Riga Technical University
Institute of Power Engineering
Department of Electrical Machines and Apparatuses

ELECTRICAL APPARATUSES
Methodical Guidelines for Laboratory and Practical Works

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These methodical guidelines for laboratory and practical works have been developed for students of the course “Electrical Apparatuses” at the Faculty of Power and Electrical Engineering, Riga Technical University. The guidelines can be used as an additional material for in-depth study of physical processes of electrical apparatuses, as well as for processing and analysis of their parameters obtained experimentally.
The material can also be used for studying electrical apparatuses as a part of qualification raising courses.
This material includes laboratory work tasks, explanations, test questions, and practical work tasks that have been developed using the materials of the Faculty of Power and Electrical Engineering, Riga Technical University.

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Contents

DESCRIPTIONS OF LABORATORY WORKS

Conditions for carrying out laboratory work

General rules

Laboratory works is a part of the course “Electrical Apparatuses” that facilitates acquisition of practical skills by familiarising students with design and methods of experimental research of electrical apparatuses.

In laboratory work, attention must be paid to the physical processes present in apparatuses, tracing of regulation characteristics, methods of regulation, and assessment of parameters.

Work descriptions include minimal theoretical explanation; therefore, individual training and preparation for laboratory work is necessary. For this, the listed information sources and lecture notes may be used, as well as questions for self-test may be answered.

Admission to laboratory work

Admission to laboratory work shall only be granted to those students who have participated in an introductory class and have been instructed regarding the work safety norms, and who have signed for that in a corresponding journal.

Students shall be divided into groups (2–4 students in a group). Before the work, students shall present to the lecturer a report form, answer test questions about the procedure of the experiment to be conducted, and hand in the report of the previous laboratory work to the lecturer.

Experiment procedure

Experiment may be started only when it is permitted by the laboratory staff. Detailed methodological guidelines are given in the description of each laboratory work. The laboratory staff may control the process of experiment and ask additional questions.

It is useful to place marks on measuring devices (according to the circuit diagram) for more convenient recording of measurement results and locating the damaged spot in a circuit. It is strictly forbidden to make marks right on the measuring devices.

To prevent any delays in the experiment process, write the measurement results in table sections and then calculate the necessary values.

If it is necessary to clarify some issues during the experiment, it is advised to disconnect the studied device from power source for that moment.

At the end, the laboratory staff shall check the results and recommend to perform some control calculations and sign the report.

Procedure for executing laboratory work

Place for stamp 8 cm × 4 cm		1 .... 2 .... 3 .... 4 ....

Laboratory work [No.]

Name of the work

Work tasks: 1 ....
2 ....
…

1. Theoretical grounds (expected results and necessary formulae).

2. Circuits of experiment work.
3. Passport data of the devices to be studied.
4. List of measuring devices used.
5. Tables of measurement results.
6. Calculation examples and result tables.
7. Graphs and diagrams, oscillograms.
8. Node diagrams.
9. Conclusions.
10. Signatures.

The most important part of the report is the critical assessment of the results and conclusions, correspondence between the results and theoretical expectations, analysis and explanation of the causes for deviations and errors, analysis of measuring methods.

Draft reports shall be kept until the test. Fair copy of the report shall be submitted for evaluation in the next class. If this requirement is not fulfilled, the lecturer shall have the right to deny admission of the student to the next laboratory work.

Sources of information

1. A. Baltiņš, A. Kanbergs, S. Miesniece. Zemsprieguma elektriskie aparāti. Riga, Jumava, 2003, 331p.; 2007, 345 p.
2. Родштейн Л. А. Электрические аппараты. Л.: Энергоатомиздат, 1989, 304 p.
3. Чунихин А. А. Электрические аппараты. – М.: Энергоатомиздат, 1988, 720 p.
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6. Сахаров, П. В. Проектирование электрических аппаратов / П. В. Сахаров. – М.: Энергия, 1971, 558 p.
7. Company catalogues.
8. World Wide Web.

Laboratory work No. 1
Heating of current-carrying parts

Purpose of the work

To establish the impact of homogeneous conductors and coil current and mode of operation on the heating process. To get familiar with the main methods of tracing coil thermal parameters of electrical apparatuses.

Work tasks

1. Experimental part

1.1. To connect coil to DC supply and to trace temperature rise on the coil's outside surface over time $\tau = f(t)$.
1.2. To connect coil to intermittent DC supply and to trace temperature rise on the coil outside surface over time $\tau = f(t)$.
1.3. To trace the average temperature rise in relay coil $\tau = f(t)$, using the resistance variation method.
1.4. To trace the parameters of an incandescent bulb and coils.
1.5. To get familiar with the operation of distance thermometer.

2. Calculations and graphical part

2.1. To draw experiment's circuit diagrams.
2.2. To calculate the coil outside temperature τ_∞ (when it is stable) and to determine it using the indirect method.
2.3. To determine the coil heating time constant T from heating curves and to compare the obtained results.
2.4. To calculate the heat-transfer factor for the outside of one DC coil.
2.5. To calculate the cooling surface area of DC coil per each power unit σ_0 discharged in coil and draw conclusions on heating conditions.
2.6. To calculate the permitted working current in coils.
2.7. To calculate the permitted working current in coils in intermittent DC supply mode.
2.8. To determine the permitted turn-on time $t_{\text{iesl\_pieļ}}$ of coil if the permitted temperature of winding insulation is +120 °C.
2.9. To determine the switching current of an incandescent bulb and filament heating temperature Θ_w.

Theoretical grounds

In practice, stable temperature rise on a coil outside surface can be calculated with sufficient accuracy using Newton's formula:

$$\tau_\infty = \frac{P}{k_T S}, \text{ °C}, \qquad (1.1)$$

where τ_∞ — stabilised temperature rise, °C;
$P = I^2 R$ — power losses in coil, W;
k_T — heat-transfer factor, W/(m^2 °C);
S — coil side surface area, m^2.

Here it has been assumed that heat is only transferred by the side surface of a coil. For calculations applying Newton's formula to be accurate, the heat-transfer factor must be selected correctly that is affected by the coil temperature, design, insulation materials, etc.

For example, values of heat-transfer factor k_T in natural convection conditions in air are as follows:

▪ for any varnished surface	12–16 W/(m^2 °C);
▪ for windings with paper insulation	10.0–12.5 W/(m^2 °C);

- for steel sheet package 10.0–12.5 W/(m^2 °C).

The heat-transfer factor can also be calculated using empirical formulae.

Description of the conductor	Formula
Coloured round conductor positioned horizontally in calm environment	$k_T = 10k_1(1 + k_2 \cdot 10^{-2}\tau)$
Round pipe with diameter d through which water is flowing with velocity w	$k_T = 1710w^{0,8}d^{0,2}(22 - \tau)^{0,4}$
Cylindrical coil with side surface area that is between 10^{-4} m^2 < S < 10^{-2} m^2	$k_T = \dfrac{2,1\left(1 + 0,005\tau\right)}{\sqrt[3]{S}}$
Cylindrical coil with side surface area that is between 10^{-2} m^2 < S < 0,5 m^2	$k_T = \dfrac{3,6\left(1 + 0,005\tau\right)}{\sqrt[5]{S}}$

where τ — temperature rise in conductor, °C;
Θ — temperature in conductor, °C;
Θ_0 — ambient temperature, °C;
k_1 — factor, which depends on the wire diameter.

Since the heating process occurs exponentially, namely,

$$\tau = \tau_\infty\left(1 - e^{-\frac{t}{T}}\right), \tag{1.2}$$

where τ_∞ — stabilised temperature rise, °C;
$T = \dfrac{cG}{k_T S}$ — heating constant which equals the ratio of conductor's heat capacity to conductivity;
c — specific heat capacity of conductor's material, J/(kg °C);
G — conductor's mass, kg,

then the stabilised temperature rise is usually determined using the indirect method. Divide the experimentally-traced part of curve in sections with similar Δt and draw ordinates (Fig. 1.1).

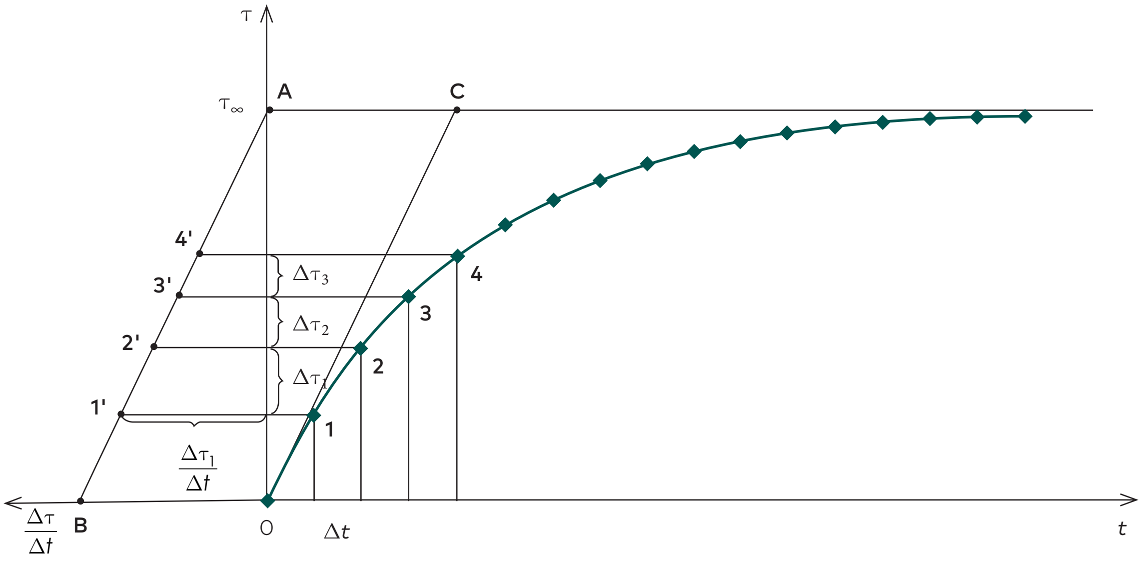

Fig. 1.1. Determining stabilised temperature rise using the indirect method.

Then the corresponding increase in temperature rise $\Delta\tau$ is established for each Δt and marked on the left side of the graph $\tau = f(\Delta\tau/\Delta t)$ on an arbitrarily selected scale. Since Δt are similar in all sections, line segments $\Delta\tau/\Delta t$ are proportional to the increase in temperature rise $\Delta\tau$. Joining the obtained points 1', 2', 3', ... with a straight line, this line will intersect the ordinate axis at point A; this point equals the value of stabilised temperature rise τ_∞, because in stable mode $\Delta\tau / \Delta t = 0$ and the intersection point B of this line with the abscissa axis yields a value proportional τ_∞ / T.

The heating time constant T from the characteristic curve $\Theta = f(t)$ is determined as the time when $\tau = 0.63\tau_\infty$, because when $t = T$,

$$\tau = \tau_\infty (1 - e^{-1}) = 0.63\tau_\infty. \tag{1.3}$$

Graphically T can be found by drawing a tangent in the straight part of the curve $\tau = f(t)$ until it intersects the straight line $\tau_\infty = \text{const}$, then the line segment $AC = T$.

Since the permitted temperature rise depends on the insulation class of coil, Newton's formula may be used for calculating the permitted current value:

$$I_{\text{pieļ}} = \sqrt{\frac{\tau_{\text{pieļ}} k_T S}{R}}, \tag{1.4}$$

where R — coil winding resistance, Ω;
$\tau_{\text{pieļ}}$ — permitted temperature rise, °C;
k_T — heat-transfer factor;
S — side surface area, m^2.

In case of similar permitted temperature rise, the permitted current may be increased n times in intermittent duty. Since usually

$$t_\text{d} + t_\text{p} < T, \tag{1.5}$$

then $(P_{\text{pieļ}})_{\text{partr\_cikl}} = n(P_{\text{pieļ}})_\infty$ and $n \approx \dfrac{t_\text{d} + t_\text{p}}{t_\text{d}}$,

where t_d — operating time of coil, s;
t_p — pause, s;
n — overload factor of coil in intermittent duty;
$(P_{\text{pieļ}})_{\text{partr\_cikl}}$ — permitted power for S3 mode, W;
$(P_{\text{pieļ}})_\infty$ — permitted power for S1 mode, W.

Similarly, the overload factor p for short-time duty may be determined:

$$p = \frac{1}{\sqrt{1 - e^{-\frac{t_\text{d}}{T}}}}, \tag{1.6}$$

which can be used for any T value. It can be seen that p increases as T value grows.

Methodical guidelines

The principle diagram of the experiment is shown in Fig. 1.2.

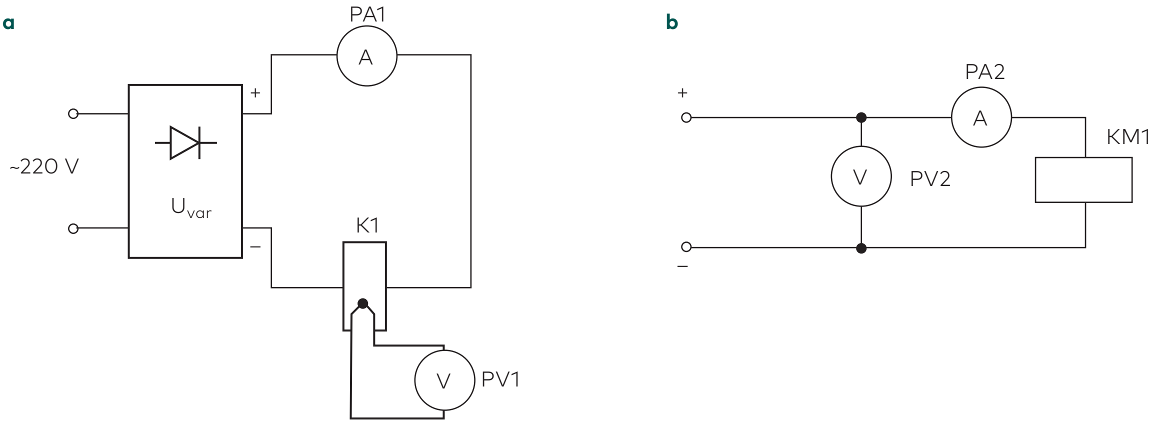

Fig. 1.2. Circuits of experiment work: a —determining temperature rise in coil heating with a thermocouple, b — determining temperature rise in coil heating with resistance variation .

For measuring temperature, use a thermocouple. The calibration curves of a thermocouple are linked with measuring devices.

Consistent power or consistent voltage modes must be ensured for coils that are to be examined in continuous duty.

The heat-transfer factor for the outside k_{T2} and inside k_{T1} of coil is determined applying Newton's formula:

$$k_{T1} = \frac{P_1}{2\pi r_1 l \tau_1}, \tag{1.7}$$

$$k_{T2} = \frac{P_2}{2\pi r_2 l \tau_2}, \tag{1.8}$$

where P_1 and P_2 — power that the coil discharges through its inside and outside respectively, W;

r_1 — inside radius of coil, m;
r_2 — outside radius of coil, m;
τ_1 — temperature rise on inside surface, °C;
τ_2 — temperature rise on outside surface, °C;
l — coil length, m.

Assuming that no heat is discharged through the coil ends

$$P_1 = P\frac{r_0^2 - r_1^2}{r_2^2 - r_1^2}, \tag{1.9}$$

$$P_2 = P\frac{r_2^2 - r_0^2}{r_2^2 - r_1^2}, \tag{1.10}$$

where P — power used by the coil for heating, W;
r_0 — radius of the coil layer with the maximum temperature.

It may be roughly assumed that $r_0 \approx r_1 + \frac{1}{3}(r_2 - r_1)$.

To assess approximately if the coil would overheat, $\sigma_0 = S/P$ is used as a value characterising cooling. In practice it has been established that the coil temperature does not exceed the permitted value if σ_0 has the following values:

- $\sigma_0 = 0.0008$ m^2/W, if $l/d < 1$;
- $\sigma_0 = 0.001$ m^2/W, if $l/d = 1$;
- $\sigma_0 = 0.0012$ m^2/W, if $l/d > 1$,

where $d = 2r_2$

Measurement results and tables

Data of incandescent bulb:

R_a = Ω — resistance of cold filament
I = A
U = V
R_k = Ω — resistance of hot filament
I_{iesl} = A — switching current of an incandescent bulb
Θ_W = °C — temperature rise in wolfram filament
$R = R_0(1 + k_T\Theta) \rightarrow \Theta$
$k_{TCu} = 0.004$ °C^{-1} – for coil
$k_{Tw} = 0.0045$ °C^{-1} – for wolfram wire

Data of the coils under study

t, min	*I*(PA1)			*U*(PV1) Nr			Θ,	Δ*T*	*I*(PA3)			*U*(PV1) Nr			Θ	Δ*T*	*I*(PA2)			*U*(PV2)			*R*	Θ	Δ*T*
	ied.	C	A	ied.	C	V	°C	°C	ied.	C	A	ied.	C	V	°C	°C	ied.	C	A	ied.	C	V	Ω	°C	°C

Questions for self-test

1. How is heat transferred to the environment?
2. What determines the permitted temperature rise in a coil?
3. Why does the form of coil affect heating?
4. At which point a coil has its maximum temperature and why?
5. What does the heating time constant express?
6. What are the advantages of a coil operating in intermittent duty?
7. How does the winding density (winding technology) affect the coil heating process?
8. How does the coil power consumption change in continuous duty?
9. What is the operating principle of a thermocouple?
10. How is the temperature rise in conductors determined using the resistance variation method?

Literature

[1] § 1.1.
[2] § 2.2., 2.3., 2.4., 2.7.

Laboratory work No. 2

Control and protective devices of a three-phase asynchronous motor

Purpose of the work

To get familiar with the design, operating principles and parameters, regulation possibilities and tracing of characteristics of protective devices of asynchronous motors.

Work tasks

1. Experimental part

1.1. To get familiar with the design of protective devices of given electric motors and laboratory equipment for their testing.
1.2. To establish actuation and reset parameters and resetting ratio of a magnetic starter and to draw a characteristic curve of starter's relay.
1.3. To trace the time-current characteristic

$t_{\mathrm{no}} = f\left(\frac{I}{I_{\mathrm{N}}}\right)$ of a thermal relay in the given position of controller.

1.4. To connect a three-phase asynchronous motor using a magnetic starter.
1.5. To measure zero sequence voltage in case of loss of a phase and to close an appropriate protection circuit.
1.6. To connect a three-phase asynchronous motor with a softstarter.

2. Calculations and graphical part

2.1. To draw experiment's circuit diagrams.
2.2. To write down the technical data of protective devices of the studied electric motors and to describe their principles of operation.
2.3. To draw the calculated and experimentally obtained safety characteristics of protective devices of electric motors and to compare them with the standard characteristics.
2.4. To present analysis of technical-economic parameters of protective devices of the studied electric motors.
2.5. According to laboratory staff's instructions, select protective devices for a specific electric motor.

Theoretical grounds

Modern electric motors have high reliability indices; however, in the course of electric drive operation there may arise situations when the actual loads differ from the calculated ones. In such cases, various emergency conditions can set in.

To prevent electric motor damage caused by emergency conditions, appropriate protective devices are used to ensure automatic disconnection of an electric motor from power supply if the controlled parameter of an electric motor or supply circuit exceeds the prescribed threshold value. In practice, the most widespread damage of electric motors is damaged insulation resulting from overheated windings, which may be caused by the following emergency conditions:

- overload or stuck of the working mechanism;
- operation of an asynchronous motor in two-phase mode (loss of a phase);
- operation under asymmetrical voltage;
- continuous start-up of motor;
- operation under reduced voltage;
- frequent turning on of motor;
- failed cooling.

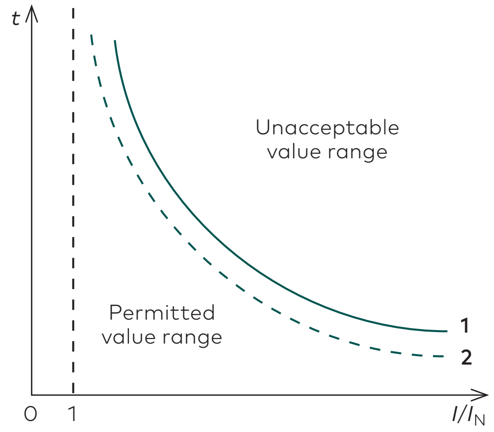

Fig. 2.1. Protection time-current characteristic: 1 — heating characteristic of electric motor; 2 — desired characteristic of protective devices of an electric motor.

Under these conditions (except for the last one), the current increases in the windings of an electric motor causing overheating of the current-carrying parts and the adjacent insulation.

Duration of overload current must be limited according to the protection characteristics (Fig. 2.1).

After examining the given characteristics, one of the main requirements for overload protection caused by current increase may be defined: protection must work depending on the overload I / I_N value (I_N — rated current of an electric motor). This rules out the possibility that protection would set in under a short-term current increase, which is caused, for example, when a motor is started. Protection may only set in when a range of inadmissible values is reached, i.e. when the permitted current value and the operation time thereof is exceeded. The desired protection characteristic 2 of protective devices of electric motors must be below the heating characteristic 1 of the electric motor under protection but as close to it as possible (Fig. 2.1). Motor's protection against overload will only be effective if the protective devices of an electric motor directly simulate the motor's reaction to overload, i.e. if the characteristic 1 and 2 are similar.

For motor protection against short-circuit, fuses or circuit breakers (automatic circuit breakers) are used. Despite the great variety of protective devices of electric motors, currently there is no perfect protection solution. There are contradictions between costs, operational safety and parameters of all protective devices of electric motors. When choosing protective devices of electric motors, a technical-economic justification must be provided.

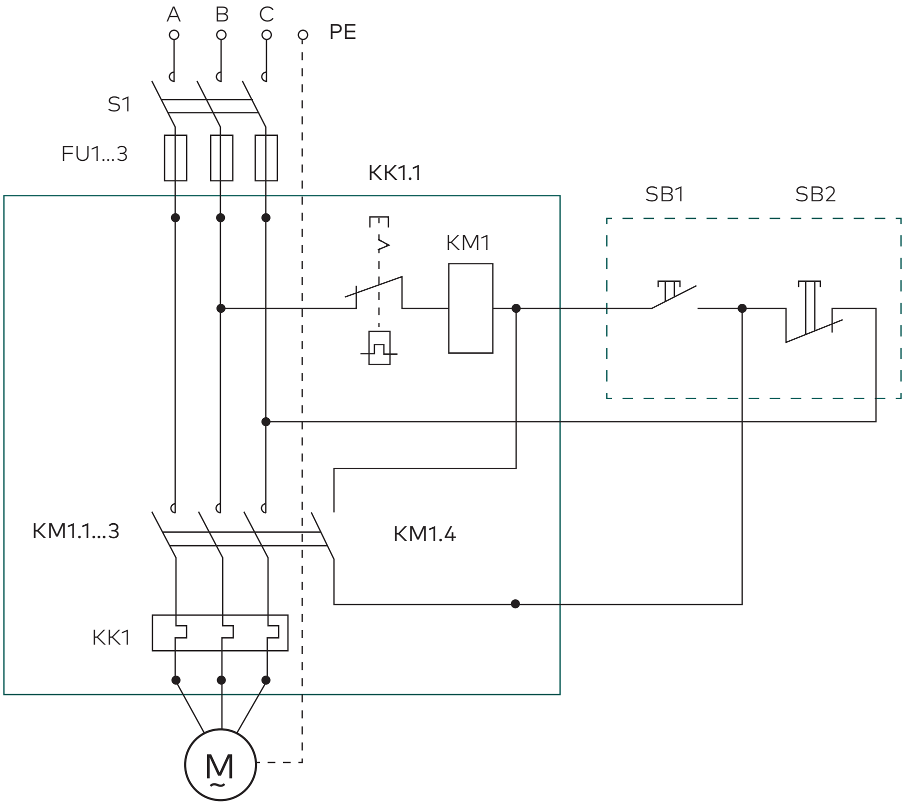

Fig. 2.2. Magnetic starter circuit: S1 — power switch; FU 1...3 — fuses; KMI — contactor; KK1 — thermal relay; SB1, SB2 — control button.

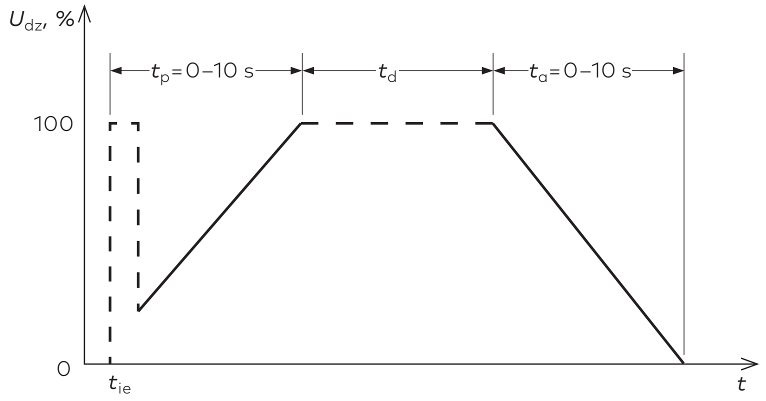

Fig. 2.3. Operational diagram of softstarter: U_{dz} — voltage connected to the asynchronous motor; t_p — starting time; t_d — working time; t_a — stop time; t_{ie} — breakaway time (~0.2 s) in the so-called kickstarter mode.

Copies of passports and design descriptions of protective devices of the studied electric motors can be found in the laboratory of electrical apparatuses.

Connection of an asynchronous motor with a magnetic starter is the most often used connection method (Fig. 2.2).

Magnetic starter, the main detail of which is a three-pole or four-pole AC contactor, is designed for remote control and protection of small- and medium-power electric motors against overload, short-circuit, and decrease in supply voltage.

Magnetic starters may be non-reversible or reversible. The last ones ensure start-up, stopping, and change of rotation direction of a motor.

To reduce the undesirable effect of an impact, rapid acceleration and retardation in the operation of lifts, cranes, transporter belts and other devices (in the electric drive thereof), softstarters are used for the control of asynchronous motors. The voltage-time diagram of softstarters is shown in Fig. 2.3, but the circuit diagram – in Fig. 2.4.

The desired starting and stop mode is ensured by setting t_p and t_a values. To move a larger mass, the so-called kickstarter mode may be used by temporarily connecting the asynchronous motor to rated voltage at the beginning of start (t_{ie} shown with a dotted line in Fig. 2.3). The actual time t_p and t_a is determined by measuring the blink time of signal lamps (LED1 for start, LED2 for stop).

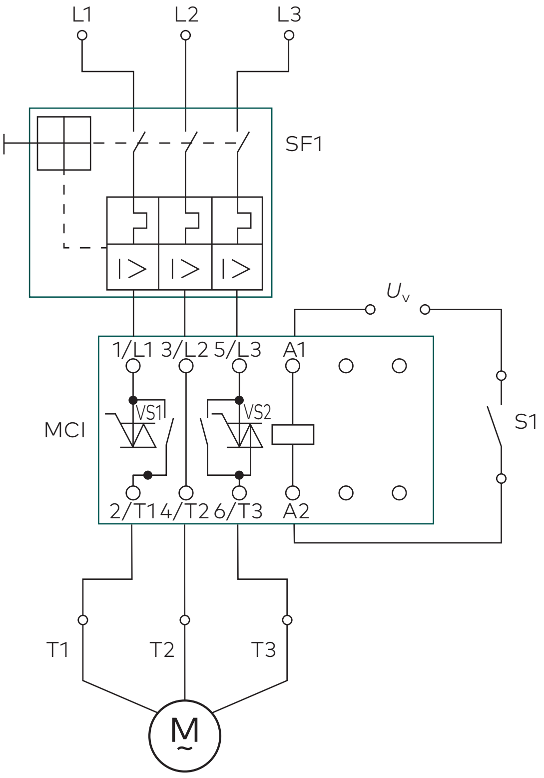

Fig. 2.4. Connection diagram of softstarter: SF1 — manual/automatic circuit breaker in a supply circuit; MC1 — softstarter; S1 — control switch; M — asynchronous motor; U_v — control voltage (U_{vmax} = 400 V).

Measurement results and tables

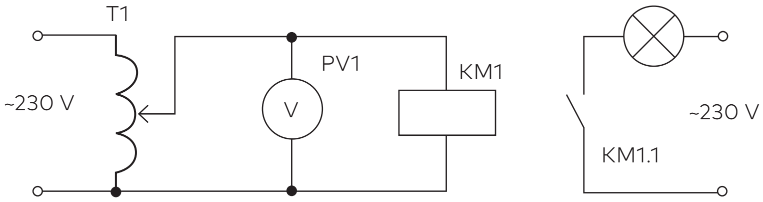

Fig. 2.5. Contactor test diagram.

Magnetic starter measurements:

U_{no}, V	U_{at}, V

U_{no} — contactor's operating voltage; U_{at} — contactor's resetting voltage.

Thermal relay measurements:

$I_N =$ A

I/I_N	I, A	ied.	t_1, s	t_2, s	t_3, s	$t_{vid.}$, s

Softstarter's t_p and t_a measurements:

Process	Setting	Measurements			Average value	Deviation. %
t_p, s						
t_a, s						

Questions for self-test

1. What are the causes for dangerous overheating of an electric motor?
2. What devices are used for protecting electric motors against short-circuit currents?
3. What are the requirements for protective devices of electric motors?
4. Explain the operating principles of thermal relay.
5. What rules must be observed when choosing and regulating thermal relays for the protection of electric motors?
6. Explain the operating principle of phase voltage symmetry control relay?
7. What devices are used for built-in thermal protection of motors?

8. What are the drawbacks of using thermal relays in protective device circuits of electric motors?
9. What makes AC contactors different from DC contactors?
10. Why does the starting current in the coil of an AC electromagnet exceed the operating current thereof several times?
11. Why are short-circuited windings used in AC electromagnets?
12. What makes magnetic starter differ from AC contactor?
13. How to select the right magnetic starter for the control and protection of an asynchronous motor?

Literature

[1] § 4.2., 4.3.1., 7.5., 7.5.1., 8.6., 9.1., 9.2.

Laboratory work No. 3

Study of DC contactor

Purpose of the work

To get familiar with the operating principles and the characteristic parameters of DC contactor.

Work tasks

1. To sketch DC contactor and to mark the magnetic flux routes.
2. To trace tractive force F of DC contactor under conditions of various working air gaps δ and three voltages: U_N, $0.8U_N$, $0.5U_N$.
3. To show graphically tractive characteristic $F = f(\delta)$ of DC contactor.
4. To measure magnetic induction in working air gap and to draw $B_\delta = f(U)$, $B_\delta = f(\delta)$.
5. To calculate tractive characteristic in nominal mode and to compare it with the experimentally obtained one.
6. To draw an equivalent replacement circuit diagram for the DC contactor.
7. To calculate magnetomotive force of DC contactor and the magnetic flux generated by it, if the magnetic circuit is unsaturated. To compare the calculated magnetomotive force with the coil's magnetomotive force (Iw).

Theoretical grounds

Tractive force may be calculated using a simple Maxwell's equation:

$$F = \frac{B_\delta{}^2 S}{2\mu_0}, \text{ N}, \tag{3.1}$$

where $S = \frac{\pi d^2}{4}$ — cross-section area of an electromagnetic pole (m^2);

d — diameter of pole (m);

$\mu_0 = 4\pi \cdot 10^{-7}$ — magnetic permeability of air, H/m.

Magnetomotive force of an electromagnet is calculated without taking into account the drop of magnetic potential in steel (if the core is unsaturated). In calculation it is assumed that leakage factor

$$\sigma = \frac{\Phi}{\Phi_\delta} \approx \sim 1{,}2, \tag{3.2}$$

where $\Phi = \Phi_\delta + \Phi_\sigma$ magnetic flux Wb generated by the coil;

Φ_δ — magnetic flux in working air gap, Wb;

Φ_σ — leakage flux, Wb.

First, the magnetic flux in working air gap is calculated: $\Phi_\delta = B_\delta S$, then the complete flux $\Phi = \sigma\Phi_\delta$. For example, if there is a horseshoe electromagnet with two working air gaps, then the magnetic conductivity of one air gap is calculated first:

$$\Lambda_\delta = \mu_0 \frac{S}{\delta}, \text{ H}, \tag{3.3}$$

and only then the total

$$\Lambda_\Sigma = \frac{\Lambda_\delta}{2}, \text{ H}. \tag{3.4}$$

The magnetomotive force generated by the coil of an electromagnet is calculated by applying the Ohm's law for magnetic circuits:

$$(Iw)_{\text{apr}} = \frac{\Phi}{\Lambda_\Sigma}, \text{ A}. \tag{3.5}$$

By comparing the actual magnetomotive force of the coil with the calculated one, the error caused by the assumptions made for the calculation can be established:

$$\gamma_{\%} = \frac{(Iw)_{\text{sp}} - (Iw)_{\text{apr}}}{(Iw)_{\text{sp}}} \cdot 100,\ \%, \qquad (3.6)$$

where $(Iw)_{\text{sp}} = I_{\text{N}} w$ and w is the number of windings in the coil of an electromagnet.

Methodical guidelines

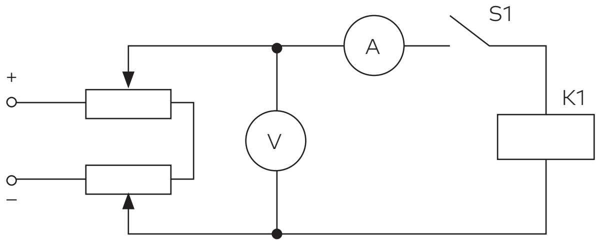

Fig. 3.1. Experiment's circuit diagram.

For measuring tractive force of an electromagnet, a laboratory dynamometer is used. Air gap δ is fixed with non-magnetic material sheets.

Magnetic induction is measured with a teslameter in 5 spots on an electromagnetic pole (along the diameter from the outside to the inside). The average value of magnetic induction for the working air gap δ is used in calculating the tractive force.

Show the magnetic work flux Φδ and leakage flux Φσ in the sketch of electromagnet.

Measurement results and table

Δ, mm	*F*		*B*	
	kg	N	mT	T
U_N = V ; I = A				
0.8U_N = V ; I = A				
0.5U_N = V ; I = A				

Questions for self-test

1. What is the name of the moving part of magnetic circuit of an electromagnet and of the other parts of magnetic circuit?
2. What does tractive force of an electromagnet depend on?
3. What must be changed in the construction of an electromagnet to increase its tractive force?
4. What is the parasitic air gap in an electromagnet?
5. What is leakage flux?
6. What are the general laws of a magnetic circuit?

Laboratory work No. 4

Study of AC electromagnet

Purpose of the work

To get familiar with the operating principles and the characteristic parameters of AC electromagnet.

Work tasks

1. To trace the dependence of coil current on the air gap $I = f(\delta)$ in electromagnet, if $U =$ const (U_N; $0.8U_N$; $0.5U_N$).
2. To calculate the operating and starting current of an electromagnet.
3. To trace the dependence of tractive force on the air gap $F = f(\delta)$.
4. To calculate tractive force of an electromagnet with various air gaps and to compare the results with the experimentally obtained one (with U_N).
5. To establish the dependence of L, X_L and cosφ on the air gap, if $U =$ const.
6. To recalculate the coil of an electromagnet for another voltage.

Theoretical grounds

Alternating currents in the coil of an electromagnet are calculated using Ohm's law:

$$I = \frac{U}{\sqrt{R^2 + X^2}}, \text{ A}, \qquad (4.1)$$

where $X = \omega L = \omega w^2 \Lambda_\Sigma$ is the inductive reactance of coil, and Λ_Σ is the magnetic conductivity of working air gaps.

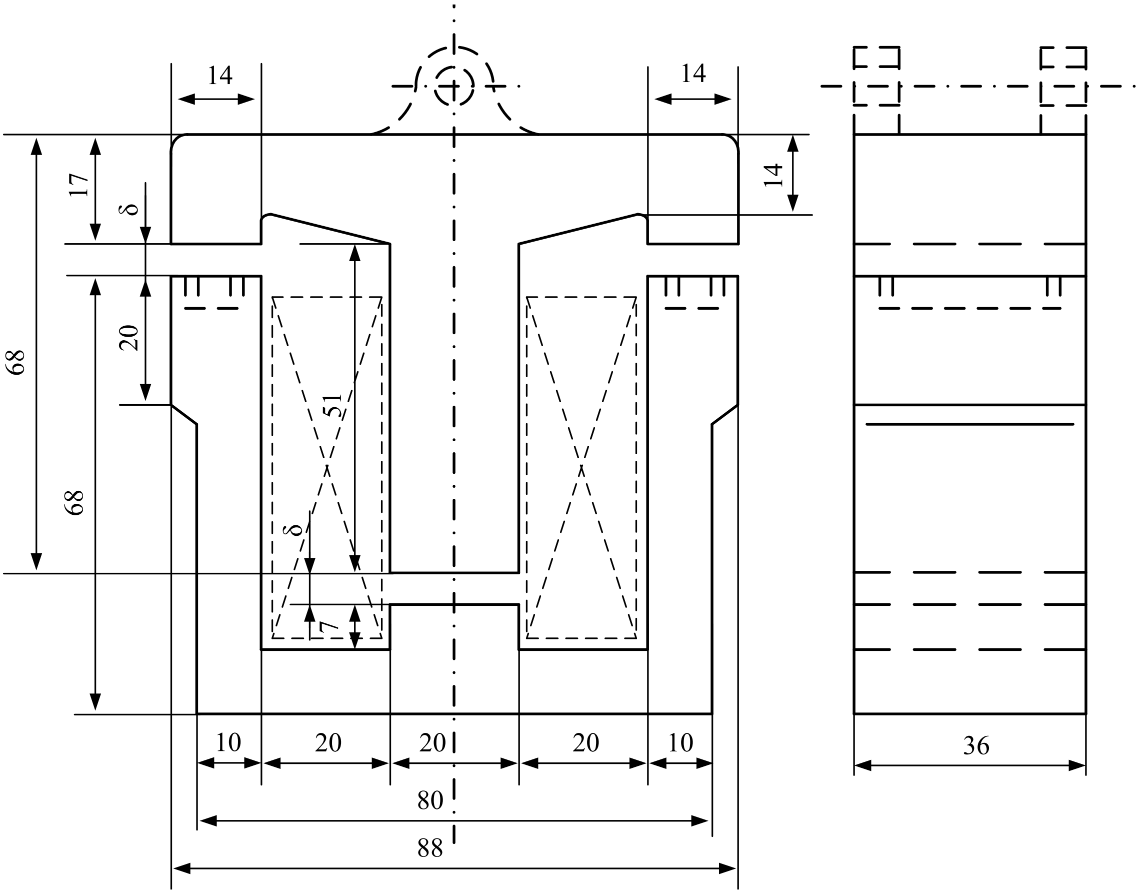

Fig. 4.1. Circuit diagram of AC electromagnet *ЭДО 7101У3*.

As shown in Fig. 4.1, there are three working air gaps in the electromagnet: the middle one through which the whole magnetic flux Φ generated in the coil flows, and two side gaps through which Φ/2 flows. Magnetic conductivity of the middle gap

$$\Lambda_1 = \mu_0 \frac{S_1}{\delta}, \text{ H}, \tag{4.2}$$

where S_1 is the cross-section area of the middle pole, m^2.

Magnetic conductivity of a side air gap

$$\Lambda_2 = \mu_0 \frac{S_2}{\delta}, \text{ H}, \tag{4.3}$$

where S_2 is the cross-section area of a side pole, m^2.

In an equivalent replacement circuit diagram (without steel resistance) in Fig. 4.2 it is shown that conductivity Λ_1 of the middle core is connected in series with two side conductivities Λ_2, which are connected in parallel.

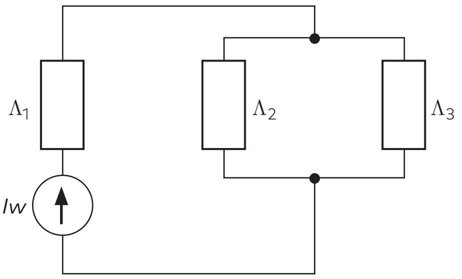

Fig. 4.2. Simple replacement circuit diagram of AC electromagnet.

Since $S_2 = \frac{S_1}{2}$, the total magnetic conductivity

$$\Lambda_\Sigma = \frac{\Lambda_1 \cdot 2\Lambda_2}{\Lambda_1 + 2\Lambda_2} = \frac{\mu_0}{\delta} \cdot \frac{S_1 \cdot 2S_2}{S_1 + 2S_2} = \frac{\mu_0}{\delta} \cdot \frac{S_1^2}{2S_1} = \mu_0 \frac{S_1}{2\delta}. \tag{4.4}$$

Tractive force of an electromagnet is calculated by applying Maxwell's equation:

$$F = \frac{B^2 S}{2\mu_0} = \frac{\Phi^2}{2\mu_0 S}, \tag{4.5}$$

where the magnetic flux generated by the coil

$$\Phi = \frac{E}{4,44\, fw} = \frac{\sqrt{U^2 - (IR)^2}}{4,44\, fw}, \tag{4.6}$$

from which:

$$\Phi = \frac{U^2 - (IR)^2}{39,4\mu_0 f^2 w^2 S}, \tag{4.7}$$

where S is the cross-section area of pole, which determines the total magnetic conductivity, i.e. $S = S_1 / 2$.

When recalculating the coil of an electromagnet for another voltage, the tractive force may not change. Therefore, it must be ensured that $\Phi_1 = \Phi_2$, $(Iw)_1 = (Iw)_2$ under $\delta_{\min}$ and current density in coil winding $j_1 = j_2$. It arises from these conditions that

$$\frac{U_1}{w_1} = \frac{U_2}{w_2} \text{ and } w_2 = w_1 \frac{U_2}{U_1};\; I_2 = \frac{(Iw)_1}{w_2}.$$

Since $j_1 = \frac{I_1}{q_1}$, where $q_1 = \frac{\pi d_1^2}{4}$ is the cross-section area of the "old" coil wire, then

$$q_2 = \frac{I_2}{j_1} \text{ and } d_2 = \sqrt{\frac{4q_2}{\pi}}.$$

Methodical guidelines

Since the starting current of an AC electromagnet is approximately ten times bigger than the operating current, then amperemeter and wattmeter current coil is connected in circuit through a current transformer TA1 (Fig. 4.3). The working air gap is fixed with non-magnetic material sheets, and tractive force is measured using laboratory dynamometer.

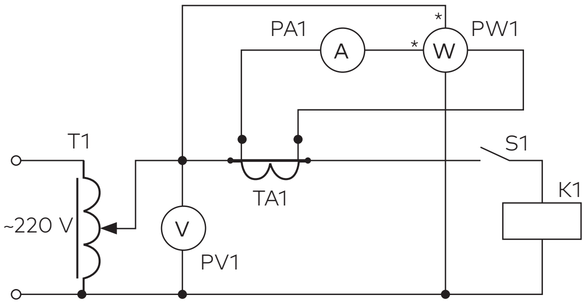

Fig. 4.3. Experiment's circuit diagram.

Measurement results are summarised in the given table, one calculation example must be provided for the calculated characteristics $F=f(\delta)$, $L=f(\delta)$, $X=f(\delta)$, $\cos\varphi=f(\delta)$ in the report, but other results must be summarised in the table and shown graphically.

Measurement results and tables

U_N =		V				I_N =		A
***I* (PA1)**			***P* (PW1)**			***F***		**δ**
i.	**C**	**A**	**i.**	**C**	**W**	**kg**	**N**	**mm**
0.8U_N =		V				0.8I_N =		A
0.5U_N =		V				0.5I_N =		A

Calculation results:

U_N =	V	I_N =	A	
Δ, mm	**F_{apr}, N**	**L, H**	**X, Ω**	**cosφ**
0.8U_N=	V	0.8I_N =	A	
0.5U_N =	V	0.5I_N =	A	

Questions for self-test

1. Why is the magnetic $\Phi = \text{const}$ in AC electromagnet?
2. Why does the coil current of AC electromagnet depend on the size of working air gap?
3. What will happen if AC electromagnet coil is connected to rated voltage without magnetic circuit?
4. What does tractive force of an AC electromagnet depend on?
5. What does coil resistance of AC electromagnet depend on?

PRACTICAL WORK TASK

Designing of electromagnet

This practical work is based on literature source [5].

Work task

To design AC or DC electromagnet according to the provided data by using the calculation formulae and other information given in the design description.

Methodology of designing an electromagnet

This methodology includes three stages of electromagnet (EM) design:

1) *initial calculation* by including applying of simplified interactions that take into consideration in the first approximation the size of magnetic circuit, coil, cross-section, as well as the number of winding turns;
2) *elaboration of EM design* by taking into consideration the results of initial calculation and by applying design factors and parameters based on the design and physical simulation experience;
3) *EM project calculation*, which determines the final adjustment of parameters, dimensions, winding data, as well as the compliance of temperature- and energy-related parameters with the effective legal norms.

The critical air gap must be set depending on the armature movement and the point at which the electromagnet has to develop the largest working capacity in order to overcome the counteracting force. The critical gap corresponds to the *critical electromagnetic force,* which must be slightly higher than the counteracting force F_{pr} corresponding to this air gap, to ensure reliable operation:

$$F_{\mathrm{em}} = k_{\mathrm{r}} F_{\mathrm{pr}}, \tag{P.1}$$

where $k_{\mathrm{r}} = 1.2–1.5$ is safety factor, which is applicable to the most unfavourable operating conditions (drop in voltage when the coil is heated).

Values of the critical force and critical air gap are the initial basic data for EM calculation. In addition, the student must be aware of the operating duty (continuous, short-time), type of current, voltage, frequency, etc.

Choice of electromagnet design form may be based on the prototype or the optimal geometric indicator (constructive factor) G:

- DC electromagnet

$$G = \frac{\sqrt{F_{\mathrm{em}}}}{\delta_{\mathrm{nepiev}}}; \tag{P.2}$$

- AC electromagnet

$$G = \frac{\sqrt{2F_{\mathrm{em}}}}{\delta_{\mathrm{nepiev}}}, \tag{P.3}$$

where δ_{nepiev} — air gap, mm;
F_{em} — electromagnetic attractive force, N.

Each economically designed design form of an electromagnet has definite G values (Table P.1) which depend on the principle of economy and mass.

Steels with low carbon content (in case of direct current) and silicon steels (in case of alternating current) are used for ***making magnetic circuits of electromagnets.***

Recommendations for ***choosing magnetic induction are as follows.***

- If the armature is in attracted position – in the place where there is the maximum flux, induction must be equal with the induction at the inclination of the magnetisation curve. For electrical steels with trademark 1212, 1411, 1511, 1521, etc. this value $B_{\max} = 1.0–1.2$ T.
- If the armature is not attracted, induction is selected according to recommendations depending on the design form and geometric criterion. The maximum induction

of a power electromagnet in case the armature is not attracted to the core $B_{\max} = 0.8–1.2$ T, of a high sensitivity electromagnets (relays) $B_{max} = 0.4–0.7$ T.
- Induction intensity in the working air gap of a power electromagnet is set from 0.6 T to 1 T. In case of alternating current, the calculation is done according to the induction range value.

Table P.1

Geometric criteria of electromagnets of various design forms

Design form of electromagnet	G	
	$N^{0.5}$/m	$kgs^{0.5}$/cm
Cylindrical electromagnet with retractable direct-moving armature		
1) consists of a coil and core armature;	< 63	< 0.2
2) with open magnetic circuit and short conical armature;	63–316	0.2–1.0
3) armature with conical end, angle 60°;	380–1600	1.2–5.0
4) armature with conical end, angle 90°;	1260–5100	4–16
5) armature with flat end	5100–30 000	16–93
Divided in pressed sheets with direct moving attractable T-, E-shaped armature and AC shell core	316–25 000	1–80
Cylindrical electromagnet with external attractable disk armature	30 000–90 000	2.7–270.0
Single-coil electromagnet with one core and external attractable armature	630–63 000	1.9–190.0

Squeezing coefficient $\sigma_{izsp} = \Phi_\delta / \Phi_{gal}$ (where Φ_δ, Φ_{gal} is magnetic flux in the air gap and on the electromagnetic pole end) may be determined if the dimensions of those parts constituting the air gap are known. In previous calculation, squeezing coefficient was assumed to be $\sigma_{izsp} = 1.0–1.8$.

Leakage factor σ_{izkl} for each part of a magnetic circuit (ratio of the maximum or average flux in a circuit part to the flux in the air gap) may be determined if the magnetic conductivity through the air gaps and leakage flux paths is known. In previous calculations, leakage factor is approximate and depends on the following considerations: the leakage flux is small if the armature is attracted; therefore, leakage factor is close to 1; if the armature is not attracted, leakage factor depends on the size of the working air gap and on the magnetic conductivity of leakage fluxes; it varies from 1.1 to 4.0 and more.

The force in calculation equals the critical force in electromagnet in case of one air gap. If the critical air gap is similar to the initial one, the calculation must be done for an unattracted position. If the critical air gap corresponds with the contacting moment, the calculation must be done for an attracted position. **The first of these variants will be used in this work**.

Equations used for DC electromagnets:

$$F_{em} = \frac{\Phi^2_{gal.nepiev}}{2\mu_0 S_{gal}} = \frac{B^2_{gal.nepiev} S_{gal}}{2\mu_0} =$$

$$= 39{,}8 \cdot 10^4 \, B^2_{gal.nepiev} S_{gal}, \text{ N}; \qquad \text{(P.4)}$$

$$S_{gal} = \frac{F_{em}}{39{,}8 \cdot 10^4 \, B^2_{gal.nepiev}}, \text{ m}^2; \qquad \text{(P.5)}$$

where $B_{gal.nepiev} = B_{\delta.nepiev} / \sigma_{izsp}$ is the induction value at the core end in an unattracted position, T.

For monophase AC electromagnets

$$S_{gal} = \frac{F_{em}}{19{,}9 \cdot 10^4 \, B^2_{gal.max.nepiev}}, \text{ m}^2; \qquad \text{(P.6)}$$

Diameter of a core with no pole tip:

$$d = \sqrt{\frac{4S_{\text{gal}}}{\pi}}, \text{ m.} \tag{P.7}$$

Dimensions of a rectangular core:

$$a = \frac{S_{\text{gal}}}{k_{\text{aizp}} \, b/a}, \text{ m,} \tag{P.8}$$

where $b/a = 1\text{–}2$.

According to the rules of a short-circuit winding, ratio of sides $b/a = 0.8\text{–}0.9$.

Fill factor for a steel package is $k_{\text{aizp}} = 0.90$ and $k_{\text{aizp}} = 0.95$, according to the insulation layers of steel sheets with thickness of 0.35 mm and 0.50 mm, respectively.

Dimensions of coil depend on the magnetising force intensity that is necessary for actuation of electromagnet.

Total magnetomotive force for actuation in case of DC:

$$F = (\text{no } 1{,}2 \text{ līdz } 1{,}6) F_\delta = (\text{no } 1{,}2 \text{ līdz } 1{,}6) \frac{B^2_{\delta.\text{nepiev}} \delta}{\mu_0}, \text{ N.} \tag{P.9}$$

Cross-section of DC winding:

$$S_{\text{tin}} = l_{\text{tin}} h_{\text{tin}} = \frac{k_{\max} F}{k_{\min} k_i j k_w}, \text{ mm.} \tag{P.10}$$

Total magnetomotive force for actuation in case of AC:

$$F = \frac{B_{\text{gal.max.nepiev}} \delta_{\text{nepiev}}}{\mu_0} + \frac{B_{\text{gal.max.nepiev}} \sigma \delta_{\text{piev}}}{\mu_0}, \text{ N;} \tag{P.11}$$

where $B_{\text{gal.max.nepiev}} = B_{\delta.\text{max.nepiev}} / \sigma_{\text{izsp}}$ is induction value at the core end in an unattracted position, T; δ_{nepiev}, δ_{piev} is air gap in case of unattracted and attracted armature, m; σ is the factor, which takes into consideration the contact travel and additional travel.

Cross-section of AC winding:

$$S_{\text{tin}} = l_{\text{tin}} h_{\text{tin}} = \frac{k_{\max} F}{k_{\min} k_I k_i j k_{\text{aiz}}}, \tag{P.12}$$

where the factor $k_{\max} = U_{\max} / U_N = 1.05$, and factor $k_{\min} = U_{\min}/U_{\text{N}} = 0.6\text{–}0.9$, in majority of cases.

Overload current factor takes into account the mode (short-time, intermittent). In continuous duty, the overload factor $k_I = 1$. Current factor $k_i = F/F_{\text{piev}} = 4\text{–}15$ (here F_{piev} — magnetomotive force in case of an attracted armature).

In continuous duty, the current density usually is $j = 2\text{–}4$ A/mm^2.

Winding fill factor depends on the form factor, winding irregularity factor and wire insulation factor $k_w = k_\varphi k_{\text{nev}} k_{\text{iz}}$, where wire insulation factor $k_{\text{iz}} = d^2 / d_{\text{iz}}{}^2$ (d, d_{iz} — diameter of non-insulated and insulated wire).

Wire form factor $k_\varphi = 1$ (rectangular wire) or $k_\varphi = 0.785$ (round wire).

Winding irregularity factor $k_{\text{nev}} = 1$ (rectangular wire) or $k_{\text{nev}} = 0.8\text{–}0.9$ (round wire with small diameter), or $k_{\text{nev}} = 0.90\text{–}0.95$ (round wire with diameter > 0.3 mm).

For rationally designed electromagnets, winding side ratio $l_{\text{tin}}/h_{\text{tin}} = 3\text{–}8$ (in DC electromagnets) depending on the design and $l_{\text{tin}}/h_{\text{tin}} = 2\text{–}4$ (in AC electromagnets) depending on the power and travel.

Analysis of the existing designs of electromagnets show that the following $l_{\text{tin}} / h_{\text{tin}}$ values may be assumed for DC electromagnets.

- With external rocking armature:
  - for small electromagnets: 6–7;
  - for big electromagnets: 4–5.

- With external direct-moving armature:
  - for small electromagnets: 7–8;
  - for big electromagnets 5–6.
- With retractable armature:
  - for short-travel electromagnets: 3–5;
  - for long-travel electromagnets: 6–8.

The following $l_{\text{tin}} / h_{\text{tin}}$ values may be assumed for AC electromagnets:

- under comparatively small travel and large power: 2.0–2.5
- under comparatively large travel and small power: 3–4.

Ift $l_{\text{tin}} / h_{\text{tin}}$ value is known, winding dimensions may be determined:

- winding thickness

$$h_{\text{tin}} = \sqrt{\frac{S_{\text{tin}}}{l_{\text{tin}} / h_{\text{tin}}}}, \text{ m}; \tag{P.13}$$

- winding length

$$l_{\text{tin}} = \frac{S_{\text{tin}}}{h_{\text{tin}}}, \text{ m}. \tag{P.14}$$

When the main dimensions of an electromagnet are determined, the sketch [5] is designed and test calculation is done, which includes calculation of magnetic circuit and coil of the electromagnet.

Table P.2

Data for the practical work

Parameter symbol	Parameter	Measurement unit	No.	Variant					
			1	1	2	3	4	5	6
Type of current DC or AC			2	2	DC	DC	DC	DC	DC
F_{pr}	Resistance force of the air gap	N	3	60	120	300	610	900	1000
k_r	Safety coefficient	–	4	1.20	1.20	1.20	1.21	1.22	1.25
$B_{\delta.nepiev}$	Magnetic induction in the air gap (DC)	T	5	0.60	0.65	0.67	0.67	0.69	0.70
$B_{\delta.max.nepiev}$	Maximum induction in the air gap (AC)	T	6	–	–	–	–	–	–
U_N	Rated voltage of the electromagnet	V	7	12.00	12.00	12.00	12.00	13.75	13.75
U_{min}	Minimum voltage of the electromagnet	V	8	9.00	8.30	10.40	9.90	11.65	11.85
U_{max}	Maximum voltage of the electromagnet	V	9	12.60	12.60	12.84	12.60	14.44	14.44
k_I	Overcurrent factor	–	10	1	1	1	1	1	1
k_i	Current factor	–	11	12.24	13.23	13.13	12.43	9.53	7.96
k_{nev}	Factor of irregularity	–	12	0.85	0.87	0.86	0.97	0.96	0.98
k_{aizp}	Fill factor for steel package, considering insulation layers of steel sheets	–	13	0.90	0.95	0.90	0.90	0.95	0.90
j	Current density	A/cm^2	14	3.38	3.77	2.74	2.64	3.27	2.60
σ	Factor, which takes into consideration the contact travel and additional travel	–	15	0.0178	0.0172	0.0141	0.0181	0.0155	0.0140
σ_{izkl}	Leakage factor	–	16	1.37	1.26	1.19	1.16	1.13	1.12
σ_{izsp}	Squeezing coefficient	–	17	1	1	1	1	1	1
Shape of the core: cylindrical (cyl.) or rectangular (rect.)			18	cyl.	cyl.	cyl.	cyl.	cyl.	cyl.
b/a	Side ratio of rectangular core	–	19	–	–	–	–	–	–
l_{tin}/h_{tin}	Winding side ratio	–	20	5.73	6.20	4.06	7.34	3.94	6.12
δ	Working air gap	m	21	0.0111	0.0101	0.0101	0.0113	0.0111	0.0108
δ_{piev}	Air gap if the armature is attracted	m	22	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
δ_{nepiev}	Air gap if the armature is not attracted	m	23	0.0111	0.0101	0.0101	0.0113	0.0111	0.0108
d_{vad}	Non-insulated wire diameter	m	24	0.640	0.640	0.800	1.120	1.740	1.810
$d_{vad.izol}$	Insulated wire diameter	m	25	0.700	0.700	0.865	1.200	1.825	1.905

Continuation of Table P.2

No.	Variant											
1	7	8	9	10	11	12	13	14	15	16	17	18
2	DC	DC	DC	DC	DC	DC	DC	DC	DC	AC	AC	AC
3	1350	1550	1900	2200	3000	3700	9500	12 000	20 000	0.6	2.5	3.0
4	1.26	1.26	1.28	1.29	1.32	1.32	1.35	1.40	1.50	1.21	1.22	1.22
5	0.720	0.730	0.735	0.800	0.840	0.900	0.920	0.945	0.963	–	–	–
6	–	–	–	–	–	–	–	–	–	0.62	0.65	0.65
7	14.5	14.5	24.0	24.0	24.0	52.0	52.0	110.0	220.0	36.0	36.0	36.0
8	12.2	12.4	17.2	17.8	21.1	40.0	46.0	94.0	184.6	29.4	27.0	31.1
9	14.935	15.950	25.200	25.200	25.200	58.240	56.420	120.120	231.000	63.000	37.800	37.800
10	1	1	1	1	1	1	1	1	1	1	1	1
11	9.29	11.96	4.39	6.86	10.43	8.12	6.47	5.80	10.28	6.35	7.02	14.16
12	0.83	0.85	0.99	0.98	0.85	0.95	0.81	0.87	0.84	0.85	0.80	0.86
13	0.95	0.90	0.95	0.90	0.95	0.95	0.90	0.90	0.95	0.95	0.90	0.95
14	2.93	3.56	2.43	2.99	2.02	2.87	2.24	2.51	2.22	2.43	3.06	2.55
15	0.02128	0.01785	0.01430	0.01404	0.01508	0.01495	0.01664	0.01950	0.01612	6.3	6.5	6.9
16	1.11	1.09	0.90	1.38	1.40	1.19	1.12	1.05	1.03	1.80	1.48	1.43
17	1	1	1	1	1	1	1	1	1	1.34	1.25	1.34
18	cyl.	cyl.	cyl.	rect.	rect.	rect.	rect.	rect.	rect.	cyl.	cyl.	cyl.
19	–	–	–	0.6	0.8	0.6	0.6	0.6	0.9	–	–	–
20	7.08	3.01	4.52	3.04	4.00	4.85	3.23	7.44	4.21	3.64	3.50	3.31
21	0.0112	0.0105	0.011	0.0102	0.0101	0.01	0.0113	0.0115	0.0109	0.005	0.0051	0.0052
22	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
23	0.0112	0.0105	0.011	0.0117	0.0116	0.0115	0.0128	0.013	0.0124	0.005	0.0051	0.0052
24	1.880	1.950	1.950	1.950	2.100	2.100	2.100	2.260	2.440	0.670	0.690	0.740
25	1.975	2.045	2.045	2.045	2.200	2.200	2.200	2.360	2.540	0.730	0.750	0.805

Continuation of Table P.2

No.	Variant											
1	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
2	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
3	14	30	40	50	150	900	1100	2000	2300	3500	2000	2800
4	1.23	1.24	1.25	1.28	1.30	1.33	1.33	1.33	1.40	1.45	1.47	1.49
5	–	–	–	–	–	–	–	–	–	–	–	–
6	0.65	0.66	0.695	0.71	0.72	0.75	0.75	0.78	0.81	0.83	0.85	0.86
7	50	50	50	230	230	230	230	230	230	230	230	230
8	40.4	42.5	35.1	171.2	174.3	190.3	177.7	199	208.9	174.2	175.9	167.6
9	54.5	52.5	52.5	236.9	241.5	243.8	248.4	241.5	241.5	241.5	246.1	241.5
10	1	1	1	1	1	1	1	1	1	1	1	1
11	5.86	8.90	9.25	6.71	8.38	6.90	14.79	10.64	5.89	11.36	8.35	5.81
12	1.00	0.94	0.95	0.99	0.97	0.89	0.98	0.91	0.96	0.85	0.81	0.81
13	0.90	0.90	0.95	0.90	0.90	0.95	0.90	0.95	0.95	0.90	0.90	0.90
14	2.69	3.25	3.82	2.60	3.97	3.04	3.82	2.82	2.22	2.40	2.04	3.85
15	6.3	6.6	6.8	6.2	6.2	6.8	6.1	6.6	6.1	6.7	6.6	6.6
16	1.21	1.16	1.15	1.11	1.11	1.09	1.16	1.16	1.04	1.07	1.03	1.04
17	1.51	1.49	1.48	1.75	1.08	1.63	1.09	1.16	1.71	1.17	1.57	1.55
18	cyl.	cyl.	cyl.	cyl.	cyl.	rect.	rect.	rect.	rect.	rect.	rect.	rect.
19	–	–	–	–	–	0.7	0.7	0.7	0.9	0.6	0.6	0.6
20	3.75	2.96	2.41	2.80	2.53	3.79	3.78	3.02	2.23	2.59	3.46	3.35
21	0.0053	0.0054	0.0055	0.0056	0.0060	0.0080	0.0080	0.0100	0.0100	0.0100	0.0100	0.0150
22	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
23	0.0053	0.0054	0.0055	0.0056	0.0060	0.0080	0.0080	0.0100	0.0100	0.0100	0.0100	0.0150
24	0.800	0.860	0.930	1.000	1.160	1.300	1.680	1.880	2.260	2.260	2.440	2.440
25	0.865	0.925	0.995	1.080	1.240	1.385	1.765	1.975	2.360	2.360	2.540	2.540