Ministry of Education and Science of Ukraine

ZAPORIZHZHA POLYTECHNIC NATIONAL UNIVERSITY

STUDY OF ELECTROMAGNETIC SYSTEMS

Methodical instructions for the laboratory works on the subject:
“Fundamentals of the Theory of Electrical Apparatus”

for the students of the specialty 141:
"Electrical Power, Electrical and Electromechanical Engineering"
(educational program **“Electric and Electronic Apparatus”**

2022

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INTRODUCTION

Performing laboratory works is one of the most important stages of studying the subject "Fundamentals of the theory of electrical apparatus", which, in turn, is key one in the study process of the students according to the educational program "Electrical and electronic apparatus" of specialty 141 – Electric power, electrical and electromechanical engineering.

In execution of the laboratory works, students perform an experimental study of processes typical for a wide variety of electrical apparatuses. In particular, this cycle of laboratory works is devoted to the study of processes taking place in electromagnetic devices. The performance of such laboratory work is usually involved in the use of electricity and facilities that represent increased hazard. Therefore, before performing a cycle of laboratory works, each student must undergo a safety briefing. Students who have not passed the briefing are not allowed to work.

The student must receive the assignment for laboratory work at least a week before its practical performance, and prepare for it in advance. He must study the content of the laboratory work and the theoretical material related to its subject, prepare a blank for a report for the work, i.e. draw up schemes of experiments, prepare tables to enter its findings, formulas for calculations, etc. At the beginning of the class, the teacher checks whether the student has credits for previously performed works and readiness for the next laboratory work. Students who did not receive credits for the previous laboratory work are not allowed to take the next one.

Before starting the practical performing the laboratory work, the student should study the construction and operation of the laboratory stand. The student must apply voltage to the stand only with the teacher's permission. After obtaining the experimental findings, the student must coordinate them with the teacher and only then disassemble the circuit. The defense on the laboratory work report is carried out only in classes or at the time determined by the teacher.

Laboratory work № 1

STUDY OF AIR-GAP PERMEANCES

Duration of the laboratory study is 4 hours

1.1 Purpose of the work

The purpose of the laboratory work is to study the technologies and perform practical work for the experimental finding the air-gap permeances for the magnetic circuits of electromagnetic devices.

1.2 Subject of the study

Magnetic circuits of the electromagnetic devices in many cases include non-magnetic (in most cases air) gaps, in particular, working ones to ensure the operating stroke of its movable parts, as well as idle ones resulted from engineering solutions in regard to its construction. Some part of the magnetic motive force (MMF) of the magnetizing coil is applied to pass magnetic flux through the gaps. To find the MMF spent for this purpose at a certain flux is possible, when the *magnetic resistance* or *reluctance* of the gap or its inverse value *magnetic conductance* or *permeance* is known. The main difficulty in determining the permeances of air gaps lies in the non-uniformity of the magnetic field in the gap. A typical pattern of the magnetic field in the air gap is given in Fig. 1.1a. For practical calculations of the permeance of non-magnetic gaps, an idealized pattern is usually used, Fig. 1.1b.

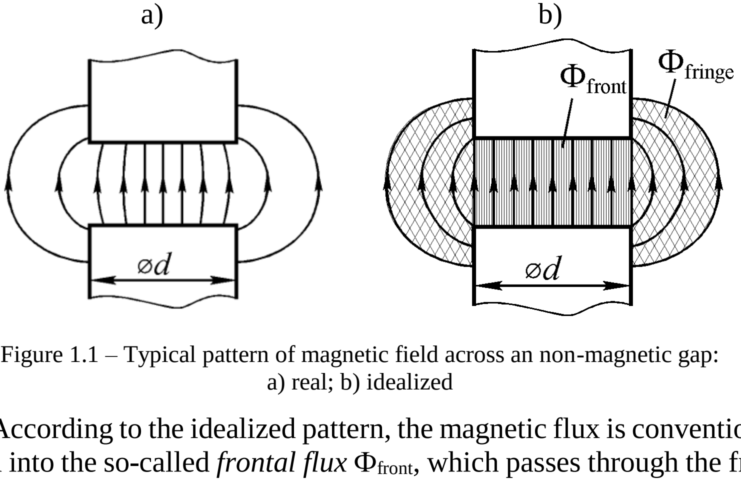

Figure 1.1 – Typical pattern of magnetic field across an non-magnetic gap:
a) real; b) idealized

According to the idealized pattern, the magnetic flux is conventionally divided into the so-called *frontal flux* Φ_{front}, which passes through the frontal surface of the pole, and the so-called *fringe flux* Φ_{fringe} passing through edges and flank surfaces of the pole. The relationship of these components of the magnetic flux is characterized by the so-called *fringe ratio*, which is the ratio of the total flux passing through the gap to the frontal flux:

$$\sigma_{\text{fringe}} = \frac{\Phi_\delta}{\Phi_{\text{front}}} = \frac{\Phi_{\text{front}} + \Phi_{\text{fringe}}}{\Phi_{\text{front}}}.$$

If the value of the gap is much smaller than the dimensions of the pole, then the fringe flux can be neglected and the gap permeance can be found under the condition of a uniform magnetic field in the air gap. In other cases, to determine the gap permeance, it should be used one of the existing calculation methods: [[2–8]]

- the method of probable paths of the flux (Roters' method);
- the use of the specific permeances from the edges and side surfaces of the pole;
- the use of pattern of the magnetic field (magnetic field mapping);
- the method of conventional poles;
- the use of empirical formulas.

1.3 Description of the experimental plant

During the laboratory work, the air-gap permeance and fringe ratio between square-shaped poles are experimentally determined wit help of the experimental plant illustrated in Figure 1.2.

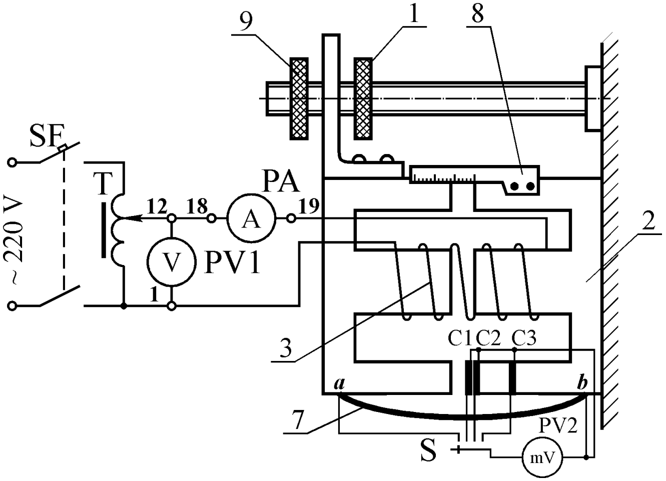

Figure 1.2 – Outline and circuit diagram of the laboratory plant

The heart of the plant is ac electromagnet with E-shaped magnetic circuit 2. The one of lateral poles of the magnetic circuit is fitted with sensing coils C$_1$, C$_2$ and C$_3$. The coils are arranged so that coil C$_1$ linkages with the flux passing through the pole frontal surface ($\Phi_1 = \Phi_{\text{front}}$), C$_2$ linkages with the total flux passing through frontal surface and edges of the pole ($\Phi_2 = \Phi_{\text{front}} + \Phi_{\text{edges}}$), C$_3$ linkages with the total flux passing through the air-gap ($\Phi_3 = \Phi_\delta$).

The terminals of the sensing coils are connected with multiposition switch S. Magnetic potential drop across the air-gap is measured with air-cored sensing coil (Rogowsky coil) 7 that is connected to switch S as well. EMFs induced by the sensing coils are measured with the millivoltmeter PV2 connected to the terminals arranged on the panel. The air-gap to be studied is adjusted with the washers 1 and 9, and controlled by the rule 8. The same washers and rule are in under-part of the magnetic circuit (not shown in Figure 1.2). The electromagnet magnetizing winding 3 is connected to adjustable supply voltage in the range from 0 to 250 V and is measured with the voltmeter PV1.

Using the measured EMFs of the sensing coils U_1, U_2, U_3 magnetic fluxes Φ_1, Φ_2 and Φ_3 are found from the following formula:

$$\Phi_i = \frac{U_i}{4{,}44 \cdot f \cdot w_{\text{c}}}, \qquad (1.1)$$

where f is the frequency of the power source;

w_{c} is the number of turns of sensing coils C$_1$, C$_2$ and C$_3$ equal to 20.

EMF induced by the Rogowsky coil is direct with its flux linkage

$$E_{\text{c}} = \omega \cdot \Psi, \qquad 1.2)$$

and flux linkage is

$$\Psi = \mu_0 \cdot S_{\text{c}} \cdot w'_{\text{c}} \cdot U_{\text{m.}a\text{-}b}, \qquad (1.3)$$

where μ_0 is the magnetic constant equal to $12.56 \cdot 10^{-7}$ H/m;

S_{c} is the cross-sectional area of the Rogowsky coil equal to $2 \cdot 10^{-5}$ m^2;

w'_{c} is reduced number of turns of the Rogowsky coil equal 13300;

$U_{\text{m.}a\text{-}b}$ is magnetic potential drop across the Rogowsky coil, A.

From the formula (1.5) it follows:

$$(Iw)_\delta = U_{\text{m.}a\text{-}b} = \frac{\Psi}{\mu_0 \cdot S_{\text{c}} \cdot w'_{\text{c}}}. \qquad (1.4)$$

If the expression for the flux linkage from the formula (1.4) is substituted to the formula (1.6), the result will be as follows:

$$(Iw)_\delta = U_{\text{m.}a\text{-}b} = c \cdot E_{\text{c}}, \qquad (1.5)$$

where c is the constant of the system Rogowsky coil–voltmeter determined by the following expression:

$$c = \frac{1}{\mu_0 \cdot S_c \cdot w'_c \cdot \omega}. \tag{1.6}$$

In such a way, measuring the Rogowsky coil EMF the magnetic potential drop across the air-gap being studied can be found. Then having values Φ_i and $(Iw)_\delta$, the studied air-gap permeance can be found by Ohm's law for a magnetic subcircuit

$$\Lambda_\delta = \frac{\Phi_3}{(Iw)_\delta}. \tag{1.7}$$

Using the found values Φ_1, Φ_2 and Φ_3, fringe ratio for the air-gap being studied can be computed

$$\sigma_{\text{fringe}} = \frac{\Phi_3}{\Phi_1}. \tag{1.8}$$

1.4 Task

1.4.1 Experimentally determine the permeances between square-shaped poles as well as fringe ratio at some values of the air-gap.

1.4.2 Compute the permeances from the pole frontal surface and total permeances as well as fringe ratios for the air-gap for the same values.

1.4.3 Plot the diagrams of the found dependences.

1.4.4 Compare experimental and computed findings.

1.4.5 Make conclusions about performed work.

1.5 Methodical instructions

1.5.1 Connect the terminals of the laboratory panel with terminals of the laboratory table with the same numbers 1–1, 12–12, 18–18, 19–19 by means of the short connectors (see Figure 1.2). Millivoltmeter PV2 should be connected to the relevant terminals as well.

1.5.2 Adjust one of the gap values (predetermined by the teacher) with help of washers 1 and 9 against the rule 8.

1.5.3 Close circuit-breaker SF and with the help of autoformer T adjust the supply voltage predetermined by the teacher against the voltmeter PV1.

1.5.4 Adjusting multiposition switch S sequentially in positions П, $К_1$, $К_2$, $К_3$, measure EMFs of the Rogowsky coil $E_п$ and the sensing coils U_1, U_2, U_3. Enter the measured findings into table 1.1.

Table 1.1 – Experimental findings

δ, mm	E_c, V	(Iw), A	EMFs of the sensing coils and values of magnetic fluxes						Computed values		
			U_1, V	Φ_1, Wb	U_2, V	Φ_2, Wb	U_3, V	Φ_3, Wb	Λ_{front}, H	Λ_δ, H	σ_{fringe}

1.5.5 Repeat items 1.5.3 and 1.5.4 for 4–5 values of the air-gap. As the air-gap value more than 10 mm, the measurements should be performed promptly as possible to avoid excessive heating of the magnetizing winding.

1.5.6 After terminating the measurements autoformer T must be zeroed and automatic breaker SF must be opened.

1.5.7 Using formulas (1.3), (1.7–1.9), compute the quantities (Iw), Φ_i, Λ_{front}, Λ_δ, and σ_{fringe} and enter them into table 1.1.

1.5.8 Permeance from the frontal surface, total permeance and fringe ratio should be computed for the same air-gap values as accepted ones during the experiment using the following formulas:

$$\Lambda_\delta = \mu_0 \left[\frac{a \cdot b}{\delta} + 0{,}52(a+b) + \frac{1{,}28 \cdot (a+b)}{\frac{\delta}{m}+1} \right]; \tag{1.9}$$

$$\Lambda_{front} = \mu_0 \cdot \frac{a \cdot b}{\delta} \tag{1.10}$$

$$\sigma_{fringe} = \frac{\Lambda_\delta}{\Lambda_{front}}, \tag{1.11}$$

where a and $в$ are the pole dimensions equal to 31 and 15 mm, respectively;

$m = (1 \ldots 2)\delta$.

1.5.9 Computed findings should be entered into table 1.2.

Table 1.2 – Theoretical findings

δ, mm	Λ_{front}, H	Λ_δ, H	σ_{fringe}

1.5.10 Report on the laboratory work should contain:

a) the title and purpose of the laboratory work;
b) outline of the experimental plant;
c) tabulated experimental and theoretical findings;
d) graphical dependences;
e) conclusions on the work.

1.6 Self-checking questions

1.6.1 Ohm’s and Kirchhoff’s laws for magnetic circuits [3–7, 9].

1.6.2 Distribution of a magnetic flux over an air gap [3–7, 9].

1.6.3 Fringe ratio of magnetic flux [3–7, 9].

1.6.4 Calculation procedures for air-gaps permeances and their content [3–7, 9].

Laboratory work № 2

STUDY OF DC ELECTROMAGNETIC SYSTEM

Duration of the laboratory study is 4 hours

2.1 Purpose of the work

The work is aimed to determine experimentally distribution of the magnetic flux along the magnetic circuit and pulling (force–travel) characteristic of dc electromagnet.

2.2 Subject of the study

As it is known, in electric circuits an electric current passes entirely through wires. In magnetic circuits, by contrast, there exist so-called *stray* or *leakage fluxes*. Even in the simplest magnetic circuits, the real pattern of the magnetic field is very complex. These fluxes can take a variety of paths, bypassing the working subcircuits (working air gaps) of the magnetic circuit. To take into account all stray fluxes is practically impossible. When practical calculations of magnetic circuits are performed, only the main stray fluxes (leakage fluxes) are usually taken into account. Figure 2.1 illustrates one of the examples of the magnetic flux distribution in a clapper-type electromagnet.

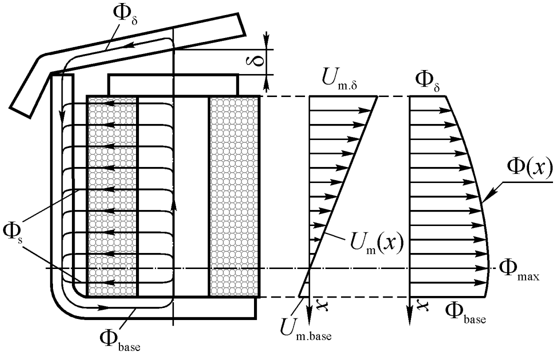

Figure 2.1 – Distribution of magnetic flux and potential drop lengthways the clapper-type magnetic circuit

The part of the magnetic flux passing between the core and yoke is, in the case, the leakage flux Φ_s. It depends on the operating air-gap value. The greater the air-gap is, the greater will be the leakage flux. At big air-gap values, the leakage flux can exceed operating one.

Relationship between fluxes through magnetic circuit is defined by means of leakage ratio. It is the relation between flux through any cross-section of the magnetic circuit and the flux across operating air-gap Φ_δ

$$\sigma_x = \frac{\Phi_x}{\Phi_\delta}, \qquad (2.1)$$

where Φ_x is the flux through the cross-section situated at distance x from the operating air-gap; respectively, this flux is added of the flux across the operating air-gap and the leakage flux:

$$\Phi_x = \Phi_\delta + \Phi_{sx}, \qquad (2.2)$$

where Φ_{sx} is the leakage flux within the section between the operating air-gap and cross-section x.

The *force-stroke* (*tractive*) *characteristic* of an electromagnet is the dependency of the electromagnetic (tractive) force on the operating air-gap value. An electromagnetic force substantially depends on the magnetic flux across the operating air-gap. At small gaps, when fringe flux can be neglected, tractive force can be found from the Maxwell's formula:

$$F_{\mathrm{e/m}} = \frac{\Phi_\delta^2}{2\mu_0 S}, \qquad (2.3)$$

where Φ_δ is the magnetic flux across the operating air-gap, Wb;

S is the cross-sectional area of the pole, m^2.

At large gaps, the computation of electromagnetic forces with the Maxwell's formula results in appreciable errors. In such cases, they are computed by the formula derived from energy balance equation of an electromagnet:

$$F_{\mathrm{e/m}} = 0.5 \cdot (Iw)_\delta^2 \frac{d\Lambda_\delta}{d\delta}, \qquad (2.4)$$

where $(Iw)_\delta$ is the magnetic potential drop across the operating air-gap, A;

Λ_δ is the permeance of the operating air-gap, H.

Behavior of force-stroke characteristic depends on the magnetic circuit design of the electromagnet. The force-stroke characteristic of clapper-type electromagnets is hyperbolical. That is, when an air-gap value is large, its reduction does not lead to a significant increase in magnetic conductivity and magnetic flux. However, when the gap is small, its slight reduction leads to a sharp increase in the magnetic conductivity of the gap, which causes a sharp increase in the flow and traction force of the electromagnet.

2.3 Description of the experimental plant.

The study is carried out using the electromagnet mechanism of the dc contactor КП-505 with removed arc-extinguishing device. At particular places of the magnetic circuit, sensing coils are installed according to Figure 2.2a. Terminals of the sensing coils are connected with the fluxmeter РФ via the multiposition switch S. Electrical circuit diagram of power supply of the electromagnet magnetizing winding is represented in Figure 2.2b. The electromagnet winding K is supplied from ac power network via the automatic circuit-breaker SF, autoformer T and rectifier VD1...VD4.

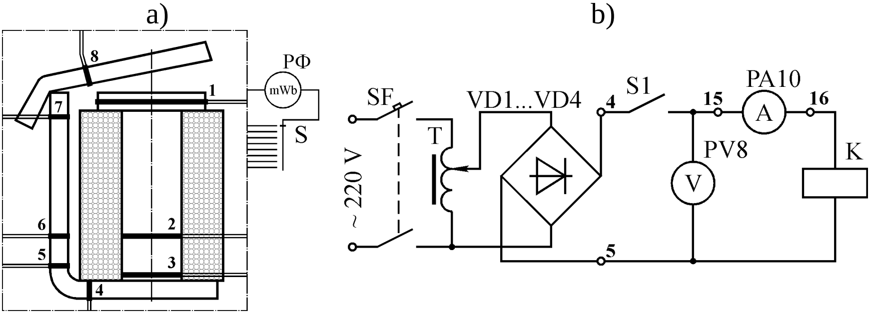

Figure 2.2 – The laboratory plant: a) outline; b) electrical circuit diagram

2.4 Task

2.4.1 Experimentally determine the distribution of magnetic flux along the magnetic core at variable operating air-gap in the range of 0 to 5 mm.

2.4.2 Experimentally determine the force-stroke characteristic of the electromagnet.

2.4.3 Compute the force-stroke characteristic of the electromagnet.

2.4.4 Plot the experimental and computational dependences:

- distribution of magnetic flux along the magnetic core;
- force-travel characteristics of the electromagnet.

2.4.5 Make conclusions in respect to performed work.

2.5 Methodical instructions

2.5.1 Connect the laboratory panel with the table using the short connectors 4–4, 5–5, 15–15, 16–16 according to circuit diagram illustrated by Figure 2.3.

2.5.2 Fix the desired operating air-gap using the non-magnetic spacers.

2.5.3 Connect the fluxmeter РФ to the relevant terminals of the laboratory panel.

2.5.4 Close the circuit breaker SF and adjust a voltage of 220 V using the autotransformer T (the voltage is controlled with the voltmeter PV8).

2.5.5 Close the toggle switch S1.

2.5.6 Place the switch S according to desired sensing coil and, respectively, the magnetic circuit cross-section.

2.5.7 Place the fluxmeter in the duty "Корректор" and adjust device's pointer in extremely left position using the relevant handle. Then change over the fluxmeter to the duty "Измерение". The indications of the device should be entered to table 2.1.

Table 2.1 – Distribution of the magnetic flux throughout the magnetic circuit

Air-gap, mm	Indications of the fluxmeter, magnetic flux	Numbers of the sensing coils							
		1	2	3	4	5	6	7	8
$\delta = 0$	α_1, divisions α_2, divisions Φ, Wb								
$\delta = 1$	α_1, divisions α_2, divisions Φ, Wb								
$\delta = 3$	α_1, divisions α_2, divisions Φ, Wb								
$\delta = 5$	α_1, divisions α_2, divisions Φ, Wb								

2.5.8 Open the toggle switch S1 and take new indication of the fluxmeter that should be entered to table 2.1. Then close the toggle switch S1.

2.5.9 The measurements according to item 2.5.8 should be taken for other sensing coils and values of the air-gap according to table 2.1.

2.5.10 Magnetic flux should be determined from the following formula:

$$\Phi_i = \frac{c \cdot (\alpha_1 - \alpha_2)}{w_{п}}, \tag{2.5}$$

where i is the number of the sensing coil;

α_1, α_2 are the initial and final indications of the fluxmeter scale, respectively;

c is the constant of the fluxmeter equal 10^{-4} Wb/div;

$w_{п}$ is the number of turns of the sensing coil equal to 6.

2.5.11 The force-stroke characteristic should be taken at power voltage of the magnetizing winding of 170 and 210 V.

2.5.12 The electromagnetic forces should be measured with spring force gauge; their value is noted at the moment of separating the armature from the core.

2.5.13 In order to determine the electromagnetic forces, mechanical diagram of the measurements should be set up and relationship between the arms should be found.

2.5.14 Computation values of electromagnetic force should be determined from the formulas (2.3) or (2.4).

2.5.15 Experimental and computed findings are entered into table 2.2.

Table 2.2 – The values of the electromagnetic forces

Findings	U_1 = 210 V				U_2 = 170 V			
	δ_1	δ_2	δ_3	δ_4	δ_1	δ_2	δ_3	δ_4
Experimental, N								
Computational, N								

2.5.16 Report on the laboratory work must contain:

a) the purpose of the work;

b) outline of the laboratory plant;

c) mechanical diagram to reduce the measured forces to electromagnet axis;

d) tables with experimental and computed findings and plotted distribution curves of magnetic flux along the core and force-stroke characteristics;

e) conclusions on the work.

2.6 Self-checking questions

2.6.1 What is leakage ratio? [3–9].

2.6.2 How does leakage ratio vary under increase of operating air-gap value? [3–9].

2.6.3 Behavior of dependence between static electromagnetic force and operating air-gap [3–7, 9].

2.6.4 Distribution of magnetic flux and potential drop lengthways electromagnet core [3–9].

2.6.5 The fundamental laws of analysis DC electromagnets [3–7, 9].

Laboratory work № 3

STUDY OF AC ELECTROMAGNETIC SYSTEM

Duration of the laboratory study is 4 hours

3.1 Purpose of the work

The purpose is to determine experimentally distribution of magnetic flux lengthways the magnetic circuit as well as effect of the area enclosed by shading ring to pulsation of electromagnetic forces.

3.2 Subject of the study

As differentiated from dc electromagnetic system, in an AC electromagnetic systems midvalue of magnetic flux peak practically does not depend on air-gap value and can be found from the formula:

$$\Phi_{\mathrm{m\,cp}} = \frac{\sqrt{2}\cdot U}{\omega\cdot w} = \frac{U}{4{,}44\cdot f\cdot w}, \tag{3.1}$$

where U is the rms power voltage of the magnetizing winding, V;

$\omega = 2\pi f$ is the angle frequency of the power source of the magnetizing winding;

w is the number of turns of the magnetizing winding.

Amplitude value of the magnetic flux through an operating air-gap is

$$\Phi_{\mathrm{m}\delta} = \frac{\Phi_{\mathrm{m.cp}}}{\sigma_{\mathrm{cp}}},$$

where σ_{cp} is the midvalue of leakage ratio corresponding to the average value the magnetic flux peak; as already noted, its magnitude is dependent upon the value of the working gap.

Thus, although midvalue of the flux peak through a magnetic circuit $\Phi_{\mathrm{m.cp}}$ is constant, the flux peak across an operating air-gap $\Phi_{\mathrm{m}\delta}$ depends on its value. Because of this, the fluxes across other subcircuits also depend on the operating air-gap. It should be noted that this dependence far less than in dc electromagnetic systems. It results from the fact that in dc electromagnetic systems the value of an air-gap effects on both magnetic flux midvalue and leakage ratio.

If leakage flux is neglected, magnetomotive force (MMF) of magnetizing winding can be found from the following expression:

$$(Iw) = \frac{\Phi_{\text{m.cp}}}{\sqrt{2}} \cdot Z_{\text{mag.}\Sigma}\,, \tag{3.2}$$

where $Z_{\text{mag.}\Sigma}$ is total magnetic impedance of the magnetic circuit.

If magnetic potential drops across the iron subcircuits and idle air-gaps as well as fringe flux in the operating air-gap are neglected, MMF can be expressed as:

$$(Iw) = \frac{\Phi_{\text{m.cp}} \cdot \delta}{\sqrt{2} \cdot \mu_0 \cdot S}$$

where μ_0 is permeability of air; it equals $4\pi \cdot 10^{-7}$ H/m;

S is the area of the operating air-gap poles, m^2;

δ is the value of the operating air-gap, m.

So, MMF and, as sequence, current through a magnetizing winding are directly dependent upon the operating air-gap. Actually dependence between MMF and operating air-gap is not direct since reluctance of iron subcircuits and idle air-gaps are available; nevertheless, it is highly substantial.

In single-phase electromagnetic systems, the magnetic flux follows to sine curve resulting in during a cycle, two zeros naturally occur. The tractive force in this case also follows to sine curve as well, but the force has two components: dc component and ac component varying with double power frequency from zero up to maximal value. In this situation there is the times intervals when the tractive force will be less than counteracting one. During these intervals, an armature exerted by counteracting force will break away from the core, and when tractive force in excess of counteracting one, the armature is attracted again to the core. This repetitive process unavoidably results in phenomenon named as “armature bounce”, which negatively effects on ac electromagnets performances.

In order to avoid this phenomenon, in single phase electromagnets variety of techniques is applied such as, increase of movable parts mass, increase friction forces in axles of rotation etc. One of effective techniques that enables to avoid armature bounce phenomenon is application of *shorted turns* (*shading rings*), which encloses a part of a pole frontal surface of the operating air-gap, as illustrated in Figure 3.1.

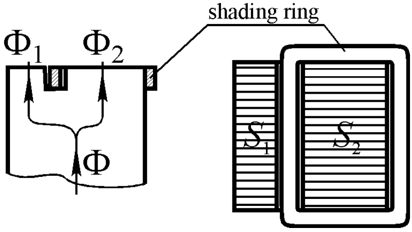

Figure 3.1 – The pole of ac electromagnet with shading ring

In this case, magnetic flux Φ is shared into two fluxes: Φ_1 passing through the area S_1 and Φ_2 passing through the area S_2 enveloped by shading ring. Under action of ac magnetic flux Φ_{20}, being excited by the magnetizing winding, EMF E_{sc} is induced in shading ring. It, in turn, excites magnetic flux Φ_{sc}. Total flux Φ_2 is geometrical sum of the fluxes Φ_{20} and Φ_{sc} shifted relatively to Φ_1 by the angle Ψ that is illustrated by Figure 3.2.

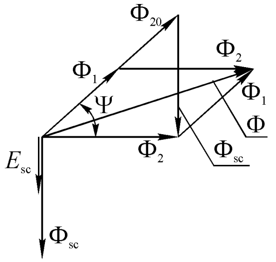

Figure 3.2 – Vector diagram of magnetic fluxes

Accordingly, the traction forces produced by the fluxes Φ_1 and Φ_2 will be shifted one from another on the angle 2Ψ. It results in decrease of pulsation of total traction force. If the conditions: $\frac{\Phi_1}{S_1}=\frac{\Phi_2}{S_2}$ and $\Psi = 90^\circ$ are fulfilled, the traction force will be constant, and its pulsation, respectively, will be zero.

It is impossible to fulfill the last condition (in actual electromagnets usually $\Psi = 50^\circ \ldots 60^\circ$) and pulsation of traction force is always available. Nevertheless, armature bounce can be precluded, provided that traction force (in particular, its minimal value) will be more than counteracting one at any moment.

3.3 Description of the experimental plant

The heart of the experimental plant illustrated by the Figure 3.3 is overvoltage relay of the type РЭ-2-100. There following basic units includes the relay being investigated: magnetizing winding 1, magnetic circuit 2 and armature 3 laminated of isolated plates to reduce eddy currents losses.

Desired value of the operating air gap is fixed with non-magnetic spacers. Sensing coils 1–8 with the number of turns 20 are installed at certain places of the magnetic circuit. They serve for measurement of magnetic flux distribution throughout the magnetic circuit. Sensing coils 9 and 10, with the same number of turns 20, serve to measure the magnetic fluxes passing through the pole face enclosed or non-enclosed by the shading ring. Terminals of the sensing coils are connected to multiposition switch S1. Electromotive forces of the sensing coils are measured with millivoltmeter PV1 connected to laboratory panel via the plug X. The magnetizing winding of the relay is supplied from the power network via the automatic breaker SF and autoformer T. Voltage across the magnetizing winding and current through it are measured with the voltmeter PV and ammeter PA7, respectively.

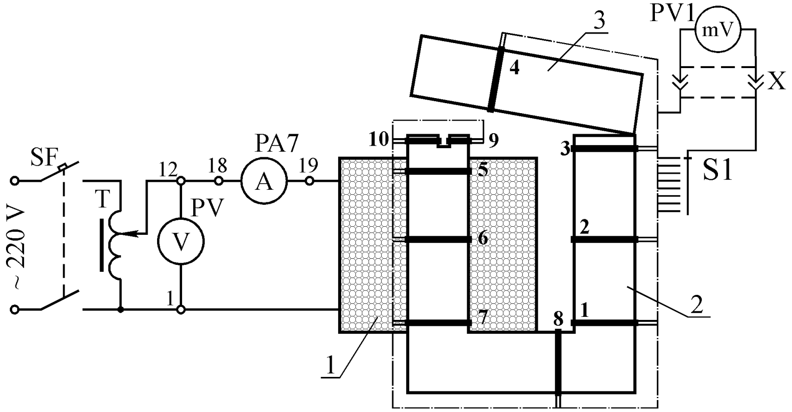

Figure 3.3 – Outline of the laboratory work and circuit diagram

3.4 Task

3.4.1 To determine experimentally the distribution of magnetic flux along the magnetic core at variable operating air-gap and plot corresponding graphical diagram.

3.4.2 To find experimentally dependency the current through the magnetizing winding vs the operating air-gap value and plot corresponding graphical diagram.

3.4.3 To determine experimentally the influence of the pole face area enclosed by shading ring on the minimal electromagnetic force and plot graphical diagram of the dependency $F_{\min} = f\left(S_2\right)$.

3.4.4 Make conclusions in respect to performed work.

3.5 Methodical instructions

3.5.1 The laboratory panel is to be connected to the power source and instruments by insertion of connecting conductors between terminals with the same numbers: 1–1, 12–12, 18–18, 19–19, 25–25, 26–26. Millivoltmeter PV1 is to be connected to the laboratory panel by means of plug X.

3.5.2 Desired value of the operating air-gap is to be fixed with non-magnetic spacers.

3.5.3 Close the automatic breaker SF and adjust a voltage of 220 V using the autotransformer T (the voltage is controlled with the voltmeter PV).

3.5.4 Measure current through the magnetizing winding with ammeter PA7. The electromotive forces generated by the sensing coils are to be measured by sequential its connection to the millivoltmeter PV1 with multiposition switch S1. Measured findings are to be entered into table 3.1.

3.5.5 Open the automatic breaker SF.

3.5.6 Perform the operations according to items 3.5.2–3.5.6 for other values of the operating air-gap.

3.5.7 The magnetic fluxes through respective cross-sections of the magnetic circuit is computed with the following formula:

$$\Phi_i = \frac{U_i}{4{,}44 \cdot f \cdot w}, \tag{3.3}$$

where U_i is the voltage across respective sensing coil, V;

w is the number of turns of the sensing coils equal to 20;

f is the frequency of the power network equal 50 Hz.

Computed findings should be entered into table 3.1.

Table 3.1 – Distribution of magnetic fluxes throughout the magnetic circuit

Air-gap, mm	Current through the field winding, A	The studied quantities	Numbers of the sensing coils							
			1	2	3	4	5	6	7	8
0		$U_{\text{к}i}$, V Φ_i, Wb								
2		$U_{\text{к}i}$, V Φ_i, Wb								
4		$U_{\text{к}i}$, V Φ_i, Wb								
5		$U_{\text{к}i}$, V Φ_i, Wb								

3.5.8 Item 3.4.3 of the task should be performed in the following order:

a) install the shading ring so that it encloses greater part of the pole frontal surface (in this case $S_2 = 2.42 \cdot 10^{-4}$ m^2);

b) close the automatic breaker SF and once the armature has been attracted, measure the electromotive forces of the sensing coils 9 i 10 (see Figure 3.3); the measured findings should be written into table 3.2;

Table 3.2 – Experimental and computed findings in respect to determine minimal value of electromagnetic force $F_{\min}$.

Non-enclosed part of the pole			Enclosed part of the pole			$F_{\min}$, N
S_1,m^2	U_9,V	Φ_1,Wb	S_2,m^2	U_{10},V	Φ_2,Wb	
$0.88\cdot10^{-4}$			$2.42\cdot10^{-4}$			

c) open the automatic breaker SF; once the shading ring has cooled down, it should be installed so that it encloses smaller part of the pole frontal surface (in this case $S_2 = 0.88\cdot10^{-4}$ m^2); the measurements should be performed according to item b); the measured findings should be written into table 3.3.

Table 3.3 – Experimental and computed findings in respect to determine minimal value of electromagnetic force $F_{\min}$.

Non-enclosed part of the pole			Enclosed part of the pole			$F_{\min}$, N
S_1,m^2	U_{10},V	Φ_1,Wb	S_2,m^2	U_9,V	Φ_2,Wb	
$2.42\cdot10^{-4}$			$0.88\cdot10^{-4}$			

3.5.9 Close automatic breaker SF and disconnect the plant.

3.5.10 Compute minimal value of electromagnetic forces for respective arrangement of the shading ring. To do this the following operations are to be performed:

a) calculate the fluxes Φ_1 and Φ_2 using the formula (3.3);

b) calculate minimal value of electromagnetic force according to the following formula:

$$F_{\min} = F_1 + F_2 - \sqrt{F_1^2 + F_2^2 + 2F_1F_2\cos 2\Psi}\ ,$$

where F_1 and F_2 are the components of electromagnetic force produced by the fluxes Φ_1 and Φ_2, respectively, computed with the following expressions:

$$F_1 = \frac{\Phi_1^2}{4\mu_0 S_1}; \quad F_2 = \frac{\Phi_2^2}{4\mu_0 S_2};$$

Ψ is the angle of phase shift between the fluxes Φ_1 and Φ_2 that can be determined from the following expression:

$$\cos\Psi = \frac{\alpha}{c},$$

where α and c the values determined by the following relationships:

$$\alpha = \frac{S_1}{S_2}; \quad c = \frac{\Phi_1}{\Phi_2}; \quad ;$$

c) computed values are to be entered into table 3.2 or table 3.3.

3.5.11 Dependence $F_{\min} = f(S_2)$ should be plotted using the findings of table 3.2 and 3.3 taking into account that when $S_2 = 0$ (shading ring is not available) as well as when $S_2 = 3.4 \cdot 10^{-4}\ \mathrm{m}^2$ (shading ring encloses the whole pole) then $F_{\min} = 0$.

3.5.12 Report on the laboratory work must contain:

a) the purpose of the work;

b) outline and circuit diagram of the laboratory plant;

c) tables 3.1, 3.2 and 3.3 and plotted dependences:

- distribution of the magnetic flux lengthways the core;
- the current through the winding as function of the operating air-gap;
- $F_{\min} = f(S_2)$

d) conclusions on the work.

3.6 Self-checking questions

3.6.1 Ohm’s and Kirchhoff’s laws for AC magnetic circuit [3–6, 8, 9].

3.6.2 How does the winding’s MMF and magnetic flux behave under variation of air-gap in AC electromagnetic systems? [3–6, 8, 9].

3.6.3 The techniques used to reduce pulsation of electromagnetic force and to avoid armature bounce in ac electromagnets [3–6, 8, 9].

3.6.4 Vector diagram of magnetic fluxes in AC electromagnetic systems with available shading ring [3–6, 8, 9].

3.6.5 Illustrate the time diagram of electromagnetic force in ac electromagnets [3–6, 8, 9].

3.6.6 How much of the pole of the electromagnet is usually enclosed by a shading ring? [3–6, 8, 9].

Laboratory work № 4

STUDY OF ACTUATION TIME DATA OF AN ELECTROMAGNET

Duration of the laboratory study is 4 hours

4.1 Purpose of the work

The purpose is to study the techniques to effect on actuation time of electromagnets, as well as practical methods to adjust time lag of the electromagnetic time relay.

4.2 Subject of the study

Actuation time of an electromagnet both at energizing and at de-energizing is sum of two components:

$$t_{\text{act}} = t_{\text{pick-up}} + t_{\text{mov}},$$

where $t_{\text{pick-up}}$ is the *pick-up* or *delay time,* i.e. the time interval from the instant when the magnetizing winding is energized (or de-energized) to the instant when the armature is started to movement;

t_{mov} is the movement time.

Lag of electromagnet actuation at energizing as well as at de-energizing from a power network is usually effected through magnetic or mechanical damping.

Magnetic damping is the phenomenon of effect on the rate of change of main magnetic flux through the magnetic circuit of the electromagnet when its field winding is energized or de-energized. Magnetic damping results from induced eddy currents within the magnetic circuit components. Magnetic fluxes excited by eddy currents are always directed so that to maintain the earlier condition of an electromagnetic system. When the magnetizing winding is energized, they inhibit the rise of the magnetic flux; when it is de-energized, they impede decay of the magnetic flux.

The greater the main magnetic flux is, the higher is efficiency of the magnetic damping. Therefore, it provides substantial lag when the electromagnet is de-energized; in this case, the inductance of its electromagnetic system is maximal. When the electromagnet is energized, the inductance of its electromagnetic system is significantly less because of big values of the operating air-gap and magnetic damping is less effective. To enhance magnetic damping effect the electromagnets, serving to gain time lag, is additionally fitted with special *short-circuited components* enclosing cross-sectional area of the magnetic circuit. Short-circuited component, known usually as *damping slug*, is made as massive (copper or aluminum) sleeve or individual short sleeves fitted on the magnetic core. Available massive sleeves or slug increase the eddy currents as well as its magnetic fluxes. The most effect at minimum expendable materials is brought about in the case when the length of the damping slug equal to the length of the magnetic core.

Application of short sleeves enables to realize variable time lags, when an electromagnet is de-energized, depending on its location on the magnetic core. As damping sleeves are placed in the neighborhood of the operating air-gap, time lag in actuation is more than in the case when it is located near basement of the magnetic core. When an electromagnet is de-energized, the damping sleeves location does not much significance because both in the first case and in the second one they linkage with practically identical fluxes.

4.3 Description of the experimental plant

The object being researched in the laboratory work is the electromagnetic system of the time relay of type РЭВ-800. Electrical circuit diagram for the research is illustrated in Figure 4.1.

At the initial position, the coil of the electromechanical timing device PT is shunted with normally closed contact of the relay to be studied. It is aimed to the timing device will be stopped. When toggle switch S2 is closed one contact connects the relay winding to dc power source while another contact shunts the coil of the timing device. When the toggle switch S2 is opened the relay's winding is de-energized and timing device is started up and operates until the relay's contact shunts its coil.

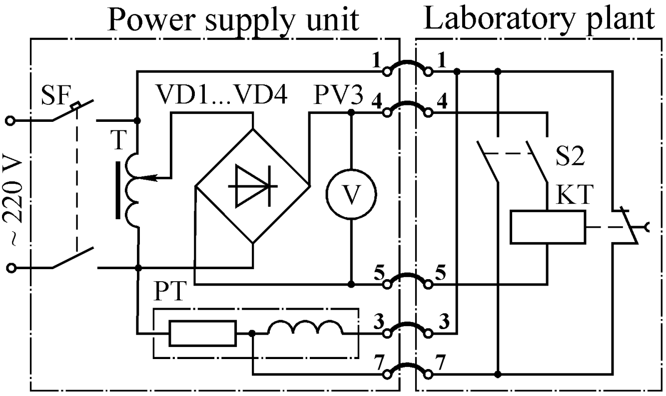

Figure 4.1 – Circuit diagram for the research

4.4 Task

4.4.1 Study the construction of time relay РЭВ-800, as well as techniques to produce the time lag applied in it [4].

4.4.2 Experimentally determine dependences of the relay time lag from the tension of its resetting spring, the value of its operating air-gap, the power voltage of its magnetizing winding.

4.4.3 Plot graphical diagrams of gained dependences, as well as to give an insight into its behavior.

4.4.4 Make deductions on the work.

4.5 Methodical instructions

4.5.1 To perform experimental part of the work, the laboratory plant should be electrically connect with power supply unit with the help of short connectors according to Figure 4.1.

4.5.2. To perform item 4.4.2 of the task proceeds as follows:

a) adjust the predetermined tension of relay's resetting spring that is step-by-step varied with the help of the figured plates placed between figured nut and washer; the spring tension will be defined by the number of plates;

b) adjust the predetermined value of the operating air-gap that is fixed with the help of non-magnetic spacers placed on the electromagnet armature with flat spring;

c) close automatic breaker SF; at this moment the lamp HL ignites;

d) close toggle switch S2 and stepping up the power voltage with autoformer T, to gain the actuation of the relay being studied and then adjust predetermined power voltage;

e) the pointer of the timing device should be zeroed;

f) open toggle switch S2 and take indications of the timing device;

g) open automatic breaker SF;

h) performing successively items a–g, take the dependence according to item 4.4.2 of the task; obtained findings should be tabulated as follows:

Table 4.1 – Experimental findings for the dependency the relay actuation time vs tension of resetting spring

δ =___ mm; U = ___ V (are predetermined by teacher)

Tension of the spring, **n**	0	1	2	3	4	5
Actuation time, s						

Table 4.2 – Experimental findings for the dependency the relay actuation time vs the operating air-gap
n =____; U = ___ V (are predetermined by teacher).

Operating air-gap, mm	0	0,1	0,2	0,3	0,4	0,5
Actuation time, s						

Table 4.3 – Experimental findings for the dependency the relay actuation time vs the power voltage
n =____; δ = ___ mm (are predetermined by teacher).

Power voltage, V	50	80	120	150	200	220
Actuation time, s						

4.5.3 After the experiment is completed, automatic breaker SF must be opened and autoformer T must be zeroed.

4.5.4 Report on the laboratory work must contain:

a) title and purpose of the work;
b) circuit diagram for the experiment;
c) tables with experimental findings and relevant plotted dependences;
d) conclusions on the work.

4.6 Self-checking questions

4.6.1 The essence of magnetic damping principle [3, 4, 6–9].

4.6.2 The techniques to effect on the pick-up time of an electromagnet [3, 4, 6–9].

4.6.3 The techniques to effect the movement time of an electromagnet [3, 4, 6–9].

4.6.4 Influence of the sleeve placement on the time lag of an electromagnet [3, 4, 6–9].

4.6.5 Influence of magnetic circuit material properties on actuation time of an electromagnet [3, 4, 6–9].

4.6.6 What is pick-up time of an electromagnet, if safety factor for pickup equals 1? [3, 4, 6–9].

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