Laboratory work 6

STUDYING OF A SINGLE PHASE TRANSFORMER

6.1. Formulation of the problem

The purpose of the work is to consolidate theoretical knowledge about the structure and principle of the transformer and obtain practical skills, calculations and experimental studies of its main parameters and performance characteristics.

Tasks of the lesson are tests of single-phase transformer in no-load mode (NL), load mode (from NL to rated load) and experimental short circuit (SC) for the purpose of subsequent determination of basic parameters and obtaining of its operational characteristics.

6.2. Object of study

The object of the study is a single-phase transformer with known rated data given on the bench.

The conventional image of the transformer T, which is explored, and the scheme for conducting experiments are shown in Fig. 6.1.
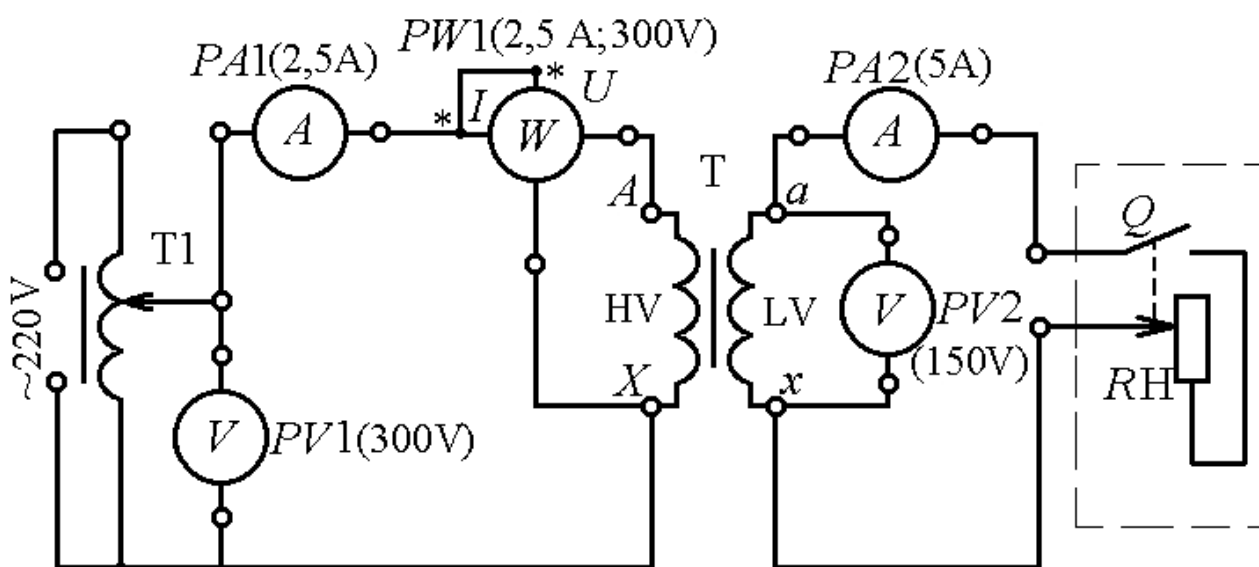

Figure 6.1

The high-voltage winding (HV) or the primary winding of the transformer T is connected to the laboratory autotransformer (LATR) T1, which, in turn, is activated in the AC network with an RMS voltage value of 220 V. A load connected to the lower voltage (LV) winding or the secondary winding is connected – the RH rheostat with the built-in contact Q.

Measuring instruments, their functional purpose and the designation of measured values, are given in Table 6.1.

Table 6.1

Appointment of the device	Measurement value	Designation of quantities
$PV1$	Voltage of the primary winding	U_1
$PA1$	Primary winding current	I_1
$PW1$	Active power coming from the network to the primary winding of the transformer	P_0, P_1, P_K
$PV2$	Voltage of the secondary winding and load	U_2
$PA2$	Load current of the secondary winding	I_2

Measuring instruments, their functional purpose and the designation of measured values, are given in Table 6.1.

6.3. The order of the experiment execution

6.3.1. Record the rated data of the transformer in Table 6.2, where S_r is total power; U_{1r}, U_{2r}, I_{1r}, I_{2r} are the rated voltages and currents of the windings.

6.3.2. Select the devices according to the rated data of the transformer, as shown in Table 6.2.

Table 6.2.

S_r	U_{1r}	U_{2r}	I_{1r}	I_{2r}
кVA	V	V	A	A

6.3.3. Assemble a basic electrical circuit for Fig. 4.1.

6.3.4. Bring the equipment to the initial state: set the LATR to zero; set the RH rheostat to the extreme left position by turning the knob counterclockwise to the stop, which will ensure that the contact Q is unlocked; switches of devices – in a position that will provide the limits of measurements that exceed the given currents and voltage of the transformer T (Table 4.1).

6.3.5. Run the experiment in NL mode. To do this, with the open circuit of the secondary winding of the transformer, apply voltage to the LATR and use it to install the clamps of the primary winding, the rated voltage $U_1 = 220$ V. Measured values of I_{10}, P_0 and U_{20} you will write in Tab.4.3 (adding the index "0" corresponds to the designation the values of NL).

Table 6.3

Given	Measured				Calculated					
$U_{10}=U_{1r}$	I_{10}	P_0	U_{20}	I_{20}	N	Z_0	R_0	X_0	i_x	P_m
V	A	W	V	A	-	Ohm	Ohm	Ohm	%	W
220				0						

6.3.6. Conduct an experiment in load mode. The initial state for the first experiment is a previous mode NL, the data of which is written in Table 6.4. When adjusting the load you are guided by the value of current I_2, which is set with a constant step, equal to approximately 1 A in the range from NL to I_{2r}. By supporting the constant voltage $U_{10} = 220$ V across the primary winding, install with the RH rheostat as the load of the transformer in the recommended range and measure in 4-5 fixed positions of the RH. Write down the measurement results in Table 6.4.

6.3.7. Conduct an experiment in SC mode, strictly adhering to the sequence of the actions specified below, as the deviation from it can lead to an accident or the output of the equipment from the working condition.

First, disconnect the LATR from the voltage source of 220 V. Secondly, bring the necessary equipment to its initial state, as indicated in clause 6.3.4.

After that, turn on the LATR for a voltage of 36 V and check with voltmeter PV1 that the voltage at the input LATR is zero.

Table 6.4

Given	Measured				Calculated			
$U_{10}=U_{1r}$	I_1	P_1	U_2	I_2	β	$\cos\varphi_1$	P_2	η
V	A	W	V	A	-	-	W	-
220								
220								
220								
220								
220								

Turn off the power supply temporarily, short circuit the secondary winding of the transformer T with a conductor that connects parallel to the RH to its clamps.

Turn on the LATR power supply and slowly increase the current I_1 slowly in the primary winding of the transformer T to the value of I_{1r}, because the criterion for the short-circuit mode is the rated current of this winding. In this position, make the

measurements U_{1k}, P_k and I_{2k} and enter the results in Table 6.5 (the index "SC" corresponds to the short-circuit).

Disconnect the power supply and turn the equipment to its initial state.

Table 6.5

Given	Measured			Calculated								
$I_{1SC}=I_{1r}$	U_{1SC}	P_{SC}	$I_{2к}$	n_1	u_{SC}	I_{SC}	Z_{SC}	R_{SC}	X_{SC}	$\cos\varphi_{SC}$	φ_{SC}	P_E
A	V	W	A	-	%	A	Ohm	Ohm	Ohm	-	degree	W

6.4. Processing of experimental results and preparation of a report on laboratory work

6.4.1. According to the results of experiments NL and SC you must determine the following parameters of the transformer:

n – voltage transformation factor,
$$n = \frac{U_{10}}{U_{20}};$$

Z_0 – impedance in NL,
$$Z_0 = \frac{U_{10}}{I_{10}};$$

R_0 – resistance in NL,
$$R_0 = \frac{P_0}{I_{10}^2};$$

X_0 – inductance in NL,
$$X_0 = \sqrt{Z_0^2 - R_0^2};$$

i_{nl} – current of NL as a percentage of I_r,
$$i_{nl} = \frac{I_{10}}{I_{1r}} \cdot 100\%;$$

P_m – magnetic loss of power in the steel core,
$$P_m = P_0;$$

n_1 – current transformation coefficient,
$$n_1 = \frac{I_{2SC}}{I_{1SC}};$$

u_{SC} – voltage of SC in percentage from U_1,
$$u_{SC} = \frac{U_{1SC}}{U_{1r}} \cdot 100\%;$$

I_{SC} – emergency current SC at $U_1 = U_{1r}$,
$$I_{SC} = I_{1r}\frac{U_{1r}}{U_{1r}};$$

Z_{SC} – impedance in SC,
$$Z_{SC} = \frac{U_{1SC}}{I_{1SC}};$$

R_{SC} – resistance in SC,
$$R_{SC} = \frac{P_{SC}}{I_{1SC}^2};$$

X_{SC} – inductance in SC,
$$X_{SC} = \sqrt{Z_{SC}^2 - R_{SC}^2};$$

$\cos\varphi_{SC}$ – power coefficient in SC,
$$\cos\varphi_к = \frac{P_{SC}}{U_{1SC}I_{1SC}};$$

φ_{SC} – phase shift angle between current and voltage in SC mode,

$$\cos\varphi_{SC} = \arccos\frac{P_{SC}}{U_{1SC}I_{1SC}};$$

P_E – electrical power consumption in the transformer windings,

$$P_E = P_{SC}\left(\frac{I_1}{I_{1SC}}\right)^2.$$

Calculated transformer parameters enter in Table 4.3, 4.4 and 4.5.

6.4.2. According to the results of measurements in load mode (see Table 4.4), calculate the values:

$$\beta = \frac{I_2}{I_{2nom}},$$

where β – load coefficient;

$$\cos\varphi_1 = \frac{P_1}{U_1 I_1},$$

where $\cos\varphi_1$ – power factor of the transformer with load;

$$P_2 = U_2 I_2 \cos\varphi_1,$$

where P_2 – active load power (taking into account the active nature of the load $\cos\varphi_1 = 1$);

η – coefficient of efficiency of the transformer $\qquad \eta = \dfrac{P_2}{P_1}.$

The results of calculations throughout the load range of the transformer, enter in Table 5.4.

6.4.3. According to the calculations of Table 5.4, draw the operational characteristics: $U_2(\beta)$ – external (load) characteristic; the dependence of $I_1(\beta)$ and $\cos\varphi_1(\beta)$, as well as the characteristic of the efficiency $\eta(\beta)$. Draw the specified characteristics by using the common axis β, but with individual axes and scales for the specified parameters.

Control questions

1. Explain the structure and the principle of the operation of a single-phase transformer.

2. What is the transformation ratio and how does it connect the voltages and currents of the transformer windings?

3. What loss of power are allocated in the transformer during its operation under load, what is their physical nature and whether they depend on the value of the load of the transformer?

4. Write the equation of electrical equilibrium of the voltages and currents in the transformer windings and explain the physical content of the quantities included in these equations.

5. How did you conduct the NL and SC experiments of a single-phase transformer and what particular transformer parameters can be determined from these experiments?

6. How did you conduct the load mode of the transformer and what characteristics are obtained from the data of this experiment?

7. What are the typical graphs of these characteristics and what explains their character?

Laboratory work 7

STUDYING OF A DIRECT CURRENT GENERATOR
WITH INDEPENDENT EXCITATION

7.1. Formulation of the problem

The purpose of the work is to consolidate theoretical knowledge about the structure and operation principle of the direct current generator (CDG) and to obtain practical skills in experimental studies of the characteristics of the CDG.

Tasks of the lesson are an experimental study of the properties of the CDG with independent excitation by removing and analyzing no-load, external and regulatory characteristics.

7.2. Object of study

The object of the study is a CDG with independent excitation, the rated data of which are given on the laboratory bench.

The removal of characteristics of the generator being investigated is carried out at the installation, the electric circuit of which is shown in Fig. 7.1.

The armature (A) of the CDG is rotated by an cage induction motor (CIM), the rotor (R) of which is connected by a mechanical coupling (M) to the shaft (S) of the investigated generator. The stator winding is connected in star ("Y"). The start of phase windings of CIM (C_1, C_2, C_3) are connected to a three-phase AC network (A-B-C) with a linear voltage of 380 V.

The generator excitation winding (EW) through the clamps F1-F2 is powered by a direct current from the rectifier (VA), which, in is turn, is powered by an AC voltage of 220 V (phase voltage of the same three-phase network is used) through the laboratory autotransformer LATR (T). It allows you to slowly adjust the current of the excitation winding from zero to the desired value.

A load of the generator is the rheostat RH with a built-in switch Q1, which in one of the extreme positions provides opening of the load circuit (by turning the handle of the rheostat counter clockwise to the stop). The RH rheostat is attached to the armature clamps A1-A2 and in the same circuit an ammeter PA1 is inserted, which simultaneously measures the load current of the I_N and the current of the armature $I_a = I_н$. The voltage across the clamps of the armature U is measured by the voltmeter PV, and the current in the excitation winding is measured by the milliammeter PA2. The limits of the values measured by the instruments are shown in Fig. 7.1.
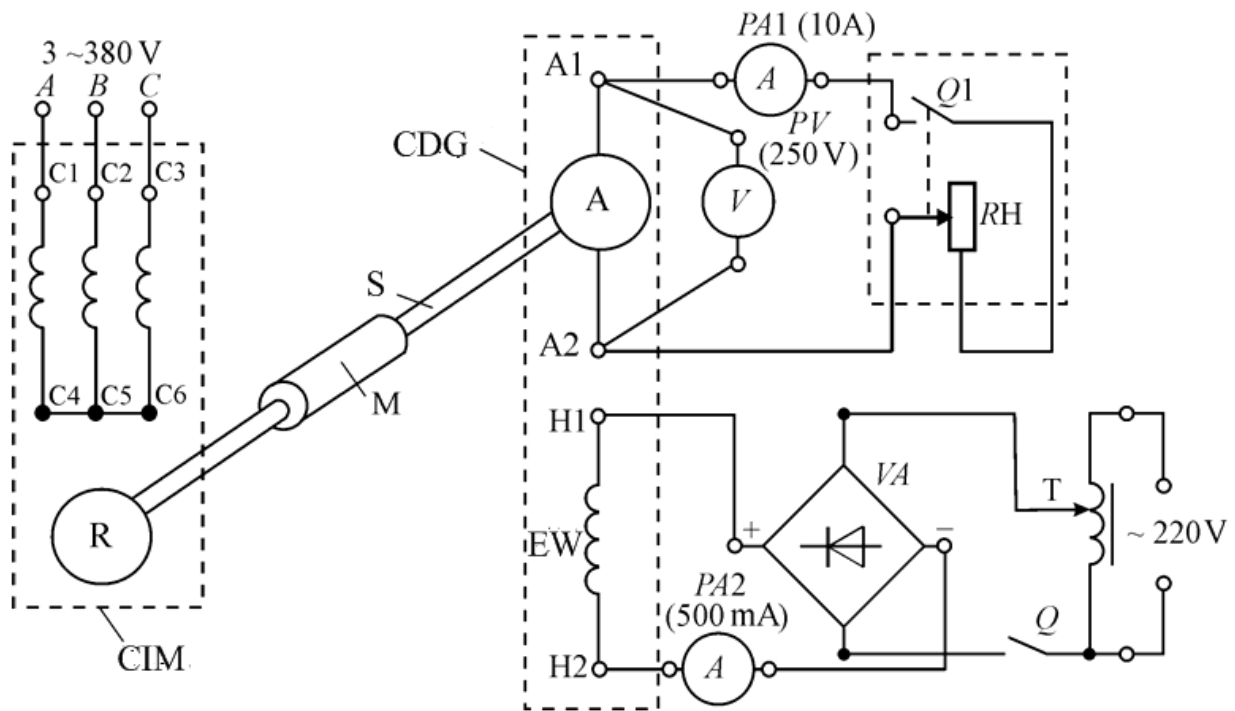
Figure 7.1

7.3. The order of the experiment execution

7.3.1. Check the rated data of the generator that is being investigated, and add them in Table 7.1.

7.3.2. Assemble a circuit for conducting experiments according Fig. 7.1.

Table 7.1

P_{2r}, W	U_r, V	I_{ar}, A	I_{er}, A	n_r, rpm.

7.3.3. Before starting each experiment, set LATR to zero.

7.3.4. Read off the open-circuit generator characteristic at NL and $I_a = 0$. To do this, start the BP, shut down the switch Q and apply voltage to the LATR T. Set the current of the excitation winding $I_e = 0$, fix the voltage U voltmeter and bring it in Table 7.2. Read off the ascending branch of open-circuit characteristic. For this which increase gradually the winding current via AV to transformer T 50 mA increments to a maximum value $I_{e\,max}$ by which the voltage at the terminals of the armature $U = E$ becomes equal $(1,05...1,1)U_r$. Changes in the withdrawal of characteristics conduct monotonously (strictly in one direction). Make the measurement results in Table 7.2. After that, remove the descending branch at the same values of the current of the excitation winding, reducing the current of this winding to zero. The results of measurements are also included in Table 7.2.

Do not turn off the power of the circuit and proceed to the removal of the following characteristics.

Table 7.2. $n_r =$ _____rpm; $I_a = 0$

	I_e, mA	0	50	100	150	200	250	$I_{e\,max}$
$U = E$, V	Ascending branch							
	Descending branch							

7.3.5. Reade off the load characteristic of the DC generator $U(I_n)$ at the rated I_{EW}, where I_L is the load current equal to the current of the armature I_a under independent excitation ($I = I_a$). Set with LATR T the rated current of the excitation winding. Set the rheostat RH knob to the leftmost position that responds $R_H \to \infty$. Secure the PV and PA1 devices, respectively, with the open-circuit speed $U_0 = E$ and the current of the armature $I_a = 0$. Enter measurement data in Table 7.3. Decreasing load resistance R_L by handle of RH, load the generator to the value of the current of the armature $I_a = (1{,}05...1{,}2)I_{ar}$. Take 6-7 measurements and add the results in Table 7.3.

Table 7.3. $I_{er} =$ _____mA; $n_r =$ _____rpm

$I_L = I_a$, A	0					
U, V	$U_0=$					

7.3.6. Read off the regulator characteristic $I_e(I_L)$ for $U_r =$ const and n_r. To do this, use the handle of the resistor RH to set the load resistance $R_L \to \infty$ ($I_a = 0$), but with the help of LATR T, increasing the current in the excitation winding, set the rated voltage to the anchor U_r. Enter these results in Table 7.4. By reducing the value, load the DC generator with a uniform step I_L to the value $I_a = I_{ar}$. Under these conditions, with the help of LATR T, change the current of the excitation winding I_e so that at each value of the load current on the armature A1-A2 clamps the voltage remains constant and equal U_r. Spend 5-7 measurements at different values I_L. Enter data in Table 7.4.

Table 7.4. $U_r =$ _____V; $n_r =$ _____rpm

$I_L = I_a$, A	0					
I_e, mA						

7.4. Processing of the results of experiments and design work

7.4.1. According to the data of Tables 7.2, 7.3, 7.4, draw the characteristics of the CDG: $U(I_e)$, $U(I_L)$, $I_e(I_L)$.

Using the external characteristic $U(I_L)$, determine the rated percentage change in the armature voltage $\Delta U_r = \dfrac{U_0 - U_r}{U_r} \times 100\%$.

Control questions

1. What is the design of a CDG?
2. Explain the principle of the CDG operation with independent excitation.
3. Explain the purpose of the commutator in the CDG.
4. Write the main formulas that characterize the CDG operation.
5. Why with load current increasing does voltage across the armature decrease?
6. Explain the nature of the change in no-load characteristics.
7. Draw the regulation characteristic of the CDG with independent excitation and explain the nature of its change.
8. What kinds of power loss occur in the generator in the process of converting mechanical energy into electric?

Laboratory work 8

STUDYING OF A THREE-PHASE CAGE INDUCTION MOTOR

8.1. Formulation of the problem

The purpose of the work is to consolidate theoretical knowledge about the design and operation principle of a three-phase cage induction motor (CIM) or three-phase induction motor with squirell cage rotor, to obtain practical skills of calculation and to study the parameters and characteristics of CIM.

The objectives of the lesson are a studying of a three-phase CIM. The study removes its mechanical and performance characteristics.

The experimental characteristics of IM are compared with the calculated ones performed on the catalog data.

8.2. Object of study

The object of the study is a CIM with rated data shown on the bench. The electrical circuit for conducting the experiment is shown in Fig. 8.1, where the required measurement limit is shown near each electric meter.
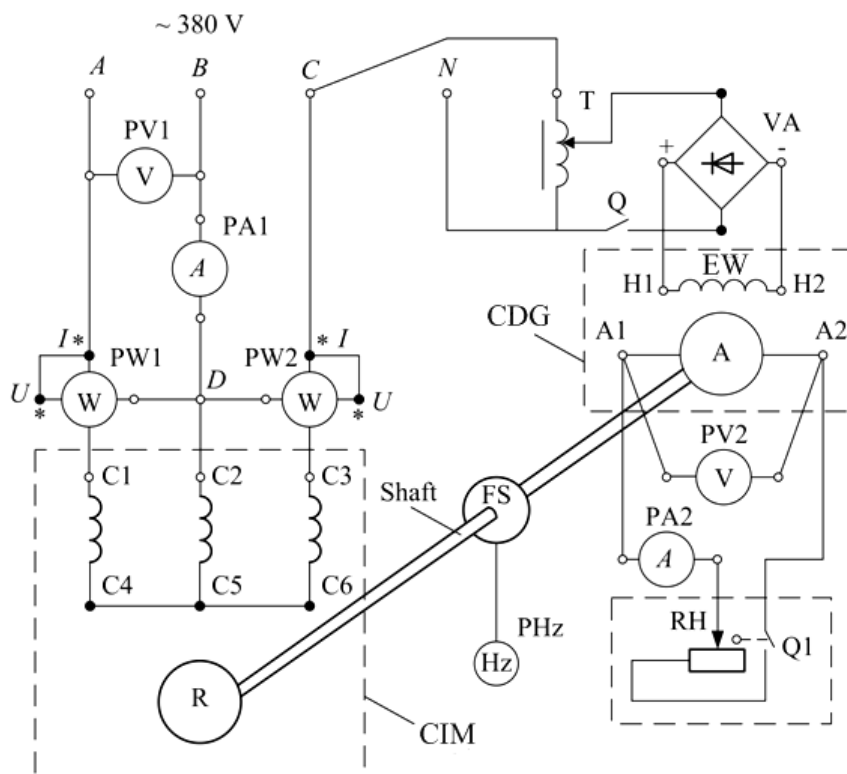

Figure 8.1

The motor is powered by a three-phase line with a voltage of 380 V. In this case, the stator winding is connected in wye. Appropriate devices are switched on in the circuit to measure the required values. The designations of these devices and the quantities they measure are given in Table 8.1.

Table 8.1

Designation of the device in the diagram	Measured value	Indication of the magnitude measured
PV	Linear voltage of stator winding	U_1
*PA*1	Linear current of CIM stator winding	I_1
PH$_z$	Rotation frequency of CIM rotor	n_2
PW	Phase power consumed from the network	P_{ph}
*PA*2	Armature current of direct current generator (CDG)	I_G

The braking torque on the induction engine shaft is created by an independent excitation DC generator (CDG). Thus, the torque on the CIM shaft is equal to the brake torque of CDG. The CDG and CIM shafts are mechanically connected by a clutch. The brake torque is changed by changing the resistance of the RH load rheostat engaged in the armature of the circuit.

The CDG excitation winding is powered by an adjustable DC source. The CDG excitation current is changed by the T1 LATR, the secondary rectifier of which is enabled by the rectifier VA. The LATR is connected to the phase C of three-phase circuit. The rotor speed of CIM is measured by a digital tachometer (HZ) from the frequency sensor (FS) mounted on the CIM shaft.

8.3. The order of the experiment execution

8.3.1. Record the CIM rated data in Table 8.2.

Table 8.2.

P_{2r}	U_{1r}	I_{1r}	f_1	n_1	n_{2r}	η_r	$\cos\varphi_{1r}$	λ_m	λ_{st}	λ_i
kW	W	A	Hz	rpm	rpm	-	-	-	-	-

The table shows:
P_{2r} – useful mechanical power on the IM shaft;
U_{1r} – linear CIM voltage;
I_{1r} – linear CIM current;
f_1 – frequency of network voltage;
n_1 – the number of revolutions of the magnetic field;
n_{2r} – rated rotor speed;
η_r – coefficient of performance;
$\cos\varphi_{1\,r}$ – motor power factor;

$\lambda_m = M_{max} / M_r$ – motor overload capacity;

$\lambda_{st} = M_{start} / M_r$ – multiplicity of starting torque;

$\lambda_i = I_{1start} / I_{2r}$ – frequency of starting current;

M_r, M_{max}, M_{start} – respectively, rated, maximum and starting torques on the shaft of the IM;

I_{1r}, I_{1start} – respectively, the rated and the starting currents of IM.

8.3.2. Assemble the electric circuit according Fig. 8.1.

8.3.3. Set the LATR to zero. Set the RH rheostat handle to the far left, which corresponds to no-load mode of the DC generator armature winding circuit. Start the CIM by turning on the three-phase 380V AC power source.

8.3.4. Use the LATR slowly to increase the excitation winding current of the DC generator until you reach the rated voltage across the armature of the CDG U_{Gr}.

8.3.5. By changing the load rheostat RH with the load current of the CDG I_L from zero to the rated value at intervals specified by the lecturer, clear the readings of all devices and the measurement results are not included in the Table 8.3. Increasing the current in the winding of the CDG armature, increases the torque of the CIM shaft, respectively, the CIM rotation decreases.

Fill in the "measured" columns of the Table 8.3.

Table 8.3

Measured							Calculation							
CIM					CDG									
U_1	I_1	n_2	P'	P''	U_G	I_G	P_{1E}	P_{2G}	η_G	$P_{1G} = P_{2E}$	M_2	S	η_E	$\cos\varphi_1$
V	A	rpm	W	W	V	A	W	W	-	W	N·m	-	-	-

8.4. Processing the results of the experiment

8.4.1. Make the necessary calculations of the values given in Table 8.3 in the calculated columns, based on the following relationships:
active power supplied from the network to the CIM,
$$P_{1E} = P' + P'';$$
generator power output (RH rheostat)
$$P_{1E} = U_G I_G;$$
Mechanical power supplied to the generator from the CIM

$$P_{1G} = \frac{P_{2G}}{\eta_G},$$

where η_r is determined by the curve $\eta_r\,(P_{2G})$ date shown on the laboratory bench for each P_{2G} value. You have to draw an efficiency curve $\eta_r\,(P_{2G})$

Mechanical power is given to the generator by CIM

$$P_{2E} = P_{1G};$$

Torque $M_2 = 9,55\dfrac{P_{2E}}{n_2}$, where P_{2E} measured in watts and n_2 in rpm;

slip $\qquad s = \dfrac{n_1 - n_2}{n_1};$

CIM efficiency $\qquad \eta = \dfrac{P_2}{P_1};$

power factor $\quad \cos\varphi_1 = \dfrac{P_1}{\sqrt{3}\cdot U_1\cdot I_1}.$

8.4.2. Determine the rated, maximum and starting torques, rated and critical slip and critical speed according to the formulas below, and record the results in Table 8.4:

$$M_{\mathrm r} = 9,55\frac{P_{2\mathrm r}}{n_{2\mathrm r}}; \qquad M_{\max} = \lambda_m M_{\mathrm r}; \qquad M_{\mathrm{Start}} = \lambda_{\mathrm{st}} M_{\mathrm r};$$

$$s_{\mathrm r} = \frac{n_1 - n_{2\mathrm r}}{n_1}; \qquad s_{\mathrm{cr}} = s_{\mathrm r}\left(\lambda_m + \sqrt{\lambda_m^2 - 1}\right); \qquad n_{2\mathrm{cr}} = n_1(1 - s_{\mathrm{cr}}).$$

Table 8.4

$M_{\mathrm r}$	$M_{\max}$	M_{start}	$s_{\mathrm r}$	s_{cr}	n_{2cr}
N·m	N·m	N·m	-	-	rpm

8.4.3. Draw an approximate mechanical characteristic $n_2(M_2)$ for the CIM by the example of Fig. 8.2 on points a, b, c, d with coordinates a $(0, n_1)$, b $(M_{2\,r}, n_{2\,r})$, c $(M_{2\,r}, n_{2\mathrm{cr}})$, d $(M_{2\mathrm{Start}}, 0)$, using the data in Table 8.2 and 8.4.

Compare the results of the experiment with the calculation

8.4.4. Draw an approximated mechanical characteristic for the CIM by the example of Fig. 8.2, and at points a, b, c, d with coordinates a $(0, n_1)$, b $(M_{2\mathrm r}, n_{2\mathrm r})$, c $(M_{2\max}, n_{2\mathrm{cr}})$, d $(M_{2\mathrm{start}}, 0)$, using the data in Table 8.1 and 8.3. Compare the results of the experiment with the calculation.

8.4.5. Draw for the induction motor an estimated approximation of the torque dependence on the slip $M_2\,(S)$ for the example of Fig. 8.5, b at points 0, a, b, c with

coordinates a (S_r, M_{2r}), b (S_{cr}, M_{2max}), c (1, M_{2start}). Compare the results of the experiment with the calculation.

8.4.4. Draw an approximated mechanical characteristic (2 2 M n) for the CIM by the example of Fig. 8.2, and at points a, b, c, d with co-ordinates a (0, n_1), b (M_{2r}, n_{2r}), c (M_{2max}, n_{2cr}), d (M_{2start}, 0), using the data in Table 8.1 and 8.3. Compare the results of the experiment with the calculation.

8.4.5. Draw for the induction motor an estimated approximation of the torque dependence on the slip M_2 (S) for the example of Fig. 8.5, b at points 0, a, b, c with coordinates a (S_r, M_{2r}), b (S_{cr}, M_{2max}), c (1, M_{2start}). Compare the results of the experiment with the calculation.
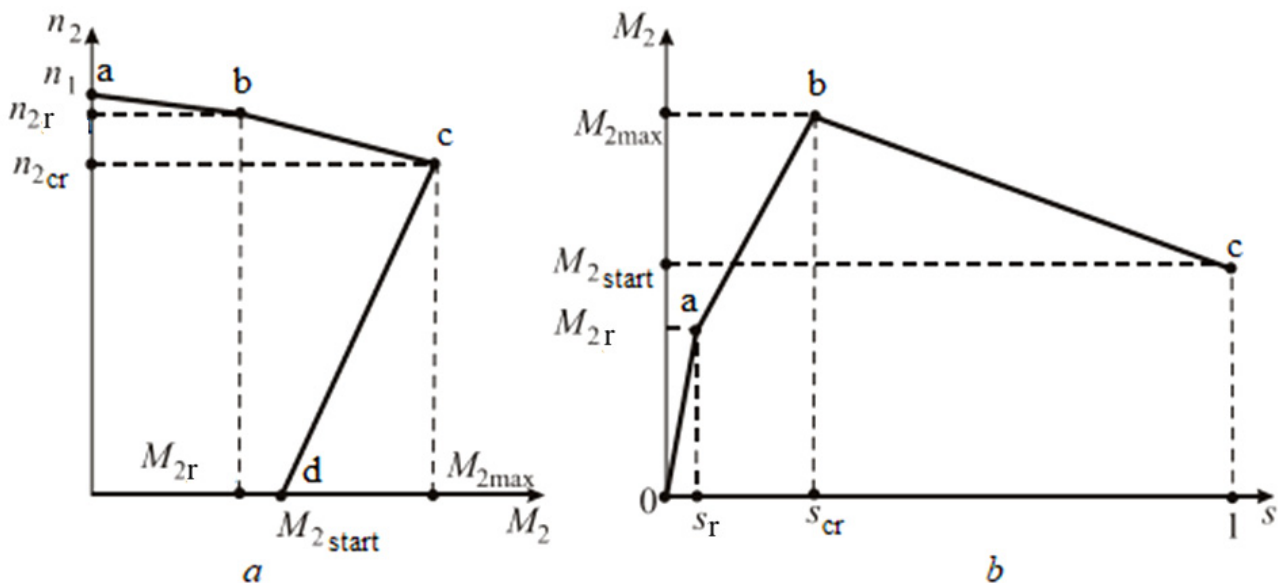

Figure 8.2

Control questions

1. Explain the design of a three-phase cage induction motor (CIM) and the principle of its functioning.

2. What conditions provide for the creation of a rotating magnetic field in a CIM? What formula determines the speed of this field?

3. Explain the difficulties encountered when starting a three-phase CIM and what are the possibilities to overcome these complications in practice?

4. What power loss occur in a CIM during its operation?

5. What is called the slip of a CIM? What expression does it define and to what extent does it change when an electric machine is running in motor mode?

6. How does the magnitude of the supply voltage affect the torque of a CIM?

7. Give the mechanical characteristics of a CIM, specify the characteristic points: no-load, rated load, maximum and starting torques.

8. Give and explain the appearance of mechanical characteristics of a three-phase CIM at different values of the supply voltage.

9. Under what conditions does a CIM run steadily and which section of the mechanical characteristic meets this condition?

10. What are the methods for adjusting the CIM speed?