Ministry of Education and Science of Ukraine
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Electrical Engineering Department

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ELECTRIC MACHINES
METHODOLOGICAL RECOMMENDATIONS FOR IMPLEMENTATION COURSE PROJECT

for students of the specialty
141 – Electrical energetics, electrical engineering, and electromechanics

Dnipro
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Electric machines. Methodical recommendations for the implementation of the course project for students of specialty 141 - Electric power, electrical engineering, and electromechanics [Text] / O.B. Ivanov, D.V. Tsyplenkov; Dnipro University of Technology – D.: DniproTech, 2021. – 119 p.

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Approved by the scientific and methodical commission for specialty 141 – Electrical energetics, electrical engineering, and electromechanics (protocol No. 21/22-1 dated 08/30/2021).

Methodical recommendations are intended to help students of the specialty 141 - Electrical energetics, electrical engineering, and electromechanics when completing a course project in the discipline "Electric machines".

Contents

INTRODUCTION

Completion of the course project and its defense is the final activity of students in the study of the discipline "Electric machines" and contributes to the consolidation of theoretical knowledge and provides an opportunity for students to better navigate the issues of electrical engineering.

Methodological recommendations are prepared to help students write a course project in the discipline "Electric machines" on the topics "Design of an asynchronous motor" and "Design of an asynchronous motor during repair and restoration work" and contain a description of the structure of course projects, a description of the content of sections, a list of questions for preparation to the defense, a list of recommended literature and cover page samples, assignment forms, and source data.

When completing the course project, the student will need to refer to textbooks, and specialized and reference literature, which will contribute to the development of the skills of independent work with literature. Another positive aspect of completing the course project will be the preparation of the student for the requirements of the final qualification work, taking into account the similar structure of its special part and the general structure of the course project.

The list of topics of the course project is previously provided to students for selection and discussion. The student completes the course project by the task and calendar under the guidance of the teacher.

The completion of the course project, the design of the explanatory note, and the graphic part is carried out by the student in the non-auditor time provided for in the curriculum for independent work. The prepared explanatory note and the graphic part are given to the supervisor and after checking, the student is given comments for revision or the project is accepted for defense.

In preparation of bachelor’s in the direction of "Electric power, electrical engineering, and electromechanics", studying the course "Electric machines" is of particular importance given that the implementation, of course, tasks allow future engineers to learn how to independently solve technical problems by choosing one or another solution.

REQUIREMENTS FOR COMPLETING THE COURSE PROJECT

The course project is submitted for defense in the form of an explanatory note, which consists of a title page, task, table of contents, introduction, sections, according to the points of the study, conclusion and list of used literature. The text of the explanatory note is drawn up on a computer in the Word Office text editor on A4 format sheets (210x297 mm) without a frame. The text of the project must be typed at one-and-a-half intervals, in Times New Roman 14-point font (left margin - 30 mm, right margin - 10-15 mm, top and bottom - 20 mm), text alignment by width (without hyphens).

Paragraph margin - 1.25 cm. The length of the explanatory note should be 40-60 pages. In general, the explanatory note to the course project is drawn up by DSTU 3008:2015. "Information and documentation. Reports in the field of science and technology. Structure and rules of design".

The project is carried out in Ukrainian. Page numbering is centered at the bottom of the page. References to the literature must be included in the text (in square brackets). Literature must be designed by DSTU 8302:2015 "Information and documentation. Bibliographic reference. General provisions and rules of drafting".

The materials of all sections of the explanatory note must be united by a common goal and logically connected. In the explanatory note, it is necessary to avoid duplication of information, excessive descriptiveness, and stereotyped judgments that do not affect the essence of the project.

The structure of the course project consists of an introductory part (cover page, tasks for the course project, abstract, calendar plan, content, and introduction), calculation part, conclusions, a list of literary sources, appendices (if necessary) and a graphic part. An example of a title page, a project assignment, and an abstract are given in the attachments.

According to the topic of the course project, the structure of the explanatory note of the course project and the approximate number of pages of each section are given in the table.

Title of sections	Number of pages
Title page (Appendix A)	1
Tasks for the course project (Appendix B)	1
Abstract (Appendix C)	1

Calendar plan (Appendix D)	1
Content	1
Introduction	1-2
1. Selection of motor basic construction and principal dimensions	1
2. Design of stator and rotor teeth areas and windings	10-12
3. Motor magnetic circuit calculation	2-3
4. Determination of motor parameters for rated operating conditions	4-5
5. Power losses in induction motors	2-3
6. Parameters and data of no-load condition	3-4
7. Motor performance characteristics	2-3
8. Calculation of starting characteristics	2-3
9. Heat and ventilation calculations	2-3
Conclusions	1
List of literary sources	1
Appendices	by necessity

The graphic part of the project consists of **two** sheets of A1 format. The content of the graphic class is given on the assignment forms (depends on the type of rotor).

CONTENTS OF SECTIONS OF THE PROJECT

Sections of the project should include

Introduction

The introduction provides the relevance of the topic, the main tasks of the project, a brief description of the main properties and the field of application of the target product.

Calculation part

The calculation part is performed according to the methodology below

Conclusions

The results of the course project are formulated in the conclusions.

List of used literature

A full bibliographic description of each source used in the preparation of the explanatory note is provided. Information about sources should be placed in the order of appearance of references to sources in the text of the explanatory note, numbered with Arabic numerals and typed with paragraph indentation.

Appendices

It is given if necessary. It can contain tables with the results of calculation of operating and starting characteristics.

DEFENSE OF THE COURSE PROJECT

The defense of the course project takes place before a committee consisting of 2-3 teachers, including the project leader, in the presence of all interested students and teachers. The composition of the commission is appointed by the head of the department.

Projects signed by the author and approved by the manager are eligible for protection. The manager's signatures must be on all drawings and the explanatory note. The explanatory note during the defense is submitted to the committee together with the score book.

At the beginning of the defense, the student makes a 4-5 minute report about the completed work, which should contain the following sections:

- Tasks for the project;
- The main dimensions of the designed machine, their relation to the height of the axis of rotation;
- The main design and calculation decisions made during the design of the electromagnetic subsystem (design and scheme of the stator winding, brand of winding wires, insulation class, shape and number of stator grooves, number of grooves per pole and phase, air gap, type of rotor winding, its material, shape and the number of rotor grooves, the material and construction of the stator core and rotor);
- Main characteristics: efficiency, power factor, multiplicity of starting and maximum moments, multiplicity of starting current;

- Basic design decisions made during the design of mechanical and thermal ventilation subsystems (performance according to the degree of protection and cooling method, performance according to the installation method, material of the housing and bearing shields, bearing units, ventilation system).

After the notification, the student may be asked several questions related to the topic of the course project as well as to the general theory, calculation and design of machines of this type.

In order to answer them correctly, preparation for project defense is necessary. Questions may relate to the following topics:

1. Selection of the main dimensions, electromagnetic loads and design of an asynchronous motor.

2. Design of individual parts and assembly units of the designed engine, their purpose and factors that determine the dimensions and structural performance.

3. Features of electromagnetic, thermal and mechanical calculations of individual machine elements; peculiarities of ventilation calculation.

4. Stator and rotor windings, their design, schemes, fastening of windings.

5. Basics of the theory of asynchronous machines; substitution schemes, the influence of various factors on the value of the parameters of the substitution scheme.

6. Issues of operation of asynchronous machines, operating and starting characteristics, starting and reversing methods, operating modes.

To prepare the answers, you should remember the information obtained during the design of electric machines, as well as study the relevant sections of the educational literature. Topics 5 and 6 require, in addition, a repetition of the sections of the general course of electrical machines relating to asynchronous machines.

Below, as an example, some of the questions that may be asked during the protection of the project are given:

- ✓ What do the main dimensions of the machine depend on?
- ✓ Will the main dimensions of machines designed for the same power, but for different rotation frequency, for different nominal voltage, differ?
- ✓ What induction in the air gap is assumed in machines similar to the designed one, and what limits the possibility of its increase?
- ✓ In what ways can the steel of the stator core be fixed in the housing, what fastening design is adopted in the designed engine?
- ✓ What ensures the exact alignment of the rotor in the stator core when assembling the engine?
- ✓ What data serve as starting points when choosing bearings?
- ✓ What bearings are installed on the designed machine?

- ✓ How is the machine cooled?
- ✓ What factors are taken into account when choosing the size of the air gap?
- ✓ Does the size of the air gap affect the engine idle current, flow, and power factor?
- ✓ Why are teeth with parallel walls used in stators with a round wire winding?
- ✓ Does the permissible value of induction in the tooth depend on its configuration?
- ✓ What determines the thermal resistance of groove insulation and the surface of the front parts of the winding?
- ✓ What determined the selection of the number of slots per pole and phase in the designed machine? What would increase or decrease this number lead to?
- ✓ Justify the design of the stator (rotor) winding selected in the project. Are other options possible and how are they worse or better than the accepted one?
- ✓ List the advantages and disadvantages of bulk stator winding. Why are bulk windings not used in high-power asynchronous machines?
- ✓ What parameters of the substitution scheme of the designed machine change when the slippage changes from unity to nominal? What explains this change?
- ✓ How do the maximum and starting torques depend on the active and inductive resistances of the stator and rotor?
- ✓ How does the change in engine load affect the main flow and the flow of groove dispersion?
- ✓ How does the starting and maximum torque of the motor change if its short-circuited rotor, which has rectangular grooves, is replaced by a rotor with a double white cage (with the same number of active resistances of the windings of both rotors)?
- ✓ How will an increase or decrease in the power supply voltage affect the power factor and efficiency of an asynchronous motor operating at nominal load?
- ✓ Explain the rotor current displacement effect. What does it affect?
- ✓ In addition to those listed, the questions may relate to the results obtained in the process of calculating the project, for example:
- ✓ What is the current density selected in the stator (rotor) winding?
- ✓ Why are the losses in the stator steel equal?
- ✓ What is the nominal slip of the engine?

DESIGNING OF THREE-PHASE INDUCTION MOTORS

1. Selection of motor basic construction and principal dimensions

1.1. Motor basic construction

Technical specification for induction motor design includes the designed machine ratings, requirements defined by it working conditions, the machine embodiment, degree of protection of enclosure, cooling system. Besides, additional requirements to the designed motor may be assigned, such as the least admissible ratio of maximum and minimum torques. For motors with squirrel-cage rotors extreme values of maximum starting current ratio and the least starting torque ratio may be specified. As regards to requirements not indicated in the motor technical specification, they should meet the existing standards.

In most cases, designing a new machine is oriented to a basic model. As such a model one of modern commercially produced machines series can be taken. At designing, decisions in relation of the machine dimensions, its construction and parameters is accepted by designer with orientation toward the machine series adopted as a design model.

Bachelor's curriculum of Electromechanics envisages project on designing of an induction motor. At the project carrying out, it is recommended to use as the model the induction motors series 4A. The design assignment includes such initial data as the motor rated power P_2, voltage U_1, mains frequency f_1, number of poles $2p$, rotor type (wound or cage), motor mounting, degree of enclosure protection, duty type. Some other requirements may be also included into the assigned data.

1.2. Determination of motor principal dimensions

The principal dimensions of the induction motor are the stator inner diameter D and the calculated length of the air gap l_δ.

1.2.1. To determine the principal dimensions, approximate value of the motor shaft height h above the supporting surface is found using the plots $h = f(P_2)$ given in Fig. 1.1, where P_2 is the motor rated output power on shaft. The curves are given for different number of poles $2p$ separately for motors having degree of enclosure protection IP44 and IP23. The shaft height is standardized (see Table 1.1). Finding the shaft height approximate value from Fig. 1.1 it is necessary to accept the next lower standard shaft height value given in Table 1.1.

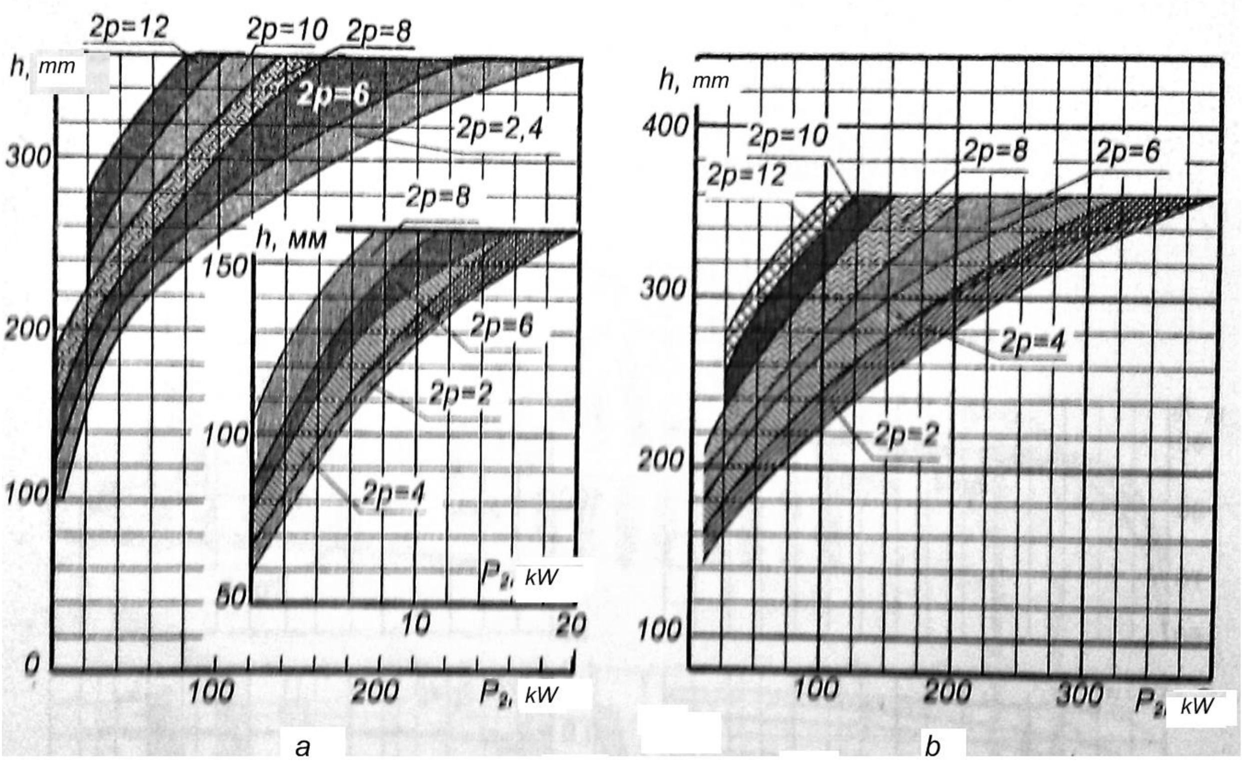


Figure 1.1 Curves for approximate value of shaft height determination for induction motors 4A series at degree of enclosure protection IP44 (a) and IP23 (b)

1.2.2. It is recommended to accept the outer stator diameter D_a value given in the same Table 1.1 corresponding to the accepted standard value of the shaft height. After that, one of the principal dimensions - the inner stator diameter value is found as

$$D = k_D D_a \tag{1.1}$$

Where k_D is a coefficient which value is accepted on the basis of number of poles $2p$ by the data of Table 1.2.

Table 1.1

Standard values of shaft height and corresponding values of stator outer diameter

h, mm	56	63	71	80	90	100	112	132
D_a, m	0.089	0.10	0.116	0.131	0.149	0.168	0.191	0.225

h, mm	160	180	200	225	250	280	315	355
D_a, m	0.272	0.313	0.349	0.392	0.437	0.530	0.590	0.660

Table 1.2

Coefficient k_D for induction motors 4A series

$2p$	2	4	6	8 - 12
k_D	0.52 – 0.57	0.64 – 0.68	0.70 – 0.72	0.74 – 0.77

1.2.3. The value of pole pitch τthat will be required for further calculations is

$$\tau = \pi D/(2p). \tag{1.2}$$

1.2.4. The estimated apparent power consumed by the motor at full load in $V \cdot A$ is found as

$$P' = P_2 \frac{k_E}{\eta \cos\varphi} \tag{1.3}$$

Where k_E is ratio of the voltage induced in the stator winding to the rated voltage across the stator terminals, η and $\cos\varphi$ are approximate values of the motor efficiency and power factor respectively. The value of k_E is defined with curves in Fig. 1.2. Approximate values of η and $\cos\varphi$ are found with the help of curves in Fig. 1.3 and 1.4 depending on degree of enclosure protection (IP44 or IP23).

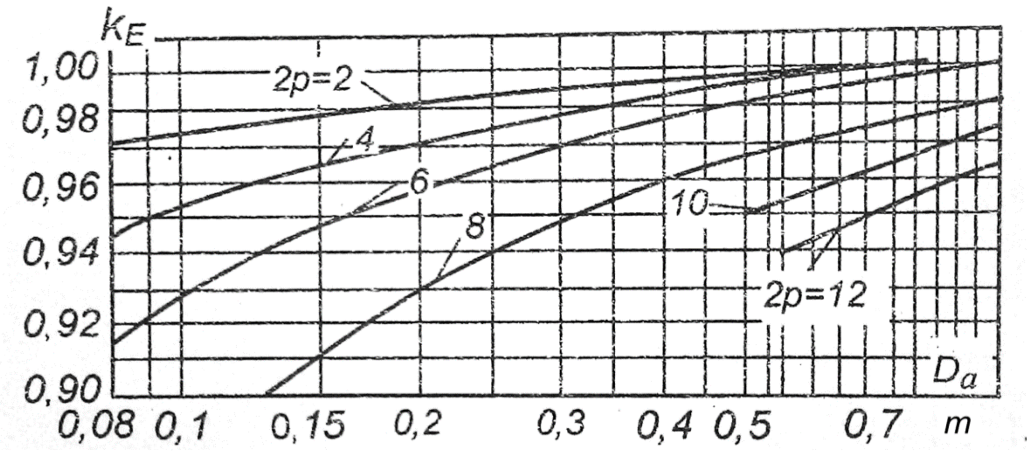


Figure 1.2 Dependence of k_E on stator outer diameter at different poles number

1.2.5. Another of the principal dimensions - axial length of the motor air gap l_δ - is equal to

$$l_\delta = \frac{P'}{D^2 \Omega_1 k_B k_{w1} A B_\delta} \tag{1.4}$$

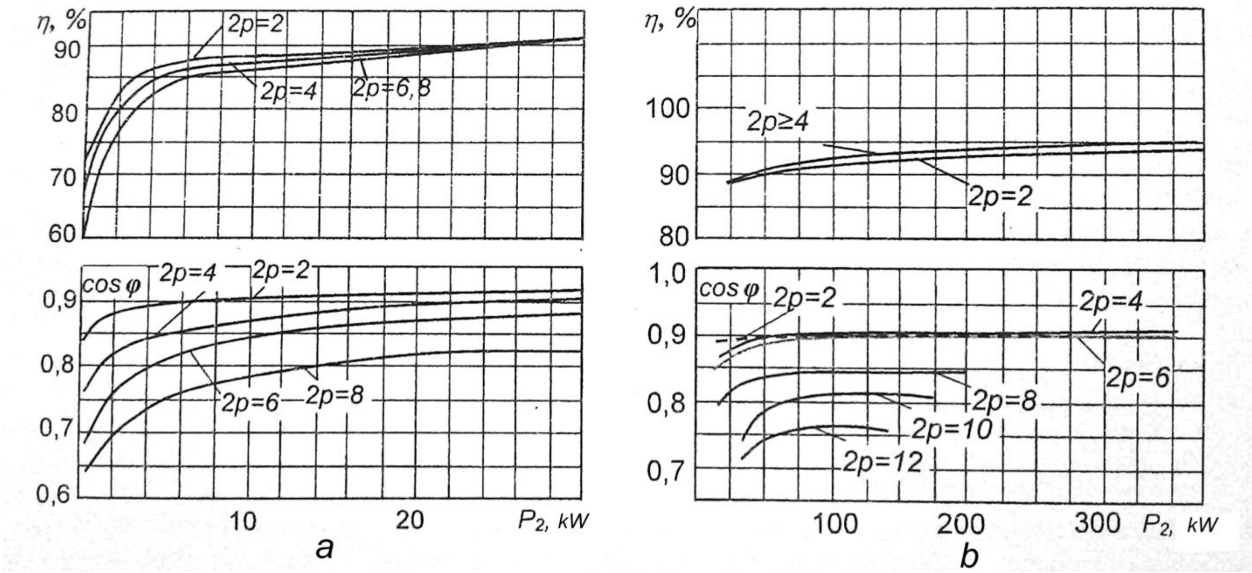


Figure 1.3 Dependence of efficiency and power factor on rated power for 4A series induction motors with enclosure protection IP44

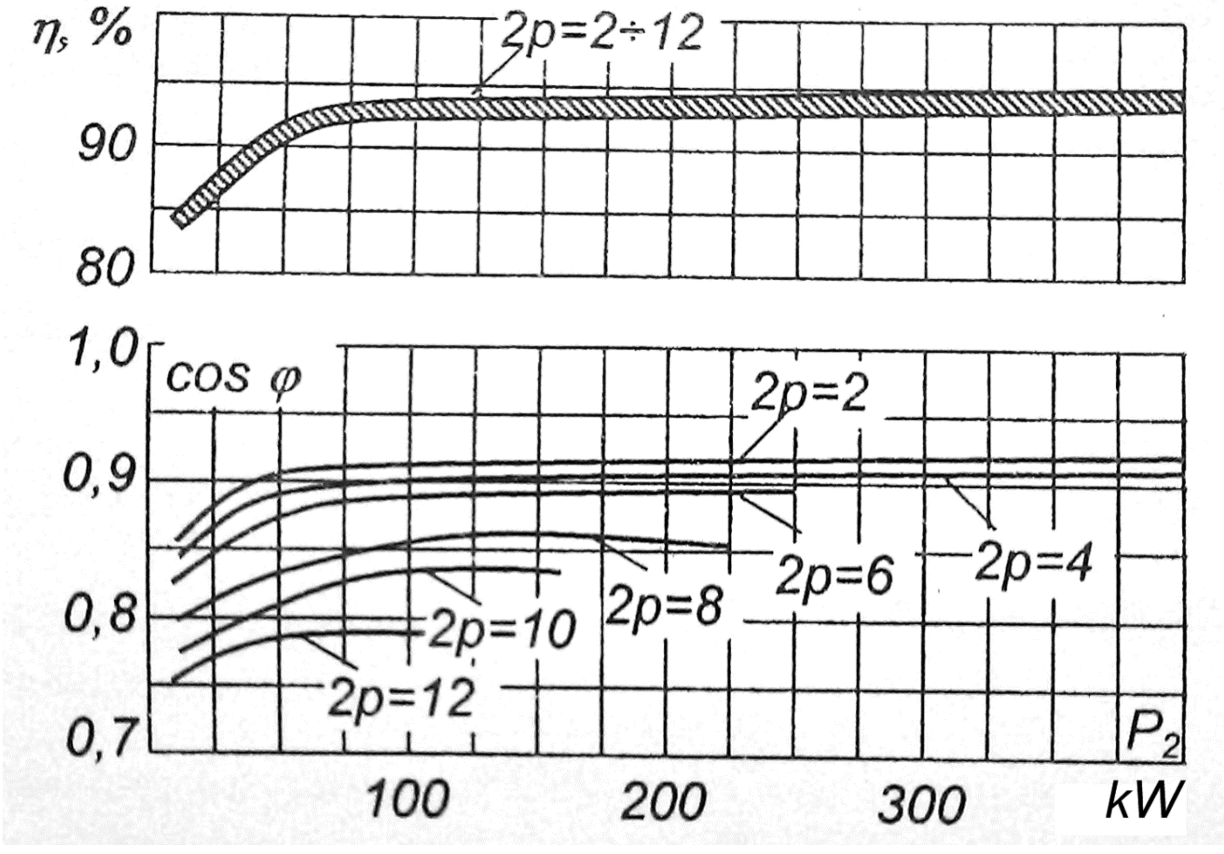


Figure 1.4 Dependence of efficiency and power factor on rated power for 4A series induction motors with enclosure protection IP23

where Ω_1= synchronous angular speed equal $\Omega_1 = 2\,\pi f_1/p$;

k_B=the machine magnetic flux form factor, it approximate value is accepted equal $k_B = 1.11$ neglecting the flux harmonics;

k_{w1} = the stator winding factor. At this stage of calculation its approximate value is preliminarily accepted on the basis of the winding type. For machines with the shaft height $h \leq 160\ mm$single layer windings are applied; for them the value $k_{w1} = 0.95 - 0.96$ is accepted. For machines with $h > 160\ mm$ twolayer windings are used; for them the winding factor is accepted equal to $k_{w1} = 0.90 - 0.91$at $2p = 2$, at greater poles number – to $k_{w1} = 0.91 - 0.92$;

A = tentative value of the electric loading of the machine in $\mathrm{A/m}$ and B_δ = tentative value of amplitude of the magnetic flux density in the air gap. These values may be found with the help of curves given in Fig. 1.5 or 1.6.

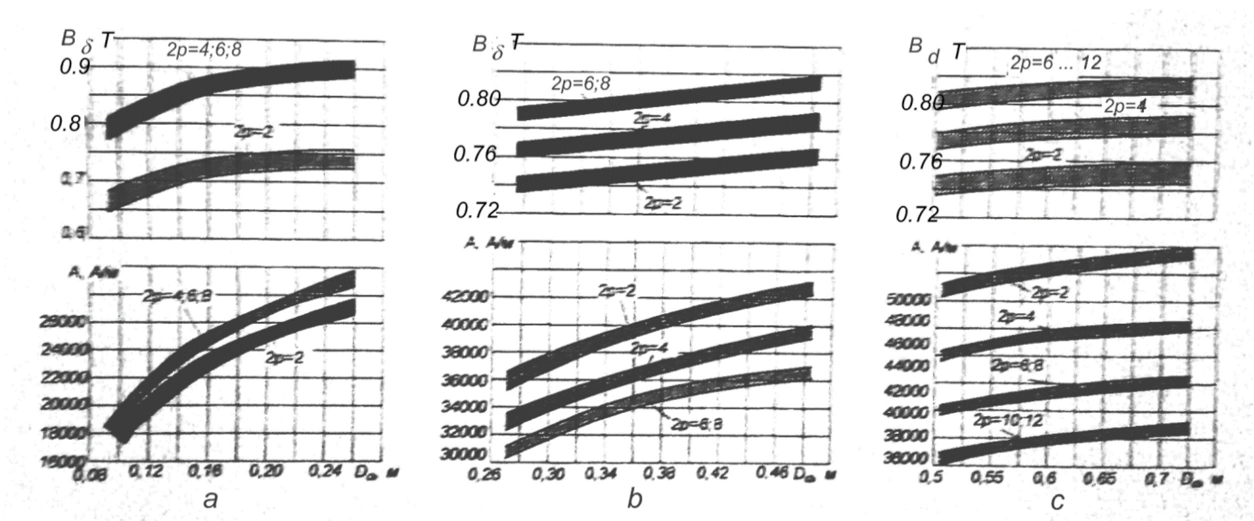


Figure 1.5 Electromagnetic loads of 4A series induction motors with enclosure protection IP44 at $h < 160\ mm$ (a), at $h = 160 - 250\ mm$ (b), at $h > 250\ mm$ and a blown through rotor construction (c)

1.2.6. The economic performance, characteristics, and cooling conditions of the motor areaffected by the ratio of the length of the motor air gap to the pole pitch $\lambda = l_\delta/\tau$. Acceptable value of λ depends on the number of poles and shaft height and can be found using the curves shown in Fig. 1.7.

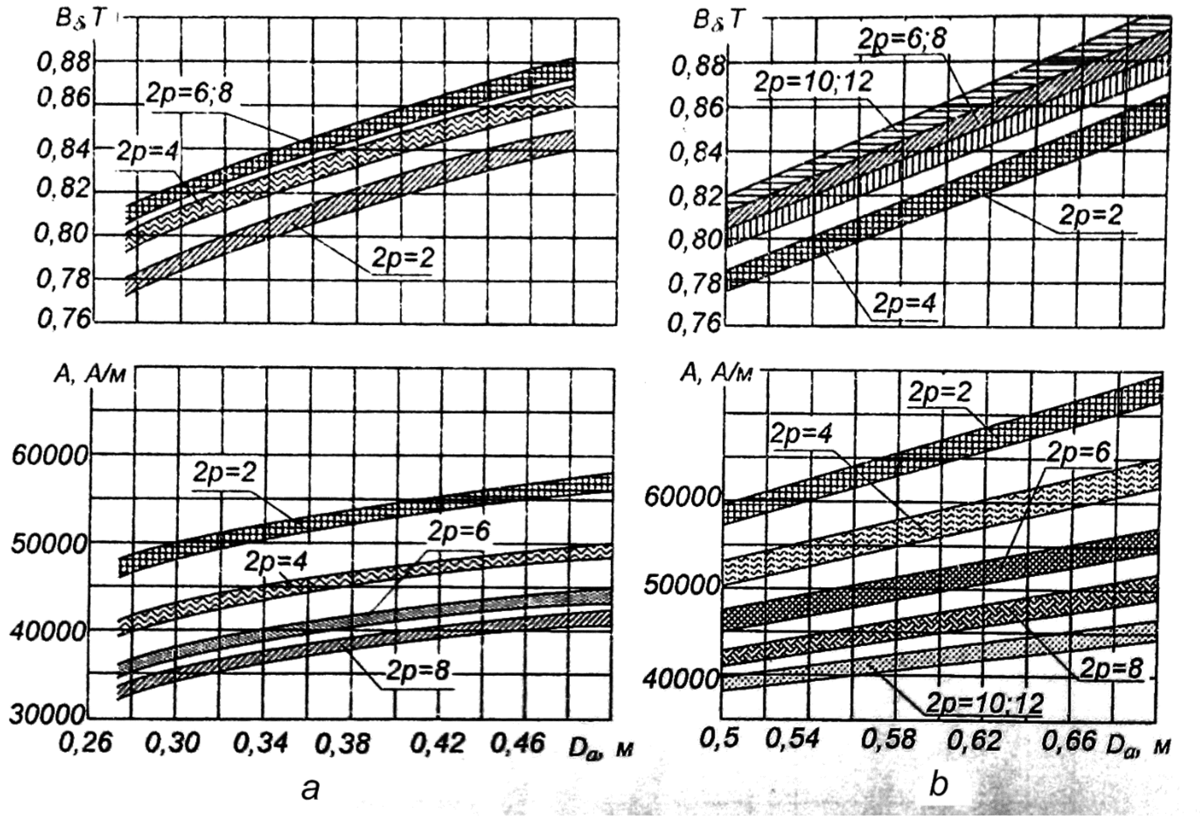


Figure 1.6 Electromagnetic loads of 4A series induction motors with enclosure protection IP23 at $h = 160 - 250\ mm$ (a), at $h \geq 280\ mm$ (b)

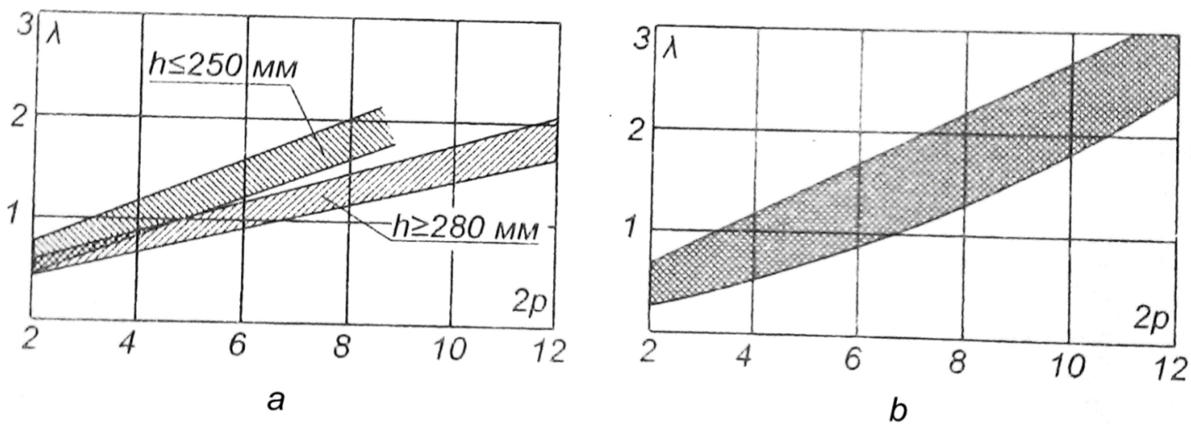


Figure 1.7 Acceptable values of λ for 4A series induction motors with enclosure protection IP44 (a) and IP23 (b)

If λ exceeds the acceptable value, it is necessary to accept another value of the motor shaft height taking the next higher standard height and to repeat calculations. At the value of λ less than the acceptable the calculations have to be repeated for the next lower shaft height standard value.

1.2.7. Full stator core design length l_1 and full core steel lamination stacks length l_{cs1} are defined with account of radial ventilation ducts.

In the case of $l_\delta \leq 250 - 300\,mm$ the radial ducts are not arranged, and the above indicated lengths are accepted equal $l_1 = l_{cs1} = l_\delta$. The rotor core length l_2 and core steel laminations stack length $l_{cs2}$are accepted in this case equal $l_2 = l_{cs2} = l_\delta$.

If the axial length of the motor air gap is $l_\delta > 300\,mm$, the stator and rotor cores are divided into several longitudinal stacks between which radial air ducts are arranged. In motors with slip-rings or welded squirrel-cage rotor each the core stack length l_{st} is taken equal to 40 – 60 mm. In motors with casted aluminum squirrel cage the length of each separate stack may be increased to 60-80 mm. Number of the steel lamination stacks must be integer and defined as

$$n_{st} = {}^{l_\delta}/_{l_{st}}. \tag{1.5}$$

The number of radial ducts is

$$n_{rd} = n_{st} - 1. \tag{1.6}$$

The radial duct width is usually accepted equal $b_{rd} = 10\,mm$.

For a stator with radial ventilation ducts full longitudinal lengths of the core lamination stacks ant of the stator are determined as

$$l_{cs1} = l_{st} n_{st} \tag{1.7}$$

$$l_1 = l_{cs1} + l_{st} n_{st}. \tag{1.8}$$

If radial air ducts are available, the estimated length of the air gap l_δ needs to be clarified taking into account the magnetic lines in the gap distortion. For that it is necessary to select the radial size of the air gap δ using Table 1.3.

Table 1.3

Air gap of induction motors

h, mm	Air gap δ, mm at number of poles equal				h, mm	Air gap δ, mm at number of poles equal			
	2	4	6 and 8	10 and 12		2	4	6 and 8	10 and 12
50	0.25	0.25	0.25	-	180	1.0	0.60	0.45	-
56	0.30	0.25	0.25	-	200	1.0	0.70	0.50	-
63	0.35	0.25	0.25	-	225	1.0	0.85	0.60	-
71;80	0.35	0.25	0.25	-	250	1.2	1.0	0.70	-
90	0.40	0.25	0.25	-	280	1.3	1.0	0.80	0.70
100	0.45	0.30	0.30	-	315	1.5	1.0	0.90	0.80
112	0.50	0.30	0.30	-	355	1.8	1.2	1.0	0.90
132	0.60	0.35	0.35	-	400	2.0	1.4	1.2	1.0
160	0.80	0.50	0.50	-	450	2.0	1.4	1.2	1.0

At $\delta < 1.5$ mm the lengthof the air gap is accepted equal $l_\delta = l_{cs}$.
At $\delta \geq 1.5$ mm the lengthof the air gap is accepted equal

$$l_\delta = l_1 - b'_{rd} n_{rd} \tag{1.9}$$

where b'_{rd} = design width of the radial air duct that is found by expressions:

$$b'_{rd} = \gamma' \delta, \tag{1.10}$$
$$\gamma' = \frac{2(b_{rd}/\delta)^2}{5+2(b_{rd}/\delta)}$$

To get the length of the air gap value obtained by expression (1.9) as close as possible to the value previously found by expression (1.4), correction of the core stack length l_{st} and possibly the number of the stacks n_{st} is made if necessary.
When the radial air ducts are available and $h < 300$ mm the rotor length l_2 is accepted equal to the stator length l_1 The total longitudinal length of the rotor core lamination stacks are found as

$$l_{cs2} = l_2 - b_{rd} n_{rd} \tag{1.11}$$

At $h \geq 300\ mm$ the rotor is made longer than the stator by 5 mm and in large high voltage machines by 10 mm by means of increase the length of its end stacks.

2. Design of stator and rotor teeth areas and windings

2.1. Basic parameters of winding and machine electromagnetic loads

2.1.1. Selection of the stator winding construction is made basing on the following. At rated voltage less or equal 660 V if the motor rated power on shaft is $P_2 \leq 100\ kW$, and also at $2p \geq 10$ if h equals 280 or 315 mm, the stator fed-in-winding is selected. At the rated power $P_2 > 100\ kW$ and voltage till 660 V, the partly form-wound windings are used. At a voltage of 3kV and more, the form-wound windings are applied.

2.1.2. For selection of the number of stator slots, define the limits of acceptable value of stator tooth pitch t_{1min} and t_{1max}. For machines with fed-in-winding it is made using the plot in Fig. 2.1. For machines with partly form-wound and form-wound windings the limits of tooth pitch are taken from Table 2.1.

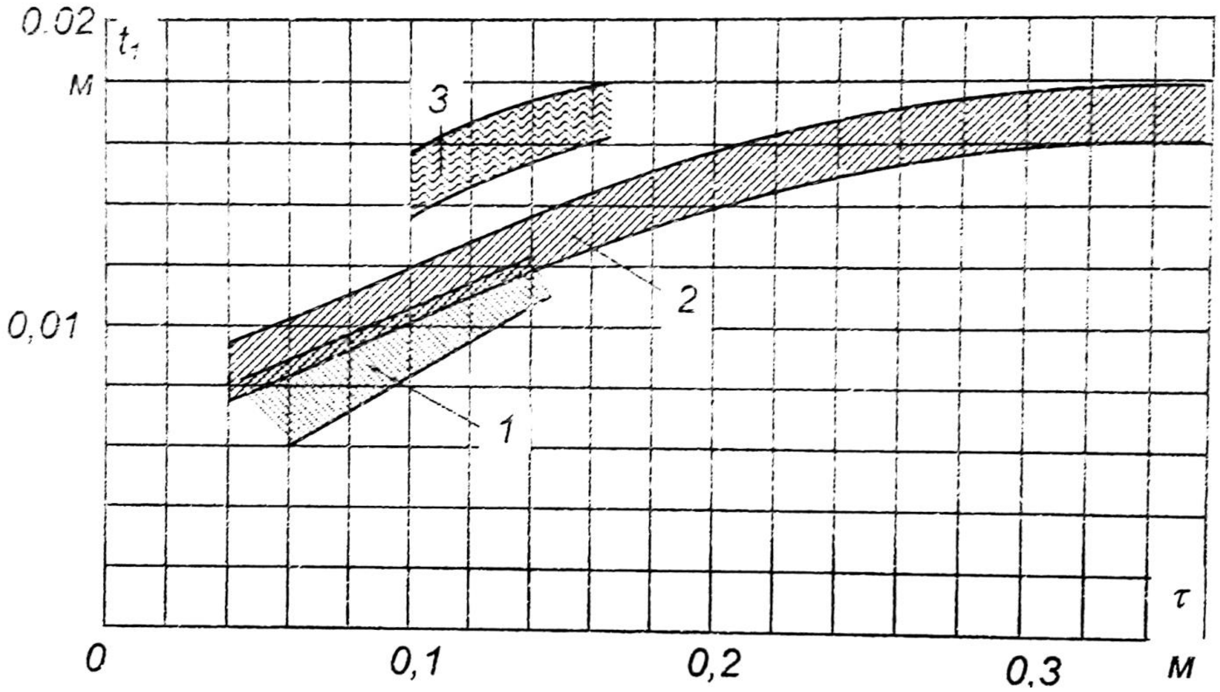


Figure 2.1 Stator tooth pitch of induction motors with fed-in-winding: area 1 – at $h \leq 90\ mm$, area 2 – at $90\ mm < h \leq 250\ mm$, area 3 – at $h \geq 280\ mm$

Table 2.1

Stator tooth pitch of induction motors with open slots (in m)

Pole pitch τ, m	Tooth pitch of motors with rated voltage (V)		
	till 660	3000	6000
< 0.15	0.016 – 0.020	0.022 – 0.025	0.024 – 0.030
0.15 – 0.40	0.017 – 0.022	0.024 – 0.027	0.026 – 0.034
>0.40	0.020 – 0.028	0.026 – 0.032	0.028 – 0.038

Acceptable number of stator slots is in the bounds of z_{1min} and z_{1max}:

$$z_{1min} \dots z_{1max} = \frac{\pi D}{t_{1max}} \dots \frac{\pi D}{t_{1min}} \ . \tag{2.1}$$

Finally, the number of stator slots z_1 is selected in the above limits so as it would be multiple of the number of machine phases m_1 and the number poles. In such a case the number of slots per pole and per phase

$$q = \frac{z_1}{2pm_1} \tag{2.2}$$

is integer. Fractional slot windings are sometimes applied in machines having great enough number of poles $2p \geq 10$. In such cases the fractional part of q has as a rule denominator equal 2.

2.1.3. The tooth pitch of the stator is found by the expression:

$$t_1 = \frac{\pi D}{2pmq}. \tag{2.3}$$

It should not go beyond the limits more than for 10 % and, at $h \geq 56$ mm , should not be less than 6 – 7 mm.

2.1.4. The number of turn sides embedded into a slot is found as

$$u_{sl} = au'_{sl} \tag{2.4}$$

where a = the number of parallel circuits in a phase winding;
u'_{sl} = the number of turn sides in a slot at $a = 1$ which is calculated without rounding by the following expression:

$$u'_{sl} = \frac{\pi DA}{I_{1r}z_1}. \tag{2.5}$$

Here A = the tentative value of the electric loading accepted at determination of $l_д$ by (1.4)

I_{1r} = the stator phase rated current in Amperes which is found by the formula:

$$I_{1r} = \frac{P_{2r}}{mU_{1r}\,\eta\cos\varphi} \qquad (2.6)$$

Where P_{2r} and U_{1r} are the rated motor power and phase voltage respectively,

m is the number of phases

Values of the efficiency η and power factor $\cos\varphi$ are taken as was accepted at determination of P' (1.3).

2.1.5.The number of parallel circuits of a phase winding is accepted out of possible numbers for the selected winding type and given number of poles values so that u_{sl} was integer number and, in the case of two layer winding - an even number. If the required value of turn sides into a slot can't be obtained in this way, the number of parallel circuits is accepted so that getting integer or even value of u_{sl}will require minimal rounding the value obtained from (2.5).

2.1.6. The number of turns of a phase winding is equal to

$$w_1 = \frac{u_{sl}z_1}{2am}. \qquad (2.7)$$

2.1.7. The final value of the machine electric loading is found by the expression:

$$A = 2I_{1r}w_1m/(\pi D). \qquad (2.8)$$

It is permitted that the obtained value of A would differ only slightly from those previously found tentative value and must be in the limits defined by plots in Fig. 1.5 or 1.6 depending on the degree of the motor enclosure protection.

2.1.8. The coil span is accepted equal:

- $y = \tau$ for single-layer windings. For them the pitch factor equals $k_p = 1$ and the winding factor equals the distribution factor, i.e. $k_w = k_d$.
- $y = (0.79 \ldots 0.83)\tau$ for double-layer windings. For them the winding factor equals to product of the pitch factor k_p and the distribution factor k_d, i.e. $k_w = k_p k_d$. In the integer slot windings the coil span (pitch) y is always multiple of the tooth pitch t_1.

The pitch and tooth factors for fundamental are found by expressions:

$$k_p = \sin(\beta \frac{\pi}{2}), \; k_d = \frac{\sin\frac{\pi}{2m}}{q \sin\frac{\pi}{2mq}} \qquad (2.9)$$

where $\beta = \frac{y}{\tau}$ is the relative coil span.

For a fractional winding having $q = b + \frac{c}{d} = \frac{bd+c}{d} = \frac{N}{d}$ the distribution factor is found as

$$k_d = \frac{\sin\frac{\pi}{2m}}{N \sin\frac{\pi}{2mN}}.$$

2.1.9. Refined value of the magnetic flux density fundamental amplitude in the air gap is determined as

$$B_\delta = \frac{\Phi}{\alpha_\delta \tau l_\delta} \cong \frac{p\Phi}{D l_\delta} \qquad (2.10)$$

where

$$\Phi = \frac{k_E U_{1r}}{4 k_B w_1 k_{w1} f_1} \tag{2.11}$$

is the magnetic flux passing through a pole pitch. Values of k_E and $k_B$were accepted at calculations by equalities (1.3) and (1.4) respectively. The coefficient of a pole arc $\alpha_\delta = 2/\pi \cong 0.64$.

If the obtained value of B_δ differs from the value defined by curves in Fig. 1.5 or 1.6 respectively by more than 5 %, it is necessary to change the value of u_{sl} at the same or other number of parallel circuits (2.4), to find a new number of the phase turns w_1 (2.7), to check a new value of the machine electric loading A (2.8) and to find a new value of the flux density $B_д$ (2.10), repeating this procedure till obtaining the sufficient value of B_δ.

2.1.10. Allowable stator current density in A/m^2 equals:

$$J_1 = (AJ)/A \tag{2.12}$$

where(AJ) = recommended value of product of the electric loading and the current density in A^2/m^3 found from Fig. 2.2,

A = electric loading in A/m.

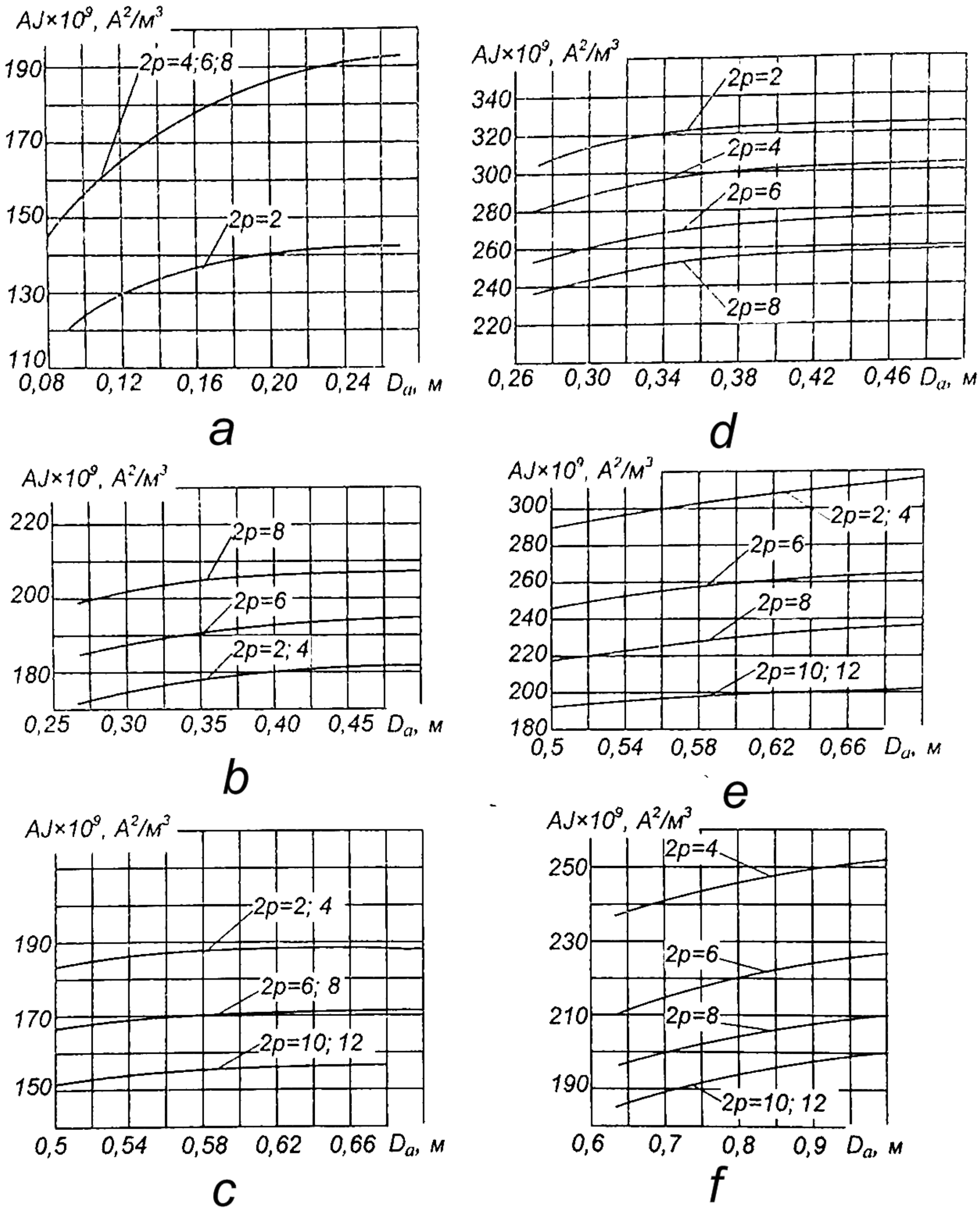


Figure 2.2 Average value of the product (AJ) for motors of 4A series with enclosure protection IP44: $h \leq 132$ mm (a), $h = 160 \ldots 250$ mm (b), $h = 280 \ldots 355$ mm for motors with blown through rotors (c)
and IP23: $h = 160 \ldots 250$ mm (d), $h = 280 \ldots 355$ mm at $U < 6000$ V (e), $h = 280 \ldots 355$ mm at $U = 6000$ V (f)

2.1.11. The coil turn side cross-section area, m^2:

$$q_{ef1} = \frac{I_{1r}}{aJ_1} \quad (2.13)$$

where I_{1r} is taken according (2.6), $a =$ number of parallel circuits of a phase winding accepted above.

2.2 Selection of stator winding wire and design of teeth area

2.2.1. To select the wire type it is necessary to choose the insulation thermal class. For three-phase induction motors of 4A series it is chosen depending on the motor shaft height as follows. For motors up to 1000 V with shaft height of 50…132 mm the insulation thermal class B is accepted. For motors having the shaft height greater than 132 mm class F should be accepted.

In the case of fed-in-winding round copper wires with enamel insulation are used. At the thermal class B are used wires ПЭТВ, at the thermal class F are used wires ПЭТ-155, ПЭТ-155М or ПЭТ-200. The wire ПЭТ-155М is used at mechanized wounding.

For fed-in-coils the round insulated conductor diameter must be not greater than 1.4 mm at mechanized wounding (motors with $h \leq 160$ mm) and not greater than 1.7 mm at hand wounding (motors with $h > 160$ mm).

2.2.2. If the obtained value of the turn side (or effective conductor) cross-section area (2.13) may be provided only at greater values of the conductor diameter, it is necessary to divide the conductor into several elementary conductors which are wound in parallel. The number of elementary conductors n_{el1} must be such that under the acceptable value of the insulated wire will be obtained equality:

$$q_{el1} \cdot n_{el1} = q_{ef1} \qquad (2.14)$$

where q_{el1} =the plain elementary conductor diameter. Standard diameters of round conductors with enamel insulation intended for electric machines windings are given in Table 2.2.

Table 2.2

Diameters and enamel insulation thickness of round conductors fof electric mashines windings

Rated diameter of non-insulated conductor in *mm*	Mean value of insulated conductor diameter in *mm*	Cross-section area of non-insulated conductor in *mm* ²	Rated diameter of non-insulated conductor in *mm*	Mean value of insulated conductor diameter in *mm*	Cross-section area of non-insulated conductor in *mm* ²
0,08	0,10	0,00502	(0,53)	0,585	0,221
0,09	0,11	0,00636	0,56	0,615	0,246
0,10	0,122	0,00785	0,60	0,655	0,283
0,112	0,134	0,00985	0,63	0,69	0,312
0,125	0,147	0,01227	(0,67)	0,73	0,353
0,14	0,162	0,01539	0,71	0,77	0,396
0,15	0,18	0,01767	0,75	0,815	0,442
0,16	0,19	0,0201	0,80	0,865	0,503
0,17	0,20	0,0227	0,85	0,915	0,567
0,18	0,21	0,0255	0,90	0,965	0,636
(0,19)	0,22	0,0284	0,95	1,015	0,709
0,20	0,23	0,0314	1,00	1,08	0,785
(0,212)	0,242	0,0353	1,06	1,14	0,883
0,224	0,259	0,0394	1,12	1,20	0,985
(0,236)	0,271	0,0437	1,18	1,26	1,094
0,25	0,285	0,0491	1,25	1,33	1,227
(0,265)	0,300	0,0552	1,32	1,405	1,368
0,28	0,315	0,0616	1,40	1,485	1,539
(0,30)	0,335	0,0707	1,50	1,585	1,767
0,315	0,350	0,0779	1,60	1,685	2,011
0,335	0,370	0,0881	1,70	1,785	2,27
0,355	0,390	0,0990	1,80	1,895	2,54
0,375	0,415	0,1104	1,90	1,995	2,83
0,40	0,44	0,1257	2,00	2,095	3,14
0,425	0,465	0,1419	2,12	2,22	3,53
0,45	0,49	0,1590	2,24	2,34	3,94
(0,475)	0,515	0,1772	2,36	2,46	4,36
0,50	0,545	0,1963	2,50	2,60	4,91

Recommended number of the elementary conductor for fed-in-windings is $n_{el1} \leq 5 - 6$ for hand wounded windings, and $n_{el1} \leq 2 - 3$ for mechanized wounded machines. Ultimate number of elementary conductors for hand wounded induction motors is $n_{el1} \leq 10 \dots 12$. If n_{el1} is greater than recommended, it is necessary to increase the number of parallel circuits in a phase winding a. In two-pole machines at $a = 2$ the number of elementary conductors may be accepted greater than the recommended but less than the ultimate value.

2.2.3. For form-wound windings, that are wound of rectangular wire, the conductors ПЭТВП (thermal class B) are recommended for use at the voltage till 660 V. The conductors ПЭТП-155 are used for the machines with class F insulation, and conductors ПЭТП-200 provide thermal class H. In high-voltage machines the conductors ПЭТВСД having enamel insulation made on the basis of polyester and covered by two-layer glass fibre glued and impregnated with thermally stable varnish are applied.

Dimensions of wires with rectangular cross-section and the insulation thickness are given in Table 2.3 (this table in the methodical manual is not given; find it in the book: Цыпленков Д.В., Куваев Ю.В., Иванов А.Б., Кириллов И.А. Проектирование электрических машин; под ред. Шкрабца Ф.П. – Днепропетровск: Национальный горный университет, 2008).

2.2.4. If the value of q_{ef1} exceeds 20 mm^2, the rectangular conductors are divided into several elementary ones. Cross-section area of the elementary conductor should be $q_{el1} \leq 17 \dots 20$ mm^2.

In the case of rigid formed coils application, open slots are used. In this case the number of elementary conductors must be $n_{el1} \leq 2$.

In the case of semi-open slots $n_{el1} = 2$.

The coil turn side (i.e. effective conductor) cross-section area must not be greater than $35-40$ mm^2. On this reason at great values of the stator current I_{1r}, greater possible number of parallel circuits in a phase winding a is accepted.

Final selection of the wire dimensions is made concurrently with design of the stator teeth area.

2.2.5. Consider ways of the stator teeth area designing.

First describe the procedure of the teeth area designing for the case of the coils made of rectangular wire. In this case the open or semi-open slots are used (Fig. 2.3 and 2.4).

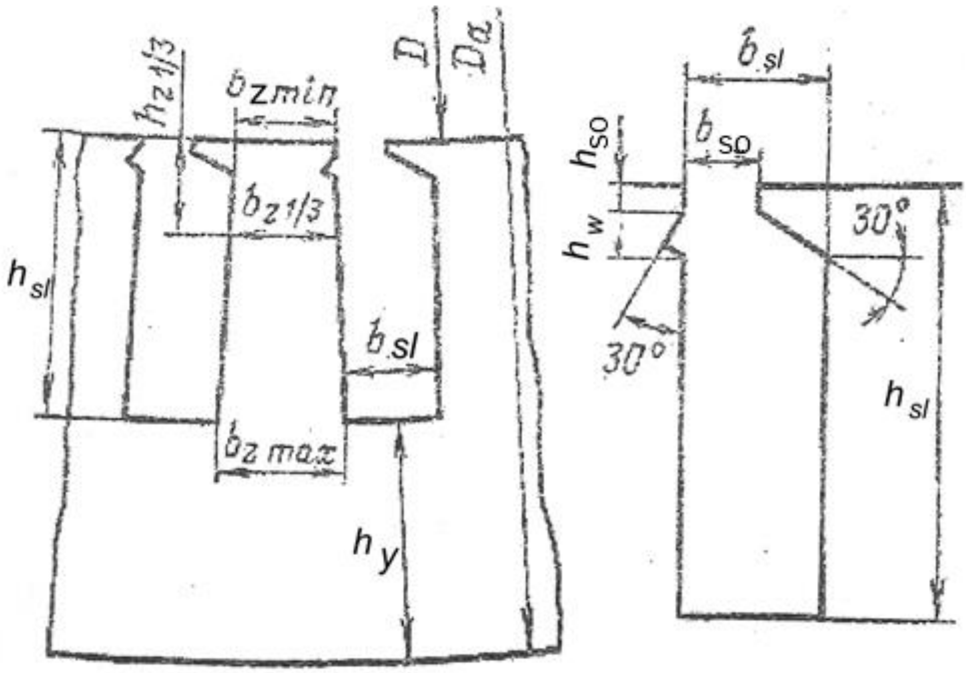


Figure 2.3 Semi-open parallel slot of stator

Open and semi-open slots have parallel sides. Therefore, the tooth width is variable increasing to the tooth base.

2.2.6. Using recommendations given in Table 2.4, the acceptable magnetic flux density in the stator core yoke B_y is accepted. Also, the flux density in the most narrow tooth section $B_{Z1\,max}$ is accepted.

Next, the stator yoke width in meters is found:

$$h_y = \frac{\Phi}{2B_y l_{cs1} k_{fill}} \tag{2.15}$$

wherek_{fill} = the fill (lamination) factor.

Permissible values of flux density in different parts of induction motor magnetic circuit

Table 2.4

Part of magnetic circuit	Denotation	Degree of protection IP44					Degree of protection IP23					
	2p	2	4	6	8	10 и 12	2	4	6	8	10	12
Stator core yoke	B_a	1,4 – 1,6			1,15 – 1,35	1,1 – 1,2	1,45 – 1,6			1,2 – 1,4		1,1 – 1,3
Stator teeths of constant cross-section (fed-in-winding)	B_{Z1}	1,7 – 1,9				1,6 – 1,8	1,9 – 2,1	1,8 – 2,0			1,7 – 1,9	
Stator teeth in narrowest cross-section, semi-open slots	B_{Z1max}	1,75 – 1,95					1,9 – 2,1	1,8 – 2,0				
open slots		1,6 – 1,8					1,7 – 1,9					
Rotor yoke: squirrel cage motor	B_j	≤ 1,45	≤ 1,25	≤ 1,15	≤ 0,85		≤ 1.55	≤ 1,35	≤ 1,25	≤ 0,95		
wound rotor		–	≤ 1,25	≤ 1,05	≤ 0,75		–	≤ 1,35	≤ 1,15	≤ 0,85		
motors with U = 6000 B		–	≤ 1,55	≤ 1,30	≤ 1,0		–	≤ 1,45	≤ 1,20	≤ 1,0		
Rotor teeth with constant cross-section (pear-shaped slots)	B_{Z2}	1,75 – 1,85					1,8 – 1,95					
Rotor slots in narrowest cross-section: cage motor	B_{Z2max}	1,5 – 1,7		1,45 – 1,69			1,6 – 1,8		1,55 – 1,7			
wound motor		1,85 – 2,05		1,75 – 1,9			2,0 – 2,2		1,9 – 2,05			

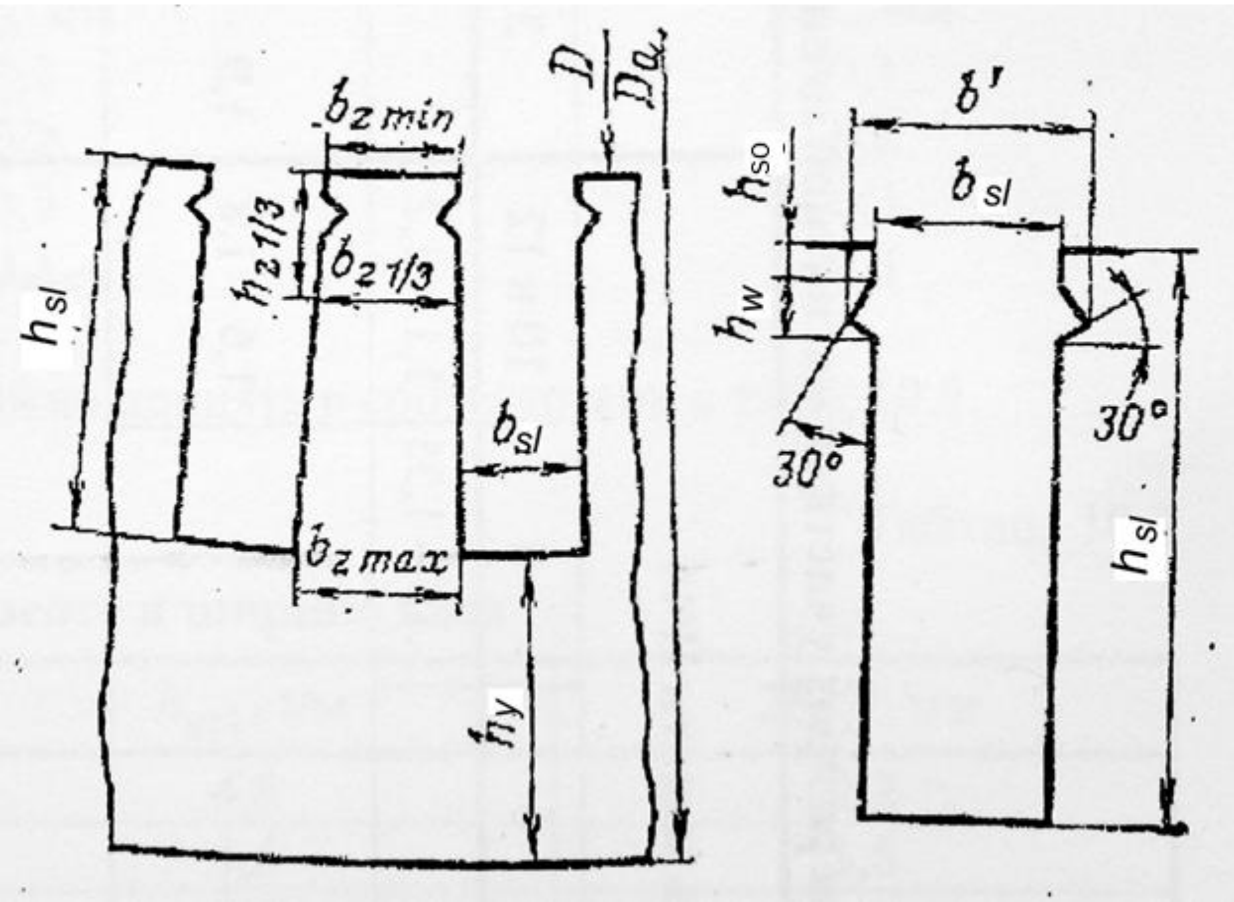


Figure 2.4 Open parallel slot of stator

Selection of the steel, the method of sheets insulation, and the fill factor value depends on the machine shaft height and is made with the help of Table 2.5.

Recommended steel grades, way of sheets insulation and values of fill factor for induction motors

Table 2.5

h, мм	U, В	Steel grade	Stator		Cage rotor		Wound rotor	
			Method of sheets insulation	k_{fill}	Method of sheets insulation	k_{fill}	Method of sheets insulation	k_{fill}
50–250	≤660	2013	Oxidation	0,97	Oxidation	0,97	–	–
280–355	≤660	2312	Varnish	0,95	Oxidation	0,97	Varnish	0,95
400–560	6000	2411	Varnish	0,95	Varnish	0,95	Varnish	0,95

2.2.7. Minimum stator tooth width, in meters, is equal to:

$$B_{Z1\,min} = \frac{B_\delta \cdot t_1 \cdot l_\delta}{B_{Z1\,max} \cdot l_{cs1} \cdot k_{fill}}. \qquad (2.16)$$

The slot dimensions:

– the slot height

$$h_{sl1} = \frac{D_a - D}{Z_1} - h_y \qquad (2.17)$$

– the slot width

$$b_{sl1} = t_1 - b_{Z1\,min} \qquad (2.18)$$

as a rule $b_{sl1} \cong (0.4 \ldots 0.5)t_1$.

2.2.8. Based on h_{sl1} and b_{sl1}, the winding conductor dimensions are selected.

In the case of $h_{el1} = 1$ the conductor width is $b = b_{sl1} - \Delta'_{ins}$ where $\Delta'_{ins} = 2b_{ins} + \Delta b_{sl}$, b_{ins} = unilateral total thickness of insulation in the slot (insulation of the coils, coil turn and conductor), Δb_{sl} = allowance for the core laminations assembling.

In the case of $n_{el1} = 2$ the width $b = 0.5(b_{sl1} - \Delta'_{ins})$.

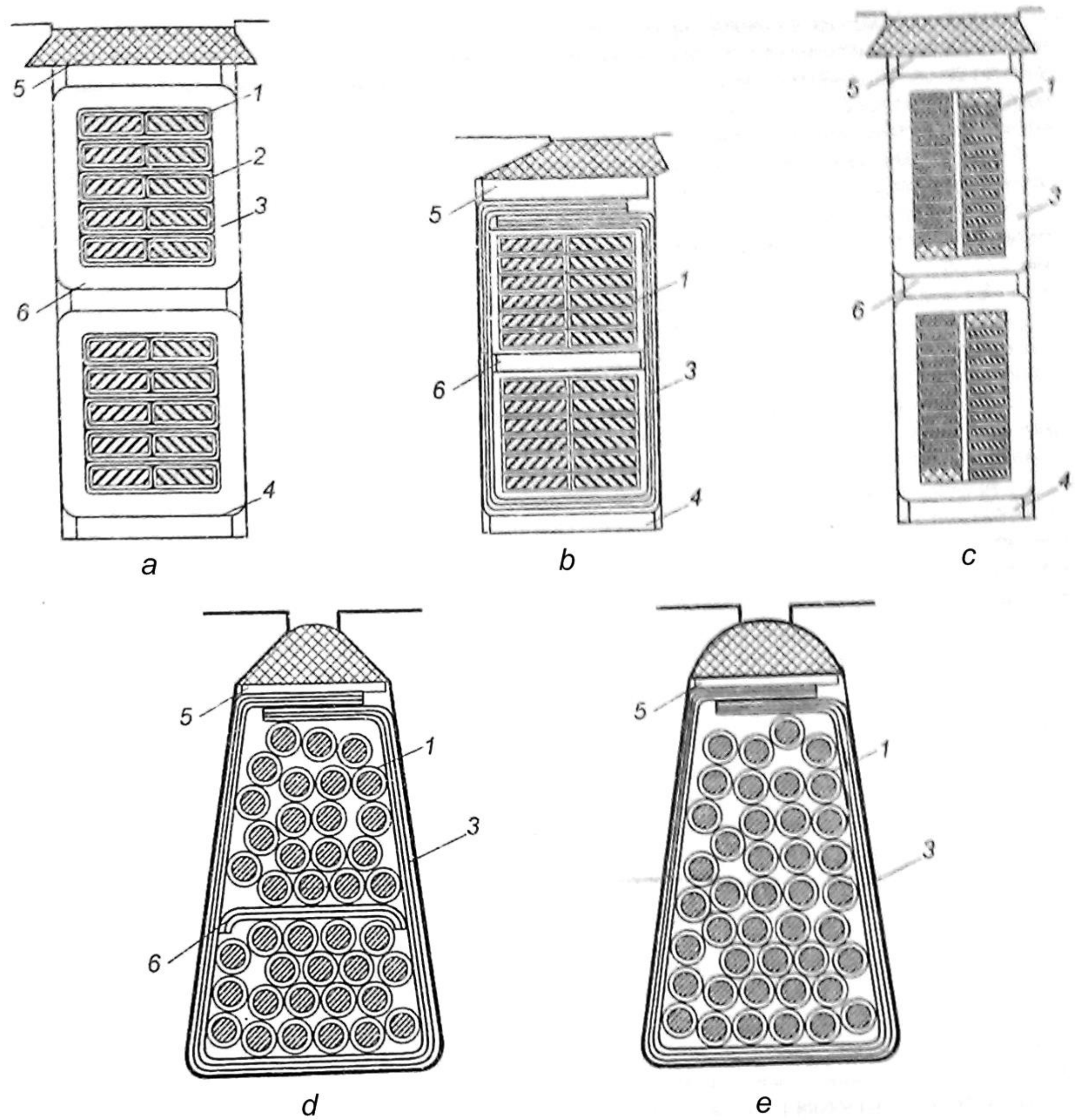


Figure 2.5 Cross-section of AC machine slots: *a* – open slots with inserted coil sides of form-wound winding, *b*- semi-open slots for insertion of form-wound winding two-section coils, *c* – open slots of large machine with bar winding, *d* – semi-closed slot with fed-in two-layer winding, e- semi-closed slot with fed-in one-layer winding. Reference numerals: 1 – wire insulation, 2 – turn insulation, 3 – slot insulation, 4 – insulating spacer at slot bottom, 5– insulating spacer under wedge, 6 – interlayer insulation

The allowances for laminations assembling are accepted depending on the motor shaft height as follows:

h, mm	Δb_{sl}, mm	Δh_{sl}, mm
50 … 132	0.1	0.1
160 … 250	0.2	0.2
280 … 355	0.3	0.3
400 … 560	0.4	0.3

The insulation thickness by the slot width and height is accepted according to Table 2.6.

Table 2.6

Insulation thickness by slot height and width

h,мм	Slot shape	h_{ins1}, мм	$2b_{ins1}$, мм
280–355	Semiopen	4,5	2,2
280–355	Open	4,5	1,8
400–450	Open	12,4	4,1

The cross-section of AC machines slots is shown in Fig. 2.5.

Based on the obtained value of the width of conductor b and the area of elementary conductor q_{el1}, select a standard wire which has the values of b and q nearest to the calculated values. At this, the conductor height must be $a \leq 2.5$ ... 3 mm that provides uniform current distribution in the wire cross-section. The conductor thickness may be some greater than indicated above in the case of small number of the coil turns.

To avoid difficulties at coils insertion into slots it is necessary that $a > 1$ mm. It is also necessary to avoid close values of a and b as in this case the conductor has tendency to twisting.

2.2.9. After the wire selection, draw up a table of the slot filling indicating the wire dimensions names, insulation thickness and layers number, and thickness of interleaving insulation. On the basis of the table the slot clear dimensions h_{sl1}, b_{sl1} are defined.

For open slots it is accepted:

$$b' - b_{sl} = 2 \ldots 5 \text{ mm}, \ \ h_{so} = 0.5 \ldots 1.0 \text{ mm}, h_w = 3.0 \ldots 3.5 \text{ mm}.$$

For semi-open slots

$$b_{so} = 0.5 b_{sl} + (1.0 \ldots 1.5) \text{ mm}, h_{so} = 0.5 \ldots 0.8 \text{ mm}, h_w = 2.5 \ldots 3.5 \text{ mm}.$$

2.2.10. After definition of the slot clear dimensions, its dimensions "in stamp" are found using previously accepted values of allowances Δb_{sl} and Δh_{sl}, and after that the tooth width is calculated as:

$$b_{Z\,min} = t_1 - b_{sl}; \, b_{Z\,max} = t_1 \left(1 + \frac{2h_{sl}}{D}\right) - b_{sl}. \qquad (2.19)$$

The tooth height: $h_Z = h_{sl}$.

2.2.11. Now consider the procedure of determination of shape and dimensions of slots for fed-in-windings. Slots for such windings are shown in Fig. 2.6.

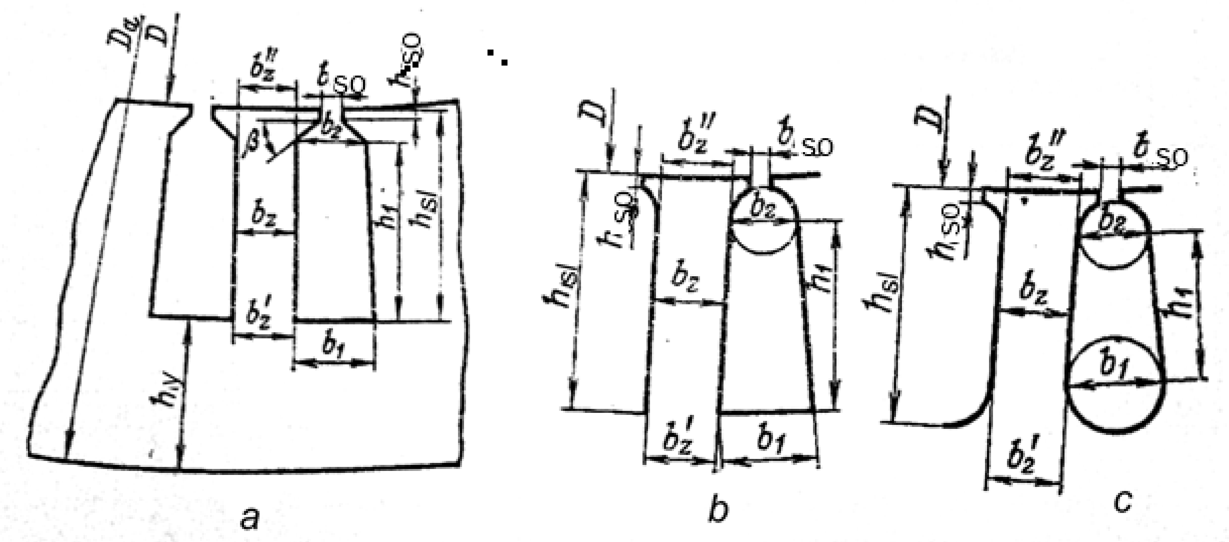


Figure 2.6 Slots for fed-in-windings

In induction motors 4A series trapezoidal slots for placing fed-in-windings are applied. The slope of the wedge part of the slot is accepted equal to $\beta = 45°$ at $h \leq 250$ mm and to в $= 30°$ at $h \leq 280$ mm and also at $2p = 10$ or 12 regardless of h.

2.2.12. Taking up the assumable values of magnetic induction from Table 2.4, find the yoke width h_y using (2.15).

2.2.13. After that the tooth width is determined as

$$b_Z = \frac{B_\delta t_1 l_\delta}{B_{Z1} \cdot l_{cs} \cdot k_{fill}}. \qquad (2.20)$$

The slot dimensions in stamp are:

$$h_{sl} = \frac{D_a - D}{2} - h_y; \;\; b_1 = \frac{\pi(D + 2h_{sl})}{Z_1} - b_Z, \qquad (2.21)$$

$$b_2 = \frac{\pi(D + 2h_{so} - b_{so}) - Z_1 b_Z}{Z_1 - \pi} \text{ at } \beta = 45°, \qquad (2.22)$$

$$b_2 = \frac{\pi\left(D + 2h_{so} - b_{so}/\sqrt{3}\right) - Z_1 b_Z}{Z_1 - \pi/\sqrt{3}} \text{ at } \beta = 30°. \qquad (2.23)$$

The obtained values should be rounded off to the nearest tenth of mm. It is recommended to accept $h_{so} = 0.5$ mm if $h \leq 132$ mm, and $h_{so} = 1$ mm if $h \geq 160$ mm; $b_{so} = d_{ins} + (1.5 \ldots 2.0)$ mm where d_{ins} = diameter of insulated wire, mm.

2.2.14. The slot cross-section area “in stamp” in m^2 is:

$$S_{sl} = (b_1 + b_2)\, h_1/2. \qquad (2.24)$$

where $h_1 = h_{sl} - (h_{so} + h_w)$.

The wedge part of slot height is

$$h_w = (b_2 - b_{so})/2 \text{ if } \beta = 45°,$$

$$h_w = (b_2 - b_{so})/\left(2\sqrt{3}\right) \text{ if } \beta = 30°. \qquad (2.25)$$

2.2.15. The slot clear dimensions are:

$$b'_1 = b_1 - \Delta b_{sl};\ b'_2 = b_2 - \Delta b_{sl};\ h'_1 = h_1 - \Delta h_{sl}$$

where Δb_{sl} and Δh_{sl} are accepted as for parallel slots (see above).

Area occupied by the slot insulation in m^2 is found as

$$S_{ins} = b_{ins}(2h_{sl} + b_1 + b_2), \quad (2.26)$$

where $b_{ins} =$ the unilateral thickness of insulation in the slot taken in m. It is accepted depending on the shaft height equal to:

h, mm	50…80	90…132	160…250	280…315
b_{ins}, mm	0.2	0.25	0.4	0.58

In motors with the shaft height $h = 180 \div 250$ mm and having two-layer winding, the area occupied by the interlayer insulation is $S_{il} = 0.4b_1 + 0.9b_2$.

In the case of two-layer winding at $h \geq 280$ mm

$$S_{il} = 0.6(b_1 + b_2).$$

In one-layer winding there is no interlayer insulation, and $S_{il} = 0$.

2.2.16. The area of the slot cross-section remaining for the wires placement is equal to

$$S'_{sl} = \frac{b'_1 + b'_2}{2} h'_1 - S_{ins} - S_{il}. \quad (2.27)$$

Correctness of the slot filing up is checked with the help of the slot fill factor

$$k_{sf} = \frac{d_{ins}^2 u_{sl} n_{el1}}{S'_{sl}}. \quad (2.28)$$

For hand wounded windings the value must be $k_{sf} = 0.70 \ldots 0.75$. For mechanized wounded windings - $k_{sf} = 0.70 \ldots 0.72$.

At less values of k_{sf} it is necessary to reduce S'_{sl} by increasing h_y and b_Z that will cause reduction of B_Z and B_y. If the magnetic flux density reduces to lower than indicated in Table 2.4 values, it is necessary to reduce the core length or to accept the near less height of the motor shaft.

At greater values of k_{sf}, when it is impossible to reduce it to the acceptable value by selection h_y and b_Z saving permissible values of $B_y$and B_Z, or by accepting greater value of q_{el1} at less value of n_{el1}, it is necessary to increase the core length or to design another version of the motor after change of the principal dimensions.

2.2.17. In the case of fed-in-windings the tooth width and height are found by expressions given in Table 2.7. Usually $b_Z' = b_Z'' = b_z$. If the obtained values of b_Z' and b_Z'' slightly differ , it is recommended to determine b_Z for further calculations as

$$b_Z = \frac{b_Z' + b_Z''}{2}.$$

If the difference is considerable, it is necessary to change the slot dimensions, or to calculate, in the following computations, the tooth mmf as for the case of parallel slots.

Table 2.7

To calculation of stator tooth dimensions at trapezoidal and pear-shaped slots for fed-in-winding

Размер	Fig. 6a	Fig. 6b	Fig. 6c
b_Z'	$\pi\frac{D+2h_{sl}}{Z_1}-b_1$	$\pi\frac{D+2h_{sl}}{Z_1}-b_1$	$\pi\frac{D+2h_{sl}-b_1}{Z_1}-b_1$
b_Z''	$\pi\frac{D+2(h_{sl}-h_1)}{Z_1}-b_2$	$\pi\frac{D+2h_{cg}+b_2}{Z_1}-b_2$	$\pi\frac{D+2h_{cg}+b_2}{Z_1}-b_2$
h_Z	h_{sl}	h_{sl}	$h_{sl}-0{,}1b_1$

2.2.18. After final selection of q_{el1}, n_{l1} and a, the current density is adjusted:

$$J_1 = \frac{I_{1r}}{a q_{el1} n_{el1}}\,. \quad (2.29)$$

2.3. Rotor winding and rotor teeth area

2.3.1. First consider the wound rotor.

A winding of the wound rotor has the same number of phases and number of pole pairs that the stator one, i.e. $m_2 = m_1 = m;\ p_2 = p_1 = p$.

The number of rotor slots should be not equal to the number of stator slots.

Preliminary value of the rotor number of slots per pole and per phase is taken as $q_2 = q_1 \pm K$ where K is accepted equal $K = 1$ or $^1/_2$. The rotor number of slots preliminary value is found as

$$Z_2 = Z_1\, q_2/q_1. \tag{2.30}$$

It is recommended to provide the stator to rotor number of slots ratio as in motor 4A series (Table 2.8). If the preliminary value of q_2 gives another number of Z_2 than indicated in the table, it is recommended to change it for recommended (Table 2.8).

2.3.2. As a rule in induction motors having the rated power till 80…100 kW the two layer lap winding is used. In machines of higher power the wave bar winding is applied.

Table 2.8

Relation of stator and rotor slor numbers in induction motors of 4A series

h, мм	Отношение Z_1/Z_2 при разном значении 2p					
	2	4	6	8	10	12
Squirrel-cage motors						
50–63	24/19	24/18	36/28	–	–	–
71	24/19	24/18	36/28	36/28	–	–
80–100	24/19	36/28	36/28	36/28	–	–
112–132	24/19	36/34	54/51	48/44	–	–
160	36/28	48/38	54/51	48/44	–	–
180–200	36/28	48/38	72/58	72/58	–	–
225	36/28	48/38	72/56	72/56	–	–
250	48/40	60/50	72/56	72/56	–	–
280–355	48/38	60/70	72/82	72/86	90/106	90/106
400–450	–	60/70	72/84	72/86	90/106	90/106
Wound motors						
200	–	48/36	72/54	72/48	–	–
225	–	48/66	72/81	72/84	–	–
250	–	60/72	72/81	72/84	–	–
280–355	–	60/72	72/81	72/84	90/120	90/108
400–450	–	60/72	72/90	72/96	90/120	90/126

To provide easier mechanical balancing of the rotor, the rotor winding leads are distributed along the circle as uniformly as possible.

2.3.3. For determination of the needed number of rotor phase turns w_2, the voltage E_2 induced in a phase of locked rotor is preliminary accepted as follows. The voltage across the slip rings of the locked rotor is usually in the range of 150…250 V (in some motors till 500 V). As the rotor winding is usually has star connection the phase induced voltage at locked rotor is accepted equal $E_2 = 85 \ldots 145\ (290)$ V. If the rotor winding is connected in delta, the induced voltage E_2 is accepted equal 150…250 (500) V.

The number of turns of the rotor phase is found as

$$w_2 = \frac{E_2}{U_{1r}} w_1 \quad (2.31)$$

The number of effective turns in the rotor slot is equal to

$$u_{sl2} = \frac{2w_2m_2}{Z_2} = \frac{w_2}{p_2q_2}. \quad (2.32)$$

The obtained value of u_{sl2} must be rounded to the nearest even number. After that the rotor turns number is adjusted according to the expression:

$$w_2 = u_{sl2}p_2q_2. \quad (2.33)$$

For two-layer wave bar winding $u_{sl2} = 2$, $w_2 = 2p_2q_2 = Z_2/m_2$.

2.3.4. After determination w_2 it is necessary to check the condition:

$$U_{sr} = \sqrt{3}U_{1r}\frac{w_2}{w_1} \leq 800 \ldots 1000 \text{ V}. \quad (2.34)$$

If it is necessary to reduce U_{sr} (the voltage between slip rings at stationary rotor), the number of parallel circuits in the rotor phase of wave bar winding may be accepted equal $a = 2$. In this case a wave bar winding is symmetrical only if q_2 is integer).

2.3.5. Preliminary rotor phase rms current is found as

$$I_{2r} = k_i \cdot I_{1r} \cdot v_i \tag{2.35}$$

where k_i = the coefficient taking into account influence of no-load current I_0 and the windings impedance onto the ratio I_2/I_1. Its value is accepted according to the curve $k_i = f(\cos\varphi)$ presented in Fig. 2.7. Value of $\cos\varphi$ is accepted according to div.1.2. The current transformation ratio

$$v_i = \frac{m_1 w_1 k_{w1}}{m_2 w_2 k_{w2}}. \tag{2.36}$$

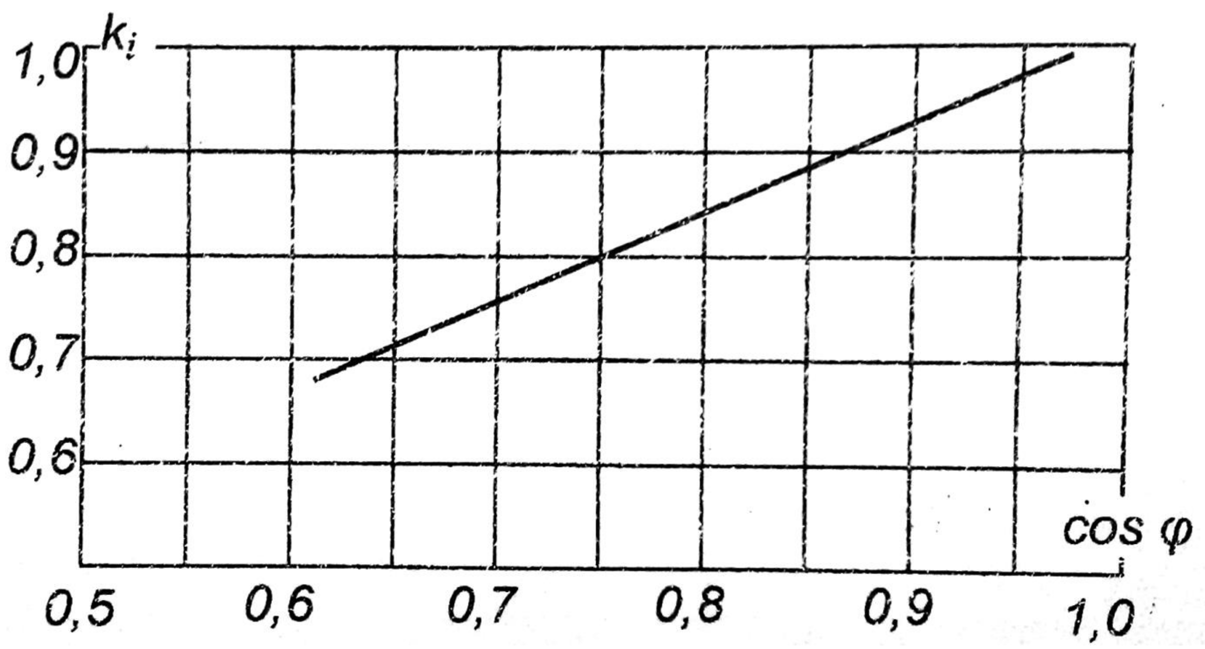


Figure 2.7 Curve for determination coefficient k_i

2.3.6. The effective rotor conductor cross-section area in m^2:

$$q_{ef2} = I_{2r}/J_2. \tag{2.37}$$

where J_2 = the rotor winding current density in A/m². For lap windings of B and F thermal class it is accepted in the limits $J_2 = (5 ... 6.5) \cdot 10^6$ A/m². For bar wave windings, $J_2 = (4.5 ... 5.5) \cdot 10^6$ A/m².

2.3.7. The rotor effective conductors are not divided into elementary ones as at the rated speed the rotor frequency $f_{2r} = s_r f_{1v}$ is very small, and the skin effect is not appreciable.

In wound rotors with the lap windings open slots with parallel sides are used, in the case of the bar wave windings – semi-closed parallel slots are made. These slots are presented in Fig.2.8.

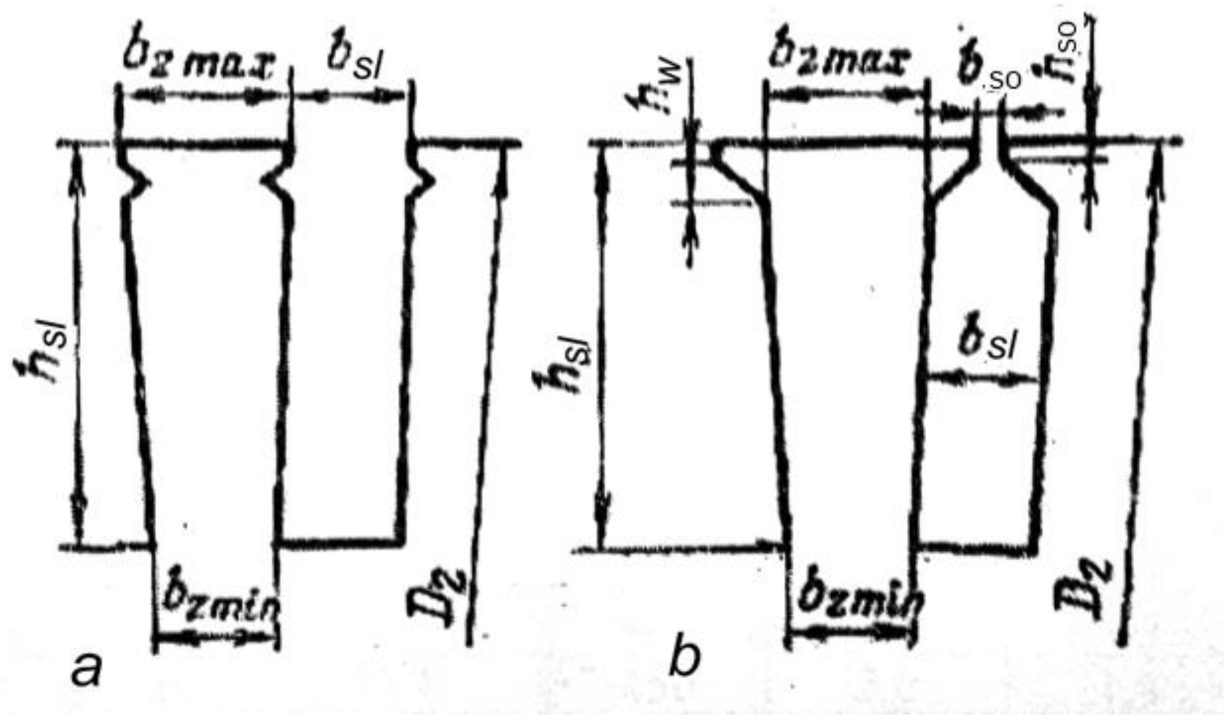


Figure 2.8 Open and semi-closed rotor slots

A parallel slot width is assumed in the range of $b_{sl2} = (o.4 ... 0.45)t_2$ where t_2 = the tooth pitch at the rotor surface. Subtracting the doubled insulation thickness by the slot width find preliminary width of the slot for placing the wires as $b_2 = b_{sl2} - 2b_{ins}$. The doubled insulation thickness for lap windings is assumed equal 2.0 mm, for bar windings at $h = 225 - 250\ mm$ equal 1.4 mm, at $h = 280 - 355\ mm$ equal 1.6 mm, and at $h = 400 - 450\ mm$ equal 3.0 mm.

Using the found values of b_2 and q_{ef2} select the conductor dimensions. After that the slot dimensions are amended.
For rotor lap windings the same grades of rectangular winding wires that for stators are applied. For bar wave winding bald copper conductors enclosed in a solid insulating sleeve are used.
The wedge height is assumed equal: $h_w = 2.5\ mm$ at $h = 280 \dots 355\ mm$ and $h_w = 3.5\ mm$at $h = 400\ mm$. Width and height of the slot opening are taken equal: $b_{so} = 1.5\ mm, h_{so} = 1.0\ mm$.
Then the slot depth h_{sl2} is determined.
After that the slot dimensions in stamp b_{sl2} and h_{sl2} are calculated by adding the allowances Δb_{sl} and $\Delta h_{sl}$for the core laminations assembling to the slot width and depth found before selection the conductor dimensions. The allowances for the core laminations assembling are assumed as it was described in item 2.2.8.
Next, minimum tooth width and maximum flux density in the rotor tooth are determined:

$$b_{z2min} = \frac{\pi(D_2 - 2h_{sl2})}{z_2} - b_{sl2}\,,\quad B_{z2max} = \frac{B_\delta t_2 l_\delta}{b_{z2min} l_{cs2} k_{fill}}. \qquad (2.38)$$

Maximum rotor tooth width in the case of open slots is

$$b_{z2max} = \frac{\pi D_2}{z_2} - b_{sl2}, \qquad (2.39)$$

and in the case of semi-closed slots it is

$$b_{z2max} = \frac{\pi D_2 - (h_{so} + h_w)}{z_2} - b_{sl2}. \qquad (2.40)$$

The teeth height is equal to the depth of the slot, i.e. $h_{z2} = h_{sl2}$.

2.3.8. Now consider the teeth area of a squirrel-cage rotor.
The number of cage rotor slots may be selected from Table 2.9 as dependence on $2p$ and z_1 with account of the rotor slots skewing availability. Such selection provides reduction of the field harmonics influence, of noise and vibration at the machine operation.

Table 2.9

Recommended number of stator and rotor slots for cage induction motors

2p	Z_1	Z_2	
		Slots without skewing	Skewed slots
2	18	15, 21, 22	19, 22, 26, 28, 31,33,34,35
	24	15, 17, 19, 32	19, 26, 31, 33,34,35
	30	22, 38	20, 21, 23, 37,39,40
	36	26, 28, 44,46	25, 27, 28, 29, 43, 45, 47
	42	32, 34, 50, 52	-
	48	38, 40, 56, 58	37, 39, 41, 55, 59
4	24	16, 17	16,18, 28, 30, 33, 34, 36
	36	26, 38, 44, 46	27, 28, 30, 34, 38, 45, 48
	48	34, 38, 56,58, 62, 64	38, 40, 57, 59
	60	50, 52, 68, 70, 74	48, 49, 51, 56, 64, 69, 71
	72	62, 64, 80, 82, 86	61, 63, 68, 76, 81, 83
6	36	26, 46	28, 33, 47, 49, 50
	54	44, 64, 66, 68	42, 43, 51, 65, 67
	72	53, 55, 62, 86, 88	57, 59, 60, 61,83, 85, 87, 90
	90	74, 76, 78, 80, 100, 102, 104	75, 77, 79, 101, 103, 105
8	36	-	28
	48	36, 44, 62, 64	35, 44, 61, 63, 65
	72	56, 58, 86, 88, 90	56, 57, 59, 85, 87, 89
	84	66, 70, 98, 100, 102, 104	-
	96	78, 82, 110, 112, 114	79, 80, 81, 83, 109, 111, 113
10	60	44, 46, 74, 76	57, 69, 77, 78, 79
	90	68, 72, 74, 76, 104, 106, 108, 110	70, 71, 73, 87, 93, 107, 109
	120	86, 88, 92, 96, 98, 102, 104	99, 101, 103, 117, 123, 137
12	72	56, 64, 80, 88	69, 75, 80, 89, 91, 92
	90	68, 70, 74, 88, 98, 106, 108, 110	86, 87, 93, 94
	108	86, 88, 92, 100, 116, 124, 128, 130	84, 89, 91, 104, 105, 111, 112

Rotor slot skewing is recommended for cage motors of not great power having small air gap. In 4A series rotor slots are skewed in motors with $h < 160\ mm$. The skew is assumed equal $b_{sc} = t_2$ where t_2 = the rotor tooth pitch.

In motors of small power the number of rotor teeth is as a rule less the number of stator teeth. In larger motors the number of rotor teeth is sometimes greater than of the stator that is made to decrease the current in cage bars and to provide more uniform conductor distribution around the circle.

2.3.9. Assuming $m_2 = z_2$ and $w_2 = {}^1\!/_2$ find the current transformation ratio:

$$\upsilon_i = \frac{m_1 w_1 k_{w1}}{m_2 w_2 k_{w2}} = \frac{2 m_1 w_1 k_{w1}}{z_2}. \quad (2.41)$$

The rotor phase current being equal the rotor bar current is found as

$$I_2 = I_1 v_i k_i \tag{2.42}$$

where k_i is assumed using Fig. 2.7 as it was made in div. 2.3.5.
The current in sections of end rings between the adjacent bars is equal to

$$I_{ring} = \frac{I_2}{2 \sin\frac{\pi p}{z_2}}. \tag{2.43}$$

The rotor bar cross-section area equals:

$$q_b = \frac{I_2}{J_b} \tag{2.44}$$

where the current density J_b in the bar is accepted equal:

- For motors with degree of protection IP44 and aluminum squirrel cage $J_b = (2.5 \ldots 3.5)10^6\ A/m^2$
- For motors with degree of protection IP23 and aluminum squirrel cage J_b is accepted by (10 … 15) % greater than at protection IP44
- For motors with copper squirrel cage J_b is accepted equal $(4.0 \ldots 8.0)10^6\ A/m^2$.

In the indicated intervals, greater values are accepted for motors of less power.
The end ring cross-section area is found as

$$q_{ring} = \frac{I_{ring}}{J_{ring}} \tag{2.45}$$

where the current density in the ring J_{ring} is accepted by (15 … 20) % less than for the bars.

2.3.10. Dimensions of a cage motor rotor slots are determined with account of their shape (see Fig. 2.9, 2.10, 2.11 and 2.12).

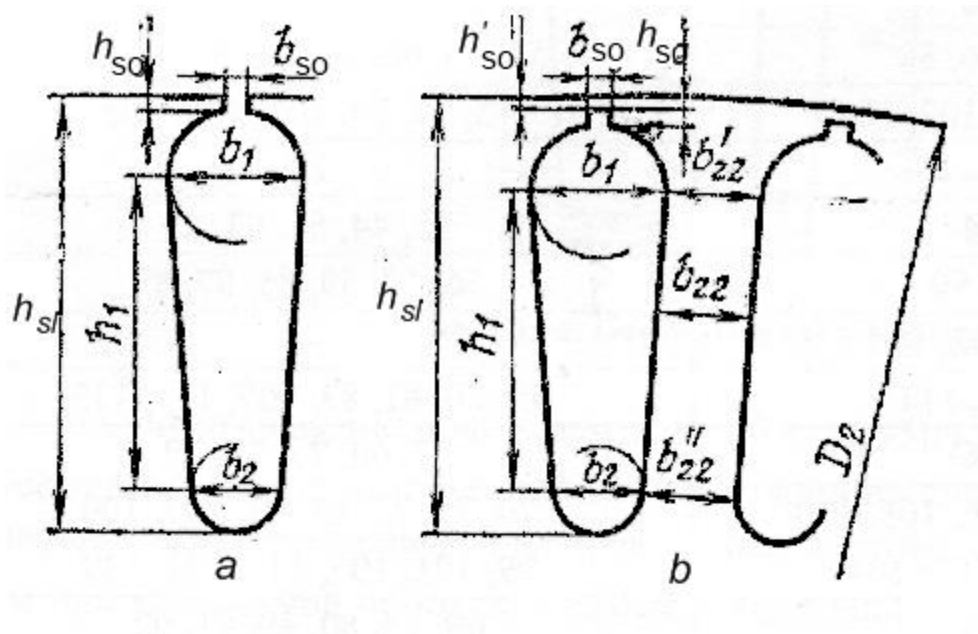


Figure 2.9 Pear-shaped semi-closed (a) and closed (b) slots

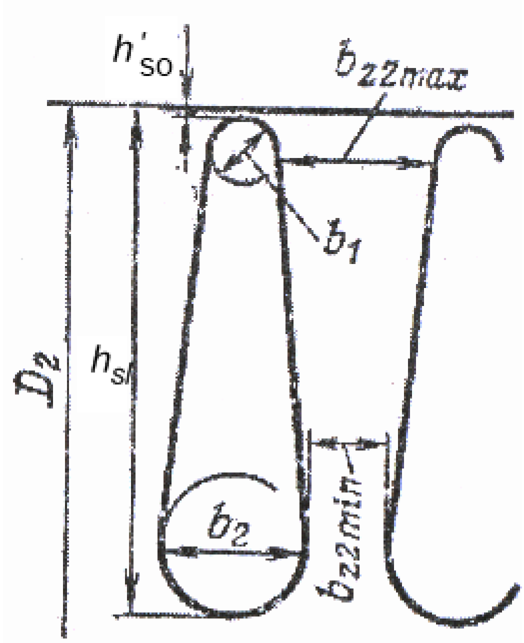


Figure 2.10 Trapezoidal closed slot

Focusing on 4A series motors it is recommended to select the rotor slot shape as follows:

- For motors with $h \leq 250$ mm the pear-shaped slots and cast aluminum squirrel cage are arranged (Fig. 2.9).
- In motors with $h = 160 \ldots 250$ mm the pear-shaped closed slots having sizes equal $b_{so} = 1.5$ mm and $h_{so} = 0.7$ mm are used; at $2p \geq 4$ the dimension h'_{so} equal 0.3 mm and at $2p = 2$ equal 1.0 … 1.5 mm is accepted.

- For motors with $h < 160$ mm the semi-closed slots are made:
  - at $h < 100$ mm the slot opening dimensions equal $b_{so} = 1.5$ mm, $h_{so} = 0.5$ mm are applied
  - at $h = (112 \dots 132)$ mm the slot opening dimensions equal $b_{so} = 1.5$ mm, $h_{so} = 0.75$ mm are accepted.
- In motors with $h = 280 \dots 355$ mm closed slots are arranged:
  - at $2p \geq 4$ the trapezoidal rotor slots (Fig. 2.10) with $h'_{so} = 0.5$ mm are used
  - at $2p = 2$ the rotor slots of shovel shape (Fig. 2.11) with $h'_{so} = 1 \dots 2$ mm and in the case of aluminum cage $h_u = 15 \dots 16$ mm.
- For high-voltage motors with $h = (400 \dots 450)$ mm open parallel rotor slots into which rectangular aluminum busses are inserted are used.

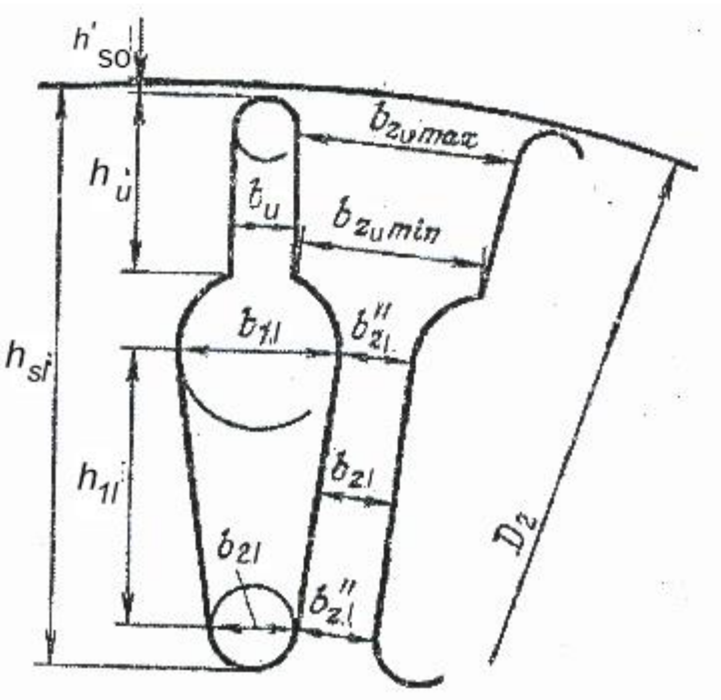


Figure 2.11 Figured slot

2.3.11. Dimensions of pear-shaped slots (Fig. 2.9) are determined to get the needed bar cross-section area q_b and to provide permanent rotor tooth width.
The tooth width is found in this case by the following expression:

$$b_{z2} = \frac{B_\delta t_2 l_2}{B_{z2} l_{sc2} k_{fill}} \qquad (2.45)$$

where B_{z2} is accepted according to Table 2.4.

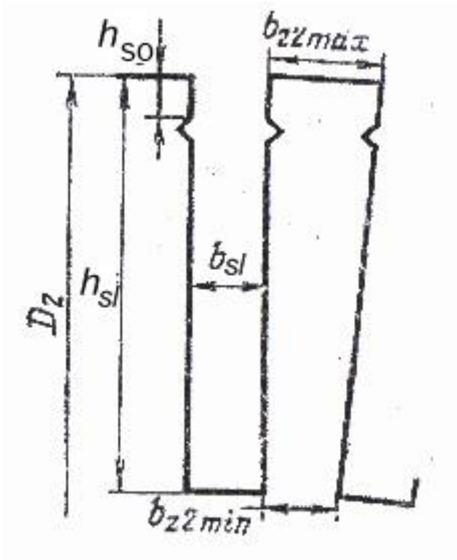


Figure 2.12 Parallel open slot for inserting aluminum bars

The slot dimensions are found as

$$b_1 = \frac{\pi(D_2 - 2h_{so} - 2h'_{so}) - z_2 b_{z2}}{\pi + z_2},\ b_2 = \sqrt{\frac{b_1^2\left(\frac{z_2}{\pi} + \frac{\pi}{2}\right) - 4q_b}{\frac{z_2}{\pi} - \frac{\pi}{2}}}, \tag{2.46}$$

$$h_1 = (b_1 - b_2)\frac{z_2}{2\pi}\,. \tag{2.47}$$

It is necessary that at $h \leq 132$ mm the width $b_2 \geq (1.5 \ldots 2.0)$mm. At $h \geq 160$ mm it must be $b_2 \geq (2.5 \ldots 3.0)$mm.

The obtained dimension values are to be rounded to the nearest tenth of mm. After that the value of the bar cross-section area is refined:

$$q_b = \frac{\pi}{8}(b_1^2 + b_2^2) + \frac{1}{2}(b_1 + b_2)h_1. \tag{2.48}$$

Then the tooth width in two cross-sections is determined:

$$b'_{z2} = \pi\frac{D_2 - 2(h_{so} + h'_{so}) - b_1}{z_2} - b_1,\ b''_{z2} = \pi\frac{D_2 - 2h_{sl} + b_2}{z_2} - b_2. \tag{2.49}$$

If b'_{z2} and b''_{z2} differ insignificantly, the average tooth width is accepted for the magnetic circuit calculations:

$$b_{z2} = \frac{b'_{z2} + b''_{z2}}{2}. \tag{2.50}$$

If the difference is considerable the magnetic circuit should be calculated as in the case of trapezoidal rotor slots (see below).

The height of rotor tooth equals

$$h_{z2} = h_{sl2} - 0.1 b_2. \tag{2.51}$$

2.3.12. In the case of trapezoidal rotor slots (Fig. 2.10) it is expedient to determine their dimensions using a graph-analytical method.

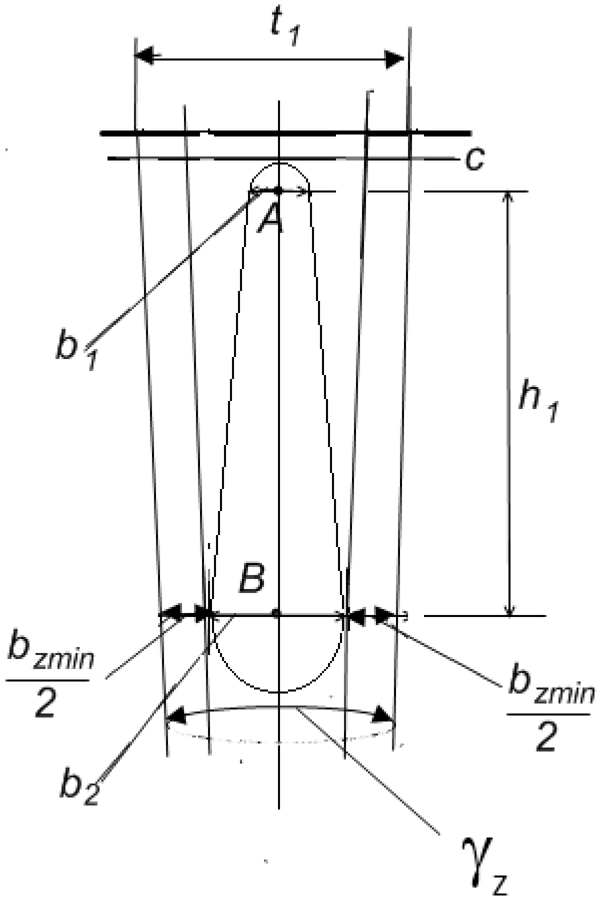


Figure 2.13 Determination of trapezoidal rotor slot of cage induction motor

First, minimum tooth width is determined:

$$b_{z2min} = \frac{B_\delta t_2 l_2}{B_{z2max} b_{sc2} k_{fill}} \quad (2.52)$$

where B_{z2max} is found by Table 2.4.
The diameter b_1 have to be not less than (3.5 … 4.0) mm.

A draft of the slot in scale about 10:1 is made (Fig. 2.13). Drawing is begun from the line of the rotor outer circumference in the bounds of the rotor tooth pitch t_2. It is meant that the slot axis passes the middle of this distance.
Then vertical lines bounding the segment t_2 and representing axes of the teeth on both sides of the slot are drawn.
After that draw straight lines *a* and *b* at a distance of $b_{z2min}/2$ from the tooth pitch bounds and parallel to them. Distance between these lines is maximum slot width b_2.
Then the line *c* is drawn at a distance of 0.5 mm with account of the drawing scale from the rotor circumference (0.5 mm is thickness of the bridge above the closed slot), and the circular arc of a diameter equal to b_1 representing the upper slot bound is drawn.
The closing stage of the rotor slot dimensions determination is selection of such a distance *AB* (or h_1) at which the needed bar cross-section area is provided. The obtained bar cross-section area is found by expression (2.48).
It is possible to vary the minimum tooth width b_{z2min}in the limits whichagree with the limiting values of B_{z2max} according to Table 2.4.
The rotor tooth dimensions are found as

$$\begin{cases} b_{z2max} = \pi \frac{D_2-(2h'_{so}+b_1)}{z_2} - b_1 \\ b_{z2min} = \pi \frac{D_2-(2h_{sl}-b_2)}{z_2} - b_2 \\ h_{z2} = h_{sl} - 0.1 b_2 \end{cases} \quad (2.53)$$

2.4. Construction of rotor core

In the case of $D_2 < 990$ mm the rotor core is fitted to the shaft directly without an intermediate landing bush.
At $h \le 250$ mm shrink fit is applied without a key. At greater shaft height the core is mounted with a key.

At $D_2 > 990$ mm is assembled from laminated segments on a mounting bush or on longitudinal edges welded to the shaft.
At $h \geq 250$ mm round axial ducts are made in the core to improve its cooling and also to reduce its weight and the moment of inertia. The ducts are arranged in one or two rows (Fig. 2.14). The ducts number and diameter is given in Table 2.10.

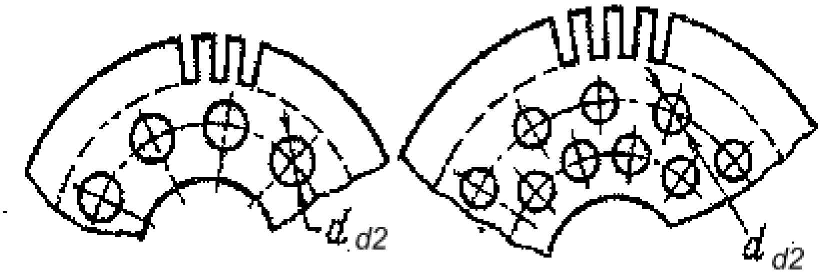


Figure 2.14 Axial ducts in rotor cores

Table 2.10

Number and diameter of axial rotor ducts

h, mm	Number of ducts n_{d2} and their diameter d_{d2} (mm) at different $2p$							
	2		4		6		8,10 and 12	
	n_{d2}	d_{d2}	n_{d2}	d_{d2}	n_{d2}	d_{d2}	n_{d2}	d_{d2}
250	10	15	10	20	10	30	10	30
280	12	20	12	32	12	40	12	40
315	12	20	12	40	12	40	12	40
355	12	20	12	50	12	50	12	50
400	-	-	9	55	9	65	9	75
450	-	-	9	65	9	75	9	90

Radial ducts are made in a rotor at $l_2 > 350$ mm. Their arrangement size and number are the same as in the stator core (see div. 1.2.7).
The inner rotor diameter at direct core fitting to the shaft is determined as

$$D_j = k_{sh} D_a \tag{2.54}$$

where k_{sh} is accepted according to Table 2.11.

Table 2.11

Values of k_{sh} for induction motor shaft diameter determination

h, mm	50 … 63	71 … 253	280 … 355		400 … 500		
$2p$	2 … 6	2 … 8	2	4 … 12	4	6	8 … 12
k_{sh}	0.19	0.23	0.22	0.23	0.20	0.23	0.25

In the case of fitting the core on a mounting bush or on a finned shaft the rotor core inner diameter D_j is found proceeding from the maximum acceptable flux density B_j in the rotor core yoke:

$$\begin{cases} h_j = \frac{\Phi}{2B_j l_{cs2} k_{fill}} \\ D_j = D_2 - 2(h_{sl2} + h_j) \end{cases} \tag{2.55}$$

3. Motor magnetic circuit calculation

Calculation of the magnetic circuit is performed to determine the magnetizing current. Calculation of the magnetomotive force may be made in two ways. The first is a method based on use of the magnetic field fundamental, it is recommended for application in this project. Another method considers actual non-sinusoidal curve of the magnetic flux distribution with account of saturation.

To determine the magnetizing current the mmf, fit at a pair of poles of the magnetic field, is found.

The values of the magnetic flux density and the magnetic field strength used at the calculation are their fundamentals amplitude values.

It is assumed that the motor magnetic circuit consists of five homogenous sections connected in series. These are **the air gap between the stator and rotor cores, the stator teeth, the rotor teeth, the stator core yoke and the rotor core yoke (or rotor core back)**. Under the calculation of the circuit sections mmf (or the magnetic tension at the sections), it is assumed that the flux density is uniformly distributed along each the section and throughout its cross-section area.

Sequence of the magnetic circuit mmf calculation is the following:

1. Determination of the cross-section area of each the section
2. Determination the magnetic flux density for each the section
3. Determination of the magnetic field strength for each the section
4. Determination of the magnetic flux path length in the bounds of each the magnetic circuit section along the medial design field line.
5. Determination of the circuit sections mmf
6. Determination of the total mmf along the closed average magnetic flux line.

Saturation of ferromagnetic material of the magnetic circuit causes flattening the magnetic field curve. To improve the calculation accuracy the saturation curves for the stator and rotor teeth obtained with account of the magnetic flux density curves flattening are used.
Availability of slots on the stator and rotor core surfaces increases the air gap reluctance. This is taken into account by the air gap coefficient being greater than 1.
If radial ducts in the stator and rotor cores are available, they cause reduction of the air gap reluctance, that is taken into account by the coefficient being less than 1.
An induction motor magnetic circuit calculation is performed for no-load condition under the rated voltage.

3.1. Determination of the cross-section area of each the section had been done at determination the magnetic flux density in sections.

3.2. The flux density fundamental amplitude in the air gap B_δ was determined in div. 2.1.8 (2.10).
The flux density in a stator or rotor tooth cross-section B_{zx} ($x$in the subscript denotes distance of the given tooth cross-section from its narrowest cross-section and defines the given cross-section position) at known value of B_δ depends on the teeth saturation causing flattening the curve of the flux density in teeth area distribution along the circle and influencing the part of the flux branching off the tooth into the slot. The flux branching off the teeth is negligible if calculated flux density value $B_{zx} \leq 1.8\,T$, and must be taken into account if $B_{zx} > 1.8\,T$.
It is recommended to find the design magnetic flux density fundamental amplitude in a tooth cross-section as if there is no influence of the teeth saturation and the flux branching off, and to take them into account in the course of the magnetic field strength fundamental amplitude determination using special magnetization curves $B_z = f(H_Z)$ for teeth. These curves are obtained with account of the magnetic field flattening and the flux branching off in the air gap.
The field strength under $B_{zx} \leq 1.8\,T$ is found by the curves without account the flux branching off into the slot due to smallness of this branching off flux. Under$B_{zx} > 1.8\,T$ the curves taking into account as flattening the magnetic flux distribution law, as branching off a part of the flux into the slot are used at the magnetic field strength in the tooth determination.
The *calculated* values of the flux density are determined:

- in the case of constant width teeth (trapezoidal stator slots or pear-shaped rotor slots) the flux density is determined as

$$B_{z1(2)} = \frac{B_\delta t_{1(2)} l_\delta}{b_{z1(2)} l_{cs1(2)} k_{fill}}; \quad (3.1)$$

- in the case of parallel slots, when the tooth has smoothly varying width,the flux density is determined:
  - if maximum flux density in the narrowest tooth cross-section $B_{z1(2)max} \leq 2.0\ T$, the tooth mmf is found using one magnetic strength value in the cross-section area at $x = \frac{1}{3} h_{sl1(2)}$. Therefore, the flux density is calculated for this tooth cross-section:

$$B_{z1(2)} = \frac{B_\delta t_{1(2)} l_\delta}{b_{z1(2),1/3} l_{cs1(2)} k_{fill}} \quad (3.2)$$

where $b_{z1(2),1/3}$ = the tooth width at $x = \frac{1}{3} h_{sl1(2)}$;

  - if maximum flux density in the narrowest tooth cross-section $B_{z1(2)max} > 2.0\ T$, the tooth mmf is found using three magnetic strength values – in narrowest, middle and widest cross-sections. Therefore, the flux density is calculated in this case for these three tooth cross-sections:

$$B_{z1(2)max} = \frac{B_\delta t_{1(2)} l_\delta}{b_{z1(2)min} l_{cs1(2)} k_{fill}} \quad (3.3)$$

$$B_{z1(2)middle} = \frac{B_\delta t_{1(2)} l_\delta}{b_{z1(2)middle} l_{cs1(2)} k_{fill}} \quad (3.4)$$

$$B_{z1(2)min} = \frac{B_\delta t_{1(2)} l_\delta}{b_{z1(2)max} l_{cs1(2)} k_{fill}} \quad (3.5)$$

where $b_{z1(2)min}$, $b_{z1(2)middle}$, $b_{z1(2)max}$ = minimal, average and maximal tooth width. The flux density in the middle cross-section may be found as the average value of $B_{z1(2)min}$and $B_{z1(2)max}$.

- In the case of figured slots the tooth mmf is found as the sum of the mmfs of upper and lower tooth parts. In the upper and lower tooth parts one or several flux density values are found depending in the tooth shape and maximum value of the flux density.

The flux density in the stator (rotor) core yokes is found by the expression:

$$B_{y1(2)} = \frac{\Phi}{2h'_{y1(2)} l_{cs1(2)} k_{fill}} \quad (3.6)$$

where$h'_{y1(2)}$= design stator (rotor) core yoke height calculated as

$$h'_{y1} = \frac{D_a - D}{2} - h_{sl1} - \frac{2}{3} d_{d1} m_{d1} \quad (3.7)$$

$$h'_{y2} = \frac{D_2 - D_j}{2} - h_{sl2} - \frac{2}{3} d_{d2} m_{d2} \quad (3.8)$$

where $d_{d1(2)}$ = the stator (rotor) axial ventilation ducts diameter, $m_{d1(2)}$ = number of the duct rows in the stator (rotor) core.

3.3. Determination of the magnetic field strength for each the magnetic circuit section is determined with account of the section material and magnetic flux distribution.

Amplitude of the **magnetic strength fundamental in the air gap** equals

$$H_\delta = \frac{B_\delta}{\mu_0} \quad (3.9)$$

whereм$_0$ = permeability of vacuum, $\mu_0 = 4\pi 10^{-7}$ H/m.

Amplitude of the magnetic field strength fundamental in the stator and rotor teeth is found in the following order.

If the flux density in a tooth cross-section is less or equal to 1.8 T the magnetic field strength in this cross-section is determined neglecting the flux branching off the tooth and only the flux distribution curve flattening is taken into consideration. In such a case the field strength H_{zx} is found at the calculated value of the flux density B_{zx} with the help of magnetization curves given in Tables 3.1, 3.2 or 3.3 in compliance with the steel grade.

Table 3.1

Magnetization curve for induction motor teeth, steel grade 2013

B, Тл	0	0,01	0,02	0,03	0,04	0,05	0,06	0,07	0,08	0,09
	H, А/м									
0,4	124	127	130	133	136	138	141	144	147	150
0,5	154	157	160	164	167	171	174	177	180	184
0,6	188	191	194	198	201	205	208	212	216	220
0,7	223	226	229	233	236	240	243	247	250	253
0,8	256	259	262	265	268	271	274	277	280	283
0,9	286	290	293	297	301	304	308	312	316	320
1,0	324	329	333	338	342	346	350	355	360	365
1,1	370	375	380	385	391	396	401	406	411	417
1,2	424	430	436	442	448	455	461	467	473	479
1,3	486	495	504	514	524	533	563	574	584	585
1,4	586	598	610	622	634	646	658	670	683	696
1,5	709	722	735	749	763	777	791	805	820	835
1,6	850	878	906	934	962	990	1020	1050	1080	1 110
1,7	1150	1180	1220	1250	1290	1330	1360	1400	1440	1 480
1,8	1520	1570	1620	1670	1720	1770	1830	1890	1950	2 010
1,9	2070	2160	2250	2340	2430	2520	2640	2760	2890	3 020
2,0	3150	3320	3500	3680	3860	4040	4260	4480	4700	4 920
2,1	5140	5440	5740	6050	6360	6670	7120	7570	8020	8 470
2,2	8920	9430	9940	10460	10980	11500	12000	12600	13200	13 800
2,3	14400	15100	15800	16500	17200	18000	18800	19600	20500	21 400

If the flux density in a tooth cross-section is greater than to1.8 T the magnetic field strength in this cross-section is determined with account as the flux branching off the tooth as the flux distribution curve flattening. In such a case, the field strength H_{zx} is found at the calculated value of the flux density B_{zx} with the help of magnetization curves given in Fig. 3.1 or 3.2 depending on the
steel grade. The magnitude of the branching off flux depends on relation between the slot and tooth width at the given cross-section which is taken in account by means of a coefficient

$$k_{slx} = \frac{b_{slx} l_{\delta}}{b_{zx} l_{cs} k_{fill}} \qquad (3.10)$$

where b_{slx} and b_{zx} = respectively the slot and tooth width in the cross-section under consideration. To find the field strength H_{zx} in the cross-section it is necessary to use the magnetization curve corresponding to a value of k_{slx}.

Table 3.2

Magnetization curve for induction motor teeth, steel grade 2211,2312

B, T	0	0,01	0,02	0,03	0,04	0,05	0,06	0,07	0,08	0,09
	H, A/m									
0,4	140	143	146	149	152	155	158	161	164	171
0,5	174	177	180	184	186	190	192	196	198	202
0,6	204	209	213	216	221	224	229	233	237	241
0,7	245	249	253	257	262	267	272	277	282	287
0,8	292	297	302	306	311	316	322	326	331	337
0,9	342	347	353	360	366	372	379	384	390	396
1,0	403	409	417	425	433	440	450	460	470	477
1,1	488	497	509	517	527	537	547	559	570	582
1,2	593	602	613	626	638	651	663	677	695	710
1,3	724	738	755	770	790	804	820	840	857	879
1,4	897	917	936	955	977	1000	1020	1040	1060	1090
1,5	1120	1150	1170	1210	1240	1270	1310	1330	1370	1410
1,6	1450	1490	1530	1560	1610	1650	1690	1750	1790	1840
1,7	1900	1940	2000	2070	2140	2220	2300	2380	2500	2600
1,8	2700	2800	2920	3050	3220	3330	3490	3610	3710	4000
1,9	4160	4350	4600	4800	5030	5330	5430	5790	6130	6420
2,0	6750	7170	7400	7790	8150	8520	9000	9400	9750	10 200
2,1	10 600	11 000	11 500	12 100	12 600	13 000	13 500	14 100	14 700	15 400
2,2	15 900	16 500	17 300	17 800	18 500	19 100	19 600	20 300	21 100	22 000
2,3	23 100	24 300	25 500	26 800	28 100	29 500	30 900	32 400	33 900	36 400

Table 3.3

Magnetization curve for induction motor teeth, steel grade 2411

B, T	0	0,01	0,02	0,03	0,04	0,05	0,06	0,07	0,08	0,09
	H, A/m									
0,4	72	73	74	75	77	78	79	80	81	82
0,5	83	84	85	86	87	88	89	90	91	92
0,6	93	94	95	96	97	98	99	101	102	104
0,7	105	106	108	110	111	113	115	117	118	120
0,8	122	124	126	128	130	132	134	136	138	140
0,9	142	144	147	149	151	155	158	160	163	165
1,0	168	171	175	177	180	184	188	191	196	200
1,1	204	207	212	216	222	227	232	237	242	247
1,2	254	259	265	272	277	284	291	298	307	316
1,3	323	333	341	351	361	372	383	394	404	421
1,4	425	432	461	480	497	518	537	554	573	596
1,5	622	644	673	700	728	756	795	828	859	890
1,6	932	976	1020	1070	1130	1180	1260	1350	1440	1520
1,7	1630	1740	1870	2020	2130	2300	2450	2630	2830	3040
1,8	3190	3410	3590	3830	4100	4400	4600	4800	5100	5400
1,9	5700	5900	6300	6600	6900	7200	7700	8100	8300	8700
2,0	9200	9700	10 000	10 500	10 900	11 400	12 000	12 700	13 100	13 700
2,1	14 200	15 000	15 800	16 500	17 200	17 900	18 700	19 800	20 600	21 600
2,2	22 600	23 700	24 600	26 100	26 900	28 700	30 000	31 400	33 200	35 400
2,3	37 600	39 900	42 200	44 600	47 000	49 500	52 000	54 600	57 200	59 800

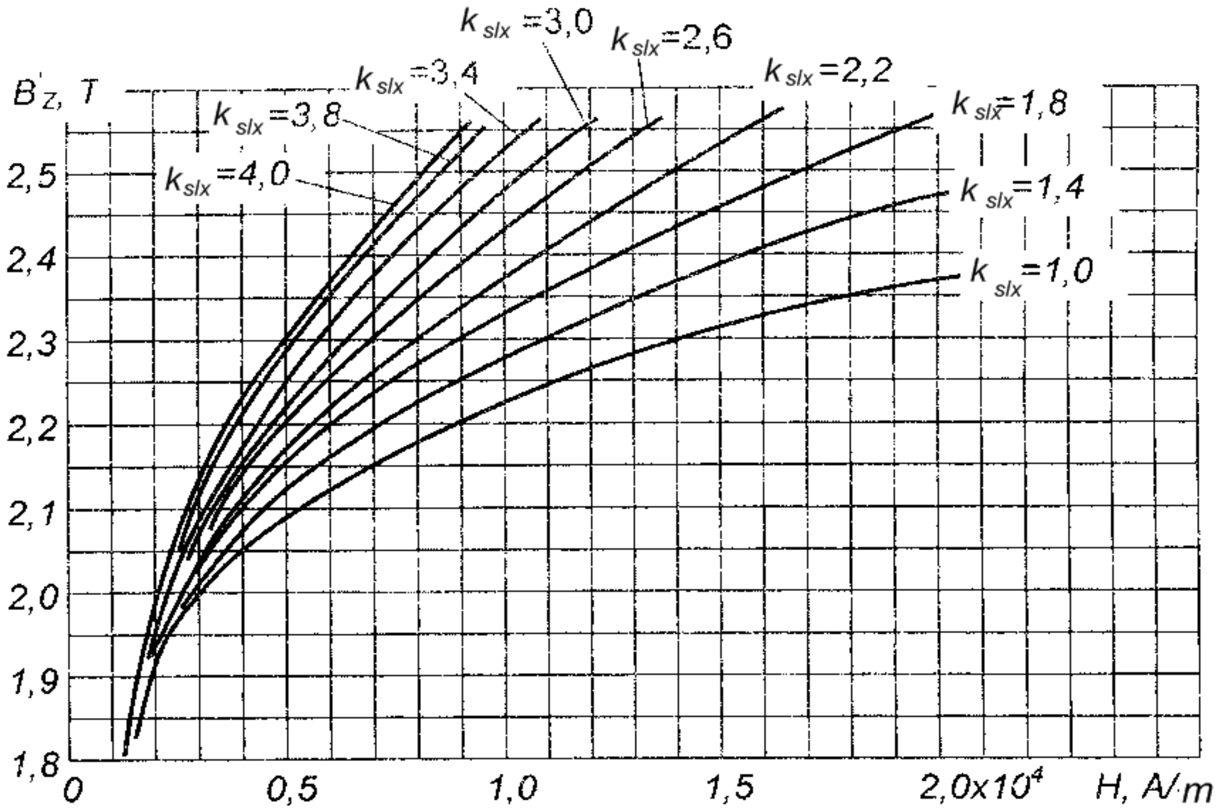


Figure 3.1 Magnetization curves for induction motor teeth with account flux branching off, steel grade 2013

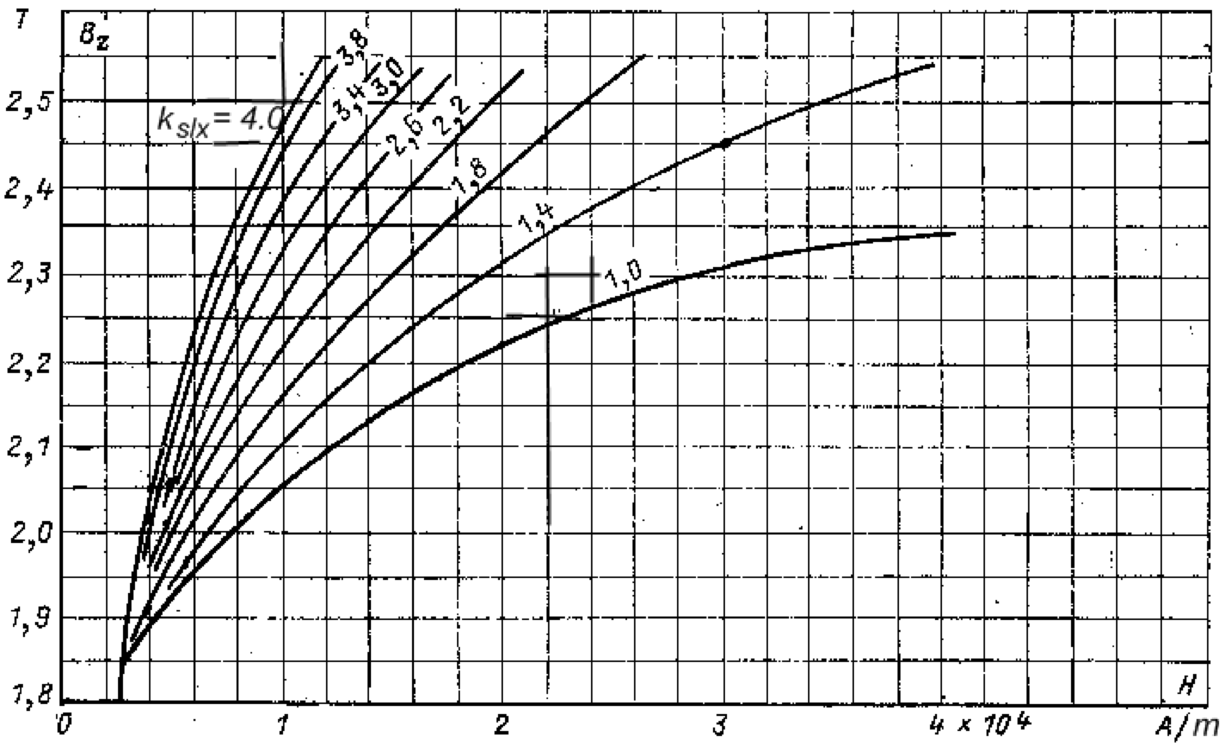


Figure 3.2 Magnetization curves for induction motor teeth with account flux branching off, steel grade 2211, 2312, 2411

In the case the stator (rotor) tooth has constant width the magnetic strength is found for the tooth cross-section in the middle of its height.

In the case of a tooth with smoothly varying width at $B_{zmax} \leq 2.0\,T$ the magnetic strength is found for the toothcross-section being away from its narrowest place also by 1/3 of the tooth height.

In the case when the stator (rotor) tooth has smoothly varying width and the flux density $B_{zmax} > 2.0\,T$, the magnetic strength is usually found as an averaged value of three values of the magnetic strength in three tooth cross-sections by the expression obtained by means of parabolic interpolation (Simpson's formula):

$$H_{z1(2)} = \frac{1}{6}(H_{z1(2)max} + 4H_{z1(2)middle} + H_{z1(2)min}). \quad (3.11)$$

Here $H_{z1(2)max}$, $H_{z1(2)midle}$ and $H_{z1(2)min}$ are the magnetic field strength values in the stator (rotor) narrowest, middle and widest tooth cross-section respectively. These magnetic field strength values are found at the flux density values $B_{z1(2)max,}$ $B_{z1(2)middle}$ and $B_{z1(2)min}$with the help of magnetization curves (Tables 3.1, 3.2, 3.3 or Fig. 3.1, 3.2) depending on the steel grade and the coefficient k_{slx} for each of the indicated tooth cross-sections.

Amplitude of the magnetic field strength fundamental in the stator (rotor) core yokes $H_{y1(2)}$is determined with the help of magnetization curve for induction motor core yokes at the calculated value of the yoke magnetic flux density $B_{y1(2)}$ (Tables 3.4, 3.5, 3.6) choosing the curve for a proper steel grade. These curves had been determined with account of the magnetic field strength along the design magnetic field line variation, of the stator and rotor teeth saturation and also of the flux density in the yoke variation due to teeth and slots at the core surface alternation.

3.4. Determination of the magnetomotive force of magnetic circuit sections

Amplitude of magnetomotive force produced by the magnetizing current at no-load is determined as the total mmf of the motor magnetic circuit sections along the medial design magnetic line per a pair of poles. The total mmf is determined to calculate the magnetizing current.

Amplitudes of the sections mmf per a pair of poles are found as it is described below.

Table 3.4

Magnetization curve for induction motor core yoke, steel grade 2013

B, T	0	0,01	0,02	0,03	0,04	0,05	0,06	0,07	0,08	0,09
	H, A/m									
0,4	52	53	54	55	56	58	59	60	61	62
0,5	64	65	66	67	69	71	72	74	76	78
0,6	80	81	83	85	87	89	91	93	95	97
0,7	100	102	104	106	108	111	113	115	118	121
0,8	124	126	129	132	135	138	140	143	146	149
0,9	152	155	158	161	164	168	171	174	177	181
1,0	185	188	191	195	199	203	206	209	213	217
1,1	221	225	229	233	237	241	245	249	253	257
1,2	262	267	272	277	283	289	295	301	307	313
1,3	320	327	334	341	349	357	365	373	382	391
1,4	400	410	420	430	440	450	464	478	492	506
1,5	520	542	564	586	608	630	654	678	702	726
1,6	750	788	826	864	902	940	982	1020	1070	1110
1,7	1150	1220	1290	1360	1430	1500	1600	1700	1800	1900
1,8	2000	2160	2320	2490	2650	2810	2960	3110	3270	3420
1,9	3570	3800	4030	4260	4490	4720	4930	5140	5350	5560
2,0	5770	6000	6300	6600	7000	7400	7900	8400	9000	9700

Table 3.5

Magnetization curve for induction motor core yoke, steel grade 2211, 2312

B, T	0	0,01	0,02	0,03	0,04	0,05	0,06	0,07	0,08	0,09
	H, A/m									
0,4	89	91	93	94	96	98	100	102	104	106
0,5	108	110	113	115	118	120	122	124	126	128
0,6	131	134	136	139	141	144	147	150	153	156
0,7	159	162	166	169	172	176	180	183	186	190
0,8	194	198	201	204	208	212	216	220	223	227
0,9	231	235	239	243	248	252	256	260	265	269
1,0	274	279	284	289	295	300	305	311	318	323
1,1	332	338	344	351	357	367	374	382	390	398
1,2	410	418	426	435	444	455	466	475	487	498
1,3	509	521	533	546	558	572	585	600	618	635
1,4	656	675	695	717	740	763	789	815	843	870
1,5	905	934	965	1000	1040	1090	1130	1190	1240	1290
1,6	1370	1440	1520	1590	1660	1720	1820	1910	2010	2100
1,7	2180	2310	2410	2550	2610	2720	2840	2980	3130	3290
1,8	3460	3630	3800	3970	4140	4301	4490	4670	4850	5040
1,9	5220	5600	6000	6400	6900	7400	7900	8500	9100	9700
2,0	10 400	11 100	11 800	12 500	13 300	14 100	14 900	15 800	16 700	17 600

Table 3.6

Magnetization curve for induction motor core yoke,
steel grade 2411

B, T	0	0,01	0,02	0,03	0,04	0,05	0,06	0,07	0,08	0,09
	H, A/m									
0,4	48	48	49	50	51	51	52	53	53	54
0,5	55	56	56	57	58	59	60	61	61	62
0,6	63	64	65	66	67	68	69	69	70	71
0,7	72	72	73	74	75	76	76	77	78	79
0,8	81	82	83	84	85	87	88	90	92	94
0,9	96	98	100	102	104	105	107	109	112	114
1,0	116	118	121	124	126	129	132	136	139	143
1,1	146	150	154	158	162	167	172	176	182	188
1,2	192	198	204	210	216	222	230	238	246	260
1,3	272	288	300	316	330	340	358	370	386	399
1,4	410	440	460	490	530	570	610	660	710	770
1,5	620	890	960	1030	1100	1170	1230	1310	1400	1480
1,6	1560	1640	1730	1820	1920	2000	2100	2260	2440	2600
1,7	2800	2960	3100	3260	3400	3580	3740	3900	4100	4300
1,8	4500	4700	5000	5300	5500	5800	6100	6400	6800	7200
1,9	7600	8000	8500	9100	9700	10 300	11 100	11 900	13 100	14 200
2,0	16 000	18 000	20 000	22 000	23 800	25 500	27 600	29 600	31 500	33 800

Mmfof the air gap is found as

$$F_\delta = 2H_\delta \delta k_\delta \tag{3.12}$$

where$k_д$ = the air gap coefficient equal to the product of the coefficients $k_{д1}$ and $k_{д2}$ accounting teeth structure of the stator and rotor cores respectively:

$$k_\delta = k_{\delta 1} k_{\delta 2}, \tag{3.13}$$

$$k_{\delta 1} = \frac{t_1}{t_1 - \gamma_1 \delta}, \qquad k_{\delta 2} = \frac{t_2}{t_2 - \gamma_2 \delta}, \tag{3.14}$$

$$\gamma_1 = \frac{(b_{so1}/\delta)^2}{5 + b_{so1}/\delta}, \qquad \gamma_2 = \frac{(b_{so2}/\delta)^2}{5 + b_{so2}/\delta}. \tag{3.15}$$

Mmf of the stator (rotor) teeth is calculated as

$$F_{z1(2)} = 2H_{z1(2)} h_{z1(2)}. \tag{3.16}$$

After determination of the magnetomotive forces F_δ, F_{z1} and F_{z2} the teeth area saturation factor k_z should be assessed with the help of the expression

$$k_z = 1 + \frac{F_{z1}+F_{z2}}{F_\delta}. \qquad (3.17)$$

If teeth saturation is in acceptable bounds, the saturation factor is in the limits of $1.2 \leq k_z \leq 1.5 \ldots 1.6$. When $k_z < 1.2$, the teeth area is insufficiently used. When $k_z > 1.5 \ldots 1.6$, the teeth are excessively saturated. In both cases it is necessary to make proper changes into the calculations.

Mmf of the stator (rotor) core yokes equals

$$F_{y1(2)} = H_{y1(2)} L_{y1(2)} \qquad (3.18)$$

where L_{y1} = design length of the magnetic flux path in the stator core yoke:

$$L_{y1} = \frac{\pi(D_a - h_{y1})}{2p}. \qquad (3.19)$$

Design stator core yoke height calculated by the expressions:

$$h_{y1} = \frac{D_a - D}{2} - h_{sl1}. \qquad (3.20)$$

Design length of the magnetic flux path in the rotor core yoke and the yoke height is found depending on the way of fitting the rotor core to the shaft by the formulae:

- at fitting the core to the shaft directly without a bush and $2p \neq 2$:

$$h_{y2} = \frac{D_2 - D_j}{2} - h_{sl2}, \qquad L_{y2} = \frac{\pi(D_j + h_{y2})}{2p} \qquad (3.21)$$

where D_j is defined by (2.54)

- at fitting the core to the shaft on a mounting bush or on longitudinal edges and $2p \neq 2$:

$$h_{y2} = \frac{D_2 - D_j}{2} - h_{sl2}, \qquad L_{y2} = \frac{\pi(D_j + h_{y2})}{2p} \qquad (3.22)$$

whereD_j is defined by (2.55)

- at $2p = 2$ the length of the magnetic flux path in the rotor core yoke

equals $L_{y2} = 2h_{y2}$ where h_{y2} is defined by (3.21) or (3.22) in accordance with the method of the rotor core fitting to the shaft.

3.5. Amplitude of total magnetomotive force

Amplitude of magnetomotive force produced by the magnetizing current is found as

$$F = F_\delta + F_{z1} + F_{z2} + F_{y1} + F_{y2}. \tag{3.23}$$

3.6. Rms value of the magnetizing current

The magnetizing current is determined by the expression:

$$I_\mu = \frac{\pi p F/2}{m_1\sqrt{2}w_1 k_{w1}} = \frac{pF}{0.9 m_1 w_1 k_{w1}}. \tag{3.24}$$

Relative value

$$I_{\mu *} = {I_\mu}\big/{I_{1r}}.$$

If the machine dimensions are determined properly, the relative value of the magnetizing current must be in the limits of 0.18 … 0.35 for motors of medium rated power (15 … 400 kW) and in the limits of 0.2 … 0.6 for small machines (<10 kW).

4. Determination of motor parameters for rated operating conditions

To the motor parameters the phase windings resistance R_1 and R_2, their leakage reactance X_1 and X_2, resistance R_{12},taking into account magnetic losses in the stator core, and the magnetization branch reactance X_{12} are referred. Their determination is necessary for definition of the equivalent circuit parameters, data of no-load condition, ratings, performance and starting characteristics.At starting conditions calculation, effects of current displacement (skin effect) in the squirrel cage bars and of the stator and rotor tooth tips saturation must be taken into account, but for the rated conditions these effects are not considerable.

The parameters for the rated conditions are determined in the following order.

4.1. Calculation of the winding resistance

4.1.1. Windings resistance of induction motor stators and wound rotors

For the indicated windings the resistance is found by the expression:

$$R = k_r \rho_\theta \frac{L}{q_{ef} a} \quad (4.1)$$

where L = total length of the phase winding effective conductors in meters; q_{ef} = cross-section area of the effective conductor in m^2; a = the number of a phase winding parallel paths; ρ_θ = specific resistance of the winding material at the design temperature in Ω·m; k_r = a coefficient taking into account increase of the resistance due to current displacement, under rated conditions it equals $k_r = 1$ for both stator and rotor winding.

For conductors with insulation of *A*, *E* and *B* temperature classes the design temperature is assumed equal θ=75°C, and with insulation of F and H classes θ=115°C. Values of ρ_θ are given in Table 4.1.

Table 4.1

Specific resistance of windings conductors

Winding kind	Material	Specific resistance (in Ω·m) under temperature (in°C)		
		20	75	115
Windings of copper	Copper	$0.01754 \cdot 10^{-6}$	$0.02128 \cdot 10^{-6}$	$0.02439 \cdot 10^{-6}$
Squirrel-cage windings	Aluminum busses	$0.02857 \cdot 10^{-6}$	$0.03571 \cdot 10^{-6}$	$0.03846 \cdot 10^{-6}$
	Casted aluminum	$0.03333 \cdot 10^{-6}$	$0.04167 \cdot 10^{-6}$	$0.04545 \cdot 10^{-6}$

Note: The casted aluminum specific resistance should be taken some greater than indicated in the Table due to arising air bulbs in the material in the course of casting and changing the material structure at it hardening in the narrow space of slots. On these reasons the specific resistance for casted aluminum conductors of a squirrel-cage is accepted equal $\rho_\theta = 0.04651 \cdot 10^{-6}\,\Omega \cdot \text{m}$ under temperatures θ=75 and 115 °C.

The total length of the winding effective conductors is

$$L = l_{av} w \quad (4.2)$$

where l_{av} = the coil turn average length in m; w = the phase winding turns number.

The average turn length

$$l_{av} = 2(l_{sl} + l_{ec}) \quad (4.3)$$

where l_{sl} = the length of thepart of effective conductor located in a slot in *m*; l_{ec} = the length of the end connection in *meters* (see Fig. 4.1 and 4.2).

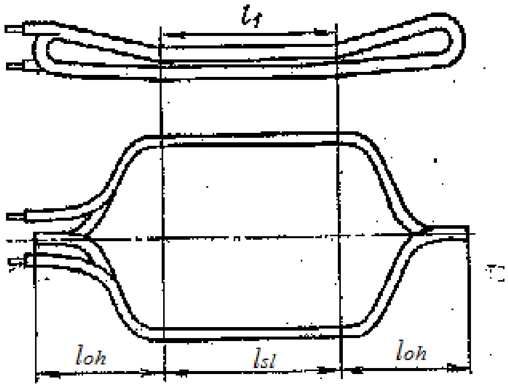


Figure 4.1 Coil of two layer fed-in stator winding

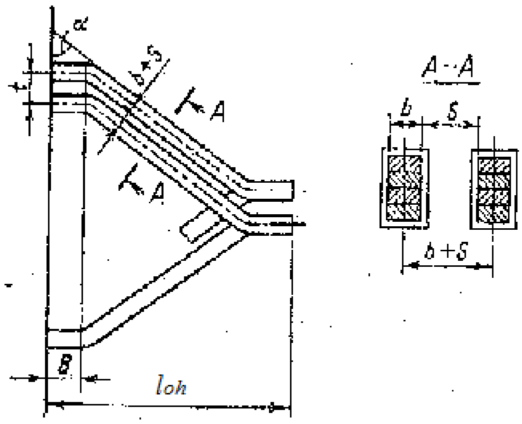


Figure 4.2 End connections of coils made wire with rectangular cross-section

For fed-in stator windings

$$l_{ec} = k_{ec} b_{coil} + 2B \qquad (4.4)$$

where

$$b_{coil} = \frac{\pi(D+h_{sl1})}{2p}\beta_1, \qquad \beta_1 = y_1/\tau_1, \qquad (4.5)$$

k_{ec} = a coefficient which values are given in Table 4.2; B - the straight part of slot conductor overhang accepted equal 0.01 m if the winding is wound before the core into the frame insertion and 0.015 m if it is wounded after the core into the frame insertion. The end connections overhang is

$$l_{oh} = k_{oh} b_{coil} + B$$

where k_{oh} is taken from Table 4.2

Table 4.2

Coefficients for calculation of fed-in-winding end connections

Number of poles $2p$	Stator coils			
	End connections non-insulated with tape		End connections insulated with tape	
	k_{ec}	k_{oh}	k_{ec}	k_{oh}
2	1.20	0.26	1.45	0.44
4	1.30	0.40	1.55	0.50
6	1.40	0.50	1.75	0.62
≥ 8	1.50	0.50	1.90	0.72

For coils wound of the wire of rectangular cross-section:

$$l_{ec} = k_{ec} b_{coil} + 2B + h_{sl} \qquad (4.6)$$

where B is accepted by Table 4.3 and $b_{coil} = \frac{\pi(D+h_{sl1})}{2p}\beta_1$ for stator windings, $b_{coil} = \frac{\pi(D-h_{sl2})}{2p}\beta_2$ for rotor windings, $\beta_2 = y_2/\tau_2$; $k_{ec} = 1/\sqrt{1-m^2}$, $m = (b+S)/t$, b = the copper width in the end connection, S = permissible minimum distance between the adjacent coils copper at the end connections (Table 4.3).

Table 4.3

Dimensions of end connections for coils wound with rectangular wire

Rated voltage, V	S, m	B, m
≤660	0.0035	0.025
3000 … 3300	0.005 … 0.006	0.035 … 0.04
6000 … 6600	0.006 … 0.007	0.035 … 0.05
≥10000	0.007 … 0.008	0.06 … 0.065

For bar wave windings of wound rotors

$$l_{ec} = k_{ec} b_{coil} + 2B_b \qquad (4.7)$$

where $b_{coil} = \pi(D_2 - h_{sl2})/(2p)$, $k_{ec} = 1/\sqrt{1-m^2}$, $m = \frac{b_2+S_2}{t_2'}$, $t_2' = \pi(D_2 - 2h_{sl2})/z_2$ is the tooth pitch at the slots bottom, b_2 = width of the rotor bar copper, S_2 = distance between copper of two adjacent bars in the end connections taken from Table 4.4, $B_b = 0.05 \dots 0.1$ m (for high-voltage machines with $P_r = 800 \dots 1000$ kW it is accepted $B_b = 0.12 \dots 0.16$ m).

Table 4.4

Distance between copper of adjacent bars in end connections for coils of rotor bar wave winding

U_{sr}, V	till 500	500 … 1000	1000 … 1500	1500 … 2000
S_2, m	0.0017	0.002	0.0026	0.0029

Resistance of the wound rotor phase referred to the stator side equals

$$R_2' = R_2 \upsilon_{12} \tag{4.8}$$

where

$$\upsilon_{12} = \frac{m_1 (w_1 k_{w1})^2}{m_2 (w_2 k_{w2})^2}. \tag{4.9}$$

4.1.2. Resistance of induction motor cage-rotors

Resistance of a cage-rotor phase equals

$$R_2 = R_b + \frac{2R_{ring}}{\Delta^2} \tag{4.10}$$

where R_b = the bar resistance, R_{ring} = resistance of the rotor end ring part between two adjacent bars, $\Delta = 2\sin(\pi p/z_2)$.
The bar and end ring section resistance is found by the expressions:

$$R_b = \rho_b \frac{l_b}{q_b} k_r, \qquad R_{ring} = \rho_{ring} \frac{\pi D_{ring,av}}{z_2 q_{ring}} \tag{4.11}$$

where ρ_b, ρ_{ring} are the bar and end ring material specific resistance under the design temperature (Table 4.1 and the note to it), l_b is the bar length, q_b and q_{ring} are the bar and end ring cross-section area (see div. 2.3.9). Average end ring diameter is $D_{ring,av} = D_2 - b_{ring}$, where D_2 = the rotor diameter, b_{ring} = the ring height which in rotors with plug-in bars equals $b_{ring} = (1.1 \ldots 1.25) h_{sl2}$ and in rotors with casted squirrel cage is $b_{ring} \geq 1.2 h_{sl2}$. The coefficient k_r takes into account the cage bar resistance growth due to current displacement; for slip values in the range of 0 ... s_r it is accepted equal $k_r = 1$.

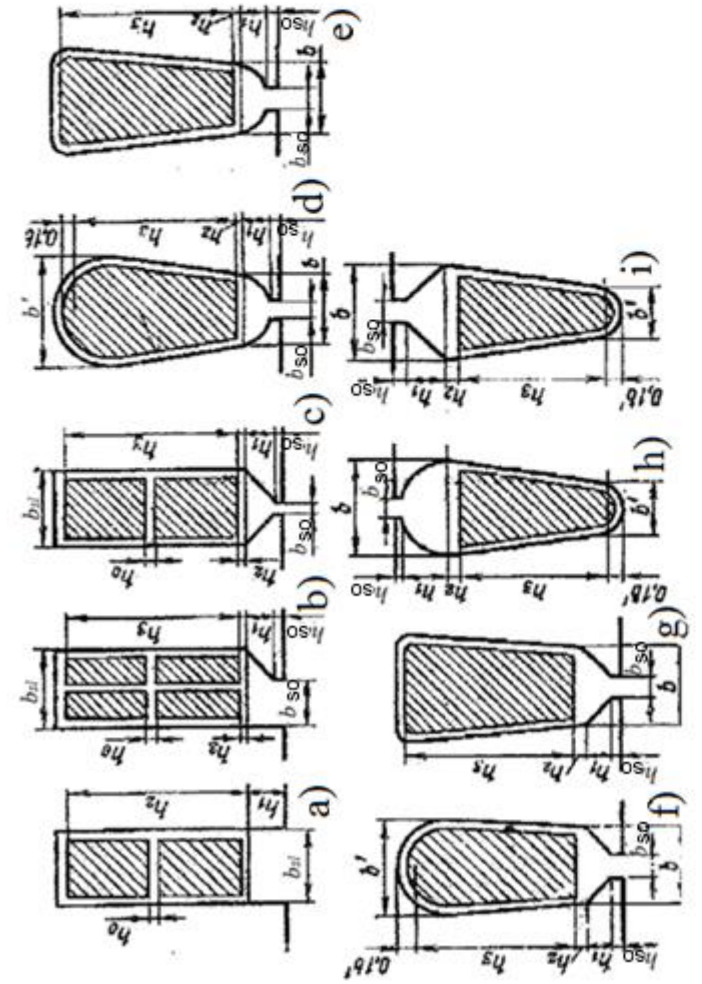


Figure 4.3 To calculation of slot leakage permeance coefficient

The rotor phase resistance referred to the stator side is found by the expression:

$$R_2' = R_2 \upsilon_{12} \tag{4.12}$$

where

$$\upsilon_{12} = \frac{4m_1(w_1 k_{w1})^2}{z_2 k_{sk}},\ \mathrm{k_{sk}} = \frac{\sin\frac{\pi\, b_{sk}}{2z_2 t_2}}{\frac{\pi b_{sk}}{2z_2 t_2}}, \tag{4.13}$$

b_{sk}, t_2 = the rotor slot skew in mm and tooth pitch in mm respectively.

4.2. Calculation of windings leakage reactance

4.2.1. Leakage reactance of wound-rotor induction motor

The stator and rotor reactance of a wound rotor induction motor is calculated by the expression:

$$X_{1(2)} = 15.8\frac{f}{100}\left(\frac{w}{100}\right)^2\frac{l'_\delta}{pq}(\lambda_{sl}+\lambda_{ec}+\lambda_d) \quad (4.14)$$

where λ_{sl}, λ_{ec}, λ_d = leakage permeance coefficients for slot part of coils, end connections and differential leakage respectively.
The slot leakage permeance coefficient is calculated by an expression selected from Table 4.5 depending on the slot shape (Fig. 4.3).

Table 4.5

Expressions for calculation of slot leakage permeance coefficients for phase windings of induction motors

Figure	Winding type	Expression for calculation
4.3 a	two-layer	$\frac{h_2-h_0}{3b_{sl}}k_\beta+\frac{h_1}{b_{sl}}k'_\beta+\frac{b_0}{4b_{sl}}$
	one-layer	$\frac{h_2}{3b_{sl}}+\frac{h_1}{b_{sl}}$
4.3 b	two-layer	$\frac{h_3-h_0}{3b_{sl}}k_\beta+(\frac{h_2}{b_{sl}}+\frac{3h_1}{b_{sl}+2b_{so}}+\frac{h_{so}}{b_{so}})\,k'_\beta$
4.3 c	two-layer	$\frac{h_3-h_0}{3b_{sl}}k_\beta+(\frac{h_2}{b_{sl}}+\frac{3h_1}{b_{sl}+2b_{so}}+\frac{h_{so}}{b_{so}})\,k'_\beta$
	one-layer	$\frac{h_3}{3b_{sl}}+\frac{h_2}{b_{sl}}+\frac{3h_1}{b_{sl}+2b_{so}}+\frac{h_{so}}{b_{so}}$
4.3 d, e, f	one-layer and two-layer	$\frac{h_3}{3b}k_\beta+(0.785-\frac{b_{so}}{2b}+\frac{h_2}{b}+\frac{h_{so}}{b_{so}})\,k'_\beta$
4.3 g, h, i	one-layer and two-layer	$\frac{h_3}{3b}k_\beta+(\frac{h_2}{b}+\frac{3h_1}{b+2b_{so}}+\frac{h_{so}}{b_{so}})\,k'_\beta$

Coefficients $k_в$ and$k'_в$ depend on the coil span $\beta=\frac{y}{\tau}$.
At $\beta=1$, $k_\beta = k'_\beta=1$ for one- and two-layer windings.
At $\frac{2}{3}\le\beta<1$, $k'_\beta=0.25(6\,\beta-1)$, and at $\frac{1}{3}\le\beta<\frac{2}{3}$, $k'_\beta=0.25(1+3\,\beta)$; for $\frac{1}{3}\le\beta<1$, $k_\beta=0.25(1+k'_\beta)$.
The leakage permeance coefficient for end connections:

$$\lambda_{ec} = 0.34\frac{q}{l'_\delta}(l_{ec} - 0.64\beta\tau)\ . \qquad (4.15)$$

In (4.14) and (4.15) quantity l'_δ is respectively determined by the expressions: $l'_д = l_1 - 0.5n_{rd1}b_{rd1}$, $l'_\delta = l_2 - 0.5n_{rd2}b_{rd2}$ where $n_{rd1(2)}$, $b_{rd1(2)}$ = number and width of the stator (rotor) radial ventilation ducts accordingly.

The differential leakage permeance coefficient for the stator and rotor windings is calculated by the expression:

$$\lambda_d = \frac{t_{1(2)}}{12\delta k_{\delta 1(2)}}\xi \qquad (4.16)$$

where coefficient ξ is determined depending on the number of slots per the phase and per the pole by the expressions:

- At integer $q \geq 2$ and $\beta = 1$

$$\xi = 2 + 0.022q^2 - k_w^2(1 + \Delta_z).$$

- At integer $q \geq 2$ and $\beta < 1$

$$\xi = k''q^2 + 2k'_\beta - k_w^2(1 + \Delta_z).$$

- At fractional $q > 2$

$$\xi = k''q^2 + 2k''_\beta - k_w(\frac{1}{d^2} + \Delta_z).$$

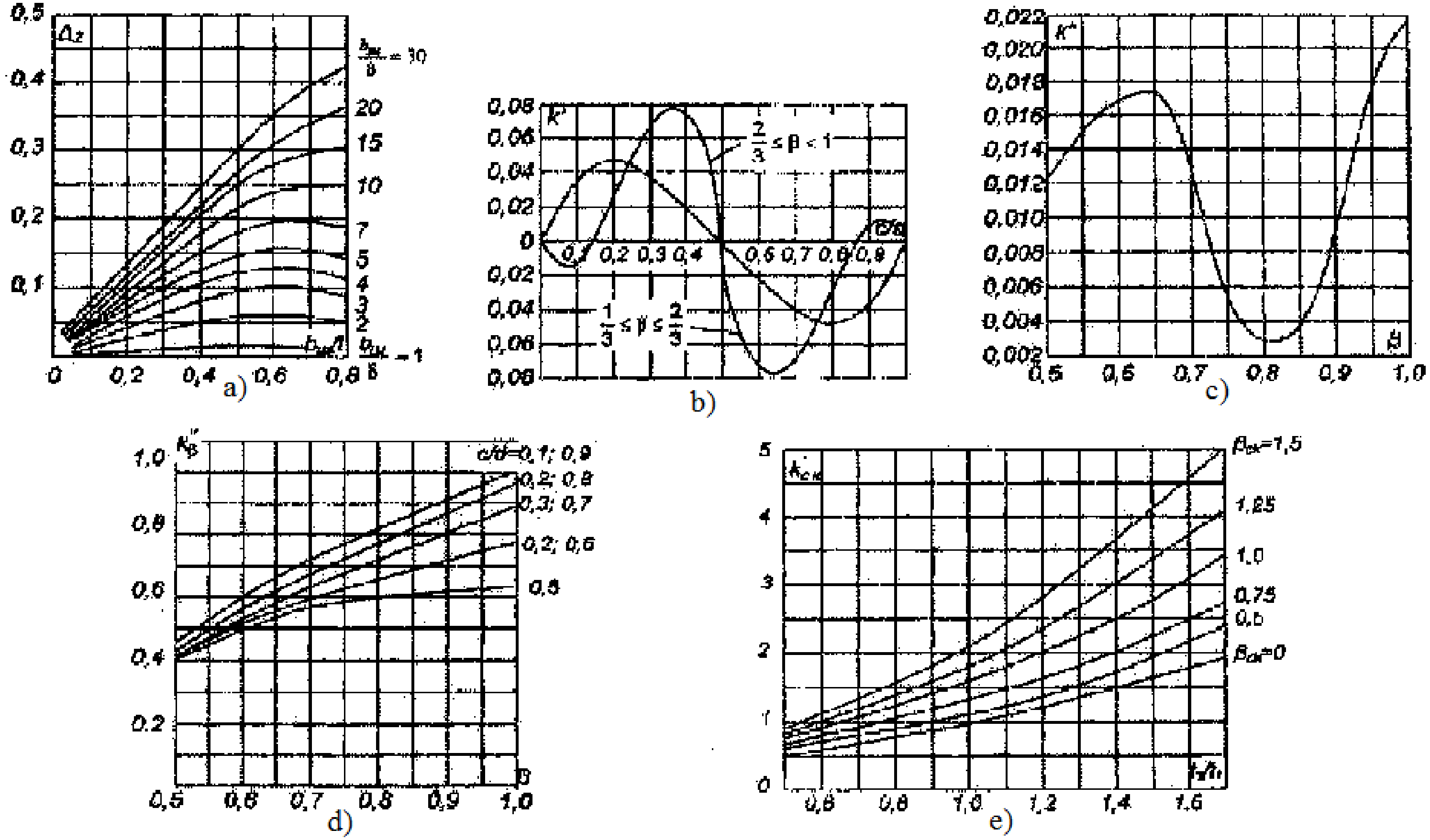
- At fractional $1 < q < 2$

$$\xi = k''q^2 + 2k''_\beta - \frac{k'}{q} - k_w(\frac{1}{d^2} + \Delta_z).$$

In the above expressions $\Delta_z, k', k'', k''_\beta$ are determined by the curves of Fig. 4.4. The coefficient k'_β is the same as was used for determination of λ_{sl}. The quantity d is the denominator of the fractional part of the number of slots per phase and per slot q.

The rotor reactance referred to the stator side equals

$$X'_2 = X_2 \upsilon_{12}. \qquad (4.17)$$



4.4 Coefficients used at determination of leakage permeance

4.2.2. Stator leakage reactance of cage induction motor

The leakage reactance of the stator of a cage motor is calculated by expression 4.14, the same as for a wound-rotor induction motor.
The permeance coefficients for the slot and for the end connections of a cage motor stator phase winding are found by expressions given in Table 4.5 and by expression 4.15 respectively.
The permeance coefficient of differential leakage for the stator winding of a cage motor is calculated by the expression:

$$\lambda_{d1} = \frac{t_1}{12\text{д}k_\delta}\xi \quad (4.18)$$

Here the coefficient ξ is found by expressions given in Table 4.7.

Table 4.6

Calculation of coefficient ξ for stator windings of cage motors

Feature of slots	Expression for calculation
Open stator slots. Stator and rotor slots are not skewed	$\xi = \left(2\frac{t_2}{t_1} - \frac{t_1}{t_2}\right)\Delta_z - k_{w1}^2\left(\frac{t_2}{t_1}\right)^2$
Semi-closed or semi-open stator slots. Slots may be skewed	$\xi = 2k'_{sk}k_\beta - k_{w1}^2\left(\frac{t_2}{t_1}\right)^2(1+\beta_{sk}^2)$

In expressions of Table 4.6 $t_1$andt_2 are stator and rotor tooth pitches; Δ_z is found from Fig 4.4 a; $k_\text{в}$ is calculated as for stators of wound-rotor machines; $\beta_{sk} = \frac{b_{sk}}{t_2}$; k'_{sk} is found from Fig. 4.4 e.

4.2.3. Leakage reactance of cage rotor

The leakage reactance of a cage rotor is found as

$$X_2 = 7.9 f_1 l'_\delta 10^{-6}(\lambda_{sl2} + \lambda_{ec2} + \lambda_{d2}). \quad (4.18)$$

The slot leakage permeance coefficient is calculated by an expression selected from Table 4.6 depending on the slot shape (Fig. 4.5).

Table 4.7

Calculation of slot leakage permeance of cage rotors

Figure	Expression for calculation
4.5 a	$\left[\frac{h_1}{3b}\left(1-\frac{\mathrm{p}b^2}{8q_{sl}}\right)^2+0.66-\frac{b_{so}}{2b}\right]k_d+\frac{h_{so}}{b_{so}}$
4.5 b	$\left(\frac{h_1}{3b}+\frac{3h_2}{b+2b_{so}}\right)k_d+\frac{h_{so}}{b_{so}}$
4.5 c	$\frac{h_1}{3b}k_d+\frac{h_{so}}{b_{so}}$
4.5 d	$\frac{h_1}{3b}k_d+\frac{h_2}{b}+\frac{2h_2}{b+2b_{so}}+\frac{h_{so}}{b_{so}}$
4.5 e	$\frac{h_1}{3b}k_d+\frac{h_2}{b}+0.785-\frac{b_{so}}{2b}+\frac{h_{so}}{b_{so}}$
4.5 f	$\left[\frac{h_1}{3b}\left(1-\frac{\mathrm{p}b^2}{8q_{sl}}\right)^2+0.66-\frac{b_{so}}{2b}\right]k_d+\frac{h_{so}}{b_{so}}$
4.5 g	$\left(0.785-\frac{b_{so}}{b}\right)k_d+\frac{h_{so}}{b_{so}}$

Notes:

1. For rated conditions $k_d = 1$.

2. For closed slots (Fig. 4.5, h, i) it is necessary to substantiate instead of $\frac{h_{so}}{b_{so}}$: for slots in Fig. 4.5, h the expression $0.3 + 1.12\, h'_{so}/I_2\, 10^6$; for slots in Fig. 4.5, i – the expression $h_{so}/b_{so} + 1.12\, h'_{so}/I_2\, 10^6$ where h'_{so} = thickness of the bridge above the slot in meters, I_2 = the rotor phase current in Amperes.

The leakage permeance coefficient for end connections for rotors with casted cage:

$$\lambda_{ec2} = \frac{2.3\, D_{ring,av}}{z_2 l'_\delta (2\sin(\pi p/z_2))^2}\, lg\, \frac{4.7 D_{ring,av}}{2a_{ring}+b_{ring}},$$

For welded rotor cages with copper or brazed bars projecting out the slots:

$$\lambda_{ec2} = \frac{2.3\, D_{ring,av}}{z_2 l'_\delta (2\sin(\pi p/z_2))^2}\, lg\, \frac{4.7 D_{ring,av}}{2(a_{ring}+b_{ring})}$$

where $a_{ring} = q_{ring}/b_{ring}$. In these expressions $D_{ring,av}$ is average diameter of end rings; $D_{ring,av} = D_2 - b_{ring}$.

The differential leakage permeance coefficient:

$$\lambda_{d2} = \frac{t_2}{12д k_\delta}\zeta, \quad \xi = 1 + \frac{1}{5}\left(\frac{\pi p}{z_2}\right)^2 - \frac{\Delta_z}{1-\left(p/z_2\right)^2}$$

where Δ_z is determined with the help of curves in Fig. 4.4, a.

The rotor phase leakage reactance referred to the stator side equals

$$X_2' = \upsilon_{12} X_2. \tag{4.19}$$

For skewed slots value of X_2 obtained above must be corrected by multiplying it by the coefficient

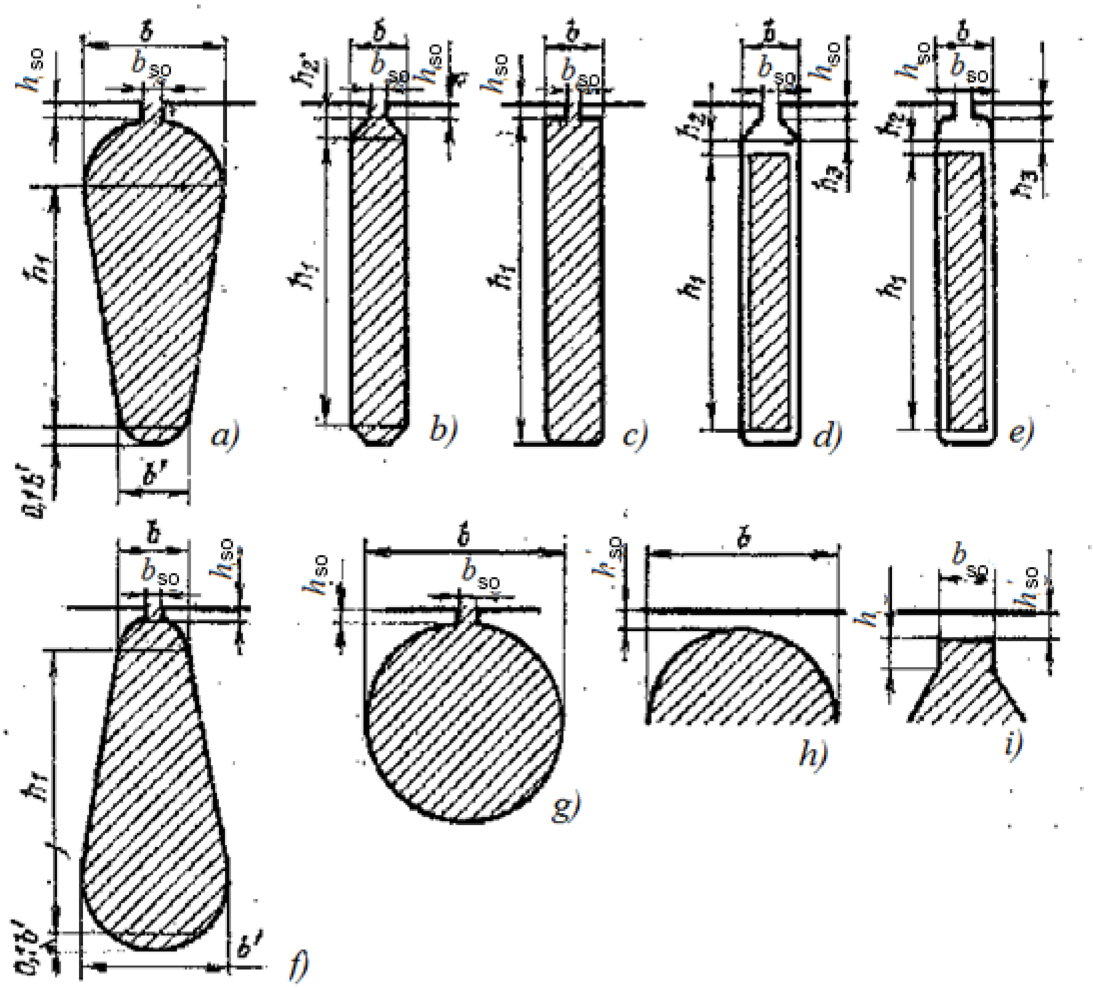


Figure 4.5 To leakage permeance caculation

$$\sigma_{sk} = 1 + 0.41 \left(\frac{b_{sk2}}{\tau_2}\right)^2 \frac{U_{1r}}{I_\mu X_1}.$$

4.3. Relative values of windings parameters

Relative values of a motor stator and rotor windings parameters are found by the following equalities:

- for a stator

$$R_1^* = R_1 \frac{I_{1r}}{U_{1r}}, \quad X_1^* = X_1 \frac{I_{1r}}{U_{1r}} \tag{4.20}$$

- for a rotor (referred values)

$$R_2'^* = R_2'^* \frac{I_{1r}}{U_{1r}}, \quad X_2'^* = X_2'^* \frac{I_{1r}}{U_{1r}}. \tag{4.21}$$

As a rule this quantities values are in the ranges:

$$R_1^* \cong R_2'^* = 0.02 \dots 0.03, \quad X_1^* = 0.08 \dots 0.14, \quad X_2'^* = 0.1 \dots 0.16.$$

5. Power loss in induction motors

5.1. Total power loss in an induction motor equals

$$\Sigma(\Delta P) = P_{c,main} + P_{c,add} + P_{w1} + P_{w2} + P_{br} + P_{mech} + P_{bf} + P_{add} \tag{5.1}$$

where$P_{c,main}$ = main magnetic loss caused by eddy currents and hysteresis stipulated by the magnetic field fundamental in the machine magnetic cores; $P_{c,add}$ = additional magnetic losses; $P_{w1}$and P_{w2} = the resistance (copper) losses in the stator and rotor winding respectively, P_{br} = electrical loss in the wound rotor brush contacts, P_{mech} = the friction losses in the bearings and ventilation loss, P_{bf} = the brush friction loss in the wound-rotor motor, P_{add} –additional loss under load.

5.2. Main magnetic loss

At the main magnetic loss determination, the magnetic loss in the rotor is neglected. The following equality is used:

$$P_{c,main} = p_{1.0/50} \left(\frac{f_1}{50}\right)^{\text{B}} \left(k_{dy} B_{y1}^2 m_{y1} + k_{dz} B_{z1middle}^2 m_{z1}\right) \tag{5.2}$$

where $p_{1.0/50}$= the specific loss in the steel of given grade and the laminations thickness under the flux density amplitude $B_m = 1\ T$ and the frequency $f = 50\ Hz$ in W/kg (Table 5.1); β = exponent (Table 5.1), k_{dy} and k_{dz}= coefficients taking into account nonuniformity of the magnetic flux in stator yoke and teeth distribution and manufacturing process influence; for motors of $P_r < 250\ kW,\ k_{dy} = 1.6$ and $k_{dz} = 1.8$; for motors of $P_r \geq 250\ kW\ k_{dy} = 1.4$ and $k_{dz} = 1.7$; B_{y1} and $B_{z1middle}$ = the flux density in the stator yoke and middle tooth cross- section in Tesla; m_{y1} and m_{z1} the magnetic circuit sections mass in kg.

The stator yoke and teeth mass are found as:

$$m_{y1} = \pi(D_a - h_{y1})h_{y1}l_{cs1}k_{fill}\gamma_{st}, \quad h_{y1} = 0.5(D_a - D) - h_{sl1},$$

$$m_{z1} = h_{z1}b_{z1middle}z_1 l_{cs1}k_{fill}\gamma_{st}, \quad b_{z1middle} = \frac{b_{z1ma[} + b_{z1min}}{2},$$

$\gamma_{st} = 7.8 \cdot 10^3\ kg/m^3$ = the steel density.

Table 5.1

Specific losses $p_{1.0/50}$ and index of powerв at lamination thickness of 0.5 mm

Steel grade	$p_{1.0/50}, W/kg$	β
2013	2.5	1.5
2211	2.6	1.5
2312	1.75	1.4
2411	1.6	1.3

5.3. Additional magnetic losses

These losses are caused by fluctuation of the flux density in the magnetic cores surface layer (surface magnetic loss) and in the stator and rotor cores teeth (pulsating loss). Total additional magnetic losses are found as the sum:

$$P_{c,add} = P_{s1} + P_{p1} + P_{s2} + P_{p2}$$

where and $P_{s1}$and P_{s2} = the surface magnetic losses in the stator and rotor cores, P_{p1} and P_{p2} = pulsating losses in the stator and rotor teeth.

The surface magnetic losses may be found in terms of the specific surface magnetic loss per $1m^2$ of a core surface:

$$P_{s1} = p_{s1}(t_1 - b_{so1})z_1 l_{cs1}, \quad P_{s2} = p_{s2}(t_2 - b_{so2})z_2 l_{cs2} \qquad (5.3)$$

where p_{s1} and p_{s2} = the specific surface magnetic loss in the stator and rotor cores in W/m^2:

$$p_{s1} = 0.5k_{01}\left(\frac{z_2 n}{10000}\right)^{1.5}(B_{01}t_2 10^3)^2$$

$$p_{s2} = 0.5k_{02}\left(\frac{z_1 n}{10000}\right)^{1.5}(B_{02}t_1 10^3)^2.$$

Here coefficients k_{01}, k_{02} take the values in the range of 1.4 … 1.8 for motors of $P_r \leq 160\ kW$ and in the range of 1.7 … 2.0 for motors $P_r > 160\ kW$; the rotating frequency is accepted equal to the synchronous one in rpm. B_{01} and B_{02} = amplitudes of the magnetic flux density in the air gap above the stator and rotor teeth edges equal to

$$B_{01(2)} = \beta_{01(2)} k_\delta B_\delta$$

where $\beta_{01(2)}$ are the coefficients found by curves of Fig. 5.1.

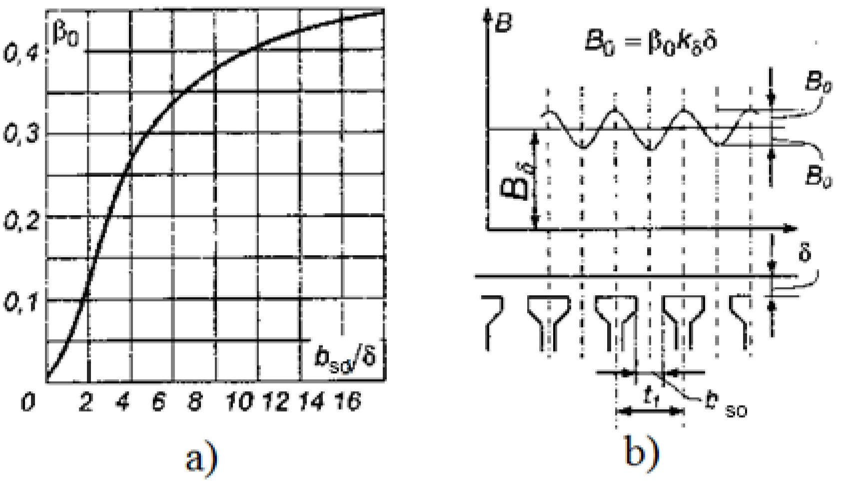


Figure 5.1 Curve for determination of coefficient β_0 (a), ripples of magnetic flux density in air gap

Pulsating losses in the stator and rotor cores teeth are calculated by expressions:

$$P_{p1} = 0.11\left(\frac{z_2 n}{1000} B_{p1}\right)^2 m_{z1}, \quad P_{p2} = 0.11\left(\frac{z_1 n}{1000} B_{p2}\right)^2 m_{z2}$$

where B_{p1} and B_{p2} = amplitudes of the magnetic flux density in the air gap above the stator and rotor teeth edges equal:

$$B_{p1} \cong \frac{\gamma_2 \delta}{2t_1} B_{z1middle}, \quad B_{p2} \cong \frac{\gamma_1 \delta}{2t_2} B_{z2middle},$$

$$\gamma_1 = \frac{(b_{so1}/\delta)^2}{5 + b_{so1}/\delta}, \ \gamma_2 = \frac{(b_{so2}/\delta)^2}{5 + b_{so2}/\delta}.$$

In the case of open slots at determination of γ_1 and γ_2 the design value of the slot opening is taken instead of b_{so1} and b_{so2}:

$$b'_{so1(2)} = \frac{b_{so1(2)}}{3}\left(1 + \frac{0.5t_{1(2)}}{t_{1(2)}b_{so1(2)} + k_\delta}\right)$$

where k_δ = is accepted by the curve in Fig. 5.2.

Mass of the rotor teeth is determined as

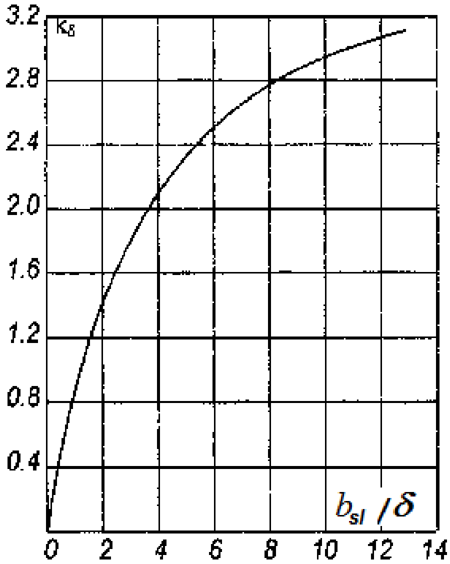


Figure 5.2 Determination of $\kappa_д$ for open slots

$$m_{z2} = h_{z2}b_{z2middle}z_2 l_{cs2}k_{fill}\gamma_{st}, \quad b_{z2middle} = \frac{b_{z2\_ax}+b_{z2min}}{2}.$$

Losses P_{s1} and P_{p1} in wound-rotor motors with bar wave winding and in squirrel cage motors are negligible and must not be calculated for such machines.

5.4. Total magnetic loss in the motor steel cores is

$$P_c = P_{c,main} + P_{c,add}. \tag{5.4}$$

Usually, additional steel core loss is by order of magnitude less than the main steel loss.

5.5. Resistance loss in windings

The resistance losses depend on the motor load.
For rated load, preliminary resistance losses are found as

$$P_{w1} = m_1 I_{1r}^2 R_1, \quad P_{w2} = m_2 I_{2r}^2 R_2. \tag{5.5}$$

The rated values of stator and rotor currents had been found at previous calculations.

5.6. Friction and ventilation losses (mechanical losses)

Calculation of this kind of losses is made in different ways depending on the method of cooling.

5.6.1. Mechanical losses in motors with radial ventilation without radial ducts and also in cage motors with ventilation blades on the cage end rings

$$P_{mech} = K_T \left(\frac{n}{1000}\right)^2 (10D)^3 \tag{5.6}$$

where D = the stator inner diameter in m, $K_T = 5$ at $2p = 2, K_T = 6$ at $2p \geq 4$ for motors with $D_a \leq 0.25$ m; $K_T = 7$ at $2p \geq 4$ for motors with $D_a > 0.25$ m.

5.6.2. Mechanical loss in self-cooled motors with external fan

Such ventilation method is applied for motors with $0.1 \leq D_a \leq 0.5$ m. The mechanical losses:

$$P_{mech} = K_T \left(\frac{n}{10}\right)^2 D_a^4 \tag{5.7}$$

where $K_T = 1$ at $2p = 2$; $K_T = 1.31(1 - D_a)$at $2p \geq 4$; $D_a =$ the outside stator core diameter.

5.6.3. Mechanical loss in motors of large and medium power with radial ventilation ducts

$$P_{mech} = 1.2 \cdot 2p\tau^3(n_{rd} + 11)10^3 \tag{5.8}$$

where n_{rd} = number of radial ventilation ducts.

5.6.4. Mechanical loss in motors with axial ventilation

$$P_{mech} = K_T \left(\frac{n}{1000}\right)^2 \left(10D_{fan}\right)^3 \tag{5.9}$$

where D_{fan} = the outside diameter of the fan in m equal $D_{fan} \cong D_a$; coefficient $K_T = 2.9$ at $D_a \leq 0.25$ m, $K_T = 3.6$ at $D_a = (0.25 \ldots 0.5)$ m.

5.6.5. Mechanical loss in motors with outside stator core diameter $0.5 < D_a < 0.9\ m$

$$P_{mech} = K_T(10D_a)^3$$

where coefficient K_T is accepted according to Table 5.2.

Table 5.2

Coefficient K_T for induction motors of large power

$2p$	2	4	6	8	10	12
K_T	3.65	1.5	0.7	0.35	0.2	0.2

5.7. Electrical loss in brush contacts and loss for brushes friction

5.7.1. The brush dimensions and grade are selected with account of the following data:

1. The brush grade is selected from the grades intended for current collection with slip rings of ac machines. The selected brushes should meet the value of speed on outer surface of the slip ring.
2. From possible grades the brushes with less values of voltage drop in the brush contacts are preferable.
3. The brush dimensions are selected from the standard range. The brush contact area $S_{br} = b_{br} l_{br}$ must provide the current density in the brush contact not exceeding but close to its specified value. It is possible to install 2 (3) brushes for each the slip ring.
4. Previously selected slip ring width may be corrected if necessary to fit it to possible dimensions of the brushes. It is better to locate the slip rings at external side of the end shield. It is desirable that the slip ring diameter was less than the outer diameter of the machine bearing that permit to take the end shield off without the slip rings removal. Usually the slip ring diameter is accepted equal $D_{sr} = (0.4 \ldots 0.5)D$.
5. The brush holders must provide reliable brush keeping in proper position and the needed pressure in the current collecting contact specified for the selected brush grade.

The contact brushes grades, the brush data and also the brush dimensions you can find inthe book [1]

5.7.2. Electrical loss in the brush contacts is

$$P_{br} = m_2 \Delta U_{br} I_{sr} \tag{5.10}$$

Where ΔU_{br} = voltage drop in the brush contact, I_{sr} = current flowing through a slip ring. If the rotor winding has Y-connection, the current $I_{sr} = I_2$, at Δ-connection $I_{sr} = \sqrt{3} I_2$.

5.7.3. Loss for the brushes friction

$$P_{bf} = k_{fr} \rho_{br} S_{br} v_{sr} \tag{5.11}$$

where $k_{fr} = 0.16 \ldots 0.17$ is friction factor; ρ_{br} = pressure in the brush contacts in Pa; S_{br} = total contact area at all three rings in m^2 equal

$$S_{br} = 3n_{br}b_{br}l_{br},$$

$$n_{br} \geq \frac{I_{sr}}{J_{br}b_{br}l_{br}}$$

where J_{br} = the brush contact current density specified for the selected brush grade in A/m^2, b_{br} and l_{br} = the brush dimensions in m^2; the line speed of the brush outside surface equals

$$v_{sr} = \frac{\mathrm{p}n}{60}D_{sr}.$$

5.8. Additional losses under load

Additional losses under rated load caused by influence of the leakage flux, the flux density fluctuation and magnetic flux harmonics are accepted equal to 0.5% of the motor rated power.

Under load which differs from the rated one

$$P_{add} = P_{add,r}(I_1/I_{1r})^2. \quad (5.12)$$

6. Parameters and data of no-load condition

Resistance, reactance and impedance of the magnetizing circuit are approximately defined as:

$$R_m = \frac{P_{c,main}}{m_1 I_\mu^2}, \quad X_m = \frac{U_{1r}}{I_\mu} - X_1, \quad Z_m = \sqrt{R_m^2 + X_m^2}. \quad (6.1)$$

Relative values of the parameters:

$$R_m^* = R_m\frac{I_{1r}}{U_{1r}}, \quad X_m^* = X_m\frac{I_{1r}}{U_{1r}}. \quad (6.2)$$

For most asynchronous machines these relative parameters are in the range:

$$R_m^* = 0.05 \ldots 0.2; \quad X_m^* = 2 \ldots 4. \quad (6.3)$$

Components of the no-load current:

$$I_{0act} = \frac{P_c + P_{mech} + P_{w10}}{m_1 U_{1r}}, \quad I_{0react} \cong I_{м} \qquad (6.4)$$

where $P_{w10} \cong m_1 I_0^2 R_1$ is electrical losses in the stator winding at no-load;
the motor no-load current equals

$$I_0 = \sqrt{I_{0act}^2 + I_{0react}^2}. \qquad (6.5)$$

The motor power factor under no-load:

$$\cos\varphi_0 = \frac{I_{0act}}{I_0}. \qquad (6.6)$$

7. Motor performance characteristics

The motor performance characteristics are the relationships $P_1 = f(P_2), I_1 = f(P_2), \cos\varphi = f(P_2), \eta = f(P_2), \ s = f(P_2)$.

It is required to determine the performance characteristics by calculation using the applied software such as MatCAD, Mathematica, etc. or programming language like C++, Pascal and others.

As the source data, the previously determined quantities are used. The calculations are carried out for the slip values in the range of $(0 \ldots 1.5)s_r$.

7.1. Values independent of the slip

The active current component under synchronous no-load operation

$$I_{0act} = \frac{P_{c,main} + 3I_0^2 R_1}{3U_{1r}}. \qquad (7.1)$$

Real and imaginary components of the complex coefficient $\underline{c_1}$ of Γ-equivalent circuit and its modulus are:

$$c_{1Re} = \frac{R_m(R_1 + R_m) + X_m(X_1 + X_m)}{R_m^2 + X_m^2}, \quad c_{1Im} = \frac{X_1 R_m - R_1 X_m}{R_m^2 + X_m^2}, \ c_1 = \sqrt{c_{1Re}^2 + c_{1Im}^2}. \qquad (7.2)$$

Real and imaginary components of the complex quantity $\underline{c_1^2} = a' + jb'$:

$$a' = c_{1Re}^2 - c_{1Im}^2, \quad b' = 2c_{1Re}c_{1Im}. \tag{7.3}$$

Impedance of the right path of Γ-equivalent circuit not depending on the slip equals $\underline{c_1}(R_1 + jX_1) + j\underline{c_1^2}X_2' = a + jb$. Its real and imaginary components are:

$$a = c_{1Re}R_1 - c_{1Im}X_1 - b'X_2', \;\; b = c_{1Re}X_1 + c_{1Im}R_1 + a'X_2'. \tag{7.4}$$

7.2. Calculations for plotting performance characteristics

It is recommended to tabulate the calculations into the table (Table 7.1).

Table 7.1

Calculations of induction motor performance characteristics

Calculated quantity	Unit of mea-sure-ment	Formula	Slips s				
			0.1 s_r	0.2 s_r	0.3 s_r	…	1.5 s_r
Resistance, reactance and impedance of right path of equivalent circuit	Ω	$R = a + a' \, {R_2'}/{s}$					
	Ω	$X = b + b' \, {R_2'}/{s}$					
	Ω	$Z = \sqrt{R^2 + X^2}$					
Current of right path	A	$I_2'' = U_{1r}/Z$					
Stator current and its components	A	$I_{1act} = I_{0act} + I_2''R/Z$					
	A	$I_{1react} = I_{м} + I_2''X/Z$					
	A	$I_1 = \sqrt{{I_{1act}}^2 + {I_{1react}}^2}$					
Consumed active power	kW	$P_1 = 3U_{1r}I_{1act}10^{-3}$					
Electrical losses	kW	$P_{w1} = 3I_1^2R_1 10^{-3}$					
	kW	$P_{w2} = 3I_2''^2 c_1^2 R_2' 10^{-3}$					
Loss in brush contact	kW	$P_{br=}P_{br,r}\, I_1/I_{1r}$					
Additional losses	kW	$P_{add} = P_{add,r}(I_1/I_{1r})^2$					
Total losses	kW	$\Sigma(\Delta P) = P_{c,main} + P_{c,add} + P_{w1} + P_{w2} + P_{br} + P_{mech} + P_{bf} + P_{add}$					
Power on shaft	kW	$P_2 = P_1 - \Sigma(\Delta P)$					
Efficiency	%	$\eta = {P_2}/{P_1}\, 100$					
Power factor	-	$\cos\varphi = I_{1act}/I_1$					

The rated value of the slip equals approximately

$$s_r = R_2' \frac{I_{1r}}{U_{1r}} . \qquad (7.5)$$

After obtaining data for all the slip values indicated in Table 7.1 it is necessary to determine data for the rated condition. For that, more accurate value of the rated slips_r is found by interpolation the slip values between ones corresponding to two power on shaft values, one of which is the nearest less and another the nearest greater to the rated power on the shaft P_{2r}. Then the data for the rating operation condition with use of the found refined value s_r are determined in the order given in the table. At this, if the obtained value of P_2 differs of the value P_{2r} specified in the task not more than for 1 … 2 %, it is assumed that this operation condition is rated one. If the difference is grater, it is necessary to repeat interpolation and calculation using the newly received data.

8. Calculation of starting characteristics

Starting properties of a squirrel cage induction motor are assessed by the torque on shaft and the stator current during the starting period. The starting torque and current of squirrel-cage motors at zero speed (i.e. under the motor short-circuit condition) are standardized (Table 8.1).

Table 8.1

Standard relative values of starting torque and current of squirrel-cage induction motors of 4A series at zero speed

Motor version	2p	$h \leq 132$ mm		$h = (160 ... 250)$ mm		$h \geq 280$ mm	
		M_{st}^*	I_{1st}^*	M_{st}^*	I_{1st}^*	M_{st}^*	I_{1st}^*
A	2	1.7 – 2.0	6.5 – 7.5	1.2 – 1.4	7.0 – 7.5	1.0 – 1.2	6.5 – 7.0
	4	2.0 – 2.2	5.0 – 7.5	1.2 – 1.4	6.5 – 7.5	1.2 - 1.3	5.5 - 7.0
	6	2.0 – 2.2	4.0 - 5.5	1.2 -1.3	5.0 – 6.5	1.4	5.5 – 6.5
	8	1.6 – 1.9	4.0 – 5.5	1.2 – 1.4	5.5 – 6.0	1.2	5.5 – 6.5
	10	-	-	1.2	6.0	1.0	6.0
	12	-	-	-	-	1.0	6.0
AH	2	-	-	1.2 – 1.3	7.0	1.0 – 1.2	6.5 – 7.0
	4	-	-	1.2 – 1.3	6.5	1.0 – 1.2	6.0 – 7.0
	6	-	-	1.2	6.0 – 7.0	1.2	6.0
	8	-	-	1.2 – 1.3	5.5 - 6.0	1.2	5.0 – 5.5
	10	-	-	-	-	1.0	5.5
	12	-	-	-	-	1.0	5.5

Note: Some motors with $h \leq 80$ mm are manufactured with reduced starting current: till $I_{1st}^* = 4.0$ at 2p=2, till $I_{1st}^* = 2.5$ at 2p=4,and till $I_{1st}^* = 3.0$ at greater number of poles.

In wound-rotor motors the starting torque and current are determined by resistance of the starting rheostat and, therefore, are not standardized. Calculation of starting characteristics for them is not performed.

Overloading capacity of an induction motor is defined by its maximum torque M_m which should be not less than 1.8 in per unit.

8.1. Starting characteristics of squirrel-cage induction motors

The starting characteristics are relationships $M^* = f(s)$ and $I_1^* = f(s)$ where M^* and I_1^* are the electromagnetic torque and the stator current expressed in per unit.

Determination of the starting characteristic of a squirrel-cage motor is made for the slip range of 1.0 … s_{cr} where s_{cr} is the critical slip at which the torque has maximum value (break down/pullout torque).

The calculations are performed in two stages:

- Calculations with account displacement of current in the cage bars.
- Redetermination the data with account as the current displacement as the teeth area saturation.

8.1.1. Calculation of starting characteristics taking into account the current displacement

In this stage it is recommended to make calculation for the slip values $s = 1, 0.8, 0.5, 0.3,\ s_{cr}$.

The reduced cage bar height ois determined taking into account decrease of equivalent bar cross-section due to current displacement. It is determined for working temperature of 75 or 115 °C depending on the temperature class of insulation and found by expressions accordingly:

- For a copper squirrel cage

$$\xi = 96.32 h_b \sqrt{s} \sqrt{\frac{b_b}{b_{sl}}}\,, \quad \xi = 89.96 h_b \sqrt{s} \sqrt{\frac{b_b}{b_{sl}}} \tag{8.1}$$

- For casted aluminum squirrel cage

$$\xi = 65.15 h_b \sqrt{s}, \quad \xi = 63.61 h_b \sqrt{s} \,. \tag{8.2}$$

Here h_b and b_b are the bar height and width, b_{sl} is the slot width, the ratio $\frac{b_b}{b_{sl}}$ is accepted equal 0.9 for cases of bars inserted into slots, and equal 1 for casted cages.

At the starting characteristics determination it is assumed that under bar current displacement it is uniformly distributed in the upper part of the bar limited by the height h_r which is called the current penetration depth (or the skin depth). The penetration depth is indicated in the slots drawings (Fig. 8.1). The penetration depth is found by the expression:

$$h_r = \frac{h_b}{1+\varphi} \tag{8.3}$$

where φ is a parameter found from the chart in Fig. 8.2.

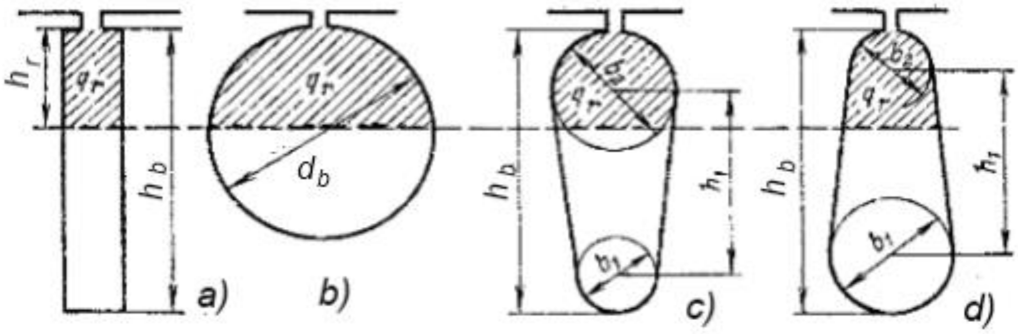


Figure 8.1 Depth of current penetration into bars of different shape

The current displacement effect causes increase of the bars effective resistance $R_{b\xi} = R_b K_r$ and decrease of the leakage reactance of the slot part of a squirrel cage $X_{b\xi}$ resulting in a decrease of the rotor phase reactance

$$X_{2\xi} = X_2 K_X \tag{8.4}$$

where the coefficients are $K_r > 1$, $K_X < 1$.

As the end rings resistance does not change at the current in bars displacement, the rotor phase resistance changes in some less degree than the resistance of bars:

$$R_{2\xi} = R_2 K_R, \qquad K_R = 1 + (K_r - 1)\frac{R_b}{R_2} < K_r \,. \tag{8.5}$$

The rotor phase resistance and reactance determined with account of the current displacement influence referred to the stator winding equal:

$$R'_{2\xi} = R_2 K_R, \qquad X'_{2\xi} = X_2 K_X. \tag{8.6}$$

Consider determination of coefficients K_R and K_X.

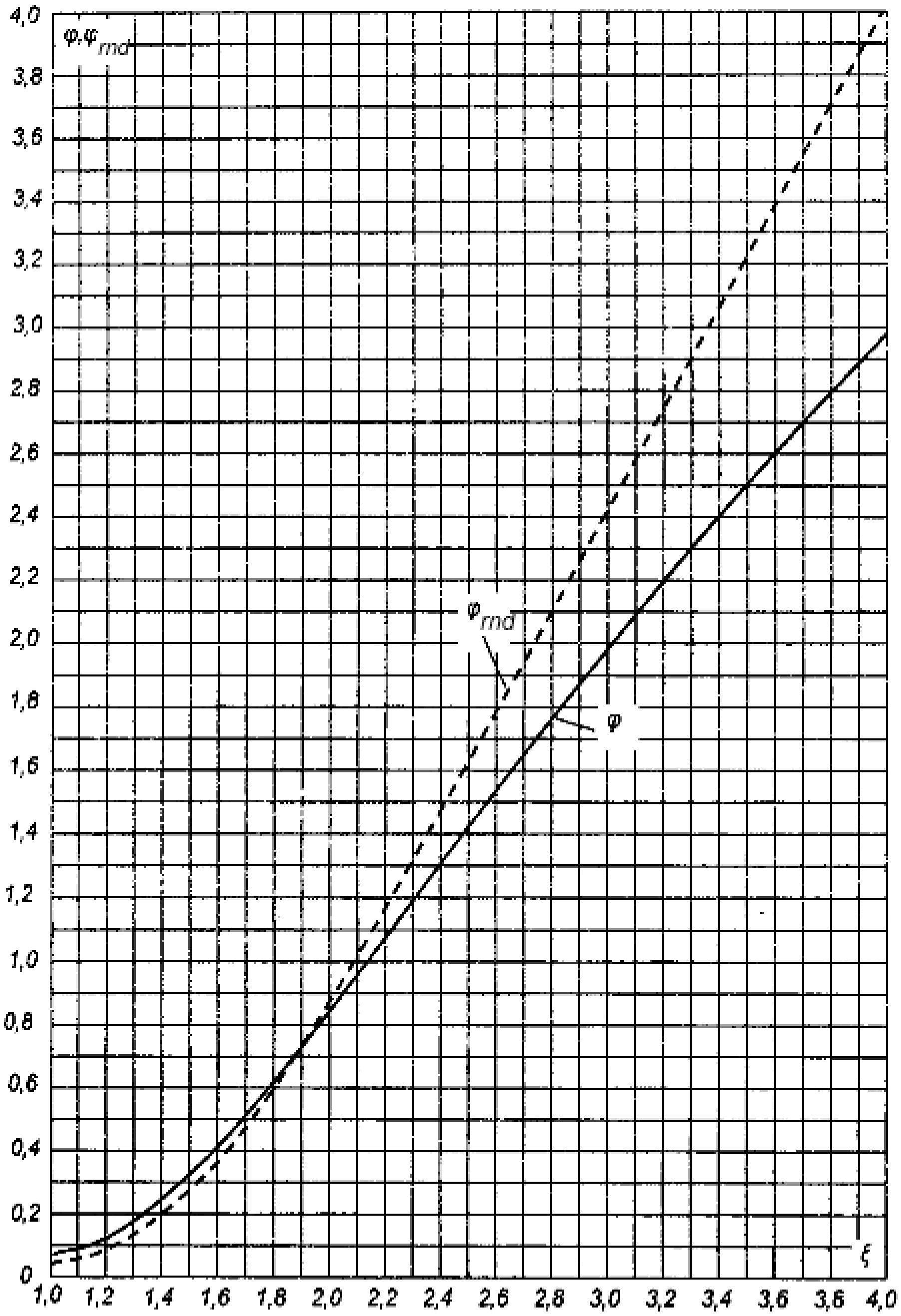


Figure 8.2 Curves of ц and ц$_{rnd}$as dependence of о
($\varphi \cong \xi - 1$ at $\xi > 4$; $\varphi \cong (4\xi^4)/45$ at $\xi < 1$)

Determination of K_R

Coefficient K_R is found by expression (8.5). To calculate it, the coefficient K_r is to be known. Its determination depends on the bar shape.

For bars of rectangular shape (Fig. 8.1, a)

$$K_r = \frac{q_b}{q_r} = \frac{h_b}{h_r} = 1 + \varphi. \qquad (8.7)$$

For bars of round shape (Fig. 8.1, b)

$$K_r = 1 + \varphi_{rnd} \qquad (8.8)$$

where φ_{rnd} is a parameter found by the chart $\varphi_{rnd} = f(\xi)$ given in Fig 8.2.

For pear-shaped bars (Fig. 8.1, c)

$$K_r = \frac{q_b}{q_r} \qquad (8.9)$$

where

$$q_b = \frac{\pi(b_1^2 + b_2^2)}{8} + \frac{b_1 + b_2}{2} h_1. \qquad (8.10)$$

The part of the bar cross-section area corresponding to the penetration depth q_r is found in different ways depending on the value of h_r:

- At $\frac{b_2}{2} \le h_r \le h_1 + \frac{b_2}{2}$

$$q_r = \frac{\pi b_2^2}{8} + \frac{b_2 + b_r}{2}\left(h_r - \frac{b_2}{2}\right), \quad b_r = b_2 - \frac{b_2 - b_1}{h_1}\left(h_r - \frac{b_2}{2}\right). \qquad 8.11)$$

- At $h_r < \frac{b_2}{2}$

$$q_r = \frac{\pi b_2^2}{4(\varphi_{rnd} + 1)} \qquad (8.12)$$

Where φ_{rnd} is found by Fig. 8.2.

For the trapezoidal bars (Fig. 8.1, d) the same relations that for the pear-shaped bars are used except for expression for b_r. In this case

$$b_r = b_2 + \frac{b_1+b_2}{h_1}\left(h_r - \frac{b_2}{2}\right). \qquad (8.13)$$

For bars of other shapes K_r is found by (8.9) where q_b is determined as cross-section area for the bar of the specified shape and q_r as this bar cross-section part area in bounds of the penetration depth h_r.

Determination of K_X

The coefficient which takes into account decrease of the rotor reactance due to the current in the bars displacement is determined on the basis of the expression:

$$K_X = \frac{X'_{2\xi}}{X'_2} = \frac{X_{2\xi}}{X_2} = \frac{\lambda_{sl2\xi}+\lambda_{ec2}+\lambda_{d2}}{\lambda_{sl2}+\xi_{ec2}+\lambda_{d2}} = \frac{\lambda_{sl2}k_d+\lambda_{ec2}+\xi_{d2}}{\lambda_{sl2}+\lambda_{ec2}+\lambda_{d2}} \qquad (8.14)$$

where $k_d = \lambda_{sl2\xi}/\lambda_{sl2}$. The coefficient $k_d = \varphi'$ where φ' is found by the chart in Fig. 8.3.

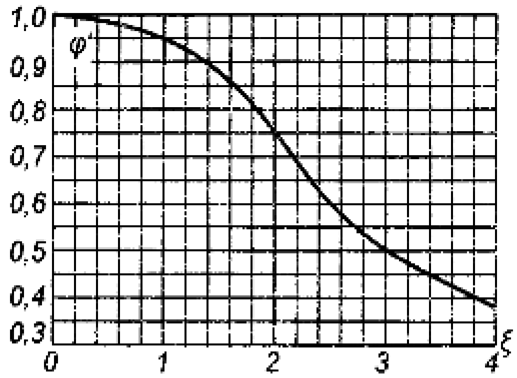


Figure 8.3 Dependence of coefficient ц′ on reduced cage bar height о

($\varphi' \cong {}^{3\xi}/_{2}$ at $\xi > 4$)

To find K_X it is necessary to determine the value of $\lambda_{sl2\xi}$ using expressions given in Table 4.7 and value of $k_d = \varphi'$. After that the coefficient K_X is calculated by (8.14).

Under starting conditions the main magnetic flux decreases, the machine magnetic circuit saturation weakens and the equivalent circuit magnetizing branch impedance increases. At the starting characteristics calculation, it is assumed that impedance Z_m in the range of slip taking place during the starting period is equal to

$$X_{m,st} = X_m \frac{F}{F_\delta}\,. \tag{8.15}$$

In this stage of calculation provisional value of the critical slip is found as

$$s_{cr} = \frac{R_2'}{\frac{X_1}{c_{1st}} + X_2'} \tag{8.16}$$

where
$$c_{1st} = 1 + \frac{X_1}{X_m} \tag{8.17}$$

In farther stage at calculation with account saturation of the teeth area more exact values of the coefficient c_{1st} and the critical slip are used.

It is recommended to tabulate the calculations of the starting curves into the table (Table 8.2).

Table 8.2

Result of starting characteristics of cage induction motor calculation with taking into account current displacement in cage bars

Quantity	Unit	Value at slip				
		1	0.8	0.5	0.3	s_{cr}
ξ	-					
φ	-					
K_r	-					
$K_R = 1 + (K_r - 1)\dfrac{R_b}{R_2}$	-					
$R_{2\xi}' = R_2' K_R$	Ω					
$k_d = f(\xi)$	-					
$\lambda_{sl2\xi} = \lambda_{sl2} k_d$	-					
$K_X = (\lambda_{sl2\xi} + \lambda_{ec2} + \lambda_{d2})/(\lambda_{sl2} + \lambda_{ec2} + \lambda_{d2})$	-					
$X_{2\xi}' = X_2' K_X$	Ω					
$X_{m,st} = X_m F/F_\delta$	Ω					
$c_{1st} = 1 + X_1/(X_{m,st})$	-					
$R = R_1 + c_{1st} R_{2\xi}'/s$	Ω					
$X = X_1 + c_{1st} X_{2\xi}'$	Ω					
$I_2' = U_{1r}/\sqrt{R^2 + X^2}$	A					
$I_1 = I_2' \sqrt{R^2 + (X + X_{m,st})^2}/(c_{1st} X_{m,st})$	A					
$I_1^* = I_1/I_{1r}$	-					
$M^* = M/M_r = (I_2'/I_{2r}')^2 K_R\, s/s_r$	-					

8.1.2. Redetermination the starting characteristics with account the current displacement and the teeth area saturation

Redetermination of starting characteristics is made based on data obtained in the previous stage of calculation.

During the starting period, the stator and rotor currents considerably exceed the values under rated conditions that causes increase of the windings leakage fluxes. The teeth become more saturated, especially in the areas of the teeth edges, and the slot coil parts leakage permeance λ_{sl1} and λ_{sl2} decrease. With account the saturation, the slot parts leakage permeance is found as

$$\lambda_{sl1sat} = \lambda_{sl1} - \Delta\lambda_{sl1}, \quad \lambda_{sl2\xi sat} = \lambda_{sl2\xi} - \Delta\lambda_{sl2}. \tag{8.18}$$

Reduction of the leakage permeance $\Delta\lambda_{sl1}$ and $\Delta\lambda_{sl2}$ caused by saturation is determined by means of introduction the slots additional openings c_1 and c_2 being equivalent by their influence on the permeance to the effect of saturation.

Calculation of starting characteristics is carried out using saturation factor k_{sat} which is defined as

$$k_{sat} = \frac{I_{1sat}}{I_1}$$

where I_1 is the stator current value found without taking saturation into account, I_{1sat} is the current value taking into account effect of saturation.

As value of k_{sat} is not known beforehand, calculation of starting characteristics is made using the iteration method. Initially the saturation factor may be assumed equal $k_{sat} = 1.25 \ldots 1.4$ for $s = 1$ and $k_{sat} = 1.1 \ldots 1.2$ for $s = s_{cr}$.

Values of $\Delta\lambda_{sl1}$ and $\Delta\lambda_{sl2}$ are determined separately for each of the accepted values of the slip.

To find c_1 and c_2, first, the average stator winding mmf per slot is calculated:

$$F_{sl,av} = 0.7\frac{k_{sat} I_1 u_{sl1}}{a}\left(k'_\beta + k_{p1} k_{w1}\frac{z_1}{z_2}\right) \tag{8.19}$$

where I_1 is the stator current at given value of the slip s taken from data of Table 8.2, $k'_в$ is the coefficient taking into account decrease of voltage induced in the slot conductors due to the coil pitch shortening which is taken equal to the value found at the slot leakage permeance calculation (see div. 4.2.1). Coefficient k_{sat} is the saturation factor taking into consideration the teeth saturation caused by the leakage fluxes.

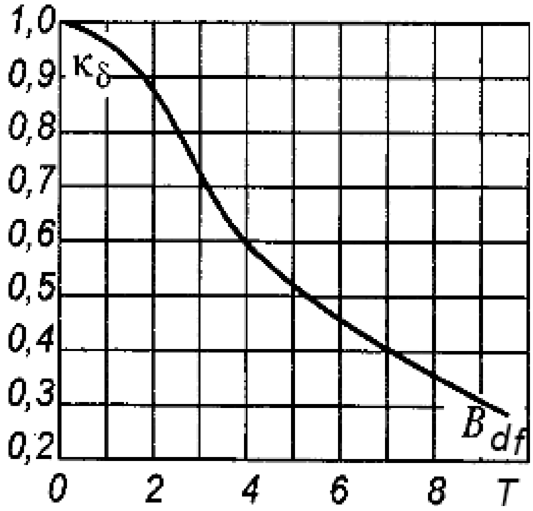


Figure 8.4 Coefficient κ_δ as a function of fictitious leakage magnetic flux density

After that the fictitious leakage magnetic flux density in the air gap is calculated:

$$B_{\delta f} = \frac{F_{sl,av}}{1.6\delta c_N} 10^{-6},\ T \tag{8.20}$$

where δ is measured in meters, coefficient $c_N = 0.64 + 2.5\sqrt{\frac{\delta}{t_1+t_2}}$.

Further, with the help of curve in Fig. 8.4 the coefficient κ_δ specifying ratio of the leakage fluxes in saturated and non-saturated tooth area are determined by the found value of $B_{\delta f}$. Then additional slots opening equivalent in its effect to the tooth area saturation (Fig.8.5) is calculated as

$$c_1 = (t_1 - b_{so1})(1 - \kappa_\delta), \quad c_2 = (t_2 - b_{so2})(1 - \kappa_\delta)\ . \tag{8.21}$$

Reduction of the leakage permeance $\Delta\lambda_{sl1}$ and $\Delta\lambda_{sl2}$ caused by saturation are defined by expressions depending on the slots shape.

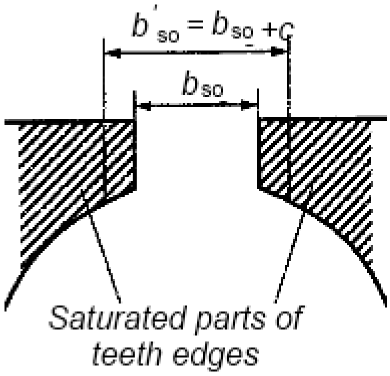


Figure 8.5 Equivalent additional slot opening taking into account teeth edges saturation

For stator slots (Fig. 8.6) it is found as:

- For open parallel slots (Fig. 8.6, a)

$$\Delta\lambda_{sl1} = \frac{h'}{b_{so}}\frac{c_1}{b_{so}+c_1}. \tag{8.22}$$

- For semi-open parallel slots (Fig. 8.6, b)

$$\Delta\lambda_{sl1} = \frac{h_{so}}{b_{so}}\frac{c_1}{b_{so}+c_1} + \frac{h'_{so}}{b_{so}+b}\frac{c_1}{b_{so}+b+c_1}. \tag{8.23}$$

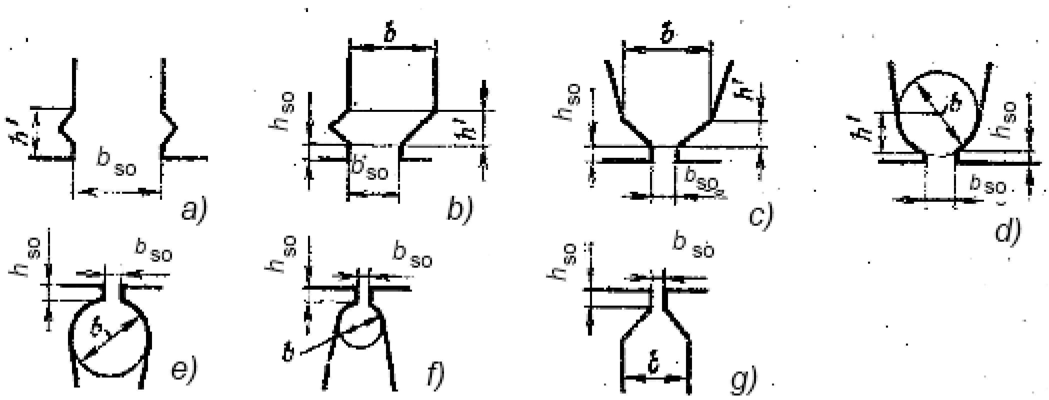


Figure 8.6 Slot dimensions taken into account at calculation of leakage permeance reduction

- For semi-closed trapezoidal slots (Fig. 8.6, c and d)

$$\Delta\lambda_{sl1} = \frac{h_{so}+0.58h'}{b_{so}}\frac{c_1}{1.5b_{so}+c_1}. \tag{8.24}$$

For rotor slots (Fig. 7.6) it is found as:

- For open parallel slots (Fig. 8.6, a)

$$\Delta\lambda_{sl2} = \frac{h'}{b_{so}} \frac{c_2}{b_{so}+c_2}. \tag{8.25}$$

- For semi-closed slots (Fig. 8.6, e, f, and g)

$$\Delta\lambda_{sl2} = \frac{h_{so}}{b_{so}} \frac{c_2}{b_{so}+c_2}. \tag{8.26}$$

- For closed slots (Fig. 8.7)

$$\Delta\lambda_{sl2} = 0.4\pi(\frac{h_{s2}}{0.05} \frac{c_2}{c_2+0.05} + \frac{c_2-0.15d}{c_2+0.6d}). \tag{8.27}$$

Dimensions are substantiated into (8.27) in centimeters.
Differential leakage permeance is also influenced by the teeth area saturation:

$$\lambda_{d1sat} = \lambda_{d1}\text{к}_{\delta}, \quad \lambda_{d2sat} = \lambda_{d2}\text{к}_{\delta}. \tag{8.28}$$

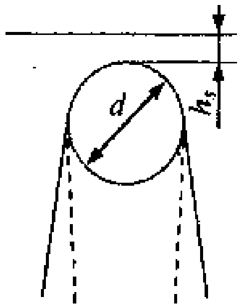


Figure 8.7 Closed slot of squirrel-cage rotor

Total leakage permeance for the stator and rotor windings determined with account of saturation and rotor current displacement equal:

$$\Sigma\lambda_{1sat} = \lambda_{sl1sat} + \lambda_{d1sat} + \lambda_{ec1}, \tag{8.29}$$

$$\Sigma\lambda_{2\xi sat} = \lambda_{sl2\xi sat} + \lambda_{d2sat} + \lambda_{ec2}. \tag{8.30}$$

Redetermination the starting characteristics taking into account the current displacement and the teeth area saturation is carried out for the same values of slip that are indicated in Table 8.2. For each value of slip the values of quantities, needed for plotting the starting characteristics with taking into account as the current displacement as the teeth area saturation, are found. Calculation is made in the following order:

- The calculation is begun from the slip $s = 1$ at which the saturation factor is accepted in the range of 1.25 …1.40.

For $s = 1$ values of $F_{sl,av}$, $B_{\delta f}$, κ_{δ}, c_1, c_2, $\Delta\lambda_{sl1}$, $\Delta\lambda_{sl2}$, λ_{sl1sat}, $\lambda_{sl2\xi sat}$, λ_{d1sat}, λ_{d2sat}, $\Sigma\lambda_{1sat}$, $\Sigma\lambda_{2\xi sat}$ are found.

Then the reactance of the stator and rotor phase windings with taking into account effect of current displacement in rotor bars and teeth saturation are found as

$$X_{1sat} = X_1 \frac{\Sigma\lambda_{1sat}}{\Sigma\lambda_1}, \quad X'_{2\xi sat} = X'_2 \frac{\Sigma\lambda_{2\xi sat}}{\Sigma\lambda_2} \tag{8.31}$$

where X_1, $\Sigma\lambda_1$ and $\Sigma\lambda_2$ are taken by data of div.4.2, $X'_{2\xi}$ - by data of Table 8.2, $\Sigma\lambda_{1sat}$ and $\Sigma\lambda_{2\xi sat}$ are calculated by expressions (8.29) and (8.30).

After that the resistance and reactance needed for the current calculation with taking into account the current displacement and saturation are found as

$$R_{st} = R_1 + c_{1st,sat} \frac{R'_{2\xi}}{s}, \tag{8.32}$$

$$X_{st} = X_{1sat} + c_{1st,sat} \frac{X'_{2\xi sat}}{s} \tag{8.33}$$

where the quantities are taken: R_1 – from div. 4.1, $R'_{2\xi}$ - from Table 8.2, X_{1sat} and $X'_{2\xi sat}$ - calculated by (8.31). Coefficient $c_{1st,sat}$ is calculated as

$$c_{1st,sat} = 1 + \frac{X_{1sat}}{X_{m,st}} \tag{8.34}$$

whereX_{1sat} is calculated by (8.31), $X_{m,st}$ is calculated by (8.15) or taken from Table 8.2.

After R_{st} and X_{st} determination the referred rotor current and stator current with taking into account current in the rotor bars displacement and saturation are found:

$$I'_{2\xi sat} = \frac{U_{1r}}{\sqrt{R_{st}^2 + X_{st}^2}}\,. \quad (8.35)$$

$$I_{1\xi sat} = I'_{2\xi sat}\frac{\sqrt{R_{st}^2 + \left(X_{st} + X_{m,st}\right)^2}}{c_{1st,sat}X_{m,st}}. \quad (8.36)$$

The saturation factor obtained as

$$k'_{sat} = \frac{I_{1\xi sat}}{I_1} \quad (8.37)$$

has to be compared with the initially accepted its value. If difference between them does not exceeds 10% the currents calculation for the specified value of the slip (in this case – for $s = 1$) is over. If not, it is necessary to change the preliminary accepted value of k_{sat}taking it between k_{sat} and k'_{sat} and repeat calculation.

When difference of the saturation factor values satisfies the requirement the relative values of the stator current and torque are determined:

$$I_1^* = \frac{I_{1\xi sat}}{I_{1r}}, \quad (8.38)$$

$$M^* = \left(\frac{I'_{2\xi sat}}{I'_{2r}}\right)^2 K_R\frac{s_r}{s}. \quad (8.39)$$

- Next calculation of the preliminary value of slip $s_{cr}$is determined according to (8.17) and is performed in the same order that is described above. Preliminary value of the saturation factor for calculation of starting parameters at s_{cr} is accepted in the range of $k_{sat} = 1.1 \ldots 1.2$.

After obtaining satisfactory value of difference between k_{sat} and k'_{sat} at critical slip, adjust the critical slip value by the expression

$$s_{cr} = \frac{R'_{2\xi}}{\frac{X_{1sat}}{c_{1st,sat}} + X'_{2\xi sat}} \quad (8.40)$$

using the quantities values received for the preliminary value of s_{cr}. For this refined value of the critical slip, determine the proper values of I_1^* and $M^* = M_{max}^*$.

- Carry out calculations of I_1^* and $M^*$for the remaining specified values of the slip $s = 0.8, 0.5, 0.3$ in the above described order accepting that the saturation factor linearly depends on slip in the range between s_{cr} and 1.

The results of calculation are recommended to tabulate (Table 8.3).

Table 8.3

Result of starting characteristics of cage induction motor calculation with taking into account current displacement in cage bars and saturation

Quantity	Unit	Value at slip				
		1	0.8	0.5	0.3	s_{cr}
k_{sat}	-					
$F_{sl,av}$	A					
$B_{\delta f}$	T					
κ_{δ}	-					
c_1	-					
c_2	-					
$\Delta\lambda_{sl1}$	-					
$\Delta\lambda_{sl2}$	-					
λ_{sl1sat}	-					
$\lambda_{sl2osat}$	-					
λ_{d1sat}	-					
λ_{d2sat}	-					
$\Sigma\lambda_{1sat}$	-					
$\Sigma\lambda_{2\xi sat}$	-					
X_{1sat}	Ω					
$X'_{2\xi sat}$	Ω					
$c_{1st,sat}$	-					
R_{st}	Ω					
X_{st}	Ω					
$I'_{2\xi sat}$	A					
$I_{1\xi sat}$	A					
k'_{sat}	-					
I_1^*	-					
M^*	-					

8.2. Multiplicity of wound-rotor motor maximum torque

It is determined with account of the teeth edge saturation as described in div. 8.1.2. In comparison with calculation for a cage motor, difference is that the current displacement in the rotor conductors is not taken into account, and instead of $R'_{2\xi}$ and $X'_{2\xi}$ the values R'_2 and X'_{2sat} are applied.

Initially the critical slip of a wound-rotor induction motoris found using (8.17), without account the teeth area saturation:

$$s_{cr} = \frac{R'_2}{\frac{X_1}{c_{1st}} + X'_2}.$$

Then calculation of currents I'_2 and I_1 with account the effect of saturation is carried out.

After that, using the motor parameters X_{1sat}, X'_{2sat}, $c_{1st,sat}$, found under the above determined critical slip value with account of teeth edge saturation (8.31), the motor critical slip value is refined:

$$s_{cr} = \frac{R'_2}{\frac{X_{1sat}}{c_{1st,sat}} + X'_{2sat}} \qquad (8.41)$$

where X_{1sat} and X'_{2sat} are determined at calculation under previously accepted value of the critical slip.

Finally, the torque M^*_{max} is determined under the critical slip value found with account the teeth area saturation but without account of the rotor current displacement:

$$M^* = \left(\frac{I'_{2sat}}{I'_{2r}}\right)^2 \frac{s_r}{s}. \qquad (8.42)$$

9. Heat and ventilation calculations

9.1. Calculation of motor heating

Calculations the machine heating is carried out based on the losses at rated operating conditions (see div. 5). The calculated loss values are increased in some degree assuming that the stator and wound-rotor windings may be heated to maximum allowable for the insulation thermal class temperature. This temperature is:

- 120°C for thermal class B;
- 140°C for thermal class F;

- 165°C for thermal class H.

The losses increase is accounted for by coefficient k_c assuming it equal:

- $k_c = c_{120}/c_{75} = 1.15$ for windings of thermal class B;
- $k_c = c_{140}/c_{115} = 1.07$ for windings of thermal class F;
- $k_c = c_{165}/c_{115} = 1.45$ for windings of thermal class H.

As a result, for a wound-rotor induction motor the stator and rotor windings temperature rise above ambient temperature should be found.

For a cage motor only the stator winding temperature rise above ambient temperature should be found. The rotor allowable temperature is higher than the stator one. It must not exceed the values dangerous to adjacent materials of the rotor itself and other machine parts. This requirement is satisfied as a rule. By this reason the squirrel cage temperature rise above ambient temperature is not calculated in this project.

9.1.1. Calculation of stator winding temperature rise above ambient temperature

Resistance power loss in the stator winding is divided into two components – the loss in slot parts $P_{w1,sl}$ and in end connections of the stator winding coils $P_{w1,ec}$:

$$P'_{w1,sl} = k_\rho P_{w1} \frac{2l_{sl1}}{l_{av1}}; \tag{9.1}$$

$$P'_{w1,ec} = k_\rho P_{w1} \frac{2l_{ec1}}{l_{av1}}. \tag{9.2}$$

Quantities l_{sl1}, l_{ec1} and l_{av1} had been found in div. 4, and power loss P_{w1} – in div. 5.

The stator core inner surface temperature rise above the air temperature inside the machine in °C equals

$$\Delta\vartheta_{surf1} = K \frac{P'_{w1,sl} + P_{c,main}}{\pi D l_1 \alpha_1} \tag{9.3}$$

where б$_1$ = coefficient of heat transfer from the core surface in W/(m^2·°C) (Fig. 9.1-9.3); K= coefficient taking into account that some part of the losses is transferred through the motor case to the environment directly, its value is taken from Table 9.1;

$P_{c,main}$ = the main magnetic loss in W (div. 5); D= the inner stator core diameter in m; l_1 = full stator core design length l_1 in m (subdivision. 1.2.7).

Table 9.1

Average values of coefficient K for 4A induction motors series

Degree of protection	Poles number $2p$					
	2	4	6	8	10	12
IP44	0.22	0.20	0.19	0.18	0.17	0.16
IP23	0.84	0.80	0.78	0.76	0.74	0.72

Temperature drop in insulation of the slot parts of the stator winding coils in °C:

$$\Delta\vartheta_{sl\ ins,1} = \frac{P'_{w1,sl}}{z_1 \Pi_{sl1} l_1}\left(\frac{b_{ins1}}{\lambda_{eqv}} + \frac{b_1 + b_2}{16\lambda'_{eqv}}\right) \quad (9.4)$$

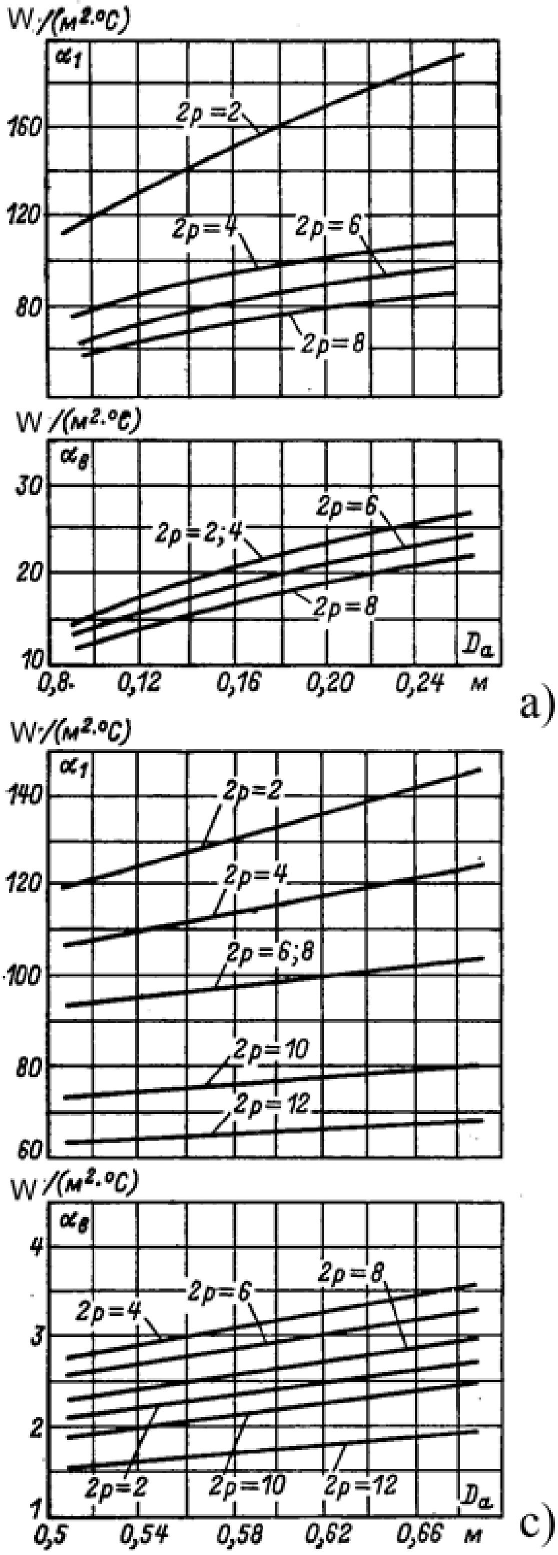
where Π_{sl1} = calculated perimeter of the stator slot cross-section in m which is found by expressions:

- $\Pi_{sl1} = 2h_{sl1} + b_1 + b_2$ (9.5)

  for semi-closed trapezoidal slots;

- $\Pi_{sl1} = 2(h_{sl1} + b_{sl1})$ (9.6)

  for parallel open and semi-open slots.



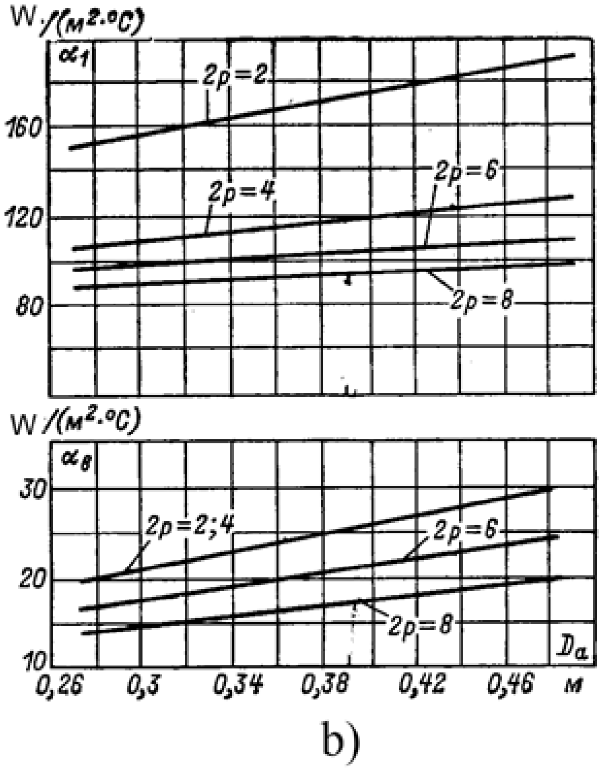
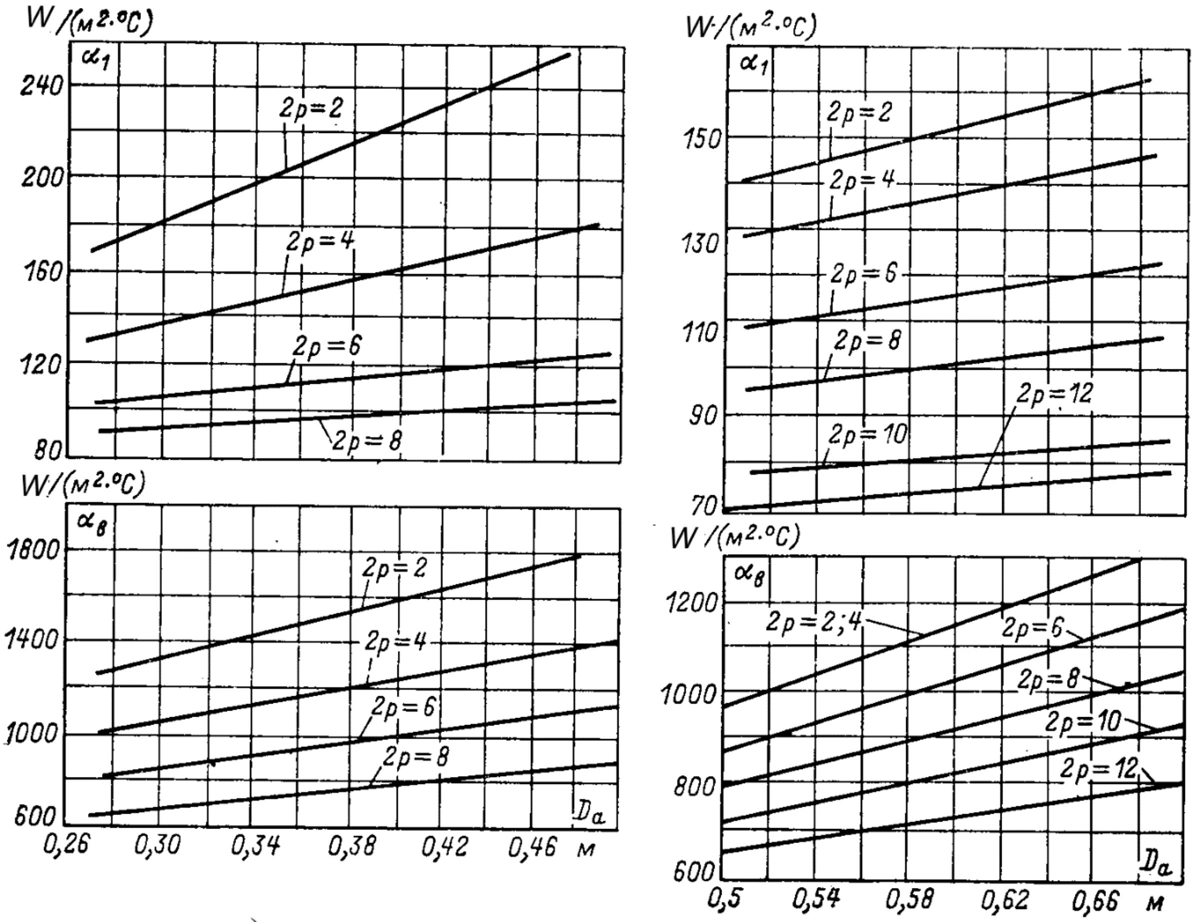


Figure 9.1 Coefficients of heat transfer fom the surface α_1 and of air heating α_β for motors of 4A series, degree of protection IP44



a) b)

Figure 9.2 Coefficients of heat transfer from the surface $\propto_1$ and of air heating $\propto_b$ for motors of 4A series, degree of protection IP23

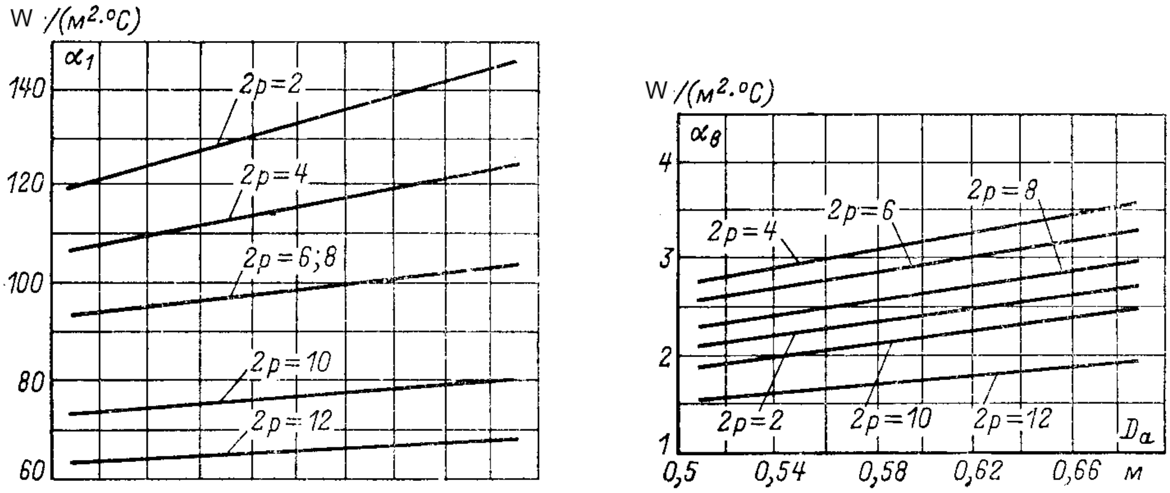
In the above expressions b_{ins1} = unilateral (one-sided) insulation thickness in the slot which value for fed-in windings is taken from previous calculation of the slot dimensions, and for windings made of rectangular wire is calculated as

$$b_{ins1} = 0.5(b_{sl} - n_{el}b); \qquad (9.7)$$

$n_{el}$and b = the number and width of non-insulated elementary conductors placed in one layer by the slot width;

λ_{eqv}= average values of coefficient of heat conduction for the slot insulation. For insulation of thermal classes B, F and H $\lambda_{eqv} = 0.16$ W/(m · °C);

λ'_{eqv} = average value of coefficient of heat conduction for inner insulation of fed-in-winding coil made of enameled wire in W/(m · °C) determined taking into account wires gapping to each other (Fig. 9.4). For windings of rectangular conductors it is assumed that $\frac{b_1+b_2}{16\lambda'_{eqv}} = 0$.



a) b)

Figure 9.3 Coefficients of heat transfer from the surface $\propto_1$ and of air heating $\propto_b$ for motors of 4A series, degree of protection IP23, voltage 6000 V

Temperature drop by thickness of the coil end connections insulation in °C is found by the expression:

$$\Delta\vartheta_{ec\ ins,1} = \frac{P'_{w1,ec}}{z_1\Pi_{ec1}lec_1}\left(\frac{b_{ins\ ec1}}{\lambda_{eqv}} + \frac{h_{sl1}}{12\lambda'_{eqv}}\right) \quad (9.8)$$

where Π_{ec1} = the perimeter of conditional cooling surface of one coil end connections in m that is assumed equal $\Pi_{ec1} \cong \Pi_{sl1}$;
$b_{ins\ ec1}$ = unilateral thickness of the coil end connections insulation in m (see tables of Appendix 11 in the book «Проектирование электрических машин»/Д.В.Цыпленков, Ю.В. Куваев, А.Б. Иванов, И.А. Кириллов; Подред. Ф.П. Шкрабца – Д.: Национальныйгорныйуниверситет, 2008). If the insulation is not available, it is accepted $b_{ins\ ec1} = 0$;
λ'_{eqv} = average value of coefficient of heat conduction taken from Fig. 9.4 for coils of fed-in windings; for coils of rectangular wire it is accepted $\frac{h_{sl1}}{12\lambda'_{eqv}} = 0$.

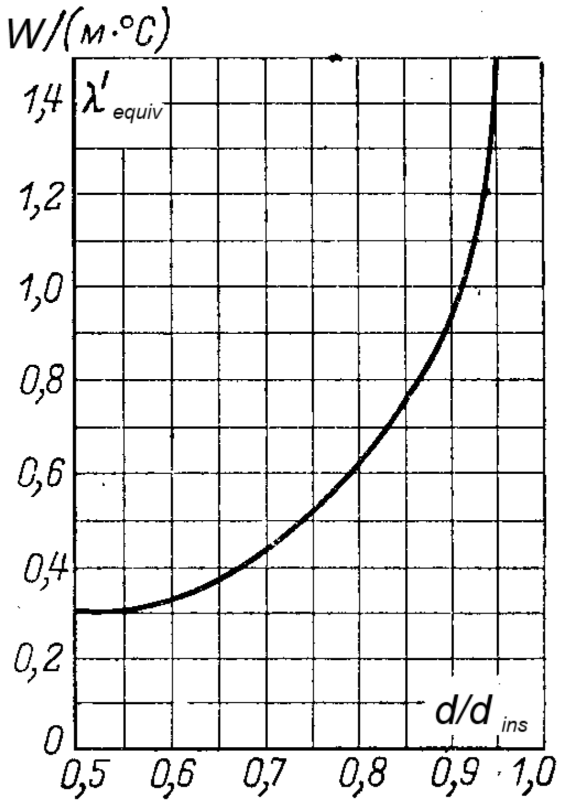


Figure 9.4 Coefficient of heat conduction of coils internal insulation for fed-in windings wound of enamel-covered wire

Temperature rise of external surface of the winding end connections above temperature of the air inside the machine in °C:

$$\Delta\vartheta_{ec,surf1} = K\frac{P'_{w1,ec}}{2\pi D l_{oh1}\alpha_1} \tag{9.9}$$

wherel_{oh1} = the stator winding coils overhang in m (Fig. 4.2). For fed-in windings it is found as

$$l_{oh1} = k_{oh}b_{coil} + B, \tag{9.10}$$

b_{coil} = the average coil width in m found by (4.5), B = the length of the straight coil part overhang in m measured from the core butt end, it is found as indicated in subdivision 4.1.1, k_{oh} = a coefficient which values are given in Table 4.2.

For a stator and rotor coils wound of the wire of rectangular cross-section

$$l_{oh1(2)} = k_{oh}b_{coil} + B + 0.5h_{sl} \tag{9.11}$$

where

$$k_{oh} = \frac{1}{2} k_{ec} m, \qquad (9.12)$$

k_{ec}, m and B have been found in subdivision 4.1.1.

For bar wave windings of wound rotors

$$l_{oh2} = k_{oh} b_{coil} + B_b \qquad (9.13)$$

where k_{oh} is calculated by (9.12), k_{ec}, m, b_{coil} and B_b have been found in subdivision 4.1.1.

Temperature rise of the stator winding above temperature of the air inside the machine in °C:

$$\Delta\vartheta_1' = \frac{(\Delta\vartheta_{surf1} + \Delta\vartheta_{sl\,ins,1}) 2 l_1 + (\Delta\vartheta_{ec\,ins,1} + \Delta\vartheta_{ec,surf1}) 2 l_{ec1}}{l_{av1}} \qquad (9.14)$$

where l_1 have been found in subdivision 1.2.7 and l_{ec1}, l_{av1}– in subdivision 4.1.1.

Temperature rise of air inside the machine above the ambient temperature in °C:

$$\Delta\vartheta_{air} = \frac{\Sigma P'_{air}}{S_h \alpha_b} \qquad (9.15)$$

where $\Sigma P'_{air}$ = the total loss dissipated to the air inside the motor, in W; α_b = the coefficient of air heating in $\mathrm{W/(m^2 \cdot {}^\circ C)}$, its values are given in Fig. 9.1 – 9.3; S_h = the equivalent motor housing cooling surface, in m^2.

The total loss dissipated to the air inside the motor is calculated as follows.

For motors with protection IP23

$$\Sigma P'_{air} = \Sigma P' - (1 - K)\left(P'_{w1,ec} + P_{c,main}\right) \qquad (9.16)$$

where

$$\Sigma P' = \Sigma P + (k_c - 1)(P_{w1} + P_{w2}), \qquad (9.17)$$

ΣP = the motor total power loss under rated operation conditions and temperature adopted for calculation.

For motors with protection IP44, power consumed by the external ventilator, mounted on the rotor shaft, and equal roughly 0.9 of total mechanical loss is not taken into account. Therefore

$$\Sigma P'_{air} = \Sigma P' - (1-K)\left(P'_{w1,ec} + P_{c,main}\right) - 0.9\ P_{mech} \tag{9.18}$$

where $\Sigma P'$ is calculated by (9.17).

The equivalent motor housing cooling surface in m^2 is found as:

- For motors with protection IP23:

$$S_h = \pi D_a (l_1 + 2l_{ec1}) \tag{9.19}$$

- For motors with protection IP44:

$$S_h = (\pi D_a + 8\Pi_{rib})(l_1 + 2l_{ec1}) \tag{9.20}$$

where Π_{rib} = the housing ribs cross-section perimeter which may be roughly found from Fig. 9.5.

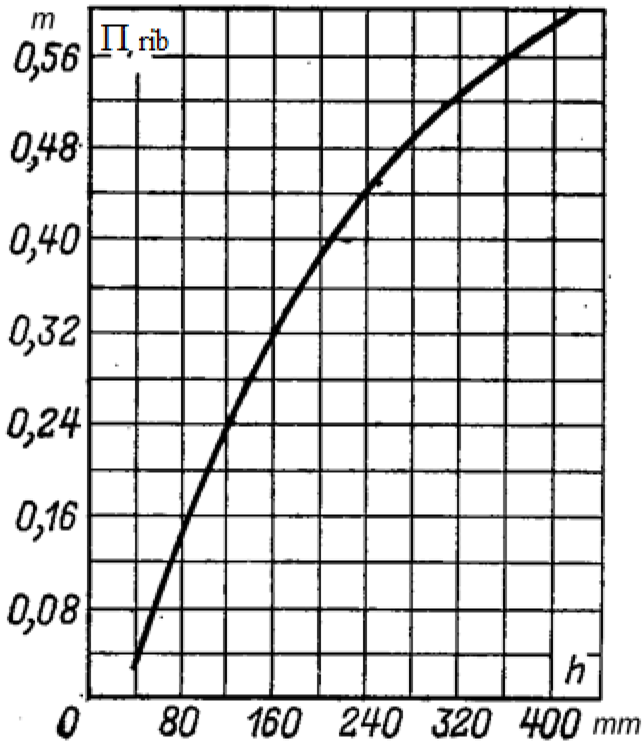


Figure 9.5 Average value of the cooling ribs cross-section perimeter for induction motors of 4A series

Temperature rise of the stator winding above the ambient temperature in °C:

$$\Delta\vartheta_1 = \Delta\vartheta_1' + \Delta\vartheta_{air}. \tag{9.21}$$

As the described calculation is simplified, the obtained value of $\Delta\vartheta_1$ is approximate. Therefore, it should be at least 10% less than allowable for the accepted temperature class of the machine insulation.

The wound–rotor winding temperature rise is calculated in the same order that for the stator winding.

The rotor core surface temperature rise above the air temperature inside the machine in °C equals

$$\Delta\vartheta_{surf2} = \frac{P_{w2,sl}'}{\pi D_2 l_2 \alpha_2} \tag{9.22}$$

where α_2 = coefficient of heat transfer from the wound rotor surface (Fig. 9.6 and 9.7); $P_{w2,sl}'$ = the resistance loss in the slot part of the rotor winding equal

$$P_{w2,sl}' = k_c P_{w2} \frac{2l_{sl2}}{l_{av2}}. \tag{9.23}$$

Temperature drop in insulation of the slot parts of the rotor winding coils in °C:

$$\Delta\vartheta_{sl\,ins,2} = \frac{P_{w2,sl}'}{z_2 \Pi_{sl2} l_2 \lambda_{eqv}} \tag{9.24}$$

where Π_{sl2} = the calculated perimeter of the rotor slot cross-section which is found for slots with parallel sides by expression:

$$\Pi_{sl2} = 2(h_{sl2} + b_{sl2}). \tag{9.25}$$

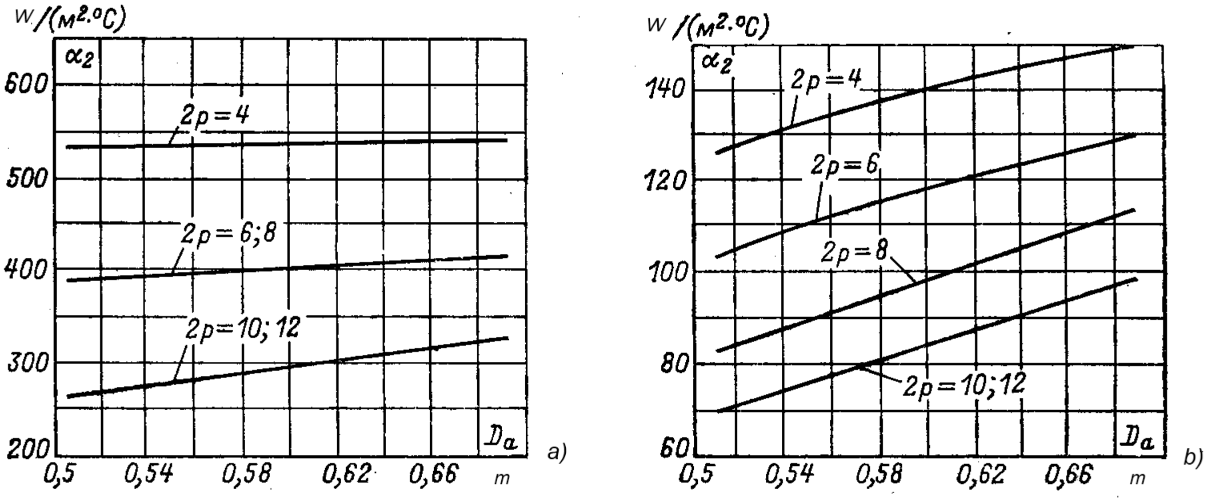


Figure 9.6 Average values of coefficient of heat transfer from the wound rotor surface at voltage of 680 V and less: a – for blown through rotors, degree of protection IP44; b - for motors with degree of protection IP23

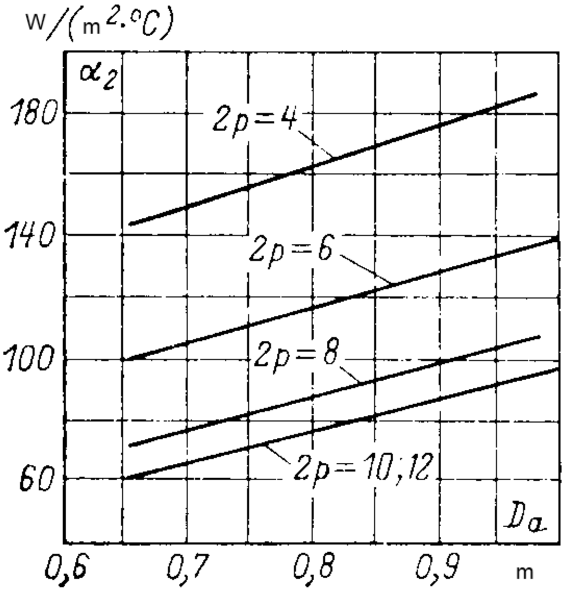


Figure 9.7 Average values of heat transfer coefficient from the wound rotors surface for induction motors with degree of protection IP23 and voltage 6000 V

Temperature rise of external surface of the rotor winding end connections above temperature of the air inside the machine in °C:

$$\Delta\vartheta_{ec,surf2} = \frac{P'_{w2,ec}}{2\pi D_2 l_{oh2} \alpha_2} \tag{9.26}$$

where $P'_{w2,ec}$ = the loss in end connections of the rotor winding coils in W:

$$P'_{w2,ec} = k_c P_{w2} \frac{2l_{ec2}}{l_{av2}}. \quad (9.27)$$

Temperature drop by thickness of the coil end connections insulation in °C is found by the expression:

$$\Delta\vartheta_{ec\,ins,2} = \frac{P'_{w2,ec}}{2z_2 \Pi_{ec2} lec_2 \lambda_{eqv}} \quad (9.28)$$

where Π_{ec2} = the perimeter of conditional cooling surface of one coil end connections that is assumed equal $\Pi_{ec2} \cong \Pi_{sl2}$;
$b_{ins\,ec2}$ = unilateral thickness of the coil end connections insulation (see tables of Appendix 11 in the book «Проектирование электрических машин»/ Д.В.Цыпленков, Ю.В. Куваев, А.Б. Иванов, И.А. Кириллов; Подред. Ф.П. Шкрабца – Д.: Национальный горный университет, 2008).

Average temperature rise of the rotor winding above temperature of the air inside the machine in °C:

$$\Delta\vartheta'_2 = \frac{(\Delta\vartheta_{surf2} + \Delta\vartheta_{sl\,ins,2})2l_2 + (\Delta\vartheta_{ec\,ins,2} + \Delta\vartheta_{ec,surf2})2l_{ec2}}{l_{av1}} \quad (9.29)$$

where l_2 have been found in subdivision 1.2.7 and l_{ec2}, l_{av2} – in subdivision 4.1.1.

Temperature rise of the rotor winding above the ambient temperature in °C:

$$\Delta\vartheta_2 = \Delta\vartheta'_2 + \Delta\vartheta_{air}. \quad (9.30)$$

The obtained value of $\Delta\vartheta_2$ is approximate. Therefore, it should be at least 10% less than allowable for the accepted temperature class of the machine insulation.

9.2. Motor ventilation calculation

Effectiveness of the motor ventilation is assessed by comparison of **the air consumption needed** for the machine cooling, and **the air consumption which may**

be provided at given the motor design and dimensions. Below the calculation method applicable for motors, designed based on induction motors of 4A series construction, is described.

9.2.1. Calculation of the needed air consumption

The air consumption Q_{air} needed for the designed motor cooling is calculated with account its degree of protection.

For motors with protection IP23 its value in m^3/s is found as:

$$Q_{air} = \frac{\Sigma P'_{air}}{1100\ \Delta\vartheta'_{air}} \tag{9.31}$$

where$\Sigma P'_{air}$ in W is determined by (9.16); $\Delta\vartheta'_{air}$ = the temperature rise of the output air above the input air temperature in ºC, $\Delta\vartheta'_{air} \cong \Delta\vartheta_{air}$.

For motors with protection IP44 the needed air consumption in m^3/s is found as:

$$Q_{air} = \frac{k_m \Sigma P'_{air}}{1100\ \Delta\vartheta_{air}} \tag{9.32}$$

where $\Sigma P'_{air}$ is determined by (9.18); k_m = the coefficient taking into account changing of cooling conditions along the motor housing. It equals

$$k_m = m\sqrt{\frac{n}{100} D_a} \tag{9.33}$$

where $m = 2.6$ for motors with $2p = 2$ at $h \leq 132$ mm and $m = 3.3$ at $h \geq 160$ mm; $m = 1.8$ for motors with $2p \geq 4$ at $h \leq 132$ mm and $m = 2.5$ at $h \geq 160$ mm. The motor rotational frequency n is substituted in rpm, D_a – in m.

9.2.2. Calculation of the provided air consumption

The air consumption provided by the motor ventilation system Q'_{air} is also calculated differently for motors with different degree of protection.

For motors with protection IP23 its value in m^3/s is found as:

$$Q'_{air} = m(n_{rd} b_{rd} + 0.1) \frac{n}{100} D_a^2 \tag{9.34}$$

where n_{rd} and b_{rd} are the number and width of radial air ducts, b_{rd} in m; n – in rpm; $m = 2.6$ for motors with $2p = 2$ and $m = 3.15$ for motors with $2p \geq 4$; D_a – in m.

For motors with protection IP44 the air consumption provided by the motor ventilation system in m^3/s is found as:

$$Q'_{air} = 0.6 D_a^3 \frac{n}{100}. \tag{9.35}$$

9.2.3. Comparison of needed and provided by the motor ventilation system air consumption

Effectiveness of the motor ventilation is satisfactory if

$$Q'_{air} \geq Q_{air}. \tag{9.36}$$

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APPENDICES

Appendix A

Sample design of the title page of the course project

MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE
DNIPRO UNIVERSITY OF TECHNOLOGY

Національний технічний університет
ДНІПРОВСЬКА ПОЛІТЕХНІКА
1899

<u>Electrical Engineering Department</u>

C O U R S E   P R O J E C T

from the discipline
"Electric machines"
on the topic: "Design of an asynchronous motor"

Performed by:
a student of the group __________ ______________ ______________________
(group) (signature) (surname and initials of the student)

Project Manager:

______________________ ______________________________________
(title, degree and position of the teacher) (signature) (surname and initials of the teacher)

Dnipro
(year of execution)

Appendix B

A sample assignment letter for a course project

TASK # ____
ON THE CALCULATION AND DESIGN OF AN ASYNCHRONOUS MOTOR

Issued to student(s) __________________ groups __________________

Perform calculation and structural development of an asynchronous motor with a **phase** rotor with the following parameters:

1	Nominal capacity		________	kW
2	Nominal voltage		________	V
3	Nominal frequency		50	Hz
4	Number of poles		________	
5	Constructive performance	IM	________	
6	Method of protection	IP	________	
7	Mode of operation	S1	________	

The graphic part of the project consists of **two** sheets of A1 format:

– **sheet 1** – simplified and expanded diagrams of the stator and rotor windings of the designed machine, their winding data, drawings of the stator and rotor grooves filled with windings of the required dimensions, a table of filling the stator and rotor grooves in the form:

Position in the figure	Purpose of the insulation element	Characteristics of the material		
		Name	Brand	Thickness

– **sheet 2 –** electrical diagram for connecting the windings to the terminal box and connecting to the motor network, its operating and starting characteristics, passport data of the designed asynchronous motor, segment of the magnetic system of the designed motor (at least 1⁄8);

The graphic part and the calculation and explanatory note must comply with the current standards.

The task for the course project has been issued « » __________ 202 p.

Project Manager:

_________________________ _____________ ______________________
(title, degree and position of the teacher) (signature) (surname and initials of the teacher)

TASK # ____
ON THE CALCULATION AND DESIGN OF AN ASYNCHRONOUS MOTOR

Issued to student(s) __________________ groups __________________

Perform calculation and structural development of an asynchronous motor with a **phase** rotor with the following parameters:

1	Nominal capacity			kW
2	Nominal voltage			V
3	Nominal frequency		50	Hz
4	Number of poles			
5	Constructive performance	IM		
6	Method of protection	IP		
7	Mode of operation	S1		

The graphic part of the project consists of **two** sheets of A1 format:

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Position in the figure	Purpose of the insulation element	Characteristics of the material		
		Name	Brand	Thickness

– **sheet 2 –** electrical diagram for connecting the windings to the terminal box and connecting to the motor network, its operating and starting characteristics, passport data of the designed asynchronous motor, segment of the magnetic system of the designed motor (at least 1⁄8);

The graphic part and the calculation and explanatory note must comply with the current standards.

The task for the course project has been issued «   » __________ 202   p.

Project Manager:

______________________________ (title, degree and position of the teacher)
______________ (signature)
______________________________ (surname and initials of the teacher)

TASK # ____
ON THE CALCULATION AND DESIGN OF AN ASYNCHRONOUS MOTOR

Issued to student(s) __________________ groups __________________

Perform calculation and structural development of an asynchronous motor with a **short-circuited** rotor with the following parameters:

1	Nominal capacity			kW
2	Nominal voltage			V
3	Nominal frequency		50	Hz
4	Number of poles			
5	Constructive performance	IM		
6	Method of protection	IP		
7	Mode of operation	S1		

The graphic part of the project consists of **two** sheets of A1 format:

– **sheet 1** – a simplified and expanded diagram of the stator winding of the designed machine, its winding data, drawings of the stator and rotor grooves filled with windings of the required dimensions, a table of filling the stator groove in the form:

Position in the figure	Purpose of the insulation element	Characteristics of the material		
		Name	Brand	Thickness

– **sheet 2 –** electrical diagram for connecting the windings to the terminal box and connecting to the motor network, its operating and starting characteristics, passport data of the designed asynchronous motor, segment of the magnetic system of the designed motor (at least 1⁄8);

The graphic part and the calculation and explanatory note must comply with the current standards.

The task for the course project has been issued « » __________ 202 p.

Project Manager:

______________________________ (title, degree and position of the teacher) ______________ (signature) ______________________________ (surname and initials of the teacher)

Appendix C

A sample of abstract design

ABSTRACT

Project explanatory note: 48 pages, 8 figures, 11 tables, 25 literary sources.

Keywords:

The course project considers the issues of …….

When performing calculations, it is determined....

Appendix D

CALENDAR PLAN

#	Назва етапів проєкту	Термін виконання етапів проєкту	Примітка

Student of the group ___________ ________________ ________________________
(group) (signature) (surname and initials of the student)

Project Manager:

__________________________ ____
(title, degree and position of the teacher) (signature) (surname and initials of the teacher)

The task for the course project has been issued « » __________ 202 p.

Compilers:
Oleksiy Borisovych Ivanov
Dmytro Volodymyrovych Tsyplenkov

ELECTRIC MACHINES.
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