***EM-2* (*English*)**

Ministry of Education and Science of Ukraine
Dnipro University of Technology

Electrical Engineering Department

Ivanov O.B., Tsyplenkov D.V.

COLLECTION OF METHODICAL MATERIALS
for laboratory work on discipline "Electric Machines" (section "Transformers") for students studying specialty 141 “Power, Electrical Engineering and Electromechanics”

Dnipro
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Recommended for publication by the educational and methodical department (protocol № from the proposal of the scientific-methodical commission on the specialty 141 "Energy, electrical engineering and electromechanics" (protocol № 21/22-01 from 30.08.21)

Collection of methodical materials for laboratory work on discipline "Electric machines" (section "Transformers") for students studying specialty 141 “Electrical Power Engineering, Electrical Engineering and Electromechanics” / O.B. Ivanov, D.V. Tsyplenkov; Dnipro University of Technology – D.: DniproTech, 2021. – 32 p.

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Methodical instructions are intended for laboratory work in the discipline of Electrical Machines (section "Transformers") students studying in specialty 141 - Energy, Electrical Engineering and Electromechanics.

LABORATORY TEST # 2/1

TRANSFORMERS CONSTRUCTION AND EXPERIMENTAL ESTIMATION OF TRANSFORMER NAMEPLATE DATA

Aim of the training is study of transformers construction and methods of estimation of a transformer nameplate data.

Work program

1. Study of a three-phase transformer construction
2. Measurement of the windings insulation resistance
3. Determination of a transformer voltage ratio and the windings number of turns.
4. Estimation of the transformer rated values.
5. The report execution.

The work procedure

Stage 1. *Measurement of the windings insulation resistance*

With the help of Megohmmeter, measure and write down the resistance of insulation between the transformer primary and secondary phases R_{Aa}, R_{Bb}, R_{Cc} and between the phases and the frame $R_{Af}, R_{Bf}, R_{Cf}, R_{af}, R_{bf}, R_{cf}$.

By the obtained results, determine whether the transformer is suitable for application in accordance with its highest rated voltage.

Stage 2. *Study of transformer construction*

Study construction of the oil-immersed and dry-type transformers available in the laboratory.

Define the ways of the transformers core assembly, the shape of the core legs and yokes cross-section, the used methods of tap changing.

See the methods of the transformers cooling.

The tested transformer is a dry-type step-down transformer used in lighting systems of underground mines. Pay attention to the auxiliary winding at one of the transformer legs and count its number of turns w_3.

Draft the figure of the core leg cross-section and measure the dimensions needed for the cross-section area calculations. Calculate the cross-section area Π.

Measure the diameter of the primary wire d_1.

Tabulate the values of w_3, Π and d_1 into Table 1.1.

Table 1.1

The results of determination the windings number of turns of and the transformation ratio

Measured				Calculated				
d_1	U_1	U_2	U_3	w_3	П	n_{12}	w_1	w_2
mm	V	V	V	-	m^2	-	-	-

Stage 3. *Determination of turn numbers and the voltage ratio*

It is well known that phase voltage of the transformer HV winding not less than 127 V.

Connect the circuit shown in Fig.1.1 and switch it on the power source.

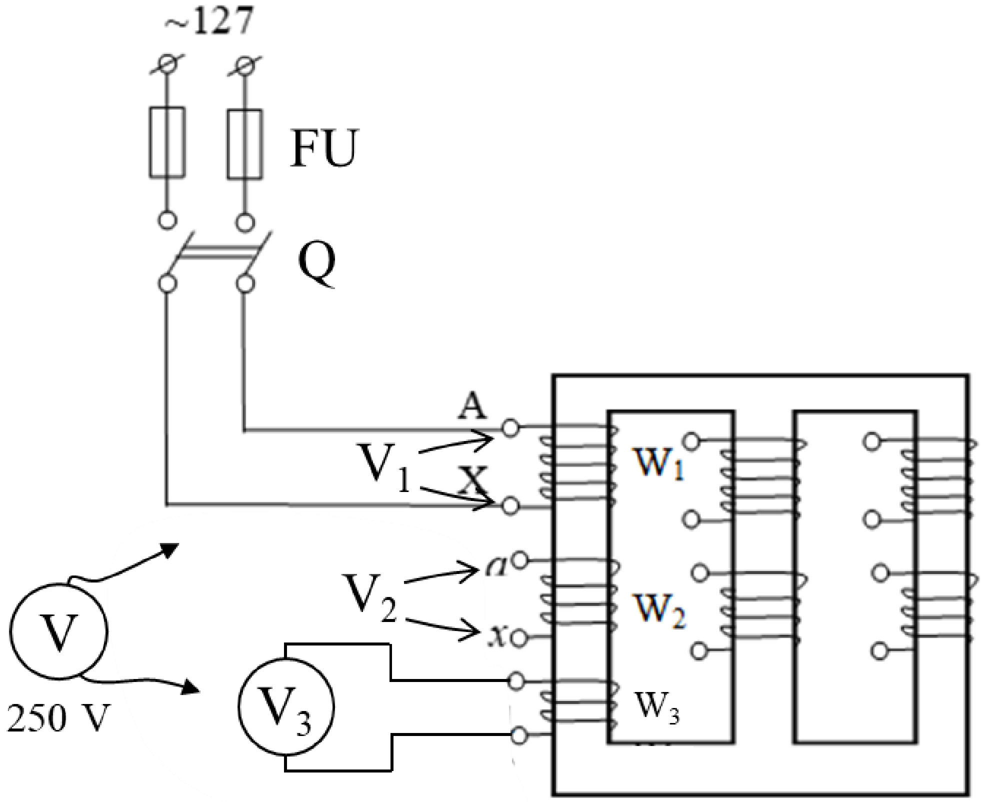

Figure 1.1 – Test circuit

Measure rms voltages $U_1, U_2\ and\ U_3$ across the windings terminals and tabulate them into Table 1.1.

Calculate the number of turns of the primary w_1 and the secondary w_2, and the transformer voltage ratio n_{12}. The obtained results tabulate into Table 1.1

Stage 4. *Estimation of the transformer rated values*

Using the data of Table 1.1, calculate and tabulate into Table 1.2 the rated values of the transformer primary and secondary line-to-line voltage U_{1lr}, U_{2lr}, line currents I_{1r}, I_{2r} and the rated transformer apparent power S_r.

Table 1.2

Calculated rated data of the transformer

Rated power S_r	Connection	Primary (HV)		Secondary (LV)	
		U_{1lr}	I_{1r}	U_{2lr}	I_{2r}
kVA	-	V	A	V	A
	Y/ Y				
	Δ/Δ				

Stage 5. *The report execution*

The report on the test should include:

1. The title of the test and its aim
2. The decision on the transformer suitability by its insulation resistance.
3. The circuit diagram (Fig. 1)
4. Tables 1 and 2 containing the measured and calculated data
5. Calculations the windings number of turns, the voltage ratio, and the transformer nameplate data (the rated values)

Methodical guideline

To stage 2

Insulation resistance of electric machines, apparatuses, and transmission lines of rated voltage below 1000V should be not less than 1 $M\Omega$ per volt of allowable voltage across insulation, which is assigned by the manufacturer of the equipment. The working voltage is the highest rms value of the ac or dc voltage across any insulation which can occur when the equipment is supplied at rated voltage.

To stage 3

The numbers of winding turns are found with use data of Table 1.1 by the formulae:

$$w_1 = \frac{W_3}{U_3} U_1, \qquad w_2 = \frac{W_1}{n_{12}}$$

where $n_{12} = \frac{U_1}{U_2}$ is the transformer voltage ratio.

To stage 4

Preliminary rms values of the rated phase voltages of a transformer are found by expressions:

$$U_{1ph\,r} \cong 4.44 f W_1 B_m \Pi_{st}, \qquad U_{2ph\,r} \cong \frac{U_{1ph\,r}}{n_{12}}$$

where $f = 50\ Hz$ is the mains frequency, B_m is the flux density amplitude T, Π_{st} is the transformer leg cross-section area falling on steel, m^2.

The amplitude of the magnetic flux density for the given transformer which core is manufactured from isotropic hot-rolled steel may be assumed over the range of 1.0 … 1.2 T.

The limb cross-section area falling on steel is found as

$$\Pi_{st} = \Pi k_{st}$$

where Π is the total leg stack cross-section area in m^2, k_{st} is the fill factor that is the ratio of the metal cross-section area to the total leg stack cross-section area. The fill factor depends on the type of the core laminations insulation and may be assumed over the range of 0.94 … 0.98.

The exact rated phase voltages should be found by selection of the nearest voltage values from the standard ranges of the primary and secondary voltage. The range of standard voltages for the primary coincides with the range of standard voltages of feeding electric networks, and for the secondary – with the range of standard voltages of power sources which are taken some greater than the networks voltages. The parts of voltage value ranges to which the sought rated voltages of the given transformer can fall are: … 127, 220, 380, 660 … V for the primary, and … 133, 230, 400,690 … V for the secondary.

After determination of the exact values of the transformer rated phase voltages, it is necessary to find the exact value of the turns ratio n_{12r}.

Approximate rated values of the primary and the secondary transformer phase currents are found as

$$I_{1ph\,r} \cong J \frac{\pi d_1^2}{4}, \qquad I_{2r} \cong I_{1ph\,r} n_{12r}$$

where the current density for dry-type transformers may be assumed over the range of 1.2 … 1.4 A/mm^2, d_1 is expressed in mm.

The rated power of a three-phase transformer is defined as the apparent power and measured in kVA. Its approximate value is found as

$$S_r \cong 3U_{1ph\,r} I_{1ph\,r} 10^{-3}.$$

The exact value of the transformer rated power is determined by selection the nearest value from the range of power transformers normalized rated power. The part of power normalized values range to which the sought rated power of the given transformer can fall is: … 1.5, 2.5, 3.5, 4.0 … kVA.

After determination of the transformer rated power, it is necessary to find the exact values of the phase rated current using the following expressions:

$$I_{1ph\,r} = \frac{S_r 10^3}{3U_{1r}}, \quad I_{2ph\,r} = \frac{S_r 10^3}{3U_{2ph\,r}}.$$

Commonly a transformer nameplate comprises the primary and secondary line to line voltages and line currents. They are expressed in terms of the phase quantities:

- at a winding Y-connection as $U_l = \sqrt{3}U_{ph}, \quad I_l = I_{ph}$
- at a winding Δ-connection as $U_l = U_{ph}, \quad I_l = \sqrt{3}I_{ph}.$

Test questions

1. Explain construction of three-phase transformers.
2. What ferromagnetic materials are used for a transformer core?
3. What for the core laminations are covered with insulation?
4. Why have a power transformer core legs stepped shape of the cross-section?
5. What is the transformer ratio?
6. What connection of a transformer windings had to be chosen to provide the given needed line-to-line voltages?
7. Why is supply a transformer with voltage exceeding the rated voltage of the primary not permissible?
8. Why is connection a transformer to a dc network not admissible?
9. How the magnetic flux density varies at variation of the primary voltage?
10. What is distinction of the step up and step-down transformer ratio n_{12}?
11. Why is the cross-section area of HV transformer winding wire smaller than of LV winding?

12. How the secondary phase and line-to-line voltages change at changing this winding connection between Y and Δ, if the primary voltage and its connection remain unchanged?

13. What for are tapings of the transformer windings made?

14. What function does the oil in the oil-immersed transformer carry out?

15. What for is an oil-immersed transformer tank equipped with an oil expander?

LABORATORY TEST # 2/2

TESTING OF TRANSFORMER UNDER CONDITIONS OF OPEN-CIRCUIT AND SHORT-CIRCUIT OPERATION

Aim of the training is study of methods of transformer parameters and performance characteristics determination using data of open-circuit and short circuit tests.

Work program

1. Choosing the transformer connections for carrying out the open-circuit and short-circuit tests.
2. Carrying out the transformer open-circuit test.
3. Carrying out the transformer short-circuit test.
4. Determination of the transformer open-circuit and short-circuit parameters.
5. Calculation and plotting the transformer performance characteristics.
6. The report execution.

The work procedure

Stage 1. *Choosing the transformer connections for carrying out the open-circuit and short-circuit tests*

In this laboratory test, the same transformer that in the laboratory test # 2/1 is studied.

Using the nameplate data obtained at fulfillment of laboratory test # 2/1 and data of available power sources and measuring instruments, take decision on the transformer connections and the winding to be fed from the power sources at carrying out the open-circuit and short circuit tests. Fill the transformer rated data for the chosen connections into Table 2.1.

Table 2.1

Rated transformer data for chosen connections for testing under conditions of open-circuit and short-circuit operation

Test	Winding connected to source	HV winding (primary)			LV winding (secondary)			u_{imp}, %	S_r, kVA
		connection	U_{1lr}, V	I_{1lr}, A	connection	U_{2lr}, V	I_{2lr}, A		
open circuit									
short circuit									

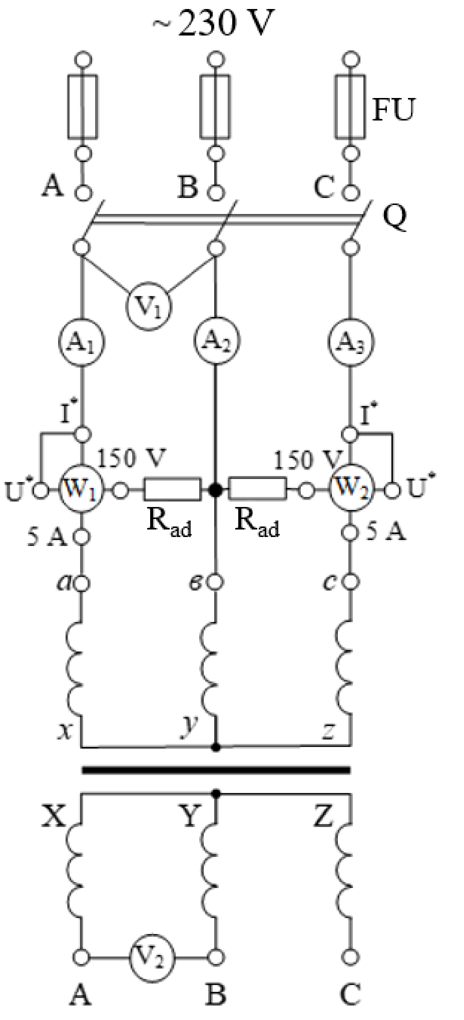

Figure 2.1 – Circuit diagram for open-circuit test

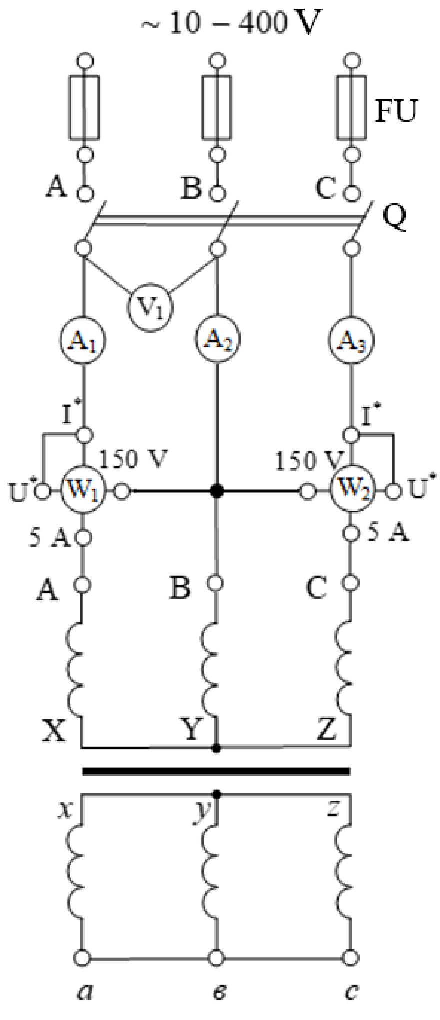

Figure 2.2 – Circuit diagram for short-circuit test

Stage 2. *Carrying out the transformer open-circuit test*

Decide whether the circuit diagram in Fig.1.1 fits the chosen condition of the open-circuit test.

Select measuring devices needed for measurement of the voltages, currents, and power at testing the transformer under open-circuit condition. Define the values of measuring instruments scale division and tabulate them in Table 2.2.

Table 2.2

Instrument scales division values

C_{V1}, V/div	C_{V2}, V/div	C_{A1}, A/div	C_{A2}, A/div	C_{A3}, A/div	C_{W1}, W/div	C_{W2}, W/div

Connect the test circuit and present it to the instructor for checking.

Turn on the switch S and carry out the open-circuit test tabulating the instruments reading into Table 2.3.

Table 2.3

Measurement results under open-circuit test

U_{1l}		U_{2l}		I_a		I_b		I_c		P_1		P_2	
div	V	div	V	div	A	div	A	div	A	div	W	div	W

Stage 3. *Carrying out the transformer short-circuit test*

Decide whether the circuit diagram in Fig. 2.2 fits the chosen condition of the open-circuit test.

Select measuring devices needed for measurement of the voltage, currents, and power at testing the transformer under short-circuit condition. Define the values of measuring instruments scale division and tabulate them in Table 2.4.

Table 2.4

Instrument scales division values

C_{V1}, V/div	C_{A1}, A/div	C_{A2}, A/div	C_{A3}, A/div	C_{W1}, W/div	C_{W2}, W/div

Connect the test circuit and present it for checking by the instructor.

Turn on the switch S and carry out the open-circuit test, tabulating the instruments reading into Table 2.4.

Table 2.5

Measurement results under short-circuit test

U_{1l}		I_a		I_b		I_c		P_1		P_2		t_{amb}
div	V	div	A	div	A	div	A	div	W	div	W	ºC

Stage 4. *Determination of the transformer open-circuit parameters*

Calculate:

- the transformation ratio for the phase and for the line-to-line voltages
- the transformer open-circuit parameters $\underline{Z}_0, R_0, X_0$
- the no-load current I_0 and the active power P_0 under open circuit in physical units and in per cent.

Tabulate the calculation results into Table 2.6.

Table 2.6

Calculated results of open-circuit test

n		P_0		I_0		Z_0	R_0	X_0
For phase voltages	*For line-to-line voltages*							
-	-	W	%	A	%	Ω	Ω	Ω

Stage 5. *Determination of the transformer short-circuit parameters*

Calculate:

- power P_{sc} consumed by the transformer under short-circuit
- impedance of short circuit Z_{sc} and its components R_{sc}, X_{sc} at the normal working temperature of 75 ºC for the transformer insulation thermal class A (maximum permissible temperature equals 105 ºC)
- the impedance voltage under short-circuit conditions at the rated primary and secondary currents and its active and reactive components in physical units and in per cent
- the active power under short circuit P_{sr} at rated primary and secondary currents

Tabulate the calculation results into Table 2.7.

Table 2.7

Calculated results of short-circuit test

P_{sc}	$P_{sc\ r}$	Z_{sc75}	R_{sc75}	X_{sc75}	$u_{imp\ r}$		$u_{imp\ r,act}$		$u_{imp\ r\ react}$	
W	W	Ω	Ω	Ω	V	%	V	%	V	%

Stage 6. *Composing equivalent circuits*

Compose and draw up equivalent circuit of the transformer separately for open-circuit and short-circuit conditions indicating their parameters in the drawings.

Stage 7. *Calculation and plotting characteristics*

Characteristics to be calculated and plotted for the case of unity load power factor are:

- curve of the transformer efficiency $\eta = f_1(\beta)$
- external (voltage regulation) characteristic $U_2 = f_2(\beta)$

where $\beta = {}^{I_2}/_{I_{2r}} = {}^{I_1}/_{I_{1r}} = {}^{S}/_{S_r}$ determined at $U_1 = U_{1r}$ is the load factor.

At the characteristics calculation, it is recommended to take the load factor values

$$\beta = 0;\ 0.25;\ 0.50;\ 0.75;\ 1.00;\ 1.25.$$

The calculation results should be tabulated into Table 2.8.

Table 2.8

Characteristics calculation results

β	0	0.25	0.50	0.75	1.00	1.25
η, %						
U_2, V						

Plot the characteristics.

***Stage 7**. Drawing up the report*

The report on the test should include:

1. The number and title of the test and its aim
2. The transformer nameplate data (Table 2.1)
3. Circuit diagrams for open-circuit and short-circuit tests (Fig. 2.1 and 2.2)
4. Instruments scale division values at the open-circuit and short-circuit tests (Tables 2.2 and 2.4)
5. Experimental data obtained at the open-circuit and short-circuit tests (Tables 2.3 and 2.5)
6. Calculated results for open-circuit and short-circuit tests (Tables 2.6 and 2.7)
7. Results of characteristics calculation (Table 2.8)

8. Plots of the transformer efficiency curve and external characteristic at load power factor $cos\varphi = 1$.

Methodical guideline

To stage 4

The calculated rms no-load current is determined as

$$I_0 = \frac{I_a+I_b+I_c}{3}, \text{ A.}$$

The open-circuit parameters in Ohms:

$$Z_0 = \frac{U_{1l}}{\sqrt{3}I_0}; \;\; R_0 = \frac{P_0}{3I_o^2}; \;\; X_o = \sqrt{Z_0^2 - R_0^2}.$$

The transformation ratio for the phase voltage is

$$n_{ph} = \frac{U_1}{U_2},$$

and for line-to-line voltage it is

$$n_{ph} = \frac{U_{1l}}{U_{2l}}.$$

As the bases values at determination of the no-load current and active power in per cent, the rated current and the rated (apparent) power are respectively taken.

To stage 5

The calculated rms short-circuit current is determined as

$$I_{sc} = \frac{I_A+I_B+I_C}{3}, \text{ A.}$$

The short-circuit parameters in Ohms:

$$Z_{sc} = \frac{U_{1l}}{\sqrt{3}I_{sc}}; \;\; R_{sc} = \frac{P_{sc}}{3I_{sc}^2}; \;\; X_{sc} = \sqrt{Z_{sc}^2 - R_{sc}^2}.$$

The short-circuit parameters reduced to the working temperature of 75 ºC:

$$R_{sc75} = R_{sc}[1 + \alpha_\rho(75 - t_{amb})];$$

$$Z_{sc} = \sqrt{R_{sc75}^2 + X_{sc}^2}.$$

The active power under short circuit at rated primary and secondary currents in Watts equals

$$P_{scr} = 3I_{1r}^2 R_{sc75}.$$

The voltage under short-circuit condition $u_{imp\,r}$ at the rated primary and secondary currents and its active $u_{imp\,r,act}$ and reactive $u_{imp\,r,react}$ components in physical units and in per cent equal

$$u_{imp\,r} = \left({I_{1r}Z_{sc75}}/{U_{1r}}\right) \cdot 100;$$

$$u_{imp\,r,act} = \left({I_{1r}R_{sc75}}/{U_{1r}}\right) \cdot 100; \quad u_{imp\,r,react} = \left({I_{1r}X_{sc}}/{U_{1r}}\right) \cdot 100.$$

<u>To stage 6</u>

The secondary voltage under load is determined as

$$U_2 = U_{2r}[1 - \beta\left(u_{imp\,,act}cos\varphi_2 + u_{imp\,r,react}sin\varphi_2\right)/100], \text{ V}$$

where $u_{imp\,r,act}$ and $u_{imp\,r,react}$ are expressed in per cent, φ_2 is the angle of phase displacement between the load voltage and current.

The transformer efficiency in per cent is equal to

$$\eta = \left(1 - \frac{P_0 + \beta^2 P_{sc\,r}}{\beta S_r cos\varphi_2 10^3 + P_0 + \beta^2 P_{scr}}\right) 100.$$

It is necessary to pay attention that the efficiency has maximum when the load factor equals

$$\beta = \beta_m = \sqrt{\frac{P_0}{Pc_{sr}}}.$$

Test questions

1. What conditions should be provided for carrying out the open –circuit and short-circuit tests?

2. In what cases the transformation ratios for phase and line-to-line voltages have different value?

3. In what parts of a transformer the power under no-load and short-circuit tests is consumed?

4. How does the winding resistance depend on temperature?

5. Why was the temperature variation of the winding resistance not considered at the open-circuit test data processing?

6. What transformer parameters affect the voltage regulation under load?

7. How the transformer open-circuit parameters for the case of feeding the transformer from the primary side can be determined using the parameters obtained under feeding from the secondary side?

8. Do values of the transformer voltage regulation obtained under lagging and leading power factor differ?

LABORATORY TEST # 2/3

INVESTIGATION OF PHASE DISPLACEMENT OF THREE PHASE TRANSFORMERS AT DIFFERENT WINDINGS CONNECTION

Aim of the training is to study dependence of phase displacement between voltages of three phase transformer windings from their marking and connection.

This aim is achieved by means of the three following tasks solving:

- Determination of a transformer phase displacement for a given marking and connections of the transformer windings
- Determination of a transformer windings marking and connections providing a given transformer connection symbol
- Experimental validation of the above two tasks solution correctness.

Work program

1. Theoretical solving of the task of determination a three-phase transformer phase displacement for a given its windings marking and connection, and the transformer potential phasor diagram plotting
2. Theoretical solving of the task of determination of a transformer windings marking and connection for a given transformer connection symbol, and the transformer potential phasor diagram plotting
3. Experimental validation of theoretically obtained results.
4. The report execution.

The work procedure

Stage 1 *Study the transformer construction and placement HV and LV terminals on terminal boards*

The transformer under study is a three-phase two-winding power transformer which magnetic circuit has three columns (legs). At the legs the coils are placed. Each the coil consists of two concentric windings one of which is HV, and another is LV winding. All the windings are wound in the same direction. Arrangement of the windings terminals on the boards is shown in Fig. 3.1. To provide easier recognition of the terminals the board on which HV terminals are placed is of greater size than the board of LV terminals.

The feature of the used transformer is that its transformation ratio equals 1. On this reason the HV and LV sides of the transformer had been established conventionally. The rated transformer phase voltages are 127 V on both sides.

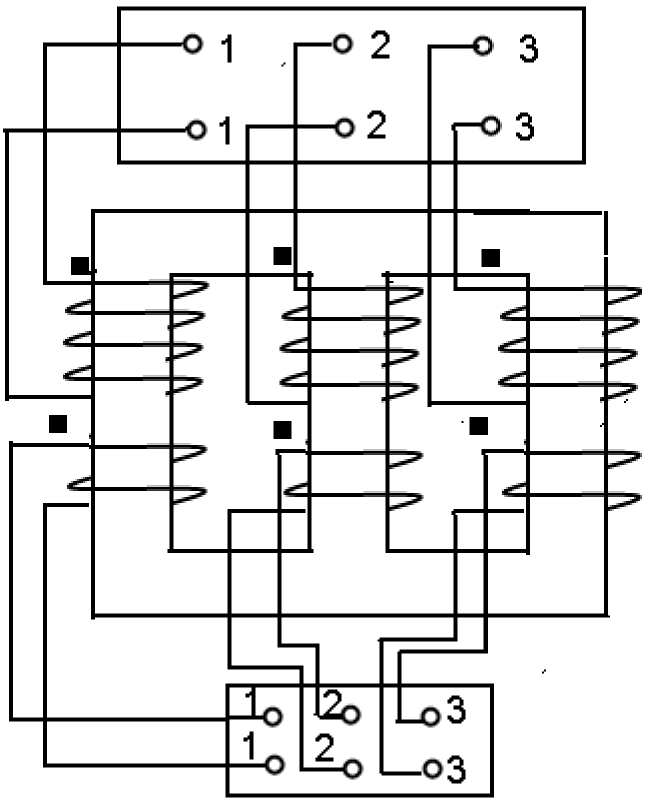

Figure 3.1 – Schematic diagram of three-phase two-winding transformer

Therefore, independently of the HV or LV phase windings connection (Y or Δ) the phase voltage across the phase terminals of every winding will be the same. If the primary supply voltage has the rated value, the voltage on terminals of every HV or LV phase is equal to 127 V. The line-to-line voltage at HV and LV sides depends on a winding connection (Table 3.1).

Table 3.1

Rated line and phase voltages of the studied transformer

Connection	Voltage on HV side, V		Voltage on LV side, V	
	line	phase	line	phase
Y/Y	220	127	220	127
Y/Δ	220	127	127	127
Δ/Y	127	127	220	127
Δ/Δ	127	127	127	127

Stage 2 *Determination of a transformer vector group for given windings marking and connection. Plotting of the transformer potential phasor diagram*

Get from the teacher the task for the transformer phase displacement determination. The task is presented as a transformer circuit diagram with a given connections of HV and LV phase windings for which the vector group should be determined.

To determine the transformer phase displacement, the potential phasor diagram must be plotted. For drawing up the potential diagram, indicate on the circuit diagram positive directions of the voltages induced in the transformer phases. It is convenient to select the voltages positive directions from the end to start point of all the transformer windings phases. The start windings points are designated with letters A, B, C (on HV side) or a, b, c (on LV side); the end points are designated with letters X, Y, Z (on HV side) or x, y, z (on LV side).

The potential phasor diagram is plotted assuming that two of line terminals, one on HV and one on LV side, marked with the same letters (for example, terminals "A" and "a") being equipotential, that physically corresponds to electrical connection of these terminals with a conductor. The point A-a potential is assumed equal zero.

The potential phasor diagram must be scaled as it is also used for comparison of theoretically and experimentally found potential differences at validation of the displacement determination correctness (Stage 3). The diagram is plotted for symmetrical voltages system having positive sequence.

The transformer vector group is found as the number obtained at division of the phase displacement angle $\Delta\psi$ between phasors $\underline{U}_{BA}$ *and* $\underline{U}_{ba}$, measured in degrees in clockwise direction, by 30º.

Another way of the transformer phase displacement determination is based on usage of the clock face notation.

While the potential phasor diagram is plotted, it is considered that voltages across terminals of HV and LV phase windings, placed at the same core leg, are in phase if positive directions of the voltages are oriented equally relative the windings terminals of the same polarity. If the positive directions of the voltages are opposite relative the windings terminals of the same polarity, the indicated voltages are opposite in phase.

In the case of a winding Y connection the points, presenting potentials of the end points of the phase windings in the diagram, coincide ($\underline{\varphi}_X = \underline{\varphi}_Y = \underline{\varphi}_Z = \underline{\varphi}_N$ or $\underline{\varphi}_x = \underline{\varphi}_y = \underline{\varphi}_z = \underline{\varphi}_n$).

In the case of a winding Δ connection, the point presenting potential of the start point of a phase winding in the diagram, coincide with a point, presenting potential of the end point of one of other phase windings. Depending on the way of connection in delta the following equalities take place:

- for a HV winding

$$\underline{\varphi}_A = \underline{\varphi}_Y, \quad \underline{\varphi}_B = \underline{\varphi}_Z, \quad \underline{\varphi}_C = \underline{\varphi}_X$$

or

$$\underline{\varphi}_A = \underline{\varphi}_Z, \quad \underline{\varphi}_B = \underline{\varphi}_X, \quad \underline{\varphi}_C = \underline{\varphi}_Y$$

- for a LV winding

$$\underline{\varphi}_a = \underline{\varphi}_y, \quad \underline{\varphi}_b = \underline{\varphi}_z, \quad \underline{\varphi}_c = \underline{\varphi}_x$$

or

$$\underline{\varphi}_a = \underline{\varphi}_z, \quad \underline{\varphi}_b = \underline{\varphi}_x, \quad \underline{\varphi}_c = \underline{\varphi}_y .$$

Stage 3 *Development the windings circuit for a given transformer connection symbol*

Get from the teacher a transformer connection symbol for solving the task of composing the transformer windings circuit diagram.

Draw up the topographic potential phasor diagram of the HV winding taking potential of terminal “A” equal zero.

Assuming terminal “a” of the LV winding being equipotential with terminal “A” of the HV winding, add the potential diagram of the LV winding. The points having equal potentials are determined in accordance with the help of recommendations given in the Stage 2. The vectors of the voltages $\underline{U}_{ba}$ and $\underline{U}_{ca}$ are built at the angle of 30º multiplied by the displacement group number N in clockwise direction to vectors $\underline{U}_{BA}$ and $\underline{U}_{CA}$ respectively. The vector $\underline{U}_{bc}$ connects the diagram points "c" and "b" being directed to the point "b". Thus, vectors of the LV- side line voltages form an equilateral triangle.

In the case of star connection of the LV winding, vectors of its phase voltages form a symmetrical star having their start points a, b, c and the ends coinciding in the point of the vectors intersection and representing the potential of the star neutral point “n”.

In the case of delta connection of the LV winding, vectors of its phase voltages form an equilateral triangle with apexes a, b, c, and coinciding with the triangle of line voltages. The equipotential points are selected using the principle described in the previous section.

Basing on the obtained potential diagram, the winding terminals are marked and the terminals having equal potentials are connected in the transformer circuit.

Stage 4 *Experimental validation of theoretically obtained results*

We must be sure that the results obtained at carrying out the previous stages are correct. Validation of the results is made experimentally by means of measurement of voltages between points of the transformer circuit and comparison them with their values found from the potential phasor diagram. If the voltage values obtained experimentally by measurement and theoretically from the diagram are the same, the results are correct.

The experimental investigations are carried out in the following sequence.

1. Validation of the relative phase displacement determination performed in Stage 2:

- Assemble the transformer HV and LV circuits
- Join terminals “A” and “a” with a conductor
- Apply the three-phase system of rated voltages to the terminals of the HV winding
- Measure the voltages indicated in the Table 3.2 and fill the obtained values into the table
- Fill in the Table the same voltage theoretical values found from the potential diagram
- Compare the experimental and theoretical data and draw the conclusion.

Table 3.2

Validation of the vector group determination (connection symbol_________)

Method of date obtaining	U_{AB}	U_{BC}	U_{CA}	U_{ab}	U_{bc}	U_{ca}	U_{Bb}	U_{Bc}	U_{Cb}	U_{Cc}	The result is (mark with a tick)	
											correct	incorrect
Experimental												
Theoretical												

2. Validation of the transformer circuits diagram drawn in Stage 3:

- Assemble the transformer HV and LV circuits
- Join terminals “A” and “a”
- Apply the rated voltage to the terminals of the HV winding
- Measure the voltages indicated in the Table 3.3 and fill the obtained values into the table
- Fill in the Table the same voltage theoretical values found from the potential diagram
- Compare the experimental and theoretical data and draw the conclusion

Table 3.3

Validation of the winding circuits development (connection symbol_________)

Method of date obtaining	U_{AB}	U_{BC}	U_{CA}	U_{ab}	U_{bc}	U_{ca}	U_{Bb}	U_{Bc}	U_{Cb}	U_{Cc}	The result is (mark with a tick)	
											correct	incorrect
Experimental												
Theoretical												

Stage 4 *The report execution*

The prepared report must include:

1. The number and title of the test and its aim
2. The transformer rated voltages (Table 3.1)
3. The given transformer circuits, plotted phasor diagram, found out the connection symbol according to the task of Stage 2 and obtained result validation (Table 3.2)
4. The given transformer connection symbol, determined transformer circuits diagram, plotted phasor diagram according to the task of Stage 3 and the obtained result validation (Table 3.3).

Methodical guideline

In accordance with definition established by IEC (International Electrotechnical Commission), the phase displacement of a transformer is the angular difference between the phasors representing the voltages between the neutral point (real or imaginary) and the corresponding terminals of two windings, a positive-sequence voltage system being applied to the high-voltage (HV) terminals, following each other in alphabetical sequence if they are lettered, or in numerical sequence if they are numbered. The phasors are assumed to rotate in a counterclockwise sense.

The phasor of HV winding is taken as the reference phasor. The vector group is determined by displacement of the low voltage (LW) winding phasor with respect to the reference phasor of the HV winding labeled with the same letter (figure). The angle is counted from the HV phasor to the LV phasor in clockwise direction. The phase displacement expressed by its number, is found as the angle $\Delta\psi$ measured in degrees divided by 30º:

$$PD = \frac{\Delta\psi}{30}.$$

Instead of the angle between phasors of the phase voltages $\underline{U}_{AN}$ and $\underline{U}_{an}$ or $\underline{U}_{BN}$ and $\underline{U}_{bn}$ or $\underline{U}_{CN}$ and $\underline{U}_{cn}$, the angle between the phasors of line voltages $\underline{U}_{AB}$ and $\underline{U}_{ab}$ or $\underline{U}_{BC}$ and $\underline{U}_{bc}$ or $\underline{U}_{CA}$ and $\underline{U}_{ca}$ which also equals $\Delta\psi$ may be taken for a transformer phase displacement determination. Such an approach is especially preferable at experimental verification of the obtained results in the case of delta connection because imaginary neutral point of the delta connection is not physically available. In this laboratory work, the angle $\Delta\psi$ is measured between phasors of line voltages at any connection of the transformer windings. As equipotential points the terminals “A” and “a” are taken.

Phase displacement may also be found using the clock face notation.

In a three-phase transformer, one of twelve its value is possible depending on transformer windings connection and a way of their marking. Possible PD for a three phase transformers are 0, 1, 2, 3,.., 11. In the case of using star and delta connections, transformers with the same connection of the HV and LV windings can have zero or one of even values: 0,2,4,6,8,10; transformers with different connections of the windings – one of odd VG: 1,3,5,7,9,11. A single phase transformer cany belong to only one of the two PD – 0 or 6.

In a transformer name plate, the connection symbol is indicated. The connection symbol is a conventional notation indicating the connections of the high-voltage, intermediate-voltage (if any) and low-voltage windings and their relative phase displacement(s), expressed as a combination of letters and clock-hour figure(s).

Examples of transformer connection symbols: Y/Y_n-0, Y/Δ-11, Δ/Y- 5, Y/Z-11. Connection of a HV winding is indicated in the numerator, of a LV winding – in the denominator.

Determination of the phase displacement of transformers is important at connection transformers in parallel. If transformers with different PD are connected in parallel, large circulating current flows between their secondary windings that causes dangerous overheating.

Now give examples of transformer connection, their potential phasor diagrams with indicated vector groups.

Example 1

It is required to determine the vector group and to write the connection symbol for the transformer which circuit diagram is given. The transformer rated voltages are known.

The given transformer circuit diagram is presented in Fig. 3.2.

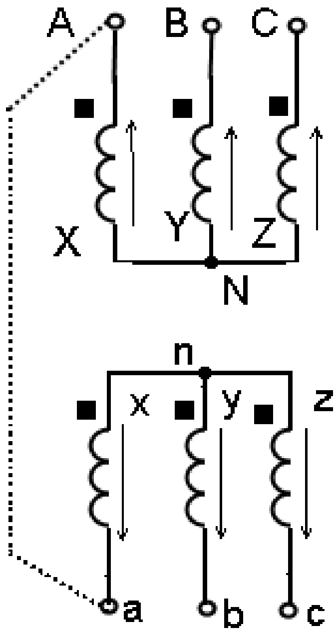

Figure 3.2 – Circuit of transformer which PD is to be determined

To determine the vector group the transformer potential diagram is plotted (Fig. 3.3).

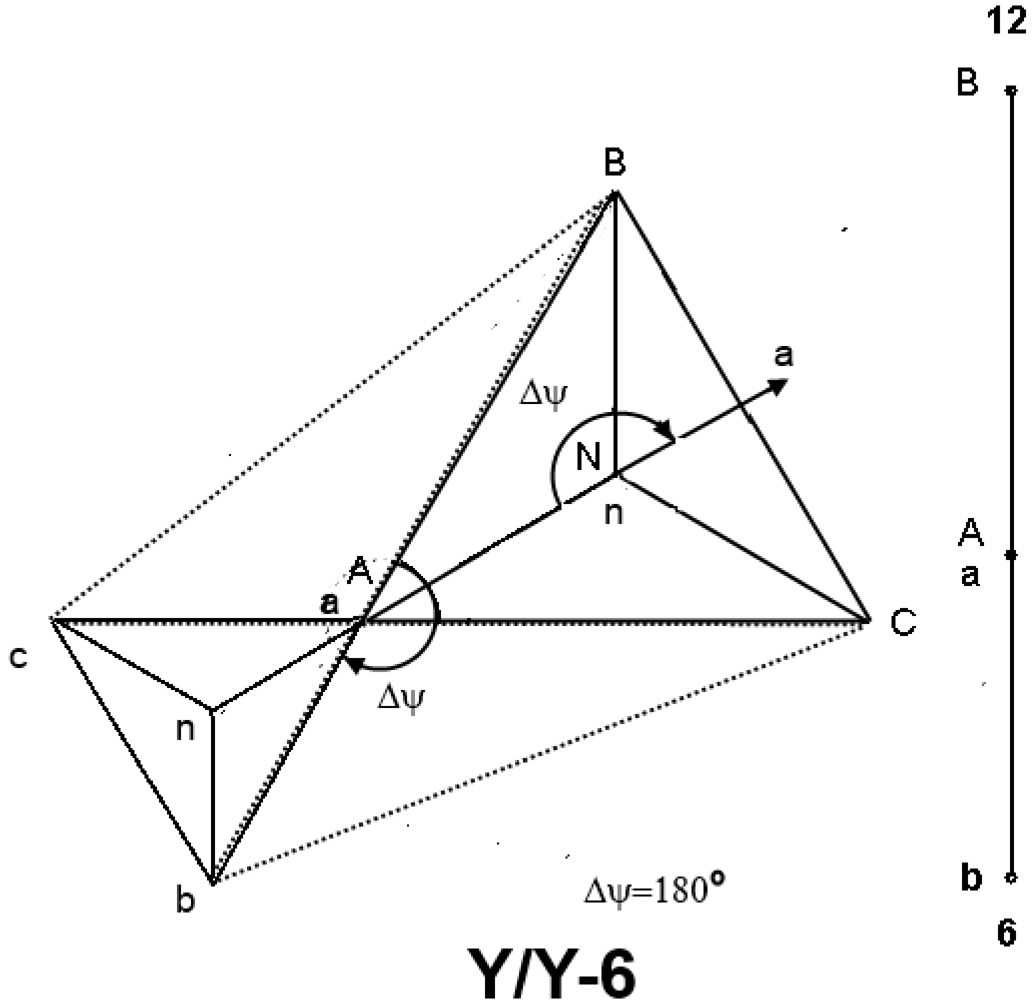

Figure 3.3 Potential diagram of transformer

The diagram is drawn up considering that terminals “A” and “a” are joined with a conductor (the dashed line in Fig. 3.2).

Based on the potential phasor diagram, the transformer connection symbol Y/Y-6 is defined.

Verification of result of PD determination is performed by comparison of voltage values obtained from the phasor diagram and by measurement with voltmeter (see Table 3.2).

Example 2

It is required to draw up the transformer circuit diagram basing on the known connection symbol Y/Δ-5.

As in the previous task the diagram is plotted taking that terminals “A” and “a” are connected, and the diagram is scaled (Fig. 3.4).

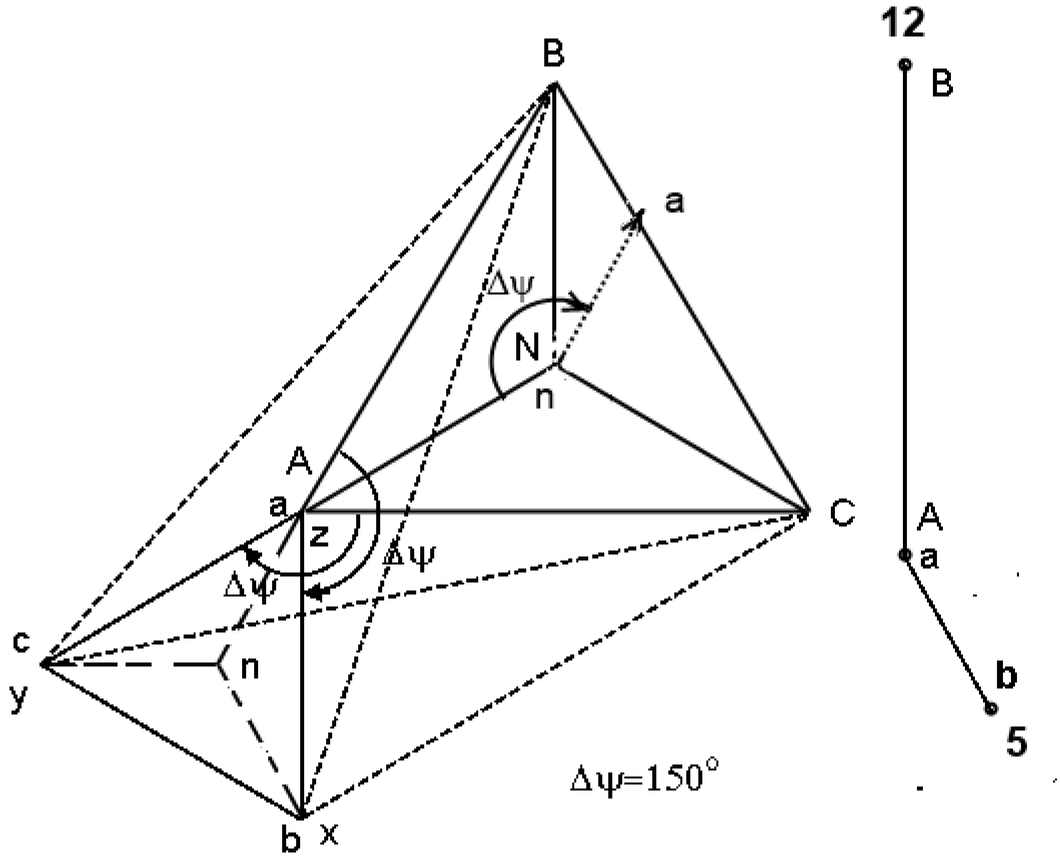

Figure 3.4 – Diagram constructed based on the known connection symbol

Using the potential diagram, the transformer circuit connection is drawn (Fig. 3.5). In this case the LV winding neutral point “n” is imaginary.

For the result validation, the voltage values obtained experimentally by measurement and theoretically based on the phasor potential diagram are compared (Table 3.3).

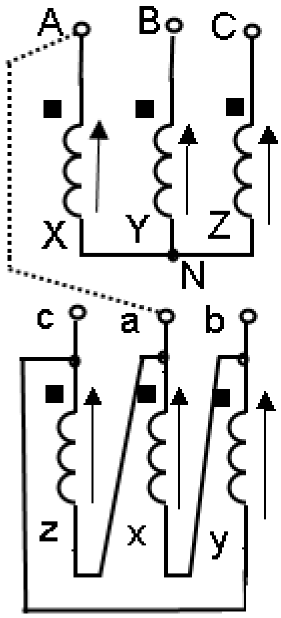

Figure 3.5 – Connection Y/Δ-5

Test questions

1. What is the vector group?
2. What is the phase displacement of a transformer?
3. What is the connection symbol of a transformer?
4. At what winding connection is the neural point real and at what is it imaginary?
5. Are the phase displacement angles determined using the phase voltages and the line voltages having the same marking equal? Please, explain.
6. Why is it necessary to connect two line terminals on HV and LV sides of a transformer marked with the same letters when correctness of the vector group is checked out experimentally?
7. What vector groups can be obtained in a single-phase transformer?
8. What vector groups can be obtained in a three-phase transformer?
9. What vector groups can be obtained in three-phase transformers with the same connections of the windings?
10. What vector groups can be obtained in three-phase transformers with different connections of the windings?

LABORATORY TEST # 2/4

INVESTIGATION OF PARALLEL OPERATION OF THREE-PHASE POWER TRANSFORMERS

Aim of the training is study the requirements for switching transformers for parallel operation and the load distribution between transformers under parallel operation.

Work program

1. Analysis of the transformers nameplate data for taking decision on possibility their switching in parallel.
2. The circuit connection and its try-out.
3. Investigation of load distribution between transformers under parallel operation.
4. The report execution.

The work procedure

Stage 1 *Analysis of the transformers nameplate data for taking decision on possibility their switching in parallel*

Examine the transformers intended for parallel operation and their nameplate data obtained at execution of laboratory tests # 2/1 and 2/2. Tabulate the transformers nameplate data into Table 4.1.

Assess compliance of the transformers data with the requirements of their switching to parallel operation.

Table 4.1

Transformers nameplate data

Number of a transformer	Connection and phase displacement	S_r, kVA	HV winding		LV winding		u_{sc}, %
			U_{1lr}, V	I_{1lr}, A	U_{2lr}, V	I_{2lr}, A	
I							
II							

Stage 2 *The circuit connection and its try-out*

Select the switching equipment, protection devices and measuring instruments for the test circuit (Fig. 4.1).

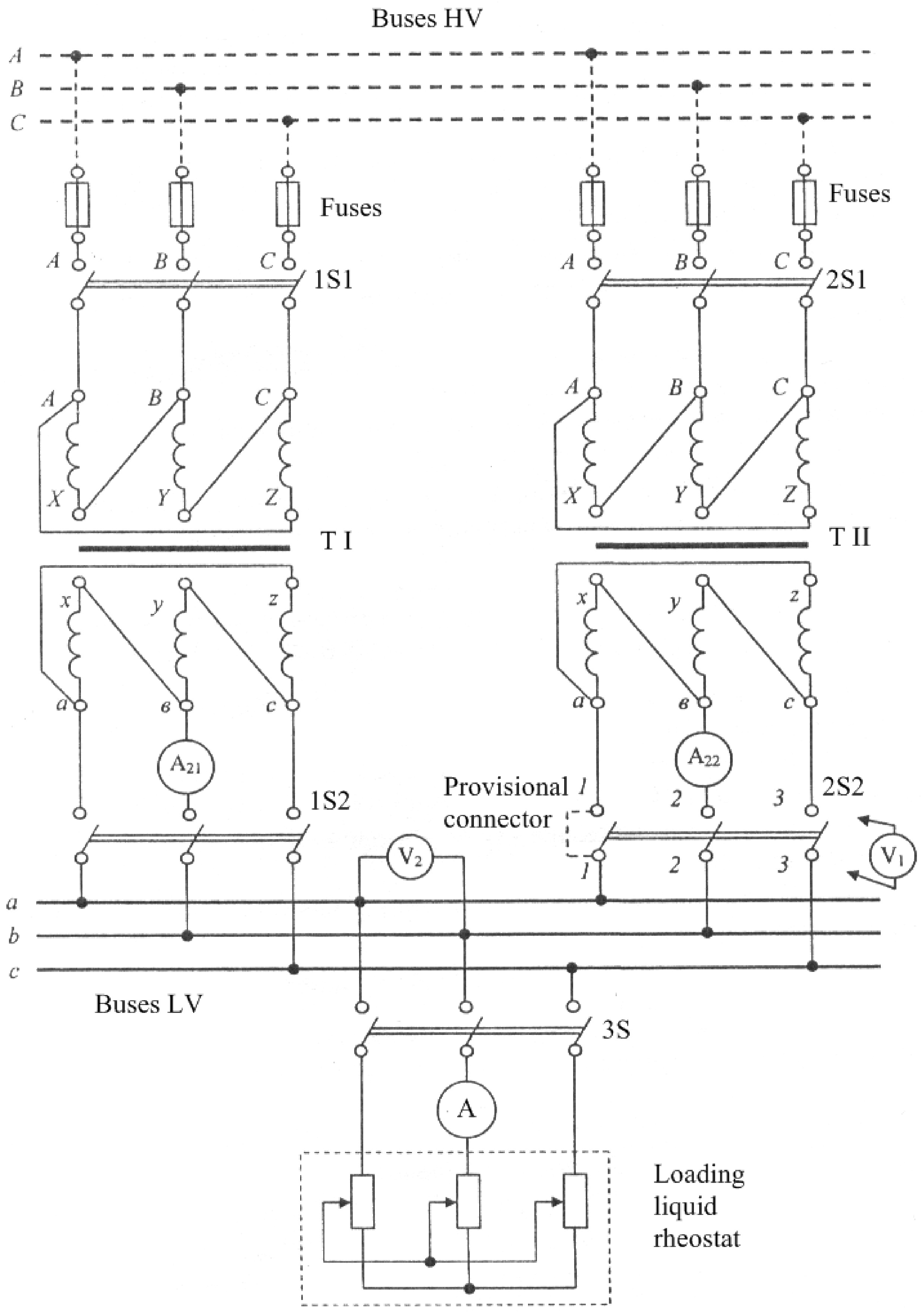

Figure 4.1 – Transformers connected in parallel

Connect the circuit, using the liquid rheostat as the load.

After checking the connected circuit by the instructor, try the circuit out:

- turn off all the switches and put on the provisional connector 1-1 at the switch 2S2
- install the fuses and turn on the switches 1S1, 1S2 and 2S1
- measure voltage between the points 2-2 and 3-3 at switch 2S2 with a portable voltmeter

If the voltage between points 2-2 and 3-3 at the switch 2S2 equals zero, the circuit is connected properly. At measurement, consider that in the case of improper circuit connection the measured voltage can reach double value of the secondary line-to-line voltage.

If appropriateness of the circuit connection has been proved, turn off all the switches, remove the fuses, then remove the temporary connector.

Stage 3 *Investigation of load distribution between transformers under parallel operation*

Install the loading liquid rheostat into position when its resistance is infinitely large. At the beginning the switch S3 remains turned off. Turn on the switches 1S1 and 2S1, then 1S2 and 2S2.

Define if the local circulating current in the circuit of the secondary windings is available. If so, measure the line circulating current value and explain by what reason these currents are caused.

Determine approximate maximum load rms current I_{max} using the transformers secondary line current rated values.

Attention! While loading the transformers stop the load current increase at achievement of the rated secondary current value in any of the transformers or the measurement limit of any of the ammeters.

Increasing the load current in the bounds of $0 \ldots I_{max}$, measure six sets of the current values I_{21}, I_{22}, I and the voltage U_2 distributing them approximately uniformly along the current range. The first registered point at $I = 0$ must be recorded obligatory. The instrument readings in each the set should be taken simultaneously to avoid errors caused by instability of the load current which can arise due to heating of the loading rheostat liquid. Record the results of measurement in Table 4.2.

Table 4.2

Results of measurement at transformers parallel operation

# of a point	U_2, V	I, A	I_{21}, A	I_{22}, A
1				

2				
3				
4				
5				
6				

Plot the external characteristic of transformers under parallel operation $U_2 = f(I)$. Using mutual coordinate system plot the curves $I_{21} = f(I)$ and $I_{22} = f(I)$.

If load current distribution between the transformers secondary windings not proportional to the transformers rated power is observed, explain the reason of such distribution.

Stage 4. *Drawing up the report*

The prepared report must include:

1. The number and title of the work and its aim.
2. The transformers nameplate data (Table 4.1) and conclusion on possibility of their parallel operation.
3. Circuit diagram of the transformers parallel connection (Fig. 4.1).
4. Results of measurement at the transformers parallel operation (Table 4.2).
5. The external characteristic of transformers under parallel operation $U_2 = f(I)$.
6. The curves of the secondary currents against the current of load $I_{21} = f(I)$ and $I_{22} = f(I)$.

Methodical guideline

Parallel operation of transformers is used for solving the task of their reservation and widening a substation. Besides, at decrease the substation load, a smaller number of transformers can be remained in parallel operation at which each of them will carry the optimal load and transform electric power with minimal losses.

Satisfactory operation of three-phase transformers in parallel requires fulfillment of the following conditions:

- All transformers must have the same phase displacement. This condition is essential.
- All transformers should have the same line-to-line voltages and voltage ratios which difference must be not greater than 0.5% to avoid inadmissible circulating current.

- The transformers per unit impedances or impedance voltages should be the same. This condition provides distribution of load between the transformers proportionally their rated powers and equality of admissible maximal load power to total rated power of transformers operating in parallel. In practice, difference of transformers impedance voltages must be not greater than 10%.
- It is recommended that the ratio of the transformers rated power was not greater than 3:1. This promotes to proper loading of each the transformer proportionally to its rating power in the case of small difference in the transformers short-circuit power factors.

In the case of unequal voltage ratios, the circulating current appears between the transformers secondary windings. In the case of two transformers this current vector adds to load current vector of one of the transformers and subtracts of the load current vector of another causing the transformers loading not proportionally to their rating powers. In the case of considerable voltage ratios difference the transformer having the less ratio is overloaded if another is loaded by its rated power.

If the transformers have unequal impedance voltage, they are loaded not in proportion to their rated powers. The transformer having less impedance voltage is overloaded if the load of other transformer reaches its rated value.

Parallel operation of transformers having different phase displacement is inadmissible due to very great circulating current arising in the circuit of secondary windings that is dangerous for the transformers.

Test questions

1. In what cases parallel operation of transformers is expedient?
2. What requirements must be fulfilled for switching transformers to parallel operation?
3. Why is the total load not equal to the sum of transformer ratings under parallel operation if their voltage ratios are not equal? Which of the transformers load does reach the rated value at the total load increase?
4. How is the load distributed between transformers under parallel operation if their impedance voltages are not equal? Which of the transformers does reach the rated power value first at the total load increase?
5. What is the restriction of the voltage ratio difference established for transformers being connected in parallel?
6. What is the restriction of the impedance voltage difference established for transformers being connected in parallel?
7. Is it permissible parallel connection of transformers having different phase displacement? Give explanation.
8. How does accuracy of transformers connection in parallel can be checked after the circuit is assembled?

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МЕТОДИЧНІ ВКАЗІВКИ
до виконання лабораторних робіт
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для студентів спеціальності
141 – Електроенергетика, електротехніка та електромеханіка
(на англ. мові)