MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE

NATIONAL TECHNICAL UNIVERSITY
«KHARKIV POLYTECHNIC INSTITUTE»

CALCULATION OF PARAMETERS AND CHARACTERISTICS OF ELECTROTECHNICAL DEVICES

METHODICAL INSTRUCTIONS FOR THE CALCULATION AND GRAPHIC WORK ON ELECTRICAL ENGINEERING

Kharkiv

2024

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Reviewer is Oleksandr Sereda, Doctor of Engineering, professor, National Technical University «Kharkiv Polytechnic Institute»

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INTRODUCTION

This publication is dedicated to calculation and graphic work from the discipline "Electrical engineering" on the topic "Calculation of parameters and characteristics of electrotechnical devices".

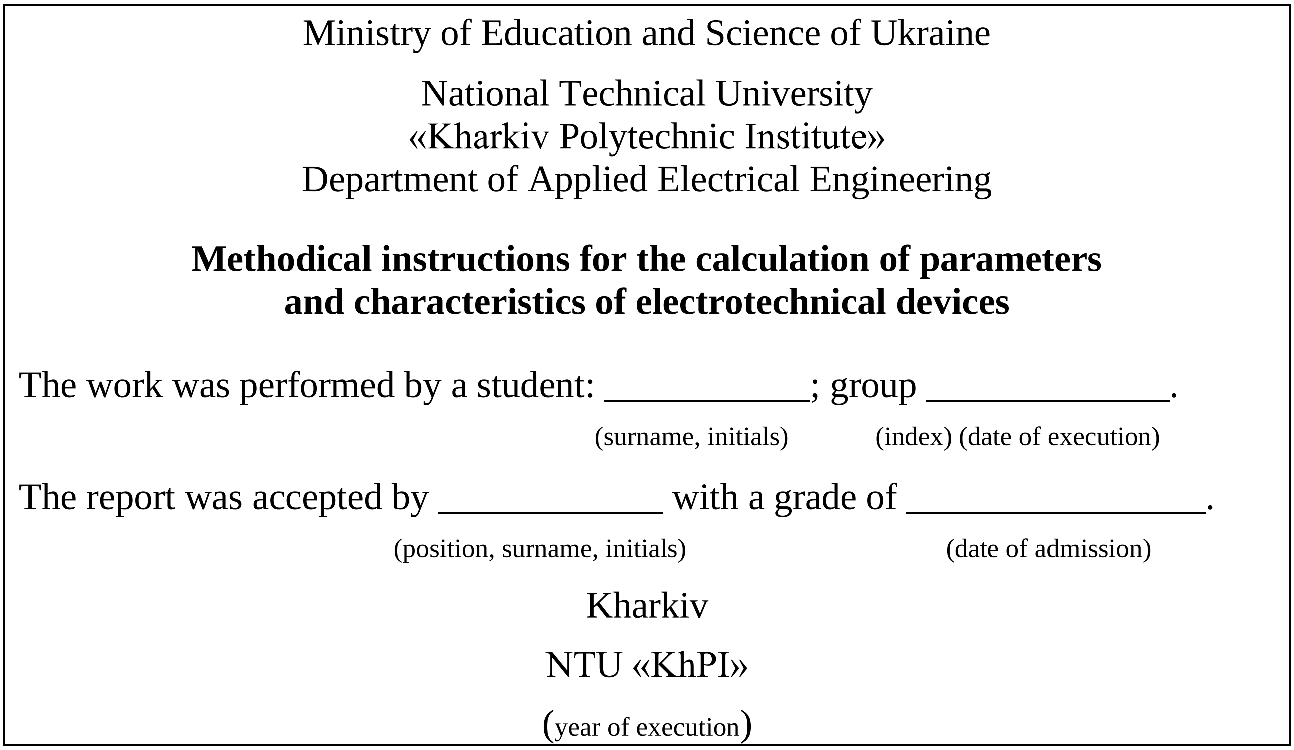
The purpose of the work is to consolidate theoretical knowledge and practice practical skills in calculating such electrotechnical devices as: single-phase transformers, shunt- and series-wound DC motors, three-phase induction motors.

Here, four control problems are formulated, input data options for them are presented, and examples of calculations of typical problems are given. The specific scope of work is specified by the lecturer who conducts a course of lectures on the specified discipline.

Input data variants for specific Problems are presented in Tables 1-4, and the headings of these Tables are provided on page 24. It is enough to copy this page and enter the specific input data of your option and, using these Tables, perform the necessary calculations.

The report on calculation and graphic work must be neat, executed in accordance with the established form. It begins with a title page, a sample of which is shown in Fig. 1. When drawing up the report, it is necessary to indicate the complete statement of the Problems and the relevant input data according to the variant, accompanying schematic diagrams, the order of calculations and its results and graphs.

Schematic diagrams are drawn with the help of tools according to state standards. Graphs of dependencies should be made with standard letter designations of values and units of measurement indicated on the axes.



Ministry of Education and Science of Ukraine

National Technical University
«Kharkiv Polytechnic Institute»
Department of Applied Electrical Engineering

Methodical instructions for the calculation of parameters and characteristics of electrotechnical devices

The work was performed by a student: ___________; group _____________.
(surname, initials) (index) (date of execution)

The report was accepted by ____________ with a grade of ________________.
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Figure 1

1. FORMULATION OF PROBLEMS

Problem 1. Parameters and characteristics of a single-phase transformer

A physical model of a single-phase transformer with a load connected to the secondary winding Z_L, shown in Fig. 2, *a*. Fig. 2, *b* shows the conventional designation of the transformer **T** in schematic diagrams.

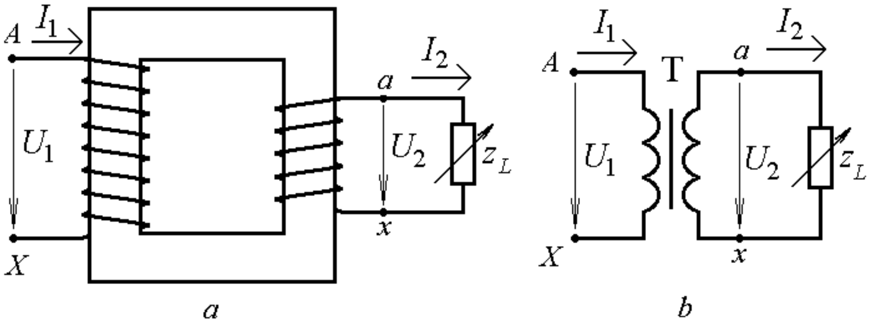

Figure 2

Variants of rated data of single-phase transformers are listed in Table 1. We assume that the primary winding of the transformer is a higher voltage winding (HV), and the secondary winding is a lower voltage winding (LV). For a given option, it is necessary to define:

1) transformation ratio;
2) rated currents of the windings, the current of the primary winding in the no-load (NL) operation (test) and the emergency short-circuit (SC) current of the same winding;
3) dependence of the efficiency factor (η) on the load current of the transformer (plot a graph of this dependence $\eta(\beta)$, where $\beta = I_2/I_{2\text{rated}}$ – load factor, that is, the ratio of the secondary winding current to its rated value);
4) the dependence of the voltage on the output terminals of the transformer on the load factor (build this dependence, which is called the external characteristic, in the form $U_2(\beta)$).

In Table 1 are marked: S_{rated} – apparent rated power; U_{HVrated}, U_{LVrated} – rated winding voltages HV and LV; i_0, P_0 – current and power losses in the no-load operation; P_{SC}, u_{SC} – power losses and voltage in the experimental short-circuit test (i_0 and u_{SC} are given as a percentage of the rated values, respectively, of the current and voltage of the primary winding $I_{1\text{rated}}$ and $U_{1\text{rated}}$); $\cos\varphi_L$ – load power factor Z_L, which is connected to the transformer.

The principle of calculation of Problem 1 is given below in the examples 1-3.

Problem 2. Parameters and characteristics of a shunt-wound DC motor

Figure 3 shows the electric circuit of the shunt-wound DC motor. Variants of rated data of these motors are given in Table 2, where it is marked $P_{2\text{rated}}$, U_{rated}, η_{rated}, n_{rated} – respectively, rated power, voltage, efficiency and speed; R_{arm} – armature circuit resistance; R_{ex} – excitation winding resistance.

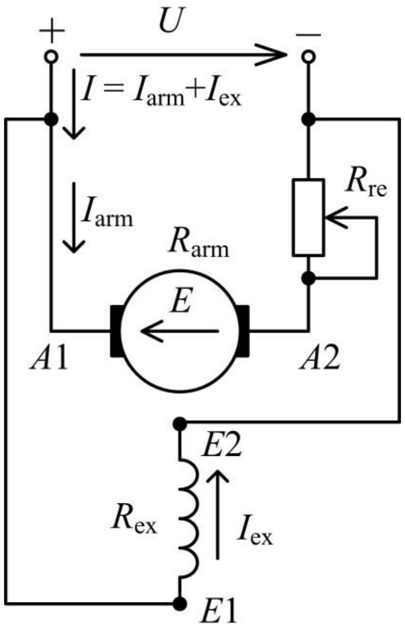

Figure 3

The following calculations must be done for a given data variant.

1. Determine the current for the rated operating condition I_{rated}, consumed by the motor from the network, excitation current $I_{ex\ rated}$; total power losses in the motor ΔP_{rated}; electromagnetic power $P_{EM\ rated}$; electromotive force (EMF) E_{rated}.

2. Determine the speed of the armature n_0 in perfect no-load condition.

3. Build a natural mechanical characteristic $n(M)$, where n, M – speed and torque of the DC motor.

4. Analytically or using the characteristic built according to claim 3 $n(M)$, determine the speed of the DC motor at the torque $M = 0{,}6\ M_{rated}$.

5. Build an artificial mechanical characteristic $n(M)$ at the rated voltage U_{rated}, if a regulating rheostat with resistance is switched on in the armature circuit $R_{re} = 2{,}4R_{arm}$.

6. Determine R_{re} the regulating rheostat resistance, which must be switched in the armature circuit (Fig. 3) to limit the armature starting current to $I_{arm\ start} = 2{,}3I_{arm\ rated}$, if the motor is switched on when starting at the rated voltage U_{rated}.

7. Find the value of the supply voltage at startup U_{start}, to which it must be lowered when the motor is turned on so that the starting current of the armature $I_{arm\ start}$ would not exceed $I_{arm\ start} = 2{,}3I_{arm\ rated}$ without switching on additional resistors. The principle of calculation of Problem 2 is presented below in examples 4-6.

Problem 3. Parameters and characteristics of a series-wound DC motor

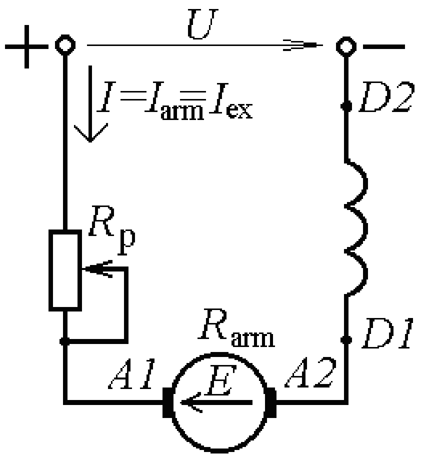

Figure 4

For a series-wound DC motor, the electric switching circuit is shown in Fig. 4. Variants of the rated data of these motors are given in Table 3, where indicated: P_{2rated}, U_{rated}, n_{rated}, η_{rated} – respectively, the rated power, voltage, speed and efficiency; R_{arm} – resistance of the armature circuit.

DPS magnetization curve $\Phi(I)$ in relative units $k_{\text{ф}}(k_I)$ shown in Fig. 5, where $k_I = I / I_{rated}$ – multiplicity of the excitation current (which is also the armature current); $k_{\text{ф}} = \Phi/\Phi_{rated}$ – the multiplicity of the excitation magnetic flux (I_{rated}, Φ_{rated} – rated values of the corresponding quantities).

For the given variant of the data, it is necessary to perform the following.

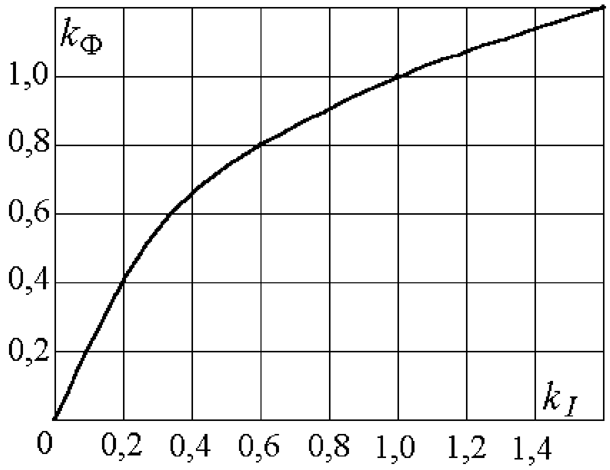

Figure 5

1. For the rated condition of operation, determine: the power consumed by the motor from the network $P_{1\text{rated}}$; current I_{rated}; total power losses in the motor ΔP_{rated}; EMF of the armature winding E_{rated}; torque M_{rated}; useful torque on the motor shaft $M_{2\text{rated}}$.

2. Build the natural mechanical characteristics of the motor $n(M)$, where n – speed of the DC motor, M – torque of the DC motor.

3. Build an artificial mechanical characteristic $n(M)$ at the rated voltage U_{rated}, if an regulating rheostat with resistance is included in the armature electric circuit $R_{\text{re}} = 2{,}5R_{\text{arm}}$ (Fig. 4).

4. Using the characteristics built according to clauses 2 and 3 $n(M)$, determine the motor speed when the torque is reduced by 60 % , as well as when increasing it by 15 % from the rated value when the regulating rheostat is turned on R_{re} and in his absence.

5. Determine the speed of the motor at the rated torque M_{rated} with a decrease in the motor supply voltage by 15 % from the rated value U_{rated}.

The principle of calculation of Problem 3 is given below in the examples 7-8.

Problem 4. Parameters and characteristics of a three-phase induction motor

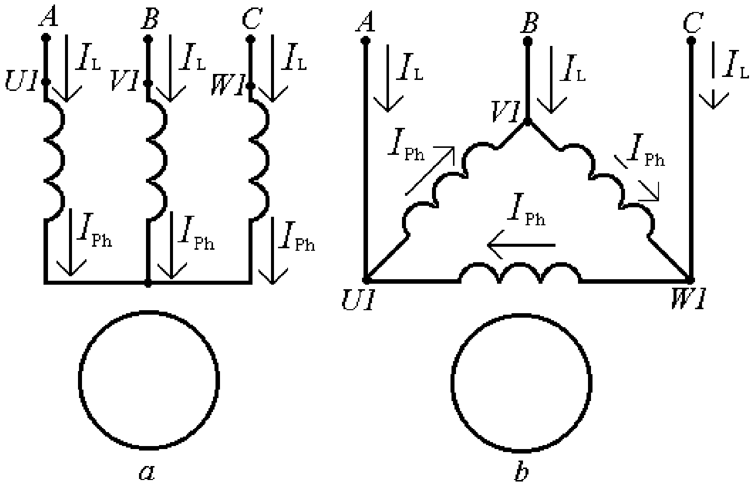

Figure 6

The electric circuit of a three-phase induction motor is shown in Fig.6.

Variants of the data of these motors are given in Table 4.

The rated voltage of these motors is 220/380 V (phase / line) at frequency $f = 50$ Hz.

In Table 4 it is marked: $P_{2\text{rated}}$ – rated power; p – the number of pole pairs formed by the stator winding; S_{rated} – rated slip; $\lambda_M = M_{\max}/M_{\text{rated}}$ – overload capacity from torque ($M_{\max}$, M_{rated} – maximum and rated torque value); $\lambda_I = I_{\text{start}}/I_{\text{rated}}$ – multiplicity of starting current (I_{start}, I_{rated} – starting and rated value of current consumed from the network); $\cos\varphi_{1\text{rated}}$ – rated power factor. Also the schematic diagram of connection of stator windings is set (Y – wye, Fig. 6, *a*, Δ – delta, Fig. 6, *b*).

According to this data, the following Problem must be performed:

1. Select the line voltage of the three-phase supply network U_{net}.

2. Determine the synchronous speed of the stator magnetic field n_1, rated $n_{2\text{rated}}$ and critical $n_{2\text{cr}}$ rotor frequencies.

3. Determine the power $P_{1\text{rated}}$, which the motor consumes from the network, and the total loss of power in the motor ΔP_{rated} in rated condition, rated I_{rated} and starting I_{start} motor currents, its rated M_{rated} and maximum $M_{\max}$ torques.

4. Calculate and build mechanical characteristics of dependence $M(S)$, where M – torque, S – slip of the rotor. From this dependence determine the starting torque of the motor M_{start} and the multiplicity of this moment $k_{\text{start}} = M_{\text{start}}/M_{\text{rated}}$.

5. Calculate and build three mechanical characteristics in one coordinate system – dependencies $n_2(M)$, where n_2 – the rotor speed, under the following conditions:

a) natural mechanical characteristics at a given mains voltage U_{net} (as in claim 3), and determine the range of rotor speeds at which stable motor operation is possible;

b) artificial mechanical characteristics at low level of supply voltage on 15 %, i.e. at $U = 0{,}85U_{\text{net}}$;

c) artificial mechanical characteristics, provided that the total active resistance in each phase of the rotor winding is in 2 times more than that of the motor for which the previous characteristics are calculated, i.e. $R_2' = 2R_2$, this is possible if this motor was a phase rotor motor (Fig. 7), and then in the phase of the rotor winding could be included control rheostats with supports $R_{\text{re}} = R_2$); the inductive reactance of the phases of the rotor winding X_{20} does not change; the mains voltage is considered equal U_{net}.

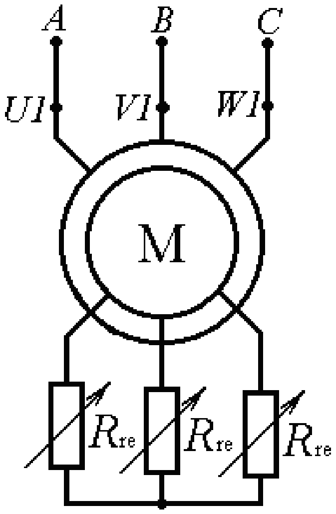

Figure 7

The principle of calculation of Problem 4 is given below in the examples 9-13.

2. VARIANTS OF INPUT DATA

Table 1 – Parameters of a single-phase transformer and its load

№ variant	Total power, kVA	Rated voltages of the windings, V		NL current, %	Power losses, W		SC voltage, %	Active-inductive power factor of the load
		HV	LV		NL	SC		
	S_{rated}	U_{HVrated}	U_{LVrated}	i_0	P_0	P_{SC}	u_{SC}	$\cos \varphi_{\text{L}}$
1	0,25	660	230	17,6	6	18	7,3	0,90
2	0,25	380	230	17,5	6	18	7,2	0,85
3	0,5	660	230	15,9	11	32	6,7	0,90
4	0,5	380	230	15,9	10	32	6,6	0,85
5	0,63	660	230	14,3	11	36	6,0	0,90
6	0,63	380	230	14,2	11	36	6,0	0,85
7	1	660	230	12,6	15	50	5,4	0,90
8	1	380	230	12,5	15	49	5,3	0,85
9	1,6	660	230	10,9	20	68	4,6	0,90
10	1,6	380	230	10,8	20	67	4,6	0,85
11	2,5	660	230	9,1	25	88	3,9	0,90
12	2,5	380	230	9,0	25	86	3,8	0,85
13	4	660	230	8,3	35	125	3,5	0,90
14	4	380	230	8,2	34	122	3,5	0,85
15	6,3	660	230	9,6	60	223	4,1	0,90
16	6,3	380	230	9,5	59	218	4,0	0,85
17	10	660	230	9,2	88	333	3,9	0,90
18	10	380	230	9,1	85	325	3,8	0,85
19	16	660	230	9,1	131	509	3,8	0,90
20	16	380	230	8,9	127	497	3,7	0,85
21	0,25	660	133	17,5	6	18	7,2	0,85
22	0,25	380	133	17,4	6	17	7,1	0,80
23	0,25	220	133	17,3	6	17	7,0	0,75
24	0,5	660	133	15,9	10	32	6,6	0,85
25	0,5	380	133	15,7	10	31	6,5	0,80

Continuation of Table 1

№ variant	Total power, kVA	Rated voltages of the windings, V		NL current, %	Power losses, W		SC voltage, %	Active-inductive power factor of the load
		HV	LV		NL	SC		
	S_{rated}	U_{HVrated}	U_{LVrated}	i_0	P_0	P_{SC}	u_{SC}	$\cos\varphi_{\text{L}}$
26	0,5	220	133	15,6	10	30	6,3	0,75
27	0,63	660	133	14,2	11	36	6,0	0,85
28	0,63	380	133	14,1	11	35	5,8	0,80
29	0,63	220	133	13,9	11	34	5,7	0,75
30	1	660	133	12,5	15	49	5,3	0,85
31	1	380	133	12,3	14	48	5,1	0,80
32	1	220	133	12,1	14	46	5,0	0,75
33	1,6	660	133	10,8	20	67	4,6	0,85
34	1,6	380	133	10,6	19	64	4,4	0,80
35	1,6	220	133	10,3	18	62	4,2	0,75
36	2,5	660	133	9,0	24	86	3,8	0,85
37	2,5	380	133	8,7	23	82	3,6	0,80
38	2,5	220	133	8,5	22	78	3,5	0,75
39	4	660	133	8,2	34	122	3,5	0,85
40	4	380	133	7,9	32	116	3,3	0,80
41	4	220	133	7,6	30	110	3,1	0,75
42	6,3	660	133	9,5	59	218	4,0	0,85
43	6,3	380	133	9,2	56	208	3,8	0,80
44	6,3	220	133	9,0	54	198	3,6	0,75
45	10	660	133	9,1	85	325	3,8	0,85
46	10	380	133	8,8	81	309	3,6	0,80
47	10	220	133	8,6	77	293	3,4	0,75
48	16	660	133	8,9	127	497	3,7	0,85
49	16	380	133	8,7	121	471	3,5	0,80
50	16	220	133	8,4	114	446	3,3	0,75

Continuation of Table 1

№ variant	Total power, kVA	Rated voltages of the windings, V		NL current, %	Power losses, W		SC voltage, %	Active-inductive power factor of the load
		HV	LV		NL	SC		
	S_{rated}	U_{HVrated}	U_{LVrated}	i_0	P_0	P_{SC}	u_{SC}	$\cos \varphi_{\text{L}}$
51	0,25	660	115	17,5	6	17	7,2	0,80
52	0,25	380	115	17,3	6	17	7,0	0,75
53	0,25	220	115	17,1	5	16	6,7	0,70
54	0,5	660	115	15,8	10	31	6,6	0,80
55	0,5	380	115	15,6	10	30	6,3	0,75
56	0,5	220	115	15,4	9	29	6,1	0,70
57	0,63	660	115	14,1	11	35	5,9	0,80
58	0,63	380	115	13,9	11	34	5,7	0,75
59	0,63	220	115	13,6	10	32	5,4	0,70
60	1	660	115	12,4	15	48	5,2	0,80
61	1	380	115	12,1	14	46	5,0	0,75
62	1	220	115	11,8	13	44	4,7	0,70
63	1,6	660	115	10,7	19	66	4,5	0,80
64	1,6	380	115	10,3	18	62	4,2	0,75
65	1,6	220	115	10,0	17	58	4,0	0,70
66	2,5	660	115	8,8	24	84	3,7	0,80
67	2,5	380	115	8,5	22	78	3,5	0,75
68	2,5	220	115	8,1	21	72	3,2	0,70
69	4	660	115	8,0	33	119	3,4	0,80
70	4	380	115	7,6	30	110	3,1	0,75
71	4	220	115	7,2	28	100	2,9	0,70
72	6,3	660	115	9,3	58	213	3,9	0,80
73	6,3	380	115	9,0	54	198	3,6	0,75
74	6,3	220	115	8,6	50	184	3,4	0,70
75	10	660	115	9,0	83	317	3,7	0,80

Continuation of Table 1

№ variant	Total power, kVA	Rated voltages of the windings, V		NL current, %	Power losses, W		SC voltage, %	Active-inductive power factor of the load
		HV	LV		NL	SC		
	S_{rated}	U_{HVrated}	U_{LVrated}	i_0	P_0	P_{SC}	u_{SC}	$\cos \varphi_{\text{L}}$
76	10	380	115	8,6	77	293	3,4	0,75
77	10	220	115	8,1	71	269	3,2	0,70
78	16	660	115	8,8	124	484	3,6	0,80
79	16	380	115	8,4	114	446	3,3	0,75
80	16	220	115	8,0	105	408	3,1	0,70
81	0,25	660	26	17,4	6	17	7,1	0,75
82	0,25	380	26	17,2	6	17	6,8	0,70
83	0,25	220	26	16,9	5	16	6,5	0,65
84	0,5	660	26	15,7	10	31	6,5	0,75
85	0,5	380	26	15,5	10	30	6,2	0,70
86	0,5	220	26	15,2	9	28	5,9	0,65
87	0,63	660	26	14,1	11	35	5,8	0,75
88	0,63	380	26	13,7	10	33	5,5	0,70
89	0,63	220	26	13,4	10	31	5,2	0,65
90	1	660	26	12,3	14	48	5,1	0,75
91	1	380	26	11,9	14	45	4,8	0,70
92	1	220	26	11,5	13	41	4,5	0,65
93	1,6	660	26	10,6	19	64	4,4	0,75
94	1,6	380	26	10,1	18	59	4,1	0,70
95	1,6	220	26	9,6	16	54	3,8	0,65
96	2,5	660	26	8,7	23	82	3,6	0,75
97	2,5	380	26	8,2	21	74	3,3	0,70
98	2,5	220	26	7,6	19	66	3,0	0,65
99	4	660	26	7,9	32	116	3,3	0,75

Table 2 – Parameters of a shunt-wound DC motor

№ variant	Power, kW	Voltage, V	Speed of rotation, rpm	Efficiency	Resistance of the armature circuit, Ohm	Excitation winding resistance, Ohm
	$P_{2\text{rated}}$	U_{rated}	n_{rated}	η_{rated}	R_{arm}	R_{ex}
1	4	220	900	0,723	1,60	191
2	3,15	220	750	0,693	2,38	255
3	2	220	450	0,576	3,16	199
4	4,25	220	730	0,680	1,61	110
5	3	220	475	0,603	3,14	139
6	3,55	220	425	0,601	2,67	117
7	15	220	1400	0,779	0,37	103
8	7,5	220	1000	0,760	0,79	175
9	6	220	875	0,740	0,80	85
10	4,25	220	580	0,650	1,84	105
11	11	220	1060	0,785	0,45	100
12	8,5	220	875	0,760	0,62	98
13	8	220	600	0,680	0,85	58
14	11	220	800	0,760	0,48	73
15	8,5	220	515	0,680	0,93	91
16	15	220	850	0,807	0,21	45
17	11	220	530	0,705	0,56	46
18	15	220	580	0,753	0,34	44
19	17	220	500	0,730	0,33	34
20	20	220	475	0,750	0,26	32
21	7,5	440	2120	0,871	1,54	1124
22	5,5	440	1450	0,814	3,06	964
23	4,25	440	975	0,740	5,93	971
24	3,14	440	730	0,690	9,64	994
25	7,5	440	1450	0,825	1,54	414

Continuation of Table 2

№ variant	Power, kW	Voltage, V	Speed of rotation, rpm	Efficiency	Resistance of the armature circuit, Ohm	Excitation winding resistance, Ohm
	$P_{2\text{rated}}$	U_{rated}	n_{rated}	η_{rated}	R_{arm}	R_{ex}
26	5,5	440	900	0,741	4,96	1304
27	4,25	440	690	0,674	6,62	438
28	10	440	1320	0,812	1,23	260
29	7,5	440	975	0,810	2,53	1045
30	5,5	440	690	0,708	5,24	671
31	30	440	3070	0,871	0,38	278
32	18,5	440	2180	0,850	0,63	264
33	15	440	1400	0,800	1,33	481
34	5,5	440	800	0,730	3,74	367
35	30	440	2300	0,863	0,42	278
36	22	440	1600	0,830	0,75	365
37	11	440	1090	0,800	1,53	352
38	8,5	440	800	0,750	2,77	459
39	23,6	440	1400	0,830	0,70	340
40	15	440	1030	0,810	1,15	341
41	11	440	825	0,780	1,72	325
42	30	440	1450	0,840	0,44	171
43	18,5	440	1090	0,820	0,65	164
44	15	440	730	0,761	1,32	191
45	22	440	1090	0,845	0,51	185
46	18,5	440	775	0,808	0,79	180
47	30	440	1030	0,855	0,36	160
48	22	440	775	0,813	0,64	157
49	45	440	1450	0,880	0,23	189
50	37	440	1150	0,850	0,32	136

Continuation of Table 2

№ variant	Power, kW	Voltage, V	Speed of rotation, rpm	Efficiency	Resistance of the armature circuit, Ohm	Excitation winding resistance, Ohm
	$P_{2\text{rated}}$	U_{rated}	n_{rated}	η_{rated}	R_{arm}	R_{ex}
51	26,5	440	775	0,780	0,61	99
52	45	440	1060	0,860	0,26	132
53	37	440	825	0,830	0,37	118
54	55	440	1000	0,849	0,25	136
55	75	440	1060	0,873	0,15	103
56	90	440	1000	0,900	0,09	96
57	110	440	1000	0,870	0,11	76
58	132	440	1000	0,870	0,08	49
59	160	440	1000	0,890	0,06	53
60	27	440	500	0,762	0,60	78
61	45	440	750	0,822	0,36	128
62	90	440	1500	0,886	0,11	90
63	37	440	500	0,786	0,56	147
64	55	440	750	0,833	0,29	143
65	110	440	1500	0,891	0,08	78
66	45	440	500	0,790	0,42	98
67	132	440	1500	0,891	0,05	18
68	50	440	500	0,776	0,43	99
69	75	440	750	0,840	0,20	108
70	160	440	1500	0,897	0,05	54
71	90	440	750	0,853	0,15	91
72	200	440	1500	0,903	0,04	43
73	75	440	500	0,822	0,23	100
74	110	440	750	0,867	0,11	76
75	250	440	1500	0,910	0,03	35

Continuation of Table 2

№ variant	Power, kW	Voltage, V	Speed of rotation, rpm	Efficiency	Resistance of the armature circuit, Ohm	Excitation winding resistance, Ohm
	$P_{2\text{rated}}$	U_{rated}	n_{rated}	η_{rated}	R_{arm}	R_{ex}
76	11	220	1000	0,830	0,24	73
77	22	440	600	0,840	0,56	246
78	45	220	750	0,870	0,04	23
79	55	440	500	0,880	0,12	103
80	10	220	1500	0,770	0,35	74
81	15	440	750	0,800	0,82	172
82	37	220	500	0,880	0,04	28
83	11	440	1000	0,830	0,82	292
84	22	220	1500	0,840	0,09	41
85	45	440	1000	0,870	0,07	74
86	55	220	600	0,880	0,04	25
87	10	440	750	0,770	1,87	372
88	15	220	500	0,800	0,27	86
89	37	440	1500	0,880	0,07	92
90	11	220	750	0,830	0,12	60
91	22	440	500	0,840	0,50	184
92	45	220	1000	0,870	0,03	18
93	55	440	1500	0,880	0,08	68
94	10	220	1000	0,770	0,37	74
95	15	440	600	0,800	0,96	344
96	37	220	750	0,880	0,04	28
97	11	440	500	0,830	1,22	486
98	22	220	1500	0,840	0,09	37
99	45	440	750	0,870	0,04	62

Table 3 – Parameters of a series-wound DC motor

№ variant	Power, kW	Voltage, V	Speed of rotation, rpm	Efficiency	Resistance of the armature circuit, Ohm
	$P_{2\text{rated}}$	U_{rated}	n_{rated}	η_{rated}	R_{arm}
1	45	220	1000	0,870	0,06
2	22	440	600	0,840	0,64
3	11	220	750	0,830	0,35
4	55	440	500	0,880	0,22
5	37	220	1500	0,880	0,08
6	15	440	750	0,800	1,07
7	10	220	500	0,770	0,46
8	45	440	1000	0,870	0,27
9	22	220	1500	0,840	0,17
10	11	440	1000	0,830	1,49
11	55	220	600	0,880	0,05
12	37	440	750	0,880	0,30
13	15	220	500	0,800	0,29
14	10	440	1500	0,770	1,99
15	45	220	750	0,870	0,07
16	22	440	500	0,840	0,62
17	11	220	1000	0,830	0,34
18	55	440	1500	0,880	0,21
19	37	220	1000	0,880	0,08
20	15	440	600	0,800	1,24
21	10	220	750	0,770	0,45
22	45	440	500	0,870	0,26
23	22	220	1500	0,840	0,17
24	11	440	750	0,830	1,44
25	4	220	900	0,723	1,45

Continuation of Table 3

№ variant	Power, kW	Voltage, V	Speed of rotation, rpm	Efficiency	Resistance of the armature circuit, Ohm
	$P_{2\text{rated}}$	U_{rated}	n_{rated}	η_{rated}	R_{arm}
26	3,15	220	750	0,693	1,96
27	2	220	450	0,576	3,55
28	4,25	220	730	0,680	1,49
29	3	220	475	0,603	2,32
30	3,55	220	425	0,601	1,96
31	15	220	1400	0,779	0,33
32	7,5	220	1000	0,760	0,71
33	6	220	875	0,740	0,93
34	4,25	220	580	0,650	1,55
35	11	220	1060	0,785	0,45
36	8,5	220	875	0,760	0,62
37	8	220	600	0,680	0,79
38	11	220	800	0,760	0,48
39	8,5	220	515	0,680	0,74
40	15	220	850	0,807	0,30
41	11	220	530	0,705	0,55
42	15	220	580	0,753	0,36
43	17	220	500	0,730	0,34
44	20	220	475	0,750	0,27
45	7,5	440	2120	0,871	1,74
46	5,5	440	1450	0,814	3,20
47	4,25	440	975	0,740	5,26
48	3,14	440	730	0,690	7,91
49	7,5	440	1450	0,825	2,24
50	5,5	440	900	0,741	4,05

Continuation of Table 3

№ variant	Power, kW	Voltage, V	Speed of rotation, rpm	Efficiency	Resistance of the armature circuit, Ohm
	$P_{2\text{rated}}$	U_{rated}	n_{rated}	η_{rated}	R_{arm}
51	4,25	440	690	0,674	6,01
52	10	440	1320	0,812	1,77
53	7,5	440	975	0,810	2,38
54	5,5	440	690	0,708	4,37
55	30	440	3070	0,871	0,44
56	18,5	440	2180	0,850	0,80
57	15	440	1400	0,800	1,24
58	5,5	440	800	0,730	4,16
59	30	440	2300	0,863	0,46
60	22	440	1600	0,830	0,75
61	11	440	1090	0,800	1,69
62	8,5	440	800	0,750	2,56
63	23,6	440	1400	0,830	0,69
64	15	440	1030	0,810	1,19
65	11	440	825	0,780	1,81
66	30	440	1450	0,840	0,52
67	18,5	440	1090	0,820	0,93
68	15	440	730	0,761	1,41
69	22	440	1090	0,845	0,69
70	18,5	440	775	0,808	0,97
71	30	440	1030	0,855	0,48
72	22	440	775	0,813	0,80
73	45	440	1450	0,880	0,27
74	37	440	1150	0,850	0,40
75	26,5	440	775	0,780	0,75

Continuation of Table 3

№ variant	Power, kW	Voltage, V	Speed of rotation, rpm	Efficiency	Resistance of the armature circuit, Ohm
	$P_{2\text{rated}}$	U_{rated}	n_{rated}	η_{rated}	R_{arm}
76	45	440	1060	0,860	0,31
77	37	440	825	0,830	0,44
78	55	440	1000	0,849	0,27
79	75	440	1060	0,873	0,17
80	90	440	1000	0,900	0,12
81	110	440	1000	0,870	0,12
82	132	440	1000	0,870	0,10
83	160	440	1000	0,890	0,07
84	27	440	500	0,762	0,78
85	45	440	750	0,822	0,38
86	90	440	1500	0,886	0,13
87	37	440	500	0,786	0,53
88	55	440	750	0,833	0,29
89	110	440	1500	0,891	0,10
90	45	440	500	0,790	0,43
91	132	440	1500	0,891	0,09
92	50	440	500	0,776	0,40
93	75	440	750	0,840	0,21
94	160	440	1500	0,897	0,07
95	90	440	750	0,853	0,16
96	200	440	1500	0,903	0,05
97	75	440	500	0,822	0,23
98	110	440	750	0,867	0,12
99	250	440	1500	0,910	0,04

Table 4 – Parameters of a three-phase induction motor

№ variant	Stator winding connection	Power, kW	Number of pole pairs	Rated slip	$\frac{M_{\max}}{M_{\text{rated}}}$	$\frac{I_{\text{start}}}{I_{\text{rated}}}$	Efficiency	Power factor
		$P_{2\text{rated}}$	p	S_{rated}	λ_M	λ_I	η_{rated}	$\cos\varphi_{1\text{rated}}$
1	Δ	0,09	1	0,086	2,2	5,0	0,600	0,700
2	Y	0,12	1	0,097	2,2	5,0	0,630	0,700
3	Δ	0,18	1	0,080	2,2	5,0	0,660	0,760
4	Y	0,25	1	0,080	2,2	5,0	0,680	0,770
5	Δ	0,37	1	0,083	2,2	5,0	0,700	0,860
6	Y	0,55	1	0,085	2,2	5,0	0,730	0,860
7	Δ	0,75	1	0,080	2,2	5,5	0,770	0,870
8	Y	1	1	0,065	2,2	5,5	0,720	0,870
9	Δ	1,1	1	0,075	2,2	5,5	0,775	0,870
10	Y	1,5	1	0,072	2,2	6,5	0,810	0,850
11	Δ	2,2	1	0,069	2,2	6,5	0,830	0,870
12	Y	3	1	0,067	2,2	6,5	0,845	0,880
13	Δ	4	1	0,065	2,2	7,5	0,865	0,890
14	Y	5,5	1	0,064	2,2	7,5	0,875	0,910
15	Δ	11	1	0,050	2,4	7,5	0,840	0,890
16	Y	0,09	2	0,086	2,2	5,0	0,550	0,600
17	Δ	0,12	2	0,080	2,2	5,0	0,630	0,660
18	Y	0,18	2	0,087	2,2	5,0	0,640	0,640
19	Δ	0,25	2	0,080	2,2	5,0	0,680	0,650
20	Y	0,37	2	0,090	2,2	5,0	0,680	0,690
21	Δ	0,55	2	0,087	2,2	4,5	0,705	0,700
22	Y	0,75	2	0,087	2,2	4,5	0,720	0,730
23	Δ	1,1	2	0,067	2,2	5,0	0,750	0,810
24	Y	1,5	2	0,067	2,2	5,0	0,770	0,830
25	Δ	2,2	2	0,066	2,2	6,0	0,800	0,830

Continuation of Table 4

№ variant	Stator winding connection	Power, kW	Number of pole pairs	Rated slip	$\frac{M_{\max}}{M_{\text{rated}}}$	$\frac{I_{\text{start}}}{I_{\text{rated}}}$	Efficiency	Power factor
		$P_{2\text{rated}}$	p	S_{rated}	λ_M	λ_I	η_{rated}	$\cos\varphi_{1\text{rated}}$
26	Y	3	2	0,066	2,2	6,5	0,820	0,830
27	Δ	4	2	0,065	2,2	6,0	0,840	0,840
28	Y	5,5	2	0,065	2,2	7,0	0,855	0,860
29	Δ	7,5	2	0,064	2,2	7,5	0,875	0,860
30	Y	11	2	0,060	2,4	7,5	0,875	0,870
31	Δ	0,6	2	0,087	2,2	4,5	0,680	0,730
32	Y	0,8	2	0,085	2,2	4,5	0,685	0,750
33	Δ	1,3	2	0,082	2,2	5,0	0,685	0,820
34	Y	1,7	2	0,080	2,2	5,0	0,700	0,820
35	Δ	2,4	2	0,078	2,2	6,0	0,760	0,820
36	Y	3,2	2	0,075	2,2	6,0	0,765	0,820
37	Δ	4,25	2	0,072	2,2	6,0	0,780	0,820
38	Y	5,6	2	0,070	2,2	7,0	0,790	0,830
39	Δ	8,5	2	0,069	2,2	7,0	0,820	0,850
40	Y	11,8	2	0,061	2,4	7,0	0,840	0,850
41	Δ	0,18	3	0,115	2,2	4,0	0,560	0,620
42	Y	0,25	3	0,108	2,2	4,0	0,590	0,620
43	Δ	0,37	3	0,080	2,2	4,0	0,645	0,690
44	Y	0,55	3	0,080	2,2	4,0	0,675	0,710
45	Δ	0,75	3	0,080	2,2	4,0	0,690	0,740
46	Y	1,1	3	0,080	2,2	4,0	0,740	0,740
47	Δ	1,5	3	0,064	2,2	5,5	0,750	0,740
48	Y	2,2	3	0,063	2,2	5,5	0,810	0,730
49	Δ	3	3	0,057	2,4	6,0	0,810	0,760
50	Y	4	3	0,056	2,4	6,0	0,820	0,810

Continuation of Table 4

№ variant	Stator winding connection	Power, kW	Number of pole pairs	Rated slip	$\frac{M_{max}}{M_{rated}}$	$\frac{I_{start}}{I_{rated}}$	Efficiency	Power factor
		P_{2rated}	p	S_{rated}	λ_M	λ_I	η_{rated}	$\cos\varphi_{1rated}$
51	Δ	5,5	3	0,049	2,5	7,0	0,850	0,800
52	Y	7,5	3	0,048	2,5	7,0	0,855	0,810
53	Δ	0,18	3	0,100	2,2	4,0	0,550	0,610
54	Y	0,25	3	0,095	2,2	4,0	0,580	0,615
55	Δ	0,37	3	0,090	2,2	4,0	0,640	0,680
56	Y	0,55	3	0,086	2,2	4,0	0,670	0,700
57	Δ	0,75	3	0,085	2,2	6,0	0,680	0,730
58	Y	1,1	3	0,083	2,2	6,0	0,730	0,730
59	Δ	1,5	3	0,080	2,2	6,5	0,740	0,735
60	Y	2,2	3	0,075	2,2	6,5	0,800	0,740
61	Δ	3	3	0,051	2,4	6,5	0,800	0,750
62	Y	4	3	0,050	2,4	6,5	0,810	0,800
63	Δ	0,4	3	0,104	2,1	3,5	0,625	0,700
64	Y	0,63	3	0,102	2,1	3,5	0,650	0,700
65	Δ	0,8	3	0,070	2,1	3,5	0,610	0,680
66	Y	1,2	3	0,078	2,1	3,5	0,665	0,730
67	Δ	0,25	4	0,110	1,7	3,5	0,560	0,650
68	Y	0,37	4	0,115	1,7	3,5	0,615	0,650
69	Δ	0,55	4	0,100	1,8	3,5	0,640	0,650
70	Y	0,75	4	0,098	1,8	3,5	0,680	0,620
71	Δ	1,1	4	0,075	2,0	3,5	0,700	0,680
72	Y	1,5	4	0,074	2,0	5,5	0,740	0,650
73	Δ	2,2	4	0,066	2,2	6,0	0,765	0,710
74	Y	3	4	0,065	2,2	6,0	0,790	0,740
75	Δ	4	4	0,055	2,4	6,0	0,830	0,700

Continuation of Table 4

№ variant	Stator winding connection	Power, kW	Number of pole pairs	Rated slip	$\frac{M_{\max}}{M_{\text{rated}}}$	$\frac{I_{\text{start}}}{I_{\text{rated}}}$	Efficiency	Power factor
		$P_{2\text{rated}}$	p	S_{rated}	λ_M	λ_I	η_{rated}	$\cos\varphi_{1\text{rated}}$
76	Y	5,5	4	0,054	2,4	6,0	0,830	0,740
77	Δ	7,5	4	0,052	2,4	6,0	0,860	0,750
78	Y	11	4	0,051	2,5	6,0	0,870	0,750
79	Δ	0,3	4	0,100	2,0	3,5	0,535	0,610
80	Y	0,45	4	0,084	2,0	3,5	0,580	0,610
81	Δ	0,6	4	0,083	2,0	3,5	0,610	0,630
82	Y	0,9	4	0,082	2,0	3,5	0,610	0,650
83	Δ	1,2	4	0,080	2,0	3,5	0,650	0,640
84	Y	1,6	4	0,078	2,0	3,5	0,690	0,630
85	Δ	2,2	4	0,095	2,0	5,5	0,680	0,650
86	Y	3,2	4	0,110	2,0	6,0	0,720	0,700
87	Δ	4,5	4	0,082	2,0	6,0	0,760	0,700
88	Y	6	4	0,075	2,0	6,0	0,770	0,700
89	Δ	7,5	4	0,096	2,0	6,0	0,815	0,800
90	Y	9	4	0,090	2,0	6,0	0,825	0,790
91	Δ	10	4	0,078	2,0	6,0	0,835	0,830
92	Y	11	4	0,084	2,0	6,0	0,835	0,850
93	Δ	12,5	4	0,069	2,2	6,0	0,870	0,790
94	Y	0,35	4	0,100	2,0	3,5	0,535	0,610
95	Δ	0,55	4	0,075	2,0	3,5	0,580	0,610
96	Y	0,7	4	0,084	2,0	3,5	0,620	0,630
97	Δ	1,4	4	0,078	2,0	3,5	0,650	0,580
98	Y	1,9	4	0,076	2,0	3,5	0,670	0,600
99	Δ	4,2	4	0,075	2,0	5,5	0,745	0,620

3. FORMS FOR INPUT DATA

Problem 1. Parameters of a single-phase transformer and its load

№ variant	Apparent power, kVA	Rated voltages of the windings, V		NL current, %	Loss of power, W		SC voltage, %	Power factor of an active-inductive load
		HV	LV		NL	SC		
	S_{rated}	U_{HVrated}	U_{LVrated}	i_0	P_0	P_{SC}	u_{SC}	$\cos\varphi_{\text{L}}$

Problem 2. Parameters of a shunt-wound DC motor

№ variant	Power, kW	Voltage, V	Speed of rotation, rpm	Efficiency	Resistance of the armature circuit, Ohm	Excitation winding resistance, Ohm
	$P_{2\text{rated}}$	U_{rated}	n_{rated}	η_{rated}	R_{arm}	R_{ex}

Problem 3. Parameters of a series-wound DC motor

№ variant	Power, kW	Voltage, V	Speed of rotation, rpm	Efficiency	Resistance of the armature circuit, Ohm
	$P_{2\text{rated}}$	U_{rated}	n_{rated}	η_{rated}	R_{arm}

Problem 4. Parameters of a three-phase induction motor

№ variant	Stator winding connection	Power, kW	Number of pole pairs	Rated slip	$\frac{M_{\max}}{M_{\text{rated}}}$	$\frac{I_{\text{start}}}{I_{\text{rated}}}$	Efficiency	Power factor
		$P_{2\text{rated}}$	p	S_{rated}	λ_M	λ_I	η_{rated}	$\cos\varphi_{1\text{rated}}$

4. EXAMPLES OF PROBLEM SOLVING

4.1. Parameters and characteristics of a single-phase transformer

Example 1. A single-phase transformer (Fig. 2) has the following rated data: total power $S_{\text{rated}} = 12$ kVA; voltage of the primary winding $U_{1\text{rated}} = 220$ V, voltage of the secondary winding $U_{2\text{rated}} = 133$ V. Short-circuit voltage $u_{\text{SC}} = 5$ % from the rated value $U_{1\text{rated}}$. No-load current $i_0 = 8$ % from the rated current $I_{1\text{rated}}$.

Determine: transformation coefficient n; rated currents of the primary $I_{1\text{rated}}$ and secondary $I_{2\text{rated}}$ winding; emergency short-circuit currents of these windings $I_{1\text{SC}}$, $I_{2\text{SC}}$; no-load current of the primary winding I_{10}.

Calculation. Transformation ratio $n = \dfrac{U_{1\text{rated}}}{U_{2\text{rated}}} = \dfrac{220}{133} = 1{,}654$.

Rated winding currents

$$I_{1\text{rated}} = \frac{S_{\text{rated}}}{U_{1\text{rated}}} = \frac{12 \cdot 10^3}{220} = 54{,}5 \text{ A}; \qquad I_{2\text{rated}} = \frac{S_{\text{rated}}}{U_{2\text{rated}}} = \frac{12 \cdot 10^3}{133} = 90{,}2 \text{ A}.$$

Voltage in experimental short-circuit test

$$U_{1\text{SC}} = \frac{u_{\text{SC}} \cdot U_{1\text{rated}}}{100} = \frac{5 \cdot 220}{100} = 11 \text{ V}.$$

Fault short-circuit currents of windings at the rated voltage

$$I_{1\text{SC}} = I_{1\text{rated}} \frac{U_{1\text{rated}}}{U_{1\text{SC}}} = 54{,}5 \cdot \frac{220}{11} = 1090 \text{ A};$$

$$I_{2\text{SC}} = I_{1\text{SC}} \cdot n = 1090 \cdot 1{,}654 = 1803 \text{ A}.$$

No-load current $I_{10} = \dfrac{i_{\text{IM}} \cdot I_{1\text{rated}}}{100} = \dfrac{8 \cdot 54{,}5}{100} = 4{,}36$ A.

Example 2. A single-phase transformer (Fig. 2) has the following rated data: voltage of the primary winding $U_{1\text{rated}} = 660$ V, voltage of the secondary winding $U_{2\text{rated}} = 400$ V; primary winding current $I_{1\text{rated}} = 3{,}8$ A. In the experimental short-circuit test, the power losses are $P_{\text{SC}} = 80$ W, voltage $U_{1\text{SC}} = 33$ V. The load has an active-inductive nature at $\cos\varphi_L = 0{,}75$.

Calculate and build the external characteristics of the transformer.

Calculation. The external characteristic of the transformer is considered to be the voltage dependence U_2 from the load factor β, i.e $U_2(\beta)$, where $\beta = \dfrac{I_2}{I_{2\text{ rated}}}$; I_2 – current of the secondary winding of the transformer; $I_{2\text{ rated}}$ – its rated current.

An approximate formula for external characteristics is known from the theory of transformers

$$U_2 = U_{20} \cdot \left[1 - \beta \cdot \frac{u_{\text{SC}}}{100} \cdot \cos(\varphi_{\text{L}} - \varphi_{\text{SC}}) \right],$$

where: U_{20} – voltage of the secondary winding in NL condition; u_{SC} – short-circuit voltage in % from the rated value $U_{1\,rated}$, which are defined by expressions

$$U_{20} = U_{2rated} = 400\text{ V};\quad u_{SC} = \frac{U_{1SC}}{U_{1rated}}\cdot 100\% = \frac{33}{660}\cdot 100\% = 5\,\%.$$

Phase angle between current and voltage on the load

$$\varphi_L = \arccos(\cos\varphi_L) = \arccos(0{,}75) = 41{,}41^\circ.$$

Phase angle between current and voltage at experimental short-circuit test

$$\varphi_{SC} = \arccos\left(\frac{P_{SC}}{U_{1SC}\cdot I_{1\,rated}}\right) = \arccos\left(\frac{80}{33\cdot 3{,}8}\right) = 50{,}36^\circ.$$

Then $U_2 = 400\cdot\left[1-\beta\cdot\frac{5}{100}\cdot\cos(41{,}41^\circ - 50{,}36^\circ)\right] = 400\cdot(1-0{,}0494\beta)$.

The external characteristic (Fig. 8) is a straight line passing through two points: *A* (coordinates $\beta = 0$; $U_2 = 400$ V), *B* (coordinates $\beta = 1$; $U_2 = 380$ V).

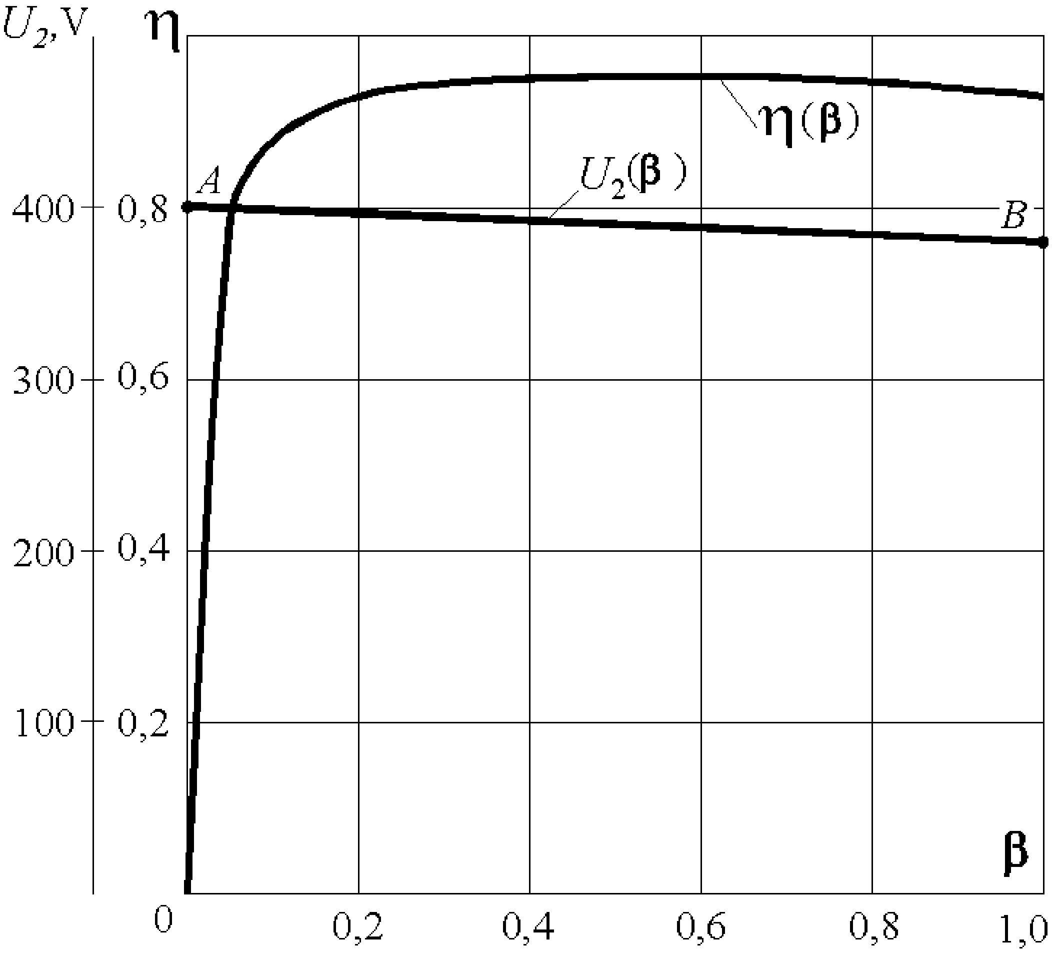

Figure 8

Example 3. A single-phase transformer (Fig. 2) has the following data: total rated power S_{rated} = 6 kVA; power losses in the no-load condition P_0 = 60 W; power loss in the experimental short-circuit test P_{SC}= 200 W. The load has an active-inductive character when $\cos\varphi_L = 0{,}75$. Calculate and graph the efficiency of the transformer $\eta(\beta)$, where $\beta = \frac{I_2}{I_{2\,\text{rated}}}$ – load factor.

Calculation. An approximate formula for calculating the dependence is known from the theory of transformers $\eta(\beta)$:

$$\eta = \frac{\beta \cdot S_{\text{rated}} \cdot \cos\varphi_L}{\beta \cdot S_{\text{rated}} \cdot \cos\varphi_{:L} + P_0 + \beta^2 \cdot P_{SC}}.$$

By substituting the specified values into this formula, we determine for this transformer

$$\eta = \frac{\beta \cdot 6 \cdot 10^3 \cdot 0{,}75}{\beta \cdot 6 \cdot 10^3 \cdot 0{,}75 + 60 + \beta^2 \cdot 200} = \frac{4500 \cdot \beta}{4500 \cdot \beta + 60 + \beta^2 \cdot 200}.$$

We take a number of specific values β from NL (β=0) to the rated load (β=1) and determine the dependence numerically $\eta(\beta)$, which is given in the Table 5.

Calculated dependence curve $\eta(\beta)$ is presented in Fig. 8.

Table 5 – Calculation data of the efficiency curve

β	0	0,05	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1,0
η	0	0,788	0,879	0,93	0,945	0,951	0,953	0,953	0,952	0,95	0,948	0,945

4.2. Parameters and characteristics of a shunt-wound DC motor

Example 4. A shunt-wound DC motor (Fig. 3) has the following data in rated load condition: the rated power $P_{2\text{rated}}$ = 90 kW; the rated voltage U_{rated} = 220 V; the DC motor speed n_{rated} = 1060 rpm; efficiency η_{rated} = 0,892. The resistance of the armature circuit is $R_{\text{arm}} = 0{,}03$ Ohm; the resistance of the excitation winding – $R_{\text{ex}} = 25{,}6$ Ohm.

Determine the power for the rated load condition $P_{1\text{rated}}$ and current I_{rated}, which the motor consumes from the network; excitation winding current $I_{\text{ex rated}}$ and armature current $I_{\text{arm rated}}$; total power losses in the motor ΔP_{rated}; EMF of the armature E_{rated}; electromagnetic power $P_{\text{EM rated}}$; rotating electromagnetic torque M_{rated} and useful torque $M_{2\text{rated}}$.

Hint: ignore the reaction of the armature when calculating it.

Calculation. For the rated condition:

The power and current that the motor consumes from the network

$$P_{1\text{rated}} = \frac{P_{2\text{rated}}}{\eta_{\text{rated}}} = \frac{90}{0,892} = 100,9\ \text{kW};\quad I_{\text{rated}} = \frac{P_{1\text{rated}}}{U_{\text{rated}}} = \frac{100,9 \cdot 10^3}{220} = 458,6\ \text{A}.$$

The rated excitation current and the armature circuit current

$$I_{\text{ex rated}} = \frac{U_{\text{rated}}}{R_{\text{ex}}} = \frac{220}{25,6} = 8,6\ \text{A};\quad I_{\text{arm rated}} = I_{\text{rated}} - I_{\text{ex rated}} = 458,6 - 8,6 = 450\ \text{A}.$$

The rated total power losses in the motor

$$\Delta P_{\text{rated}} = P_{1\text{rated}} - P_{2\text{rated}} = 100,9 - 90 = 10,9\ \text{kW}.$$

The rated EMF of the armature

$$E_{\text{rated}} = U_{\text{rated}} - I_{\text{arm rated}} \cdot R_{\text{arm}} = 220 - 450 \cdot 0,03 = 206,5\ \text{V}.$$

The rated electromagnetic power

$$P_{\text{EM rated}} = E_{\text{rated}} \cdot I_{\text{arm rated}} = 206,5 \cdot 450 = 92925\ \text{W}.$$

The rated rotating electromagnetic and useful torques

$$M_{\text{rated}} = 9,55 \frac{P_{\text{EM rated}}}{n_{\text{rated}}} = 9,55 \frac{92925}{1060} = 837,2\ \text{N·m};$$

$$M_{2\text{rated}} = 9,55 \frac{P_{2\text{rated}}}{n_{\text{rated}}} = 9,55 \frac{90 \cdot 10^3}{1060} = 810,8\ \text{N·m}.$$

Example 5. A shunt-wound DC motor (Fig. 3) has the following data in the rated load condition: voltage $U_{\text{rated}} = 440$ V; armature current $I_{\text{arm rated}} = 200$ A. A resistance of the armature is $R_{\text{arm}} = 0,15$ Ohm.

Determine the resistance of the regulating rheostat R_{re}, which must be included in the armature circuit to limit the starting current of the armature to $I_{\text{arm start}} = 2,2 I_{\text{arm rated}}$, if the motor turns on at start-up at the rated voltage U_{rated}, and also find the value of the supply voltage U_{start}, to which it must be reduced so that the starting current of the armature $I_{\text{arm start}}$ would not exceed the value $I_{\text{arm start}} = 2,5 I_{\text{arm rated}}$ in the absence of a regulating rheostat.

Calculation. The resistance of the regulating rheostat at U_{rated} is determined from the formula for the armature current $I_{\text{arm}} = \frac{U_{\text{rated}}}{R_{\text{arm}} + R_{\text{re}}} = 2,2 I_{\text{arm rated}}$.

After conversion

$$R_{\text{re}} = \frac{U_{\text{rated}}}{2,2 I_{\text{arm rated}}} - R_{\text{arm}} = \frac{440}{2,2 \cdot 200} - 0,15 = 0,85\ \text{Ohm}.$$

Supply voltage U_{start} at $R_{\text{re}} = 0$ for $I_{\text{arm start}} = 2,5 I_{\text{arm rated}}$ is determined from the formula for the armature current $U_{\text{start}} = 2,5 \cdot I_{\text{arm rated}} \cdot R_{\text{arm}} = 2,5 \cdot 200 \cdot 0,15 = 75\ \text{V}$.

Example 6. A shunt-wound DC motor (Fig. 3) has the following the rated data: voltage $U_{\text{arm}} = 220$ V; armature and excitation currents: $I_{\text{arm rated}} = 130$ A, $I_{\text{ex rated}} = 5$ A; speed of rotation $n_{\text{rated}} = 1000$ rpm. The resistance of the armature is $R_{\text{arm}} = 0{,}1$ Ohm.

Build mechanical characteristics $n(M)$ at the rated voltage U_{rated}: a) natural one with a resistance $R_{\text{re}} = 0{,}2$ Ohm.

Analytical or, using a natural mechanical characteristic, determine the motor speed of rotation at $M = 0{,}5 \cdot M_{\text{rated}}$.

<u>Calculation</u>. It is known that the EMF of the motor is E and the electromagnetic torque M are determined by formulas:

$$E = C_E \cdot \Phi \cdot n; \quad (1) \qquad M = C_M \cdot \Phi \cdot I_{\text{arm}}, \quad (2)$$

where C_E, C_M – electric and mechanical motor constants; Φ – magnetic flux; I_{arm} – armature current.

In the rated condition:

$$E_{\text{rated}} = C_E \cdot \Phi_{\text{rated}} \cdot n_{\text{rated}}, \quad (3) \qquad M_{\text{rated}} = C_M \cdot \Phi_{\text{rated}} \cdot I_{\text{arm rated}}. \quad (4)$$

From formulas (1-4) we have

$$\frac{E}{E_{\text{rated}}} = \frac{\Phi \cdot n}{\Phi_{\text{rated}} \cdot n_{\text{rated}}}, \quad (5) \qquad \frac{M}{M_{\text{rated}}} = \frac{\Phi \cdot I_{\text{arm}}}{\Phi_{\text{rated}} \cdot I_{\text{arm rated}}}. \quad (6)$$

If the supply voltage is constant, then in the motor with parallel excitation, the magnetic flux Φ almost does not change even when its load changes. Therefore, given that $\Phi = \Phi_{\text{rated}}$, we have from the formulas (5) and (6)

$$n = n_{\text{rated}} \frac{E}{E_{\text{rated}}}, \quad (7) \qquad I_{\text{arm}} = I_{\text{arm rated}} \frac{M}{M_{\text{rated}}}. \quad (8)$$

It is also known that the EMF is determined by the formula

$$E = U - I_{\text{arm}} \cdot R_{\text{arm}}. \quad (9)$$

Substitute the current value from formula (8) into formula (9) and obtain

$$E = U - I_{\text{arm rated}} \cdot R_{\text{arm}} \cdot \frac{M}{M_{\text{rated}}}. \quad (10)$$

Substituting the value of E into formula (7), from formula (10) we have the basic formula for calculating mechanical characteristics

$$n = n_{\text{rated}} \frac{U}{E_{\text{rated}}} - \frac{I_{\text{arm rated}} \cdot n_{\text{rated}}}{E_{\text{rated}} \cdot M_{\text{rated}}} \cdot M \cdot R_{\text{arm}}. \quad (11)$$

For this motor, the following are defined:

the rated EMF

$$E_{\text{rated}} = U_{\text{rated}} - I_{\text{arm rated}} \cdot R_{\text{arm}} = 220 - 130 \cdot 0{,}1 = 207 \text{ V};$$

the rated electromagnetic power

$$P_{\text{EM rated}} = E_{\text{rated}} \cdot I_{\text{arm rated}} = 207 \cdot 130 = 26910 \text{ W};$$

the rated electromagnetic torque

$$M_{\text{rated}} = 9{,}55 \frac{P_{\text{EM rated}}}{n_{\text{rated}}} = 9{,}55 \frac{26910}{1000} = 257 \text{ N} \cdot \text{m}.$$

Natural mechanical characteristics $n(M)$ at $U = U_{\text{rated}}$ is determined by the basic formula (11) as follows

$$n = n_{\text{rated}} \frac{U_{\text{rated}}}{E_{\text{rated}}} - \frac{I_{\text{arm rated}} \cdot n_{\text{rated}}}{E_{\text{rated}} \cdot M_{\text{rated}}} \cdot M \cdot R_{\text{arm}} = n_0 - C \cdot M \cdot R_{\text{arm}}, \qquad (12)$$

where the motor speed of rotation at no-load condition ($M = 0$)

$$n_0 = n_{\text{rated}} \frac{U_{\text{rated}}}{E_{\text{rated}}} = 1000 \frac{220}{207} = 1063 \text{ rpm};$$

the motor constant

$$C = \frac{I_{\text{arm rated}} \cdot n_{\text{rated}}}{E_{\text{rated}} \cdot M_{\text{rated}}} = \frac{130 \cdot 1000}{207 \cdot 257} = 2{,}444 \ {}^{\text{r}}\!/_{\text{min} \cdot \text{Ohm} \cdot \text{N} \cdot \text{m}}.$$

The natural mechanical characteristic is a straight line (Fig. 9), which can be drawn along two points: point *A* with coordinates ($M = 0$, $n = n_0 = 1063$ rpm) and point *B* with coordinates ($M = M_{\text{rated}} = 257 \text{ N} \cdot \text{m}$, $n = n_{\text{rated}} = 1000$ rpm).

Artificial mechanical characteristic $n(M)$ when turning on the regulating rheostat with resistance $R_{\text{re}} = 0{,}2$ Ohm and when saving $U = U_{\text{rated}}$ is determined by the basic formula (11) as follows

$$n = n_{\text{rated}} \frac{U_{\text{rated}}}{E_{\text{rated}}} - \frac{I_{\text{arm rated}} \cdot n_{\text{rated}}}{E_{\text{rated}} \cdot M_{\text{rated}}} \cdot M \cdot (R_{\text{arm}} + R_{\text{re}}) = n_0 - C \cdot M \cdot (R_{\text{arm}} + R_{\text{re}}),$$

$$n = n_0 - C \cdot M \cdot (R_{\text{arm}} + R_{\text{re}}) = 1063 - 2{,}444 \cdot 257 \cdot (0{,}1 + 0{,}2) = 875 \text{ rpm}.$$

Speed of the motor n' at U_{rated} and $M = 0{,}5 \cdot M_{\text{rated}}$ and in the absence of a control rheostat is determined by the formula (12):

$$n' = n_0 - C \cdot 0{,}5 M_{\text{rated}} \cdot R_{\text{arm}} = 1063 - 2{,}444 \cdot 0{,}5 \cdot 257 \cdot 0{,}1 = 1031{,}5 \text{ rpm}.$$

We obtain the same result graphically from the natural mechanical characteristic for $M = 0{,}5 \cdot M_{\text{rated}}$ (Fig. 9, point *D*).

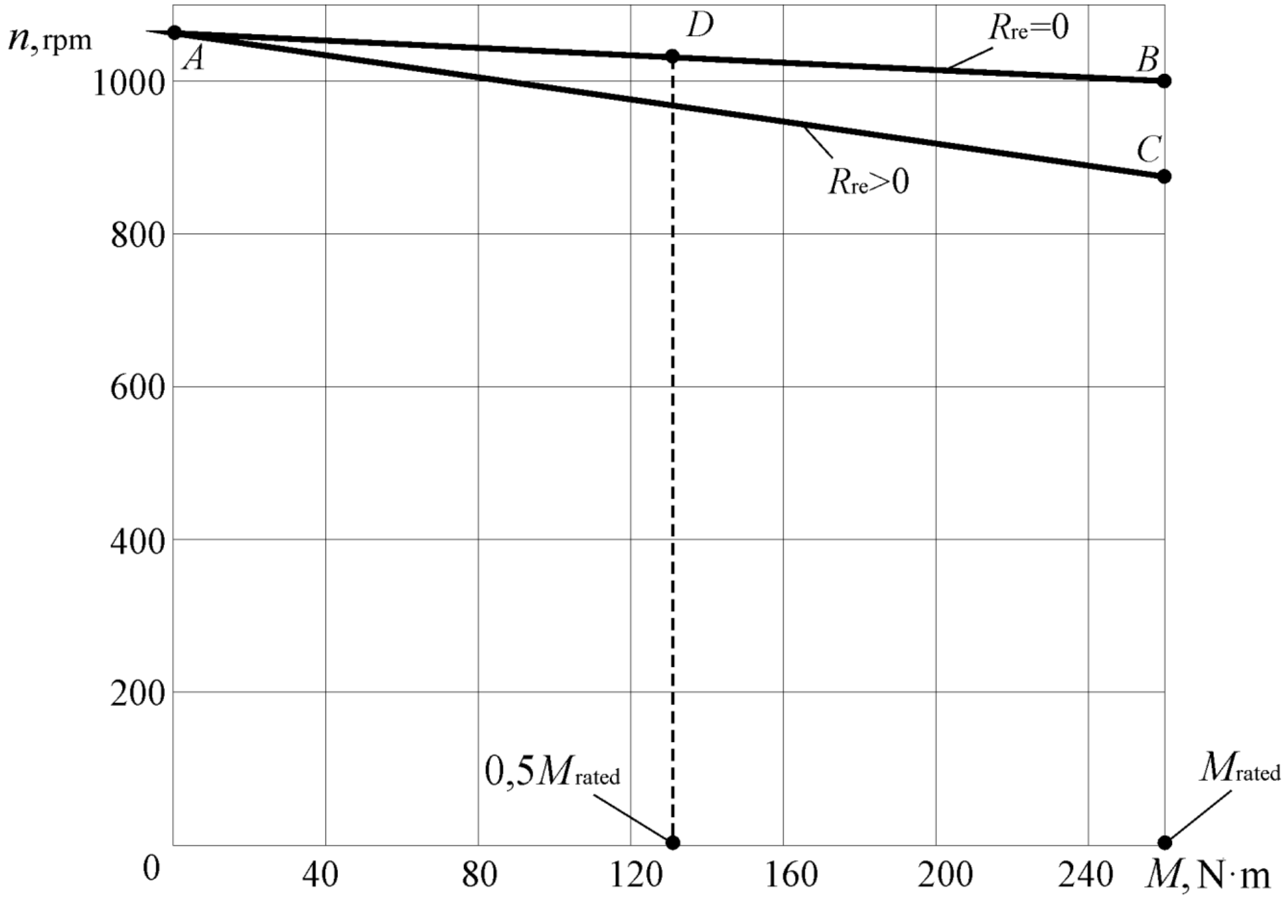

Figure 9

4.3. Parameters and characteristics of a series-wound DC motor

Example 7. A series-wound DC motor (Fig. 4) has the following rated data: power $P_{2\text{rated}} = 12$ kW; voltage $U_{\text{rated}} = 220$ V; speed of rotation $n_{\text{rated}} = 600$ rpm; efficiency $\eta_{\text{rated}} = 0{,}83$. The resistance of the armature circuit, taking into account the excitation winding, is $R_{\text{arm}} = 0{,}2$ Ohm .

Determine for the rated condition: power $P_{1\text{rated}}$ and current I_{rated}, which the motor consumes from the network; total power losses in the motor ΔP_{rated}; EMF of the armature E_{rated}; electromagnetic power $P_{\text{EM rated}}$; rotating electromagnetic torque M_{rated} and useful torques $M_{2\text{rated}}$.

Calculation. For the rated condition:

the power and current that the motor consumes from the network

$$P_{1\text{rated}} = \frac{P_{2\text{rated}}}{\eta_{\text{rated}}} = \frac{12}{0{,}83} = 14{,}46\ \text{kW};\quad I_{\text{rated}} = \frac{P_{1\text{rated}}}{U_{\text{rated}}} = \frac{14{,}46\cdot 10^{3}}{220} = 65{,}7\ \text{A};$$

the armature circuit current $I_{\text{arm rated}} = I_{\text{rated}} = 65{,}7$ A;

the total power losses in the motor

$$\Delta P_{\text{rated}} = P_{1\,\text{rated}} - P_{2\,\text{rated}} = 14{,}46 - 12 = 2{,}46 \text{ kW};$$

the EMF of the armature circuit

$$E_{\text{rated}} = U_{\text{rated}} - I_{\text{arm rated}} \cdot R_{\text{arm}} = 220 - 65{,}7 \cdot 0{,}2 = 206{,}86 \text{ V};$$

the electromagnetic power

$$P_{\text{EM rated}} = E_{\text{rated}} \cdot I_{\text{arm rated}} = 206{,}86 \cdot 65{,}7 = 13591 \text{ W};$$

the rotating electromagnetic and useful torques

$$M_{\text{rated}} = 9{,}55 \frac{P_{\text{EM rated}}}{n_{\text{rated}}} = 9{,}55 \frac{13591}{600} = 216{,}3 \text{ N} \cdot \text{m};$$

$$M_{2\text{rated}} = 9{,}55 \frac{P_{2\,\text{rated}}}{n_{\text{rated}}} = 9{,}55 \frac{12 \cdot 10^3}{600} = 191 \text{ N} \cdot \text{m}.$$

Example 8. A series-wound DC motor (Fig. 4) has the following rated data: the rated voltage $U_{\text{rated}} = 110$ V; the rated current $I_{\text{rated}} = 100$ A; speed of rotation $n_{\text{rated}} = 750$ rpm. The resistance of the armature circuit, taking into account the excitation winding, is $R_{\text{arm}} = 0{,}2$ Ohm. Characteristics of DCM magnetization $\Phi(I)$ – dependence of the magnetic flux Φ from the current I in relative units $k_{\Phi}(k_I)$ shown in Fig. 5.

Build with U_{rated}: *a*) natural and *b*) artificial mechanical characteristics $n(M)$. Build an artificial mechanical characteristic when in the armature circuit a regulating rheostat with resistance $R_{\text{re}} = 0{,}2$ Ohm is included.

Using built natural and artificial mechanical characteristics $n(M)$, determine the motor speed when the torque is reduced by 50 %, as well as when increasing it by 20 % from the rated value when the regulating rheostat with resistance is turned on R_{re} and in his absence.

Determine the speed of rotation at the rated torque M_{rated}, but with a decrease in the motor supply voltage to 20 % from the rated U_{rated} at $R_{\text{re}} = 0$.

Calculation.

To build mechanical characteristics $n(M)$ of a series-wound DCM can't directly use formula (11), which was obtained for a shunt-wound DCM (see example 6). The fact is that now a series-wound DCM has a magnetic flux of excitation Φ depending on the armature current I_{arm}, which is presented in Fig. 5 in relative units k_{Φ} (k_I), and changes with it ($I_{\text{arm}} = I = I_{\text{ex}}$, where I, I_{ex} – respectively, the current consumed by the motor from the network and the current of the excitation winding).

Therefore, the following transformations of formulas (1, 2, 9) were made from the example 6.

From the EMF formula $E = C_E \cdot n \cdot \Phi$ it is $n = \dfrac{E}{C_E \cdot \Phi}$.

Let's put it in the last one $E = U - R_{\text{arm}} \cdot I_{\text{arm}}$, and receive

$$n = \frac{U - R_{\text{arm}} \cdot I_{\text{arm}}}{C_E \cdot \Phi}. \tag{1}$$

Using relative values k_I and k_Φ we express the armature current and the magnetic flux:

$$I_{\text{arm}} = k_I \cdot I_{\text{arm rated}}; \qquad \Phi = k_\Phi \cdot \Phi_{\text{rated}}. \tag{2}$$

Let's substitute this in formula (1) and then

$$n = \frac{U - k_I \cdot I_{\text{arm rated}} \cdot R_{\text{arm}}}{C_E \cdot k_\Phi \cdot \Phi_{\text{rated}}} \tag{3}$$

In the rated condition, the EMF of the armature

$$E_{\text{rated}} = C_E \cdot n_{\text{rated}} \cdot \Phi_{\text{rated}},$$

from where $\Phi_{\text{rated}} = \frac{E_{\text{rated}}}{C_E \cdot n_{\text{rated}}}$, taking into account what from (3) we get the formula for calculating the speed of rotation of the motor

$$n = n_{\text{rated}} \frac{U - k_I \cdot I_{\text{arm rated}} \cdot R_{\text{arm}}}{k_\Phi \cdot E_{\text{rated}}}. \tag{4}$$

In addition, based on the torque formula $M = C_M \cdot \Phi \cdot I_{\text{arm}}$ taking into account (2), we have $M = C_M \cdot k_\Phi \cdot k_I \cdot \Phi_{\text{rated}} \cdot I_{\text{arm rated}}$, and, because of that $M_{\text{rated}} = C_M \cdot \Phi_{\text{rated}} \cdot I_{\text{arm rated}}$, we get the formula for calculating the rotating electromagnetic torque

$$M = k_I \cdot k_\Phi \cdot M_{\text{rated}}. \tag{5}$$

To build mechanical characteristics, we will find the following data:

the rated EMF

$$E_{\text{rated}} = U_{\text{rated}} - I_{\text{arm rated}} \cdot R_{\text{arm}} = 110 - 100 \cdot 0{,}2 = 90 \text{ V};$$

the rated electromagnetic power

$$P_{\text{EM rated}} = E_{\text{rated}} \cdot I_{\text{rated}} = 90 \cdot 100 = 9000 \text{ W};$$

the rated rotating electromagnetic torque

$$M_{\text{rated}} = 9{,}55 \frac{P_{\text{EM rated}}}{n_{\text{rated}}} = 9{,}55 \frac{9000}{750} = 114{,}6 \text{ N} \cdot \text{m}.$$

To build a natural mechanical characteristic $n(M)$ let's use the formula (4), which is at rated voltage $U = U_{\text{rated}}$ has the appearance of

$$n = n_{\text{rated}} \frac{U_{\text{rated}} - k_I \cdot I_{\text{arm rated}} \cdot R_{\text{arm}}}{k_\Phi \cdot E_{\text{rated}}}, \tag{6}$$

as well as formula (5) and the magnetization curve $k_\Phi(k_I)$ in relative units, shown in Fig. 5.

By given values k_I, we define k_Φ according to Fig. 5, and values M and n by formulas (5) and (6). We summarize the data of all calculations in Table 6. According to the calculation results, Fig. 10 shows the natural mechanical characteristics (curve 1).

Table 6 – Calculation data of mechanical characteristics

k_I	0,4	0,6	0,8	1,0	1,2
k_Φ	0,65	0,8	0,91	1,0	1,08
M, N · m	29,8	55,0	83,4	114,6	148,5
n, rpm at $R_{\text{re}} = 0$ Ohm	1308	1021	861	750	664
n, rpm at $R_{\text{re}} = 0{,}2$ Ohm	1205	896	714	583	478

To build an artificial mechanical characteristic $n(M)$ again at U_{rated}, but with additional resistance in the armature circuit $R_{\text{re}} = 0{,}2$ Ohm from formula (6) we get a modified formula

$$n = n_{\text{rated}} \frac{U_{\text{rated}} - k_I \cdot I_{\text{arm rated}} \cdot (R_{\text{arm}} + R_{\text{re}})}{k_\Phi \cdot E_{\text{rated}}} . \tag{7}$$

The rest remains as in the previous case, that is, we use formula (5) and the magnetization curve $k_\Phi(k_I)$.

Being set by values k_I, we define k_Φ according to Fig. 5, and values n and M by formulas (5) and (7). All calculations are summarized in Table 6. According to the calculation results, Fig. 10 shows the artificial mechanical characteristics (curve 2).

Using the natural mechanical characteristic, we determine the speed of the armature:

n_A=1000 rpm at $M = 0{,}5 \cdot M_{\text{rated}} = 57{,}3$ N · m (point A),

n_B=685 rpm at $M = 1{,}2 \cdot M_{\text{rated}} = 137{,}5$ N · m (point B).

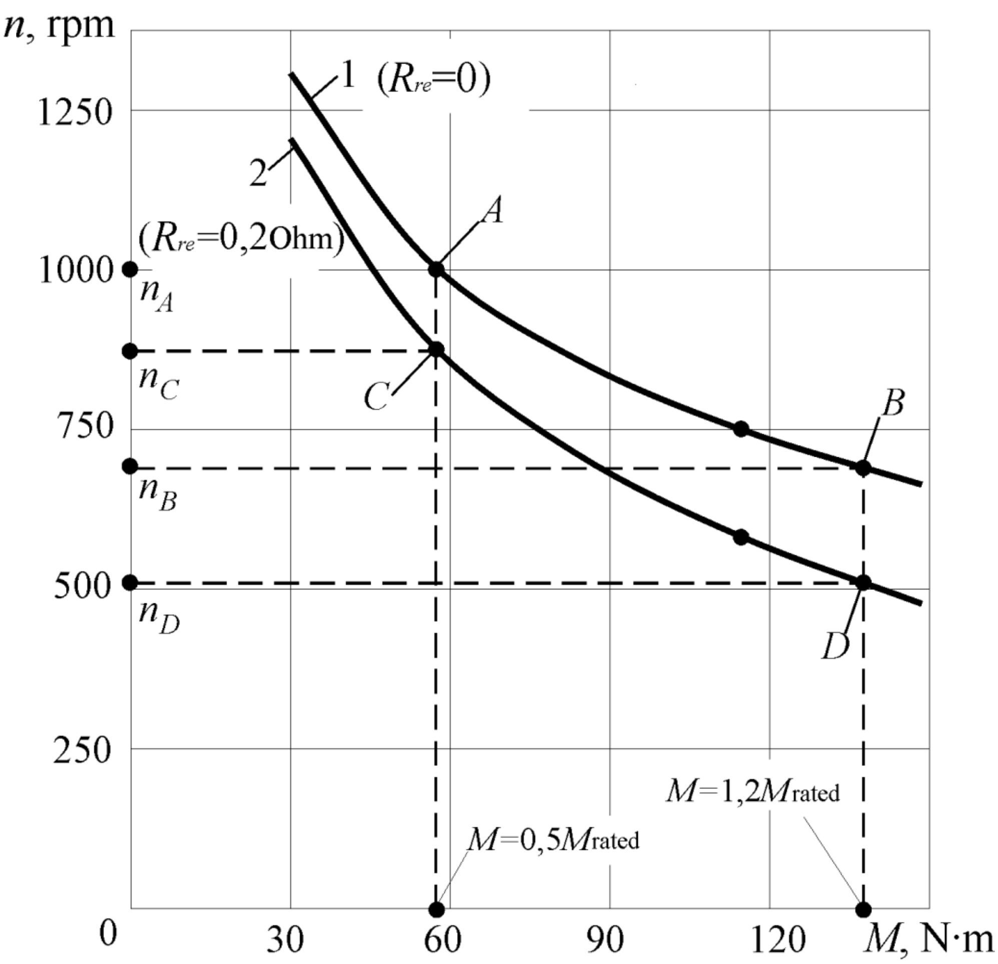

Figure 10

Using an artificial mechanical characteristic, we determine the speed of the motor:

$n_C = 875$ rpm at $M = 0{,}5 \cdot M_{\text{rated}} = 57{,}3\ \text{N} \cdot \text{m}$ (point *C*),

$n_D = 510$ rpm at $M = 1{,}2 \cdot M_{\text{rated}} = 137{,}5\ \text{N} \cdot \text{m}$ (point *D*).

When reducing the supply voltage to 20 %, compared to its rated value, the speed of rotation of the motor at M_{rated} and $R_{\text{re}} = 0$ is defined as follows.

To obtain by formula (5) $M = M_{\text{rated}}$ must be taken $k_I = 1$; $k_\Phi = 1$. Then, using formula (4), taking into account that in this case $U = 0{,}8 \cdot U_{\text{rated}}$, we have

$$n = n_{\text{rated}} \frac{0{,}8 \cdot U_{\text{rated}} - I_{\text{arm rated}} \cdot R_{\text{arm}}}{E_{\text{rated}}} = 750 \frac{0{,}8 \cdot 110 - 100 \cdot 0{,}2}{90} = 567\ \text{rpm}.$$

4.4. Parameters and characteristics of a three-phase induction motor

Example 9. A three-phase induction motor has the following data: the rated voltage 220/380 V (phase/line) at the frequency $f_1 = 50$ Hz; the rated slip $S_{\text{rated}} = 0{,}05$; the number of pairs of poles $p = 6$; overload capacity from torque $\lambda_M = 1{,}8$. The connection scheme of the stator windings is a star (Fig. 6, *a*). Select the line voltage of the power supply network U_{net} and determine the rated synchronous speed of the stator magnetic field, rated $n_{2\text{rated}}$ and critical $n_{2\text{cr}}$ speed of rotation of the rotor.

Calculation. When connecting the stator windings in a wye "Y" $U_{\text{L}} = \sqrt{3} \cdot U_{\text{Ph}}$, where U_{L} and U_{Ph} – respectively, line and phase voltages of the stator winding. Therefore, the line voltage of the network $U_{\text{net}} = U_{\text{L}} = 380$ V.

Synchronous speed of the stator magnetic field

$$n_1 = \frac{60 \cdot f_1}{p} = \frac{60 \cdot 50}{6} = 500 \text{ rpm.}$$

The rated speed of rotation of the rotor

$$n_{2\text{rated}} = n_1(1 - S_{\text{rated}}) = 500(1 - 0{,}05) = 475 \text{ rpm.}$$

To determine the critical rotor speed

$$n_{2\text{cr}} = n_1(1 - S_{\text{cr}}),$$

it is necessary to know the critical slip of the motor S_{cr}. This is the meaning of slip S, at which the torque M reaches the maximum value M_{max}.

To define S_{cr} we use the well-known Kloss's formula

$$M = \frac{2 \cdot M_{\text{max}}}{S/S_{\text{cr}} + S_{\text{cr}}/S}$$

and the rated operating condition of the motor, in which the rated value of the slip corresponds to the rated value of the torque

$$M_{\text{rated}} = \frac{2 \cdot M_{\text{max}}}{S_{\text{rated}}/S_{\text{cr}} + S_{\text{cr}}/S_{\text{rated}}}.$$

Considering that the overload capacity from the torque $\lambda_{\text{M}} = M_{\text{max}}/M_{\text{rated}}$, from the previous formula we have

$$\frac{S_{\text{cr}}}{S_{\text{rated}}} + \frac{S_{\text{rated}}}{S_{\text{cr}}} = 2\lambda_{\text{M}},$$

from which we get the quadratic equation

$$S_{\text{cr}}^2 - 2\lambda_{\text{M}} S_{\text{rated}} S_{\text{cr}} + S_{\text{rated}}^2 = 0,$$

the solution of which gives the expression and value of critical slip

$$S_{\text{cr}} = S_{\text{rated}}(\lambda_{\text{M}} + \sqrt{\lambda_{\text{M}}^2 - 1}) = 0{,}05(1{,}8 + \sqrt{1{,}8^2 - 1}) = 0{,}165.$$

Thus, the critical speed of rotation of the motor

$$n_{2\text{cr}} = n_1(1 - S_{\text{cr}}) = 500(1 - 0{,}165) = 417{,}5 \text{ rpm.}$$

Example 10. A three-phase induction motor has the following data in the rated condition: power on the shaft $P_{2\text{rated}} = 22$ kW; voltage 220/380 V (phase/line); efficiency $\eta_{\text{rated}} = 0{,}9$; power factor $\cos\varphi_{1\text{rated}} = 0{,}88$. Multiplicity of starting current $\lambda_I = 5{,}5$. The connection diagram of the stator windings is a delta (Fig. 6, *b*). Select the line voltage of the power supply network U_{net} and determine the rated and starting currents of the stator winding.

Calculation. When connecting the stator winding in a delta $U_{\text{L}} = U_{\text{Ph}}$, therefore the line voltage of the network $U_{\text{net}} = U_{\text{L}} = U_{\text{Ph}} = 220$ V.

Considering that the power consumed by the motor from the network has an expression from one side, $P_{1\text{rated}} = \dfrac{P_{2\,\text{rated}}}{\eta_{\text{rated}}}$, and from another – $P_{1\text{rated}} = \sqrt{3}\,U_{\text{net}} I_{\text{L rated}} \cos\varphi_{1\text{rated}}$, we get the rated line and phase currents of the motor stator winding

$$I_{\text{L rated}} = \frac{P_{2\text{rated}}}{\sqrt{3}\cdot U_{\text{net}}\cdot\eta_{\text{rated}}\cdot\cos\varphi_{1\text{rated}}} = \frac{22\cdot 10^3}{\sqrt{3}\cdot 220\cdot 0{,}9\cdot 0{,}88} = 72{,}9 \text{ A;}$$

$$I_{\text{Ph rated}} = \frac{I_{\text{L rated}}}{\sqrt{3}} = \frac{72{,}9}{\sqrt{3}} = 41{,}7 \text{ A.}$$

Starting line and phase currents of the motor stator winding

$$I_{\text{L start}} = \lambda_I \cdot I_{\text{L rated}} = 5{,}5\cdot 72{,}9 = 401 \text{ A;}$$

$$I_{\text{Ph start}} = \lambda_I \cdot I_{\text{Ph rated}} = 5{,}5\cdot 41{,}7 = 229 \text{ A.}$$

Example 11. A three-phase induction motor is connected to the network with line voltage $U_{\text{net}} = 380$ V and has the following data in rated condition: power on the shaft $P_{2\text{rated}} = 45$ kW; voltage 220/380 (phase/line); the rotor speed of rotation $n_{2\text{rated}} = 580$ rpm; efficiency $\eta_{\text{rated}} = 0{,}9$; power factor $\cos\varphi_{1\text{rated}} = 0{,}81$. In addition, the motor has a multiple of starting current $\lambda_I = 5{,}0$; its torque overload capacity $\lambda_M = 1{,}8$. Determine the rated power $P_{1\text{rated}}$, consumed by the motor from the network; the sum of all power losses in the motor ΔP_{rated}; rated and starting currents of the motor stator winding; rated M_{rated} and the maximum $M_{\max}$ rotating torques.

Calculation. The rated power consumed by the motor from the network

$$P_{1\text{rated}} = \frac{P_{2\,\text{rated}}}{\eta_{\text{rated}}} = \frac{45}{0{,}9} = 50 \text{ kW.}$$

The sum of all losses in the motor

$$\Delta P_{\text{rated}} = P_{1\text{rated}} - P_{2\,\text{rated}} = 50 - 45 = 5 \text{ kW.}$$

At a given network voltage $U_{\text{net}} = 380\text{ V}$ the phases of the stator winding will be wye-connected “Y” (Fig.6, *a*). At the same time, the line and phase currents are the same:

$$I_{\text{L rated}} = I_{\text{Ph rated}} = \frac{P_{2\text{rated}}}{\sqrt{3}\cdot U_{\text{net}}\cdot\eta_{\text{rated}}\cdot\cos\varphi_{1\text{rated}}} = \frac{45\cdot 10^3}{\sqrt{3}\cdot 380\cdot 0{,}9\cdot 0{,}81} = 93{,}8 \text{ A.}$$

Starting currents: $I_{\text{L start}} = I_{\text{Ph start}} = \lambda_I \cdot I_{\text{L rated}} = 5{,}0\cdot 93{,}8 = 469$ A.

The rated and maximum torque

$$M_{\text{rated}} = 9{,}55\frac{P_{2\,\text{rated}}}{n_{2\,\text{rated}}} = 9{,}55\frac{45\cdot 10^3}{580} = 741 \ \text{N}\cdot\text{m};$$

$$M_{\max} = \lambda_M \cdot M_{\text{rated}} = 1{,}8\cdot 741 = 1334 \ \text{N}\cdot\text{m}.$$

Example 12. A three-phase induction motor has the following data in rated condition: power on the shaft $P_{2\text{rated}} = 15\,\text{kW}$; speed of rotation of the stator magnetic field $n_1 = 1500$ rpm; slip $S_{\text{rated}} = 0{,}05$. Overload capacity from torque $\lambda_M = 2{,}5$. Calculate and plot the dependence of the torque on sliding *M*(*S*) and determine the starting torque M_{start} and its multiplicity k_{start} relative to the rated torque.

Calculation. For practical calculations, dependence *M*(*S*) at $U_{\text{net}} = \text{const}$ is determined by the Kloss’s formula:

$$M = \frac{2\cdot M_{\max}}{S/S_{\text{cr}} + S_{\text{cr}}/S} = \frac{2\cdot 250}{S/0{,}24 + 0{,}24/S} = \frac{500}{S/0{,}24 + 0{,}24/S} \ \text{N}\cdot\text{m}.$$

Critical slip

$$S_{\text{cr}} = S_{\text{rated}}(\lambda_M + \sqrt{\lambda_M^2 - 1}) = 0{,}05(2{,}5 + \sqrt{2{,}5^2 - 1}) = 0{,}24.$$

Rated motor speed

$$n_{2\text{rated}} = n_1(1 - S_{\text{rated}}) = 1500(1 - 0{,}05) = 1425 \ \text{rpm}.$$

Rated and maximum torque

$$M_{\text{rated}} = 9{,}55\frac{P_{2\,\text{rated}}}{n_{2\,\text{rated}}} = 9{,}55\frac{15\cdot 10^3}{1425} = 100 \ \text{N}\cdot\text{m};$$

$$M_{\max} = \lambda_M \cdot M_{\text{rated}} = 2{,}5\cdot 100 = 250\,\text{N}\cdot\text{m}.$$

Now, given the values of *S* from 0 to 1, it is necessary to determine the value of the torque according to the Kloss’s formula. At the same time, we note that there is a dependence on time *M*(*S*), which corresponds to stable engine operation conditions ($0 \le S \le S_{\text{cr}}$), it is enough to have four points at

$$S = 0; \quad S = S_{\text{rated}}; \quad S_{\text{rated}} \le S \le S_{\text{cr}}; \quad S = S_{\text{cr}}.$$

In the part of dependence *M*(*S*) with unstable motor operating conditions ($S_{\text{cr}} < S \le 1$) the following slip values can be specified *S*: 0,3; 0,4; 0,6; 0,8; 1.

The calculation results are summarized in Table 7.

The starting torque of the motor is determined at $S = 1$ and is equal to $M_{\text{start}} = 113 \ \text{N}\cdot\text{m}$, then the multiplicity of this moment

$$k_{\text{start}} = \frac{M_{\text{start}}}{M_{\text{rated}}} = \frac{113}{100} = 1{,}13.$$

Table 7 – Dependency calculation data $M(S)$

S	0	$S_{\text{rated}}=$ $=0{,}05$	0,1	$S_{\text{cr}}=$ $=0{,}24$	0,3	0,4	0,6	0,8	1,0
M, Н·м	0	100	178	250	244	221	172	137	113

According to the data in Table 7, Fig. 11 shows the dependence $M(S)$.

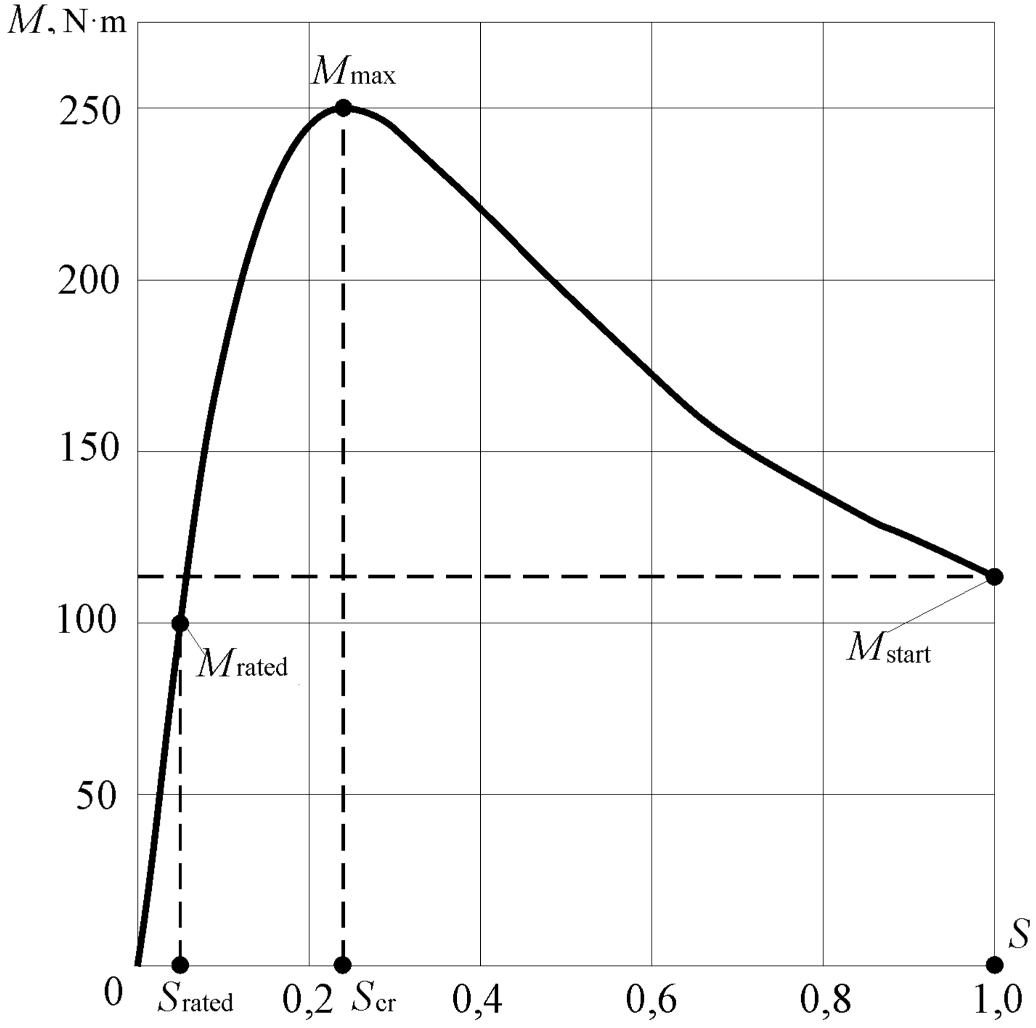

Figure 11

Example 13. A three-phase induction motor has the following data in rated condition: power on the shaft $P_{2\text{rated}} = 11$ kW; speed of rotation of the stator magnetic field $n_1 = 1000$ rpm; slip $S_{\text{rated}} = 0{,}06$. Overload capacity from torque $\lambda_M = 2{,}5$. Calculate and build in one coordinate system three mechanical characteristics – the dependence of the rotor speed of rotation on the torque $n_2(M)$ under the following conditions:

a) natural mechanical characteristic at network voltage $U_{\text{net}} = 380$ V, and also to determine from it the range of the rotor speed of rotation at which stable operation of the motor is possible;

b) artificial mechanical characteristic at a reduced voltage of the power supply network 10 %, that is, at $U = 0{,}9U_{\text{net}}$;

c) an artificial mechanical characteristic under the condition that the total resistance in each phase of the rotor winding became twice as large as that of the engine for which the previous characteristics were calculated, i.e. $R_2' = 2R_2$ (this is possible if this motor was a wound-rotor motor (Fig. 7) and then in the phase of the rotor winding it would be possible to turn on the regulating rheostats with resistances R_{re}, which are equal to R_2), while the inductive reactance of the phases of the rotor winding X_{20} does not change; consider the network voltage to be equal U_{net}.

Calculation. Rated motor speed

$$n_{2\text{rated}} = n_1(1 - S_{\text{rated}}) = 1000(1 - 0{,}06) = 940 \text{ rpm.}$$

Critical slip

$$S_{\text{cr}} = S_{\text{rated}}(\lambda_M + \sqrt{\lambda_M^2 - 1}) = 0{,}06(2{,}5 + \sqrt{2{,}5^2 - 1}) = 0{,}288 .$$

The rated and maximum torque:

$$M_{\text{rated}} = 9{,}55\frac{P_{2\text{rated}}}{n_{2\text{rated}}} = 9{,}55\frac{11 \cdot 10^3}{940} = 112 \text{ N} \cdot \text{m} ;$$

$$M_{\max} = \lambda_M \cdot M_{\text{rated}} = 2{,}5 \cdot 112 = 280 \text{ N} \cdot \text{m} .$$

Natural mechanical characteristic $n_2(M)$ at $U_{\text{net}} = \text{const}$ obtained by separate calculations of speed of rotation and torque, given by slip values S from 0 to 1 in formulas:

$$n_2 = n_1(1 - S) = 1500(1 - S) \text{ rpm;}$$

$$M = \frac{2 \cdot M_{\max}}{S/S_{\text{cr}} + S_{\text{cr}}/S} = \frac{2 \cdot 280}{S/0{,}288 + 0{,}288/S} = \frac{560}{S/0{,}288 + 0{,}288/S} \text{ N} \cdot \text{m} .$$

Now, in order to obtain a natural mechanical characteristic, it is enough to set a number of S values from 0 to 1 and perform calculations according to the given formulas. The slip value S for the mechanical characteristic is selected in the same way as in example 12. In addition, it is always necessary to make a calculation for the slip values S_{rated} and S_{cr}.

The calculation results are summarized in Table 8, where the value is added $S'_{\text{cr}} = 0{,}576$, which is defined below (S'_{cr} is important for third characteristic – artificial given in Table 8).

According to the data in Table 8, Fig. 12 shows the natural mechanical characteristics $n_2(M)$ at $U = U_{\text{net}}$, $R_{\text{re}} = 0$

Table 8 – Calculation data of the mechanical characteristics of the induction motor

S	0	0,06	0,1	0,2	0,288	0,4	0,576	0,6	0,8	1,0
n_2, rpm	1000	940	900	800	712	600	434	400	200	0
M, $\text{N}\cdot\text{m}$ at $U = U_{\text{net}}$, $R_{\text{re}} = 0$	0	112	173	262	280	265	223	218	178	149
M, $\text{N}\cdot\text{m}$ at $U = 0{,}9U_{\text{net}}$, $R_{\text{re}} = 0$	0	90	140	212	227	215	201	177	144	120
M, $\text{N}\cdot\text{m}$ at $U = U_{\text{net}}$, $R_{\text{re}} = R_2$	0	58	94	173	223	262	280	278	265	242

To obtain an artificial mechanical characteristic when reducing the voltage of the power supply network by 10 %, that is, at $U = 0{,}9U_{\text{net}}$, we will use the same formulas as in the previous case for natural mechanical characteristics. But at the same time, it should be taken into account that the maximum torque varies depending on this voltage in this way

$$M'_{\max} = \left(\frac{U}{U_{\text{net}}}\right)^2 M_{\max} = (0{,}9U_{\text{net}})^2 M_{\max} = 0{,}81 \cdot 280 = 227\ \text{N}\cdot\text{m}.$$

That is, the artificial mechanical characteristic under such conditions is determined for the same values of slip S and speed of rotation of the rotor n_2, calculating the torque using the formula

$$M = \frac{2M'_{\max}}{S/S_{\text{cr}} + S_{\text{cr}}/S} = \frac{2 \cdot 227}{S/0{,}288 + 0{,}288/S} = \frac{454}{S/0{,}288 + 0{,}288/S}\ \text{N}\cdot\text{m}$$

(as you know, the value S_{cr} does not depend on the value of the supply voltage).

The results of the calculations are summarized in Table 8.

According to the data in Table 8, Fig. 12 shows an artificial mechanical characteristic $n_2(M)$ at $U = 0{,}9U_{\text{net}}$, $R_{\text{re}} = 0$.

In order to obtain an artificial mechanical characteristic when regulating rheostats with resistances are switched into the phases of the rotor winding $R_{\text{re}} = R_2$, the calculation will be based on the same formulas that were already used. But it should be remembered that the critical slip depends on the total resistance of the phase and in this case is equal to $S_{\text{cr}} = R_2 / X_{20}$.

Therefore, when adding to resistance R_2 also an regulating rheostat with resistance $R_{\text{re}} = R_2$ and preserving the inductive reactance of the stator winding phase X_{20}, compose the proportion and get a new value of the critical slip for the considered artificial mechanical characteristic, i.e.

$$S'_{\text{cr}} = \frac{R_2 + R_{\text{re}}}{R_2} S_{\text{cr}} = \frac{R_2 + R_2}{R_2} S_{\text{cr}} = 2\, S_{\text{cr}} = 2 \cdot 0{,}288 = 0{,}576\,.$$

Maximum torque $M_{\max}$ does not depend on resistances R_2 and R_{re} and is preserved in such a way that for the natural mechanical characteristic (it will now be obtained at the new value of critical slip S'_{cr}). Note that this artificial mechanical characteristic is calculated at the supply voltage $U = U_{\text{net}}$.

Thus, an artificial mechanical characteristic under certain conditions ($R_{\text{re}} = R_2$, $U = U_{\text{net}}$) we obtain for the same values of slip S and speed of rotation of the rotor n_2, as previously, calculating the torque according to the modified formula

$$M = \frac{2\, M_{\max}}{S/S'_{\text{cr}} + S'_{\text{cr}}/S} = \frac{2 \cdot 280}{S/0{,}576 + 0{,}576/S} = \frac{560}{S/0{,}576 + 0{,}576/S}\ \text{N} \cdot \text{m}\,.$$

The results of the calculations are summarized in Table 8.

According to the data in Table 8, Fig. 12 shows an artificial mechanical characteristic $n_2(M)$ at $U = U_{\text{net}}$ and $R_{\text{re}} = R_2$.

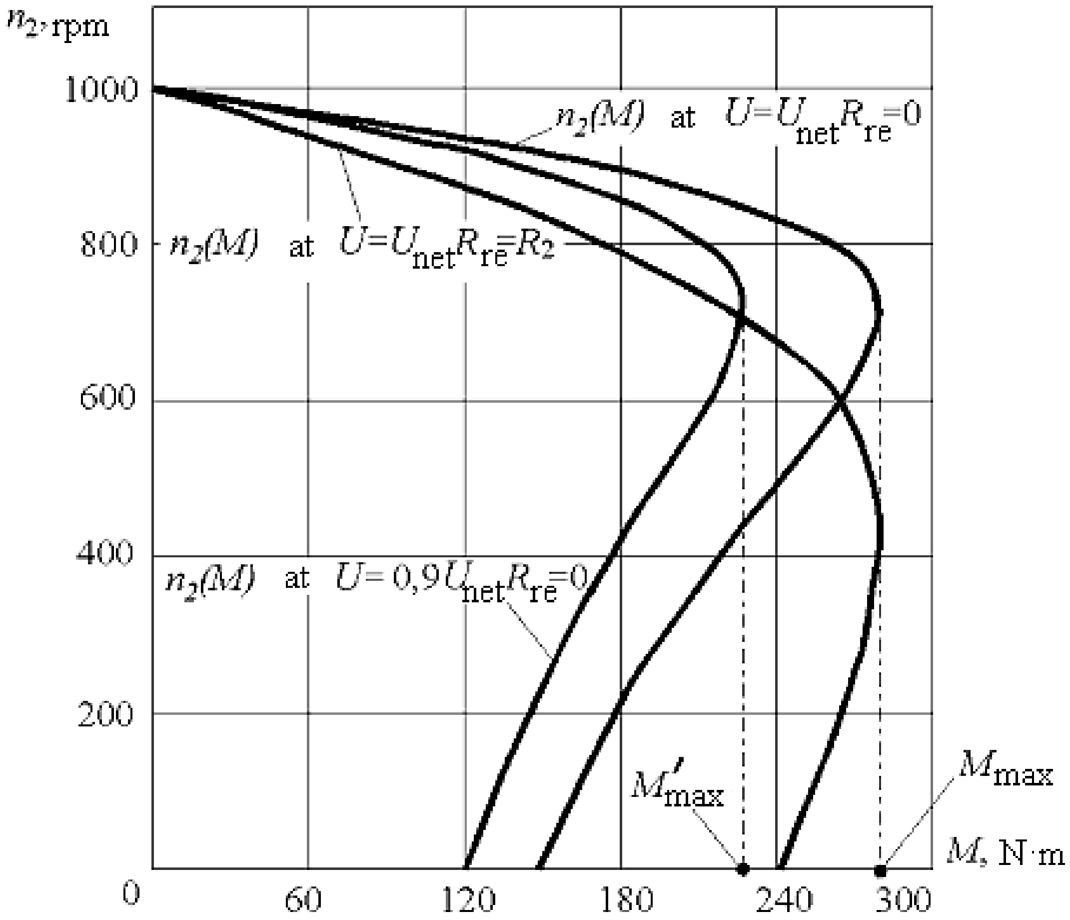

Figure 12

BIBLIOGRAPHY

1. Lectures on electrical engineering / Tutorial for students. V. Boliukh, K. Korytchenko, V. Markov and others. – Kharkiv, NTU “KhPI”, 2023. – 272 p.

2. Розрахунок електричних кіл та електротехнічних пристроїв : навч. посібник / В.Ф. Болюх, К.В. Коритченко, В.С. Марков, І.В. Поляков. – Харків: НТУ «ХПІ», 2019. – 288 с.

3. Болюх В.Ф. Основи електротехніки, електроніки та мікропроцесорної техніки: навч. посіб / В.Ф. Болюх, В.Г. Данько, Є.В. Гончаров; за ред. В.Г.Данька : НТУ «ХПІ» – Харків: Планета-Прінт, 2019. – 248 с.

4. Клименко Б.В. Електричні та магнітні пристрої, електричні аксесуари, електричні установки. Терміни, тлумачення, коментарі. Навчальний посібник. – Харків: Точка, 2009. – 272 с.

5. Electric and magnetic devices: meth. instructions for laboratory works on electrical engineering. In three parts. P. II / V.F. Boliukh, E.V. Honcharov, V.S.Markov and others. – Kharkiv, NTU “KhPI”, 2023. – 38 p.

6. John Bird Electrical Circuit Theory and Technology. – Oxford Revised: Newnes, 2003, 984 p.

7. DOE fundamentals handbook electrical science Volume 1 of 4. – Washington, D.C.: U.S. Department of Energy, 1992.

8. Navy Electricity and Electronics Training Series. Edition Prepared by ETCS(SW) Donnie Jones, 1998.

9. Alan L. Sheldrake Handbook of Electrical Engineering: For Practitioners in the Oil, Gas and Petrochemical Industry, John Wiley & Sons, Ltd, 2003, 625 p.

10. https://www.electropedia.org IEC 60050 International Electrotechnical Vocabulary.

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Розрахунок параметрів та характеристик електротехнічних пристроїв.

Методичні вказівки до розрахунково-графічної роботи з електротехніки
(англ. мовою)

з навчальної дисципліни
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та заочно-дистанційної форми навчання

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