated according to the mark and length of a wire up to the receiver, assigned by the teacher. V_3 should be estimated.

3.8. By accepting 380/220 V buses of the shop transformer substation allowed values of deviations are: $V_L^{(+)} = 5$ %, $V_L^{(-)} = 0$ determine corresponding deviations which a power supply company should provide at the balance inventory boundary of the networks for modes of maximum and minimum loads.

Maximum time ranges from 8 till 12 a.m., minimum time – from 2 till 5 a.m. In the laboratory work the operation of compensating devices is not considered. Compensation of reactive loads is considered in the following laboratory work.

3.9. Prepare the laboratory work report which should contain:

- Statement of investigation problems;
- Analysis and estimation results of voltage deviations in the simulated network of item 3.1;
- Justification of the off-circuit tap-changer setting of the transformer T4;
- Daily graph of tap switching of the transformer T2;
- Measurement results of item 3.6;
- Voltage values of points 3.7 and 3.8;
- Conclusions and answers to test questions.

Note. Analysis and estimation of voltage deviations are necessary to divide all range of voltage deviations into e n qual intervals: (-5 …-2,5) %; (-2,5 … 0) %; (0 … 2,5) %, etc. To find mathematical expectation or average value of voltage deviations:

$$V_a = \sum_1^n V_i P_i \ , \qquad (2)$$

where V_i – midpoint coordinate of i bar chart interval; P_i – probability of deviations in this interval.

Dispersion of voltage deviations is defined as

$$\sigma_v^2 = \sum_1^n (V_i - V_a)^2 P_i \qquad (3)$$

And mean-square deviation

$$\sigma_v = \sqrt{\sigma_v^2}. \qquad (4)$$

4. Preparation

Self-preparation for the laboratory work includes:

1) revision of theoretical material [1];

2) processing the voltage measurement results in item 3.1 according to the laboratory work № 1;

3) preparation for answers to test questions;

4) calculation of voltage losses in the transformers T2 and T4 for modes of maximum and minimum loads necessary for item 3.7 and 3.8 of the task.

5. Test questions

1. What are the allowed voltage deviations in industrial electrical networks in accordance with State Standard13109-97. Why?

2. How does operation of various electric receivers depend on the voltage value in a network?

3. What ways of voltage improvement are used in industrial electrical networks and in networks of power supply systems?

4. Plot the vector diagram of current and voltage for the elementary network with resistance $R + jx$ and current $I' - jI''$.

5. What estimations of voltage levels are available and how are they calculated?

LABORATORY WORK № 3

COMPENSATION OF REACTIVE LOADS IN THE SYSTEM

1. Purpose

The purpose of the work is to study the main principles of reactive load compensation in industrial networks. The work provides: calculation of compensating device capacity, implementation of reactive power design conditions at the laboratory model, estimation of reactive load compensation influence on voltage mode and economic efficiency design.

2. Introduction

"Rules on electric and thermal power use" regulate the reactive power exchange between the enterprise power supply system and the electric power system [4]. Control over these rules observance is entrusted to "Gosenergonadzor". Specific requirements to the reactive power mode of each enterprise are ascertained at annual contract for electric energy consumption. Economically sound input reactive powers (Q_{e1} and Q_{e2}) [4] are targeted differentially to the enterprises depending on power consumed and enterprise electric remoteness from the main energy sources (power plants). Q_{e1} and Q_{e2} values are determined by computing optimal operating conditions of power network at peak (Q_{e1}) and minimum (Q_{e2}) loads.

This laboratory work studies the load node which equivalent circuit is shown in fig. 10.

The circuit contains only one of the main step-down substation sections (the right one) as the second one is conventionally considered to be absolutely similar. Balance inventory boundary is provided on the level of transformer high-voltage bushing of the main step-down substation. Control balances of active and reactive powers are brought at the boundary. The control is carried out at successive half-hour time intervals using energy meters with peak recording or special information and measuring systems.

The laboratory model has the following reactive power sources: the electric power system (Q_{e1}, Q_{e2}), the synchronous motor (Q_m), 10 kV capacitor units BK1, BK2 (Q_{chv}) and 0,4 kV capacitor units BK3, BK4 (Q_{cl}). Load at 10,5 kV buses (Q_1) and transformer substation load (Q_2) are its consumers.

The mode conforming to a minimum value of annual calculated consumption and meeting the electric power system requirements is the optimal mode of reactive loads compensation [4]. To compute this mode the calculated consumption function (target function) is made and the restrictions are recorded [4, 5]. Optimal powers are the powers of compensating devices at which the target function takes a minimum value in the region of feasibility. The region of feasibility is determined by the restrictions imposed on compensating device capacity. Compensating device optimal capacities are calculated by the methods of mathematical programming.

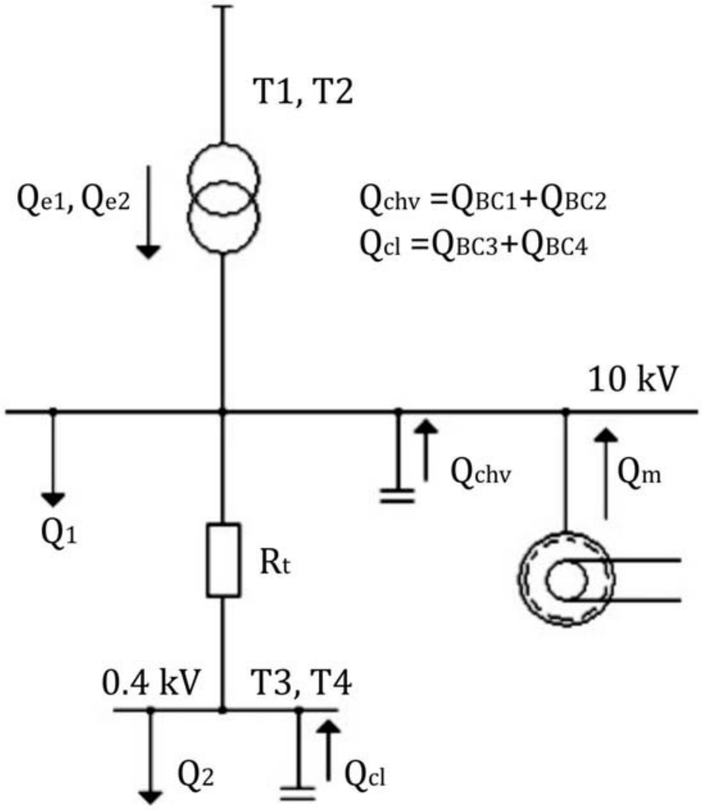

Fig. 10. Load node equivalent circuit

Not the whole industrial network is simulated in the laboratory unit but only the main step-down substation and one of shop substations with a feeding cable power transmission line. Load Q_1 represents a total reactive power consumed by the other transformer substation with unknown power and quantity. Under these conditions the optimization problem of compensating devices arrangement may be solved by dividing it into two stages without applying optimization techniques.

The first stage. The transformer substation is considered (fig. 11) and optimal value Q_{cl} is determined according to the annual calculated consumption function:

$$Z = (Q_{cl}) = E \cdot \Delta K_r \cdot Q_{cl} + C_o \left[\Delta P_r \cdot Q_{cl} + \frac{R_t}{10^3 \cdot U^2} \left(Q_2^m - Q_{cl} \right)^2 \right], \quad (1)$$

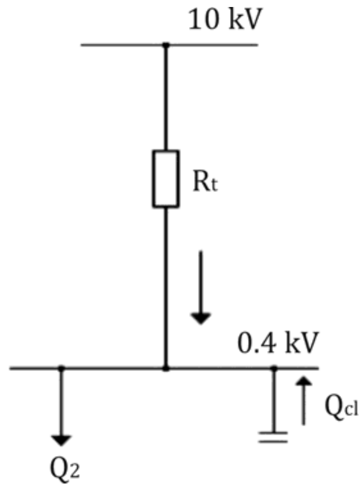

Fig. 11. The design equivalent circuit for the first stage

where E is the coefficient of investment contributions (standard contributions, contributions for equipment operation and reconditioning). E numerical value should be accepted equal 0,223 p.u.; ΔK_{r} is the specific cost of low voltage capacitor units (6 r/kVAr); C_o is the specific cost of active power loss (it is assigned by a teacher in the range from 40 to 70 r/kW); ΔP_{r} is the active power specific loss in low voltage capacitor units (0,003 kW / kVAr); R_{t} is the resistance of the transformer at the shop transformer substation and the feeding transmission line reduced to 10 kV voltage (Ohm). The magnitude of this resistance is determined by the data in the Table 1; U is the average voltage at the main step-down substation buses (10 kV); Q_2^m is the highest reactive power of the transformer T4 load at peak active power of electric supply network demand (to simplify the work assume that the transformer T3 is disconnected and not consider its data in the calculation). It is determined by the T4 load curve obtained in the laboratory work № 1. The peak period is prescribed in the laboratory work № 2.

$$R_{\mathrm{t}} = \frac{\Delta P_{\mathrm{sc}} \cdot U^2}{S_{\mathrm{rt}}^2} 10^3 + r_o \cdot l \ , \tag{2}$$

where ΔP_{sc} is the short circuit loss in the transformer, kW (Table 1); S_{rt} is the design capacity of the transformer, kVA; r_{o} is the active resistivity of the transmission line, Ohm/km; l is the transmission line length, km.

The capacitor bank power is determined by the equation:

$$\frac{dZ}{dQ_{\mathrm{cl}}} = 0. \tag{3}$$

The design expression is of the form:

$$Q_{cl} = Q_2^m - \frac{E \cdot \Delta K_r + Co \cdot \Delta P_r}{2C_o \cdot R_t} U^2 \cdot 10^3 \text{ , } kVAr. \quad (4)$$

The second stage. The problem of calculating optimal values of Q_{chv} and Q_{m} is considered at this stage (fig. 12). The value of uncompensated power transmitted through the transformer T4 is shown on the diagram as Q_{t} .

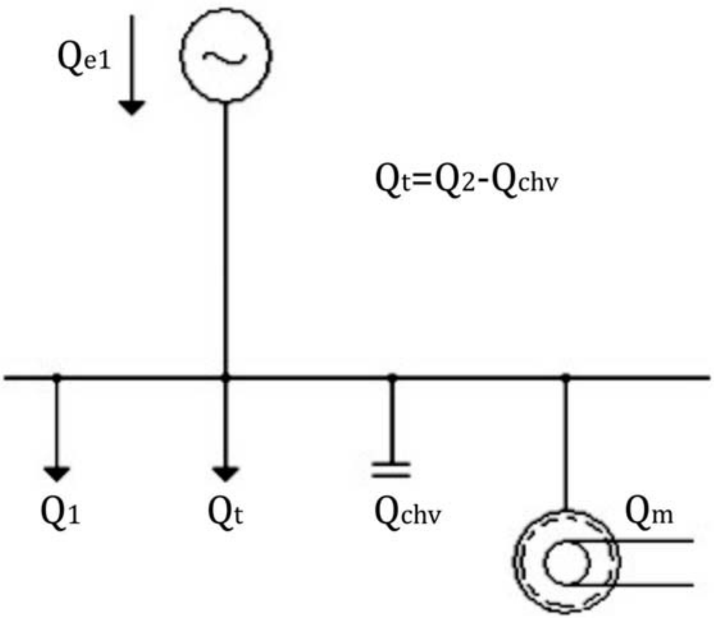

Fig. 12. The design equivalent circuit for the second calculation stage

The function of annual calculated consumptions for this stage of work is of the form:

$$\begin{aligned} &Z\left(Q_{chv}, Q_m\right) = E \cdot \Delta K_V \cdot Q_{chv} + \\ &+C_o\left(\Delta P_{chv} \cdot Q_{chv} + K1 \cdot Q_m + K2 \cdot Q_m^2\right), \ rub / year \ , \end{aligned} \quad (5)$$

where E, C_o (see the expression 1); ΔK_v is the specific cost of the high-voltage capacitor banks (5 r/kVAr); ΔP_{chv} are the specific losses of active power in high-voltage capacitor units (0,002 kW/kVAr); $K1$, $K2$ are the coefficients characterizing active power losses in a synchronous motor depending on Q_{m} ($K1$ = 0,011 kW/kVAr, $K2$ = 0,00019 kW / kVAr).

Lagrangian function:

$$L = \left(Q_{chv}, Q_m, \lambda\right) = Z\left(Q_{chv}, Q_m\right) + \lambda\left(Q_1^m + Q_t - Q_{e1} - Q_{chv} - Q_m\right), \quad (6)$$

where Q_1^m is the reactive power of the load at 10 kV buses of the main step-down substation at peak active power of electric system load.

Powers Q_{chv} and Q_m are determined by the equation system solution:

$$\frac{dL}{dQ_{chv}} = 0;$$
$$\frac{dL}{dQ_m} = 0; \qquad (7)$$
$$\frac{dL}{d\lambda} = 0.$$

We obtain general expression for calculating Q_{chv} and Q_{m} from (7)

$$Q_m = \frac{1}{K2}\left(\frac{E \cdot \Delta K_v}{C_o} + \Delta P_{chv} - K1\right), \ kVAr; \qquad (8)$$

$$Q_{chv} = Q_1^m + Q_t - Q_{e1} - Q_m, \ kVAr. \qquad (9)$$

By (4), (8), (9) one can calculate required design powers of the capacitor banks and the highest reactive power of the synchronous motor necessary for supporting optimal operative conditions of electric power systems. Negative values of design capacity indicate the absence of financial viability in using proper source of the reactive power. Its value is taken equal to zero. Q_m value should be less than accepted values according to heating conditions of the synchronous motor starter and rotor considering its active power load. The synchronous motor check by heating conditions is not provided in the laboratory work.

Total use of all compensating devices is economically sound only at a peak load of the electric power system. Compensating device should be adjusted to a considerably changing curve of the load reactive power. The laboratory unit provides discrete regulation of Q_m and automatic control of capacitor banks during the whole day. The curves of compensating device regulation are formed based on optimization calculations considering electric system requirements (Q_{e1} and Q_{e2}). Compensating device regulation must support minimum losses of electric power and the required voltage quality level.

A separate load node studied in this work does not require optimization. The curves of compensating device regulation can be formed in this case without calculation. The base for their formation is a curve of reactive load at 10 kV and 0,4 kV buses. The following should be considered at regulation curve plotting:

1. The reactive power consumption should not exceed Q_{e1} at peak active power of the electric power system load.
2. At minimum load the consumed reactive power should be not less than Q_{e2}.

3. Work procedure (task)

3.1. Obtain the following initial information from a teacher:

a) Q_{e1} and Q_{e2} values;

b) time intervals corresponding to active power peak and minimum periods of the electric power system load (assigned in the laboratory work № 2);

c) specific cost of active power losses C_o.

3.2. Determine compensating device powers (two stages) by the equations (4), (8), (9). Round the values obtained to the nearest possible values introduced in Table 1. Take load power by the curve obtained in the laboratory work № 1; other necessary information is in Table 1.

3.3. Check the reactive power balance at the main step-down substation buses at the peak moment of the electric power system active load. If necessary, adjust the compensating device powers for supporting balance.

3.4. Calculate the capacitor bank powers in 10 kV and 0,4 kV networks as it is necessary to support specified cos(φ) during a daily load curve. Put the calculations in Table 4.

To carry out calculations and select compensating devices it is necessary, first of all, to fill in columns 1, 2 and 3 of Table 4 with the data from Table 2 of the laboratory work № 1.

Then the desired reactive power Q_d can be determined at each hour of the load curve. At this power consumption the maintenance of a specified cos(φ) can be shown as: $Q_{\text{в}i} = P_i \cdot \text{tg}\varphi$,(10)

Table 4

Selection of compensating devices at 0,4 kV buses of the transformer T4

Day hour, *h*	Active power *P*, *kW*	Reactive power *Q*, *kVAr*	Desired reactive power Q_d, *kVAr*	Reactive power to be c ompensated ΔQ, *kVAr*	Power of compensating devices Q_{chv}, amount/ *kVAr*
1	2	3	4	5	6
1	P_1	Q_1			
2	P_2	Q_2			
………	……..	………	………	………	……..
24	P_{24}	Q_{24}			

where P_i is the active power at *i* hour of the load (column 2); $\text{tg}\varphi_{sp}$ conforms to the specified $\cos\varphi_{sp}$.

Then the reactive power ΔQ can be determined. It should be compensated:

$$\Delta Q = Q - Q_{\text{в}}. \tag{11}$$

On the basis of the obtained calculations (column 5) the daily graph of compensating power regulation is formed (column 6). In this column the number of the capacitor banks should be specified in numerator. The fact that standard capacitor bank has the power 105 kVAr should be taken into account (Table 1). The total compensating power is given in denominator.

The calculations carried out for filling in Table 4 should be confirmed by the example for characteristic hour of the load which must precede table 4.

The compensating devices are selected and the regulation graph at 10 kV buses of the transformer T2 is formed as it has been described before. However, it should be taken into consideration, that when determining power which must be compensated ΔQ in the equation (11) the power compensated on 0,4 kV side and synchronous motor power which is planned to be used for compensating should be subtracted. The calculations should be confirmed as well by the example preceding the compensation table Q_{chv} compilation.

One should pay attention to technical and economic characteristics and the efficiency of the arranged compensating devices forming the regulation curve of compensating power.

3.5. Check the reactive power balance at the buses of the main step-down substation at minimum load of the electric power system.

3.6. Initialize the laboratory model of the power supply system (turn on S1, T4, synchronous motor; turn off T3, BC1, BC 2, BC 3, BC4). Leave the automatic control system of T2 taps and off-circuit tap-changer setting of the transformer T4 in position assigned in the laboratory work № 2. Check your variant of the task according to the regulation graphs of compensating powers on 0,4 kV side and 10 kV side.

3.7. Launch the program and carry out the following:

a) record the curve of changing active, reactive powers and current of loads of the transformers T2 and T4 by the data considering design power of compensating devices and their regulation;
b) record the voltage at 10 kV buses of the main step-down substation and 0,4 kV buses of the transformer substation by the voltmeter readings considering implementation of their improvement procedures (see the laboratory work № 2). Load and voltage curves (a and b) should be recorded simultaneously.

3.8. Plot the load curves (P, Q, S, J) considering compensating devices and compare them with the curves obtained in the laboratory work № 1.

3.9. Plot the bar chart, calculate mathematical expectation and voltage dispersions at 10 kV and 0,4 kV buses considering reactive load compensation. Estimate compensating device influence on voltage mode comparing the results obtained with those of the laboratory works № 1 and № 2.

3.10. Estimate economic efficiency of reactive load compensation at day time interval in kilowatt-hours of saved electricity. Estimate the efficiency comparing energy losses in the transformers T2, T4 and the cable line calculated in the laboratory work № 1 by the load curves ignoring compensating devices, and losses in the same elements considering compensating devices and their regulation.

3.11. Prepare a report on the laboratory work which should contain:

a) table of initial data for work implementation including parameters given by the teacher;
b) calculation of compensating device powers;
c) graphs of compensating device regulation;
d) combined curves of active, reactive and total powers and load current of T2 and T4 considering compensating device without reactive load compensation;
e) combined curves of voltage change at 10 kV buses of the main step-down substation and 0,4 kV buses of the transformer substation (initial, after voltage regulation and after reactive power compensation);
f) bar charts of voltage at 10 kV buses of the main step-down substation and 0,4 kV of transformer substation;
g) economic efficiency calculation;
h) conclusions and test questions answers.

4. Preparation

Self-preparation for the laboratory work includes:

1) studying the description of the laboratory work № 3;
2) studying the references and proper chapters of lecture abstracts;
3) preparation of sheets for recording instrument readings;
4) comprehension of test question answers.

5. Test questions

1. Give the notion of the reactive power; explain its physical meaning and features in comparison with the active one.
2. How can we determine the limit values of the reactive powers which a synchronous machine feeds to the network?
3. Give the comparison characteristic of the reactive power sources used in the power supply system of industrial enterprises.
4. How does reactive power influence on the voltage mode of the electric network?
5. Enumerate requirements made by the electric system to the reactive

power mode of the power supply system of industrial enterprises.
6. What is the way of estimating economic efficiency of introducing optimal design conditions of enterprise load compensation?
7. What is the purpose of adjusting compensating device powers?
8. Explain principles of forming graphs for compensating device regulation.
9. Why input reactive powers are differentially specified by the enterprise?
10. What is meant by optimization mode of load reactive power compensation?

LABORATORY WORK № 4

RESEARCH OF AN ECONOMICALLY FEASIBLE TRANSFORMER OPERATING MODE AT THE SHOP TRANSFORMER SUBSTATION

1. Purpose

The purpose of the work is to study a calculation method and implementation of the economically feasible transformer operating mode.

2. Introduction

For a two-transformer substation with equally loaded transformers at constant voltage and variable load, power losses change in time:

$$\Delta P(t) = 2\Delta P_{nl} + 2\Delta P_{sc} K_1^2(t) \ , \qquad (1)$$

where $K_1(t) = \dfrac{S(t)}{2S_{rt}}$ – transformer load factor; ΔP_{nl} – transformer no-load losses;ΔP_{sc} – resistance losses in transformer windings at nominal load (short circuit loses); S_{rt} – transformer capacity; $S(t)$ – two-transformer substation load.

If one transformer operates, power losses under load equal

$$\Delta P(t) = \Delta P_{nl} + \Delta P_{sc} K_1^2\left(t\right), \qquad (2)$$

where $K_1(t) = \dfrac{S(t)}{S_{rt}}$.

Dependences of losses on load (1) and (2) are shown in fig. 13.

Crossing of curves 1 and 2 corresponds to load, when power losses in two transformers are equal to losses if one transformer is operating. Thus, if $S(t) > S_A$ operation of two transformers is feasible whereas if $S(t) < S_A$ one transformer should be disconnected.

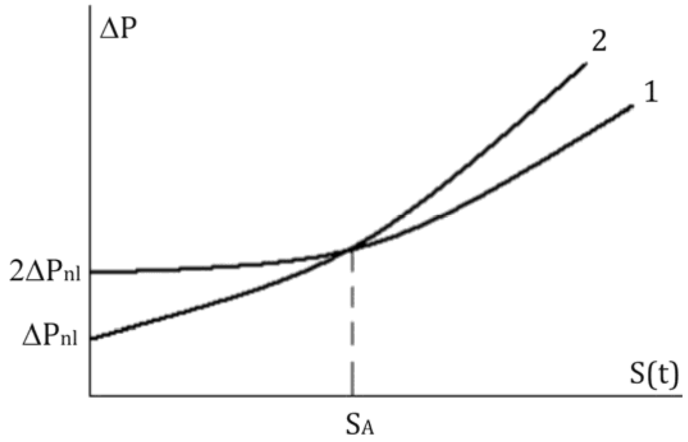

Fig. 13. Dependence of power losses in transformers on load: 1 – two transformers operate; 2 – one transformer operates

Value of S_A can be calculated if the right parts of equations are equal (1) and (2):

$$2\Delta P_{nl} + 2\left(\frac{S_A}{2S_{rt}}\right)^2 \Delta P_{sc} = \Delta P_{nl} + \left(\frac{S_A}{2S_{rt}}\right)^2 \Delta P_{sc} \ .$$

By neglecting intermediate transformations, we get the following equation:

$$S_A = S_{rt}\sqrt{\frac{2\Delta P_{nl}}{\Delta P_{sc}}} \ . \qquad (3)$$

In practice the economically feasible operating mode of transformers is seldom. It is caused by many factors: rather small economic efficiency, difficulty of the substation equipment maintenance because of frequent switching of one of transformers, difficulties in providing reliability of electric power supply, etc.

In the laboratory work all these factors are not considered. The economically feasible operating mode of transformers is implemented at day time interval to determine electric energy saving at this mode.

3. Work procedure (task)

3.1. Calculate the value of S_A for the shop transformer substation by the equation (3) and put it on the graph of the substation total power from the previous laboratory work (№ 3).

3.2. Determine the time of switching the transformer T3 by the graph of the substation total power and set the program for automatic control implementation of T3 by the time of day.

3.3. Set up the laboratory panel for "run" of a daily load curve with parameters and settings from the previous works. Start doing the task. Watch the accuracy of the shop transformer substation operating mode and record load current of the transformers T3 and T4.

3.4. Plot the load curves for the transformers T3 and T4 by current and the received current records. Calculate electric power losses in the transformers T3 and T4 and electric energy saving due to implementation of the economically feasible operating mode of transformers in relation to continuous operation of one transformer (the data of the laboratory work №1).

3.5. Calculate electric power losses in the transformers T3 and T4 for the mode of transformer continuous operation during a day. Compare these losses with electric power losses at the economically feasible operating mode.

3.6. Prepare a report on the laboratory work which should contain:

- Calculation and forming dependences of power losses in transformers on their load (fig. 13);
- Calculation of the value of S_A;
- Justification of time settings choice for implementation of the economically feasible operating mode of transformers;
- Graphs of current $I(t)$ of the transformers T3 and T4 at the economically feasible mode and calculation of power losses;
- Calculation of power losses at the continuous operation mode of the transformers T3 and T4 during a day;
- Estimation of electric energy saving due to implementation of the economically feasible operating mode of transformers, in relation to continuous operation mode of only one and two transformers;
- Conclusions and answers to test questions

4. Preparation

Self-preparation for the laboratory work includes:

1) studying the contents of laboratory work № 4, the work procedure and preparation of the rated data;

2) studying the references and lectures about components of electric power losses in transformers in their connection with operating conditions.

5. Test questions

1. What kinds of power losses can occur in transformers and what do they depend on?

2. Where and why is parallel operation of transformers used? Give the conditions of parallel operation of transformers.

3. Explain the implementation principle of the economically feasible operating mode of transformers.

4. Explain the major causes restraining wide application of the economically feasible operating mode of transformers.

LABORATORY WORK № 5

RESERACH AND DETERMINATION OF THE ESTIMATED ELECTRICITY WORKLOAD

1. Purpose

Research the process of heating one electric cable at changing load and definition of settlement load.

2. Introduction

A heating process of a three-core cable by current I is described by the differential equation of thermal balance:

$$3I^2 R_o dt = C d\vartheta + A\vartheta dt \ , \qquad (1)$$

where R_o – specific resistance of a vein of a cable, Ohm/km; C – a thermal capacity of a cable in 1 km, W·s/°C·km; ϑ – temperature of an overheat of a cable concerning environment; A – factor of heat loss,, *W·s*/°C·km; *t* – time, *s*.

The equation (1) can be transformed to a more convenient type for the solution :

$$\frac{C}{A}\frac{d\vartheta}{dt} + \vartheta = \frac{3I^2 R_o}{A}$$

Or

$$T_o \frac{d\vartheta}{dt} + \vartheta = \vartheta_m, \qquad (2)$$

where $T_O = \dfrac{C}{A}$ – a constant of time of heating the cable, c, $\vartheta_m = \dfrac{3I^2 R_o}{A}$ – The maximum temperature of a cable overheat at a current I.

The solution of the equation (2) is

$$\vartheta(t) = \vartheta_m - (\vartheta_m - \vartheta_o)e^{-\frac{t}{T_o}}, \qquad (3)$$

where ϑ_0 – reference temperature of an overheat of the cable.

For the schedule of the current shown in fig. 14, $\vartheta(t)$ at $t < 0$, $I(t) = 0$, $\vartheta(t) = 0$ it is possible to find dependence by the following way.

At the moment of time t = 0 the current joins and the cable heating which process of change is described by exponent (3)

At the moment of time t = 0 the current joins and the cable heating which process of change is described by exponent (3) at $\vartheta_0^{'} = 0$ и $\vartheta_m^{'} = \frac{3I^2R_0}{A}$, $\vartheta'(t) = \vartheta_m^{'}(1 - e^{-\frac{t}{T_0}})$.

At the moment of time t = t1 current stops running and cools down. Process of cooling of a cable is expressed in the equation (3) at

$$\vartheta_m^{''} = 0 \text{ и } \vartheta_0^{''} = \vartheta_m^{'} : \vartheta''(t) = \vartheta_0^{''} e^{-\frac{t}{T_0}} = \vartheta_m^{'} e^{-\frac{t}{T_0}}.$$

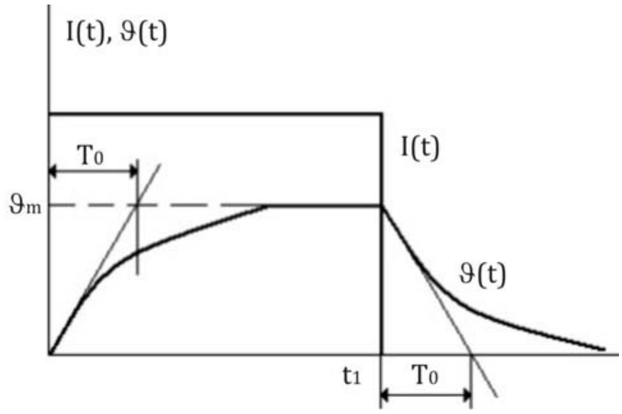

Fig. 14

Thus, overheat process is inertial in comparison with process of change of load that causes some complexity in definition of settlement load at a changeable current I (t) [1].

Admit that schedule ϑ (t) for set I (t) is received in any way then settlement load is defined from expression:

$$I_p = \sqrt{\frac{\vartheta_{\max} A}{3R_0}}, \tag{4}$$

where $\vartheta_{\max} = \max\ \vartheta(t)$.

In the laboratory work the schedule of dependence $\vartheta(t)$ is experimental by means built in the stand of the temperature gage of an overheat cable. Record of schedule $\vartheta(t)$ on a daily cycle of time is made on the monitor screen.

At a choice of cables it is necessary to mean that the maximum value is long admissible temperature of overheat $\vartheta_{\max}$ and, hence, is long an admissible current in cable I_{cc} is limited to admissible heating of the isolation, therefore one of the conditions of a cable choice is the choice on heating degree in a normal mode that is expressed by parity $I_d \le I_{cc}$ is. It is long admissible current

I_{cc} also it is possible to find on expression (4) recognizing that the maximum temperature of a cable (50…80) C is defined by its mark and ambient temperature. It is considered that ambient temperature is equal 15 °C at a cable lining in the earth and is equal to 25 °C at a cable lining on air.

Tasks

3.1. Prepare installation for work: switch on power supply, include transformer T4, disconnect T3, and disconnect BC3, BC4.

3.2. Start installation by clicking "Start-up" and make registration of schedule $\vartheta(t)$ and current value of a current cable T4.

3.3. Construct the schedule of a current of the cable feeding transformer T4 and the schedule of an overheat of the cable $\vartheta(t)$.

3.4. Calculate according to expression (3) schedule $\vartheta(t)$ and compare it with schedule $\vartheta(t)$, received experimentally for a site of the schedule set by a teacher. For such calculation use average on consecutive hour intervals of time schedule I (t).

3.5. Find under the schedule ϑmax = max $\vartheta(t)$ and define expression (4) settlement current Ip. Put size Ip on schedules $I(t)$ and $\vartheta(t)$. Analyze results and make conclusions.

3.6. Prepare a report on laboratory work which should contain:

- formulation of a problem of laboratory research;
- schedules $I(t)$, $\vartheta(t)$ and $\vartheta(t)$ settlement, drawn in one picture;
- calculation $\vartheta(t)$ for the set site of the schedule (under item 3.4);
- calculation of size I_d;
- conclusions and answers to control questions.

4. Preparation

Self-study work:

1) studying theoretical material about settlement electric loadings [1];
2) preparation for answers to control questions;
3) realization a settlement part of item 3.4 of the task of laboratory work № 5.

5. Test questions

1. Make definition of settlement electric loading.
2. What is a long continuous cable load? Why does it depend on the way a cable is laid?

3. How can a value of cable overheat at changeable schedule in time $I(t)$ be measured?

4. What factors define size of maximum overheat ϑmax = max {ϑ (t)} at changeable $I(t)$?

5. What limits maximum cable overheat?

6. What is the essence of a probability model of settlement load?

7. Explain concept of a constant time T_o and its practical application.

LABORATORY WORK № 6

STUDY OF HIGHER HARMONIC CURRENTS AND VOLTAGES IN DISTRIBUTION NETWORKS AND THEIR COMPENSATION FUNCTIONS

1. Purpose

Research of higher current and voltage harmonics in industrial electric systems and operation of a filter-compensation device.

2. Introduction

Sources of higher harmonics of currents and voltage in distributive electric systems are so-called nonlinear loads. These are electric power consumers which current-voltage characteristic is not linear. They are: valve converters, gas-discharge lamps, electro arc furnaces and welding installations. Nonlinear loads consume nonsinusoidal current from the network that leads to distortion of a voltage curve in the network.

Higher harmonics affect work of electric networks and some electro receivers, therefore in some cases special actions aimed at improving a voltage curve in the network should be taken.

It is possible to expand a periodic nonsinusoidal voltage curve U(t) in Fourier series:

$$U(t) = U_0 + \sum_{\nu=1}^{\infty} U_{\nu m} \cdot \sin(\nu\omega t + \Psi_\nu), \qquad (1)$$

where U_0 – a constant component. In three-phase industrial electric systems a constant voltage component, as a rule, is missing [7], therefore U_0 = 0; $U_{\nu m}$ – peak value of a voltage harmonic; Ψ_ν – a phase of ν- load harmonic.

In certain cases Fourier series can be expanded differently:

$$U(t) = \sum_{\nu=1}^{\infty} (U'_{\nu m} \cdot \cos\nu\omega t + U''_{\nu m} \cdot \sin\nu\omega t).$$

For calculation of this series it is necessary to find out $\Psi_\nu = \mathrm{arctg}\, U''_{\nu m} / U'_{\nu m}$. Number factors are defined as follows: amplitude of sinus V- harmonic of a number:

$$U'_{\nu m} = \frac{2}{m} \sum_{i-1}^{m} U_i \sin \nu\Theta_i; \qquad (2)$$

Amplitude of a cosine V-harmonic of a series:

$$U''_{\nu m} = \frac{2}{m} \sum_{i-1}^{m} U_i \cos \nu\Theta_i, \qquad (3)$$

where m – number of quantization intervals of initial nonsinusoidal curve $U(t)$ on an interval, to the equal one period; U_i, Θ_i – curve ordinate $U(t)$ and angle corresponding to i interval of quantization (i = 1, 2, …, m).

In formulas (2) and (3) $\sin \nu\Theta$ and $\cos \nu\Theta$ also correspond to values of functions $\sin \nu\Theta$ и $\cos \nu\Theta$ when $\Theta = (i = 0{,}5)\Delta\Theta$, i.e. in the middle of i interval of quantization, a $\Delta\Theta = 2\pi/24 = 15^o$ (m = 24).

Values of angles Ψ_v v in the formula (1) depend on $U'_{\nu m}$ and $U''_{\nu m}$, and the amplitude of V- harmonic is defined as:

$$U_v = \sqrt{(U'_{vm})^2 + (U''_{vm})^2}\,. \qquad (4)$$

When calculating $U'_{\nu m}$ and $U''_{\nu m}$, odd v, it is necessary to consider that values of the sinus and cosines components for the first half-cycle is equal to the values of the similar sums for the second half-cycle that will allow reducing calculation, doubling result of calculations for one half-cycle.

According to GOST 13109-97 level of the higher voltage harmonics in a network is estimated by a nonsinusoidality factor:

$$K_{ns} = \frac{\sqrt{\sum_{\nu=2}^{\infty} U_\nu^2}}{U_r}, \qquad (5)$$

where U_r – network rated voltage; U_ν – operating voltage value of ν – harmonic (ν = 2, 3, 4, …, 13).

Level of higher harmonics of voltage or current in operating electric installations can be estimated in two ways: settlement (calculation the factors of a number on the initial nonlinear curve removed by means of an oscillograph) and hardware (measurement operating values of voltage harmonics by means of the special measuring device).

Reduction of level of higher voltage harmonics in distributive networks is reached by means of connection of nonlinear loads to a separate transformer, increase in number of phases of straightening in gate circuits, reduction in system resistance, and also installation of special filter-compensatory devices (FCD). FCD is set up for filtration of a specific higher harmonic prevailing in a discrete spectrum. It represents a consistently connected reactor and a condenser battery [1].

In a modeled system of an electrical supply a source of higher harmonics is a nonlinear load connected to a joint venture (fig. 1). This load represents a powerful single-phase uncontrollable rectifier, fed by the network of 220W, containing higher harmonics [1]. The order (numbers) of harmonics of network currents is defined by expression:

$$\nu = n \cdot p \pm 1,$$

where p –is a number of converter phases; n = 1, 2, 3, …, and a current of a harmonious component $I_\nu = \frac{I_1}{\nu}$.

A joint venture has considerable electric remoteness from a transformer substation, i.e. it feeds from the line of 380W with high resistance, therefore on joint venture tires there is essential level of thigher harmonics. To decrease this level a power filter of the third harmonic has been is established.

Laboratory work includes two stages of researches. The first – estimation of the level of higher harmonics and factor of nonsinusoidality load on joint venture tires when power filters of the third harmonic are turned off. The second – estimation of decrease in level of higher harmonics by means of a power filter of the third harmonic.

Definition of higher harmonics of a nonsinusoidal curve of a current or voltage is possible in two ways: by means of special devices – measuring instruments of nonlinear distortions (nonsinusoidality) – or a way graphic-analytical calculation (under formulas (2)). In the laboratory work the second way is used. The investigated nonsinusoidal curve from the screen is transferred on paper. Development time of the screen for calculations convenience should make the period of industrial frequency (0,02. On paper the period breaks into m equal parts (m = 24) and by means of a ruler coordinates of the curve are measured in m + 1 points (along the edges of all m intervals).

Results of measurements are fixed in the tabular form. Calculated peak values of the middle of i interval of quantization and their phase shift are given here as well.

After data preparation a calculation of amplitudes sinus and cosin components of each harmonic under formulas (2) and (3) is made. For this purpose it is necessary to present them in a numerical kind, and also results of their calculations. After that it is necessary to calculate amplitudes 1, 3 and 5th harmonics under the formula (5). Phase shift of harmonics is defined through $\mathrm{tg}\,\Psi_\nu = U''_{\nu m} / U'_{\nu m}$.

On received settlement parameters write down numerical expression for nonsinusoidal voltage curve in the form of the formula (1) and construct this dependence in the form of the schedule which is necessary for comparing experimentally removed curve.

The error of calculations is defined by accuracy of oscillography of the investigated curve. The oscillography of "drawing" a curve from the monitor screen, of course, can't give exact results, but all of them can be used for approximate estimations (if there are no measuring devices).

FCD or a power filter for a specific, for example, k-harmonics, represents consistently connected condenser battery, reactor and active resistance [1] which parameters are defined by the following:

$$\frac{1}{k\omega C} = k\omega L_p; \quad R = 0,1 - 0,2 \quad Ohm.$$

For *k*-harmonics FCD represents a "short-circuit" in the network [$X_{FCD}(k) = 0$]for the first basic harmonic – the compensating device with equivalent capacitance X_{FCD} (fig. 15).

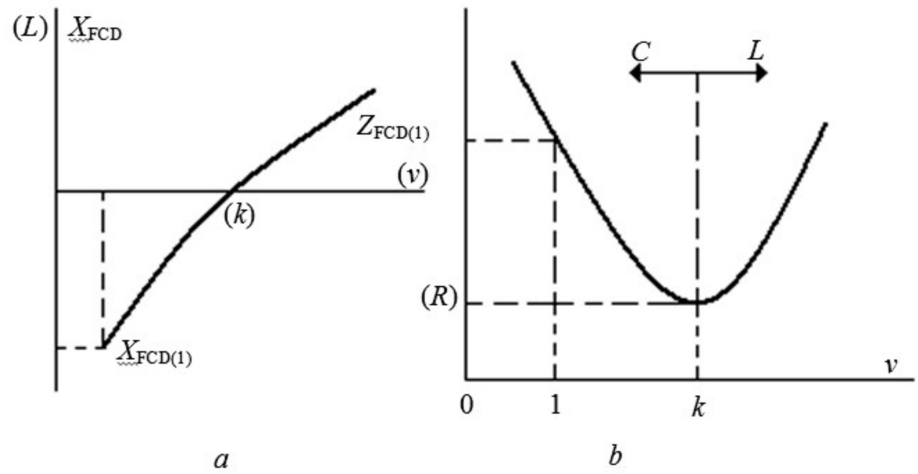

Fig. 15. Frequency characteristic k – harmonic: a – reactance; b – FCD impedance

3 Tasks

3.1. Prepare the stand: plug on the installation, plug on S1 load, T4 transformer (other elements of a symbolic circuit can be in any condition), switch off FCD. Start installation by clicking "Start-up". It is possible to watch the form of the investigated curve on the monitor screen having clicked twice on a symbol of the nonlinear load fed from the joint venture.

3.2. Sketch an investigated voltage curve on joint venture tires.

3.3. Proceed with processing of the oscillogram for calculation of higher harmonics according to item 2. Calculate higher harmonics in voltage curves. For a voltage curve calculate nonsinusoidality factor under the formula (5), draw nonsinusoidal voltage curve on the schedule, and also the first, third and the fifth harmonics. Write down the general expression for nonsinusoidal voltage curve and construct an oscillogram on its basis.

3.4. Include FCD and proceed with oscillography of voltage on joint venture tires. Switch off the installation.

3.5. Like in item 3.3 process oscillograms and calculate harmonics for investigated curves U (t). For voltageon joint venture tires calculate a nonsinusoidality factor and compare its value to the value calculated in the item 3.3.

3.6. Prepare a report on the laboratory work which should contain:

- formulation of a problem of laboratory research, representation of U (t) and their 1st, 3rd and 5th harmonics for a mode without FCD;
- schedules U (t) under the settlement data;
- calculation of a nonsinusoidality voltage factor and factors of 3rd and 5th harmonics;
- schedules U (t) for a mode with connected FCD;
- calculation of corresponding factors;
- conclusions and answers to test questions.

4. Preparation

Self-study:

1) study theoretical material [1, 3, 6, 7];
2) prepare answers to test questions.

5. Test questions

1. What are the admissible values of a nonsinusoidality factor accepted by GOST 13109-97 [2] for electric networks and why?
2. What are the reasons of higher voltage harmonics in the electric networks of industrial enterprises?
3. Why does a valve converter consume nonsinusoidal current from the network?
4. What ways of reduction of higher voltage harmonics in industrial electric systems do you know?
5. Draw a vector diagram of FCD currents and voltage (for the first harmonic).
6. Why is active resistance used in FCD circuits?

LABORATORY WORK № 7

RESEARCH OF DISTURBANCES IN POWER SUPPLY OF INDUSTRIAL NETWORKS

1. Purpose

Research of voltage falls in industrial electric systems which cause interference in power supply for digital devices, pulse control systems of installations with different functions.

2. Introduction

In all-union state standard (GOST) [2] new quality levels for electric energy characterizing short-term voltage distortions in networks and arising at various transients have been introduced. It is caused by short-term voltage distortions that are disturbances in power supply for digital and pulse devices. All disturbances in power supply can be divided into two kinds: long (falls and voltage surges with duration from milliseconds up to several seconds) and pulse – switching surge voltage with duration measured in мs (millisecond) and mcs (micro second).

This laboratory work studies voltage falls, for which the following parameters are introduced by GOST [2]: Δt – duration of a voltage fall, with; ΔU – depth of a voltage fall, %.

Causes of voltage falls in industrial networks are considered in the research work [1, 6]. These causes can be divided into two kinds. The first – voltage falls "coming" from the networks of a power supply system, the second – voltage falls caused by various phenomena in industrial networks (peak loads, emergency switchings, etc.).

In the laboratory work both specified kinds of voltage falls are simulated. The failure of the second kind is caused by peak loads of 0,4 kV shop transformer substation and is caused by voltage loss from peak loads on transformer resistance 10/0,4 sq.

In the laboratory work it is necessary to define time of voltage falls by means of the monitor, their depth and duration, and also allocate failures of the first and second kind among the fixed failures. Depth ΔU of failures of the second kind can be reduced by parallel work of transformers T3 and T4.

3. Tasks

3.1. Turn on the laboratory stand, start load S1, disconnect transformer T3. Other elements of a symbolic circuit can be in any condition (turned on or disconnected). Connect the monitor for voltage control on tires 0,4 kV shop T3.

3.2. Start the installation by clicking “Start” and, attentively observing the screen, fix voltage falls (time, depth, duration). Analyze results of supervision, among fixed ones reveal those falls which are caused by peak loads in the network 0,4 Kv shop T3.

3.3. Switch on the transformer T3 in parallel work with transformer T4 and repeat experiment according to item 3.2; estimate degrees of voltage fall reduction caused by peak loads in the network 0,4 sq.

3.4. Prepare a report on the laboratory work which should contain:

- formulation of a problem of laboratory research;
- results of supervision item 3.2. And 3.3 in the form of the table with instructions, duration and depth, and also a kind (the first or the second);
- conclusions and answers to test questions.

4. Preparation

Self-study work:

1) study theoretical material [1, 2, 3];
2) prepare answers to test questions.

5. Test questions

1. What the reasons of voltage falls occurrence in industrial networks?
2. Describe the mechanism of influence of voltage falls on digital and pulse control systems.
3. In what way can you provide a stability of digital control systems to pressure failures?
4. What are the norms on voltage falls introduced by GOST 13109-97 [2]

REQUIREMENTS FOR REGISTRATION REPORT

The laboratory work consists of seven laboratory works carried out on one installation, represents complex research of operating typical ESIE modes. Students prepare a report including a title, a table of contents, description of laboratory installation including a symbolic circuit (Fig. 1), model parameters (Tab. 1), purposes and work problems, necessary calculations, analysis and conclusions.

All pages of the report are numbered. All drawings and tables should be also numbered, drawings should have the name, tables – headings according to the all-union state standard (GOST).

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