EXPERIMENTAL INVESTIGATION

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. Determination of a transformer voltage ratio and the windings number of turn.
3. Estimation of the transformer rated values.
4. Measurement of the windings insulation resistance.
5. The report execution.

The work procedure

<u>Stage 1</u> 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. Its rated voltages are below 1000 V. 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.

Table 1

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	-	-	-

<u>Stage 2</u> Determination of turn numbers and the voltage (turns) ratio

Determine the rough permissible primary current value as $J\pi d^2/4$, where J is rough value of the current density, assuming $J = 1\ A/mm^2$.

Connect the circuit shown in Fig.1. After setting maximum resistance of the rheostat connected into the primary circuit, switch it on the power source.

After that, reduce the rheostat resistance till receiving approximately the found current value but not more than it.

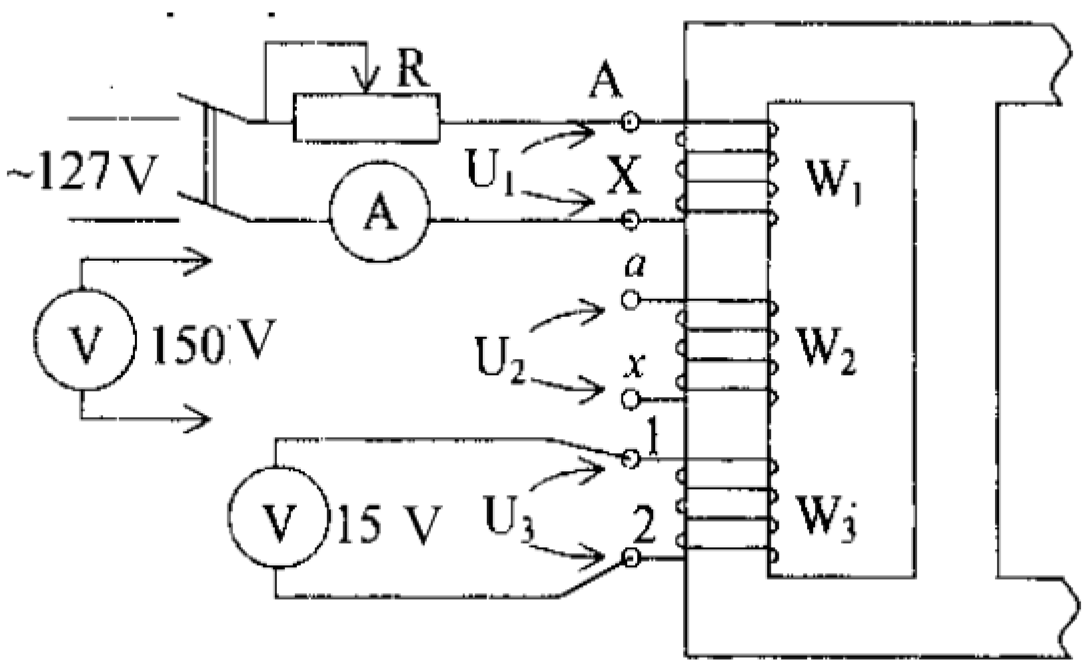

Figure 1 Test circuit

Measure rms voltages U_1, U_2 *and* U_3 across the windings terminals and tabulate them into Table 1.

Calculate the number of turns of the primary w_1 and the secondary w_2, and the transformer voltage ratio (turns ratio) n_{12}. The obtained results tabulate into Table 1.

<u>Stage 3</u> Estimation of the transformer rated values

Using the data of Table 1, calculate and tabulate into Table 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 2

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

<u>Stage 3</u> Measurement of the windings insulation resistance

With the help of an insulation resistance meter, 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 to its highest rated voltage.

<u>Stage 4</u> The report execution

The report on the test should include:

1. The title of the test and its aim
2. The circuit diagram (Fig. 1)
3. Tables 1 and 2 containing the measured and calculated data
4. Calculations of the transformer nameplate data (the rated values)
5. The results of suitability of the transformer by its insulation resistance.

Methodical guideline

<u>To stage 2</u>

The turn number of windings is found with use of the data of Table 1, where the values of voltage had been obtained from the test at no-load, by the formulae:

$$w_1 = \frac{w_3}{U_3} U_3, \; w_2 \frac{w_1}{n_{12}}$$

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

<u>To stage 3</u>

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

$$U_{1r} \cong 4.44 f w_1 B_m \Pi_{met}, \qquad U_{2r} \cong \frac{U_{1r}}{n_{12}}$$

where $f = 50\ Hz$ is the mains frequency, B_m is the flux density amplitude value in T, Π_{met} is the transformer limb cross-section area falling on steel in 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

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

where Π_{st} is the total limb stack cross-section area in m^2, k_{st} is the stacking factor that is the ratio of the metal cross-section are to the total limb stack cross-section area. The stacking 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 adopted some greater than the networks voltages. The parts of voltage values 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.

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

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

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 kV◌A. ts pproximate alue s ound s

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

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 … kV·A.

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

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

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 $U_l = U_{ph}, \quad I_l = \sqrt{3}I_{ph}.$

To stage 4

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

Test questions

1. Explain construction of a three-phase transformer.
2. What ferromagnetic materials are used for a transformer core?
3. What for the core laminations are covered with insulation?
4. Why a power transformer core limbs have 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 not permissible to supply a transformer with voltage exceeding the rated voltage of the primary?
8. Why is connection of 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 conductor 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 tapping of the transformer windings are made?
14. What function the oil in the oil-immersed transformer carries out?
15. What for an oil-immersed transformer tank is equipped with an oil expander?

EXPERIMENTAL INVESTIGATION

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:

6. Choosing the transformer connections for carrying out the open-circuit and short-circuit tests.
7. Carrying out the transformer open-circuit test.
8. Carrying out the transformer short-circuit test.
9. Determination of the transformer open-circuit and short-circuit parameters.
10. Calculation and plotting the transformer performance characteristics.
11. The report execution.

The work procedure

<u>Stage 1</u> *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 1.

Table 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_{sc}, %	S_r, kV·A
		connection	U_{1lr}, V	I_{1lr}, A	connection	U_{2lr}, V	I_{2lr}, A		
open-circuit									
short circuit									

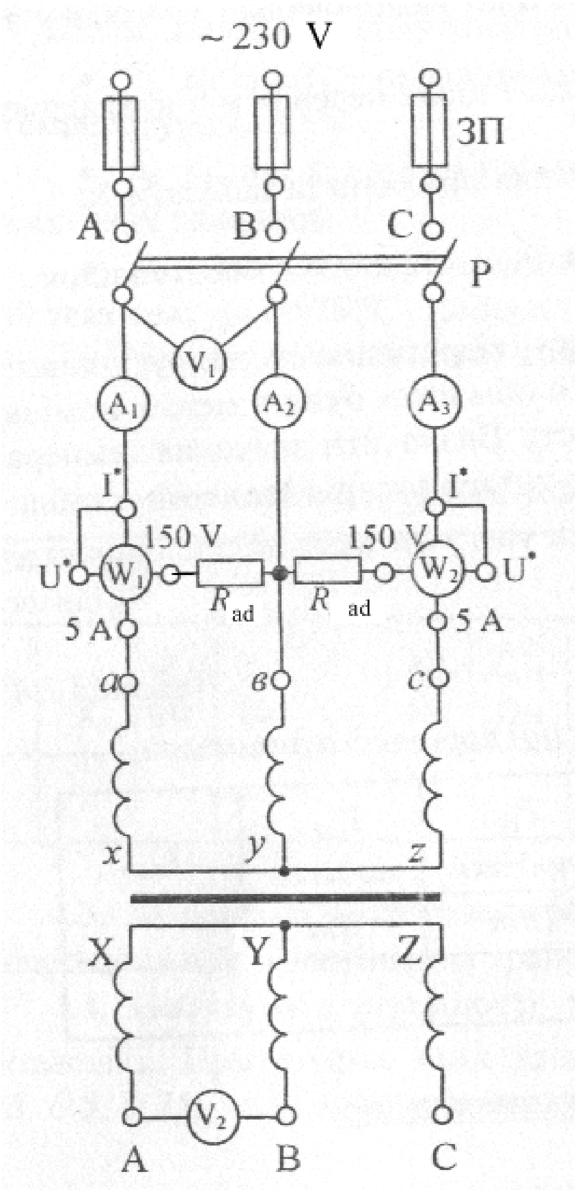

Figure 1 Circuit diagram for circuit test

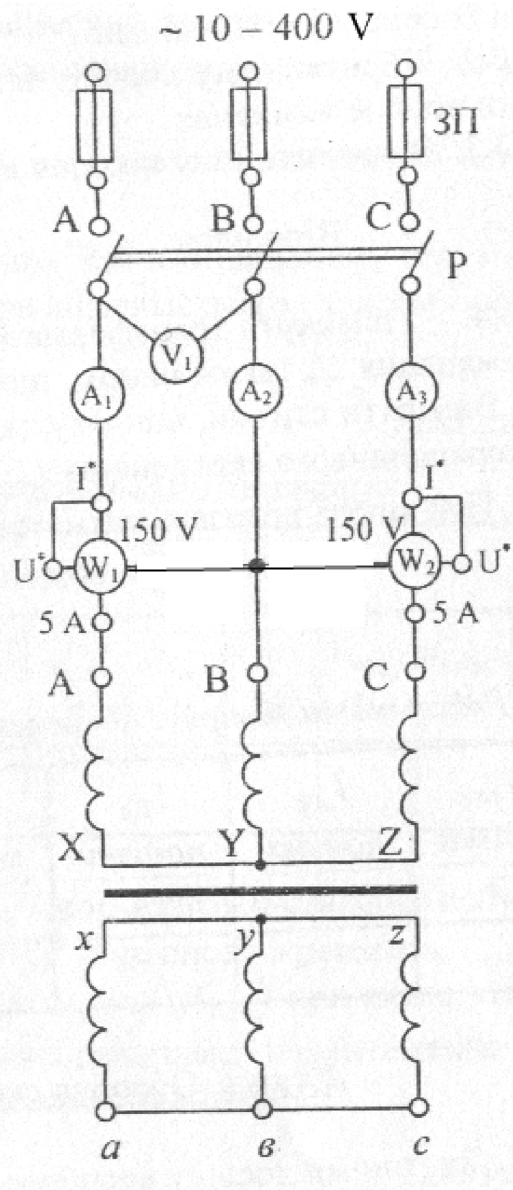

Figure 2 Circuit diagram for short-circuit test

<u>Stage 2</u> Carrying out the transformer open-circuit test

Decide whether the circuit diagram in Fig.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.

Table 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 for checking by the instructor.

Turn the switch S on and carry out the open-circuit test tabulating the instruments reading into Table 3.

Table 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

<u>Stage 3</u> Carrying out the transformer short-circuit test

Decide whether the circuit diagram in Fig.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 4.

Table 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 the switch S on and carry out the open-circuit test, tabulating the instruments reading into Table 4.

Table 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

<u>Stage 4</u> 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 6.

Table 6

Calculated results of open-circuit test

n		P_0		I_0		Z_0	R_0	X_0
ph	*line-to-line*							
-	-	W	%	A	%	Ω	Ω	Ω

<u>Stage 5</u> Determination of the transformer short-circuit parameters

Calculate:

- power P_s consumed by the transformer under short-circuit covering resistance losses in the transformer windings
- impedance of short circuit Z_s and its components R_s, X_s at the normal working temperature of 75 ºC for the transformer insulation thermal class A (maximum permissible temperature equals 105 ºC)
- the voltage under short-circuit conditions u_{sr} at the rated primary and secondary currents and its active $u_{sr,act}$ and reactive $u_{sr,react}$ 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 7.

Table 7

Calculated results of short-circuit test

P_s	P_{sr}	Z_{s75}	R_{s75}	X_{s75}	u_{sr}		$u_{sr,act}$		$u_{sr,react}$	
W	W	Ω	Ω	Ω	V	%	V	%	V	%

<u>Stage 6</u> Composing equivalent circuits

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

<u>Stage 6</u> 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 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.

It is recommended to take the load factor values $\beta = 0, 0.25, 0.50, 0.75, 1.00, 1.25$ at the characteristics calculation.

The calculation results should be tabulated into Table 8.

Table 8

Characteristics calculation results

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

<u>Stage 7</u> Drawing up the report

The report on the test should include:

6. The number and title of the test and its aim
7. The transformer nameplate data (Table 1)
8. Circuit diagrams for open-circuit and short-circuit tests (Fig. 1 and 2)
9. Instrument scales division values at fulfillment the open-circuit and short-circuit tests (Tables 2 and 4)
10. Experimental data obtained at the open-circuit and short-circuit tests (Tables 3 and 5)
11. Calculated results for open-circuit and short-circuit tests (Tables 6 and 7)
12. Results of characteristics calculation (Table 8)

13. 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 Ω:

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

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 no-load current is determined as

$$I_s = \frac{I_A+I_B+I_C}{3}, \text{ A}$$

The short-circuit parameters in Ω:

$$Z_s = \frac{U_{1l}}{\sqrt{3}I_s}, \; R_s = \frac{P_s}{3I_s^2}, \; X_s = \sqrt{Z_s^2 - R_s^2}.$$

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

$$R_{s75} = R_s[1 + \alpha_\rho(75 - t_{amb})]$$

$$Z_s = \sqrt{R_{s75}^2 + X_s^2}$$

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

$$P_{sr} = 3I_{1r}^2 R_{s75}.$$

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

$$u_{sr} = \left({I_{1r}Z_{s75}}/{U_{1r}}\right)100$$

$$u_{sr,act} = \left({I_{1r}R_{s75}}/{U_{1r}}\right)100$$

$$u_{sr,react} = \left({I_{1r}X_s}/{U_{1r}}\right)100$$

To stage 6

The secondary voltage under load is determined as

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

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

The transformer efficiency in per cent is equal to

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

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

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

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. What is difference between tee open-circuit and sort-circuit parameters?
4. How does the no-load current depend on the limbs cross-section area if the coils and the primary voltage remain the same?
5. In what parts of a transformer the power under no-load and short-circuit tests is consumed?
6. How does the winding resistance depend on temperature?
7. Why the temperature variation of the winding resistance was not taken into account at the open-circuit test data processing?
8. What transformer parameters affect the voltage regulation under load?
9. How the open-circuit parameters, net and output voltage, no-load power and current may be determined for the case of feeding the primary of the transformer using the parameter and other quantities values obtained under feeding the secondary?
10. Will be another values of the transformer voltage regulation obtained under loading it by a load with lagging or leading power factor?
11. Why do the no-load phase currents of the transformer differ?

EXPERIMENTAL INVESTIGATION

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

Work program:

12. Theoretical solving of the task of a given three phase transformer vector group determination for a given its windings marking and connection and the transformer potential phasor diagram plotting
13. 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
14. Experimental validation of theoretically obtained results.
15. The report execution.

The work procedure

<u>*Stage 1*</u> *Studying 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. 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.

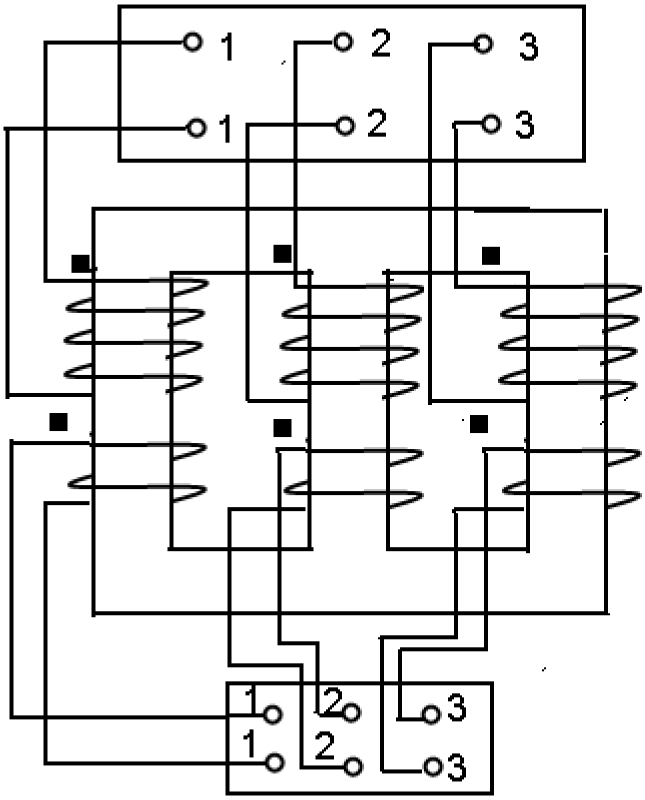

Figure 1 Schematic diagram of three-phase two-winding transformer

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 side depends on a winding connection (Table 1).

Table 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 vector group 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 vector group the transformer potential phasor diagram have to 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 for the case of two line terminals, one on HV and one on LV transformer side, marked with the same letters (for example, terminals “A” and “a”) being equipotential that physically corresponds to electrical connection of these terminals by means of a conductor. The point A-a potential is assumed equal some definite value (for example, 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 group determination correctness (Stage 3). The diagram is plotted for the case of positive sequence symmetrical system of rated voltages across the HV transformer line terminals.

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 vector group determination with the help of the potential phasor diagram is based on usage of the clock face notation.

While the potential phasor diagram is plotted, it is taken into account 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 star 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 delta connection the point, presenting potential of the start point of a phase windings 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

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

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 vector 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 the phase voltages form a symmetrical star having their ends in the points $\mathrm{a}, \mathrm{b}, c$ and the starts coinciding in the point of the vectors intersection 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 $\mathrm{a}, \mathrm{b}, c$ 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 windings terminals are marked and the terminals having equal potentials are connected in the transformer circuit diagram.

<u>Stage 4</u> Experimental validation of theoretically obtained results

It is necessary to 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 under three phase system of rated voltages, applied to line terminals of one of the windings, and comparison them with their values found with from the potential phasor diagram. If the voltage values obtained experimentally by measurement and theoretically from the diagrams are the same the results are correct.

The experimental investigations are carried out in the following sequence.

1. Validation of the vector group determination performed in Stage 2:

- Collect the transformer circuit
- Connect terminals “A” and “a”
- Apply the rated voltage to the terminals of the HV winding
- Measure the voltages indicated in the Table 2 and set the obtained values into the table
- Set the same voltage theoretical values found from the potential diagram
- Compare the experimental and theoretical data and draw the conclusion

2. Validation of the windings circuits depicting in Stage 3:

- Collect the transformer circuit
- Connect the terminals “A” and “a”
- Apply the rated voltage to the terminals of the HV winding
- Measure the voltages indicated in the Table 3 and set the obtained values into the table
- Set the same voltage theoretical values found from the potential diagram
- Compare the experimental and theoretical data and draw the conclusion

Table 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 (tick)	
											correct	incorrect
Experimental												
Theoretical												

Table 3

Validation of the windings 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 (tick)	
											correct	incorrect
Experimental												
Theoretical												

16. 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 1)
3. The results obtained in Stage 2 and their validation: the given transformer circuit diagram; its potential diagram; measured and theoretically found values of voltages, the transformer connection symbol and conclusion regarding the vector group (Table 2)
4. The results obtained in Stage 3 and their validation: the given transformer connection symbol; the transformer potential diagram; the transformer circuit diagram; measured and theoretically found values of voltages and conclusion regarding correctness of the circuit development (Table 3).

Methodical guideline

The vector group indicates the phase displacement of a transformer. In accordance with definition established by IEC (International Electrotechnical Commission), the 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 counter-clockwise sense.

The phasor of the 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 group expressed by its number is found as the phase displacement $\Delta\psi$ measured in degrees divided by 30º:

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

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 the vector group 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.

VG may be also found using the clock face notation.

In a three phase transformer one of twelve VG is possible depending on transformer windings connection and a way of their marking. The possible vector groups for three phase transformers are 0, 1, 2, 3,.., 11. Transformers with the same connection of the HV and LV windings may have zero or one of even VG: 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 may belong to only one of the two VG – 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), i.e. the vector group, expressed as a combination of letters and clock-hour figure(s).

Examples of the transformer connection symbol: 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 vector group of transformers is important at connection transformers in parallel. If transformers of different vector groups are connected in parallel, large circulating current flows between their secondary windings that is very detrimental.

Now give examples of transformers 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. 2.

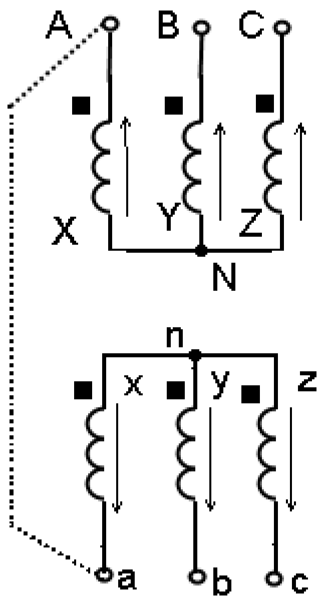

Figure 2 Circuit of transformer which vector group is to be determined

To determine the vector group the transformer potential diagram is plotted (Fig.3). The diagram is drawn up taking that terminals "A" and "a" are connected with a conductor (the dashed line in Fig. 2)Taking into account that the result of the VG determination must be verified experimentally, the diagram should be scaled.

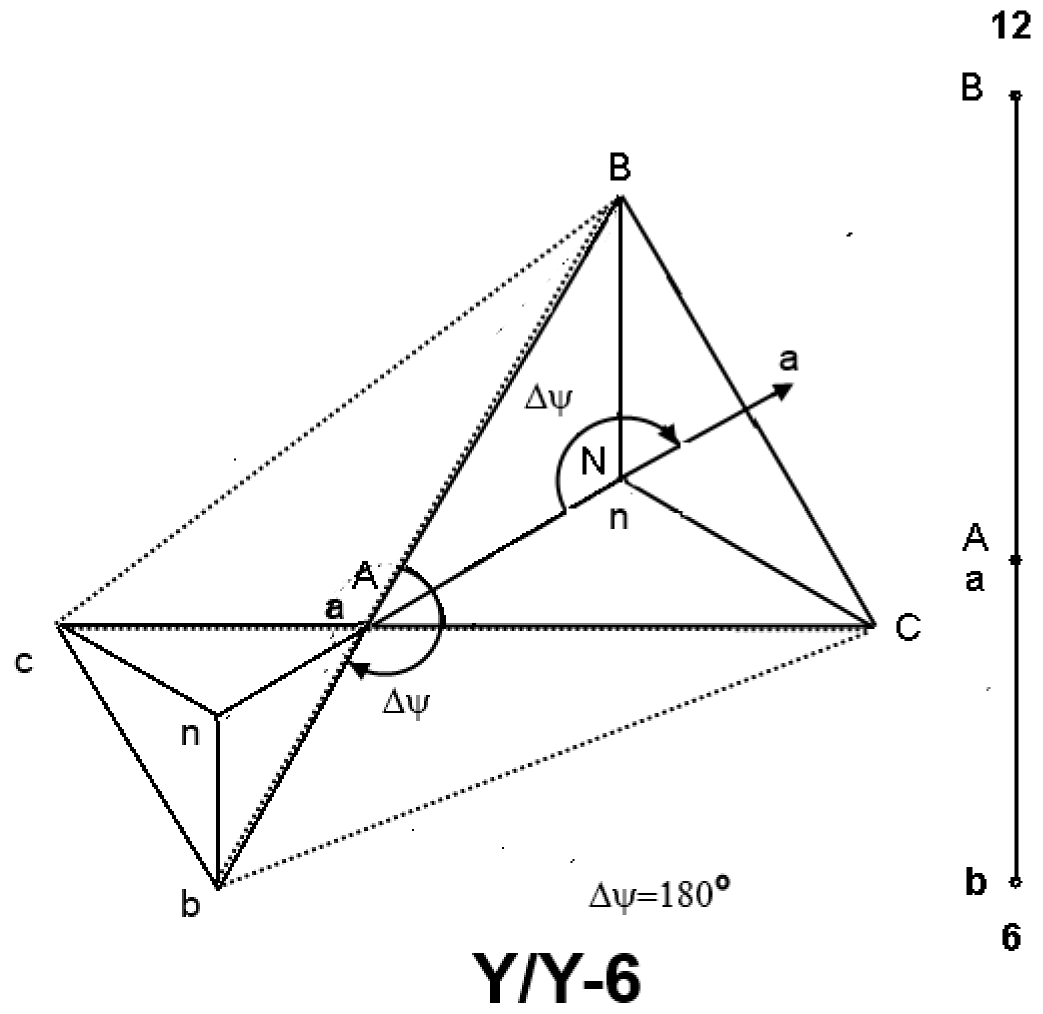

Figure 3 Potential diagram of transformer

Basing on the way of transformer connection and the potential diagram, find the transformer connection symbol: Y/Y-6.

Experimentally found values of the voltages between line terminals of the HV and LV windings (see Table 2) are compared with length of the dashed lines in Fig. 3.

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. 4).

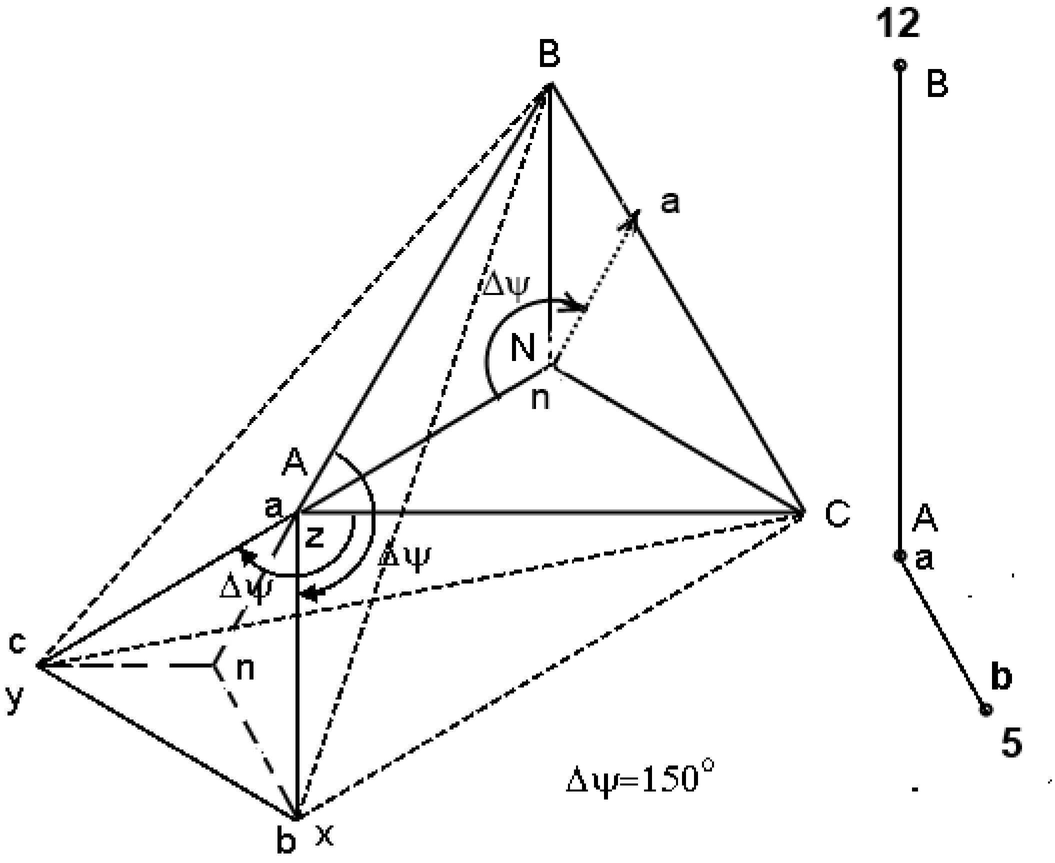

Figure 4 Diagram constructed basing on the known connection symbol

Using the potential diagram the chart of the transformer circuit connection is drawn (Fig. 5). In this case the LV winding neutral point “n” is imaginary.

For the result validation, experimentally and theoretically obtained values of the voltages presented in the potential diagram with dashed lines are compared.

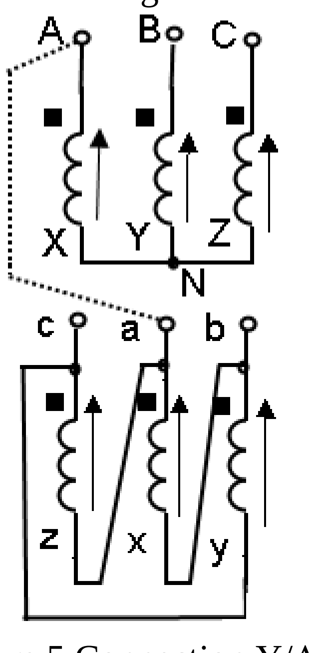

Figure 5 Connection Y/Δ-5

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 the neural point is real and at what it is 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?
11. In what cases have the transformer phase displacement to be taken into account?

EXPERIMENTAL INVESTIGATION

Laboratory test # 2/4

INVESTIGATION OF PARALLEL OPERATION OF THREE-PHASE POWER TRANSFORMERS

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

Work program:

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

The work procedure

<u>Stage 1</u> *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 1.

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

Table 1

Transformers nameplate data

Number of transformer	Connection and phase shift group	S_r, kV·A	HV winding		LV winding		u_{sc}, %
			U_{1lr}, V	I_{1lr}, A	U_{2lr}, V	I_{2lr}, A	
I							
II							

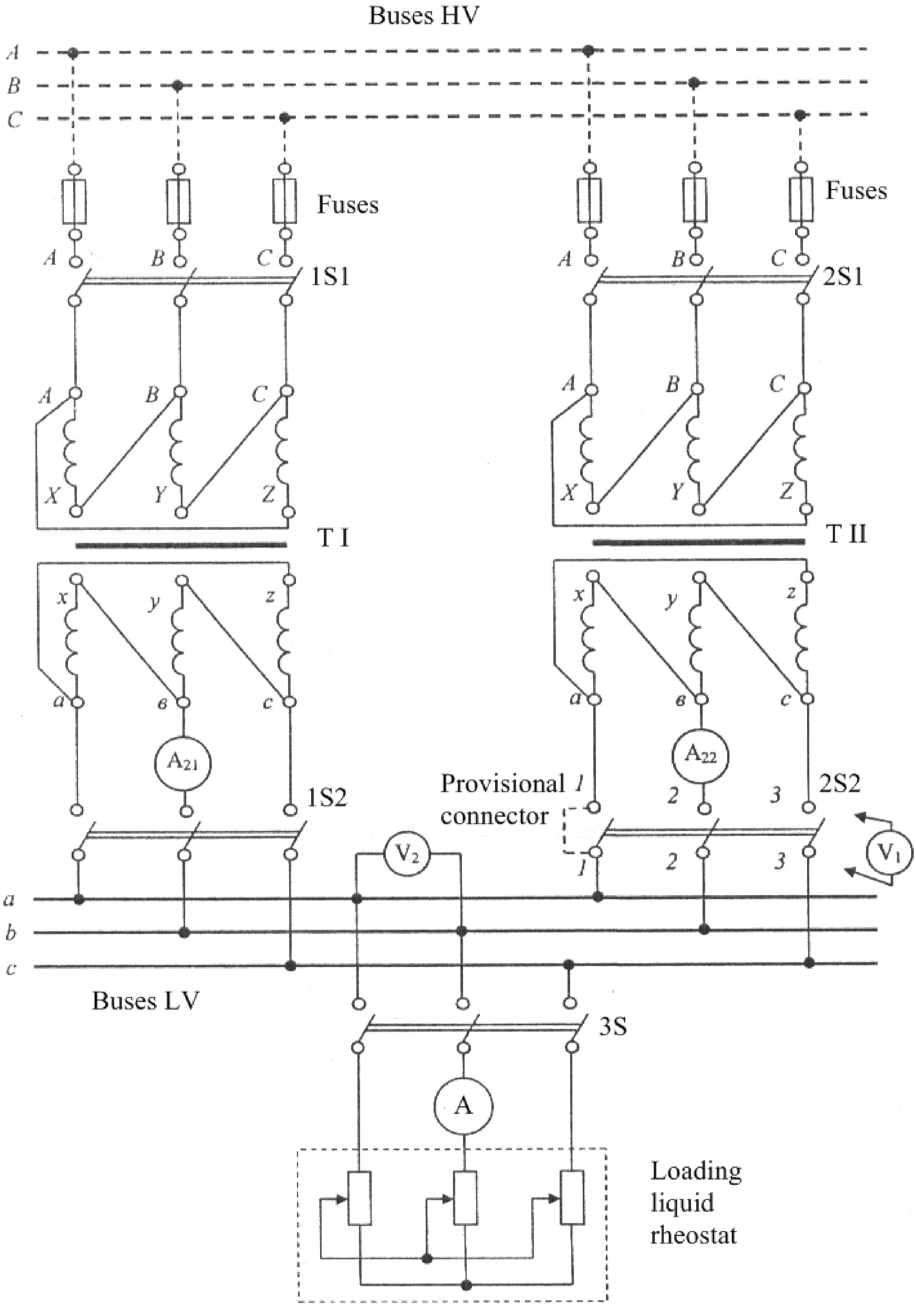

Figure 1 Transformers connected in parallel

Stage 2 The circuit connection and its try-out

Select the switching equipment, protection devices and measuring instruments for the test circuit (Fig.1).

Connect the circuit, using the liquid rheostat as the load. The hatched feeding line is yet available at the test bench.

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 take into account 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 provisional 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. Turn on the switches 1S1 and 2S1, then 1S2 and 2S2. At the beginning the switch S3 remains turned off.

Define if the local circulating currents in the circuit of the secondary windings are 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 … 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 all 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 2.

Table 2

Results of measurement at transformers parallel operation

# of 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.

21.<u>Stage 4</u> Drawing up the report

The prepared report must include:

5. The number and title of the test and its aim
6. The transformers nameplate data (Table 1) and conclusion on possibility of the transformers parallel operation
7. Circuit diagram of the transformers parallel connection (Fig. 1)
8. Results of measurement at the transformers parallel operation (Table 2)
9. The external characteristic of transformers under parallel operation $U_2 = f(I)$
10. 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 practical in the cases of considerable reduction or disappearance of the supplied network load; of essential increase of the consumers power demand; of sharp variation of the load power demand during day and night period; of necessity to provide uninterrupted power supply.

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

- All transformers must belong to the same group as regards phase shift. This condition is absolutely essential.

- All transformers should have the same line-to-line voltages and voltage ratios. Only a very small difference in ratio can be permitted without undue circulating current.
- The per unit impedances or impedance voltages should be the same. This condition should be met if the transformers are to share the load in proportion to their rating powers, and are thus able to give a total load equal to the sum of their ratings.
- 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 close to proportional to their rating powers in the case of small difference in the 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 proportional 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. Parallel operation of transformers is permitted if their voltage ratios differ not more than by 0.5 % at the ratio greater than 3, and by 1.0 % at the ratio less than 3.

If the transformers have unequal impedance voltages 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. On this reason it is impossible to give a total load equal to the sum of the transformers ratings. The transformers impedance voltages difference must be not larger than 10 %. In the ideal case impedance voltages and their active and reactive components of all the transformers have the same values.

Parallel operation of transformers belonging to different groups as regards phase shift is inadmissible due to very great circulating current arising between the secondary windings of the transformers. This inadmissible and dangerous to transformers circulating current arises because of great magnitude of the transformers secondary induced voltages taking place if the transformers belong to different groups and due to small impedance of the circulating current path.

Test questions

12. In what cases parallel operation of transformers is expedient?
13. What requirements must be fulfilled for switching transformers to parallel operation?
14. 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?

15. How is the load divided between transformers under parallel operation if their impedance voltages are not equal? Which of the transformers load does reach the rated value at the total load increase?
16. What are the restrictions of the voltage ratio difference established for transformers being connected in parallel?
17. What is the restriction of the impedance voltage difference established for transformers being connected in parallel?
18. Is it permissible parallel connection of transformers belonging to different phase shift groups? Give explanation.
19. How does accuracy of transformers connection in parallel can be checked after the circuit is assembled?
20. By what reason parallel is connection of transformers in parallel not recommended if their rated powers ratio exceeds 3:1?