Ministry of Education and Science of Ukraine
ZAPORIZHZHIA POLYTECHNIC NATIONAL UNIVERSITY

METHODICAL INSTRUCTION

to the computational and graphic task in the discipline:
"Fundamentals of the theory of electrical apparatus"

for students of all educational forms
of the first (bachelor) higher education level
of specialty:
141 – Electric power, electrical and electromechanical engineering
(educational program **"Electrical and electronic apparatus"**)

2021

Methodical instructions to the computational and graphic task in the discipline "Fundamentals of the theory of electrical apparatus" for students of all educational forms of the first (bachelor) higher education level of specialty 141 – Electric power, electrical and electromechanical engineering (educational program "Electrical and electronic apparatus)" / Compiled by O.V. Blyzniakov. – Zaporizhzhia: Zaporizhzhia Polytechnic NU, 2021. – 18 p.

Compiled by docent O. V. Blyzniakov.

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Approved at the meeting of the department
"Electric and Electronic Apparatuses".
Minutes No. 2 dated August 31, 2021

Recommended for publication by
scientific-and-methodical commission
of Electrical Engineering Department.
Minutes No. 2 of September 23, 2021

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INTRODUCTION

Students execute computational and graphic task (CGT) during the 5th semester. The main object of the CGT is electromagnetic systems of electrical apparatuses learned in corresponding section of the discipline. It should be noted that electromagnetic systems at present time have very extensive application in electric equipment and technologies. Electromagnetic systems are used in electrical devices:

- first and foremost, as an *electric drive*, that is, an electromagnetic mechanism executing useful work to travel the device movable parts; for example, close-open operations of switching devices contacts;
- as measuring components of electrical and non-electrical parameters;
- as components to switch mechanical load: to transmit torque, to generate braking torque in electromagnetic clutches and brake electromagnets, etc.
- as converting components, such as instrument transformers, chokes, electric reactors, magnetic amplifiers, etc. [1–4].

Taking into consideration that electrical apparatuses are mass products of the electrical industry, as well as the available fierce competition in the global and domestic markets of electrical equipment, permanent improve its technical level is basic challenge. In particular, concerning electromagnetic systems, there are the problems to improve their performances, as well as reduce mass and size indexes, power demand, technological costs for production, etc.

Thus, in studying the discipline the task is, first, to study qualitatively physical phenomena occurring in electromagnetic systems. In particular, the execution of the calculation and graphics task is aimed to derive the initial practical skills of electromagnetic system calculations, that is, to learn to determine, by computation way, the basic parameters of magnetic circuits and electromagnets in general. This, in turn, should contribute to a better mastery of the materials of professional disciplines: electrical apparatus for automation and control, high voltage electrical apparatus, the basics of design of electrical and electronic apparatus, course and diploma design.

1 GENERAL INSTRUCTIONS TO CGT

The subject of CGT can be typical, for example "Calculation of a direct current electromagnet" or "Calculation of an alternating current electromagnet" or atypical by individual mutual agreement of the student and the teacher. To perform the CGT, the student receives individual initial data to be issued by the teacher. Variants of the initial data for a typical calculation of the electromagnet are given in Appendix A.

The explanatory note to the CGT should contain the following structural components:

1. Title page.
2. Initial data.
3. The text of the explanatory note, which contains the following sections:

- determination of the magnetomotive force of the electromagnet winding;
- calculation of the electromagnet winding;
- determination of electromagnetic forces;
- determination of the response time of the electromagnet;
- reference list.

The explanatory note text should contain all the necessary information that explains the progress of the CGT performance, namely:

- schemes and sketches, designed as figures with information about their content and corresponding explanations;
- formulas accompanied by explanations in respect to the parameters, which they include, and the corresponding justifications as for their application;
- explanations to the calculations, as well as conclusions on their findings.

Monotonous calculations should not be repeated in the explanatory note; their results should be tabled. The section "Reference list" must contain a complete list of literature used in the course of the CGT performance (books, articles, methodical instructions, Internet resources, etc.).

The explanatory note to the CGT should be drawn in compliance with the current national standards of Ukraine [12, 13].

2 INSTRUCTIONS FOR DC ELECTROMAGNET CALCULATIONS

The DC electromagnet calculation is performed in the following sequence [2, 3, 5, 7–11]:

1. According to the given dimensions of the electromagnetic system, for the initial value of the working air gap δ_{in} and flux density in it B (see table A.1), it is necessary to determine the value of the winding magnetomotive force. In other words, it should be solved a direct problem of the magnetic circuit calculation. To do this, it is necessary:

a) to construct the magnetic equivalent circuit of the electromagnet without taking into account reluctance of its ferrous components and to agree it with the teacher;

b) calculate the permeances of the working Λ_δ and idle $\Lambda_{\mathrm{idle}\ i}$ air gaps, specific leakage permeance λ_s, as well as the total permeance of airgaps $\Lambda_{\delta\Sigma}$;

c) to calculate the fringe coefficient for the working airgap σ_{fringe} and determine the magnetic flux in the working airgap:

$$\Phi_\delta = B_\delta S_{\mathrm{face}} \sigma_{\mathrm{fringe}} ,$$

where S_{face} is the area of the pole face;

d) determine the derivative of the working air gap permeance $d\Lambda_\delta/d\delta$ as well as the electromagnetic force;

e) divide the magnetic circuit along the height of the electromagnet winding core into several sections (not less than three) and calculate the leakage coefficients and magnetic fluxes at the boundaries of the sections and at the core basement, as well as average fluxes at all sections of the magnetic circuit;

e) determine the flux density values on all ferrous sections of the magnetic circuit:

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

where S_i is the cross sectional area of the corresponding section of the magnetic circuit;

g) using the magnetization curves, to determine the magnetic intensity H_i and the magnetic potential drop $H_i l_i$ for each section of the magnetic circuit;

h) the required magnetomotive force value of the electromagnet winding is determined as the sum of the magnetic potential drops in the ferrous sections of the magnetic circuit and the working and idle airgaps:

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

For convenience, large digital material of the calculations should be represented in a table.

2. Taking into consideration the safety factor for pick-up of the electromagnet κ_s (usually in the range of 1.3 to 1.5), determine final value of the magnetomotive force of the magnetizing winding:

$$\left(Iw\right)=\kappa_{\text{s}}\cdot\left(Iw\right)_{\text{req}}.$$

Using the calculated value, determine the parameters of the winding and its geometric dimensions. To do this, it is necessary:

a) to determine the required cross sectional area and diameter of the winding wire;

b) using the wire gauge [6], to choose the wire make-up and diameter of the wire without insulation (the nearest larger), as well as to determine the actual value of the wire cross sectional area;

c) determine the winding turns number; this can be done based on the allowable current density j_{all}, which in this case can be taken in the range of 2 to 4 A/mm^2

$$w=\frac{U}{j_{\text{all}}\rho_0\ \ 1+\alpha\cdot\vartheta_{\text{all}}\ \ l_{\text{t.av}}},$$

where $l_{\text{t.av}}$ is the average length of the winding turn;

ϑ_{all} is allowable heating temperature of the winding, which in this case can be taken as equal to 105°C;

d) accepting the height of the winding as equal to the height of the "window" of the magnetic circuit (see table A.1), determine its thickness;

e) determine the specified values of active resistance and magnetomotive force of the winding.

3. According to the found winding magnetomotive force value, the magnetic flux and electromagnetic force are required to determine in the working gap for its final value $\delta_{\text{к}}$. In other words, it should be solved inverse problem of the magnetic circuit calculation. To do this, it is necessary:

a) to calculate the permeances of the working and idle airgaps for the final position of the armature, as well as the total permeance of the airgaps in compliance with the equivalent circuit;

b) calculate the initial approximation of the magnetic flux in the working airgap without taking into account the magnetic potential drop in the ferrous components of the magnetic circuit, as well as the leakage flux;

c) determine the flux density in the magnetic circuit; if the found value significantly exceeds the saturation one, it should be taken as equal to the saturation flux density and, basing upon this value, to determine the initial approximation of the magnetic flux;

d) determine the first and subsequent approximations of the magnetic flux in the working air gap, taking into account the magnetic potential drop in the ferrous components of the magnetic circuit; that is, it is necessary to solve nonlinear equation (2.1) using the simple iteration method; this calculation is recommended to perform with the help of a PC using appropriate software (for example, the MathCad);

e) the calculation outcome can be considered as final when the accuracy of the calculations (the relative difference between the following and previous approximations of the magnetic flux) does not exceed 5%;

h) calculate the electromagnetic force basing upon the found value of the magnetic flux in the working air gap.

4. According to the found parameters of the magnetic circuit and winding, the response time of the electromagnet is required to determine. To do this, it is necessary:

a) to calculate the inductance of the electromagnet winding for the initial value of the working airgap

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

b) calculate the pick-up time of the electromagnet, accepting the safety factor in the range of 1.3 to 1.5;

c) calculate the mass of moving parts and the movement time of the electromagnet, provided that the average value of the counteracting force is 70% of the average value of the electromagnetic force.

d) calculate the response time of the electromagnet.

3 INSTRUCTIONS FOR AC ELECTROMAGNET CALCULATIONS

The AC electromagnet calculation is performed in the following sequence [2, 3, 5, 7–11]:

1. According to the given dimensions of the magnetic circuit for the final value of the working airgap δ_{final} (i.e., when the armature is in attracted position, see table A.2), it should be determined the DC and AC components of the electromagnetic force, its minimum value and pulsation, as well as the winding magnetomotive force. To do this, it is necessary:

a) to construct the equivalent magnetic circuit of the electromagnet taking into account reluctance of ferrous components (leakage magnetic flux not to consider) and to agree it with the teacher;

b) calculate the reluctances of both pole parts of the working airgap provided that $\delta_1 = \delta_2 = \delta_{final}$:

- the pole part not enveloped by short-circuited turn $R_{m\delta1}$;

- active $R_{m\delta2}$, and reactive $X_{m\delta1}$ components of the reluctance of the pole part enveloped by short-circuited turn;

c) determine the reluctance of the idle airgap $R_{m\delta0}$, provided that $\delta_0 = \delta_{final}$;

d) according to the given material and value of flux density in the ferrous sections of the magnetic circuit (see table 1.2), to determine the specific values of active ρ_R and reactive ρ_X components of the reluctance using the magnetization curve [6];

e) to determine the active and reactive components of reluctance of the magnetic circuit ferrous sections according to their cross sectional area and length of the average magnetic field line;

e) in accordance with the equivalent circuit to determine the total reluctance of the magnetic circuit $Z_{m\Sigma}$ (the calculation is usually performed in a complex form);

g) determine the amplitude value of the magnetic flux in the ferrous sections of the magnetic circuit $\Phi_m = B_m S_{fer}$, as well as the amplitude value of the magnetomotive force of the winding $F_m = \Phi_m Z_{m\Sigma}$;

h) determine the amplitude values of magnetic fluxes in both parts of the working air gap: $\Phi_{\delta1m}$ – the flux in the pole part not enveloped by short-circuited turn; $\Phi_{\delta2m}$ – the flux in the pole part enveloped by short-circuited turn [6];

j) determine the dc and ac components, as well as the minimal value and ripple of the electromagnetic force.

2. Basing upon the found value of the magnetomotive force, as well as the given supply voltage, determine the basic parameters and geometric dimensions of the electromagnet winding. To do this, it is necessary:

a) determine the number of turns of the winding:

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

b) determine the preliminary (i.e., without considering active resistance) rms value of the winding current:

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

c) to calculate the required cross sectional area and diameter of the winding wire, basing upon the permissible current density j_{perm}, which in this case (for given cooling conditions of the winding) can be accepted in the range of 2 to 4 A/mm^2;

d)) using the wire gauge [6], to choose the wire make-up and diameter of the wire without insulation (the nearest larger), as well as to determine the actual value of the wire cross sectional area;

e) basing upon the winding height, that is, the height of the "magnet window" (see Table A.2), to determine the winding thickness;

f) to calculate the resistance (taking into account the active losses in the ferrous sections of the magnetic circuit) and reactance of the winding, as well as more exact value of the current in the winding for the final value of the operating airgap.

3. For the initial value of the working airgap δ_{in}, it is necessary to determine the average value of the electromagnetic force acting on the electromagnet armature. To do this, it is necessary:

a) calculate the permeance of the working airgap (with no considering the permeance of the short-circuited turn) Λ_δ, as well as its derivative $d\Lambda_\delta/d\delta$;

b) calculate the permeance of the idle airgap $\Lambda_{\delta 0}$, as well as the specific leakage permeance λ_s;

c) calculate the total conductivity of air gaps $\Lambda_{\delta\Sigma}$, as well as the average value of the leakage coefficient:

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

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

d) calculate the average value of the magnetic flux amplitude over the height of the core:

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

e) basing upon the average value of the leakage coefficient, determine the magnetic flux amplitude in the working airgap;

f) calculate the electromagnetic force.

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APPENDIX A
Initial data to the typical calculation of the electromagnet

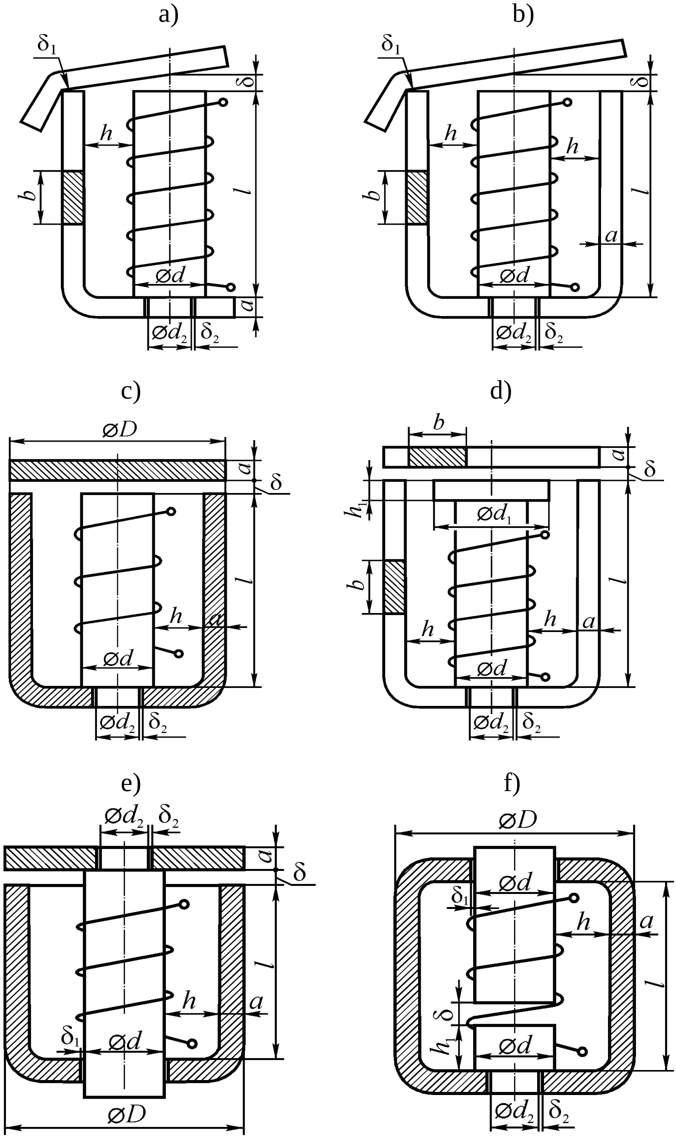

Figure A.1 – Variations of DC electromagnets

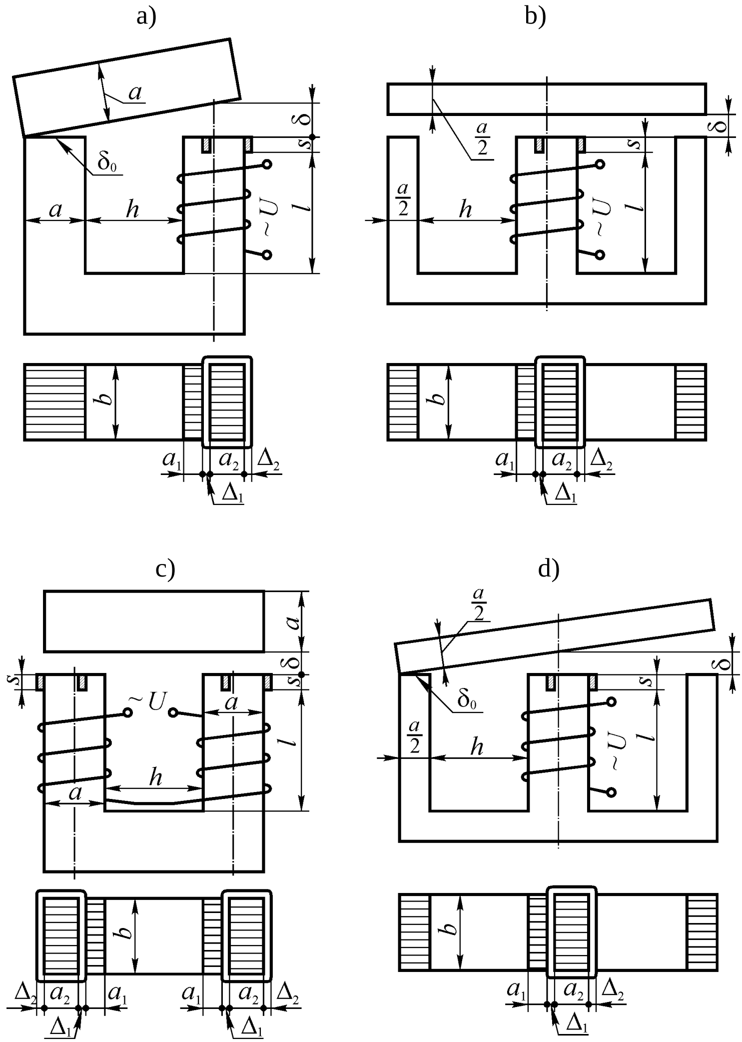

Figure A.2 – Variations of AC electromagnets

Table A.1 – Initial data for dc electromagnet calculations

The numbers of variants	Design of the magnetic circuit	Geometrical dimensions, mm										Operating air-gap, mm		Flux density, T (at $\delta=\delta_{in}$)	Material of the magnetic circuit	Supply voltage of the winding, V
		a	***b***	***l***	***h***	h_1	***d***	d_1	d_2	δ_1	δ_2	δ_{in}	δ_{final}	***B***		
1	Drawing. A.1a	2	20	30	15		8		5			3			Structural steel of quality 10	6
2		3	25	40	18		10		8			4				12
3		4	30	50	20		14		10			5				48
4		5	35	60	25		15		12		0,1	6	0,2	0,08		60
5		6	40	75	30		18		15			7				110
6		8	50	90	35		22		18			8				220
7		10	70	100	40		25		20			10				440
8	Drawing. A.1b	3	25	80	36		10		8			3			Structural steel of quality 20	6
9		4	30	100	40		14		10			4				12
10		5	35	120	50		15		12			5				48
11		6	40	150	60		18		15		0,1	6	0,2	0,1		60
12		8	50	180	70		22		18			7				110
13		10	70	190	80		25		20			8				220
14		12	80	200	90		30		25			10				440
15	Drawing. A.1c	2		80	36		10		8			3			Steel of quality 50HXC	6
16		2		100	40		14		10			4				12
17		3		120	50		15		12			5				48
18		3		150	60		18		15		0,1	6	0,2	0,12		60
19		4		200	70		22		18			7				110
20		4		250	80		25		20			8				220
21		4		300	90		30		25			10				440

Continuation of table A.1

The numbers of variants	**Design of the magnetic circuit**	**Geometrical dimensions, mm**										**Operating air-gap, mm**		**Flux density, T** (at $\delta = \delta_{in}$)	**Material of the magnetic circuit**	**Supply voltage of the winding, V**
		a	b	l	h	h_1	d	d_1	d_2	δ_1	δ_2	δ_{in}	δ_{final}	B		
22		4	25	80	36	7	10	20	8			4				6
23		5	30	100	40	8	14	25	10			5				12
24		6	40	120	50	9	15	30	12			6				48
25	Drawing. A.1d	8	50	150	60	10	18	35	15	0,1	0,1	7	0,1	0,15	Steel of quality 49КФ	60
26		10	60	200	70	10	22	40	18			8				110
27		11	80	250	80	12	25	45	20			10				220
28		12	90	350	90	12	28	50	20			12				440
29		2		80	18		20		8			4				6
30		2		100	20		25		10			5				12
31		3		120	25		30		12			6				48
32	Drawing. A.1e	3		150	30		35		15	0,1	0,1	7	0,1	0,15	Structural steel of quality 20	60
33		4		180	40		40		18			8				110
34		4		190	50		45		20			10				220
35		4		200	60		50		22			12				440
36		2		80	36		10		4			4				6
37		3		100	40		14		4			5				12
38		4		120	50		15		5			6				48
39	Drawing. A.1f	5		150	60		18		5	0,1	0,1	7	0,1	0,2	Structural steel of quality 10	60
40		6		200	70		22		5			8				110
41		8		250	80		25		6			10				220
42		10		300	90		24		6			12				440

Table A.2 – Initial data for ac electromagnet calculations

The numbers of variants	Design of the magnetic circuit	Geometrical dimensions, mm									Operating air-gap, mm		Flux density, T (at $\delta = \delta_{final}$)	Material of the magnetic circuit	Supply voltage of the winding, V
		a	***b***	***l***	***h***	a_1	a_2	Δ_1	Δ_2	**s**	δ_{in}	δ_{final}	B_m		
43	Drawing. A.2a	14	22	55	22	4	8	2	3	3	5	0,05	0,8	Electrical-sheet steel of quality 1212	12
44		11	18	50	20	3	6	2	2	2	4		0,85		60
45		15	25	65	25	4	8	3	4	4	6		0,75		110
46		15	25	70	25	4	8	3	4	4	6		0,9		220
47		16	28	75	25	5	9	2	3	3	7		0,9		380
48		16	30	80	30	4	9	3	4	4	7		1,0		660
49		18	32	90	30	5	10	3	4	4	8		1,0		220
50		18	35	95	32	6	10	2	3	3	8		1,1		127
51		20	40	100	35	6	12	2	3	3	8		1,2		380
52		11	20	70	22	3	6	2	3	3	2		0,8		660
53	Drawing. A.2b	16	35	80	25	5	9	2	3	3	5	0,05	1,0	Electrical-sheet steel of quality 1511	12
54		18	35	80	25	5	10	3	4	4	6		1,0		60
55		19	40	90	30	5	11	3	4	4	7		1,1		110
56		20	40	95	30	6	12	2	4	4	8		1,2		220
57		20	40	100	32	6	12	2	3	3	10		0,8		380
58		22	45	100	35	6	1311	3	3	3	122		0,85		660
59		18	20	36	20	5	15	2	3	3	3		0,75		220
60		25	30	60	30	8	19	2	2	2	4		0,9		127
61		32	35	80	36	10	28	3	4	4	5		0,9		380
62		45	50	100	40	14	30	3	4	4	6		1,0		660

Continuation of table A.2

The numbers of variants	Design of the magnetic circuit	Geometrical dimensions, mm									Operating air-gap, mm		Flux density, T (at $\delta = \delta_{final}$)	Material of the magnetic circuit	Supply voltage of the winding, V
		a	b	l	h	a_1	a_2	Δ_1	Δ_2	s	δ_{in}	δ_{final}	B_m		
63	Drawing. A.2c	14	25	70	25	4	8	3	4	4	6	0,05	0,75	Electrical-sheet steel of quality 1212	12
64		11	28	75	25	5	9	2	3	3	7		0,8		60
65		15	30	80	30	4	9	3	4	4	7		0,85		110
66		15	32	90	30	5	10	3	4	4	8		0,9		220
67		16	35	95	32	6	10	2	3	3	8		0,95		380
68		16	40	100	35	6	12	2	3	3	8		1,0		660
69		18	20	70	22	3	6	2	3	3	2		1,1		220
70		18	25	65	20	3	7	3	2	2	3		1,2		127
71		20	28	75	25	4	8	2	4	4	4		1,3		380
72		11	30	90	30	5	9	3	3	4	5		1,4		660
73	Drawing. A.2d	20	40	95	30	6	11	2	4	4	7	0,05	0,75	Electrical-sheet steel of quality 1511	12
74		20	40	100	32	6	12	2	3	3	8		0,8		60
75		22	45	100	35	6	13	3	3	3	9		0,85		110
76		18	20	36	20	5	14	2	3	3	10		0,9		220
77		25	30	60	30	8	15	2	2	2	11		0,95		380
78		32	35	80	36	10	19	3	4	4	12		1,0		660
79		45	50	100	40	14	28	3	4	4	13		1,1		220
80		48	50	120	50	16	30	2	3	3	14		1,2		127
81		55	60	150	60	18	35	3	4	4	15		1,3		380
82		65	70	200	70	22	40	3	4	4	16		1,4		660