

MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE

**NATIONAL TECHNICAL UNIVERSITY  
"KHARKIV POLYTECHNIC INSTITUTE"**

**Methodical instructions**  
for laboratory works  
on the discipline “Electric machines”

for foreign students of the academic and scientific institute of  
power engineering, electronics and electromechanics

Edited by prof. Milykh V. I.

Approved  
by the Editorial Committee  
of NTU “KhPI”,  
protocol № 2 of 17.05.2019

Kharkiv  
NTU “KhPI”  
2019

**Methodical instructions** for laboratory works on the discipline “Electric machines” for foreign students of the academic and scientific institute of power engineering, electronics and electromechanics / compilers: Shevchenko V.V., Duniev O.O., Shilkova L.V., Lazareva O.Ya.; edited by prof. Milykh V. I. – Kharkiv: NTU “KhPI”, 2019. – 40 p.

Compilers: V.V. Shevchenko, O.O. Duniev, L.V. Shilkova, O.Ya. Lazareva

Reviewer: prof. Shevchenko S.Yu.

Department of Electrical Machines

## INTRODUCTION

This edition is dedicated to expand the theoretical knowledge of foreign students on the “Electric machines” discipline.

The objects of study are transformers and electric machines, which are the basis of electric power in various industries.

The subject of this course is electric machines, which are used in practice to convert one form of energy into another: mechanical to electrical (generator), electrical to mechanical (electric motors), and power transformers, which are used to convert the parameters of AC current and voltage.

After the fulfillment of the laboratory works the student has to know the structure, basic elements, the principle of operation and characteristics of transformers and electric machines, features of motors starting, the ways of their frequency rotation control and braking.

The report shall begin with a cover page, where you should write the name of the University, the department of Electrical Machines, the topic of the laboratory work, your group, your name, and the name of your lecturer. The detailed sample of a cover page is given in virtual Appendix at the end of these methodical instructions.

In the report you should define the problem, specify the input numerical data, provide tables with your experimental data, make specific calculations, plot charts and graphs. At the end of the report student has to make a conclusion of the laboratory work.

## Laboratory work 1

### DETERMINING THE POLARITY OF THE WINDINGS OF THE THREE-PHASE TRANSFORMER

#### 1.1 The purpose of the work

The purpose of laboratory work is to determine the polarity of the windings of a three-phase transformer, draw the necessary circuits and determine the circuits and groups of connections of the transformer windings.

#### 1.2 Laboratory work plan

1. Examine the design of the analyzed transformer and the test stand setup.
2. According to the instructions (1.4) mark the beginnings and the ends of the winding, and determine the transformer polarity of the winding.
3. Assemble the schemes and connection groups assigned by the teacher, measure and make relevant calculations of the corresponding voltages.

#### 1.3 Description of the test setup

The scheme of experimental studies is shown in Fig. 1.1.

The analyzed transformer is a three-phase three-legged double winding transformer  $T$ . This transformer has 12 winding outputs: each of three phases refers to two windings; each winding has two outputs.

All the winding outputs of the transformer  $T$  are randomly connected to terminals 1 – 12 on the stand.

The laboratory stand is powered by three-phase 220 V supply and one-phase 36 V supply. Automatic switches  $QF1$  and  $QF2$  are used to supply the voltage to the stand. The indicator  $HL1$  shows the presence of three-phase voltage. The outputs of one of the windings of the transformer  $T$  are determined using an incandescent lamp  $EL$ , which is connected to the 36V circuit. To measure the voltage on the low- and high-voltage windings, the stand is equipped with two voltmeters  $PV1$  and  $PV2$  respectively.

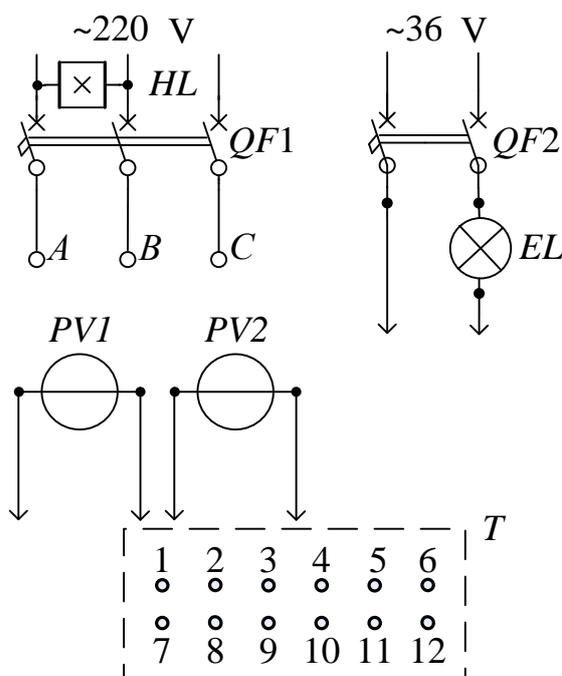


Figure 1.1 – The scheme of experimental studies

## 1.4 Guidelines to the laboratory work performance

1. Determine the terminals to which the outputs of one of the windings are connected using the indicator lamp  $EL$  (Fig.1.2).

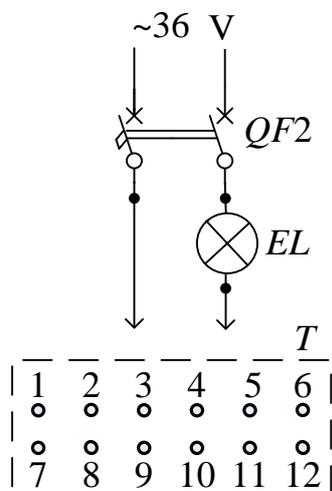


Figure 1.2 - Scheme for determining the winding outputs

To do this, connect any terminal to one of the clamps of the switch  $QF2$  and the conductor with indicator lamp  $EL$  – to the other. By connecting the conductor with the indicator lamp to different terminals one by one, find such a pair of terminals which makes the lamp switch on. Since electric resistance of the high voltage winding is higher than that of the low voltage winding, the faint light of the lamp means that the outputs of the high-voltage (HV) winding have been found. When the lamp is connected to the outputs of the low-voltage (LV) winding, the light will be brighter. In the test report, put down whether the clamps belong to HV or LV winding.

2. Make arbitrary marking of the starts of high-voltage windings as  $A, B, C$  and the ends – as  $X, Y, Z$ .

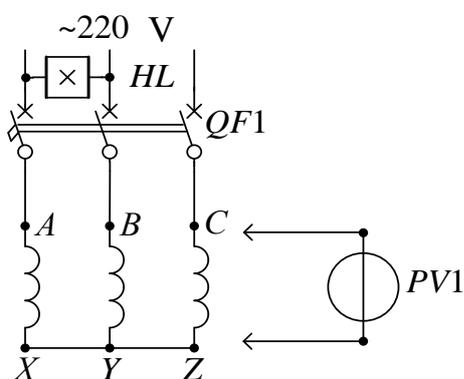


Figure 1.3 – Scheme for determining high voltage phase windings

To check if the marking is correct, connect the phase winding in a star, joining the clamps  $X, Y, Z$  in a single point, and attach outputs  $A, B, C$  to the clamps of the 220 V circuit. Feed the supply voltage using the switch  $QF1$  and measure phase voltages using voltmeter  $PV1$  (Fig. 1.3).

If the marking is correct, the phase voltages will be equal. If phase voltage of one of the windings is higher than that of others, the marking of outputs of this winding should be changed to the opposite. In the test report, register the final correspondence of the clamps to the marking of HV winding outputs.

3. Determine HV and LV coils located on the same leg. To do this, you have to apply 220 V voltage to the ends  $A - X$  using the switch  $QF1$  and to measure the voltage at the ends of LV windings using the voltmeter  $PV2$  (Fig. 1.4). The LV winding with the highest voltage is located on the same leg as the winding  $A-Z$  connected to the circuit. Randomly mark the ends of this winding as  $a - x$ .

Repeat this procedure with the phases  $B$  and  $C$  with random marking the ends of the windings as  $b - y, c - z$ .

4. Determine polarities of low-voltage windings.

Connect the HV winding end with randomly marked end  $a$  of the LV winding. Connect the ends  $A - X$  to a 220 V circuit and measure the voltage between the ends  $A$  and  $x$  using the voltmeter  $PV1$  (Fig. 1.5).

If the measured voltage is higher than 220 V, the LV winding marking  $a - x$  should be considered correct, otherwise if the voltage is lower than 220 V, then LV winding marking should be changed to the opposite.

In the test report, fix the final correspondence of the terminals to the LV winding ends marking.

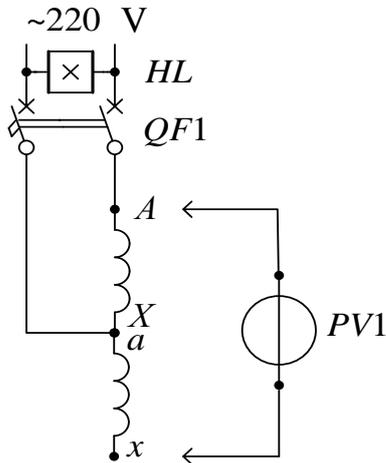


Figure 1.5 – Scheme for determining low voltage winding outputs

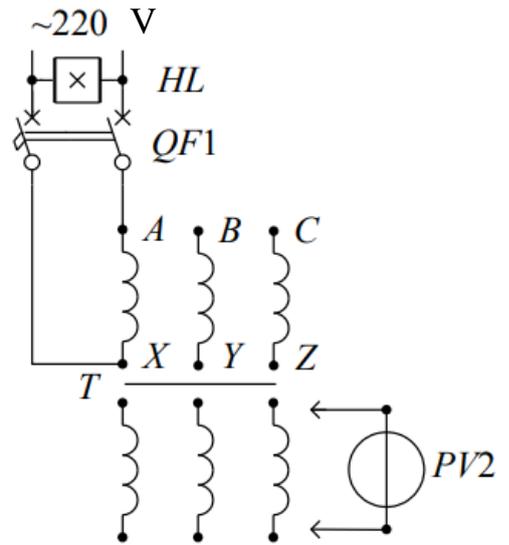


Figure 1.4 – Scheme for determining low voltage phase windings

Repeat this procedure with phases  $B$  and  $C$ .

5. Assemble the schemes and winding connection groups assigned by the teacher, considering the obtained marking of the transformer winding ends. Show the assembly to the teacher.

Connect the scheme points  $A$  and  $a$ . Turn on the switch  $QF1$ , measure the voltages given in the table 1.1 and put down the measurement readings into the same table.

6. De-energize the test setup, disconnect the conductors and bring the equipment back to the initial conditions.

### 1.5. Test results processing

1. Build the vector diagram of the completed connection groups. To do this, draw an equilateral triangle of the HV winding linear voltages, given the measured value of the voltage  $U_{AB}$  and the chosen scale. The triangle of LV winding linear voltages is built based on the measured values of inter-phase voltages. The point  $a$  coincides with the point  $A$ . The point  $b$  is found at the intersection of arcs drawn by radii  $U_{Bb}$  and  $U_{Cb}$ . Draw a triangle of low voltage winding linear voltages by connecting points  $a, b, c$ . Determine the angle  $BAb$ . Calculate the group number by dividing the angle by  $30^\circ$ . Compare the obtained number with the initial one.

2. Calculate the transformation ratio of a three-phase transformer given the measured linear voltages  $U_{AB}$  and  $U_{ab}$  of HV and LV winding respectively:

$$n = \frac{U_{AB}}{U_{ab}} \quad (1.1)$$

Applying the formulae in table 1.2 and the formulae 1.1, calculate the coefficients  $Bb, Bc, Cb, Cc$  using the calculated transformation ratio  $n$ , and then the voltages given in the table 2.1 according to the relations  $U_{Bb} = Bb \cdot U_{ab}$ ;  $U_{Bc} = Bc \cdot U_{ab}$ ;  $U_{Cb} = Cb \cdot U_{ab}$ ;  $U_{Cc} = Cc \cdot U_{ab}$ . Compare the measured and calculated values.

Table 1.1 – Test results

Scheme and group	Linear and inter-phase voltages, V, and transformation ratio of the transformer										
	$U_{AB}$	$U_{ab}$	$n$	$U_{Bb}$		$U_{Bc}$		$U_{Cb}$		$U_{Cc}$	
given by the teacher	measured	measured	calculated								

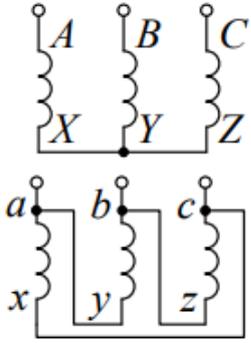
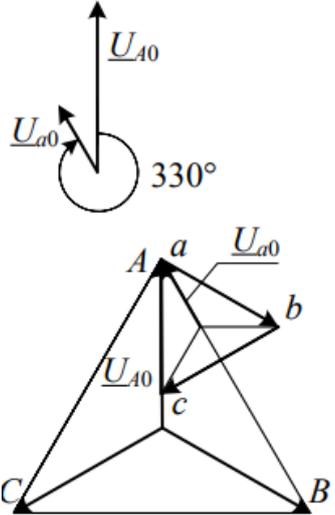
Additional formulae to determine the transformation ratio in dependence of transformer group and its winding connection scheme:

$$\begin{aligned}
 n_\varphi &= \frac{U_p}{U_s} && \text{for Y / Y and } \Delta / \Delta; \\
 n &= \sqrt{3} n_\varphi = \frac{\sqrt{3} U_{\varphi h}}{U_{\varphi l}} && \text{for Y / } \Delta; \\
 \frac{n_\varphi}{\sqrt{3}} &= \frac{U_{\varphi h}}{\sqrt{3} U_{\varphi l}} && \text{for } \Delta / \text{Y}.
 \end{aligned} \tag{1.2}$$

Table 1.2 – Transformer groups' research

Transformer marking	Phase windings connection scheme	Vector diagram	Interfacial voltage ratio
Y/Y-0			$Bb = n - 1$ $Bc = \sqrt{n^2 - n + 1}$ $Cc = n - 1$ $Cb = \sqrt{n^2 - n + 1}$

Ending of table 1.2.

Transformer marking	Phase windings connection scheme	Vector diagram	Interfacial voltage ratio
Y/Δ-11			$Bb = \sqrt{n^2 - \sqrt{3}n + 1}$ $Bc = \sqrt{n^2 - \sqrt{3}n + 1}$ $Cc = \sqrt{n^2 - \sqrt{3}n + 1}$ $Cb = \sqrt{n^2 + 1}$

### Test questions

1. When is a transformer's polarity determined?
2. What are the main steps in determining a transformer's polarity?
3. What is a transformer connection group?
4. What factors define the transformer connection group?
5. How to obtain paired and odd transformer connection groups?
6. Why different transformer connection groups are used?
7. What connection groups are used in one-phase and three-phase transformers?
8. Why do the standards limit the number of transformer groups?
9. How to determine the transformer group if the winding connection pattern is known?

## Laboratory work 2

### ANALYSIS OF PARALLEL OPERATION OF THREE-PHASE TWO-WINDING TRANSFORMER

#### 2.1 The purpose of the work

The purpose of the work is experimental study of the procedure of transformer activation for parallel operation and analysis of their parallel operation with the same and different short circuit voltages.

#### 2.2 Laboratory work plan

1. Get acquainted with the studied transformers and the stand setup.
2. Get transformers ready to parallel operation, i.e. check if the following conditions are met:
  - secondary voltages of the transformers must be equal;
  - transformers must be of the same group.
3. According to the instructions (2.4) make experimental analysis of parallel operation of the transformer with the same and different short circuit voltages.

#### 2.3 Design of the test setup

The scheme of experimental studies is shown in Fig 2.1.

Two step-up three-phase transformers  $T1$  and  $T2$  with the same rated characteristics indicated on the laboratory stand will work parallel.

Both transformers are fed from the common AC grid using the automatic switch  $QF$  and contactor  $KM$ . The light indicator  $HL$  will show if there is grid voltage. To simulate transformer operation with different short circuit voltages, use the switch  $QS1$  to turn on additional resistors  $R1, R2, R3$  with the same resistances to each phase of the secondary winding of the transformer  $T1$ .

Automatic switch  $QS2$  activates parallel operation of the transformer  $T2$ . Potential regulator  $T3$ , which works as a regulation inductance, loads the transformers. The transformers are connected to the load using automatic switch  $QS3$ .

Additionally, the scheme includes the following measuring instruments, which show:

- voltmeter  $PV1$ : linear voltage on the primary transformer windings;
- ammeter  $PA1$ : summed current of the primary transformer windings;
- ammeter  $PA2$ : phase current of the primary winding of the transformer  $T1$ ;
- ammeter  $PA3$ : phase current of the primary winding of the transformer  $T2$ ;
- ammeter  $PA4$ : phase current of the secondary winding of the transformer  $T1$ ;

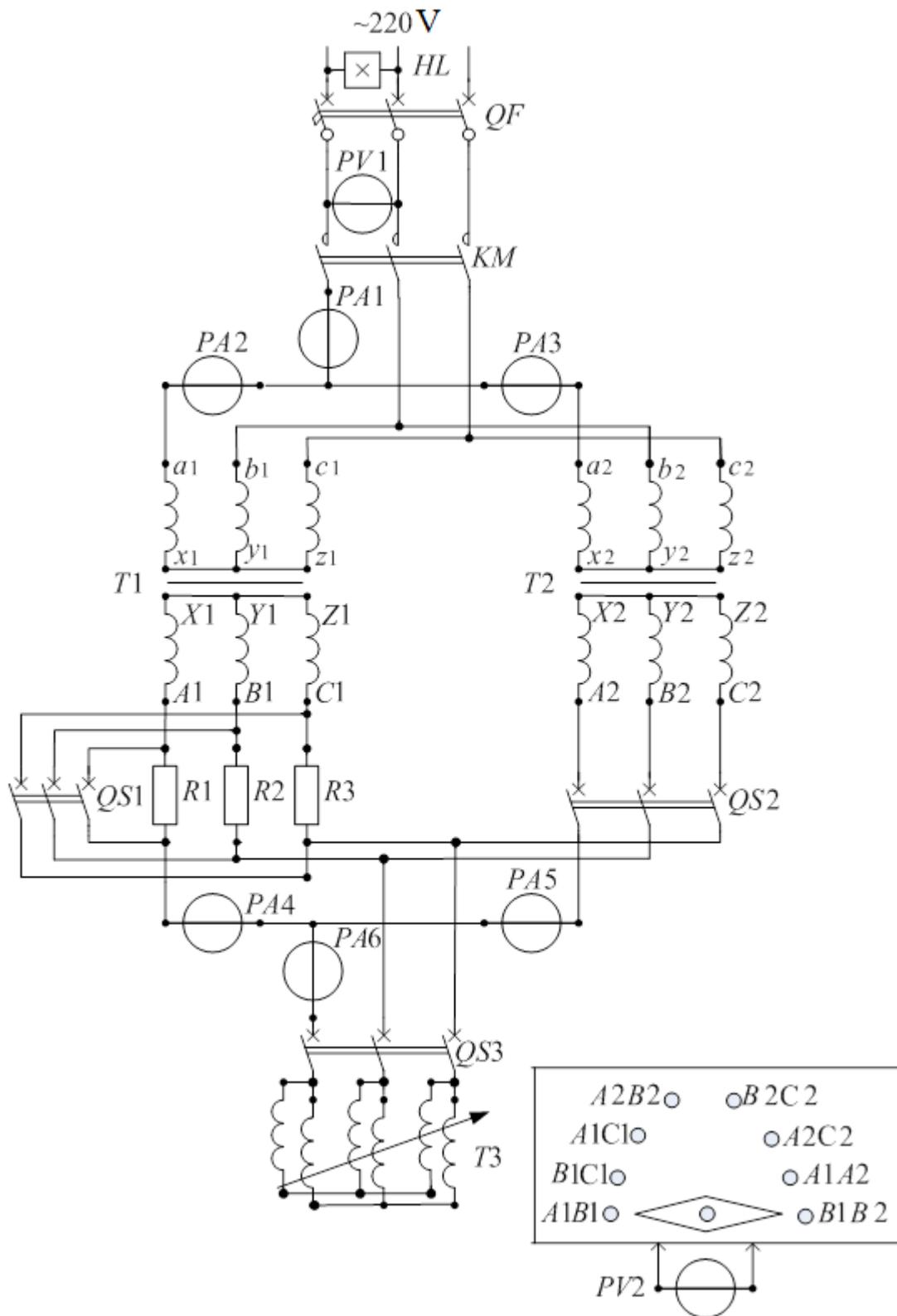


Figure 2.1 – The scheme of experimental studies

ammeter *PA5*: phase current of the secondary winding of the transformer *T2*;  
 ammeter *PA6*: summed current of the secondary windings of the transformers;  
 voltmeter *PV2*: voltage between definite points of the electric circuit; the instrument is designed to check the connection conditions for parallel operation.

## 2.4 Guidelines to the laboratory work performance

1. Into the test report, put down the transformers' rated characteristics indicated on the laboratory stand.

2. To analyze parallel operation of the transformers, assemble a test setup according to the scheme shown in Fig. 2.1.

3. Before turning on the transformers for parallel operation, check:

a) if the transformation coefficients are equal by comparing the magnitudes of secondary voltages.

Before starting the test, check if all switches are open. Turn on the automatic switch  $QF$  and contactor  $KM$ . Measure the secondary voltages  $U_{AB}$ ,  $U_{BC}$ ,  $U_{AC}$  of both transformers using the voltmeter  $PV2$ . If these voltages are equal, then the condition of the transformation coefficients equality is true. Otherwise, parallel operation of the transformers is unacceptable.

b) if the transformers belong to the same group.

To do this, de-energize the setup by switching off the contactor  $KM$  and automatic switch  $QF$ . Wire up the two similar ends of the secondary windings of both transformers, e.g.  $C1$  and  $C2$ . Turn on the automatic switch  $QF$  and contactor  $KM$ . Using the voltmeter  $PV2$ , measure the voltage between other pairs of similar ends of the secondary windings; in the given example these are  $A1$  and  $A2$ ,  $B1$  and  $B2$ .

If the measured voltages equal zero, then the condition that the transformers belong to the same group is true.

If the voltages do not equal zero, this may mean either incorrect connection of the primary windings to the grid or the secondary windings to the load; otherwise it may mean that transformers belong to different groups. To properly connect the primary windings to the grid or the secondary windings to the load, you should swap the outputs of the transformers  $a1$  to  $b1$  or  $a2$  to  $b2$  with the ends  $C1$  and  $C2$  connected. If the voltages  $U_{A1A2}$  and  $U_{B1B2}$  are not equal to zero, we can conclude that the transformers belong to different groups. In this case parallel operation of the transformers is inadmissible.

When the test is over, de-energize the test setup and remove the wire which connected the clamps  $C1$  and  $C2$ .

4. If the prerequisites for transformers' parallel operation are met, turn on the transformers for parallel operation. To do this, turn on the automatic switch  $QF$ , contactor  $KM$  and isolating switch  $QS2$ . After the isolating switch  $QS2$  is on, the transformers are in a no-load mode. Using voltmeters  $PV1$  and  $PV2$ , measure no-load voltages of the primary and secondary windings  $U_{abo}$  and  $U_{ABo}$ , which are equal for both transformers in parallel operation. Using the ammeter  $PA1$ , measure the summed current of both transformers in no-load mode  $I_{ao}$ . Using the ammeters  $PA2$  and  $PA3$ , measure their currents in no-load mode  $I_{p01}$  and  $I_{p02}$ . Put down the obtained readings into the test report (Table 2.2, no-load mode)

Table 2.2 – Tests of no-load mode and load mode

Transformer winding circuit	Primary circuit				Secondary circuit			
Magnitude	$U_{ab}, V$	$I_a, A$	$I_{a1}, A$	$I_{a2}, A$	$U_{AB}, V$	$I_A, A$	$I_{A1}, A$	$I_{A2}, A$
Instrument	$PV1$	$PA1$	$PA2$	$PA3$	$PV2$	$PA6$	$PA4$	$PA5$
Test results	no-load mode							
	$U_{abo}=\phantom{0}$	$I_{ao}=\phantom{0}$	$I_{po1}=\phantom{0}$	$I_{po2}=\phantom{0}$	$U_{ABo}=\phantom{0}$	0	0	0
	The first position of the isolating switch $QS1$							
	The second position of the isolating switch $QS1$							

5. Make the test of loading the parallel operating transformers with one of the positions of the switch  $QS1$ . To load parallel operating transformers, turn on the automatic switch  $QS3$ . Put the switch  $QS1$  in either position. Using the potential regulator  $T3$ , the load is changed so that the transformers' currents should not exceed the rated values. Register 4-5 points and put down the readings of the instruments in the primary and secondary circuits into table 2.2 (the first position of the switch  $QS1$ ).

6. Make the test of loading parallel operating transformers with the second position of the switch  $QS1$ . Turn the switch  $QS1$  to the second position. Repeat the test of loading the transformers similar to step 5. Put down the readings of the instruments in the primary and secondary circuits into table 2.2 (the second position of the switch  $QS1$ ). De-energize the test setup.

### 2.5 Test results processing

1. Using the data from table 2.2, build relations  $I_{a1}(I_a)$  and  $I_{a2}(I_a)$  at the first and second positions of the switch  $QS1$  in the same coordinate system.

2. Using the data from table 2.2, build relations  $I_{A1}(I_A)$  and  $I_{A2}(I_A)$  at the first and second positions of the switch  $QS1$  in the same coordinate system.

3. Based on the type of the built relations, make a conclusion: in which case the short circuit voltages are equal (the test was made with additional resistors  $R1, R2, R3$  turned off) and in which case they are different (the test was made with additional resistors  $R1, R2, R3$  turned on).

## Test questions

1. In what cases is parallel operation of transformers used?
2. What are the prerequisites for switching transformers for parallel operation?
3. Why should transformers have the same transformation coefficients?
4. Why should transformers have the same short circuit coefficients?
5. Why should transformers have the same winding connection groups?
6. How to determine the equality of transformation coefficients of parallel operating transformers?
7. How to determine that the parallel operating transformers belong to the same group?
8. How to determine that short circuit voltages of the parallel operating transformers are equal?
9. How is the load distributed between two parallel operating transformers at different short circuit voltages?

## Laboratory work 3

### MECHANICAL CHARACTERISTICS OF ASYNCHRONOUS MACHINE

#### 3.1 The purpose of the work

The purpose of the laboratory work is practicing one of the methods of experimental evaluation of mechanical characteristics of an asynchronous machine (AM) with slip-rings in different operation modes.

#### 3.2 Laboratory work plan

1. Get acquainted with the studied asynchronous motor and the setup design.
2. According to the guidelines (3.4), make experimental analysis of the asynchronous motor and determine mechanical characteristics of the slip-ring AM with short-circuited rotor phase winding and additional active resistances included into its circuit.

#### 3.3 Description of the test setup

The scheme of experimental studies is shown in Fig. 3.1.

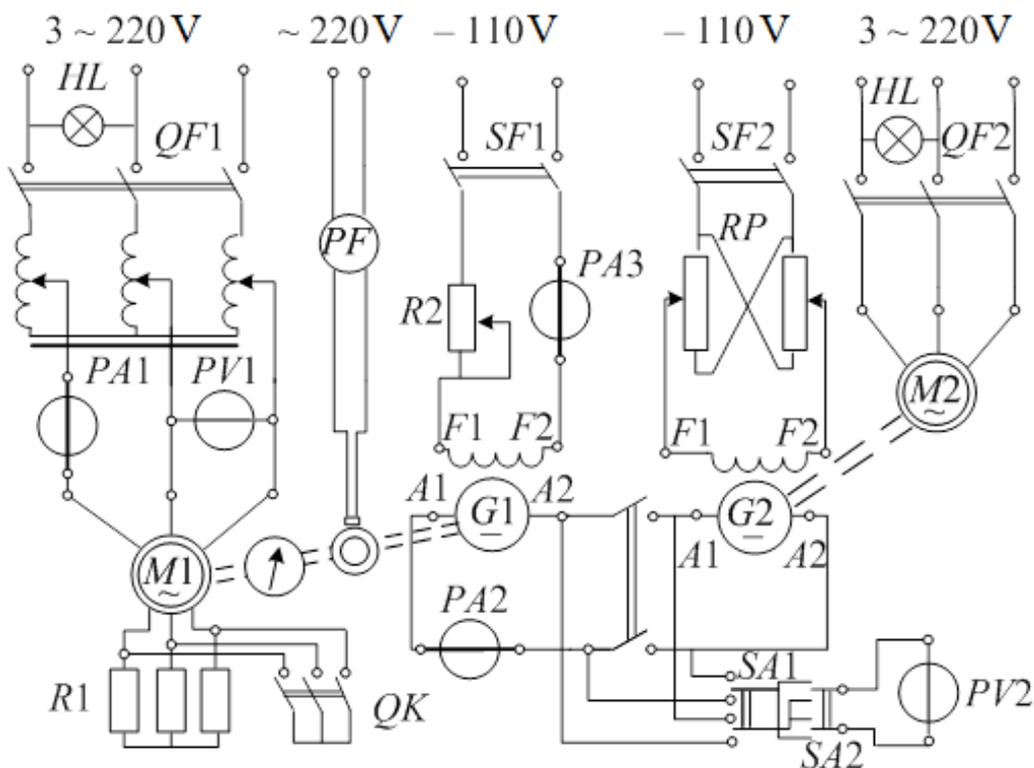


Figure 3.1 – The scheme of experimental studies

A three-phase slip-ring asynchronous motor (AM) designated as  $M1$  is used as an analyzed asynchronous machine (AM). Its stator winding is star-connected. A three-phase rheostat  $R1$  is connected to the rotor's phase winding outputs via slip-rings and brushes, besides these outputs can be short-circuited using the switch  $QK$ .

The machine  $M1$  is mechanically connected to a balance generator (BG)  $G1$ , this is a direct current machine (DCM). For the motor mode of the machine  $M1$ , BG is a mechanical load. The second machine unit consists of AM  $M2$  and DCM  $G2$ , which can also be switched to the motor and generator operation modes. To regulate the input voltage of AM  $M1$ , a three-phase autotransformer ( $T$ ) is utilized. Commutation of the electric circuits of the machines is made automatically using the switches  $QF1$ ,  $QF2$ ,  $SF1$  and  $SF2$ . The presence of voltage in the alternating current grid is signaled by the indicators  $HL1$  and  $HL2$ . To control the linear voltages and stator current of the AM  $M1$ , the ammeter  $PA1$  and voltmeter  $PV1$  are included in its input circuit.

Armature circuits of the machines  $G1$  and  $G2$  are connected via the switcher  $Q$ , they can also switch to motor and generator operation modes. The current in their common circuit is controlled by the ammeter  $PA2$ , and the voltage – by the voltmeter  $PV2$ . With switcher  $Q$  opened, the voltmeter can be connected in turn to clamps of the machines  $G1$  and  $G2$  using the switch  $SA1$ , while the switch  $SA2$  is used to provide corresponding polarity of the voltmeter. The excitation winding  $F1-F2$  of the machine  $G2$  is fed from a similar grid, but its current is regulated by the potentiometer  $RP$  to provide possibility to change the excitation current in the winding  $F1-F2$ . The potentiometer  $RP$  consists of two parallel branches, which provides the range of the voltage on the winding  $F1-F2$  from -110 V up to +110 V. By regulating the excitation currents of the DCMs  $G1$  and  $G2$ , one can obtain the required torque of the BG  $G1$  depending on the required mode of the analyzed asynchronous machine.

The AM's rotor rotational speed  $n$  is determined by the indicator  $PF$  (Fig. 3.1) located on the digital revolution indicator TLI-3M. The revolution indicator receives the signal from the sensor  $BR$ , which is a photodiode.

The AM's torque  $M1$  is measured because  $G1$  is used as a balancing generator BG. Its stator is suspended on the bearings, and using the lever which is rigidly coupled with the stator BG, it transmits the force on the weighing platform, whose scale is indexed in the units of the torque  $T$ . In Fig. 3.1, this system of measuring the torque  $T$  is conventionally designated as an instrument  $PM$ .

### 3.4 Guidelines to the laboratory work performance

1. Get acquainted with the test stand and the equipment set presented in Fig. 3.1, put down the rated data of the utilized electric machines into the test report.
2. Assemble the setup given in Fig. 3.1; in case it is assembled, check the assembly accuracy and the instrument measurement range. In the stator circuit of the

examined AM, the measurement range  $(0.4 \div 0.5) U_N$  will be enough for the voltmeter *PV1*, because the test is made at lower voltage to limit the stator current.

3. Set the equipment into the initial state. All the automatic switches *QF1*, *SF1*, *QF2*, *SF2* are turned off, auto-transformer *T* is in the position of a minimal output voltage, the switch *QK* is closed, the isolator *Q* is open, the rheostat *R2* and the potentiometer *RP* are in the positions at which the excitation currents of the DCM are minimal.

4. Switch in turn both electric machine units starting from alternating current. Start the AM *M1*: to do this, turn on the automatic switch *QF1* and using the auto-transformer *T* smoothly raise the voltage up to the level shown by the teacher (about  $0.5 U_N$  to avoid subsequent excess currents). Turn on the automatic switch *QF2* and start the AM *M2*.

5. Using the automatic switches *SF1*, *SF2*, in turn activate the excitation circuits of the both DCM. Using the rheostat *R2* and the potentiometer *RP*, set the voltages equal by the magnitude and polarity on the clamps of the armature circuits of the machines *G1* and *G2* (connecting the voltmeter *PV2* to a definite machine and changing its polarity is performed using the switches *SA1* and *SA2*). Close the isolator *Q*, providing the mode of mutual load of DCMs. Note that when the no-load voltages and hence the electromotive forces of the both DCMs are equal, there should not be any current in their armature circuits. That is why all the machines, according to the scheme in Fig. 3.1, in fact operate in no-load mode.

6. Check the operability of the tested machine *M1* in the given modes as well as the range of change and measurement of its rotational speed and torque. The electric machines of the test stand are switched into different modes by regulating the excitation current of the ACM *G2* using the potentiometer *RP*. The voltage in AM *M1* and the excitation current of the BG *G1* stay constant.

7. Register the mechanical characteristic of the motor with short-circuited rotor winding (the switch *QK* is closed). Meanwhile, the given voltage *U* in AM *M1* must be kept constant as well as the excitation current  $I_{EG1}$  of the DCM *G1*. Put down the results into table 3.1.

Table 3.1 – Data of the mechanical characteristic of the tested AM with no additional resistances in the winding circuit of its rotor

Given $U =$ $V$ ; $n_s =$ $\text{rpm}$													
Measured													
$n, \text{rpm}$													
$M, \text{N}\cdot\text{m}$													
Calculated													
$s,$													

8. Register the mechanical characteristic of the motor with additional resistances introduced into the rotor winding (the switch  $QK$  is open). The experiment procedure is the same. Put down the results into table 3.2.

Table 3.2 – Data of the mechanical characteristic of the tested AM with additional resistances in the winding circuit of its rotor

Given $U=$ V; $n_s=$ rpm															
Measured															
$n$ , rpm															
$M$ , N·m															
Calculated															
$s$															

### 3.5. Test results processing

1. Based on the data from tables 3.1 and 3.2, make a plot of the mechanical characteristics  $n(M)$  of the tested AM in the common coordinate system.

2. In tables 3.1 and 3.2, calculate the slip  $s$  using the formula  $s = \frac{n_s - n}{n_s}$  and make

a plot of the mechanical characteristics  $M(s)$  of the tested AM in the common coordinate system.

3. Analyze the results obtained in tables 3.1 and tables 3.2 and shown by the plotted characteristics. Compare the characteristics of two different experiments and decide how well they agree with the theoretical concepts of AM.

### Test questions

1. Draw the design of an AM with contact rings and explain the general ideas of its operation in the motion mode.

2. Draw the complete mechanical characteristic of an AM and explain what modes of its operation correspond to definite sections of the characteristic.

3. What are the directions of rotating magnetic field, rotating rotor, electromagnetic torque and external torque on the axle of an asynchronous motor in the studied operation modes?

4. How does the studied AM switch to different modes of operation?

5. What are the modes of operation of the electric machines of the test setup when the studied AM operates in a) the generator mode; b) the motion mode; c) the mode of electromagnetic brake?

6. How will the mechanical characteristic of the studied AM change if the test is made not at lower but at the rated voltage? What problems would arise if the AM was tested under the latter conditions?

7. What is the influence of the active resistance in the AM rotor winding circuit on the form of the mechanical characteristic?
8. What are other ways and factors that influence the mechanical characteristic of an AM?
9. In what cases, under operating conditions, can the AM generator mode and electromagnetic brake mode occur?
10. Why are asynchronous machines so rarely used as generators?

## Laboratory work 4

### ANALYSIS OF THE SYNCHRONOUS GENERATOR, WHICH WORKS ON AUTONOMOUS LOAD

#### 4.1 The purpose of the work

The purpose of the work is experimental evaluation of synchronous generator (SG) characteristics under stand-alone load and assessment of the performance of the SG based on the experimental data obtained.

#### 4.2 Laboratory work plan

1. Get acquainted with the analyzed generator and the setup design.
2. Make a no-load test with recording the no-load characteristic.
3. Make a three-phase short-circuit test with recording the short-circuit characteristic.
4. Perform experimental evaluation of the SG load characteristic under inductive and active loads.
5. Perform experimental evaluation of the external and regulatory characteristics of the SG under active and active-inductive loads.

#### 4.3 Description of the test setup

The scheme of experimental studies is shown in Fig 4.1, where *GS* is the analyzed SG, *M* is the drive-type asynchronous motor (AM), *R* is the active load (a three-phase rheostat), *L* is the inductive load (three-phase inductive regulator), *RP* is the potentiometer to regulate the voltage and hence the excitation current of the SG.

Electrical circuits are switched by automatic switches *QF* and *SF*. The presence of voltage in DC and AC networks is monitored by light indicators *HL1* and *HL2*. The SG load mode is chosen by using the switches *QK*, *QS1* and *QS2*.

The SG excitation current  $I_E$  is controlled by the ammeter *PA1*. The SG phase current  $I_s$  is controlled by the ammeter *PA2*. The SG linear voltage  $U$  is controlled by the voltmeter *PV*, and, if necessary, the phase voltage  $U_s = U/\sqrt{3}$ .

The power factor  $\cos\varphi$  is monitored by the device  $P\varphi$ , which is switched on via the current transformer *TA*.

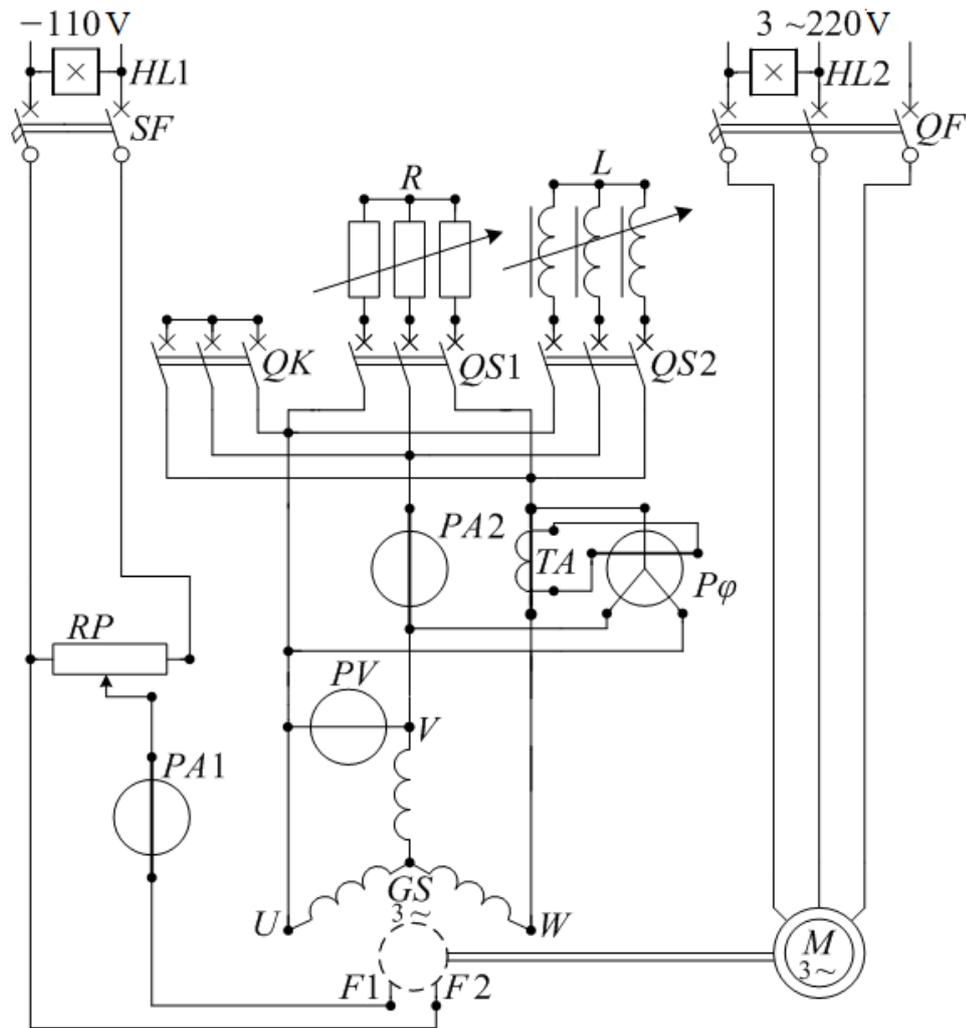


Figure 4.1 – The scheme of experimental studies for investigation of the synchronous generator during stand-alone operation

#### 4.4 Guidelines to the laboratory work performance

1. Get acquainted with the design and put down the rated data of the SG.
2. Make a no-load test and register the no-load characteristic (NLC)  $E_{s0}(I_E)$  at  $I_s = 0$ .

Previously, disconnect the load from the SG and set the potentiometer  $RP$  to zero position. Using the automatic switch  $QF$ , apply voltage to the AM and thus start it directly. Apply power to the potentiometer  $RP$  with the automatic switch  $SF$ .

Register the descending part of the no-load characteristics. To do this, first use the potentiometer  $RP$  to increase the SG excitation current  $I_E$  so as to bring its EMF to  $E_0 = (1,2 \div 1,3)U_N$ . After that gradually decrease the excitation current  $I_E$  down to zero and make 6-8 measurements. While registering the no-load characteristic, the

excitation current should be changed only downwards not to deviate from the downward part of the characteristic. Put down the measurement results into table 4.1.

Turn off the automatic switches  $QF$  and  $SF$ .

Given the fact that the voltmeter  $PV$  measures the linear value of EMF  $E_0$ , you should calculate the phase EMF value according to the formula  $E_{s0} = E_0 / \sqrt{3}$  and also put down the results into table 4.1.

Table 4.1 – No-load characteristic  $E_{s0}(I_E)$  at  $I_s=0$  and  $f_s=f_{sN}$

$I_E$	A							
$E_o$	V							
$E_{s0}$	V							

3. Make a test of three-phase short circuit while registering the short-circuit characteristic  $I_{sk}(I_E)$ .

While the setup is completely de-energized, short-circuit all three phases of the SG stator using the switch  $QK$ . Set the potentiometer  $RP$  into zero position. Directly activate the AM using the automatic switch  $QF$ . Supply power to the potentiometer  $RP$  using the automatic switch  $RP$ .

Register the short-circuit characteristic  $I_{sk}(I_E)$ . To do this, use the potentiometer  $RP$  to gradually increase the excitation current  $I_E$  from zero up to the value when the stator current reaches the value  $I_{sk}=1,2 \cdot I_{sN}$ . Within this interval, make 3-4 measurements and put them down into table 4.2.

Table 4.2 – Short-circuit characteristic  $I_{sk}(I_E)$ , at  $U_s=0$  and  $f_s=f_{sN}$

$I_E$	A						
$I_{sk}$	A						

Set the potentiometer into zero position. Open the switch  $QK$  and automatic switches  $SF$  and  $QF$ .

4. Register induction load characteristic (ILC)  $U_s(I_E)$  at  $I_s=I_{sN}$  and  $\cos\varphi = 0$ .

Using the switch  $QF$ , directly activate the AM. Using the automatic switch  $SF$ , supply power to the potentiometer  $RP$ .

Turn on the induction load  $L$  using the switch  $QS2$ . Set the load  $L$  and the excitation current  $I_E$  to such values that at the liner voltage  $U=U_N$  the current under the load is  $I_s=I_{sN}$ . While decreasing the linear voltage  $U$  by lowering the current  $I_E$  and maintaining the load current  $I_s=I_{sN}$  by regulating  $L$ , make 4-5 measurements and put down the results into table 4.3.

Set the potentiometer  $RP$  into zero position. Turn off the switch  $QS2$ . Calculate the phase voltage  $U_s$  and put it down into table 4.3.

Table 4.3 – Load characteristic  $U_s(I_E)$  at  $I_s = const$ ,  $\cos\varphi = const$ ,  $f_s = f_{sN}$

$I_E$	A					
$U$	V					
$U_s$	V					

5. Register load characteristic  $U_s(I_E)$  at the active load ( $\cos\varphi = 1$ ,  $I_s = I_{sN}$ ).

Turn on the switch  $QS1$  thus connecting the active load to the SG. Make the test similar to the previous one (section 4). Put down the measurement results into a table similar to table 4.3.

6. Register the external characteristic  $U_s(I_s)$  at active load ( $\cos\varphi = 1$ ).

Using the switch  $QS1$ , turn on the active load. By simultaneous regulating the excitation current  $I_E$  using the potentiometer  $RP$  and the load  $R$ , set the linear voltage  $U = U_N$  and the phase current  $I_s = I_{sN}$ . While changing the value of the load  $R$  without changing the preset excitation current, register the external characteristic when the current  $I_s$  ranges from zero (no-load) up to  $1,2 \cdot I_{sN}$ . On making 4-5 measurements, put down their results into table 4.4.

Calculate the phase voltage  $U_s$  and put down the results also into table 4.4.

Table 4.4 – External characteristic  $U_s(I_s)$  at  $I_E = const$ ,  $\cos\varphi = const$ ,  $f_s = f_{sN}$

$I_s$	A					
$U$	V					
$U_s$	V					

7. Register external characteristic  $U_s(I_s)$  at the rated excitation current and rated power factor  $\cos\varphi_N$ .

Turn on the mixed load using the switches  $QS1$  and  $QS2$ . By simultaneous regulating the potentiometer  $RP$  and the load components  $R$  and  $L$ , set the rated mode of SG operation with the parameters  $U=U_N$ ,  $I_s=I_{sN}$ ,  $\cos\varphi=\cos\varphi_N=0.8$ . Without changing the excitation current, gradually increase  $R$  and  $L$  so that the value  $\cos\varphi=0.8$  stays the same. Watch the changes in voltage and current and make 4-5 measurements including the one with the load off when you turn off the switches  $QS1$  and  $QS2$  ( $I_s=0$ ) at the end of the experiment. Put down the results of the measurements into a table similar to table 4.4. Set the potentiometer  $RP$  to a zero position.

8. Register the regulatory characteristic  $I_E(I_s)$  at active load ( $\cos\varphi=1$ ) and at the rated voltage  $U=U_N$ .

In the no-load mode ( $I_s=0$ ), set the excitation current using the potentiometer  $RP$  so that the voltage is  $U=U_N$ . Using the switch  $QS1$ , turn on the active load  $R$ . By de-



where  $I_{sk}$  is the phase short-circuit current, A;  
 $E_{s0}$  is the phase value of the EMF, Ohm.

4. Build the load characteristics in the same axes as the no-load characteristic. Build a reactive triangle and determine the inductive dissipation resistance  $X_{\sigma s}$ , Ohm:

$$X_{\sigma s} = \frac{CD}{I_{sN}}$$

where CD is the voltage drop at the desired inductive resistance (Fig. 4.3);

$I_{sN}$  – the nominal generator current, A.

Point  $K$  corresponds to the excitation current  $I_E$  at  $U_s = 0$  and the rated value of the armature current. From the point  $A$  on the ILC, where the phase voltage is  $U_s = U_{sN}$ , draw a segment  $AB = I_{Ek}$  parallel to the abscissa axis where the excitation current  $I_{Ek}$  is found by the short-circuit characteristic at the stator current  $I_{sk} = I_{sN}$ . From the point  $B$ , draw a segment  $BC$  parallel to the linear initial part of the no-load characteristic up to the intersection with the latter.

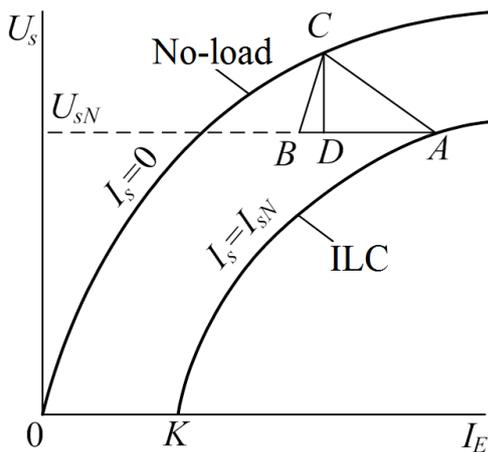


Figure 4.3 – No-load and induction load characteristics

the point  $B$ , draw a segment  $BC$  parallel to the linear initial part of the no-load characteristic up to the intersection with the latter.

5. In the same coordinate system, build external characteristics according to Fig. 4.4 and determine the rated change of the voltage  $\Delta U_{sN}$ :

$$\Delta U_{sN} = \frac{E_{s0} - U_{sN}}{U_{sN}} \cdot 100 \%$$

Usually  $\Delta U_{sN} = (25-35) \%$ .

6. In the same coordinate system build both regulatory characteristics  $I_E(I_s)$ .

7. Put down the SG parameters determined from the experiment into table 4.6.

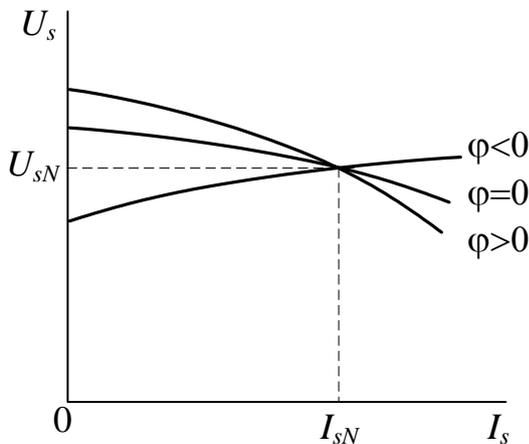


Figure. 4.4 – External characteristics of SG

Table 4.6 – SG parameters

$\bar{X}_s$	$X_{\sigma s}$	$K_k$	$\Delta U_{sN}$
Ohm	Ohm	–	%

### Test questions

1. Explain the design and operating principle of a SG.

2. What does the voltage of SG no-load operation depend on?
3. What is the SG armature reaction? How does the armature reaction influence the voltage magnitude at active, inductive and capacitive load?
4. What do the SG external characteristics show? How are they registered? What are the reasons of the generator's voltage changes with the growth of the load at different values of  $\cos\varphi$ ? What is a rated change of voltage?
5. What do the SG regulatory characteristics show? How are they registered? How and why do the characteristics at different loads differ?
6. What do the load characteristics show? How are they registered? How are these characteristics located relative to no-load characteristic?
7. What is the pattern of the stator winding current at three-phase short circuit? Explain the straightness of the short-circuit characteristic. What is the short circuit ratio?
8. What is the SG synchronous inductive resistance  $X_s$ ? Why in practice should you know this resistance?
9. How to determine the stator winding inductive dissipation resistance  $X_{\sigma s}$ ?

## Laboratory work 5

### ANALYSIS OF THE SYNCHRONOUS GENERATOR IN PARALLEL WORK WITH THE ELECTRICAL NETWORK

#### 5.1 The purpose of the work

The purpose of the work is to check and ensure the necessary conditions for the inclusion of a three-phase synchronous generator (SG) for parallel work with the electrical network, experimental determination of its characteristics in different modes of operation with the network.

#### 5.2 Laboratory work plan

1. To get acquainted with the generator being investigated and the installation scheme.
2. Start the drive motor and check that the synchronization conditions of the SG are fulfilled for parallel operation with the power grid.
3. To conduct an experimental determination of the regulating characteristics of SG for different characters of its load.
4. Adjusting the torque on the SG shaft to conduct an experimental study of the characteristics of its power, stator current and power factor at a constant excitation current.
5. Conduct an experimental study of the *U*-shaped characteristics of SG with its constant load.

#### 5.3 Description of the test setup

The diagram of an experimental study of the synchronous generator inclusion for parallel operation with an electrical network is shown in Fig. 5.1. The investigated synchronous machine (*SM*) is a three-phase synchronous generator (*SG*), designated as *GS*. Its stator winding is connected according to the “star” scheme. *SG* is driven by a DC motor (*M*) parallel excitation. To limit the starting current of the motor is used starting rheostat *R2*. Its resistance is selected so that the inrush current does not exceed the rated current more than twice.

Switching electrical circuits of machines are performed by automatic switches *QF1*, *QF2*. The presence of voltage in the networks of direct and alternating current is controlled by the light indicators *HL1* and *HL2*. To control the linear voltage and current of the SG stator, a *PV3* voltmeter and a *PA3* ammeter are included in its armature circuit. The *PV2* voltmeter measures the line voltage of the network, which is equal to the *QF2* when the circuit breaker is closed.

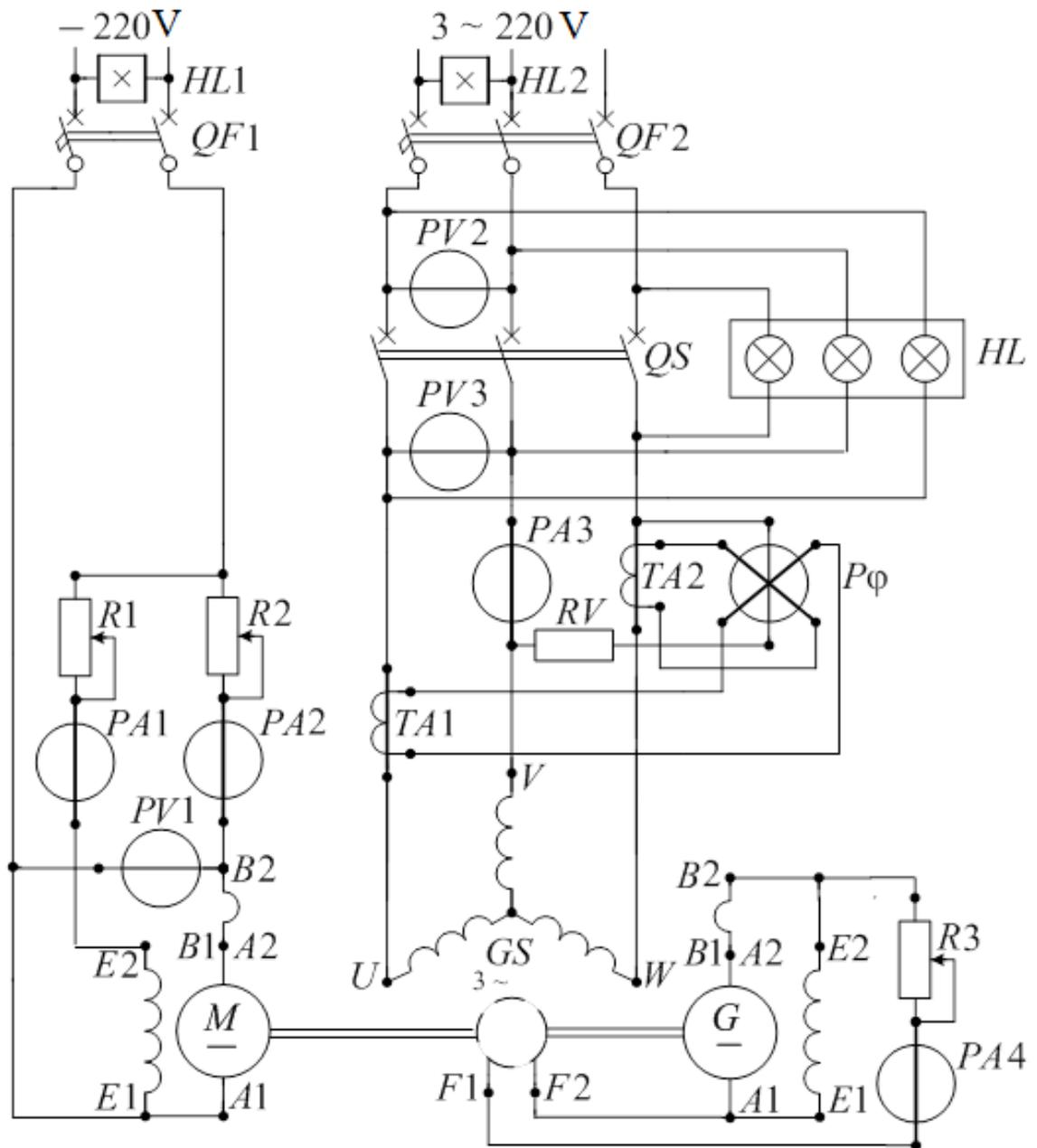


Figure 5.1 - The diagram of an experimental study of the synchronous generator inclusion for parallel operation with an electrical network

To regulate the rotational speed and torque of the *DCM*, an adjusting rheostat *R1* is used in its excitation winding circuit (*E1-E2*). It provides the ability to control the excitation current of the engine.

The rheostat *R3* regulates the excitation current of the *SG*, which comes from a DC generator connected to the shaft of the *SG*. At the same time, power factor  $\cos\phi$  *SG* control is ensured in the same way. Ammeters *PA3* and *PA4* measure the phase current of the stator winding  $I_s$  and the excitation current of *SG*  $I_E$ . Voltmeter *PV1* measures the voltage at the anchor of the DC motor. Ammeters *PA1* and *PA2* measure, respectively, the excitation current  $I_{EM}$  and the armature current of this motor.

To measure the power factor ( $\cos\phi$ ), a phase meter is included in the circuit, which is switched on through the  $TA1$  and  $TA2$  instrument current transformers and an additional  $RV$  resistor. For the implementation of accurate synchronization of the SG with the network, the lamp synchroscope  $HL$  is used, in which the lamps are switched on according to the “fade out” scheme. The  $QS$  disconnecter is switched on only after all the requirements for precise synchronization are met at the moment of extinction of three lamps  $HL$ , provided that the readings of the voltmeters  $PV2$  and  $PV3$  are equal.

### 5.4 Guidelines to the laboratory work performance

1. Familiarize yourself with the design and record the nominal data of a synchronous generator and a DC motor.

2. Ensure the initial state of the equipment: the  $QF1$  and  $QF2$  circuit breakers, the  $QS$  disconnectors are turned off, and the  $R2$  is switched to the position where the armature current of the DC motor will be minimal.

3. Perform accurate synchronization. To do this, you must fulfill a number of conditions:

- the EMF of the generator  $E_0$  at the moment of its connection to the network must be equal and opposite in phase to the mains voltage ( $E_0 = -U_c$ );

- the frequency of the EMF of the generator  $F_g$  must be equal to the frequency of the alternating voltage in the network  $f_c$ ;

- the order of the phases on the outputs of the generator should be the same as at the terminals of the network.

Failure to comply with any of the synchronization conditions leads to the appearance in the stator winding of large equalizing currents, the excessive value of which may cause an accident.

For accurate synchronization, follow the instructions clearly.

Launch DC motor. As it accelerates, remove the starting adjustable rheostat  $R2$ . In this case, the SG pathogen  $G$  is self-excited and provides the SG excitation current, so a voltage appears at the terminals of the latter. With the  $QS$  disconnecter open, turn on the circuit breaker  $QF2$  to apply mains voltage to the synchroscope. Synchroscope lamps will flash. Simultaneous extinction of all the lamps indicates that the order of alternation of the phases of the EMF SG  $E_s$  and the voltage of the network  $U_\phi$ . Smoothly adjusting the excitation current of the generator  $GS$  with a rheostat  $R3$  and at the same time adjusting the excitation current  $I_{EM}$  of the motor  $M$  with a rheostat  $R1$  so as to achieve equality of  $E_s$  and  $U_\phi$  (equality of values on the  $PV2$  and  $PV3$  devices), as well as approximate equality of the frequency  $f_s$  and  $f$  (the lamps flash very rarely).

**In the presence of the teacher**, connect the SG to the network with a  $QS$  disconnecter, but always at the time of the lamps go out.

4. To carry out the regulation of the SG load at the power factor  $\cos\varphi = \text{const}$ , which is monitored by a phase meter and remove three adjustment characteristics  $I_E(M)$ :

a) with  $\cos\varphi = 1$  ( $\varphi = 0$  - active load) for realizing the load, the excitation current  $I_{EM}$  of the driving DC motor should be gradually reduced with a resistor  $R1$ . At the same time, the excitation current of the SG should be controlled by a rheostat  $R3$  so that  $\cos\varphi=1$  and remains constant during the experiment. Perform 8 measurements with an increase in the load current SG  $I_s$  from zero to  $I_{sN}$  (in increments of 1 A). The measurement results make a table. 5.1.

b) repeat the experiment with  $\cos\varphi = 0.8$  ( $\varphi > 0$  - active-inductive load) in the same range of stator current measurement. Measurement data record in the table 5.1.

c) repeat the experiment with  $\cos\varphi = 0.8$  ( $\varphi < 0$  - active-capacitive load) in the same range of stator current measurement. Measurement data recorded in the table 5.1.

Table 5.1 - the regulation of the load SG at  $\cos\varphi = \text{const}$

Experiment						Calculations				
SG			DC motor							
$U$	$I_s$	$I_E$	$U_M$	$I_a$	$I_{EM}$	$P_{inm}$	$P_{elm}$	$P_{om}$	$P_M$	$M$
V	A	A	V	A	A	W	W	W	W	N·m
PV3	PA3	PA4	PV1	PA2	PA1	—	—	—	—	—
$\cos\varphi = 1$										
	0									
	4									
	5									
	..									
	$I_{sN}$									
$\cos\varphi = 0,8 (\varphi > 0)$										
$\cos\varphi = 0,8 (\varphi < 0)$										

5. Carry out the regulation of the SG load at  $I_E = \text{const}$  and register the dependences  $P(M)$ ,  $I_s(M)$ ,  $\cos\varphi(M)$ .

Using a resistor  $R1$ , load the synchronous generator with  $I_s = I_{sN}$  current and adjust its excitation current  $I_E$  with a rheostat  $R3$  so as to obtain  $\cos\varphi = 1$ . Fix the excitation current  $I_{EN}$  SG corresponding to this condition ( $I_{EN}$  is the nominal excitation current for this load). Supporting  $I_E = \text{const}$ , reduce the load on the generator by increasing the excitation current  $I_{EM}$  of the driving DC motor with the help of the resistor  $R1$ . Measurement data record in the table 5.2.

Table 5.2 – Regulation of the SG load at  $I_E = const$

Experiment							Calculations					
SG				DC motor								
$U$	$I_s$	$I_E$	$\cos\varphi$	$U_M$	$I_a$	$I_{EM}$	$P$	$P_{inM}$	$P_{elm}$	$P_{om}$	$P_M$	$M$
V	A	A	–	V	A	A	W	W	W	W	W	N·m
	$I_{sN}$	$I_{EN}$	1									
	10											
	8											
	6											

6. Build  $U$ -shaped characteristics and  $\cos\varphi(I_E)$  and  $Q(I_E)$  dependencies for two values of active power  $P$ , which are recommended by the teacher.

Set the power of the SG  $P = 0$ . To do this, adjust the excitation currents of the motor  $M$  and the generator  $GS$  with rheostats  $R1$  and  $R3$  so as to set the stator winding current  $I_s = 0$  (normal excitation for SG no-load mode).

To draw a plot of  $U$ -shaped characteristics in the mode of overexcitation, rheostat  $R3$  needs to gradually increase the excitation current  $I_E$  of the synchronous generator  $GS$  until the stator current  $I_s$  becomes  $I_{sN}$ .

The value of the engine power must be kept constant ( $U_M = 205$  V;  $I_a = 14$  A). Write 4÷5 values of the stator current is in table. 5.3.

Build a plot of the  $U$ -shaped characteristics in the mode of under-excitation.

To do this use a resistor  $R3$  to set the rated excitation current  $I_E$  of the synchronous generator  $GS$ . Reduce the excitation current  $I_E$  of the  $GS$  generator as long as the stator current rises to the  $I_{sN}$  value. In this case, the  $\cos\varphi$  of the  $GS$  generator decreases to a value of 0.5. Write 3÷4 values of the stator current  $I_s$  in the table. 5.3.

After this rheostat  $R3$  should again set the rated current. At the end of the experiment, it is necessary to use a rheostat  $R1$  to reduce the power of the DC motor ammeter  $PA2$ . At the same time also:

- SG current must be zero ( $PA3$  ammeter),
- the power factor of the synchronous generator  $GS$  (rheostat  $R3$ ) should increase to the value  $\cos\varphi = 1$  (phase meter  $P\varphi$ ).

Switch off the  $QS$  disconnecter, then the  $QF1$ ,  $QF2$  circuit breakers and thereby stop the units. Take rheostat  $R2$  to its original position.

### 5.5 Test results processing

1. Calculate the power of the DC motor, which it consumes from the grid, is equal to, W

$$P_{inM} = U_M I_a. \quad (5.1)$$

Table 5.3 –  $U$ -shaped characteristic plot at  $P_{inM} = \text{const}$

Experimental data of SG				Calculation	
$U$	$I_s$	$I_E$	$\cos\varphi$	$\sin\varphi$	$Q$
V	A	A	p.u.	p.u.	var
$P_{inM} =$ kW. Overexcitation Mode					
$P_{inM} =$ kW. Under-excited mode					

Power loss in motor armature winding, W

$$P_{elM} = I_a^2 R_a. \quad (5.2)$$

Motor power on the shaft, which it transmits to the synchronous generator, W

$$P_M = P_{inM} - P_{oM} - P_{elM}. \quad (5.3)$$

Torque on the motor shaft, N·m

$$M = \frac{30 \cdot P_M}{\pi \cdot n_{nM}} = 9,55 \frac{P_M}{n_{nM}}. \quad (5.4)$$

where  $n$  – is the engine speed, rpm.

Reactive power of synchronous generator GS, var

$$Q = 3U_s I_s \sin \varphi. \quad (5.5)$$

Active power of synchronous generator GS, W

$$P = 3U_s I_s \cos \varphi. \quad (5.6)$$

For calculations, use the phase voltage value, V:

$$U_s = \frac{U}{\sqrt{3}},$$

where  $U$  – linear voltage on the winding of the synchronous generator  $GS$ , V.

2. Build characteristics  $I_E(M)$  for the three values of  $\cos\varphi$  according to the table 5.1 in the general coordinate system (on the one graphic field).

3. Plot characteristics  $I_s(M)$ ,  $P(M)$ ,  $\cos\varphi(M)$  at  $I_E = \text{const}$  according to the table 5.2 in the general coordinate system (on the one graphic field).

4. Plot characteristics  $I_s(I_E)$ ,  $\cos\varphi(I_E)$ ,  $Q(I_E)$  at  $P = \text{const}$  according to the table 5.3 in the general coordinate system (on the one graphic field).

### Test questions

1. What are the conditions for the inclusion of  $SG$  on parallel work with the electrical network? How can you verify that these conditions are met?

2. What are the main areas of the  $U$ -shaped characteristics of a synchronous generator? How much power does the synchronous generator give in the overexcitation mode?

3. How much power does the synchronous generator  $SG$  give in the under-excitation mode?

4. How to transfer the synchronous generator  $SG$  from under-excited mode to over-excited mode?

5. Explain the definition of the boundary of stable operation on the  $U$ -shaped characteristic of a synchronous generator.

6. How can I adjust the  $SG$  reactive power?

7. How does the response of the armature of the synchronous generator change when the nature of the load on the network (active, capacitive, inductive) changes?

8. In what excitation mode (under-excitation mode or over-excitation mode) do synchronous generators usually work in power plants? Why?

## Laboratory work 6

### ANALYSIS OF THE DC GENERATOR CHARACTERISTICS

#### 6.1 The purpose of the work

The purpose of the laboratory work is to obtain skills of experimental work with DC machines. As an example students will study a DC generator through experimental analysis of its characteristics under independent excitation.

#### 6.2 Laboratory work plan

1. Starting the machine.
2. Registering no-load characteristics, load characteristic, external and regulatory characteristics of the DC generator under independent excitation.

#### 6.3 Description of the test setup

The basic scheme of the test stand is shown in Fig. 6.1, DC generator  $G$  is driven by a three-phase asynchronous motor  $M$ , which provides a virtually constant speed: it is almost equal to the nominal speed  $n_N$ .

The asynchronous motor is connected to a three-phase alternating current grid with a voltage of 220 V by an automatic switch  $QF1$  and magnetic contactor  $KM$ .

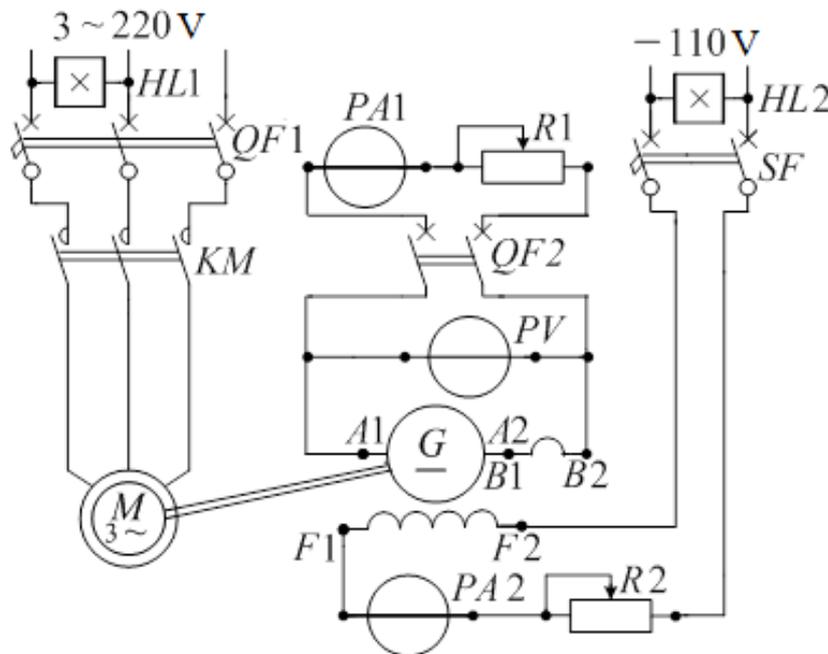


Figure 6.1 – Stand schematic diagram for DC generator investigation at independent excitation

The armature circuit of the generator  $G$ , which includes the armature winding  $A1-A2$  and the winding of the additional poles  $B1-B2$ , is connected to the automatic switch  $QF2$  and the load rheostat  $R1$  by its external outputs  $A1-B2$ . To measure armature voltage and current, the voltmeter  $PV$  and the ammeter  $PA1$  are included.

Under independent excitation of the DC generator (Fig. 6.1), the excitation winding uses the outputs  $F1-F2$  to connect to the 110 V DC generator by the automatic device  $SF$ .

### 6.4 Guidelines to the laboratory work performance

1. Get acquainted with the design and put down the rated data and parameters of the studied DC generator.

2. Analyze the DC generator at independent excitation.

Assemble the electric circuit of the setup for DC generator investigation at independent excitation according to the schematic diagram (Fig. 6.1) and show it to the teacher. Put the equipment into an initial state: the automatic devices  $QF1$ ,  $QF2$ ,  $SF$  and contactor  $KM$  are off; the rheostats  $R1$  and  $R2$  are completely activated, i.e. they provide maximum resistance. Turn on the automatic device  $QF1$  and then press the button  $START$  of the contactor  $KM$ . This activates the asynchronous motor and makes the generator rotate at the rated speed  $n_N$ .

2.1 Register the DC generator no-load characteristics at independent excitation, i.e. the dependence  $U_0(I_E)$  at  $I_a = 0$  and  $n = n_N$ , where  $U_0$  is the voltage at the outputs of the armature circuit, which in this mode is equal to the EMF  $E$  of the armature winding. To meet the condition  $I_a = 0$ , the generator's armature circuit stays open using the automatic device  $QF2$ . Make the first measurement when the automatic device  $SF$  is off, which makes  $I_E = 0$ . Put down the readings of the voltmeter  $PV$  into the table 6.1.

Table 6.1 – Parameters of the DC generator no-load characteristic  $U_0(I_E)$  at  $I_a = 0$ .

Parameters	Ascending branch							Descending branch							
$I_E, A$															
$U_0, V$															

After that, register two branches of the characteristic: ascending and descending ones. Turn on the automatic device  $SF$  and slowly increase the excitation current with the rheostat  $R2$  from  $I_E = 0$  to the value  $I_E$  at which  $U_0 = 1,2 \cdot U_N$ , then gradually decrease it to  $I_E = 0$ . Change  $I_E$  only in one direction (increasing or decreasing) to avoid partial hysteresis. Make 6-8 measurements using devices  $PA2$  and  $PV$  for each branch in the determined range of  $U_0$  change and put down the results into the table 6.1.

2.2. Determine the parameters of the load characteristic  $U(I_E)$  at  $I_a = I_{aN}$  and  $n = n_N$ . This characteristic differs from the no-load characteristic in that it is registered

in the presence of current  $I_a$  in the armature circuit. Fix the rheostat  $R2$  in the position which corresponds to the minimum possible value of  $I_E$  (using the device  $PA2$ ). Turn on the automatic device  $QF2$  and completely disengage the load rheostat  $R1$  (such a mode corresponds to a generator's short circuit mode). Using the rheostat  $R2$ , increase  $I_E$  up to the value when  $I_a = I_{aN}$ , and put down the readings of the devices  $PA2$  and  $PV$  into table 6.2.

Table 6.2 – Parameters of the DC generator load characteristic  $U(I_E)$  at  $I_a = I_{aN} = \text{const}$ .

$I_E, A$								
$U, V$								

Gradually engage the load rheostat  $R1$  simultaneously increasing  $I_E$  to maintain  $I_a = I_{aN}$ . The ultimate maximum value of armature voltage is  $U = 1,1U_N$ . Put down the measurements of 6-8 points also into table 6.2.

2.3. Determine the parameters of the DC generator's external characteristic at  $I_E = \text{const}$ .

Simultaneously regulate the rheostats  $R1$  and  $R2$  to load the generator up to the current value of  $I_a = I_{aN}$  at the armature voltage  $U = U_N$ . After that, without changing the excitation current  $I_E$ , change the DC generator load in the armature circuit up to the current value  $I_a = 1,2 I_{aN}$  using the rheostat  $R1$ . Register this measurement and put down the readings of the devices  $PA1$  and  $PV$  into table 6.3.

Table 6.3 – Parameters of the external characteristic of the DC generator  $U(I_a)$  at  $I_E = \text{const}$ .

$I_a, A$								
$U, V$								

Gradually decrease the load using the rheostat  $R1$  without changing the excitation current  $I_E$  to reach  $I_a = 0$ . Make 6-8 measurements and put them down into table 6.3.

2.4. Determine the parameters of the regulatory characteristic  $I_E$  at  $U = U_N = \text{const}$ .

You should register the parameters starting from the generator's no-load operation ( $I_a = 0$ ). To do this, use the automatic device  $QF2$  to switch off the rheostat  $R1$ , which is the DC generator's load. Using the rheostat  $R2$ , set the excitation current to such a value that will provide  $U = U_N$ ; put down the readings of the device  $PA2$  into table 6.4. After that provide the maximum resistance of the rheostat  $R1$  and switch on the automatic device  $QF2$ . Use the rheostat  $R1$  to increase the load current up to

$I_a = 1, 2 I_{aN}$ , , make 6-8 measurements and put down the readings of the devices *PA1* and *PA2* into table 6.4. Meanwhile, keep the voltage  $U$  stable by regulating the excitation current using the rheostat  $R2$ . Disconnect the assembly from the mains. To do this, stitch off the automatic devices *QF1* and *QF2*.

Table 6.4 – Parameters of the regulatory characteristic  $I_E(I_a)$  at  $U = U_N$

$I_a, A$	0							
$I_E, A$								

### 6.5 Test results processing

1. Make a plot of the characteristics:

a) using data from tables 6.1 and 6.2, plot the no-load characteristic  $U_0(I_E)$  and load characteristic  $U(I_E)$  in one coordinate grid; the no-load characteristic must have an ascending and descending branches, to which you should add an estimated characteristic, which is assumed as a middle line between the ascending and descending branches;

b) using data from tables 6.3 and 6.4, plot the generator's external characteristics  $U(I_a)$  at independent excitation;

c) using data from table 6.4, plot the generator's regulatory characteristic  $I_E(I_a)$ .

2. Determine the level of the generator's magnetic system saturation using the saturation coefficient

$$k_\mu = \frac{F_o}{F_\delta}, \quad (6.1)$$

where  $F_0$  is the magnetomotive force (MMF) which is necessary for driving the main magnetic flux through all parts of the machine's magnetic core;  $F_\delta$  is the MMF which is necessary to drive the magnetic flux only through the air gap.

For medium-saturated machines  $k_\mu = 1.2 \div 1.6$ . At  $k_\mu > 1.6$  the machine is highly saturated; if  $k_\mu < 1.2$  the machine is weakly saturated.

The coefficient  $k_\mu$  can be determined from the estimated no-load characteristic (curve 1 in Fig. 6.2), which in a different scale is the machine's magnetic characteristic  $\Phi_o(F_E)$ .

Through point A, which corresponds to the rated voltage  $U_N$ , draw the horizontal line AC to the intersection with the curve 1. As the air magnetic permeability is constant, then to determine  $F_\delta$  it is sufficient to draw the straight line 2, tangent to the

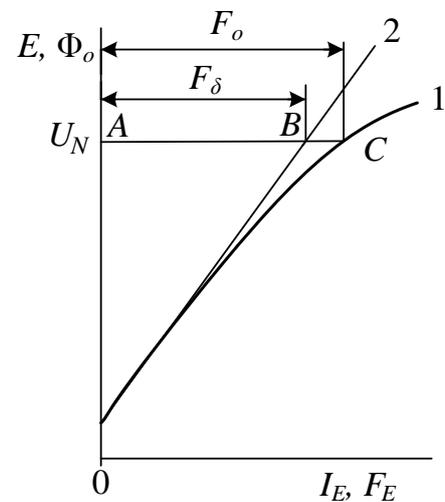


Fig. 6.2 – No-load characteristic

initial part of the no-load characteristic. This line will cut off the segment  $AB = F_\delta$  on the segment  $AC \cong F_0$ , so  $k_\mu = AC/AB$ .

3. Determine the generator's rated voltage change by percentage

$$\Delta U_N = \frac{U_o - U_N}{U_N} \cdot 100\%, \quad (6.2)$$

which according to the standards (GOST 183-84) is called voltage change at its terminals when the load changes from the rated value to zero, it being expressed as percentage of the rated voltage.

For non-compensating machines, i.e. those that do not have a compensating winding,  $\Delta U_N = 10 \div 15\%$ . To determine the voltage change, use the external characteristic at independent excitation of the generator.

4. Build a characteristic triangle.

To build a characteristic triangle, both an ascending branch of the no-load characteristic and load characteristic (for which an ascending branch is taken) must be built on the same plot. Starting from pint A on the load characteristic, which corresponds to the rated voltage, mark off vertically a segment, V:

$$AB = I_{aN} \cdot \Sigma R_a = I_{aN} \cdot \Sigma R_{a(75^\circ)} + 2\Delta U_b,$$

which characterize the voltage drop in the armature circuit and in the brush contact. Here  $\Delta U_b = 1\text{ V}$  is the voltage drop in one brush contact:  $\Sigma R_{a(75^\circ)}$  is the resistance of the armature winding copper and additional poles that reached the temperature of  $75^\circ\text{C}$ , which corresponds to the machine's heating, Ohm:

$$\Sigma R_{a(75^\circ)} = \Sigma R_a \frac{235 + 75}{235 + t_0}, \quad (6.7)$$

where  $\Sigma R_a$  is the total resistance of the armature windings and additional poles in a cool state, i.e. at an ambient temperature  $t_0 = 20^\circ\text{C}$ .

The horizontal segment CB corresponds to the demagnetizing MMF of armature reaction in the scale of the excitation current.

The difference between the horizontal legs of the triangles  $ABC$  и  $A_1B_1C_1$  (note that  $A_1B_1 = AB$ ) built on different sections of the characteristics allows understanding the influence of the machine's magnetic circuit saturation on the action magnitude of the lateral demagnetizing armature reaction.

Build characteristic triangles for  $I_E = (0.5; 0.8; 1.0; 1.1) I_{EN}$ .

## Test questions

1. Explain the design and operation principles of a direct current generator.
2. Explain the stand setup for the DC generator research.
3. Write down and explain the formula of an EMF generator.
4. How to register the generator's no-load characteristic?
5. Explain why the ascending and descending branches of the no-load characteristic split.
6. How to register load characteristic?
7. What is the armature reaction of a direct current machine?
8. How to build a characteristic triangle?
9. What is the external characteristic of a generator?
10. How to register the external characteristics of a generator at independent excitation?
11. What is the percentage change of a generator's voltage?
12. What is a regulatory characteristic of a generator and how to register it?

## Appendix to methodical instructions

Scan it



## LIST OF INFORMATION SOURCES

1. Stephen J. Chapman. Electric Machinery Fundamentals, McGraw-Hill Education, 2011. – 704 p.
2. Вольдек А.И. Электрические машины: учебник. – Л.: Энергия, 1979.– 816 с.
3. Мілих В.І., Шавьолкін О.О. Електротехніка, електроніка та мікропроцесорна техніка: підручник. За ред. В.І. Мілих. – К.: «Каравела», 2007. – 688 с.
4. Кацман М.М. Электрические машины: учебник. – М.: Высшая школа, 1990, 2000, 2006.
5. Мілих В.І. Літерні позначення величин та параметрів електричних машин. Методичні вказівки до використання в навчальному процесі кафедри «Електричні машини».– Х.: НТУ «ХП», 2007.– 31 с.

## CONTENTS

INTRODUCTION.....	3
1. Laboratory work 1. DETERMINING THE POLARITY OF THE WINDINGS OF THE THREE-PHASE TRANSFORMER .....	4
2. Laboratory work 2. ANALYSIS OF PARALLEL OPERATION OF THREE-PHASE TWO-WINDING TRANSFORMER .....	9
3. Laboratory work 3. MECHANICAL CHARACTERISTICS OF ASYNCHRONOUS MACHINE.....	14
4. Laboratory work 4. ANALYSIS OF THE SYNCHRONOUS GENERATOR, WHICH WORKS ON AUTONOMOUS LOAD .....	19
5. Laboratory work 5. ANALYSIS OF THE SYNCHRONOUS GENERATOR IN PARALLEL WORK WITH THE ELECTRICAL NETWORK.....	26
6. Laboratory work 6. ANALYSIS OF THE DC GENERATOR CHARACTERISTICS.....	33
LIST OF INFORMATION SOURCES.....	39

Навчальне видання

**Методичні вказівки**  
до лабораторних робіт  
по курсу «Електричні машини»

для іноземних студентів  
навчально-наукового інституту енергетики, електроніки та  
електромеханіки

У к л а д а ч і :

ШЕВЧЕНКО Валентина Володимирівна, ДУНЄВ Олексій Олександрович,  
ШИЛКОВА Лариса Василівна, ЛАЗАРЄВА Ольга Ярославна

Відповідальний за випуск *доц. Єгоров А.В.*

Роботу до видання рекомендував *проф. Любарський Б.Г.*

План 2019 р., поз.182

Підп. до друку 21.06.2019. Формат 60×84 1/16. Папір офісний. *Riso* – друк.

Гарнітура Таймс. Ум. друк. арк. 1,7. Наклад 50 прим.

Зам. № . Ціна договірна

---

Видавець і виготовлювач: ФОП Панов А. М.  
Свідоцтво серії ДК №4847 від 06.05.2015 р.  
м. Харків, вул. Жон Мироносиць, 10, оф. 6  
тел.+38(057)714-06-74, +38(050) 976-32-87  
[copy@vlavke.com.ua](mailto:copy@vlavke.com.ua), <http://vlavke.com.ua>