MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE

National Technical University

"Kharkiv Polytechnic Institute"

CALCULATION OF TRANSFORMERS AND ELECTRIC MACHINES CHARACTERISTICS

Methodical instructions for performing calculation tasks
on the discipline "Electric machines"
for full-time foreign students
of specialty 141 – Power engineering, electrical engineering
and electromechanics

Kharkiv – 2022

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Electrical Machines Department

INTRODUCTION

This edition is dedicated to the implementation of calculation task « Calculation of characteristics the transformers and electric machines» on the discipline «Electric machines», which students of electrical engineering specialties study in the 5th semester.

The purpose of this discipline is to consolidate theoretical knowledge and develop practical skills for calculating the characteristics of transformers and alternation current (AC) and direct current (DC) electric machines.

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

The subject of discipline are the electric machines, which are used to convert one form of energy to another: mechanical energy to electrical (the generators), electrical energy to mechanical (the engines), and power transformers, which are necessary to convert the alternating current and voltage parameters in the process of transmission and distribution of electricity.

After training, the student must know the transformers and electric machines structure, there operation principle and characteristics, peculiarities of motors starting, the ways of rotation frequency control and braking; know the features of electric generators operation of different types power plants. The student should be able to evaluate new electrical equipment, take into account technical and economic requirements.

These methodological instructions contain five homework tasks. Each task has control questions, calculation tasks and recommendations for answering questions and solving these tasks. Completion of the calculation task is necessary for the student to master the discipline "Electric Machines". The progress report must be completed in writing and defended by the exam date. Tasks and scope of work must be agreed with the teacher of this discipline.

The report should begin with a title page, the sample of which is given in Appendix A. When drawing up a report, it is necessary to formulate the task, show the procedure for performing calculations: write down a formula, and then put numbers in this formula and show the result of the calculation. The report should contain the necessary diagrams and graphs. At the end of the work student has to give the list of information sources that were used in the work. Graphs and diagrams should be built on graph paper, indicating the scale and dimension of the physical quantity on the axes. If the graph was built on a regular sheet of paper, then a uniform "grid" should be drawn on the graph field.

Students choose the number of a variant for the work according to the number in the academic group list. New modern notation symbol system of electrical, magnetic, mechanical and energy values, which correspond to the state standards and the international system of units SI, are used in this study course.

1 DESIGN DESCRIPTION AND PARAMETERS CALCULATION OF THE TRANSFORMERS IN THE NOMINAL MODE

1.1 Theoretical assignments

1) Make the classification of transformers.

2) Perform a sketch of three-phase power transformer with two windings per phase and oil-cooled. Describe the oil tank main elements.

3) Write the definition of next parameters: transformation ratio of the transformer, short circuit voltage, transformer magnetizing current.

4) Write down the turning conditions of three-phase transformer for parallel operation with other transformers and with network.

5) What schemes of transformer windings connection are? What groups of transformer windings connection are used in industry?

1.2. Practical task

Calculation of the transformer nominal parameters according to the results that were obtained in the idling test and in the test in the laboratory short circuit mode

1) Build the three-phase transformer equivalent circuits in the three modes (in the idle mode, in laboratory short circuit mode and in nominal mode) and calculate the parameters of these schemes (m=3, where m – is a number of phases). The transformer operates in the power grid with a voltage frequency f = 50 Hz and has the data shown in Fig. 1 and in the Table 1. Calculate the transformer parameters in the nominal mode according to the idling mode data and the data of laboratory short-circuit mode.

Indicate the numerical values of the elements, currents, electrical moving force (EMF) and voltages on Fig. 2.

***Note*:** in the section the following notations are used:

– primary winding is the index p (*prime*);

– secondary winding is the index s (*second*);

– active resistance R_p and reactive resistance X_p of the primary winding;

– equivalent active resistance $R_s^/$ and equivalent reactive resistance $X_s^/$ of the secondary winding;

– active and reactive resistance of the transformer magnetization core (R_m and X_m).

All circuits and calculations are performed for one phase.

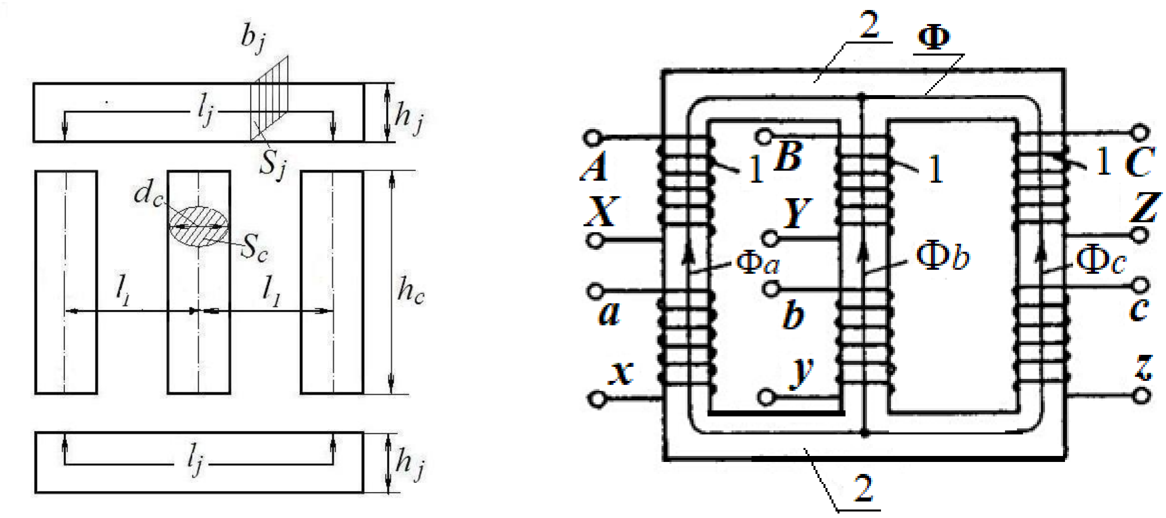


Figure 1 – The sketch and the dimensions of the three-phase transformer core

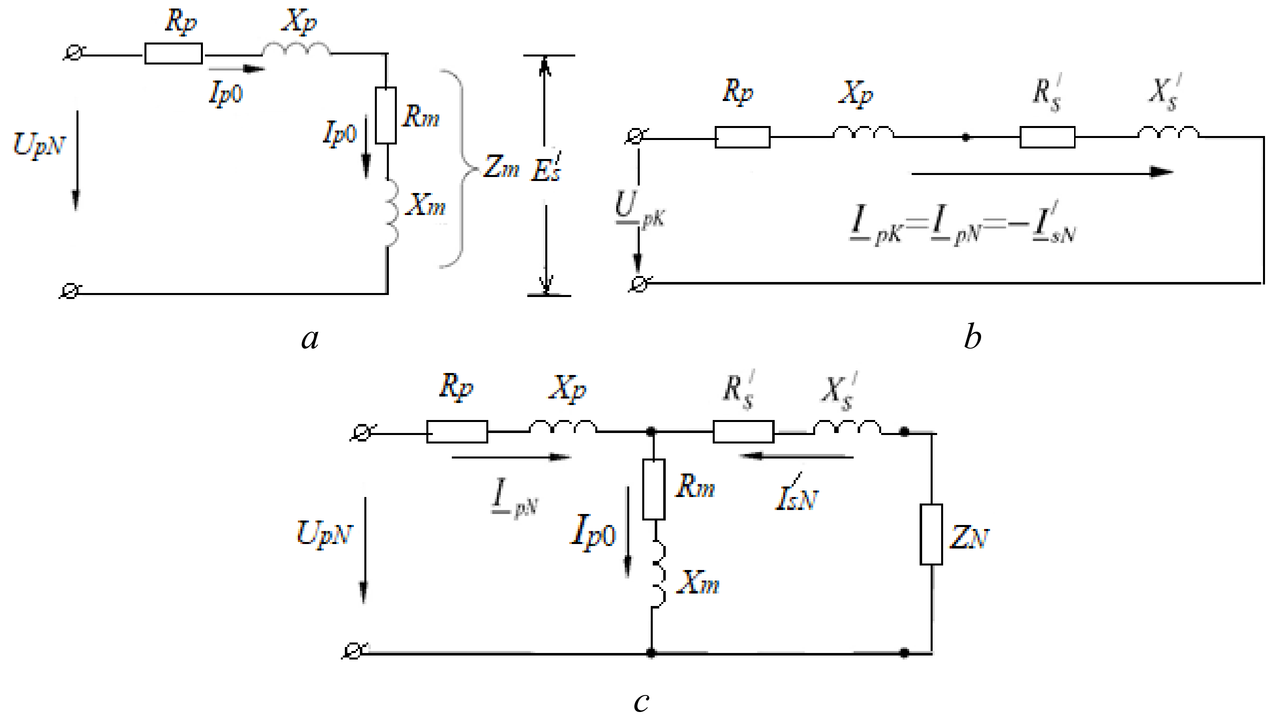


Figure 2 – Equivalent circuit diagram of the transformer in different modes:
a – the idling mode; *b* – the laboratory short circuit mode; *c* – the nominal mode

2) Calculate and build the transformer characteristics in the idling mode $P_0(U_{pN})$, $I_{p0}(U_{pN})$, $\cos\varphi_{p0}(U_{pN})$ and in the laboratory short circuit mode $P_k(U_{pk})$, $I_{pk}(U_{pk})$, $\cos\varphi_{pk}(U_{pk})$.

Calculate the rated efficiency of the transformer and the load value (in terms of rated power) at which the efficiency of the transformer will be maximum.

Table 1 – Parameters of the three-phase transformers

Number of variants	Total nominal power S_N kV·A	Nominal voltage of the primary winding U_{pNl} kV	Nominal voltage of the secondary winding U_{sNl} kV	Number of turns of the secondary winding N_s	Effective cross-sectional area of the rod S_c cm^2	Cross sectional area of the yoke S_j, cm^2	Core height h_c cm	Yoke height h_j cm	Distance between the axes of the rods l_1, cm	Short-circuit voltage u_k, %	Power factor $\cos\varphi_{sN}$ r.u.	The loss in the laboratory shorting mode P_k, kW	Schemes and winding connection groups
1	50	6.0	0.525	192	89	90	25	12	25	5.5	0.82	1.1	Y/Δ-11
2	100	35.0	6.0	200	580	570	41	14	35	6.5	0.82	2.10	Y/Y-0
3	180	31.5	6.0	280	410	400	52	16	39	6.5	0.83	3.60	Y/Y-0
4	320	35.0	6.0	360	330	326	39	18	35	5.5	0.80	5.60	Y/Y-0
5	5600	110.0	10.0	200	900	920	72	19	45	6.5	0.81	32.8	Y/Y-0
6	1000	35.0	3.47	470	220	210	83	41	46	5.5	0.80	10.54	Y/Δ-11
7	1800	35.0	6.0	640	310	300	85	28	57	6.5	0.85	12.22	Y/Y-0
8	3200	35.0	6.3	660	500	510	100	31	62	7.0	0.84	17.0	Y/Y-0
9	5600	35.0	6.0	600	320	300	110	37	70	7.5	0.85	29.6	Y/Y-0
10	20	6.0	0.40	100	75	72	30	19	21	5.5	0.83	0.95	Y/Y-0
11	60	35.0	6.0	200	580	600	41	34	31	6.5	0.83	2.2	Y/Y-0
12	100	35.0	0.66	150	86	84	38	34	46	5.5	0.80	3.46	Y/Y-0
13	180	35.0	3.15	300	200	180	42	36	49	5.5	0.84	3.60	Y/Δ-11
14	320	35.0	6.0	330	350	340	63	47	51	6.5	0.85	5.23	Y/Y-0
15	20	10.0	0.66	380	322	316	40	50	20	6.5	0.83	0.84	Y/Y-0

1.3 Methodological instructions for the practical assignment implementation

Calculate nominal phase voltages of the transformer primary winding (U_{pN}) and secondary one (U_{sN}) using the line voltages (U_{sNl} and U_{pNl} respectively) given in Table 1. Only the transformer phase voltages must be used in further calculations.

If the transformer winding is star-connected, then the phase voltage is, V:

$$U_{sN} = \frac{U_{sNl}}{\sqrt{3}}.$$

If the transformer winding is delta-connected (Δ), then the phase voltage is equal to the line voltage $U_{sN}=U_{sNl}$.

Define the magnetic flux in the transformer core, Wb:

$$\Phi = \frac{U_{sN}}{4{,}44 \cdot f \cdot N_s}.$$

Calculate the magnetic field induction in the transformer rods (B_C) and in the yokes (B_j), Tl:

$$B_c = \frac{\Phi}{k_{Fe} \cdot S_c}; \qquad B_j = \frac{\Phi}{k_{Fe} \cdot S_j},$$

where k_{Fe} – is the filling factor of the transformer core steel. k_{Fe}=0.95 when insulating varnish steel sheets.

The values of magnetic field induction should be within the range 1.3-1.6 Tl.

If the induction values do not fall within the specified interval, change the cross-sections of transformer rods and yokes.

Do the recalculation:

1) Select the values of induction in rods and yokes from the range 1.3–1.6 Tl.

For example, assume that B_c = 1.4 Tl and B_j = 1.5 Tl.

2) Recalculate the cross-section of the transformer rods and yokes (S_c and S_j respectively), m^2:

$$S_c = \frac{\Phi}{k_{Fe} \cdot B_c}; \qquad S_j = \frac{\Phi}{k_{Fe} \cdot B_j}.$$

In further calculations, use the new values of the cross-section of the transformer rods and yokes.

If the induction value immediately fell into the interval 1.3-1.6 Tl, you must continue the calculation according to the Table 1 data.

Calculate rods diameter (d_c, m) and the height of the yoke (h_j, m):

$$d_c = \sqrt{\frac{4S_c}{\pi}}; \quad h_j = \frac{S_j}{b_j}; \quad b_j = d_c.$$

Choose the strength of the magnetic field in the rods and yokes (H_c and H_j, respectively) for electrotechnical steel 3411 by value of magnetic field induction according to Table 2 or Fig. 3.

Calculate the magneto-motive force (MMF) per one phase of transformer, A:

$$F_a = H_c \cdot h_c + \frac{2}{3} H_j \cdot l_j + \frac{7}{3} \cdot \frac{B_c}{\mu_0} \cdot \delta,$$

where $\mu_0 = 4\pi \cdot 10^{-7}$ Gn/m – is the magnetic constant;

the length of magnetic field line in the yoke of the transformer (see Fig. 1), m:

$$l_j = 2 \cdot l_1 + h_j.$$

When calculating the MMF you must take into account the air gaps in the joint's rods and the yokes of transformers. Number of the air gaps (per each phase) is 7/3. The total air gap is assumed to be $\delta = 5 \cdot 10^{-5}$ m per phase.

Table 2 – Magnetic field strength and unit magnetic power losses for electrotechnical steel 3411

Magnetic field induction, B, Tl	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6
Magnetic field strength, H_c, A/m	190	260	318	397	502	647	843	1140	1580	2500	4370
Specific magnetic losses, p_{mag}, W/kg	0.54	0.61	0.76	0.96	1.20	1.46	1.76	2.10	2.45	2.80	3.37

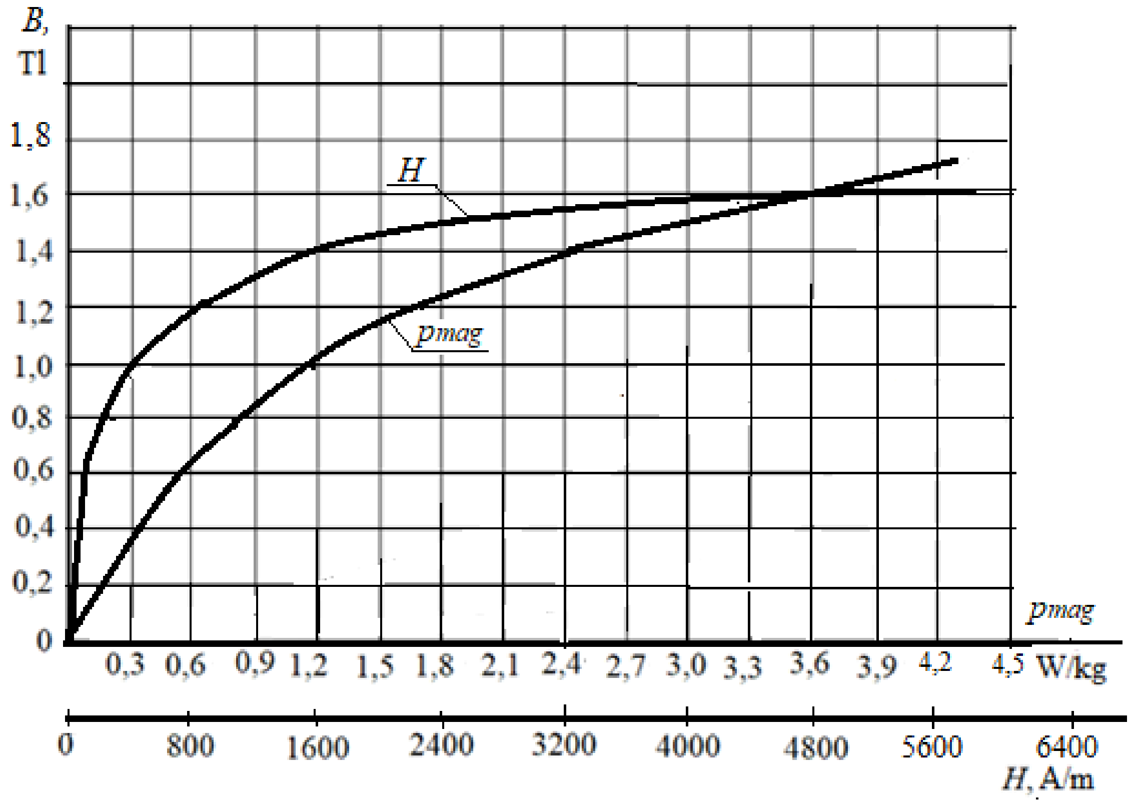


Figure 3 – Magnetic field strength and unit magnetic power losses for electrotechnical steel 3411 from which the transformer core is made

We accept that the magnetic field induction in the gap, in the rods and yokes joint is equal to the magnetic field induction in the rod B_c.

Calculate the number of the transformer primary winding turns:

$$N_p = \frac{N_s \cdot U_{pN}}{U_{sN}}.$$

Attention! The number of turns must be an integer.

Calculate the reactive of magnetizing current component, A:

$$I_{p0r} = \frac{F_a}{\sqrt{2} \cdot k_g \cdot N_p}$$

where k_q – is the factor that implies higher harmonics in the magnetizing current. Its value lies within the range from 1.5 to 2 (k = 1.5–2.0).

Calculate the steel weight of the transformer rods (m_c) and yokes (m_j), kg:

$$m_c = N_c \cdot S_c \cdot h_c \cdot \gamma_{Fe} \cdot k_{Fe}; \qquad m_j = N_j \cdot S_j \cdot l_y \cdot \gamma_{Fe} \cdot k_{Fe} =,$$

where $l_y = 2 \cdot l_1 + d_c$– is the yoke length, m;

N_c = 3 and N_j = 2 - are the number of transformer rods and yokes;

$\gamma_{Fe} = 7.8 \cdot 10^3$ =7800 kg/m^3 – is specific weight of steel.

Determine the magnetic losses in the transformer core (basic and additional), W:

$$P_{mag} = (k_d + 1) \cdot (p_{magc} \cdot m_c + p_{magj} \cdot m_j)$$

where p_{magc}, p_{magj} – are the specific magnetic losses in the transformer rods and yokes. Their values should be selected from the Table 2 or from the Fig. 3 according to the magnetic field induction, W/kg;

k_d =0,12– is the factor of additional losses registration P_{ad} chosen from the range 0.1-0.15.

Determine the active component of the current in an idling mode, A:

$$I_{p0a} = \frac{P_{mag}}{m \cdot U_{pN}}.$$

Determine the full idling current (A) in the primary winding (magnetizing current), and the transformer power factor in an idling mode using the formulas:

$$I_{p0} = \sqrt{{I_{p0r}}^2 + {I_{p0a}}^2}, \text{A}$$

$$\cos \varphi_0 = \frac{P_{mag}}{m \cdot U_{pN} \cdot I_{p0}} =, \text{r.u.}$$

Define parameters of the transformer equivalent circuit in the idling mode using the following formulas:

– total resistance of the equivalent circuit in the idling mode, Ohm:

$$Z_0 = \frac{U_{pN}}{I_{p0}};$$

– active resistance of the equivalent circuit in the idling mode, Ohm:

$$R_0 = \frac{P_{mag}}{m \cdot I_{p0}^2};$$

– reactive resistance of the equivalent circuit in the idling mode, Ohm:

$$X_0 = \sqrt{{Z_0}^2 - {R_0}^2}.$$

Calculate the transformer equivalent circuit parameters in the laboratory short circuit mode using the following formulas:

– total resistance of the equivalent circuit in the laboratory short circuit mode, Ohm:

$$Z_k = \frac{U_{pk}}{I_{pN}};$$

where U_{pk} – is the voltage of the laboratory short circuit mode, V:

$$U_{pk} = \frac{u_k}{100\ \%} \cdot U_{pN};$$

– nominal primary winding current, A:

$$I_{pN} = \frac{S_N}{m \cdot U_{pN}};$$

– active resistance of the equivalent circuit in the laboratory short circuit mode, Ohm:

$$R_k = \frac{P_k}{m \cdot I_{pN}^2};$$

– inductive resistance of the equivalent circuit in the laboratory short circuit mode, Ohm:

$$X_k = \sqrt{Z_k^2 - R_k^2};$$

– the transformer power factor in the laboratory short circuit mode, r. u.:

$$\cos\varphi_k = \frac{P_k}{m \cdot U_{pk} \cdot I_{pN}}.$$

The calculation the transformer equivalent circuit parameters in the nominal mode is carried out according to the data of the idling mode and mode of the laboratory short circuit:

– the transformer primary winding active resistance is equal to the equivalent reactive resistance of the transformer secondary winding, Ohm:

$$R_p = R_s^{'} = \frac{R_k}{2};$$

– the transformer primary winding reactive resistance is equal to the equivalent reactive resistance of the transformer secondary winding, Ohm:

$$X_p = X_s^{'} = \frac{X_k}{2}.$$

Then the resistances of the transformer magnetizing circuit are equal to, Ohm:

$$R_m = R_0 - R_p; \qquad X_m = X_0 - X_p.$$

The value of the transformer secondary winding electromotive force ($E_s^{/}$) may be defined from transformer vector diagram in the idling mode, Fig. 4.

Build the diagram using the following algorithm:

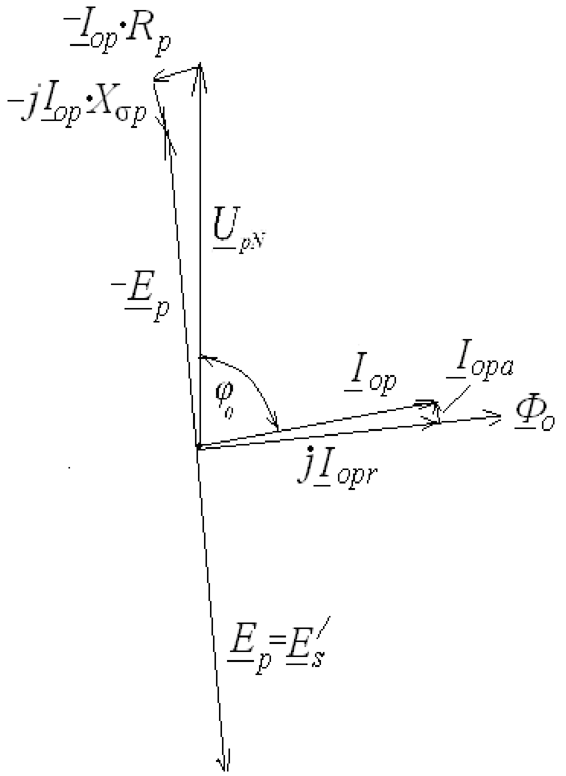


Figure 4 – Vector diagram of the transformer in the idling mode

1) make the equations system for the transformer idle mode:

$$\begin{cases} -E_p = U_p - I_{p0}\cdot R_p - j\cdot I_{p0}\cdot X_p; \\ I_{p0} = I_{p0a} + j\cdot I_{p0r}; \\ E_p = E_s^{/}; \end{cases}$$

2) select the scale for voltage, EMF and currents;

3) Plot a diagram using the above equations. To determine the transformer secondary winding electromotive force $E_s^{/}$ on the diagram, measure the length of the vector. Given the accepted scale for EMF, determine the value of $E_s^{/}$. Next, you use that E_p=$E_s^{/}$, and sign the value in the Fig. 2, *a*.

Determine the transformer nominal efficiency from the known values of losses in the idling mode and in the laboratory short circuit mode, r. u.:

$$\eta_N = 1 - \frac{P_0 + \beta_{Is}^2\cdot P_k}{\beta_{Is}\cdot S_N\cdot\cos\varphi_{sN} + P_0 + \beta_{Is}^2\cdot P_k},$$

where P_0 – is the losses on the idling mode, which are the magnetic losses in the transformer magnetic core, $P_0=P_{mag}$, W;

$\beta_{Is} = \frac{I_p}{I_{pN}}$, r. u. – is the transformer load factor. At the nominal loading $\beta_{Is}=1$.

The transformer efficiency maximum is achieved when the constant and variable losses are equal. Calculate the load value (in parts of the nominal capacity) at which the transformer efficiency is maximum, r. u.: $\beta_{Is\max} = \sqrt{\frac{P_0}{P_k}}$.

Then the transformer maximum efficiency can be calculated as follows, r. u.:

$$\eta_{\max} = 1 - \frac{P_0 + \beta_{Is\max}^2 \cdot P_k}{\beta_{Is\max} \cdot S_N \cdot \cos\varphi_{sN} + P_0 + \beta_{Is\max}^2 \cdot P_k}.$$

Define the transformer characteristics in the idling mode P_0, I_{p0}, $\cos\varphi_{p0}(U_p)$ and in the laboratory short circuit mode P_k, I_{pk}, $\cos\varphi_{pk}(U_p)$.

To do this, repeat the transformer parameters calculations at the idling mode and at the laboratory short circuit mode for different voltage values:

U_{p0}* = 0.2; 0.4; 0.6; 0.8; 1.1; U_{pk}* = 0.02; 0.04; 0.08; 0.1.

The calculation results are recorded in Table 3 and Table 4.

Attention: the numbers in the tables are given as an example.

Build the characteristics of transformer in the idling mode $P_0(U_p)$, $I_{p0}(U_p)$, $\cos\varphi_{p0}(U_p)$ and in the laboratory short circuit mode $P_k(U_p)$, $I_{pk}(U_p)$, $\cos\varphi_{pk}(U_p)$.

An example of characteristics is shown in Fig. 5.

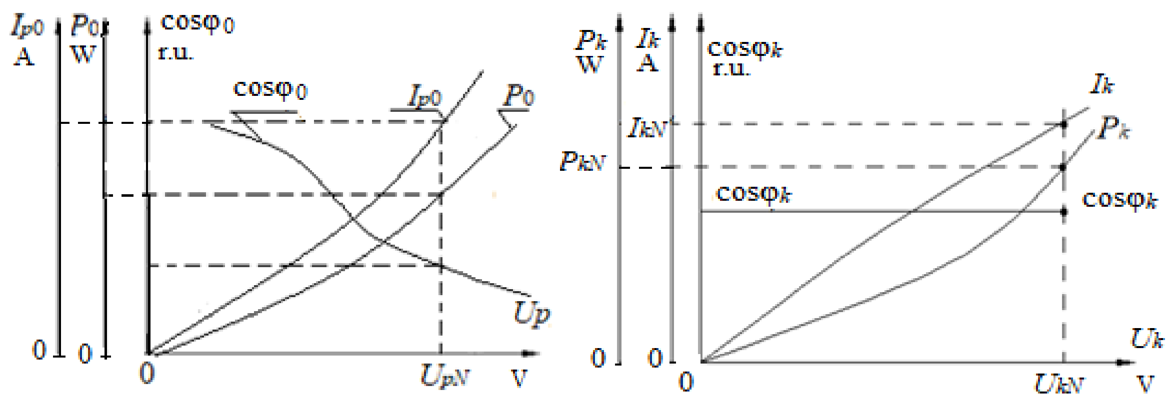


Figure 5 – The example of plotting the transformer characteristics in the idling mode and at the laboratory short-circuit mode

Table 3 – Calculated values for the transformer characteristics design in the idling mode

Values	Measurements					
$U_{p0}*$, r.u.	0.2	0.4	0.6	0.8	1.0	1.1
$U_p = U_{p0}* \cdot U_{pN}$, V	693	1386	2078	2771	3464	3810
$U_s = U_{p0}* \cdot U_{sN}$, V	120	240	360	480	600	660
$\Phi = \frac{U_s}{4{,}44 \cdot f \cdot N_s}$, Wb	0.023	0.045	0.068	0.09	0.113	0.124
$B_c = \frac{\Phi}{k_{Fe} \cdot S_c}$, Tl	0.29	0.57	0.86	1.14	1.43	1.57
$B_j = \frac{\Phi}{k_{Fe} \cdot S_j}$, Tl	0.28	0.57	0.85	1.13	1.41	1.55
$H_c = f(B_c)$, A/m, from the table 2 or Fig. 3	120	210	350	780	1850	3850
$H_j = f(B_j)$, A/m, from the table 2 or Fig. 3	130	220	360	720	1720	3450
$F_a = H_c \cdot h_c + \frac{2}{3} H_j \cdot l + \frac{7}{3} \cdot \frac{B_c}{\mu_0} \cdot \delta$, A	480	930	1270	1440	1710	1990
$I_{p0r} = \frac{F_a}{\sqrt{2} \cdot k_g \cdot N_p}$, A	18	36	54	61.3	72.8	84.7
p_{magc}, W/kg, from the table 2 or Fig. 3	0.261	0.513	0.772	1.56	2.72	3.17
p_{magj}, W/kg, from the table 2 or Fig. 3	0.254	0.513	0.766	1.52	2.60	3.05
$P_{mag} = (k_d + 1) \cdot (p_{magc} \cdot m_c + p_{magj} \cdot m_j)$, W	9.52	1.34	19.7	22.8	27.6	30.4
$I_{p0a} = \frac{P_{mag}}{m \cdot U_{pN}}$, A	0.03	0.11	0.19	0.22	0.27	0.29
$I_{p0} = \sqrt{I_{p0a}^2 + I_{p0r}^2}$, A	18	36.1	54.05	61.4	72.9	84.9
$\cos\varphi_0 = P_{mag}/(m \cdot U_{pN} \cdot I_{p0})$, r.u.	0.112	0.084	0.068	0.05	0.03	0.018

Table 4 – Calculated values for the transformer characteristics design in the laboratory SC mode

Values	Measurements				
U_{pk*}, r.u.	0.02	0.04	$u_{k\%}$, r.u.	0.08	0.1
$U_{pk} = U_{pk*} \cdot U_{pN}$, V	70	140	192.5	280	350
$I_{pk} = U_{pk*} \cdot I_{pN}$, A	35	70	96	140	175
$P_k = m \cdot I_{pk}^2 \cdot R_k$, kW	2.0	7.99	15.0	32.0	49.9
$\cos\varphi_{pk} = \frac{P_k}{m \cdot U_{pk} \cdot I_{pN}}$, r.u.	0.272	0.272	0.272	0.272	0.272

2 CONSTRUCTIONS OF THE ALTERNATING CURRENT MACHINE STATOR WINDING AND CALCULATION THE EMF OF THIS WINDING

2.1 Assignments

Draw two-layer three-phase (m_s=3) stator winding of the alternating current (AC) machine. The winding steps by the grooves are shortened. Data are given in Table 5.

Table 5 – Data for constructing the circuit of the AC machines stator winding

Variant number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Number of the stator teeth, Q_s	36	24	24	12	36	18	36	48
Number of poles, 2p	4	2	4	2	2	2	6	8
Shortening of the step, β_s	8/9	4/5	5/6	5/6	5/6	5/6	5/6	11/12
Scheme of the winding connection	Y	Y	Δ	Y	Δ	Y	Δ	Δ
Variant number	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Number of the stator teeth, Q_s	54	36	36	48	30	24	18	36
Number of poles, 2p	6	4	2	4	2	4	2	4
Shortening of the step, β_s	8/9	7/9	7/9	2/3	5/6	2/3	5/6	7/9
Scheme of the winding connection	Y	Y	Y	Y	Y	Y	Δ	Y

Calculate the distribution and shortening stator winding coefficients for 1st, 5th and 7th harmonics of the current and voltage, and winding coefficients for these harmonics.

Answer the questions in the written form:

1) Why are the AC machines stators windings shortened and distributed?

2) How do the shortening and the distribution of the stator windings effect the magnitude of the first harmonic EMF?

2.2 Methodological instructions for the assignment implementation

Calculate the number of grooves per pole and phase:

$$q_s = \frac{Q_s}{2p \cdot m_s},$$

where Q_s – is the stator core grooves number; p – is the number of stator pole pairs.

To construct a winding circuit, you can propose the following sequence:

– on a sheet with an interval of 1.0 cm indicate the numbers of slots according to the task;

– mark the pole pitch τ_p in the stator teeth with vertical dashed lines;

– connect the slotted and frontal parts of the stator winding.

When building, it is recommended to use pencils (pens) of different colors for different phases. This will help reduce the number of errors when building a circuit.

The example of the construction of the three-phase two-layer scheme deployed shortened stator winding (β_s=5/6) for phase *A* is shown in Fig. 6.

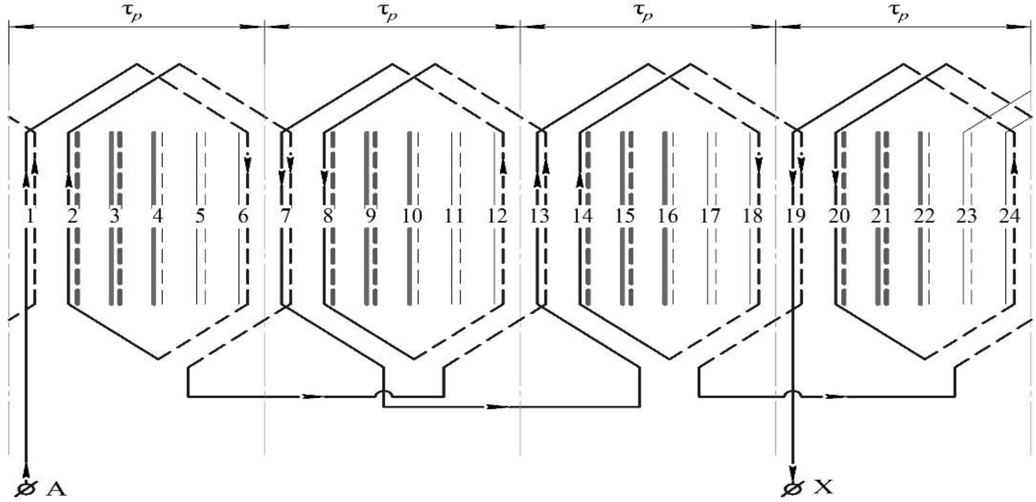


Figure 6 – The example of construction of the scheme of three-phase, two-layer, distributed, shortened (β = 5/6) stator winding (for one phase A):

Q_s = 24, 2p = 4, β_s = 5/6, q_s = 2, $y_{s.sh}$ = 5

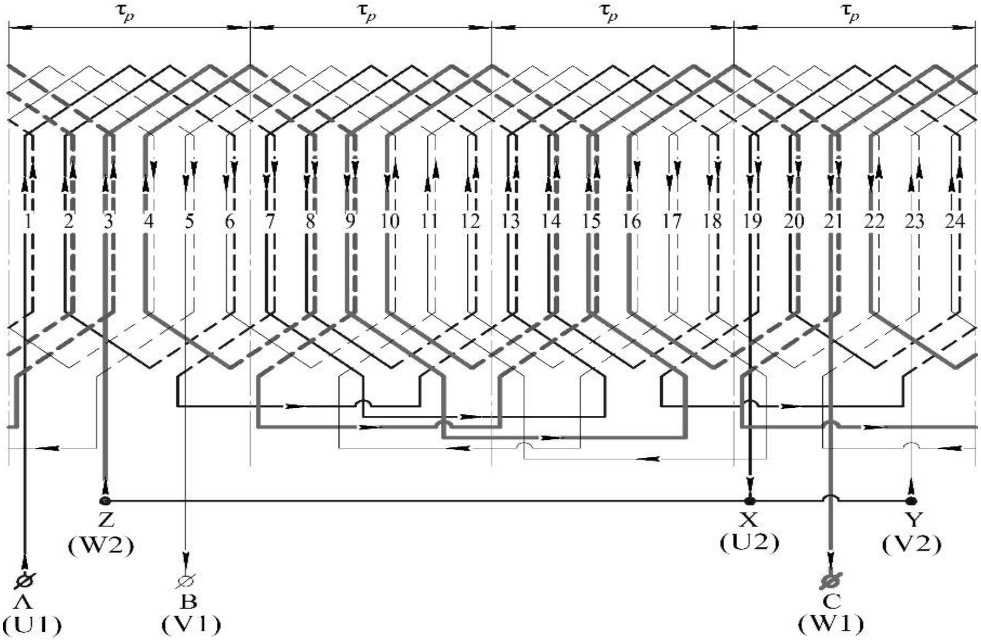


Figure 7 – The example of the scheme construction three-phase two-layer, distributed, shortened stator winding (β=5/6) (for three phases):

Q_s=24, 2p=4, β_s=5/6, q_s=2, $y_{s.sh}$=5

As an example, in Fig. 7 the scheme construction three-phase two-layer, distributed, shortened stator winding (β_s=5/6) for three phases which connected in «Y» is shown.

Calculate the pole pitch (in the tooth divisions) as follows:

$$\tau_p = \frac{Q_s}{2p}.$$

Take pencils of three colors (for example, black for phase *A*, blue for phase *B*, red for phase *C*). Mark the lower layer of the stator windings by the solid lines in different colors, according to the value of q_s. Calculate the steps of the stator winding regarding β_s (without shortening $y_{s.d}$, with shortening $y_{s.sh}$). Here are the steps by the grooves for diametric and shortened winding, respectively:

$$y_{s.d} = \frac{Q_s}{2p}; \qquad y_{s.sh} = \beta_s \cdot \frac{Q_s}{2p}.$$

According to the instructions, connect the winding into "star" or "triangle".

The AC machines stator windings of general industrial design are always made distributed. If the winding is two-layer, then it is made not only distributed, but also shortened. The winding distribution and shortening reduces the influence of the 5th and 7th harmonics on the first harmonic of current and voltage. It should be remembered that for the operation of an electric machine, both in generator mode and in engine mode, only the first harmonic is needed. If special measures are not taken, then high-order harmonics will distort the first harmonic, which is unacceptable.

The shortening and distribution of the stator winding changes (reduces) the EMF that is induced in it. Electrical engineers who calculate, design and build electrical machines understand this. But this is necessary to improve the quality, "purity" of the first harmonic.

To take into account the effect of shortening and distribution of the stator winding, winding coefficients are used: distribution coefficient and shortening coefficient.

These coefficients are always less than one and show how much the EMF of a distributed and shortened winding will decrease compared to a diametrical (not shortened) winding concentrated in one groove.

The product of the distribution coefficient and the shortening coefficient is called the winding coefficient.

Calculate winding coefficients ($K_{W\nu}$) for the 1-st, 5-th and 7-th harmonics (harmonics ν=1, 5, 7):

$$K_{W\upsilon} = K_{p.\upsilon} \cdot K_{d.\upsilon},$$

where $K_{p.\nu}$ is the shortening coefficient, $K_{d.\nu}$ is the distribution coefficient.

The shortening coefficient $K_{p.\nu}$ takes into account the decrease in the EMF of the ν-th harmonic of the diametric winding in comparison with the shortened winding EMF:

$$K_{p.\upsilon} = \sin\left(\frac{\pi}{2} \cdot \beta_s \cdot \upsilon\right).$$

$K_{d.\nu}$ – is the distribution coefficient, which accounts the decrease the ν-th harmonic of EMF winding distributed along the grooves compared with concentrated winding EMF:

$$K_{d.\upsilon} = \frac{\sin(\pi\upsilon/2m)}{q_s \cdot \sin(\pi\upsilon/(2m \cdot q_s))}.$$

Record the calculation results for the 1st, 5th and 7th harmonics in table 6.

Table 6 – Calculation of winding coefficients

Harmonica number ν	The distribution coefficient $K_{d\nu}$	The shortening coefficient $K_{p\nu}$	Winding coefficient $K_{W\upsilon} = K_{p\upsilon} \cdot K_{d\upsilon}$, в.о.
ν=1			
ν=5			
ν=7			

The first harmonic of EMF (ν=1) for shortened and distributed stator winding is, V:

$$E_s = 4{,}44 \cdot \Phi \cdot f \cdot N_s \cdot K_{W1},$$

where $K_{W1} = K_{p1} \cdot K_{d1}$ – is the winding coefficient of the first (working) harmonic.

The value K_{W1} for shortened and distributed stator winding is always less than one. Therefore, the EMF value of the first (working) harmonic in AC machines will be less. But we do it on purpose.

This is done to improve the shape of a circular rotating magnetic field by reducing the effect of higher harmonics (5th and 7th harmonics).

3 CALCULATING AND BUILDING THE ENERGY DIAGRAM OF ASYNCHRONOUS MOTOR

3.1 The task

Build the energy diagram of the three-phase asynchronous motor (AM) with a phase rotor using the data in Table 6.

Table 6 – Data for an asynchronous motor

Variant number	Nominal power	Number of pole pairs	Nominal slip	Nominal voltage of the stator winding	Efficiency	Nominal power factor	Results of laboratory experience short-circuit	
							Reactive resistance	Active resistance
	P_N, kW	p	s_N, %	U_s, kV	η_N, %	$\cos\varphi_N$, r.u.	X_k, Ohm	R_k, Ohm
1	10.0	4	4.3	0.4	80.5	0.87	1.1	0.26
2	15.0	3	2.7	0.4	80.0	0.83	1.0	0.26
3	20.0	2	3.1	0.4	81.8	0.83	0.98	0.13
4	30.0	1	3.5	0.4	83.0	0.84	1.1	0.12
5	40.0	3	2.0	0.66	86.5	0.89	0.91	0.11
6	50.0	2	3.0	0.66	85.5	0.86	1.0	0.12
7	75.0	1	3.2	0.66	87.5	0.81	1.5	0.30
8	11.0	4	4.7	0.4	88.0	0.75	1.2	0.24
9	15.0	1	2.3	0.4	90.0	0.91	1.6	0.32
10	18.5	2	2.7	0.4	90.0	0.88	1.6	0.79
11	22.0	3	2.5	0.4	89.0	0.90	1.5	0.34
12	30.0	4	2.0	0.66	90.5	0.81	1.3	0.28
13	37.0	5	1.8	0.66	90.5	0.81	1.6	0.40
14	45.0	3	2.5	0.66	91.0	0.85	1.5	0.36
15	55.0	3	2.5	0.66	92.5	0.89	1.6	0.48

The stator winding is connected in the Y.

The frequency of voltage is $f = 50$ Hz.

Take the given values of rotor and stator winding resistances, Ohm:

$$R_r^{/} = \frac{1}{4} \cdot R_k; \quad R_s = \frac{3}{4} \cdot R_k; \quad X_r^{/} = \frac{1}{3} \cdot X_k; \quad X_s = \frac{2}{3} \cdot X_k.$$

3.2 Methodical instructions for solving task

Conversion of electrical energy into mechanical energy in AM, as in other electrical machines, occurs with losses, therefore, the useful power of the motor P_N (nominal mechanical power) is always less than the power consumption P_{inN} by the amount of these losses ΔP, W:

$$P_N = P_{inN} - \Delta P_N,$$

where P_{in} is the power, which an asynchronous motor draws from the electric grid, W:

$$P_{inN} = \frac{P_N}{\eta_N}.$$

The losses in electrical machines ΔP are divided into basic and additional. The basic losses include magnetic, electrical and mechanical losses.

For the calculations take values:

– mechanical losses $P_{mec} = 0.02\ P_N$, W;

– magnetic losses $P_{mag} = 0.015\ P_N$, W;

– additional losses $P_{ad} = 0.005\ P_N$, W.

In engineering calculations, it can be assumed that the mechanical and magnetic losses are constant and equal to the losses in idling mode.

At the current frequency in the electric grid $f = 50$ Hz and within the rated motor slip $s_N = 2–8$ %, the frequency of the rotor reversal magnetization is equal to a few Hertz ($f_r = f_s \cdot s_N = 1–4$ Hz). Therefore, the magnetic losses in the rotor core are not taken into account in practice and is not shown in the energy diagram.

Additional losses include all kinds of losses that were not taken into account earlier: from the higher harmonics of the MMP, from pulsation of the magnetic induction in the teeth, etc. Additional losses can be attributed to the constant losses with a sufficient accuracy.

Electric losses in the asynchronous motor stator and rotor windings (P_{el}) are variable and depend on the load:

1) nominal electric loss in the stator winding, W:

$$P_{el.sN} = m_s \cdot I_{sN}^2 \cdot R_s,$$

where I_{sN} – is the stator nominal current, A:

$$I_{sN} = \frac{P_{inN}}{m_s \cdot U_{sN} \cdot \cos \varphi_N};$$

U_{sN} – is the stator nominal phase voltage when the winding connected in a "star", V:

$$U_{sN} = \frac{U_N}{\sqrt{3}};$$

R_s – is the stator winding active resistance, Ohm;

2) The nominal electrical loss in the rotor winding is directly proportional to the slip, W:

$$P_{el.rN} = s_N \cdot P_{emN},$$

where P_{emN} – is the asynchronous motor nominal electromagnetic power, W:

$$P_{emN} = P_{inN} - \left(P_{mag} + P_{el.sN}\right).$$

The AM total losses with a variable load are characterized by a load coefficient β. In nominal mode, this coefficient is β=1. Calculates the total losses of an asynchronous motor in nominal mode: W:

$$\Delta P_N = P_{mag} + P_{mech} + P_{ad} + \beta^2 \cdot (P_{el.s} + P_{el.r}).$$

An energy diagram, like all diagrams, must be drawn to scale. Therefore, before plotting a diagram, choose a power scale.

Example of the AM energy diagram construction is shown in Fig. 8.

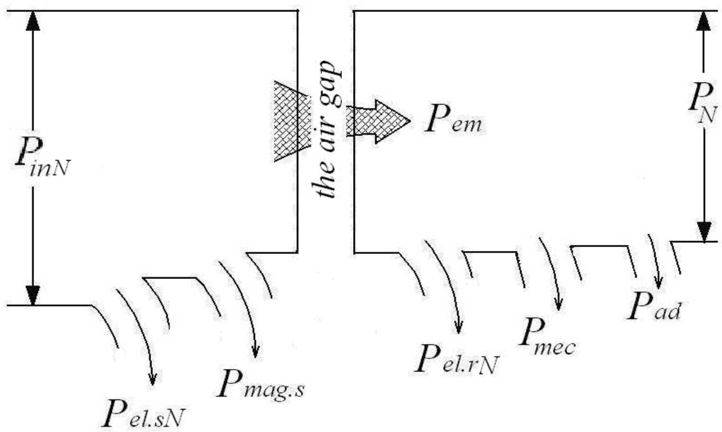


Figure 8 – The asynchronous motor energy diagram

The nominal efficiency of asynchronous motor is, r. u.:

$$\eta_N = \frac{P_N}{P_{inN}} = 1 - \frac{\Delta P_N}{P_{inN}},$$

where ΔP_N – is the asynchronous motor losses in the nominal mode, which include the constant and variable losses, W:

$$\Delta P_N = P_{const} + P_{varN};$$

– the constant losses of the asynchronous motor are, W:

$$P_{\text{const}} = P_{mag} + P_{mec} + P_{ad};$$

– the variable losses of the asynchronous motor are, W:

$$P_{varN} = P_{el.sN} + P_{el.rN}.$$

You get the efficiency value after calculating the adjusted motor loss. Compare the obtained efficiency value with the efficiency given in the table 6.

4 DETERMINATIONS OF THE SYNCHRONOUS GENERATOR OVERLOAD CAPACITY

4.1 Theoretical task

1) Describe the synchronous generators (SG) rotors design features, which are used in the thermal power plants (including nuclear powers) and at the hydro powers.

Explain why the rotors of these generators are different. Draw sketches of rotors of SG with explicit and implicit poles.

2) Write down the conditions for turning on SG for parallel operation with the electrical network at the accurate synchronization.

4.2 Task

1) Construct the three-phase synchronous hydro-generator angular characteristic with explicit pole rotor by the data in Table 7, and calculate its overload capacity.

2) Compare the angular characteristics for a three-phase SG-s with explicitly and implicitly pole rotors. Explain why they are different.

Plot the angular characteristic of a synchronous generator with implicit pole rotor (turbogenerator) and calculate its overload capacity.

4.3 Methodological instructions for the task implementation

Calculate nominal phase voltage of the stator winding, V. The stator winding of the generator is connected in a "star".

The electromagnetic moment M_{em} in synchronous machines is proportional to electromagnetic power P_{em}. Therefore, we can build angular characteristic as dependency $P_{em}(\theta)$ or $M_{em}(\theta)$, where θ is the angle of load – it is the angle between the rotor winding flux and anchor reaction flux, or between the vector EMP E_{s0} and the vector of the stator voltage U_s.

Table 7 – Data for a three-phase synchronous generator

Variant number	Stator winding nominal voltage	Nominal power factor	Relative value of EMF in the idling mode	Cross inductive reactance	Longitudinal inductive reactance	The angle between the stator current and EMF vectors	The stator winding scheme connections
	U_{sN}, kV	cosφ$_N$, r.u.	$E^*_{s0} = \dfrac{E_0}{U_{sN}}$, r.u.	X_q, Ohm	X_d, Ohm	ψ_N, el. degr.	
1	6	0.90	1.30	4.21	6.42	52	Y
2	0.4	0.91	1.33	0.935	1.42	54	Y
3	10	0.92	1.31	5.35	8.82	53	Y
4	6	0.93	1.34	2.48	3.82	52	Y
5	6	0.90	1.32	3.12	5.04	54	Y
6	0.4	0.89	1.36	5.20	7.46	54	Δ
7	0.4	0.89	1.30	4.02	6.18	52	Y
8	6	0.90	1.33	2.12	3.44	53	Y
9	6	0.91	1.37	1.96	3.12	52	Y
10	10	0.90	1.30	5.00	7.36	54	Y
11	10	0.91	1.44	3.18	6.84	50	Y
12	6	0.92	1.20	5.10	7.44	51	Y
13	6	0.93	1.35	4.18	6.54	52	Y
14	6	0.92	1.22	5.24	7.85	54	Y
15	0.4	0.91	1.35	3.36	5.68	55	Δ

Build angular characteristic as a dependency $P_{em}(\theta)$, W:

$$P_{em} = \frac{m_s \cdot U_{sN} \cdot E_{s0}}{X_d} \cdot \sin\theta + \frac{m_s \cdot U_{sN}^2}{2} \cdot \left(\frac{1}{X_q} - \frac{1}{X_d}\right) \cdot \sin 2\theta, \tag{4.1}$$

where $E_{s0} = E^*_{s0} \cdot U_{sN}$, V – EMF, which the rotor magnetic flux induces in the stator winding before the load is switched on (in the idling mode).

Angular characteristics of synchronous generators with explicitly and with implicitly pole rotors are different, because in the generators with explicit pole rotors $X_q < X_d$, while in the generators with implicitly pole rotors $X_q = X_d$.

The data of the angular characteristic's calculation are presented in Table 8.

Critical load angle at which the electromagnetic power is maximum is, el. degrees:

$$\theta_{cr} = \arccos(\sqrt{\beta^2 + 0{,}5} - \beta),$$

where the design factor equals, r. u.:

$$\beta = \frac{E_{s0}}{4 \cdot U_{sN} \cdot \left(\frac{X_d}{X_q} - 1\right)}.$$

Table 8 – Calculation of the three-phase synchronous generator angular characteristic with explicitly pole rotor

Parameters	Values of load angle θ, el. degr.									
	0	θ_N	30	60	θ_{cr}	90	120	135	150	180
sinθ, r. u.	0		0.5	0.87		1.0	0.87	0.71	0.5	0
$\frac{m \cdot U_{sN} \cdot E_{s0}}{X_d} \cdot \sin\theta$, W										
sin2θ, r. u.	0		0.87	0.87		0	-0.87	-1.0	-0.87	0
$\frac{m \cdot U_{sN}^2}{2} \cdot \left(\frac{1}{X_q} - \frac{1}{X_d}\right) \cdot \sin 2\theta$, W										
$P_{em} = \frac{m_s \cdot U_{sN} \cdot E_{s0}}{X_d} \cdot \sin\theta + \frac{m_s \cdot U_{sN}^2}{2} \cdot \left(\frac{1}{X_q} - \frac{1}{X_d}\right) \cdot \sin 2\theta$, W										

The nominal load angle equals, el. degrees:

$$\theta_N = \psi_N - \varphi_N,$$

where ψ_N – is the angle between the vector stator current I_{sN} in nominal mode and the vector stator winding EMF (E_{s0}) in idling mode, el. degr;

φ_N – is the angle between the vector of stator voltage U_{sN} and the vector stator current I_{sN} in nominal mode, el. degrees:

$$\varphi_N = \arccos Y,$$

where Y– is the $\cos\varphi_N$ value from the table 7.

The example angular characteristic of the three-phase SG with explicitly pole rotor is presented in Fig. 9.

In fact, the graph of angular characteristic of three-phase SG with explicitly pole rotor design is the sum of two characteristics i.e., the first and the second elements in the formula (4.1). Therefore, it can be constructed analytically using the last function in Table 9, (Graph 3, Fig. 9). Or you can first construct graphs on the first and the second elements (the second and fourth lines in Table 9, graph 1 and graph 2 in Fig. 9), and then add them up graphically.

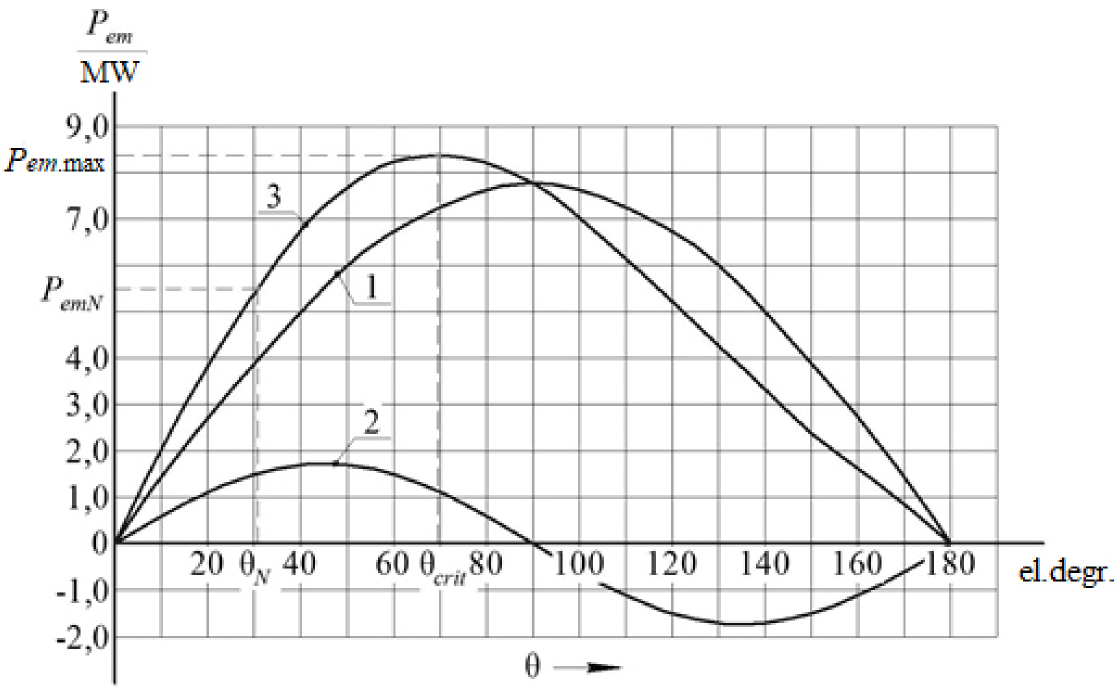


Figure 9 – The angular characteristic of the three-phase SG with implicitly pole rotor (hydro-generator)

The maximum electromagnetic power (P_{max}) is at the critical load angle (θ_{crit}).

Usually for the SG with implicitly poles rotor critical load angle is, el. degrees:

$$\theta_{cr} = 75\text{–}80.$$

Calculate the static overload coefficient (overload capacity) of the synchronous generator using the formula:

$$K_{Mm} = \frac{P_{em.\max}}{P_{em.N}}.$$

Build angular characteristic as a dependency $P_{em}(\theta)$ for turbogenerator (with implicitly pole rotor). You must remember, that for turbogenerators $X_q=X_d$. Therefore, angular characteristic of turbogenerator (SG with implicitly pole rotor) can be constructed by (4.2), W:

$$P_{em} = \frac{m \cdot U_{sN} \cdot E_{s0}}{X_d} \cdot \sin\theta. \quad (4.2)$$

Usually for real generators at the thermal and atomic power plants (turbogenerators), and at the hydro power plants (hydro-generators) K_{Mm} value is within the range: for hydro-generators K_{Mm} = 1.3–1.5; for turbogenerators K_{Mm} = 1.7–1.8.

Your task may have slightly different meanings, because these are educational tasks.

5 STUDY OF THE DC MOTORS DESIGNS AND ANALYSIS THEIR CHARACTERISTICS DEPENDING ON THE MAIN POLES WINDINGS CONNECTIONS SCHEME

5.1 Theoretical assignments

Indicate the advantages and disadvantages of direct current motors (DC motors) compared to other types of machines. Describe their principle of operation.

Draw a sketch of a four pole DC motor and possible schemes to incorporate field windings: an independent, parallel, serial and mixed.

In the written form respond to the questions for the DC machines with different schemes of the connection excitation winding according to the plan:

– in which electrical drives DC motors are used?

– how to regulate the speed of rotation and perform reverse of DC motors?

– what are the ways of braking DC motors?

– what problems exist while DC motors starting and how to solve them?

5.2 Methodological instructions for the task implementation

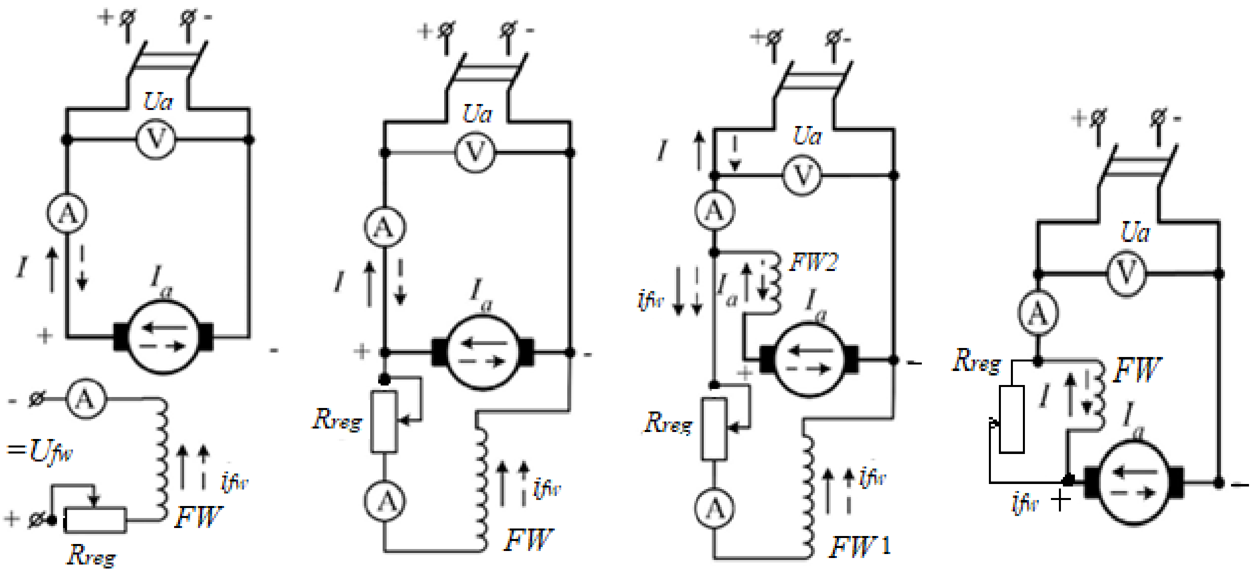
There are DC machine with an independent, parallel, serial and mixed excitation, Fig. 10. For motors used by all schemes include excitation windings. The serial excitation schemes are not used for DC generators, Fig. 10, *c*.

The winding of the main poles in motors with independent excitation is powered by two separate DC power sources (see Fig. 10, *a*).

The winding of excitation and the anchor winding in the motors with parallel excitation are connected in parallel and need only one DC source of (see Fig. 10, *b*).

The windings of the main poles in motors with mixed excitation have two parts: the first windings are connected in parallel with the anchor winding, and the second one – in series. These machines need only one DC source too (see Fig. 10, *c*).

The excitation windings in motors with series excitation are connected in series with the anchor winding (see Fig. 10, *d*).



a *b* *c* *d*

Figure 10 – Wiring excitation windings of the DC machines
a – independent excitation; *b* – parallel excitation;
c – mixed excitation; *d* – series excitation.
FW – field winding; i_{fw} – field winding current

The rotational speed of DC motor is equal to (it is called the "basic equation"), rpm:

$$n = \frac{U_a - I_a R_{a.k.}}{C_E \cdot \Phi},$$

where U_a, V – is the voltage that is supplied to the anchor DC motor;

Φ, Wb – is the main poles magnetic flux;

I_a, A – is anchor current;

$R_{a.k}$ – is the total resistance of the main chain windings, Ohm:

$$R_{a.k} = R_a + R_{ad} + R_{comp} + f(R_W),$$

R_a, Ohm – is the anchor-winding resistance;

R_{ad}, Ohm – is the additional poles winding resistance;

R_{comp}, Ohm – is the compensation winding resistance;

$f(R_W)$, Ohm – is the excitation winding resistance with the circuit to turn it on;

$$C_E = \frac{p \cdot N_a}{60 \cdot a} - \text{is the motor constant,}$$

where p – is the number of the main pole's pairs;

a – is the number of the parallel branches pairs of the anchor winding;

N_a – is the number of the anchor-winding conductors.

The motors with parallel and mixed excitation are the most widely used. The independent excitation is used for very powerful motors, which are installed on drives of the technological equipment in the steel industry, for mine hoists, large machine tools, etc.

The motors with parallel excitation are generally used in the machine tool industry, in low and average power drives.

The most commonly used DC motors with mixed excitation winding. Such motors are sometimes called the motors with parallel winding and with stabilizing one. The parallel winding of execration is the main and the series winding stabilizes the change of the motor rotation frequency of the engine when the load changes. The motors with series excitations are usually used to drive the electric drive train (tram, trolley, subway and railway).

DC generator is electrical machine whose main function is to convert mechanical energy into electricity. A DC generator is the type of electrical generator that converts mechanical energy into direct current electricity. In DC generators, the energy conversion is based on the principle of dynamically induced EMF production. These generators are most suitable for off-grid applications. DC generators supply continuous power to electric storage instruments and power grids (DC).

The DC generators with independent excitation are generally more expensive than self-excited DC generators because of their requirement of separate excitation source. Because of that their applications are restricted. They are generally used where the use of self-excited generators is unsatisfactory.

Because of their ability of giving wide range of voltage output, they are generally used for testing purpose in the laboratories. The DC generators with independent excitation operate in a stable condition with any variation in field excitation. Because of this property they are used as supply source of DC motors, whose speeds are to be controlled for various applications.

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APPENDIX A

Example of the title page of the calculated jobs

Ministry of Education and Science of Ukraine

National Technical University
"Kharkiv Polytechnic Institute"

Department of Electric Machines

THE CALCULATION TASKS
ON THE DISCIPLINE
«ELECTRIC MACHINES»

by a third-year student
group ____________________________

____

(Student's full name)

Section name	Date of completion mark the teacher's signature
1. Design description and parameters calculation of the transformers in the nominal mode	
2. Construction of the alternating current machine stator winding and calculation of the EMF of this winding	
3. Calculating and building the energy diagram of asynchronous motor	
4. Determination of the synchronous generator overload capacity	
5. Study of the DC motors designs and analysis their characteristics depending on the main poles windings connections scheme	

Kharkiv – 20___ p.

Навчальне видання

РОЗРАХУНОК ХАРАКТЕРИСТИК ТРАНСФОРМАТОРІВ І ЕЛЕКТРИЧНИХ МАШИН

Методичні вказівки до виконання розрахункових завдань
з дисципліни "Електричні машини"
для іноземних студентів денної форми навчання за спеціальністю
141 – Електроенергетика, електротехніка та електромеханіка
Англійською мовою

Укладач: ШЕВЧЕНКО Валентина Володимирівна

Відповідальний за випуск проф. Мілих В.І.
Роботу рекомендував до друку проф. Любарський Б.Г.

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