Ministry of Education and Science of Ukraine

ZAPORIZHZHA NATIONAL TECHNICAL UNIVERSITY

ELECTROMAGNETS CALCULATIONS

Methodical Instructions

to Perform the course work:
"FUNDAMENTALS OF ELECTRICAL APPARATUSES THEORY"

for the students studying on the direction
141 – Electromechanics

2017

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INTRODUCTION

The magnetic circuit is the heart of electromagnetic systems which are most widely applied in electrical apparatuses and some other devices. In electrical apparatuses the electromagnetic systems have very different applications, such as following:

- **the electromagnetic actuators** are electromagnetic mechanisms which perform useful work to drive movable parts of the apparatus (for example, close and open operations of switches contacts);
- t**he elements to perform measurement, control and regulation of electric circuit parameters:** measuring relays, releases of circuit-breakers, instrument transformers, chokes, electrical reactors, magnetic amplifiers etc.;
- **the elements to perform measurement and control of non-electrical parameters:** inductive and transformer transducers of travels, velocities, accelerations and other parameters;
- **the elements to perform switching mechanical load:** to transmit torque, to force brake torque (electromagnetic clutches, brake electromagnets etc.).

Taking into account the mass production of electrical apparatuses as well as strong competition in the global and internal markets of electrics, permanent enhancement of its technological level is vital important. That is reduction of the mass-and-dimensional indexes, power consumption, improvement of speed of response, decrease in technological expenditures etc.

Thus, during the studying electromagnetic systems, the challenge is to study qualitatively the physical phenomena occurring in magnetic circuits. In particular, in the computational and graphical task the problem is to gain initial skills of their design: to have learned to determine the basic parameters of magnetic circuits and electromagnets as a whole by means of analysis. It should improve studying special subjects: simulation in electrical apparatuses, electrical apparatuses of control, electrical apparatuses of a high voltage, electrical apparatuses automated design, terms and final educational designing and other.

1. GENERAL DIRECTIONS

For the course work the student is individually tasked by the adviser. The assignment is executed in a special form confirmed by the university educational department, and is signed by the adviser. The subject of the work can be either typical (for example "DC electromagnet calculations" or "AC electromagnet calculations") or non-typical under the mutual agreement between the student and the adviser. The task variants for the typical electromagnet calculations presented for the work are placed in the appendix.

The explanatory paper on the work must contain:

a) title page;
b) table of content;
c) body of the explanatory paper containing some sections, for example:
    1) Electromagnet winding MMF calculations;
    2) Electromagnet winding calculations;
    3) Electromagnetic forces calculations;
    4) Electromagnet actuation time calculations;
    5) Conclusions;
    6) The reference list.

The explanatory paper must contain all necessary schemes, drawings, formulas with defined values which contain; explanations in respect to the calculations performed as well as deductions about their results. There is no need to repeat uniform calculations, their results is to be presented as the tables. The explanatory paper body should not exceed 30-35 pages of the manuscript text. The explanatory paper will be formed in compliance with СТП15-96.

2. DIRECTIONS FOR THE CALCULATIONS OF DC ELECTROMAGNETS

The calculations of dc electromagnet are to be performed in the following order:

1. In compliance with predetermined dimensions and design of magnetic circuit for the initial value of the operating air-gap $\delta_{п}$ and induction in it (see table A.1) the magnetic motive force (MMF) of the winding is to be calculated. In other words, it is necessary to solve the direct task of the magnet circuit calculations. Proceed as follows:

- to set up an equivalent circuit of the electromagnet magnetic circuit without taking into account reluctances of the iron subcircuits and the adviser of the WORK should be consulted;
- to calculate permeances of the operating air-gap Λ_δ, idle air-gaps $\Lambda_{нi}$, specific leakage permeance λ_s as well as total permeance of air-gaps $\Lambda_{\delta\Sigma}$;
- to calculate fringe ratio for the operating air-gap $\sigma_{вп}$ and magnetic flux through it

$$\Phi_\delta = B_\delta S_{т} \sigma_{вп} ,$$

where $S_{т}$ is the pole face area;

- to determine the derivative of operating air-gap permeance $d\Lambda_\delta/d\delta$ and electromagnetic force;
- to divide the magnetic circuit along the vertical extent of the core to some subcircuits (no less than three) and to calculate leakage factors as well as magnet fluxes for all magnetic subcircuits;
- to determine the magnet inductions for all iron subcircuits

$$B_i = \frac{\Phi_i}{S_i} ,$$

where S_i is the cross-sectional area of the respective iron subcircuit;

- from the magnetization curve to determine the magnetic intensity H_i and magnetic potential drop $H_i l_i$ across each iron subcircuit;
- the required value of MMF of the electromagnet winding is determined as the total magnetic potential drops across iron subcircuits as well as both operating and idle air-gaps

$$(Iw)_{тр} = \sum\left(\frac{\Phi_{\delta i}}{\Lambda_{\delta i}}\right) + \sum(H_i l_i) \qquad (2.1)$$

Considerable numeral material of the calculations is to be presented as the tables for the sake of convenience.

2. The parameters and geometrical dimensions of the magnetizing winding are to be calculated. Proceed as follows:

- to determine finally MMF of the winding taking into consideration safety factor $(\kappa_з = 1{,}3 - 1{,}5)$

$$(Iw) = \kappa_з \cdot (Iw)_{тр};$$

- to determine the required cross-sectional area of the winding wire and its diameter;
- from the wire gauge [5] select the type and diameter of the wire without insulation and determine the précised wire cross-sectional area;
- to calculate turns number of the winding; it may be performed basing upon permissible current density $j_{доп}$, which for continuous duty and given cooling conditions may be accepted in the range 2–4 А/мм^2;

$$w = \frac{U}{j_{доп}\rho_0 (1 + \alpha\vartheta_{доп}) l_{в.сер}},$$

where $l_{в.ср}$ is the average length of the winding turn;

$\vartheta_{доп}$ is permissible temperature of the winding that in this case may be accepted 105ºC;

- to determine width of the winding assuming that its height equal to height of the magnetic circuit "window" (see tab. A.1);
- to determine précised values of pure resistance and MMF of the winding.

3. Taking into account the winding MMF, the magnetic flux through the operating air-gap for its end value $\delta_к$ is to be determined. In other words, it is necessary to solve reversal task of the magnet circuit calculations. Then electromagnetic force for this value of operating air-gap is to be calculated. Proceed as follows:

- to calculate the permeances of operating and idle air-gaps for the armature end position as well as total permeance of the air-gaps in accordance with the structure of the equivalent circuit;
- to calculate initial approximation of the magnetic flux through the operating air-gap with not taking into account magnetic potential drop across iron subcircuits and calculate the magnetic induction in the core; if the induction derived considerably exceeds saturation induction, then the

induction is to be accepted equal the saturation one and the initial approximation of the magnetic flux is to be accepted for this value of the induction;

- to determine first and furthers approximations of magnetic flux through the operating air-gap taking into account magnetic potential drop across iron subcircuits; in other words, the nonlinear equation (2.1) is to be solved by simple iteration method; these calculations are to be performed with available computer software (MathCad, MathLab etc.); outcome of the calculations may be accepted as ultimate, when relative difference between prior and new approximations of the magnetic flux does not exceed 1%;
- basing upon the ultimate magnitude of the magnetic flux through the operating air-gap, calculate the electromagnetic force.

4. Basing upon the determined parameters of both the magnetic circuit and the winding, an actuation (response) time of the electromagnet is to be determined. Proceed as follows:

- to calculate inductance of the magnetizing winding for the initial value of the operating air-gap

$$L = w^2 \Lambda_{\delta\Sigma} ;$$

- to determine the pick-up time of an electromagnet accepting safety factor in the range 1,3–1,5;
- to determine mass of the movable parts and movement time of the electromagnet accepting that the average magnitude of counteracting force comprises 70% from the average value of electromagnetic force;
- to determine the actuation (response) time of the electromagnet.

3. DIRECTIONS FOR CALCULATIONS OF AC ELECTROMAGNETS

The calculations of ac electromagnet are to be performed in the following order:

1. In compliance with predetermined magnetic circuit dimensions for the end value of operating air-gap $\delta_к$ (in other words, for the tractive armature position, see table A.2) the winding MMF as well as direct and alternating components of electromagnet force, its minimal value and pulsation are to be determined. Proceed as follows:

- to set up equivalent magnet circuit of the electromagnet taking into account reluctance theirs ferromagnetic elements (leakage flux is not taken into account); the equivalent magnetic circuit is to be agreed with the adviser;
- to calculate reluctances of operating air-gap at $\delta_1 = \delta_2 = \delta_к$: for the pole part non-enclosed with short-circuited turn $R_{\delta 1}$; for the pole part enclosed with short-circuited turn $R_{\delta 2}$; reactive reluctance resulted from presence of short-circuited turn $X_{\delta 2}$;
- to determine reluctance of idle air-gaps $R_{\delta 0i}$ accepting that $\delta_{0i} = \delta_к$;
- in compliance with predetermined value of induction in the magnetic circuit (see tab. A.2) specific reluctances components ρ_R and ρ_X as well as reluctances of the iron subcircuits are to be determined;
- according to the equivalent circuit the total reluctance of magnetic circuit $Z_{м\Sigma}$ is to be determined;
- to determine amplitude value of the magnetic flux through the magnetic circuit

$$\Phi_m = B_m S_{ст} \kappa_з ,$$

where $\kappa_з$ is the space factor of magnetic circuit iron, which can be accepted in the range 0,85–0,95;

- to determine amplitude value of the winding MMF

$$F_m = \Phi_m Z_{м\Sigma} ;$$

- to determine amplitude values of the magnetic fluxes through both parts of the operating air-gap: non-enclosed with short-circuited turn Φ_{1m}; enclosed with short-circuited turn Φ_{2m}; these calculations are to be performed with taking into consideration saturation of the pole part non-enclosed with short-circuited turn [13];

- to determine direct and alternating components as well as minimal value and pulsation of electromagnetic force.

2. In compliance with resulting value of the winding MMF as well as predetermined supply voltage the basic parameters and geometrical dimensions of the electromagnet magnetizing winding are to be determined. Proceed as follows:

- to determine turns number of the winding

$$w = \frac{U}{4{,}44 \cdot f \cdot \Phi_{\mathrm{m}}};$$

- to determine initial estimate (without taking into account pure resistance) of the current through the winding

$$I = \frac{F_{\mathrm{m}}}{\sqrt{2} \cdot w};$$

- to calculate the required cross-sectional area and diameter of the winding wire basing upon permissible current density $j_{\text{доп}}$, which for continuous duty and given cooling conditions may be accepted in the range 2–4 А/мм^2;
- from the wire gauge [5] select the type and diameter of the wire without insulation and determine the précised wire cross-sectional area;
- to determine width of the winding assuming that its height equal to height of the magnetic circuit "window" (see table A.2);
- to calculate active (taking into account active losses in the magnetic circuit) and reactive impedance of the winding as well as précised value of the current through the winding for end value of a operating air-gap.

3. For initial value of the operating air-gap $\delta_{\text{п}}$ direct component of electromagnetic force exerting on the electromagnet armature is to be determined. Proceed as follows:

- to calculate a permeance of the operating air-gap (without taking into account of a permanence resulted from presence of short-circuited turn) as well as its derivative $d\Lambda_{\delta}/d\delta$;
- to calculate permeances of idle air-gaps δ_{0i}, and also specific leakage permeance λ_{s};
- to calculate the total permeance of the air-gaps as well as the average value of the leakage factor

$$\sigma_{cp} = 1 + \frac{\lambda_s \cdot l}{3 \cdot \Lambda_{\delta\Sigma}},$$

where l is height of the magnetic circuit "window" (see tab. A.2);

- to calculate average value of the magnetic flux amplitude along height of the core

$$\Phi_{m(c(c} = \frac{U}{4{,}44 \cdot f \cdot w};$$

- using average value of the leakage factor to determine magnetic flux through the operating air gap;
- to calculate the electromagnetic force.

REFERENCES

1. Электрические и электронные аппараты: Учебник для вузов/ Под ред. Ю. К. Розанова. – 2-е изд., испр. и доп. – М.: Информэлектро, 2001. – 420 с.

2. Таев И.С. Электрические аппараты: Общая теория. – М.: Энергия, 1977. – 272 с.

3. Основы теории электрических аппаратов: Учеб. для вузов/ Под ред. И.С. Таева. – М.: Высшая школа, 1987.– 496 с.

4. Новиков Ю.Н. Теория и расчет электрических аппаратов. – Л.: Энергия, 1970. – 328 с.

5. Теория электрических аппаратов/ Г.Н Александров, В.В. Борисов, В.Л. Иванов и др.; п/ред. проф. Г.Н. Александрова. – М.: Высшая школа, 1985. – 354 с.

6. Буткевич Г.В., Дегтярь В.Г., Сливинская А.Г. Задачник по электрическим аппаратам. – М.: Высшая школа, 1987. – 232 с.

7. Буль Б.К., Буткевич Г.В., Годжелло А.Г. и др. Основы теории электрических аппаратов/ Под ред. Г.В. Буткевича. – М.: Высшая школа, 1970. – 600 с.

8. Гордон А.В., Сливинская А.Г. Электромагниты постоянного тока. – М.-Л.: ГЭИ, 1969. – 370 с.

9. Гордон А.В., Сливинская А.Г. Электромагниты переменного тока. – М.: Энергия, 1968. – 138 с.

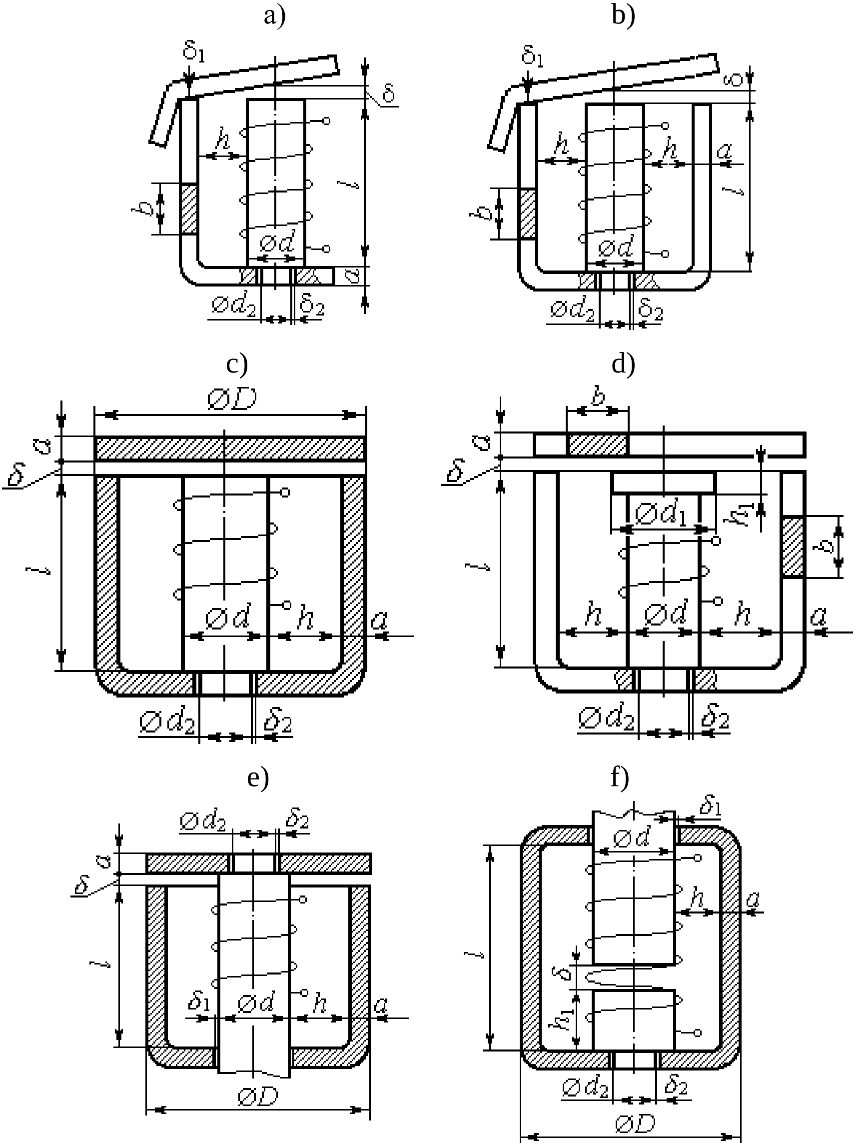
10. Любчик М.А. Оптимальное проектирование силовых электромагнитных механизмов. – М.: Энергия, 1974. – 392 с.

11. Никитенко А.Г., Гринченков В.П., Иванченко А.Н. Программирование и применение ЭВМ в расчетах электрических аппаратов. – М.: Высшая школа, 1990. – 231 с.

12. Никитенко А.Г. Оптимальное проектирование электромагнитных механизмов. – М: Энергия, 1974. – 136 с.

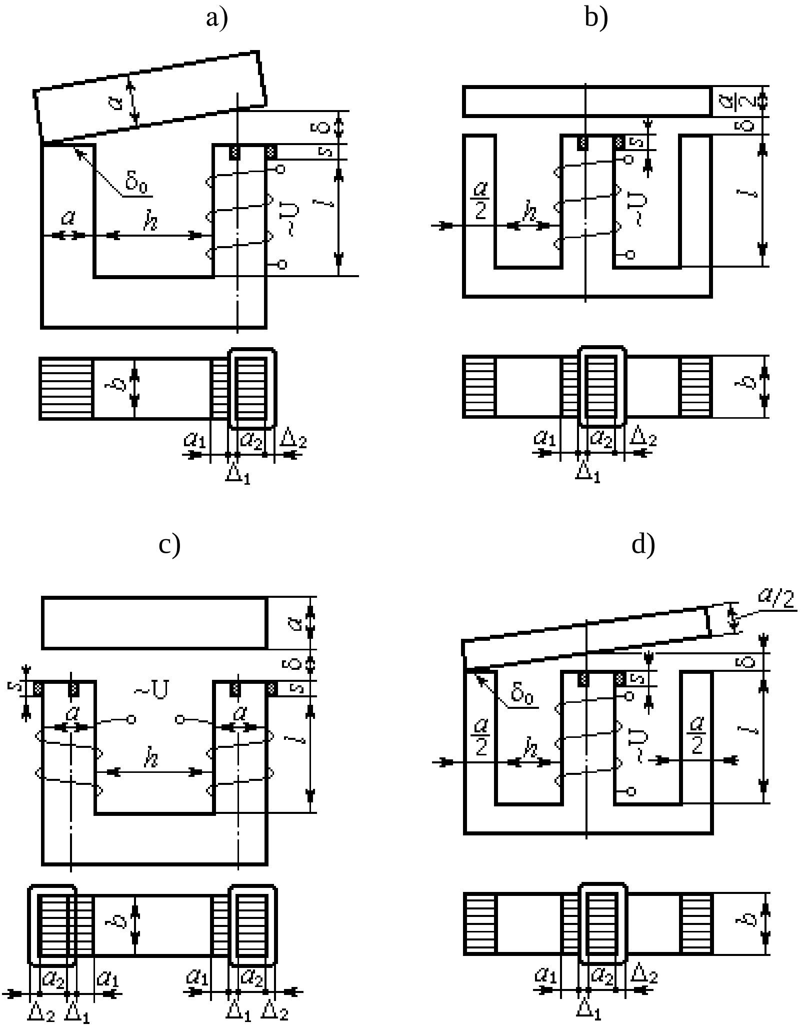
Appendix A

Initial data for the electromagnet calculations



a) b) c) d) e) f)

Drawing A.1 – DC electromagnet designs



a) b) c) d)

Drawing A.2 – AC electromagnet designs

Table A.1 – Initial data for dc electromagnet calculations

№№ of variants	Magnetic circuit design	Geometrical dimensions, mm										Operating air-gap, mm		Induction $(\delta=\delta_{\text{п}})$, T	Magnetic circuit material	Winding voltage supply, V
		a	b	l	h	h_1	d	d_1	d_2	δ_1	δ_2	$\delta_{\text{п}}$	$\delta_{\text{к}}$	$\boldsymbol{B}$		
1	Drawing A.1a	2	15	18	10		5		3		0,05	2	0,15	0,1	Structural steel of quality 10	24
2		3	20	30	15		8		5		0,1	3	0,1	0,15		36
3		4	25	40	18		10		8		0,1	4	0,15	0,05		48
4		5	30	50	20		14		10		0,08	5	0,22	0,12		110
5		6	35	60	25		15		12		0,12	6	0,12	0,08		220
6		8	4050	75	30		18		15		0,06	7	0,18	0,2		110
7		10	60	90	35		22		18		0,1	8	0,15	0,15		48
8		10	70	100	40		25		20		0,15	10	0,2	0,1		36
9		8		80	40		24		20		0,08	8	0,15	0,06		24
10	Drawing A.1b	2	15	36	20		5		3		0,05	2	0,15	0,1	Structural steel of quality 20	24
11		3	20	60	30		8		5		0,1	3	0,1	0,15		36
12		4	25	80	36		10		8		0,1	4	0,15	0,05		48
13		5	30	100	40		14		10		0,08	5	0,22	0,12		110
14		6	35	120	50		15		12		0,12	6	0,12	0,08		220
15		8	40	150	60		18		15		0,06	7	0,18	0,2		110
16		10	50	180	70		22		18		0,1	8	0,15	0,15		48
17		8	70	190	80		25		20		0,15	10	0,2	0,1		36
18		8	80	200	90		24		20		0,08	8	0,15	0,06		24
19	Drawing A.1c	2		36	20		5		3		0,05	2	0,15	0,1	Steel of quality 50HXC	24
20		3		60	30		8		5		0,08	3	0,1	0,15		36
21		4		80	36		10		8		0,1	4	0,15	0,05		48
22		5		100	40		14		10		0,12	5	0,22	0,12		110
23		6		120	50		15		12		0,18	6	0,12	0,08		220
24		8		150	60		18		15		0,2	7	0,18	0,2		110
25		8		200	70		22		18		0,22	8	0,15	0,15		48
26		10		250	80		25		20		0,25	10	0,2	0,1		36
27		10		300	90		24		20		0,28	12	0,15	0,06		24

Continuation of table A.1

№№ of variants	Magnetic circuit design	Geometrical dimensions, mm										Operating air-gap, mm		Induction (δ=$\delta_п$), T	Magnetic circuit material	Winding voltage supply, V
		a	b	l	h	h_1	d	d_1	d_2	δ_1	δ_2	$\delta_п$	$\delta_к$	$\boldsymbol{B}$		
28	Drawing A.1d	2	15	36	20	5	5	10	3		0,05	2	0,05	0,1	Steel of quality 49КФ	24
29		3	20	60	30	6	8	15	5		0,08	3	0,08	0,15		36
30		4	25	80	36	7	10	20	8		0,1	4	0,1	0,05		48
31		5	30	100	40	8	14	25	10		0,1	5	0,12	0,12		110
32		6	40	120	50	9	15	30	12		0,12	6	0,15	0,08		220
33		8	50	150	60	10	18	35	15		0,16	7	0,18	0,2		110
34		10	60	200	70	10	22	40	18		0,18	8	0,2	0,15		48
35		11	80	250	80	12	25	45	20		0,2	10	0,22	0,1		36
36		12	90	350	90	12	28	50	20		0,25	12	0,25	0,06		24
37	Drawing A.1e	2		36	10		10		3	0,05		2	0,15	0,1	Structural steel of quality 20	24
38		3		60	15		15		5	0,1		3	0,1	0,15		36
39		4		80	18		20		8	0,12		4	0,15	0,05		48
40		5		100	20		25		10	0,15		5	0,22	0,12		110
41		6		120	25		30		12	0,18		6	0,12	0,08		220
42		8		150	30		35		15	0,2		7	0,18	0,2		110
43		10		180	40		40		18	0,22		8	0,15	0,15		48
44		8		190	50		45		20	0,25		10	0,2	0,1		36
45		8		200	60		50		22	0,28		12	0,25	0,06		24
46	Drawing A.1f	2		36	20		5		2	0,05		2	0,15	0,1	Structural steel of quality 10	24
47		3		60	30		8		3	0,05		3	0,1	0,15		36
48		4		80	36		10		4	0,05		4	0,15	0,05		48
49		5		100	40		14		4	0,1		5	0,22	0,12		110
50		6		120	50		15		5	0,1		6	0,12	0,08		220
51		8		150	60		18		5	0,1		7	0,18	0,2		110
52		8		200	70		22		5	0,15		8	0,15	0,15		48
53		10		250	80		25		6	0,15		10	0,2	0,1		36
54		10		300	90		24		6	0,15		12	0,15	0,06		24

Table A.2 – Initial data for ac electromagnet calculations

№№ of variants	Magnetic circuit design	Geometrical dimensions, mm									Operating air-gap, mm		Induction (δ=δ$_к$),T	Magnetic circuit material	Winding voltage supply, V
		a	b	l	h	a_1	a_2	Δ_1	Δ_2	s	$\delta_п$	$\delta_к$	B_m		
55	Drawing A.2a	14	22	55	22	4	8	2	3	3	5	0,05	0,8	Electrical-sheet steel of quality 1212	127
56		11	18	50	20	3	6	2	2	2	4		0,85		220
57		15	25	65	25	4	8	3	4	4	6		0,75		380
58		15	25	70	25	4	8	3	4	4	6		0,9		660
59		16	28	75	25	5	9	2	3	3	7		0,9		220
60		16	30	80	30	4	9	3	4	4	7		1,0		127
61		18	32	90	30	5	10	3	4	4	8		1,0		380
62		18	35	95	32	6	10	2	3	3	8		1,1		660
63		20	40	100	35	6	12	2	3	3	8		1,2		220
64		11	20	70	22	3	6	2	3	3	2		0,8		127
65		13	25	65	20	3	7	3	2	2	3		0,85		220
66		14	28	75	25	4	8	2	4	4	4		0,75		380
67		17	30	90	30	5	9	3	3	4	5		0,8		660
68	Drawing A.2b	16	35	80	25	5	9	2	3	3	5	0,05	1,0	Electrical-sheet steel of quality 1511	127
69		18	35	80	25	5	10	3	4	4	6		1,0		220
70		19	40	90	30	5	11	3	4	4	7		1,1		380
71		20	40	95	30	6	12	2	4	4	8		1,2		660
72		20	40	100	32	6	12	2	3	3	10		0,8		220
73		22	45	100	35	6	1311	3	3	3	122		0,85		127
74		18	20	36	20	5	15	2	3	3	3		0,75		220
75		25	30	60	30	8	19	2	2	2	4		0,9		380
76		32	35	80	36	10	28	3	4	4	5		0,9		660
77		45	50	100	40	14	30	3	4	4	6		1,0		220
79		48	50	120	50	16	35	2	3	3	7		1,0		127
80		55	60	150	60	18	40	3	4	4	8		1,1		380
81		65	70	200	70	22		3	4	4			1,2		660

Continuation of table A.2

№№ of variants	Magnetic circuit design	Geometrical dimensions, mm									Operating air-gap, mm		Induction ($\delta=\delta_к$),T	Magnetic circuit material	Winding voltage supply, V
		a	b	l	h	a_1	a_2	Δ_1	Δ_2	s	$\delta_п$	$\delta_к$	B_m		
82	Drawing A.2c	14	22	55	22	4	8	2	3	3	5	0,05	0,8	Electrical-sheet steel of quali-ty 1212	127
83		11	18	50	20	3	6	2	2	2	4		0,85		220
84		15	25	65	25	4	8	3	4	4	6		0,75		380
85		15	25	70	25	4	8	3	4	4	6		0,9		660
86		16	28	75	25	5	9	2	3	3	7		0,9		220
87		16	30	80	30	4	9	3	4	4	7		1,0		127
88		18	32	90	30	5	10	3	4	4	8		1,0		380
89		18	35	95	32	6	10	2	3	3	8		1,1		660
90		20	40	100	35	6	12	2	3	3	8		1,2		220
91		11	20	70	22	3	6	2	3	3	2		0,8		127
92		13	25	65	20	3	7	3	2	2	3		0,85		220
93		14	28	75	25	4	8	2	4	4	4		0,75		380
94		17	30	90	30	5	9	3	3	4	5		0,8		660
95	Drawing A.2d	16	35	80	25	5	9	2	3	3	5	0,05	1,0	Electrical-sheet steel of quali-ty 1511	127
96		18	35	80	25	5	10	3	4	4	6		1,0		220
97		19	40	90	30	5	11	3	4	4	7		1,1		380
98		20	40	95	30	6	12	2	4	4	8		1,2		660
99		20	40	100	32	6	12	2	3	3	10		0,8		220
100		22	45	100	35	6	131	3	3	3	122		0,85		127
101		18	20	36	20	5	1	2	3	3	3		0,75		220
102		25	30	60	30	8	15	2	2	2	4		0,9		380
103		32	35	80	36	10	19	3	4	4	5		0,9		660
104		45	50	100	40	14	28	3	4	4	6		1,0		220
105		48	50	120	50	16	30	2	3	3	7		1,0		127
106		55	60	150	60	18	35	3	4	4	8		1,1		380
107		65	70	200	70	22	40	3	4	4			1,2		660