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Snigirov V. M.
Zhornyak L. B.

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Reviewers:

Gorkunov B. M. – Doctor of Technical Sciences, Professor of the Department of Devices and Methods of Non-Destructive Testing of the National Technical University «KhPI»;

Volkov O. V. – Doctor of Technical Sciences, Professor, Head of the Department of Hydropower ZSEA;

Radchenko V. V. – Candidate of Technical Sciences, Associate Professor of the Department of Hydropower ZSEA.

C53 **Snigirov V. M.**

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The textbook is devoted to the course "Electromechanical automation devices". The devices used for control, protection and signaling of electric circuits are considered. The study guide is intended for students of electrical engineering faculties.

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CONTENT

Introduction

Electromechanical automation devices (EMADs) refers to electrotechnical devices that are used at all stages of electricity usage from generation and then transportation, distribution, conversion and finally consumption. EMADs are designed to turn on and off, measure, protect and control, stabilize and re-control certain parameters of equipment, facilities and installations, and to control and convert non-electrical quantities in electrical for later use in such systems as automated control and regulation (respectively SAC and SAR). Moreover, nowadays EMADs include electro-technical devices for managing energy, information and energy flows of various kinds: electrical, mechanical, thermal and others [11, 15, 16, 25]. For example, the flows of mechanical energy from the engine to the process machine can be directed by the help of an electromagnetic coupling, or the flow of thermal energy by the by-aid of the solenoid valves and dampers, etc. According to the principle of operation, electrical devices (EDs) are divided into electromechanical contacts (usually they have at least one moving part) and contactless (when the switching of the electrical circuit occurs without physical breaking of the circuit itself). All the rest - General industrial EDs which are electromechanical contact devices in which the current is changed with the physical disruption of the electrical circuit.

EMADs can be distinguished into the following groups:

- primary electromechanical measuring converters;
- various electromechanical relays;
- indicators of control and regulation;
- electromagnetic couplings, valves, etc .;
- electrical and magnetic supports and suspensions.

In addition, EMADs differ in magnitude of commuting current at low current - up to 10 A (with lower limits reaching 10-9 A) and high current - more than 10 A (with current relays having nominal currents up to several hundred amperes) .

1 Electro-mechanical relays

Encyclopedias and technical dictionaries define relay (relay - change; French relais, from relayer - change, replace) as a device for automatic switching of electrical circuits according to an external signal. Any relay device consists of a relay element (with two states of stable equilibrium) and a group of electrical contacts that are closed (or opened) when the state of the relay element changes [12,13,18].

The relays are widely used in automatic regulation, control, signaling, protection and switching devices. Depending on the physical nature of the control signal, the relays differ in electrical, thermal, mechanical, optical, etc. Electric relays respond to such electrical parameters as current, voltage, power, electric current, etc., or to temperature, amount of heat, etc. Relays in which the thermal action of the current is used are related to electrical, and accordingly called electrothermal. Mechanical relays respond to force, pressure, speed, displacement, etc. Depending on the field of use, the relays are distinguished: industrial automation, protection of power systems, radioelectronics, aircrafts, sea and river vessels, systems of regulation of railway traffic and safety on the railways, mining and oil industry, etc [3, 5, 6, 11, 29]. In general, the relay element is a technical device that performs a jump change of the output (that is controlled) value of energy Y at a certain value of the input (controlling) signal of energy X. It should be noted that the jump change of value Y depends on the value of the energy input signal X, not time dependent. Such dependence Y=f(X) has the form of a loop (piecewise linear function) and is called a relay characteristic. Here, we mean the abrupt change in Y over time, depending on X.

Relays are devices designed to make abrupt changes in signals in the output circuits at specified values of electrical control signals.

Electromechanical relays are electrical relays whose operation is based on the use of relative displacement of its mechanical elements as a result of the influence of electric current flowing through the input circuits.

Electromagnetic relays are electromechanical relays whose operation is based on the influence of a fixed field magnetic field on a moving ferromagnetic element. A brief classification of electromagnetic relays by functional characteristics is shown in fig. 1.1.

Monostable relays are those that change their state under the influence of the input signal but return to their original state (on-position) when this signal is removed.

Bistable relays are those that change their state under the influence of the input signal, but return to their original state (on-position) only when another signal appears.

Neutral (nonpolarized) relays are those that use pulses of any polarity, and polarized ones - only a certain polarity.

Electromagnetic relays in terms of the type of current are divided into direct and alternating current.

Switching current relays in terms of frequency are divided into low frequency and high frequency. Low-frequency relays are those having a power supply (control circuit) of constant or alternating current with a nominal frequency of 50 or 400 Hz and intended for co-mutation (circuit, break, switch) of electrical circuits up to 100 kHz. High frequency designed for switching signals over 1000 kHz.

By the sensitivity of the input signal and the magnitude of the switching current, the relays are divided into hypersensitive ($10^{-7} \ldots 10^{-10}$)A 10^{-5}V, high- and normal-sensitive, as well as low-current (10^{-6} – 10)A.

More powerful relays that switch currents above 50 A and with voltage over 1000 V are called contactors and high-voltage relays, respectively. In terms of the time of activation (t_{act}), relays are divided into:

- inertialess when $t_{act} \leq 0.001$ s;
- high-speed, when $t_{act} = 0.001 \ldots 0.05$ s;
- delayed action when $t_{act} = 0.05 \ldots 1.0$ s;
- time relay when $t_{act} > 1,0$ s.

By weight (volume) relays divided into:

- microminiature - up to 6 g in weight and up to 2 cm^3 in volume;
- miniature - up to 16 g in weight and 2… 6 cm^3 in volume;
- small-sized – weighing 16 ... 40 g and in volume up to 6-15 cm^3
- normal - weighing more than 40 g and more than 15 cm3 in volume;

Fig. 1.2 shows the simplest design of an electromagnetic relay with a locking contact and fixed cantilever contact springs. Here, the gap between the contacts is denoted as β, the gap between the pole and anchor as δ. And $\delta > \beta$.

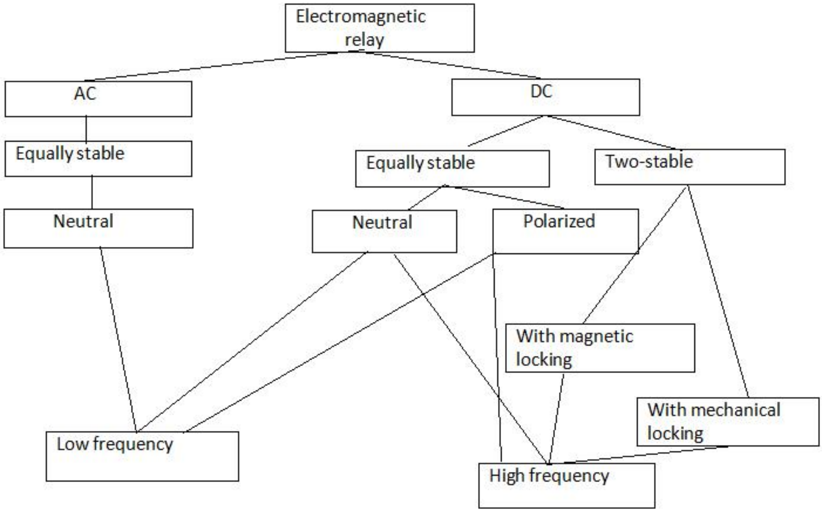


Figure - 1.1 Classification of electromagnetic relays

The DC (direct current) relays usually have a peg (or non-magnetic gasket) that serves to prevent the "sticking" of the relay's anchor through the final magnetism due to the long running in the on state. Sometimes a bulge is squeezed out instead of a non-magnetic gasket. To reduce the area of contact with the core (this does not affect the quality of operation of the DC relay, since the value of the current does not depend on the gap between the anchor and the core) in modern relays used elastic polymeric non-magnetic gasket.

Fig. 1.3 presents typical control characteristics of the relay principle devices, on which the following designations are adopted: *Xact* - activation parameter; Xret - return parameter (return); Xw - working signal (parameter); Ymax, Ymin - maximum and minimum value of output signal (parameter); Xacc- the acceptable value of the signal. In the AC (alternating current) relay, there is no pin-pin and pole tip and a magnetic system provides shielding of a portion of the magnetic pole to separate the total magnetic flux.

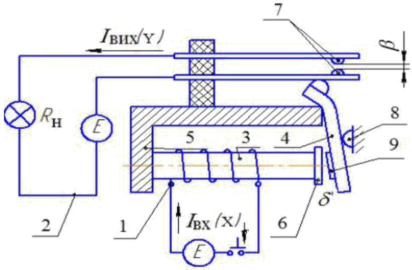


Figure 1.2 – Simplified design of electromagnetic relay:
1 - winding of the control wheel; 2 - switchingcircuit(load);
3, 4, 5 - magnetic circle (3 - core, 4 - anchor, 5 - yoke);6 - pole tip;
7 - contact details; 8 - emphasis; 9 - peeling pin.

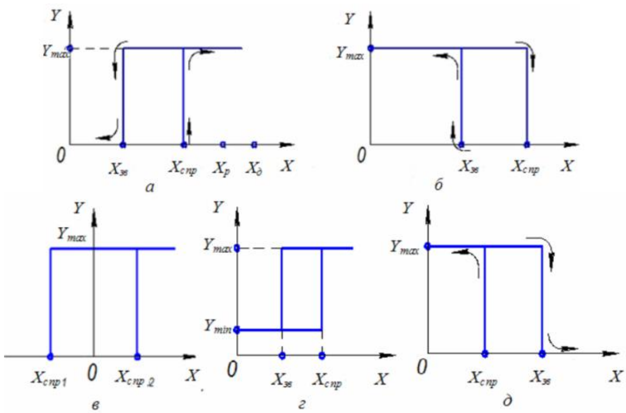


Figure 1.3 – Typical operating characteristics of relay units:a, b, c, e - electromechanical; d - static electric; a, b, d, e - one-stable; c- two-stable; a, b, d - maximum; e - minimal; a, d, e - those who work on the circuit;b - those working on the break

1.1 Relay contacts

Physical processes in the work of contacts are determined by the design, material properties, environmental conditions, processes in a closed electric circuit, when switched on and off [23, 38]. Fig. 1.4 shows a brief classification of electrical contacts. Basic concepts according to the standard (GOST14312-79): [36]

-the working surface of the contact detail (c.d.) is the part of the surface that is intended to provide electrical contact;

-the conditional contact area is the part of the working surface of the contact detail that is contacted with another contact detail;
-effective contact area is the portion of the conditional contact area through which electrical current flows from one c.d. to another;
-the gap of the contact of the electric circuit is the shortest distance between the moving and the fixed contact details when they are opened; the failure of the electrical circuit contact is the distance or excess travel of the contact element which is defined as the relative displacement occurring in the contact element after the contact takes its closed (open) position for the locked (open) option contact – detail.
-pressing is the force acting between the two closing contact details, normal to the surfaces of their collision *Fk*;
-the resistance of the contact of the electric circuit consists of the resistance c.d. *Rcd* and the transient resistance of the contact *Rtran* electric circuit, ie *Rc* =*Rcd*. + *Rtran*;
-the transient resistance *Rtran* of the contact of the electric circuit is the electrical resistance of the contact zone, determined by the effective contact area and is equal to the ratio of the voltage drop at the contact junction to the current through this junction.
It is known that the conditions of operation of electrical contacts in the closed state are determined by a number of thermophysical, mechanical and electrical processes occurring in the plane of contact. Micro-topography of the surface of electrical contact is characterized by macro-deviations of form, waviness and roughness.
In fact, even perfectly smooth surfaces are compressed at no more than threpoints (places) according to the microgeometry of the section (Fig. 1.5, a).

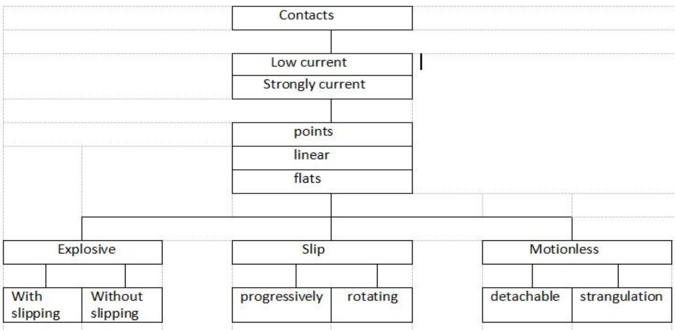


Fig 1.4 – A brief classification of electrical contact

In this case, the electric current passes only in places without direct contact and therefore the area *Sc* through which the current passes through is reduced. It can be clearly seen that the current lines seem to contract to the real area of pressure (Fig. 1.5b) and this, in turn, causes the emergence of the resistance of the charge *Rc* .On the surface of the contacts, films are formed mainly when the material is contacted with the environment. This is especially important for low-power contacts. The main types of films include: adsorbed oxygen (adhesive) films and films of darkening (oxide or sulfide). The films contribute to the appearance of the film resistance *Rfil*. In addition to those films which are formed upon contact with the environment, the contacts may become contaminated during the production of relays by the organic (hydrocarbon) substances of the plastic coil frame and the insulation of the coil conductors and, if soldering, also parts of solder and flux. But these contamination must be carefully removed before sealing the relay.Each single contact spot can consist of different areas:

-with pure metal contact;

-with quasi-metallic contact (when the contact elements are separated by a thin adhesive film or a thin darking film of up to 20 A^0);

-with non-metallic contact covered with thick darkening films.

In the general case, the resistance formed by the curvature of the crystal lattice in the deformation zone *Rcr* is added to the two resistances *Rc* and *Rfil*. Then the total resistance will be equal to $R_{tran} R_c \quad R_{fil} \quad R_{cr}$. (1.1) .Usually Rcr does not exceed a few hundredths of one percent of *Rc* and *Rcr*, so in most cases it can be disregarded. Numerical contacts have a resistance of *Rtran= 0*.

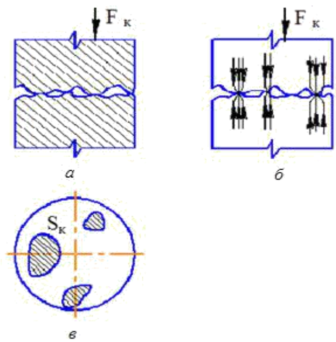


Figure 1.5 - Picture of the current flow through a contact connection:a - cross-section; b - places of current draw; c - places of real points of contact

Adhesive films are usually very thin and have tunneling conductivity as they are capable of transmitting electrons.This contact spot is called quasi-metallic.Oxidizing and sulfide films are electrically penetrated, ie by electrocution occurring at a certain value of the electrostatic field inside the film. Such a breakdown is called fretting.Fretting leads to an increase in the molecular adhesion forces between pure metals and subsequent micro-trapping with deep ejection during shutdown. In practice, there are constructive, technological and preventive methods to get rid off the films.For example, the operating time is limited to 8 hours with the destruction of films at periodic switches on and off, arc firing, switching and so on in continuous mode. However, if the electrical devices cannot be turned off under operating conditions, then the rated IN currents must be reduced by approximately 20% in order to reduce heating, etc.

In addition, since the contact resistance depends mainly on the contact material, the number of contact surfaces and pressing forces, the copper contacts are covered with silver or the work areas of the contacts are provided with silver overlays. When repairing fixed contacts, microslides are used to destroy films. The positive effect of the films is that they prevent the possibility of the development of excessively large intermolecular adhesion forces on the contact surface of the contact.

The following empirical formula can be used for engineering calculations of transient resistance [2, 27, 30]:

$$R_{tran} = \frac{K_1 + \left(1 + \frac{2}{3}\alpha \cdot \Delta\theta\right)}{\left(0{,}102 \mathrm{F_K}\right)^m} \qquad (1.2)$$

where K1 is the factor that takes into account the material and condition of the contact surfaces;

α is the temperature factor of the contact material;

$\Delta\theta = \theta p - 0_0$ is the contact overheating temperature, at operating temperature θp in comparison with the ambient temperature 0_0;F_c - force of contact pressing;m is the shape factor of the contact surface which is accepted as 0.5 for point contact; 0.5 ... 0.8 - for linear and 1.0 - for plane.Low-power breaking relay contacts are made of the noble and refractory metals Au, Ag, W, Mo, Pt, Pd, Rh, Ir, Ru of their alloys [4, 20, 36]. These are the best materials because they either do not oxidize or do not form a sulfur-conductive layer (film), thus providing a stable *Rtran*. The greatest current of arcing in them (0.35 ... 0.45) A, and in Pt - even 0.9 A.

Platinum Pt in pure form is used for contacts very rarely due to its low hardness, but the following alloys are us

Pt + Ir - resistant to electrical erosion;

Pt + Ru - is less prone to welding and stronger than

Pt + Ir;

Pt + Ni - resistant to needle-forming and welding;

Pt + Rh - has low volatility at high temperatures.

Palladium Pd - as contact material is inferior to Pt and its cost is about 4 times less. Its alloys are characterized by the following properties:

Pd + Ag - has a stable *Rtrans*;

Pd + Cu and Pd + Ir - have high hardness but require special heat treatment.

Au gold and its alloys are more prone to arcing than Pt and Pd, and in pure form is only applicable to precision (high-precision) contacts operating at low pressure and low voltage. Alloys are subject to electrical erosion and have the following properties:

Au + Ag - does not form sulfur films;

Au + Pt and Au + Ag + Cu - have high hardness;

Au + Ni and Au + Ag + Ni - in addition to hardness, it acquires resistance against needling;

Au + Pd + Ni is the most solid refractory alloy

Ag silver is of the highest importance for electrical and thermal conductivity which provides comparatively less heating of contacts, but it is a very scarce material, so the question of economics and its replacement in electrical engineering and electronics are urgent. Its oxides are electrically conductive and are destroyed when heated. Its alloys have the following properties:

Ag + Cu - has high hardness, used at high pressures, but at low pressures - it is unsuitable due to non-resistance Rtrans;

Ag + Cd - used as ceramic.

Tungsten W has increased resistance to arc formation, electrical erosion and welding. Used for large clicks. W + Mo molybdenum alloy is particularly commonly used. Ag + Cu or Ag + Cu + Zn alloys are used as solder joints to contact springs.

1.2 Framework of the theory of magnetic circuits

It is known that a magnetic circuit (MC) is a simplified phenomenon about a magnetic system and its magnetic field, in which electromagnetic processes can be described by equations that have such definitions as magnetomotive force (MMF), difference of scalar magnetic potentials (magnetic tension), magnetic flux, magnetic resistance, magnetic conductivity. These concepts are formally analogous to electric motor force, electric voltage, current, resistance, conductivity of the electric circuit, respectively. Therefore, the concept of a magnetic circuit was introduced for the calculation of magnetic

systems by field theory methods, which were developed mainly for electric circuits.
Electric current flows in an environment whose conductivity is significantly higher than the conductivity of the insulation that surrounds the conductor. Likewise, the conductivity of the environment through which the main magnetic flux (magnetic circuit) passes exceeds the conductivity of the non-magnetic environment that surrounds the magnetic circuit. This analogy is formal because the magnetic field and the electric current field are different physical types of matter.
The magnetic circuits of most EMADs are open non-magnetic gaps that do not interrupt the magnetic flux but only increase the magnetic resistance in its path. The table. 1.1 shows an analogy between the parameters of electric and magnetic circuits, in which the number of turns of the winding is denoted by the letter W [15, 21, 25, 27, 30]. It is known that a magnetic field arises between the magnetic poles, the force of which can be graphically explained by the fig.1.6.
The following designations: $F_{L.G.}$- longitudinal straight lines or “longitudinal gravity” forces, and $F_{L.S.}$ - in the transverse direction, or " lateral spacing" forces. In addition, magnetic power lines have the ability to be locked down the shortest path. The forces of " lateral spacing " form the so-called "bulging" of the magnetic flux in the lateral direction.

Table 1.1 – An analogy between the parameters of electrical a

Electrical quantities			Magnetic quantities		
Quantity	Equation	Unit	Quantity	Equation	Unit
Amperage	$I=\frac{\partial Q}{\partial t}$	A	Induction voltage	$U=-W\cdot\frac{\partial F}{\partial t}$	V
Voltage	$U=E\cdot d$	V	Magnetomotive force	$E=H\cdot l$	A
Charge	$Q=I\cdot t$	$Kl=A\cdot C$	Magnetic flux	$F=B\cdot S$	$Wb=V\cdot C$
Capacity	$C=\frac{Q}{U}$	$F=Kl\cdot V$	Field inductance	$L=\frac{B\cdot W}{I}$	$Gn=B\frac{C}{A}$
Field strength	$E=\frac{U}{d}$	$\frac{Kl}{m^2}$	Field strength	$H=\frac{I\cdot W}{l}$	$\frac{A}{m}$
Field energy	$E_v=\frac{C\cdot U^2}{2}$	$J=Wt\cdot C$	Magnetic induction	$B=\frac{F}{S}$	$Tl=V\cdot\frac{C}{m^2}$
Energy is constant	$\varepsilon=\frac{1}{\mu_0\cdot C^2}$	$\frac{F}{m}$	Field energy	$E_v=\frac{L\cdot I^2}{2}$	$J=Wt\cdot C$
The relative dielectric constant of the medium, which shows how many times in a given medium the force of interaction between charges decreases compared to vacuum	ε	–	Relative magnetic permeability of the medium - shows how many times the magnetic induction of the field created by the current in the medium is greater than in vacuum	μ	–
Electric displacement	$D\frac{Q}{S}$	V/m	Magnetic constant	$\mu_0=\frac{1}{\varepsilon_0\cdot C^2}$	$\frac{Gn}{m}$
Absolute dielectric constant	$\varepsilon_a=\varepsilon_0-\varepsilon$	$\frac{F}{m}$	Absolute magnetic constant	$\mu_a=\mu_0-\mu$	$\frac{Gn}{m}$

Fig. 1.7 presents an electromagnet consisting of a magnetic line (yoke - 1, anchor - 2, core - 3) made of magnetic material (steel) which has a small magnetic resistance that allows to increase the working magnetic flux $Ф\delta$ in the air gaps 4 and 5, where the magnetic resistance is high compared to steel. The magnetic flux of $Фб$ that does not close through the air gaps is called the scattering flux. On the heart is the winding control unit - 6.

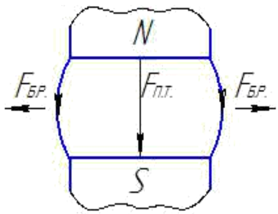


Figure 1.6 – Distribution of magnetic force lines between poles and magnetic values.

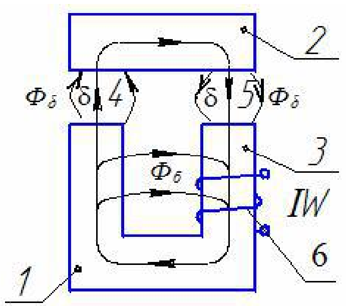


Figure 1.7 – Magnetic circle of solenoid valve type with two working gaps

1.2.1 The laws of magnetic circles

Ohm's law for a simple unbranched circle:

$$Ф = \frac{I \cdot W}{R_M} \tag{1.3}$$

where R_M is the resistance of the magnetic circuit to the flow of flux;
I – curent in the control winding ;
W – the number of turns of the winding.

Kirchhoff's first law. The algebraic sum of magnetic fluxes at any intersection of the magnetic circuit is zero:

$$\sum \Phi_x = 0. \tag{1.4}$$

Kirchhoff's Second Law: The sum of voltage drops on the circuit elements (resistors, diodes, etc) equals to the sum of the electromotive forces (of batteries and inductors) along a closed loop of an electrical circuit:

$$0\int \Phi \cdot dR_M = \sum I \cdot W \tag{1.5}$$

Total current law. Circulation of the field intensity vector H in a closed loop is equal to the resulting magnetizing force of this circuit:

$$0\int H \cdot dl = I \cdot W \tag{1.6}$$

where l is the length of the midline of the magnetic circuit;
H– field strength in the magnetic system.
Then, assuming that the field is homogeneous, we can write:

$$H \cdot l = I \cdot W \tag{1.7}$$

The magnetic resistance is determined by analogy with the electric circuit, specifically for a section with finite length l will be:

$$R_M = \frac{1}{\mu} \cdot \frac{l}{S}$$

and, accordingly, the magnetic conductivity is defined as:

$$\Lambda = \frac{1}{R_M} = \mu \cdot \frac{S}{I},$$

where μ – relative magnetic permeability of the material
S and l - intersection and length of a part of magnetic circuit, respect
Biot Savart law (also known as Laplace's law) sets the value and direction of the magnetic induction vector dB at any point C of the magnetic field formed by the element dl of the conductor with current I. fig. 1.8. tively

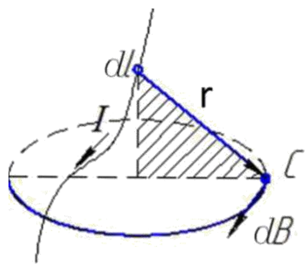


Figure 1.8 – Element of electromagnetic field.

Determination of magnitude and direction of magnetic induction.

Then we write the law in scalar form:

$$dB = \mu_0 \frac{\mu}{4\pi} \cdot \frac{I \cdot dl \cdot \sin(dl, r)}{r^2} \qquad (1.8)$$

where r – the radius vector drawn from the conductor element to the point of the magnetic field at which the induction is determined;
μ_0 – absolute magnetic permeability of air equal to $4 \cdot \pi \cdot 10^{-7}$ H/m;
μ_0 – relative magnetic permeability of the environment.
The direction of dB is determined by the Maxwell rule (right-hand screw rule- if you screw the driller in the direction of the current in the conductor, the direction of movement of the drill handle will indicate the direction of the magnetic induction line).

1.3 Electromagnetic forces

Several methods can be used to determine electromagnetic forces. For example, physical or energy approaches [15, 21, 25, 27, 30].

The physical approach is to study the physics of the interaction of a magnetic field with a ferromagnet. According to the law of Biort Savart, a body element of volume dV with a volumetric current density j will be exerted by a force B with the induction from the side of the magnetic field which is determined by the formula:

$$d\overline{F} = \left[\overline{B} \cdot \overline{j}\right] dV, \qquad (1.9)$$

Therefore, full force:

$$\overline{F} = \oint_V \left[\overline{B} \cdot \overline{j}\right] dV \qquad (1.10)$$

Maxwell made this formula look like this:

$$F = \frac{l}{\mu} \cdot \oint_S \left[\left(\overline{B} \cdot \overline{n}\right) \cdot B + \frac{1}{2} \cdot B^2 \right] \cdot dS, \qquad (1.11)$$

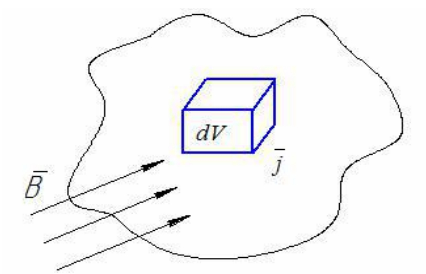


Figure 1.9 – Ferromagnet in electric field.

Determination of Electro-Dynamic forces where B is the induction of the external field;
S is the surface area of the ferromagnet;
J= n_0 • *e*• *V* is the current density,where n_0 is the number of conduction electrons per unit volume,
e is the absolute value of the electron charge, V is the average velocity of ordered electron motion.
Then, if at any point of the surface B S or collinear B || n and their derivative is zero, the force will be defined as:

$$F = \frac{l}{\mu_0} \cdot \oint B^2 \cdot dS, \qquad (1.12)$$

and for a homogeneous field where the induction at any point is the same:

$$F = \frac{B^2 S}{2\mu_0}, \qquad (1.13)$$

Or in flux $\Phi = B \cdot S$, then

$$F = \frac{\Phi^2}{2\mu_0 S}. \qquad (1.14)$$

The relations (1.13) and (1.14) are called the Maxwell's formulas used for the approximate calculations of electromagnetic force due to the assumption that the field is homogeneous (with relatively small air gaps) and the magnetic force lines are perpendicular to the anchor surface (magnetic permeability of the material is infinite, or the magnetic resistances of steel are zero).

The energy approach is to study the conversion of energy into the electromagnet during operation.

The following applies to the electromagnet circuit:

$$U = iR + \frac{d\psi}{dt} \qquad (1.15)$$

Multiply the right and left sides of the equation by *i*• *dt*, integrate, and then obtain the energy balance equation:

$$\int_0^t U \cdot i \cdot dt = \int_0^t t^2 R \cdot dt = \int_0^\psi i \cdot d\psi . \qquad (1.16)$$

W_e – eletrical energy; W_t – thermal coast; W_{EM} – electromagnetic energy

If W_{EM} = *We – Wt* meaning that electrical energy is converted into electromagnetic energy and heat losses are generated. In addition, electromagnetic energy is converted to mechanical energy during anchor movement.

In the general case, the total electromagnetic energy that was accumulated by the magnetic system will be determined by the area "0 - 1 - 2 - 3 - 0" in the change of the gap δ, current I and coupling ψ. on the fig. 1.10. In the first step, when the anchor remains stationary ($\delta = \delta_1$), the coupling increases to ψ_1 along the magnetization curve δ_1. Moreover, the energy proportional to «0 - 1 - 4 - 0» is converted to magnetic. At current I_1, the anchor starts to move and the coupling changes in the transient curve 1 - 2. The energy which is proportional to the area "1 - 2 - 3 - 4 - 1", will be converted into magnetic energy.

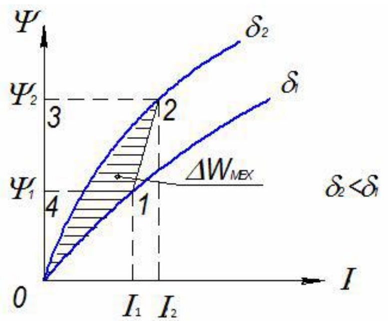


Figure 1.10 – To the question of definition ΔW_{mech}

The magnetic energy reserve in the system at ($\delta = \delta_2$) is characterized by the area "0 - 2 - 3 - 0", and the energy outlined by the area "0 - 1 - 2 - 0" during the anchor movement has already been expended, ie made by electromagnetic force to overcome opposing forces, friction forces, inertia of moving parts. This is the mechanical energy of W_{mech} . Then the electromagnetic force will be equal to:

$$F_{EM} = \frac{\Delta W_{mech}}{\Delta x} = -\frac{\Delta W_{mech}}{\Delta \delta} \quad , \tag{1.17}$$

or with infinitesimal movement:

$$F_{EM} = \frac{dW_{mech}}{dx} = -\frac{dW_{mech}}{d\delta}, \quad (1.18)$$

where Δx and Δδ are the displacement of the anchor and the gap, and because the gap decreases as the anchor moves, then Δx = -Δδ.

Therefore, if the magnetization curves are given in the graphical view, then the electromagnetic force for the mean gap between δ_1 and δ_2 can be determined by the area 0 - 1 - 2 - 0 if we divide it by the displacement of the anchor. Assuming that the area of the figure 0 - 1- 2 - 0 is the area of a triangle, you can enter the term "linear magnetic system" and, therefore, to apply the energy approach. For a linear magnetic system, the formula for determining electromagnetic force is:

$$F_{EM} = -\frac{1}{2}\cdot(I\cdot\frac{d\psi}{d\delta} - \psi\cdot\frac{dI}{d\delta}), \quad (1.19)$$

and for the electromagnets with the rotating anchor we get the electromagnetic moment:

$$M_{EM} = -\frac{1}{2}\cdot\left(I\cdot\frac{d\psi}{d\varphi} - \psi\cdot\frac{dI}{d\varphi}\right), \quad (1.20)$$

The current will not change in a steady state for DC electromagnets because, according to Ohm's law, its value is determined by the supply voltage and the winding resistance (I =U / R). Let us transform the force formula taking into account the winding inductance, the number of its turns and the coupling ($\psi = L \cdot I = N \cdot \Phi = N \cdot (I \cdot N) \cdot \Lambda = N^2 \cdot \Lambda \cdot I$), we have:

$$F_{EM} = -\frac{1}{2}\cdot(I\cdot W)_{\delta}^{2}\cdot\frac{d\Lambda_{\delta}}{d\delta}, \quad (1.21)$$

where N – the number of turns of the winding

Λ_δ - conductivity of working air clearance ;

$(I\cdot N)\delta$ – the working value of the working air gap MMF, defined as $(I\cdot N)\delta$ = I · N - $(I \cdot N)_{ST+SP}$ (I · N) - full MMF of electromagnet,

$(I \cdot N)_{ST+SP}$ - losses in steel and spurious gaps).

The obtained energy formula for calculating force is more universal than the Maxwell formula, since it gives the possibility to determine forces for saturated magnetic systems taking into account the heterogeneity of the magnetic field in the working gaps.

1.4 Characteristics of electromagnets: loading, counteracting and traction

The load characteristic is the dependence of the electromagnetic force F_{EM}, or the electromagnetic moment of rotation M_{EM} on the magnitude of the electrical signal applied to the winding at a certain position of the anchor (for translational movement of the anchor - F_{EM} = f (I, IN, U) at δ = const; and for rotary anchor motion - M_{EM} = f (I, IN, U) at φ = const). In other words , it shows how much the electromagnet can be loaded with force at certain anchor position and electrical signal (Fig. 1.11)

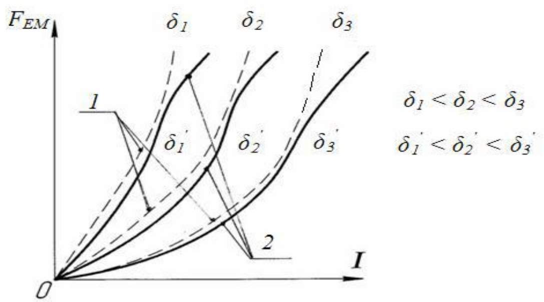
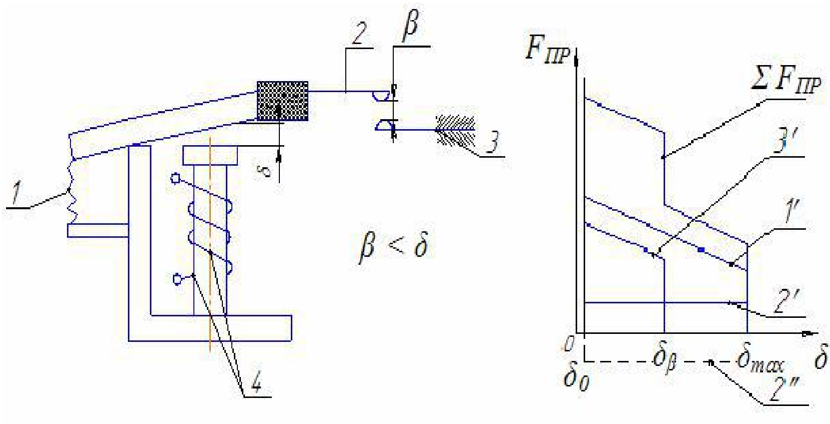


Figure 1.11 – Load characteristic

Assuming that the magnetic resistance is zero, then according to the formula $F_{EM} = -\frac{1}{2}\left(IW\right)_{\delta}^{2} \cdot \frac{d\Lambda\delta}{\delta}$ we have a quadrature dependence in the form of a parabola (1 – denoted «– – – »). But the real characteristics (2 – denoted «——») will be different from the parabola because part of the winding MMF is lost due to the fall in magnetic voltage in the steel and spurious gaps, which is especially noticeable when high currents are present when the magnetic system is saturated. The relay anchor is acted upon by the reaction force (counteracting force) of the mechanical F_{EM} system, which drives the anchor into motion. This force is directed in the opposite direction to the electromagnetic force, so it is called the counteraction force $F_{co} = f(\delta)$, or counteracting moment depending on the anchor position $M_{co} = f(\varphi)$. The mechanical system of a relay usually consists of several components (nodes) of the structure that come into operation when moving the anchor.

Consider a simple system whose contacts are open in the normal position (Fig. 1.12 a), which includes a return spring (1) and contact springs (2, 3). When the voltage is applied to the coil (4), the anchor magnet starts to move and, therefore, the reaction from the spring (1) in fig. 1.12, b (polynomial curve (1 ')) simultaneously reacts with the mass of the moving parts 2' (the anchor, the transmitting nodes, etc.), and this weight can be subtracted, depending on what the relay has during operation (line 2 ").



a b

Figure 1.12 – Simplified design of the electromagnetic relay and its counteracting characteristic: *a* – kinematic scheme; *б* – counteracting characteristic

Then the spring (3) starts to work at a certain magnitude of the gap δβ (dependence 3 '). The distance β that the movable contact moves before colliding with a fixed one (counteracting characteristic corresponds to the distance which is equal to $\beta=\delta_{max} - \delta_\beta$). Then the total dependence of ΣF_{co} is the complete counteracting characteristic.

Note that:

1) The force characteristics of the springs do not start from scratch, since there is their pre-compression (stretching), so the reaction will be a vertical line.

2) Depending on the orientation of the relay relative to the vertical plane, the reaction from the mass of the movable parts can be positive or negative. This reaction is usually ignored for low power relays.

3) The reaction from friction is also neglected.

Traction characteristic is the dependence of the electromagnetic force $F_{EMT} = f(\delta)$ or the electromagnetic moment on the anchor position $M_{EMT} = f(\varphi)$. There are static and dynamic characteristics (fig. 1.13).
The static characteristic is constructed at the unchanged MMF of the winding which is possible with an infinitely slow motion of the anchor (curve 1, Fig. 1.13). The dynamic characteristic is constructed taking into account the transition processes that occur during the actuation or return of the electromagnet (curve 2, Fig. 1.13).

x

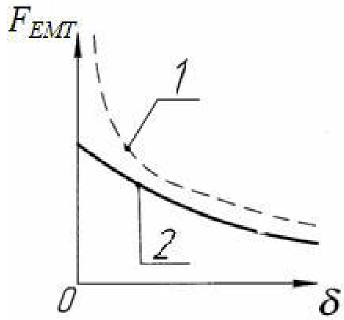


Figure 1.13 – Statistic and dynamic traction characteristics of relays

Conductivity for a uniform field in the gap is $\Lambda_\delta = \frac{\mu_0 \cdot S}{\delta}$, then derivative is $\left(\frac{\mu_0 \cdot S}{\delta}\right)' = -\frac{\mu_0 \cdot S}{\delta^2}$, then according to the formula (1.21) we have

$F_{EMT} = \frac{1}{2} \cdot (I \cdot W)_\delta^2 \cdot \frac{\mu_0 \cdot S}{\delta^2}$. We can see from the graphic that as the gap decreases the force increases sharply and becomes infinite at $\delta \approx 0$. This is a static characteristic.
In fact, as the gap decreases, the magnetic voltage drop in the steel increases resulting in a decrease in the working value of the MMF $(I \cdot W)_\delta$; therefore, according to formula (1.21), the real value of the force will be less than without taking into account the steel resistance, and at $\delta \approx 0$ the force will have a finite value.
Fig. 1.14 shows the principle of harmonization of traction and counteracting characteristics of the relay. The harmonization of the characteristics is that the F_{EMT} traction characteristic must be necessarily higher than the

counteracting F_{co}, and the reverse F_{rev} must necessarily be below the counteracting one. This placement can be obtained if:
a) reduce the stiffness of the springs, ie "release" F_{co};
b) apply a pole tip, ie change the nature of F_{EMT},)
c) change the motive force (ie change Φ_δ), etc.
If the characteristic is F_{EMT1} - switching on will not happen because when the anchor is released, the point "a1" lies below the point "a". If F_{EMT2}, there is a delay in the offsets at the moment of contact and the contacts can be welded or if the driving part of the relay has a reserve of kinetic energy (shaded area on the graph), then they can turn on but there will be an instantaneous overheating of the contact point. Do not have a large F_{EMT} stock at point δ, as a strong hit will occur at the time of the closure. The F_{rev} must pass below the F_{co}. In the case where the return force is equal to F_{rev1}, then at point b1 due to the low value of the pressing force (with point b below), the contacts can be welded.

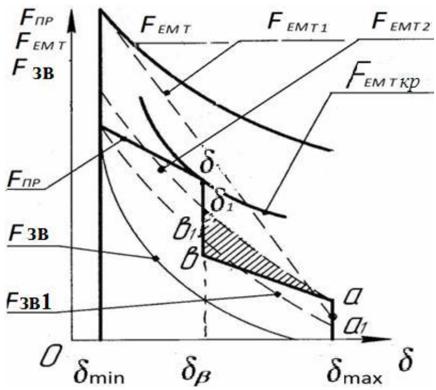


Figure 1.14 – Matching of relay characteristic

1.5 Electromagnetic DC relays

Depending on the location of the anchor and the nature of the influence on it of the magnetic flux, such basic magnetic systems are used (Fig. 1.15). A characteristic feature of the "b" and "c" circuits is that the anchor (1) is drawn and is both in the working gap and in the scattering field which increases the electromagnetic force. This field is formed by a coil (2) that is mounted on a core connected to the yoke (3). Moreover, the additional force at large values of the working gap is comparable to the basic force [2, 4]. With the magnetic system "d" the anchor moves "across" the magnetic force lines in the working gap. This makes it possible to get special appearance features.

1.5.1 The influence of the pole tip on the traction characteristic of the DC relay

Assuming that the valve electromagnets differ from each other only in that one has a pole tip with a diameter d_t and the other does not (Fig. 1.16) [15, 21, 25, 27, 30]. If we take into account that the resistance of steel $R_{ST} = 0$, then at a large gap at the energy approach for the electromagnet on the figure 1.16, a we have

$$F_{EM} = \frac{1}{2} \cdot (I \cdot W)^2_\delta \cdot \frac{\mu_0 \pi \cdot d^2}{4\delta^2}, \tag{1.22}$$

and for the electromagnet on the fig.1.18, b respectively is

$$F'_{EM} = \frac{1}{2} \cdot (I \cdot W)^2_\delta \cdot \frac{\mu_0 \pi d_H^2}{4\delta^2}. \tag{1.23}$$

By dividing the equation (1.23) by the equation (1.22), we have:

$$\frac{F'_{EM}}{F_{EM}} = \frac{d_H^2}{d^2}, \tag{1.24}$$

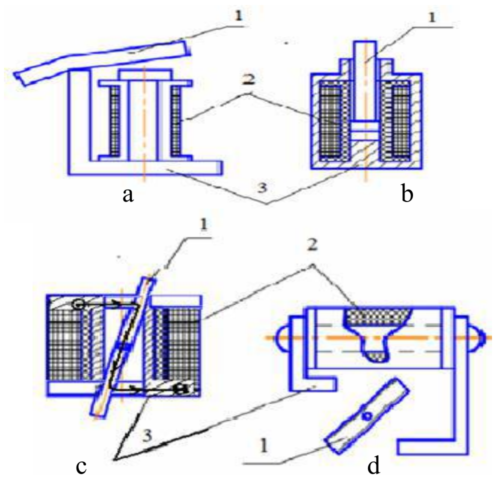


Figure 1.15 – Electromagnetic relay designs: a– with an external unbalanced valve type anchor; b- with an anchor of solenoid type; c - with an internal coil balanced anchor; d - with an external balanced anchor of the swivel type.

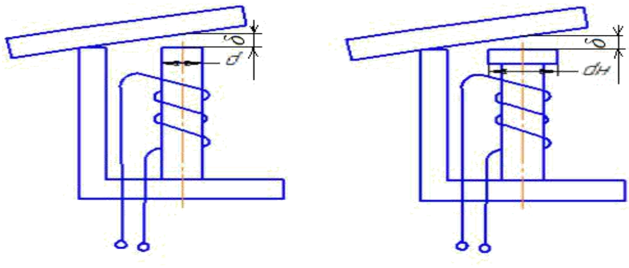


Figure 1.16 – To the question of the purpose of a pole tip: a – a relay diagram without a pole tip,*b* –with a pole tip.

The equation (1.24) shows that $F'_{EM} > F_{EM}$ or the presence of a pole tip under all other conditions leads to an increase in the electromagnetic force in the region of large gaps. When approaching the anchor to the core and when the anchor position is drawn, when it can be assumed that B S, BI| n from formula (1.14), we have for the variant of the design of the electromagnet without the pole (a):

$$F_{EM} = \frac{\Phi^2}{2\mu_0 \frac{\pi d^2}{4}}, \tag{1.25}$$

and for variant (*b*):

$$F'_{EM} = \frac{\Phi^2}{2\mu_0 \frac{\pi d_H^2}{4}}, \qquad (1,26)$$

By dividing equation (1.26) by (1.25), we have:

$$\frac{F'_{EM}}{F_{EM}} = \frac{\dfrac{\Phi^2}{2\mu_0 \dfrac{\pi d_H^2}{4}}}{\dfrac{\Phi^2}{2\mu_0 \dfrac{\pi d^2}{4}}} = \frac{\Phi^2 \cdot 2\mu_0 \cdot \dfrac{\pi d^2}{4}}{\Phi^2 \cdot 2\mu_0 \cdot \dfrac{\pi d^2}{4}} = \frac{d^2}{d_H^2}, \qquad (1.27)$$

From these formulas we can see that $F'_{EM} > F_{EM}$ or that the presence of a pole tip causes a decrease in electromagnetic force in the area of small gaps. It can be concluded that the traction characteristic of an electromagnet with a pole tip is higher than the characteristic of an ordinary electromagnet at large gaps and is below at small gaps, as shown in Fig. 1.17.

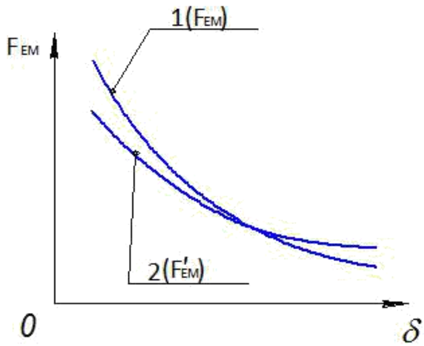


Figure 1.17 – Static traction characteristics of DC valved magnets:1 – without a pole tip; 2 – with a pole tip

In other words, the pole tip has a positive effect on "tearing" the anchor from the place at the beginning of its displacement and at the end of the movement, when the traction force becomes smaller, there will be a smaller impact on the pole. In structural terms, this will reduce the additional rivet on the switching contacts because there will be no breaking of the magnetic circuit. It should be noted that increasing the diameter of the pole tip is advisable only to a certain value, since further increase in diameter will increase the loss of flow (Fσ).An example of a DC relay is the design of a single-coil non-polarised relay with two switching contact groups shown in Fig. 1.18. Two pole tips(7) L-shaped, flat core (5) and anchor (4) with half-axes arranged along the short axis of the anchor symmetry. All parts of the magnetic system are made of electrical steel. During the process of assembling the anchors and the pole tips are tightly pressed together by planes, then the pole tips are connected to their ends by welding with a stand (10) and a strap (8) made of nickel silver. In this case, the anchor pins are included in the holes of the rack and strips and in the initial position the anchor is fixed by a rotating spring (9). A coil (6) is located on the core (5) and the projecting ends of the core are welded to the free ends of the pole tips.

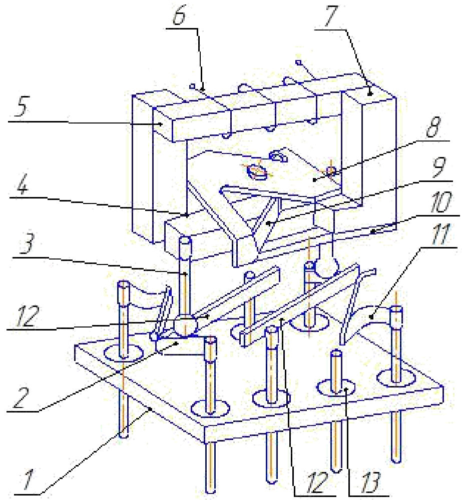


Figure 1.18 – Design of the single-coil non-polarised relay

The contact system has fixed breaking and closing contacts (11) covered with a thin layer of gold, a movable contact spring (12) made of a contact-spring alloy. The contact group details are attached to the terminals (1) by laser welding. Switching contacts when the relay is triggered and the anchor is rotated due to the glass balls on the pushers (3). The relay is then adjusted, closed with a sealed casing, pumping air and filling with dried gas through a hole that is sealed in the hull.

1.6 Electromagnetic AC relays

The AC relay shows an inductive resistance $X_L = \omega L$ unlike the DC relay, where the current is limited only by the active resistance R. Moreover, X_L »R, therefore, the winding resistance can be ignored in the analysis of processes in electromagnetic systems of the AC relay. Change in the current and voltage over time, even in steady-state mode, results in characteristic features compared to DC electromagnets.

1.6.1 Electromagnetic force ripple

It is known that the parameters characterizing the state of the AC circuits vary according to the sinusoidal law:

$e = E_m \bullet \sin\omega t;$ $\quad u = U_m \bullet \sin\omega t;$

$i = I_m \bullet \sin\omega t;$ $\quad i = \Phi_m \bullet \sin\omega t;$

where *Em*, *Um,*, *Im* ,Φ_m - the amplitude values of the field strength, voltage, current and magnetic flux, respectively.

If you neglect the nonlinearity of the magnetic circuit, then in the case of a sinusoidal voltage of the power source, the magnetic flux in the working gap also changes according to the same law. According to Maxwell's formula (1.14), we obtain:

$$F_{EM} = \frac{\Phi^2}{2\mu_0 S} = \frac{\Phi_m^2}{2\mu_0 S} \cdot \sin^2 \omega t = \frac{\Phi_m^2}{4\mu_0 S} - \frac{\Phi_m^2}{4\mu_0} \cdot \cos 2\omega t. \qquad (1.28)$$

In other words, the instantaneo value of force is represented as two components: constant $\Phi_m^2 / 2\mu_0 S$ and variable ($\Phi_m^2 / 2\mu_0 S$) $\cdot \cos 2\omega t$ (fig. 1.19). Moreover, the latter varies with double frequency relative to the frequency of the power source which is always positive $F_{EMmean} = \Phi^2 / 4\mu_0 S$. At AC, there is force that the electromagnet develops, given its mean value:

$$F_{EMmean} = F_{EMmean} + F_{EMmean} \cdot \cos 2\omega t, \qquad (1.29)$$

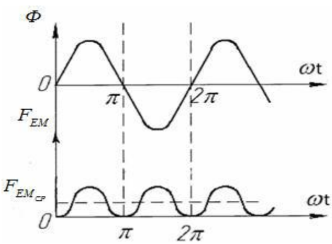


Figure 1.19 – Magnetic flux and electromagnetic force of the AC relay

Other things being equal an AC electromagnet will develop fotce about two times smaller than a DC electromagnet. The influence of force ripple on the anchor in the actuation process has little effect on the nature of the movement due to the relatively large inertia of the moving system (Fig. 1.20). In the position (in the interval of time), when $F_{EM} > F_{CO}$ - the anchor is pulled and when $F_{EM} < F_{CO}$, it departs from the stop. This happens with double-frequency and the anchor vibrates.

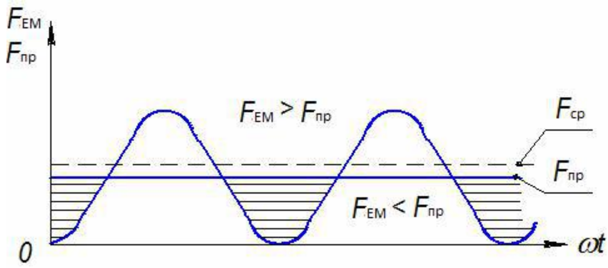


Figure 1.20 – Characteristics of the AC relay

1.6.2 Anchor vibration

This phenomenon is extremely undesirable and leads to vibration of contacts, heating of coils, loosening of the magnetic system and unpleasant noise. Therefore, mechanical damping and AC rectification are used to combat vibration, or the magnet-system is made of two separate magnetic circuits when the coil of one of them is connected to the power supply, and the other through a capacitance, ie the flow in the second magnetic circuit will be phase-shifted relative to the first, but the most common is the method based on a short-circuit spiral screening of one of the parts of the pole. (Fig. 1.21).

As a screen, a shortened winding can be used or a short-circuit spiral that is most common. In the magnetic circuit, it performs the function of the magnetic resistance $X\mu$, whereby the main flux Φ is divided into two fluxes Φ_{sc} and Φ_n, displaced relative to each other by the angle φ (Fig. 1.21, b).

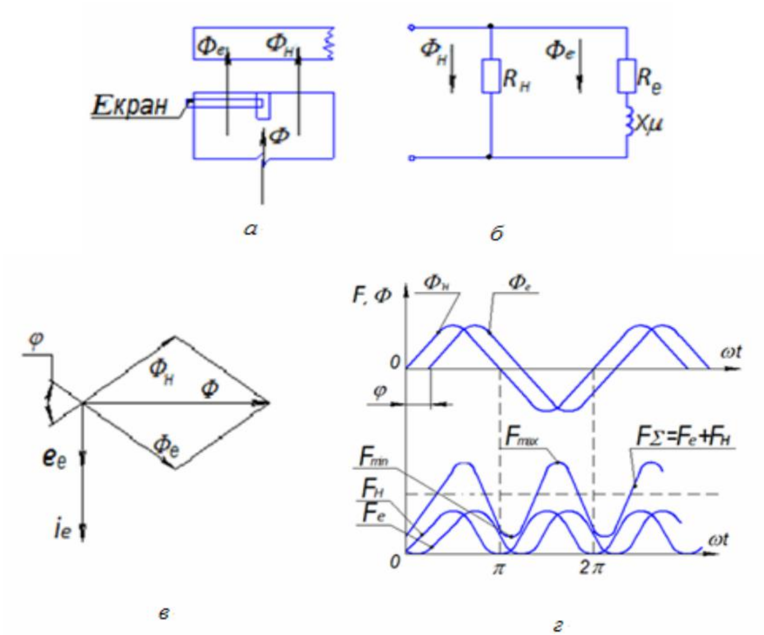


Figure1.21 - Part of a magnetic system with a short-circuit spiral: a) schematic diagram of the pole screening to determine the distribution of the magnetic flux; b) electrical scheme for magnetic circuit replacement; c) vector diagram; d) the resulting electromagnetic force - F_{Σ}.

By changing the electromotive force (EMF) *ee*, the emerging current *ie* will also be shifted to a certain angle, but the angle will be close to zero since the inductance is small. The interaction of this flow with the flows, which would be in its absence in the screen and non-screen parts of the pole, forms the displacement of the fluxes Φ_{sc} and Φ_n by the angle:

$$\varphi = \frac{arctgX \cdot \mu_{\delta E}}{R_{\delta E}}. \qquad (1.30)$$

As a result, the force F_{Σ} that moves the anchor consists of F_n (non-screen part) and F_{sc} (screen part), and at any time it is different from zero. The amplitude of the variable component:

$$F_{\Sigma} = \sqrt{F_{cp.e}^2 + F_{cpp.}^2 + 2F_{cp.e} \cdot F_{cp.n} \cdot \cos 2\varphi}. \qquad (1.31)$$

It is believed that the optimal ratio of the non-screen part of the pole S_n and the screen part – S_{sc}, in which the mini-ripple is within the range S_{sc} / S_n = 0.68 ... 0.80 (Fig. 1.22) [15, 21, 25, 27, 30].

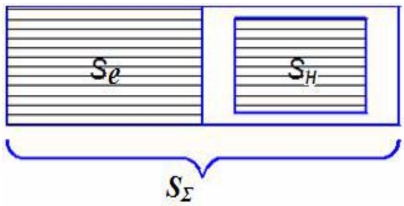


Figure 1.22 – Screening the pole with a short-circuit spiral.

1.7 Polarised electromagnetic relays

Polarised relays refer to a DC relay which state change depends on the polarity of its current input value [5, 6, 15, 25, 32].
In contrast to neutral, they are characterised by the presence of two independent magnetic fluxes - polarising – Fp which is usually formed by a permanent magnet, and the working -Fw. Due to this, the action of the relay depends not only on the value of the current in the work winding, but also on its direction. When the working winding is unlocked, the force generated by the permanent magnet (the most common variant of designs) or a special winding from an autonomous power source acts on the anchor of the electromagnet. Polarised relays are subdivided into high-sensitivity ones which typically have one switch contact node, and normal ones that have up to 12 switching nodes. The MMF and P_{act} (P_{act} = 10… 150 μW) of high-sensitivity relays are smaller and the fast action is higher than that of the most sensitive neutral relays (P_{act} = 20… 100 mW). Multi-contact polarised relays, which are often referred to as remote switches, have about the same MMF compared to neutral electromagnetic relays. Some polarised relays have two or more windings, allowing flexible design of electrical circuits, control of currents of different polarity, in addition, these devices can be used not only as switching, but also as logical elements.There are three main types of magnetic relay circuit (Fig. 1.23): serial (consecutive) , differential and bridge. In a relay with a serial magnetic circuit (Fig. 1.23, a) there is only one way of closing the polarising Φp and working Φw fluxes, since the sources of MMF are switched on in series, so the resistance on the Φw path is greater. Such schemes are rarely used.

In the relay with the differential magnetic system (Fig. 1.23, b), the sources of MMF are switched on in parallel, and Φw almost does not pass through a permanent magnet. In differential circuits, force acts on an axis of an anchor or a flat spring suspension due to the action of electromagnetic forces on the anchor. Relays with a bridge circuit (Fig. 1.23, c) do not have this disadvantage. MMF sources are included in the diagonal of the bridge, which is why Φp and Φw are found mostly in working gaps. They have advantages over relays in differential circuits such as the ability to reduce overall dimensions, higher resistance to external mechanical influences, and higher stability of parameters when changing the ambient temperature.

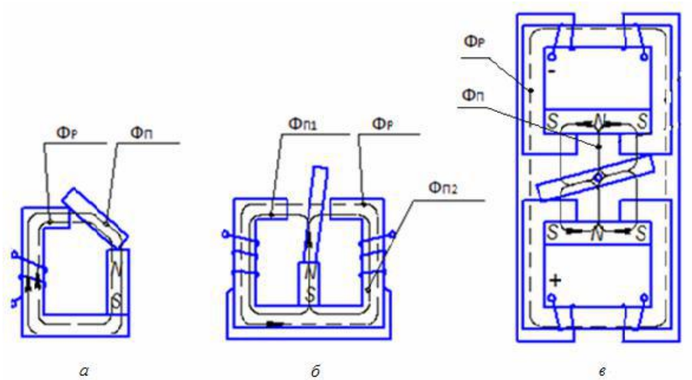


Figure 1.23 – Types of magnetic systems of polarised relays a–serial (consecutive) ; b –differential; c–bridge

Polarised relays are one-stable and two-stable and differ in type of regulation. Two-stable, in turn, come with two-position and three-position control.

When operating, the anchor relay can take several positions and an anchor is always in one position in the two-position predominant control system if the current in the working winding is not present. The predominance can be provided either by adjustment or mechanically, for example, by a spring. In a two-position relay without predominance, when current is absence in the operating winding, the contacts (anchors) are near one of the two contacts (poles), and this depends on the previous direction of current in the winding. The triggering (actuation) occurs after the direction of the current is changed relative to its initial state. The anchor of the three-position relay (in the absence of current in the operating winding) is in the middle position.

At actuated signal, the anchor moves either to the left or to the right depending on the direction of current [5, 6, 15, 25, 27, 32]. This is achieved by securing the anchor on a sufficiently rigid suspension return spring. Let us have a look at the electromechanical characteristics of a polarised relay with a parallel magnetic circuit (Fig. 1.24).

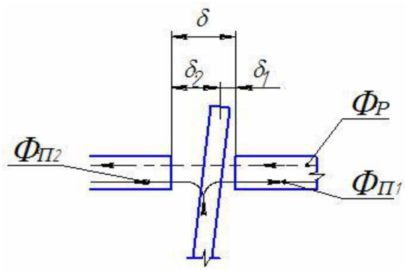


Figure 1.24 – Adjusting of the anchor of a polarised relay; δ– working gap, δ_1 and δ_2 - right and left gaps of relay poles, respectively

An anchor with a parallel magnetic circle is subjected to two opposing forces. One force *F1*, for example, is directed toward the right pole, and force *F2* - towards the left pole, then the resulting force Fem will be equal to:

$F_{EM}=F_1 - F_2$

Moreover, in the left gap, the working Φw and polarising Φ_{P1}, Φ_{P2} fluxes are added and in the right are subtracted:

$\Phi_1= \Phi_{P1} - \Phi_W,\ \Phi 2= \Phi_{P2}+ \Phi_W$

Assuming that the resistance of steel Rst, scattering and buckling of the magnetic flux are absent, and that the permanent magnet is the source of flux, we have that the total flux will be unchanged, ie:

$\Phi_P= \Phi_{P1} + \Phi_{P2} = const$.

Then taking into account the magnetic resistance of the $R_\delta = \dfrac{\delta_1+\delta_2}{\mu_0 S_\delta} = \dfrac{\delta}{\mu_0 S_\delta}$, MMS of working and polarising source we can have the following ratios:

$$\Phi_R = \frac{I\cdot W_P}{R_\delta}, \Phi_{P1} = \Phi_P \cdot \frac{\delta_2}{\delta}, \Phi_{P2} = \Phi_P \cdot \frac{\delta_1}{\delta} \qquad (1.32)$$

where W_P - the number of turns of the winding;

I – winding current;

μ_0 – magnetic constant;

S_δ – the area of the working gap

According to Maxwell's formula (1.14), the resultant force will be equal to:

$$F_{EM} = \frac{\left(\Phi_{P1} - \Phi_r\right)^2}{2\mu_0 S_\delta} - \frac{\left(\Phi_{P2} - \Phi_r\right)^2}{2\mu_0 S_\delta}. \qquad (1.33)$$

Let us include the components of the formula (1.33) into the equation (1.32) and get the following:

$$F_{EM} = \frac{\Phi_P^2\left(\delta_2 - \delta_1\right)}{2\mu_0 S_\delta} - \frac{\Phi_P \cdot \left(I \cdot W_P\right)}{\delta}. \qquad (1.34)$$

If we denote $\frac{\delta_2 - \delta_1}{2} = X$ movement the anchor from the neutral position, we have:

$$F_{EM} = \frac{\Phi_{P1}^2 \cdot X}{\mu_0 \cdot S_\delta} - \frac{\Phi_{P2} \cdot \left(I \cdot W_P\right)}{\delta}. \qquad (1.35)$$

Let us construct the characteristics of the load relay *F=f (IN*$_w$*)* and traction *FEM= f(X) w*ithout taking into account the resistance of the steel, the flow of scattering and protrusion (Fig. 1.25).

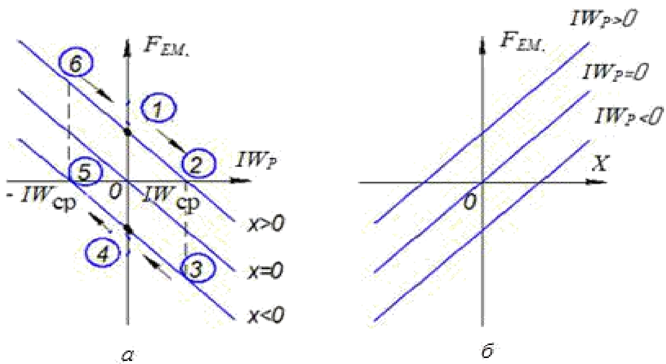


Figure 1.25 - Characteristics of the polarised relay: a-load characteristic F=f(IN$_w$); *b*–traction characteristic F_{EM} =f (X)

In real conditions, when the steel resistance, fluxes of scattering and buckling are taken into account, the electromechanical characteristics will appear as a nonlinear character (Fig. 1.26).

Due to the high sensitivity, low power consumption and high frequency of thermal stability, polarised relays are widely used to implement the functions of relay, voltage and power with switching on through rectifiers.

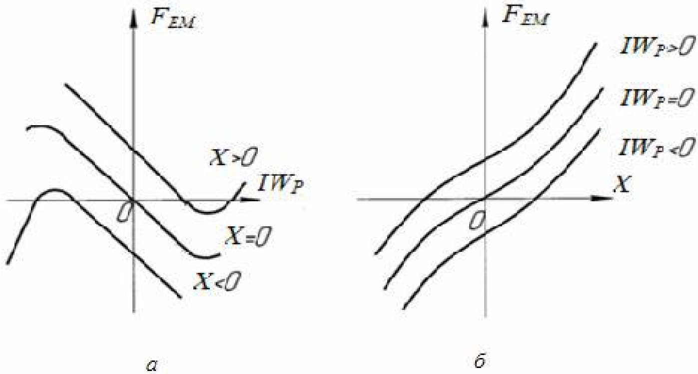


Figure 1.26 – Real characteristics of the polarised relay: a-load characteristic; *b* – traction characteristic

1.8. Induction relay

Electromechanical relay, the operation of which is based on the interaction of alternating magnetic fields of fixed windings with the currents induced by these fields in the moving element [15, 25, 26, 29, 32]. Since these currents can only be induced by changing the magnetic field over time, induction systems operate only on alternating current. And to create the moment of rotation, it is necessary that at least two magnetic fluxes are displaced through the conductive element, which are displaced relative to each other. The phase shift is due to the windings supplied from different sources or by means of short-circuited coils located at the poles of the magnetic system. Discs, drums and short-circuited frames made of aluminium, copper or brass can be used as an electrically conductive movable element.

The conductive element must have a small moment of inertia to ensure rapidity. According to this indicator, the induction systems are located as follows: with short circuit, drum and disc. Induction relays are distinguished by the design of the magnetic system and the movable element (Fig. 1.27). A core in a magnetic system with a drum and a frame is used to reduce the magnetic resistance in the magnetic flux path and is made of magnetic steel.

1.8.1 Torque of an induction system

Let us have a look at the torque on the example of an induction system with a disk (Fig. 1.28). A magnetic field with a variable sign is formed when alternating current in the air gaps is flowing through the windings. The magnetic fluxes Φ1 and Φ2 will be induced in the EMF disk E1 and E2 which determine the transformation currents I1 and I2. Assuming that the flows are sinusoidal and shifted relative to each other in phase by angle α, then

$\Phi_1 = \Phi_{1m} \sin\omega t$,

$\Phi_2 = \Phi_{2m} \sin(\omega t-\alpha)$

where W_1 ,W_2 – *the number of turns in both windings, respectively ;*

a_1, a_2 –force applying shoulders *F1*, *F2*;

F_1, F_2 –forces;

I_1, I_2 – *currents in the disk under the poles*

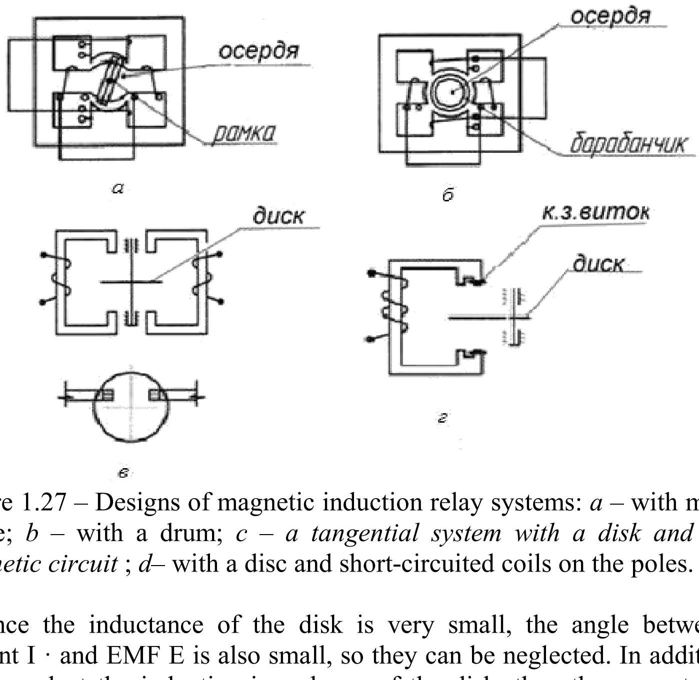


Figure 1.27 – Designs of magnetic induction relay systems: *a* – with movable frame; *b* – with a drum; *c – a tangential system with a disk and a split magnetic circuit* ; *d*– with a disc and short-circuited coils on the poles.

Since the inductance of the disk is very small, the angle between the current I · and EMF E is also small, so they can be neglected. In addition, let us to neglect the inductive impedance of the disk, then the current vectors coincide in direction with the vectors of the corresponding EMFs, which in turn will lag behind the fluxes by 90^0 (Fig. 1.28) [15, 25, 26, 29, 32]. It is known that a conductor of length l with current i in a magnetic field with induction B is subject to force

$F=i \cdot B \cdot l.$

If the currents I_1 and I_2 are sinusoidal and phase-shifted by angle ψ, then it can be determined:

$F(t)= l \cdot I_m \cdot \sin(\omega t - \psi) \cdot B_m \cdot \sin\omega t,$ (1.36)

where I_m – the amplitude value of the current; B_m – the amplitude value of the induction; – shear angle between I_m and B_m .

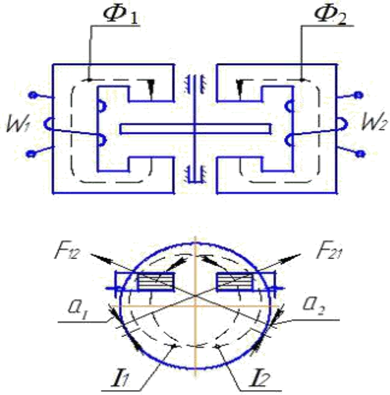


Figure 1.28 – Design of an induction relay with a disk

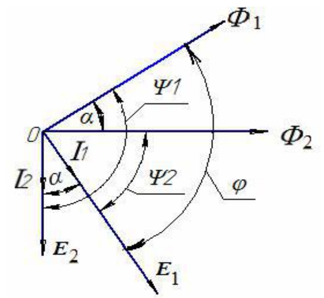


Figure 1.29 – Vector diagram of EMF, currents and magnetic fluxes of an induction relay with a disk

Then the average (mean) value of the force for the period T is equal to:

$$F_{cp} = \frac{1}{T}\int_0^T F(t)dt. \qquad (1.37)$$

Substitute into equation (1.38) equation (1.37) and obtain:

$$F_{cp} = \frac{I_m \cdot B_m \cdot l}{2}\cos\varphi. \qquad (1.38)$$

The total force exerted on a disk will be equal to:

$$\Sigma F = F_{11} + F_{12} + F_{22} + F_{21}, \qquad (1.39)$$

where *F11* – the force of interaction between the flow*Φ1* and the current *I1*;
F12- the force of interaction between the flow*Φ1* *and* the current *I2*;
F22 -the force of interaction between the flow *Φ2 and the current I2 ;*
F21 - the force of interaction between the flow *Φ2 and the current I1 ;*

Due to the fact that the phase shift angle between the eponymous flow and the current is equal 90^0 ($cos\ \varphi = cos\ 90^0 = 0$) then from the equation (1.39) $F_{11}=F_{22}=0$ get the total force:

$$\Sigma F = F_{12} + F_{21}. \qquad (1.40)$$

The torques created by these forces are directed in different directions.

Assume positive direction of the moment from force F_{21}, then:

$$\sum M = F_{12} \bullet a_2 - F_{21} \bullet a_1, \qquad (1.41)$$

where a1, a2 - applying shoulders of the forces

The value of currents in the disk can be calculated by Ohm's law electromagnetic induction

$$I_{m1} = \frac{2\pi f \cdot \Phi_{m1}}{R_1}, I_{m2} = \frac{2\pi f \cdot \Phi_{m2}}{R_2} \tag{1.42}$$

where R1and *R2* – active resistances in a disk on the current transformation path;

f - frequency of the power source

The active resistance of a disk depends more on its geometry and is approximately defined as:

$$R = \frac{\rho}{\Delta} K_R$$

where ρ – specific electrical resistance of the disc material;

Δ– disk thickness;

K_R – geometric coefficient of resistance.

From the vector diagram (Fig. 1.31) we find cos ψ1 = -sin α, cos ψ2 = sin α, taking into account the equations (1.40… 1.42) we obtain for working torque:

$$M_\rho = \frac{f \cdot \Delta}{\rho} \cdot \Phi_{m1} \cdot \Phi_{m2} \left(\frac{\pi l_1 \alpha_1 \beta_1}{S_1 K_{R1}} + \frac{\pi l_2 \alpha_2 \beta_2}{S_2 K_{R2}} \right) \cdot \sin \alpha, \tag{1.43}$$

where *l1* and *l2* – equivalent lengths of current lines under the poles of the magnetic circuit;

S1 and *S2* – the intersection area of the poles;

β1 and *β2* – coefficients that take into account the part of the current that flows only below the poles.

The sum of the components in the brackets of equation (1.43) depends on the geometrical relations of the induction system and is called the geometric constant:

$$\left(\frac{\pi l_2 \alpha_2 \beta_2}{S_2 K_{P2}} + \frac{\pi l_1 \alpha_1 \beta_1}{S_1 K_{P1}} \right) = x. \tag{1.44}$$

Then in general form for the working torque can be written:

$$M_\rho = \frac{f \cdot \Delta}{\rho} \cdot x \cdot \Phi_{m1} \cdot \Phi_{m2} \sin \alpha. \tag{1.45}$$

The direction of rotation of the disk - from the pole with the forward stream to the pole with the trailing stream. In addition to the currents of transformation, there are cutting currents in the movable element due to the intersection of the rotating disc with magnetic force lines (Fig. 1.30).

The nature of cutting currents is illustrated by the example of a frame made of a conductor in a magnetic field. When the contour is moving, the flow associated with it changes:

$$\Phi_x = B \cdot S_x = B \cdot l \cdot x \,, \tag{1.46}$$

The EMF given in the circuit at B = const, we have:

$$e = -\frac{\partial \Phi_x}{\partial t} = -B \cdot l \frac{\partial x}{\partial t} = -B \cdot l \cdot V, \tag{1.47}$$

where V - speed of contour movement.

From the formula (1.47) the EMF cutting is proportional to the speed of movement of the contour and is directed so that its motion is slowed down. The nature of the cutting current in the disc is similar.Assuming that the shear angle between the flow and the cutting current is zero (Fig. 1.31). Then, as a result of the interaction between the fluxes Φ_1 and Φ_2, as well as the cutting currents I_{p1} and I_{p2}, a braking moment is create:

$$M_T = K_2 \omega \left(\Phi_{m1}^2 + \Phi_{m2}^2 \right), \tag{1.48}$$

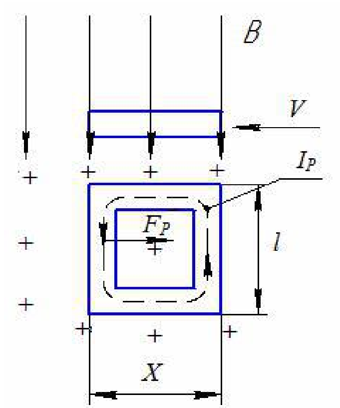


Figure 1.30 – Location of the frame in a magnetic field

where K_2 – a coefficient that depends on the system parameters, the value is usually large;

Φ_{m1} , Φ_{m2} – amplitude values of flows

Taking into account the formula (1.48), the total torque acting on the disk will be determined

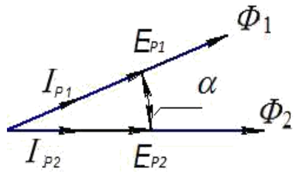


Figure 1.31 – Vector diagram of currents, EMFs and flows

$$M_{OB} = K_1 \cdot \Phi_{m1} \cdot \Phi_{m2} \cdot \sin\alpha \left(\Phi_{m1}^2 + \Phi_{m2}^2\right), \qquad (1.49)$$

where $K_1 = \frac{f \cdot \Delta}{\rho} \cdot x$; ω – angular velocity

As follows from (1.49), the M_{Torque} depends primarily on the magnetic fluxes, the shear angle between them and the geometric dimensions. Relays of current, voltage, resistance and power operate on the basis of induction systems . Let us have a look at the power relay (Fig. 1.32).

1.8.2 Induction power relay

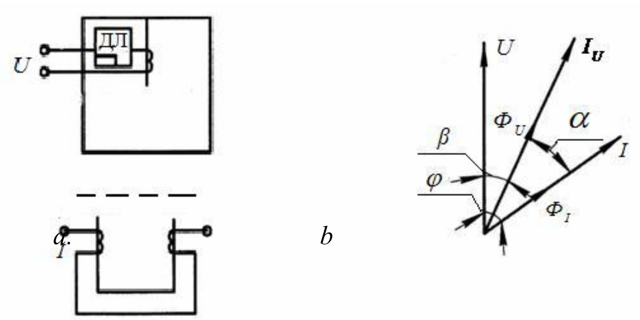


Figure 1.32 – Power relay with a vector diagram of its currents and flows

If a signal proportional to voltage is applied to the winding of the upper magnetic system (Fig. 1.32, a) and current is applied to the lower windings, then the torque will be equal to $M=K \bullet \Phi_1 \bullet \Phi_U \bullet \sin\alpha$, and $\Phi_U = U$; $\Phi_I = I$. So,

$$M = K \cdot U \cdot I \cdot \sin\alpha , \qquad (1.50)$$

From the vector diagram (Fig. 1.32, b) we obtain $\alpha = \varphi - \beta$.

Then M=K• U• I • sin (φ - β). I.e. the moment is proportional to the total power and depends on the shear angle φ between the current I and the voltage U and the "inner" angle β, which in turn depends on the ratio of active and reactive resistance of the voltage coil circuit.
By including in series with the voltage coil an additional chain (AC) from the resistor, capacitor and throttle or their various combinations, it is possible to obtain a different angle β, which will determine what power the relay will respond to.
For the case when the angle $\alpha=90^0$, since β $=90^0$ - φ (Fig. 1.33, a) as well as $\sin 90^0 = 1$, the relay will respond to the change in full power:

$$M = K \cdot U \cdot I . \qquad (1.51)$$

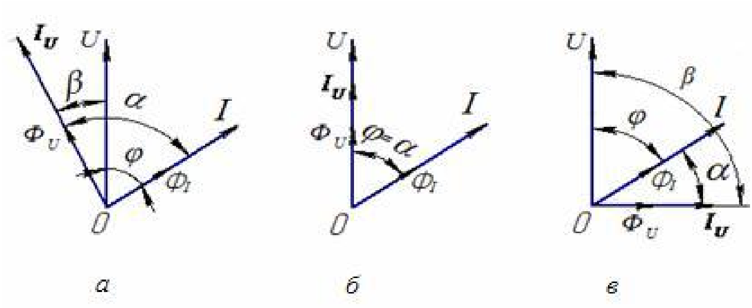


Figure 1.33 – Vector diagram of power relay currents, flows and voltages

For the case when the angle $\beta=0, \alpha=\varphi$ (Fig. 1.33, b), the relay will react to reactive power:

$$M = K \cdot U \cdot O \cdot \sin\varphi , \qquad (1.52)$$

For the case when the angle $\beta = 90^0$, $\alpha = 90^0 - \varphi$, $\sin \alpha = \cos \alpha$, (fig.1.33, *c*) the relay will react to active power:

$$M = K \cdot U \cdot I \cdot \cos\varphi , \qquad (1.53)$$

It should be noted that, in general, induction systems with a disk are distinguished by a low sensitivity and a large time of operation due to the considerable moment of inertia of the movable element - the disk. In practice, the current relays PT 80 and PT 90 are implemented to obtain the current-dependent response time characteristicThey are used in AC devices to protect electrical machines, transformers, power lines and switchgear from overloads and short circuit.For the development of more sensitive and high-speed induction relays, systems with a movable aluminium cylinder rotor or sector (for example, in single-phase power direction relays such as РБМ-170 and РБМ-270) are used with two windings. One of them connects to a current transformer and has a secondary current and the other to a voltage transformer and has a current proportional to the voltage at the winding clamps. The torque arising on the rotor is proportional to the power on the relay clamps and its direction depends on the direction of this power. Such relays are used in relay protection circuits for detecting and unlocking lines where a short circuit has occurred. On the basis of this system with the mobile sector, a relay of a series of ДСШ was created, which is used in the automatics of railway transport [15, 25, 26, 29, 32].

1.9 Magnetoelectric relays

Magnetoelectric relays are electromechanical relays whose operation is based on the interaction of magnetic fields of a fixed permanent magnet and the movable winding excited by current. The movable winding is made in the form of a frame on which the winding is wound (Fig. 1.34) [15, 25, 26, 29, 32].In the air gap between the poles of the system (can be made of soft magnetic steel (Fig. 1.34, a), or of magnetically solid material (Fig. 1.34, b) and a core forms a magnetic field with a movable frame in it. There is no core in the structure for reducing the overall dimensions (Fig. 134, c), and there is a magnet inside. In the design on the figure 1.34,d there is a frame that performs a translational motion . If a signal is transmitted to the frame in time, then the frame will be in oscillatory motion due to its small mass, so the magnetoelectric systems on AC are not used.

When applying a signal to the conductors of a frame in a magnetic field, the torque is acting:

$$M_T=2\bullet B\bullet I_p\bullet\ l\bullet N\bullet\ a\ , \qquad (1.54)$$

where B – magnetic field induction in the gap; I – frame current;

l – width of poles;

N – the number of turns of the frame;

a – shoulder strength

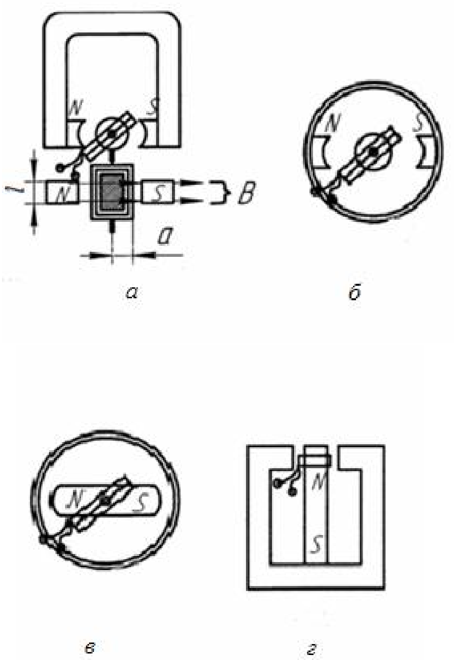


Figure 1.34 – Magneto-electric relay designs: a– with a horseshoe-shaped magnetic circuit ; *b* – with an annular magnetic circuit; c– with the internal location of the magnet; *d* –with the frame propulsion

When moving a frame in a magnetic field, it is subjected to a braking torque which is usually small in magnitude because of the great value of the impedance of the power circuit, and therefore cannot be taken into account.

$$M_{TB} = 2 \cdot \frac{(B \cdot l \cdot W \cdot a)^2}{r_P + r} \cdot \frac{d\varphi}{dt},$$

where r_P , r - frame supports and power circuit, respectively; φ – rotation angle.

If the frame is made on a metal frame (conducts heat well), then it is essentially a short circuit and the braking torque in this case can be of great importance, so it should be taken into account:

$$\sum M = M_T + M_{TB}$$

The direction of rotation of the frame for the propulsion system is determined by the right-hand pitch [25]. Such relays have a contact system with a low cut-off ability and a gap between the contacts of 0.3… 0.5 mm. The operation time of the relay has a range from 0.01 to 0.2 s. They are usually used as zero indicators in rectified current and are still in operation.

1.10 Electrodynamic relay

The operation of electrodynamic relay is based on the interaction of the magnetic fields of the movable and fixed windings, excited by currents drawn from the outside (Fig. 135). Electrodynamic relay has two coils [15, 25, 26, 29, 32]. One is fixed (1), and there is a movable (2)coil inside it. The movable coil starts to move when simultaneously we give the signal to two coils. The force and torque are determined as follows (Fig. 1.36).

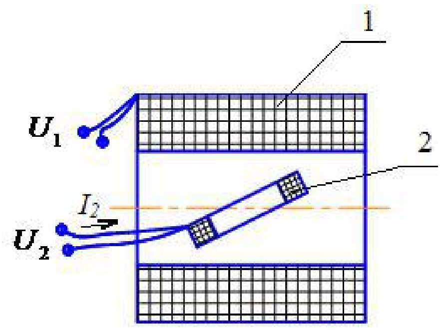


Figure 1.35 – Principle of operation of the electrodynamic relay

Electrodynamic force F is applied to the turns of the movable coil from the side of the magnetic field of the fixed coil, which is directed perpendicular to the force lines of the field. If you look at the vector diagram, then the DC power will be defined as

$$F = B_1 \cdot I_2 \cdot l_2 \cdot W_2 \quad (1.55)$$

where $B1$ – field induction in the gap created by a fixed coil;

$I2$ – current of the movable coil;

$l2$ – the width of the movable coil;

N_2 – the number of turns of the movable coil.

AC power:

$$F = \frac{B_{m1} \cdot I_{m2} \cdot l_2 \cdot W_2}{2} \cdot \cos\varphi \quad (1.56)$$

where B_{m1} – maximum field induction in the gap;
I_{m2} – maximum current of the movable coil;
φ – angular shear by phase between complex vectors B, I.

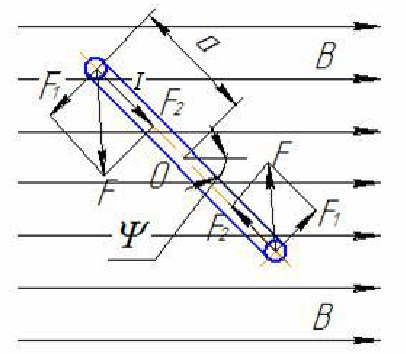


Figure 1.36 – Determination of the force F and the torque M_T of the movable coil in a magnetic field

Normal force component:

$$F_1 = F \cos\psi,$$

where ψ – frame angle.
Then the torque at DC will be equal to:

$$M = F \cdot a \cdot \cos\psi = B_1 \cdot I_2 \cdot l_2 \cdot W_2 \cdot a \cdot \cos\psi, \qquad (1.57)$$

where a – shoulder strength.
The torque at AC is equal to:

$$M_{cp} = F \cdot a \cdot \cos\varphi \cdot \cos\psi = \frac{B_1 \cdot I_2 \cdot l_2 \cdot W_2}{2} \cdot a \cdot \cos\varphi \cdot \cos\psi. \qquad (1.58)$$

Therefore, the moment of the electrodynamic system depends on the position of the frame and will be maximal when the movable frame is located along the force lines of the field of the fixed coil (ψ=0, cosψ= 1), and during its rotation the moment is reduced to zero. When AC power is supplied, the system becomes sensitive to phase change. The moment becomes maximum when complex induction vectors B_1 and current I_2 coincide in phase [15, 25, 26, 29, 32].

1.11 Thermal relay (thermorelay)

Long-term overload currents (up to 5… 7 IHOM) rather overheat electrical equipment, so there are thermal protection devices with thermo-bimetallic actuators [38, 39, 40] for automatic protection in excess of the allowable temperature [38, 39, 40]. These are the electromechanical relays that operate at a certain temperature of the measuring element (Fig. 1.37, a). The measuring element is heated by the current flowing through this element (direct heating) or through a separate heater (indirect or oblique heating) (Fig. 1.37, b). There is also a combined heating of the thermo-bimetallic element. Sensitive elements are a two-layer plate with different coefficients of linear expansion and are made of alloys with different coefficients of thermal expansion, bodies with variable magnetic permeability or of those in which the electrical resistance changes with temperature, or made from thermobimetal that have received the most distribution. When heated, the layer of thermoactive metal expands which has a coefficient of expansion *a1* (1 in Fig. 1.37, a), and a layer of thermoinert metal with a coefficient *a2*(2 in Fig. 1.37, a) almost does not deform. A plate with a larger *a* is called active (for example, brass, chromium-nickel steel,
$a=(15…20)\cdot 10^{-6}$ m/degrees) and with a smaller coefficient - inert (more often made from invar (Ni – 36%, Fe – 64%,
$a=10^{-6}$ m/degrees). If one end of the bimetal plate is rigidly secured, the other free end has the ability to bend. The maximum bending will be in this case:

$$\beta = \frac{3}{4}(\alpha_1 - \alpha_2)\frac{l^2\theta}{\delta},$$

where l – length of bimetal plate;
θ– bimetal plate temperature exceeding ambient temperature;
δ - the total thickness of the bimetal plate.
δ - the total thickness of the bimetal plate.

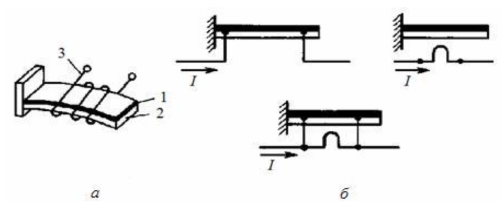


Figure 1.37 – Bimetallic plate with heating element (a) and methods for heating them (b).

In a thermal relay contacts cannot be placed on a bimetallic plate because it moves slowly, in addition, an arc arises during commutation and the contacts can burn. Therefore, according to constructive solutions, the contacts are arranged in such a way that they move faster as indicated in the figure. 1.38. When the bimetallic plate bends away from heat, at some point it releases the latch and quickly breaks the contact under the action of the spring. The main disadvantage of such relays is the response to ambient temperature.

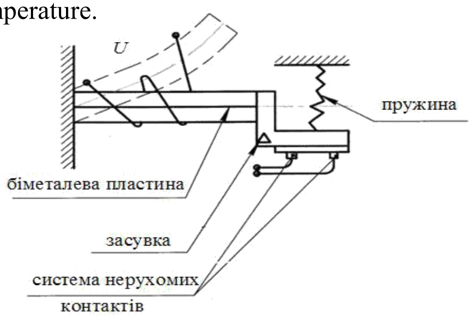


Figure 1.38 – The principle of design of thermal relays

To eliminate this drawback, temperature compensation measures are used such as those shown in Fig. 1.39. a) the event when the bimetal plates, at different coefficients of expansion α (from ambient temperature), bend in one direction or another to the same value (keeping the value β constant) and only the current flowing in the winding will make the contacts close, and in Fig. 1.39, b) is when at different coefficient α the bimetallic plates will bend in different directions and the insulating plate (1) will keep β1 and β2 unchanged. The relay is triggered by the signals entering the windings W1 and W2.

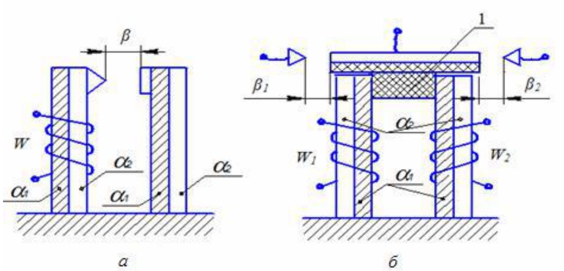


Figure 1.39 – Methods of compensating the ambient temperature in the thermal relay

When designing a thermal relay with bimetals it is necessary to take into account the phenomenon of hysteresis which causes residual deformation, even with allowable, but long-term temperature actions.

1.12 Features of choice and development trends of electromechanical relays

The variety of types and designs of the relay raises the question of the feasibility of using one or another type of relay for the implementation of the required functional tasks in specific operating conditions [2, 3, 24, 41, 42, 43]. At the design stage of the relay or equipment where the relay will be installed, the general requirements for sensitivity, speed, frequency and switching range, and so on, are formed.Reliability requirements can be estimated by the formula:

$$\lambda = \frac{\ln P}{n \cdot N \cdot k}, \tag{1.59}$$

where P- the probability of fail-free operation;
n- number of relays required;
N- number of actuations required;
k- number of contact relays.

It is recommended to predict the operating reserves with the use factor *ku*, which is essentially the ratio of the current parameter of the device to its maximum permissible value according to the technical documentations (tabl. 1.2).

Table 1.2- Recommended values *ku*

Parameter	*ku*	Parameter	*ku*
		5. Switching current	
1.Duration of continuous winding being under current	0.8	at load:	0.9
		active	
2. Number of actuations	0.7	capacitive	0.7
3. The cumulative voltage	1.0	Inductive	0.5
4. High temperature and humidity	0.8	6. Supply voltage	0.9

In terms of structural design, the advantage must be in favour of hermetic relays, especially for humid environments and reduced operating temperatures, to prevent the formation of non-transparent films on the contacts, rapid aging of insulation, etc.

However, it should be noted that hermetic relays have certain disadvantages (the heat transfer from the conductive circuit deteriorates in vacuum conditions , and as a consequence, the service life of the coil decreases, and in the course of time aggressive gases are absorbed into the relay and films are formed).

Nowadays, the development of electromechanical relays according to traditional design principles has come close to the limit of technical possibilities.

$$Q = \frac{P_{k\max} N}{V}, \qquad (1.60)$$

where $P_{k\max}$ – maximum commuting power,W;

N – number of actuation, quantity;

V – volume of relay, cm^3 .

At the end of the last century, this figure grew rapidly due to miniaturisation, increased sensitivity, speed, quality and reliability of the nodes. Now it can grow due to the development of common or hybrid relay scheme with integrated microchips with the following tasks:

1)transition to separate sealing of contact systems; it is expected that this will improve the quality and reliability of switching by about 100 times, especially with microcurrents;

2)High-power relays (for currents greater than 10 A) should also be sealed;

3)to develop relays with control system, both on alternating and direct currents, without built-in rectification system;

4)increase the efficiency of magnetic systems by using polarised relay systems which will reduce the mass and dimensions by up to three times and increase the sensitivity by up to two times compared to neutral systems.

In addition, for the miniaturisation of relays, systems with an internal coil anchor are being improved, conductors with polyamide insulation, tape and spool coils are used, etc. An example of successful development is the miniature relays РПК 65 and РЭК 65 in a sealed metal-glass low-profile hull centigrid type with dimensions 9,53• 9,53 •6,99 mm^3 (without considering the length of the pins). These dimensions allow them to be used in double-sided printed circuit boards. However, there is no data yet regarding technical solutions for a noticeable increase in the speed and frequency of operation of electromechanical relays.

1.13 Reed relays

1.13.1 Sealed magnetically operated contacts and reed relays

Magnetically operated contact (MC) or reed relay, is called an element of an electric circuit that changes the state of that circuit by mechanical locking or breaking under the influence of a control magnetic field on contact details that combine the functions of contacts and parts of electrical and magnetic circuits. The magneto-directional contact located in a sealed cylinder is called a sealed magneto-directional contact (SMC), or reed [3, 14, 19,25, 26, 29, 33, 36]. For the first time MCs were proposed by V. I. Kovalenkov (A. C. CRCR No. 466) in 1922, and V. Ellwood in 1942 suggested sealing such contacts (US Patent No. 2289830).

Sealed magnetically operated contacts allowed to solve several problems:

- eliminate the impact of the environment, as well as many of the products formed during commutation, on the contact area which has expanded the possibilities for switching of circuits with very low currents (10^{-10}… 10^{-12} A) and voltage (10^6 V);
- increase the mechanical wear resistance of 10^9 cycles and even more;
- solve many complex circuit tasks;
- increase the speed up to 0.5 ms, have a transient resistance RT up to 0.05 Ohms, and reduce the control power up to 50 mW;
- exclude mechanical coupling with the influencing body, as well as galvanic coupling between control and switching circuits.

Reed relays usually differ depending on:

-magnetic system- on neutral and polarised;

-nature of switching – on the closing, breaking and switchable

- power – on low power (up to 60 V · A), medium power (60… 1000 V · A), power with improved conditions of heat transfer (more than 1000 V · A).

The industry produced reed relays with a length from 9 to 52 mm, with a diameter of 2.2… 5.2 mm, with a working gap of 0.05… 0.3 mm and with overlapping of the extremities of the contact parts from 0.2 to 2 mm. Figure 1.40 presents a sketch of a symmetrical reed relay.

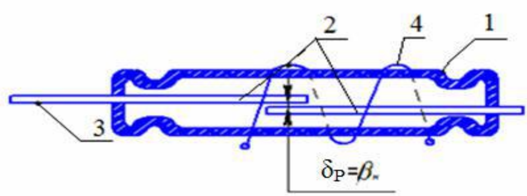


Figure 1.40 – Sketch of symmetric magnetically operated closing contact

In the classical version, the reed relay is a glass cylinder 1 (note that the glass of reed relays is usually green due to the presence of iron ions when infused with a glass cylinder by infrared radiation or resistive welding) into which soldered contact details 2 (as they combine several functions are also referred to as contact cores (CCs),which are made of a magnetic alloy with a large magnetic permeability (most often permalloy) and terminals 3. This reed relay is located in the control coil 4. Permalloys are alloys of iron and nickel which have high initial permeability in the area of weak magnetic field associated with the practical absence of anisotropy and magnetostriction.

The switching parts of the contact details (Fig. 1.41) are covered with a layer of precious metals (Rp = const), such as rhodium Rh, gold Au and their alloys. Inside the glass cylinder, either a vacuum is formed, or the cylinder is filled with dry gas (nitrogen N, hydrogen H, or their mixture) that does not react chemically with the contact material. If you place the reed relay in a magnetic field created by an electromagnetic coil, an electromagnet or a permanent magnet, a certain magnetic flux passes through the contact details [25, 26, 33, 36]

In the contact gap δ_{max} there is an electromagnetic force F_{EM} and when this force exceeds the mechanical forces of elasticity of the contact details, short circuit to the value of contact surface *a* occurs. Assuming that the magnetic conductivity of the "contact detail" is equal infinity, then we get a picture of the magnetic field (Fig. 1.42), on which the lines separating some characteristic sections of the field from the others are called separatrix.

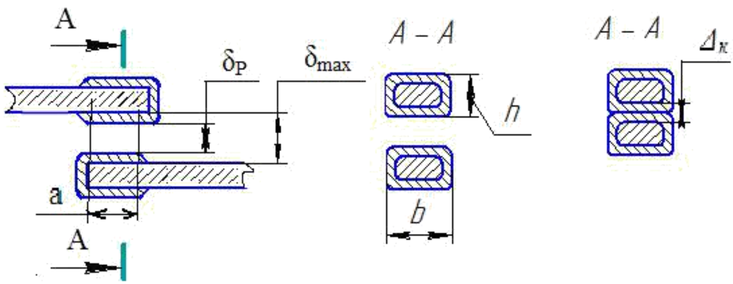


Figure 1.41 – Open and closed position of the contact part of the closing reed Δ_t – terminal (contact coating) gap; δ_w – working divergence of contacts; $\delta max = \delta_w + \Delta_t$ – non-magnetic working gap in the absence of a control magnetic field.

The maximum flow consists of the following flows:

$$\Phi_{max} = \Phi'_{max} = \Phi_{\delta} + K_1 \cdot \Phi_1 + K_2 \cdot \Phi_2, \qquad (1.61)$$

where $\Phi\delta$ – flow in the working gap;
$\Phi 1 = \Phi' 1$ – scattering streams (subject to symmetry) that are locked to one contact piece;
$\Phi 2 = \Phi' 2$ – scattering flows that are locked through the air;
$K1$ and $K2$ – coefficients that take into account input and output losses in the areas of contact details.

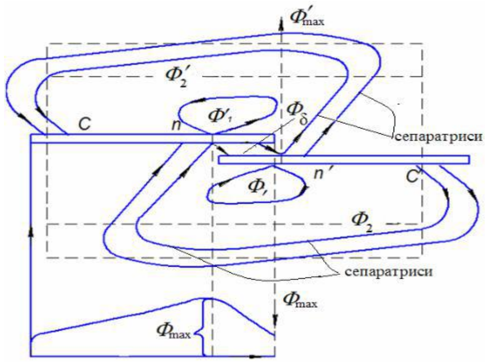


Figure 1.42 – Magnetic field distribution of contact details

1.13.2 Mechanical (counteracting) and traction characteristics of reed relays

Magnetic fluxes Φ and traction force F are the main characteristics by which sensitivity can be evaluated and control parameters can be calculated. Traction force is determined by the Maxwell formula:

$$F_{EM.m} = \frac{\Phi_\delta^2}{2\mu_0 S_\delta}, \tag{1.62}$$

where S_δ – the cross-sectional area of the working gap.

The mechanical force of contact details is defined as the force of a cantilever-mounted beam:

$$F = c \cdot x = c\left(\delta - \delta_0\right) \cdot K_{CM}, \tag{1.63}$$

where c – rigidity of contact details, N / m;
x – motion of a contact detail or force points equal to the difference between the working and technological gaps, $(\delta - \delta 0)$, *m;*
K_{CM} – symmetry coefficient.

Figure 1.43 presents the traction *FEM = f(δ)* and mechanical *FM = f (δ)* characteristics of Reed relays.

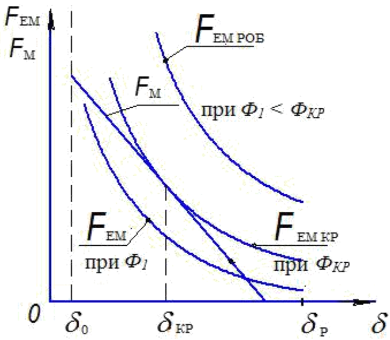


Figure 1.43 – Reed relay characteristics

The first stage of approximation of the cantilevered contact details occurs at any small value of the magnetic flux (for example, Φ_1) and is of the nature of their preliminary approximation.
In the course of increasing the magnetic flux intensity to the Φ_{cr}, a second stage occurs in which the contact details are jumped abruptly until they are closed and at this stage the further increase of the magnetic flux is not required in the working gap (due to inertia of motion, further reduction of the flow losses in the air gap, change (distortion) of the picture of the magnetic field as a whole, etc.).The Φ_{cr} flux corresponds to the critical magnitude *δcr* of the working gap and for approximate calculations for symmetric reed relays we can take:

$$\delta_{KP} = \frac{1}{2}\delta_p, \quad (1.64)$$

where δ_w – working gap.

1.13.3 Ways to control reed relays

Let us have a look at a few controls for reed relays, such as:
- linear or angular movement of the reed relay or permanent magnet (Fig. 1.44, a);
- changing the parameters of the magnetic circle with screens (shutters) with slots (windows), which allow to receive the operation of the reed when connecting the shutter with a permanent magnet, and for more rigidity the

thin-walled shutter is made of a two-layer, the second layer is of non-magnetic material (Fig. 1.44, b.);

- change of magnetised force by means of regulation windings (Fig. 1.44, c, 1.45, 1.46, and 1.47)

In the presence of a single winding in the control circuit (Fig. 1.45), it develops a sufficiently large force *Fwor*, which ensures reliable operation of the reed relay and keeps its contacts in a closed state under all pre-conditioned operating conditions.

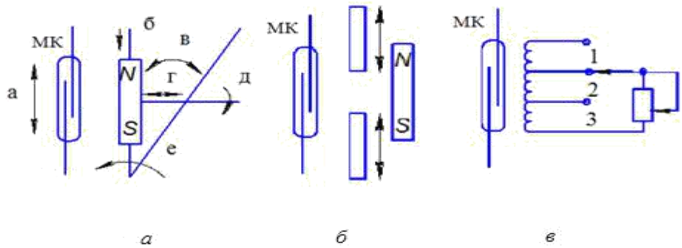


Figure 1.44 – Tools and control schemes of Reed relay

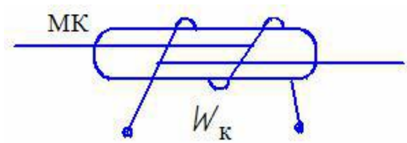


Figure 1.45 – Reed relay control system with windings

In the presence of two control windings that have a shift relative to the working gap (Fig. 1.46), it is possible to implement the logical function "OR" (if the MMF windings $F1 = F2 \geq F_{act}$), or the function "AND" (if F1, F2 $<F_{act}$) will only actuate if F1 + F2 ≥ Fact. This arrangement does not allow you to specify a significant factor of the stock on the actuation - *Kst*. Indeed, if workforce (Fwor) is the MMF of two windings, then $F_{wor}=F_1+F_2=F_{act}\bullet K_{st}$ and the total stock coefficient should be $K_{st} < 2$. One of the windings can be used as a polarising (magnetising) to accelerate the reed relay, in this case $\Phi_p < \Phi_{rel}$, which will release the reed relay if the signal is removed from the main control winding. To implement the «NO» function, the windings are switched counter.

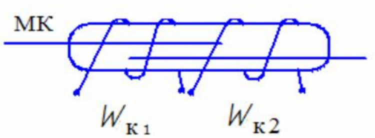


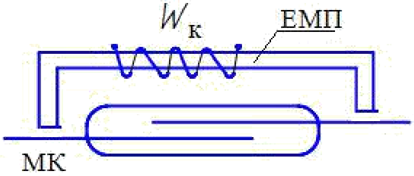
Figure 1.46 – A Reed relay. Control system. Circuit diagram .

To implement different logical functions, reed relays with several contact details have several windings (Fig. 1.47). The *WK1* main winding holds the reed relay in the on state and the *WK2, W K3, W K4, WK5* windings are switchable and allow the free contact detail 1 to occupy one of the positions between the lateral contact details (2-3 and 4-5). For example, in order to provide a chain "2-1-4", it is necessary to ensure concurrence in the direction of magnetic fluxes flowing through them.

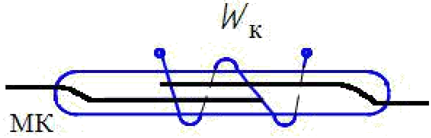
1.13.4 Ferrides

Electromechanical magnetically operated memory contact devices or ferrides are electrical devices consisting of a reed relay and a magnetic circuit with an element of magnetic memory (EMM) for various automation systems and to provide performance. The EMM is performed with medium coercive (HC = 2… 6 kA / m) of metal ferromagnets with large residual induction value (B r 1.6… 1.8 T) and hysteresis loop rectangularity coefficient equal to 0.85… 0, 9 [3, 8, 10, 14, 15]. Ferrides are used to implement complex schematic solutions and to reduce the duration of the control signal to the micro-second range and, as a consequence, to reduce control power. If the part of the relay that performs the function of the EMM is located outside the cylinder of the MC, such a device is called a ferride with external memory (Fig. 1.48).

If the contact details or their parts perform the role of magnetic memory, then the ferride is called with internal memory («гезакон») (Fig. 1.49). Thus, in a «гезакон», the contact system, the conductor, the magnetic circuit and the electromagnetic memory are combined in one.



1.48



1.49

Figure 1.48 – Ferride with external memory. Circuit diagram
Figure 1.49 –Ferride with internal memory.

Circuit diagram by the corresponding current pulses (Fig. 1.50).
In both circuits, magnetic memory is created and destroyed by the corresponding current pulses (Fig. 1.50).

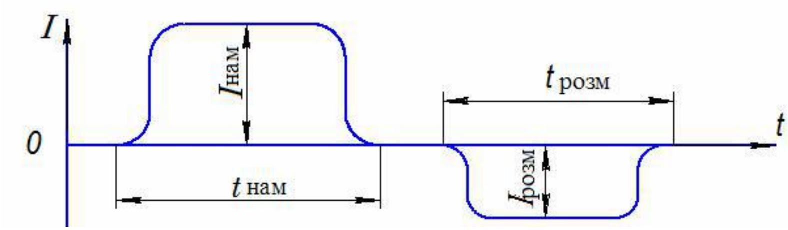


Figure 1.50 – Control pulses of the simplest ferrides

To activate the MC, a magnetising current is applied to the winding I_{mag}, the contact cores (contact details) are closed and, then, after the signal is removed, remain in the closed state due to the residual magnetic flux of the EMM. To release the MC (switching to open state), demagnetised current *I*demag of the reverse polarity pulse is applied to the winding. The amplitude and duration of the demagnetising pulse must be strictly determined in order for the EMM not to be reversed in the opposite direction and to re-lock (faulty) the contact detail.

To eliminate false actuations (a disadvantage inherent in single winding ferrides), there are the following methods:

1) the demagnetisation of the EMM by alternating fading magnetic field;
2) mutual shunting of EMM parts;
3) counter magnetisation of EMM parts;
4) orthogonal reversal magnetisation of EMM .

The first method is quite known, so let us have a look at the principle of the second method which is structurally implemented in parallel ferrides with external EMM (Fig. 1.51). Here the EMM consists of two semicircles with windings placed on them which supply current pulses. The control is carried out by half currents (additive control), i.e., each of the windings *WK1* and *WK2* develops a magnetic flux equal to half the magnetic flux required to close the contact details (core).
When applying current pulses of the inclusion of the same polarity to the control windings in each part of the magnetic circuits ,magnetic fluxes are developed which are summed up in the contact parts and lead to their closure. When applying the turn-off current pulses of different polarity to the windings, the magnetic currents in the contact part are mutually compensated. The nuclei are magnetised by opposite signs and the contact details open. All of these ferrides have the same feature - they need to be re-magnetised in opposite directions, preferably along the full cycle of the hysteresis loop of at least one part of the electromagnetic memory. The third method is implemented by sequential ferrides. The fourth method is not widespread.

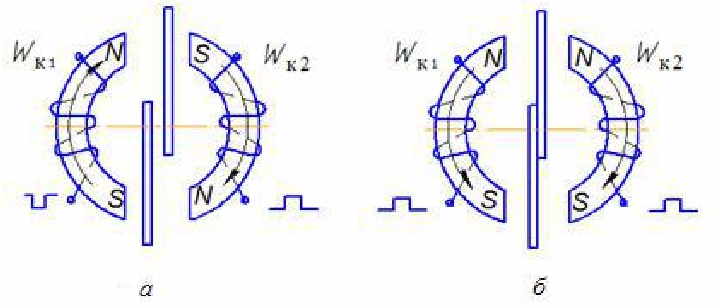


Figure 1.51 – The principle of action of a parallel ferride. Shunting of EMM sections: *a* – disabled state; *b* – on state.

1.14 Test questions and tasks

1. How to determine electromagnetic force (physical and energy approaches)?

2. Electromagnetic relay. The purpose. Main characteristics. Structural elements.

3. Electromechanical, logic and measuring relays.

4. Resistance and traction characteristic of relays. Consistency of these characteristics. Release characteristic.

5. The influence of the pole tip on the redistribution of electromagnetic force.

6. Difference between electromagnetic AC relay and DC. Anchor vibration.
7. Relay contact systems. Materials of low-strength breaking contacts of noble and refractory metals - platinoids.
8. Polarised electromagnetic relays. Working cycle.
9. Induction relay. The purpose. Determination of torque.
10. Relay of current, voltage, power and resistance of the induction system.Methods of increasing the sensitivity and speed of the relay.
11. Magnetoelectric relay. Designs. Determination of rotation and braking torques. Why is this system not used on AC power?
12. Electrodynamic relay. Power and torque at AC and DC currents. Phase sensitivity. Magnetohydrodynamic system as a kind of electrodynamic.
13. Ferrodynamic relay with rotary and gradual motions. Determination of the torque on DC and AC currents.
14. Thermal (thermo-) relays. Why it is impossible to place contacts on a bimetal plate? Ambient temperature compensation.
15. Features of choice and trend of electrodynamic relays development.
Projected development assessment. Building general relay circuits with integrated microchips.
16. Sealed magnetically operated contacts (reed relays). Building and basic features.
17. AC relay on reed switches.
18.Ways of control the reed relays. Implementation of logical functions. Logic matrix relays.
19. Ferrides with external and internal memory. Ways to eliminate false actuations. Parallel ferride with differential control.
20. Features of collaboration of several reed relays in one control winding.
21. **Task 1.** Calculate the traction characteristic of a solenoid valve type DC relay using the energy formula. Initial data for calculation: MMF of the coil *Fnom*=280A, critical MMF = 0,65 · *Fnom* = 182A, air gap $\delta = 1{,}1 \cdot 10^{-3}$m. The electromagnet magnetisation curves are taken from the reference literature.
22. **Task 2.** Calculate reed relay control coil (the sketch of the coil is presented in Fig. 1.52), determine the diameter of the wire, the number of turns and resistance, the temperature exceeding in the most adverse working conditions and specify its overall dimensions. Initial data for calculation: nominal MMF of coil control *Fnom* is equal to 250A, nominal voltage *UNOM* = 24 V, range of change of voltage on the coil from 0.85 to 1.1 *UNOM*, operating temperature range from 233 ^{0}K to 328 ^{0}K, operating mode is prolong .
lK=$48\cdot10^{-3}$ м; A′=$34\cdot10^{-3}$ м; A=$26\cdot10^{-3}$ м; B′=$16\cdot10^{-3}$ м;

B=8·10^{-3} м; H=4·10^{-3} м; P_K=80·10^{-3}м.

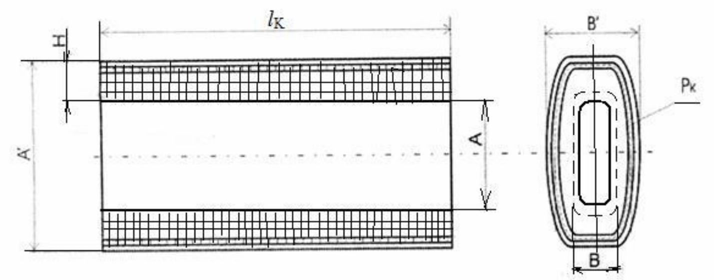


Figure 1.52 – Sketch of the relay coil on Reed switch

23. **Task 3**. Determine the sizes of the shielding coil of the electromagnetic relay of alternating current at the given: square intersection of the pole S = 1,2·10^{-4} m^2, the heating temperature of the coil 170 °C, the width of the groove Δ = 2,1 · 10^{-3} m, the fill factor of steel is K_{fs} = 0,91.

24. **Task 4**. Calculate a rheostatic displacement sensor and depict a sketch of this sensor when given: the length of the winding on the frame l = 40 mm, the lower temperature limit of the hull Ө = 20 °C, the maximum ambient temperature Өmax = 40 °C, the winding resistance R = 800 Ohms, the winding current = 0.01 A, the material of the winding is nichrome X15H60.

2.Control and regulation indicators (sensors). Converters

An indicator is an electrical device that converts a controlled value from one type to another, more convenient for influencing the operative organ of an automatic control system (ACS) [1, 5, 11, 15, 25, 30]. An indicator is the first element of a measuring channel, usually an analog device that provides information about system parameters and the processes that take place in it. Preferably, the indicators convert non-electric quantities into electrical ones, i.e., instead of a physical variable (speed, pressure, temperature, etc.), an equivalent electrical signal is generated (I, U, etc.) that are a function of these variables. In other words, $y=f(x)$, where x is the input variable of the controlled or regulated physical process, and the function y is the output variable of the indicator .(Fig. 2.1 and 2.2)
2.1 i 2.2).

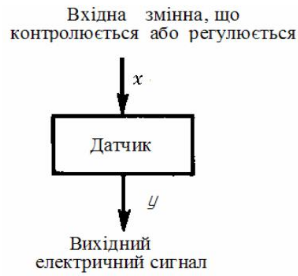
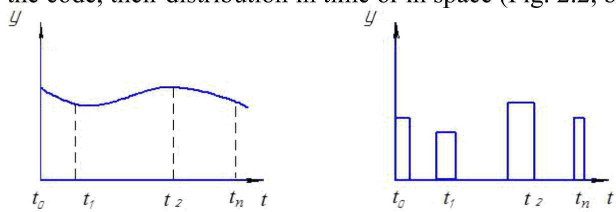


Figure 1.2. Characteristics of input and output signals of indicators.

There are two main forms of signals:

- continuous, reflecting a certain physical process; information about which is determined by certain informative parameters: current, frequencies, phases and others (Fig. 2.2, a) [25] ;
- discrete (encoded), the information carriers are the number of elements of the code, their distribution in time or in space (Fig. 2.2, b).



a b

Figure 2.2 – indicator characteristics for continuous (a) and discrete (b) output signal

Indicators complement and empower the senses and feelings of a person. There is an analogy between any technical system (automatic machine, robot) and biological system (human) (Fig. 2.3). In the absence of indicators, the quality control of products, production and consumption of electricity, pattern recognition (shape, size, chemical composition, speed of movement, etc.), and the creation of manipulators and robots are not possible.

In modern production, the indicators are used as an element of process monitoring, which allows to improve the quality and quantity of final products due to the possibility of simultaneous regulation and adjustment of the production process.

The indicators may include a sensing element that directly senses the change in the signal being monitored, as well as a converter and amplifier to match the output and input signals.

For reliable operation of the whole system, the indicators are subject to such requirements as:

-high reliability;

-long term fail-free operation;

- high accuracy $\% = (У/У_{nom}) \cdot 100\%$ (relative deviation of the output signal B to its nominal *Унom* value, given as a percentage);

-the ability to respond to minor variations in the value of the signal being measured;

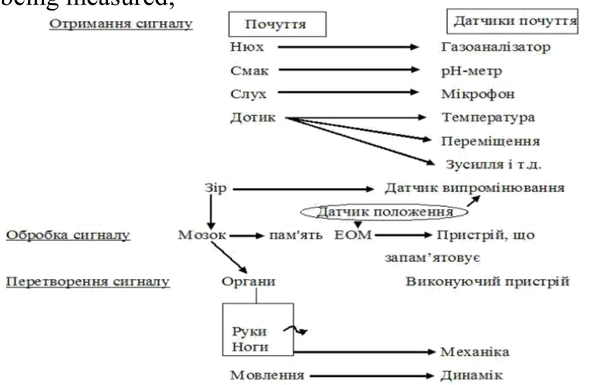


Figure 2.3 – The analogy of the functional relationship between the processes of receiving, processing and converting signals in biological (human) and technical (automatic) systems

-high sensitivity, which should not depend on the value and law of change of the controlled value;
-stability and uniqueness of characteristics and independence from external influences (aging of circuit elements, instability of voltage supply and resistance at output of measuring body, influence of environment, etc.);
-high efficiency, ie maximum output signal at minimum input energy, etc.
Indicators are classified according to several features and criteria:
-the physical phenomena on the basis of which indicators work(eg, the law of electromagnetic induction, Hall effect, magnetostriction, etc.);
-the presence of movable elements (electromechanical) or their absence (static);
-by the principle of action;
-by design;
-by purpose;
-by controlled magnitude (eg pressure, moisture , acceleration, rotation angle, etc.);
-by object (eg oven temperature, engine speed, etc.);
-by type of transfer function (e.g., inertialess, inertial, with a delay, etc.)
All indicators are passive or parametric, active or generator.

Parametric indicators include indicators in which a change in the controlled value causes a corresponding change in the parameter in the electrical circuit. They cannot form an electrical signal on their own, and a power source (eg resistive, inductive and capacitive indicators) is required for their operation.

Generators include indicators that are themselves sources of electrical energy, i.e., they do not require an additional power source, but themselves generate an electrical signal, usually in the form of an EMF, with the output energy being proportional to the magnitude they control. Examples are induction, thermoelectric, photoelectric, piezoelectric indicators, self-synchronising indicators, and more.

The main characteristic of the indicator $y = f(x)$ can be linear or nonlinear. More often a linear characteristic is required, i.e. a proportional change in the output value from the input.
Indicator sensitivity is determined by the formula:

$$S = \frac{\Delta y}{\Delta x}, \qquad (2.1)$$

Relative sensitivity is determinate by the formula:

$$S_{REL} = \frac{\Delta y \cdot x}{\Delta x \cdot y}, \qquad (2.2)$$

where *x* and *y* – complete changes of input and output values. If S=const, then the indicator is «linear», if S=var, then the indicator is «nonlinear». Transient duration is determined by the speed.

The total error of the indicator is defined as

$$\Delta E = +/- (\Delta XA + \gamma_S), \qquad (2.3)$$

where ΔXA – an additive error which does not depend on the input value, its source is external guidance, losses in circuit diagrams, noise of circuit elements and so on;

γ_S – a multiplicative error which depends on the input value, its source is instability and inconsistency with the nominal values of the transmission coefficients of individual functional nodes, etc

2.1 Contact indicators

Contact indicators are essentially parametric type, in which the electrical resistance changes when a certain mechanical value is changed. When the measured value reaches a certain value, the electrical contacts 1 and 2, which are included in the circuits, are closed or open. This is a signal that there is a movement greater than or less than a certain normative value (Fig. 2.4). The static characteristic has a relay character because its output value is the resistance of the electrical circuit and, accordingly, is changed by a jump. For example, in sorting machines, these indicators allow dividing products up to 40 groups with a productivity of several hundred per minute.

To control the size *l* of details and rejection of unsuitable products $l + \Delta l$(1…3) in the diagrams in Fig.2.4 included a lamp. If the size differs from the normative one, it lights up and allows the controller to control the production. The choice of contact material is of great importance for the operation of the indicators. Positive results are obtained with contacts made from palladium and iridium alloys or tungsten and rhenium alloys. When designing indicators, engineers focus on low breaking power so that contacts (1) and (2) are less burned. The contact materials depend on the contact pressure *Pc* which in turn depends on the sensitivity. If the *Pc* is within 0.2 N, the contacts are made of gold; if the *Pc* is within 1.0 N - silver; if the *Pc* is within 3.5 N - of tungsten and molybdenum alloy.

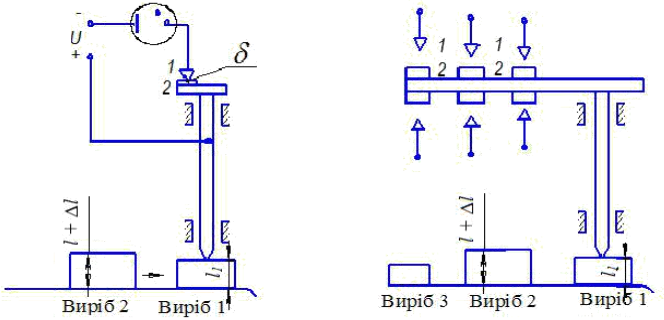


Figure 2.4 – Schematic diagram of the action of contact indicators to control the size of parts a-single limit contact indicator;*b*-multidirectional contact indicator

Contact indicators have advantages such as high precision and sensitivity, the ability to use in alternating and constant circuits and relatively low cost, but also disadvantages such as contact warming and large errors in vibration and shaking.

2.2 Potentiometric indicators

These indicators belong to common displacement (movement) indicators that can measure both linear displacement (translational movement) and rotation angle (when rotating). They belong to the indicators of the parametric type and transform the mechanical movements into changes in the active resistance of the electrical circuit, and are also called resistive indicators with variable resistance. Potentiometric indicators are made of materials characterised by the following resistances:
-constantan (Cu + Ni) with support ρ = 0.49 Ohm• mm2 / m;
-nichrome (Mn + Ni + Fe + Cr) ρ = 1.08 Ohm •mm2 / m;
-manganin (Cn + Ni + Mn) ρ = 0.42 Oh •mm2 / m;
-platinum alloy and iridium (Pt + Ir) ρ = 0.23 Ohm • mm2 / m;
-tungsten (W) ρ = 0.056 Ohm •mm2 / m.

The wire is wound on a flat, cylindrical ring frame made of dielectric (textolite, electric ebonite, paper-based laminate, etc., and for particularly accurate indicators - on a metal framework, sprayed insulating oxides (eg *A12O3*) which dissipate heat well. Sliders are usually made of alloys of palladium with iridium, silver, or cobalt (Pd + Ir, Pd + Ag, Pd + Ag + Co) and others. To ensure contact when moving from turn to turn, the slider must touch both the previous turn and the next (Fig. 2.5).

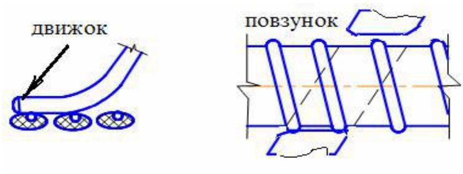


Figure 2.5 – The principle of operation of the potentiometric indicator

Of the various existing switching schemes, the simplest scheme has become the most widespread (Fig. 2.6).
With the various existing switching schemes, the simplest scheme has become the most widespread (Fig. 2.6).

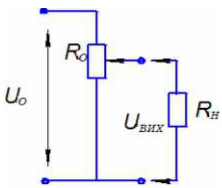


Figure 2.6 – Circuit electrical connection of the displacement indicator

If the cross section of the frame on which the wire is wound is the same along its entire length, the resistance of the indicator varies in proportion to the angle of rotation, or displacement x. If the input resistance in the circuit, whose parameters are measured, is of a great importance, then the output voltage *Uout* will depend only on the angle of rotation or linear displacement x, and will not depend on the resistance R_0.

$$U_{out} = \frac{U_0}{\alpha_{\max}} \cdot \alpha, U_{out} = \frac{U_0}{x_{\max}} \cdot x \qquad (2.4)$$

where $\alpha_{\max}$ – maximum angle of rotation;

$x_{\max}$ – maximum movement of the slider.

The sensitivity of the indicator with a linear movement of the movable contact defined as

$$S_D = \frac{dU_{out}}{dx} = \frac{U_0}{x_{\max}}. \qquad (2.5)$$

To increase the sensitivity of the indicators usually increase the supply voltage *U0*, however, this increases the power dissipated by the indicator . The maximum sensitivity of S_{max} is equal to:

$$S_{\max} = \frac{\sqrt{P_{\max} \cdot R_0}}{x_{\max}}, \qquad (2.6)$$

where $P_{\max}$ – the maximum allowable power of the potentiometric indicator with R_0.

The error of the indicator depends on the stability of the supply voltage *U0*, the accuracy of the manufacture of structural parts, temperature stability and material. An important indicator of the quality of the tensiometer is the smooth change of the output voltage. This characteristic determines which the smallest angle of rotation or the amount of movement of the slider, the indicator is able to respond. As can be seen from the graph (Fig. 2.7), the voltage of the wire indicators changes not continuously, but by steps (non-linearly).Physically, this can be explained by the fact that the element of the slider, which removes the current, does not come into contact with the surface of the wire along its entire length, but only as a "jump" (a - b - c – d). Then the deviation of the output voltage from the calculated one via re-jumping on the steps will be equal to ΔUst < *U0* / 2n (where n- is the total number of turns, and *U0* - is the supply voltage).

To estimate the numerical value of the error caused by jumping steps, an understanding of the electrical ability to distinguish the potentiometer δp(%) was introduced. This is the magnitude of the increase in resistance or voltage when moving the slider of a potentiometer one turn. It determines the maximum possible accurateness (without errors) of the potentiometric indicator .

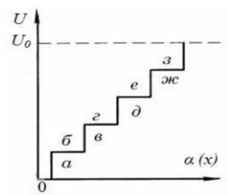


Figure 2.7 – Characteristics of conductive indicators when changing the length of movement or angle of rotation

To improve the distinguishing ability of the potentiometer, the number of turns n is increased. This can be achieved either by lengthening the winding or by reducing the cross section of the wire itself. However, the first option leads to an increase in the size of the potentiometer, and the second - to a decrease in the mechanical strength of the conductor, as well as technological difficulties in the manufacture of the potentiometer, etc. Single-turn potentiometers have values of δp = (0.02 ... 0.4)%. To change δp, you can use complex multi-turn potentiometers. Only linear potentiometers have a constant distinguishing ability. However, in addition to the advantages (the ability to obtain a linear characteristic, simple design and low cost), they have certain disadvantages (relatively high effort to move, burning contacts, mechanical wear and chemical corrosion).

This can result in a change in gear characteristic throughout the service life. Resistive sensors can be frame and frameless (liquid or electrolytic) (Fig. 2.8). The basis of frame indicators [25] (Fig. 2.8, a - d) is a high-impedance wire which performs the function of resistance.

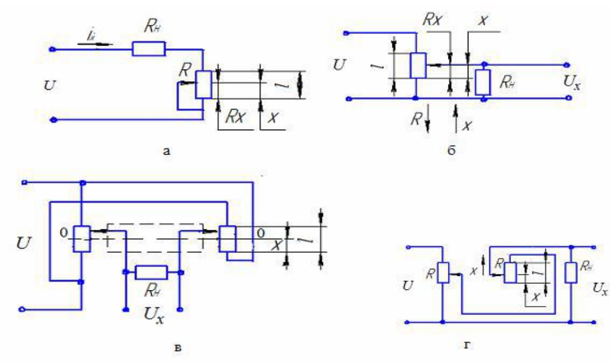


Figure 2.8 – Frame resistive position indicators.
Electrical and circuit diagrams.

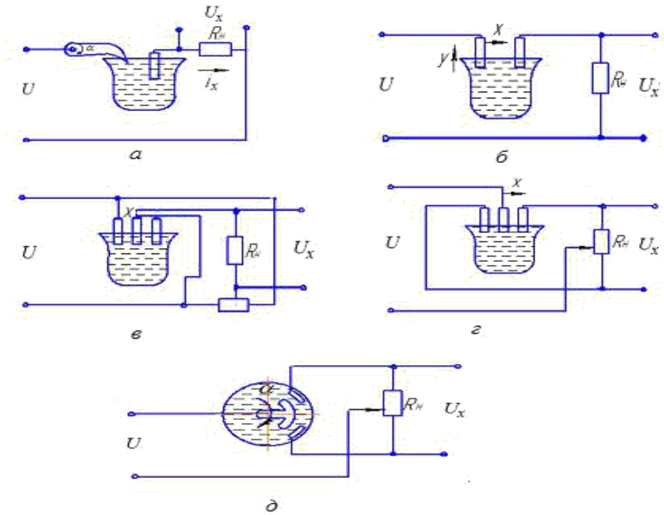


Figure 2.9 –Electrolytic resistive position indicators. Electrical and circuit diagrams.

Indicators with variable channel length and cross section are used to approximate the coupling weight (Fig. 2.11). The resistance of the electrolytic indicator *Ri* of length *L* can be defined as R = 1 / Λ, where Λ is the conductivity of the electrolyte (in the general case, it is determined by constructing a picture of the electric field and summing the conductivity of individual sections).

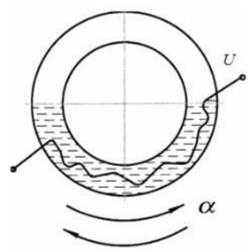


Figure 2.10 – The principle of operation of the stepless indicator

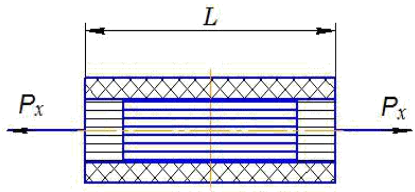


Figure 2.11 –An indicator with variable length and cross section of the channel

2.3 Ohmic strain gauges

The action of these indicators is based on the change in the active resistance of conductive and semiconductor materials under the action of external mechanical elastic forces. They are parametric indicators and are used to convert small deformations (about 10^{-3} mm) into an electrical signal (Fig. 2.12) [1, 15, 25]. Usually the deformation in the direction of force in the zone of elastic deformations occurs in accordance with Hooke's law [20,27].

$$\delta_t = \frac{\Delta l}{l} = \frac{\sigma}{E},$$

where δ_t - relative longitudinal deformation ;

σ- mechanical stress in the conductor;

l – conductor length;

Δl – change in length as a result of deformation;

E – modulus of elasticity (Young's modulus).

The change in resistance is characterised by strain sensitivity:

$$S_D = \frac{\frac{\Delta R}{R}}{\frac{\Delta l}{l}} = E \cdot \frac{\frac{\Delta R}{R}}{\sigma}, \qquad (2.8)$$

where R and ΔR – resistance and increase in resistance due to deformation, respectively.

If we denote the relative elogation as $\xi = \Delta l / l$, then the modulus of elasticity will be equal.

$$E = \sigma / \xi \qquad (2.9)$$

The principle of operation of strain gauges is based on the fact that the resistance of the metal changes due to changes in geometric dimensions and resistivity of the material. Under the action of deformation of the strain-sensitive element - the details change its geometric dimensions and resistivity which affects the overall change in resistance.

$$R = \frac{\rho \cdot l}{S}, \qquad (2.10)$$

where ρ – resistivity of the material of the strain-sensitive element;

l and S – the length and cross section of the element respectively.

Conductive strain gauges are wire and foil. Sensitive elements of the indicators are made of metal wire or foil - tape, as well as semiconductors of round or rectangular cross section. The strain gauge (Fig. 2.12) is a thin strain-sensitive element - wire or foil (2), which is enclosed in a zigzag pattern on a thin elastic insulating plate (1) made of paper or film. Output petals (3) are soldered or welded to the terminals of the element. To protect against moisture, they are seal

ed with metal casings, foil, or rubber.

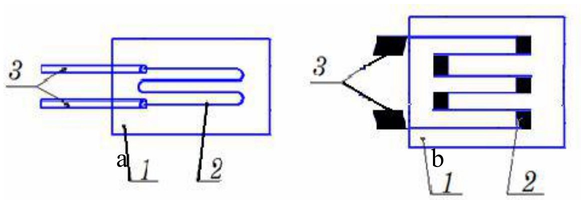


Figure 2.12 – Scheme of strain gauges of wire and foil construction

Wire elements (Fig. 2.12, a) usually have a wire diameter of 0.015 mm to 0.030 mm, are made, for example, of a constantan (composition of 60% Cu + 40% Ni), which has a resistivity of 0.44… 0.52 Ohm mm^2 / m, the temperature coefficient of linear expansion *Kt*, equal to 12.5 when heating the indicator element to 100 ^{0}C. Permissible operating temperature of the indicator is 400 ^{0}C. Other material can be made of alloy 479 (92% Pt + 8% W) which has a resistivity of approximately 0.1 Ohm mm^2 / m, the coefficient *Kt* = 9 and the allowable operating temperature is 1300 ^{0}C. Foil strain gages (Fig. 2.12, b) are similar to drift one and their elements are made of thin foil of rectangular cross-section with a thickness of 0.004 mm to 0.012 mm, which is applied to the lacquer base. They are made by photochemical method, ie the image of the strain gauge circuit is transferred photographically to the surface of the foil covered with a light-sensitive layer. Then the contour is developed, which makes it acid-resistant. Foil elements are made of alloys "gold-silver" (Au + Ag) (the best foil sensors), "copper-nickel" (Cu + Ni), or "titanium - aluminum" (Ti + Al). The latter provide measurement of relative deformation up to 12% and can work in aggressive environments. On the reverse side of the foil, shellac is applied, and areas of the foil that are not protected by an acid-resistant layer are etched.

Foil strain gages in comparison with wire have the following advantages:

-high heat transfer which is carried out through a larger area of the foil and, accordingly, better contact of the strips of foil with the detail;

-technologically apply a large area of foil and ensure good adhesion;

-increases the value of current through the indicator , which increases the strain sensitivity by about 40%;

-the deformation of the object under study is better perceived due to the high value of the ratio of the perimeter of the flat strip to the area of its intersection, so the accuracy of measuring the deformation increases;

-it is possible to increase the cross section of the thermistor, which allows you to more securely fasten the terminals.

All ohmic strain gauges have advantages such as:

- inertia, which makes it possible to measure rapidly changing loads;
- stability;
- small hysteresis;
- possibility to place in hard-to-reach places;
- small size and weight, as well as relatively low cost.

The temperature error and small relative change in resistance are the disadvantages of such indicators. A small relative change in resistance leads to the need to use measurement schemes of significant sensitivity (eg, bridge), and the temperature error can be compensated by a special switching scheme [1, 20]. Sticking strain gauges leads to the fact that they have stable characteristics in only one batch during their production and, accordingly, only single use.

Structurally, there are non-adhesive strain gauges. They can be used to identify significant efforts (forces). For example , in heavy transport conveyors, coupled wagons and trucks for the purpose of an approximate estimation of effort (with an error to ± 10%) it is possible to use the indicator made of the constantan wire coiled on insulators (fig. 2.13) which fasten on the parts moving mutually . The force that can be obtained by stretching a bundle of wires by the number N can be determined by the formula:

$$P = N \cdot \frac{\pi \cdot d^2}{4} \cdot E \cdot \frac{\Delta l}{l}$$

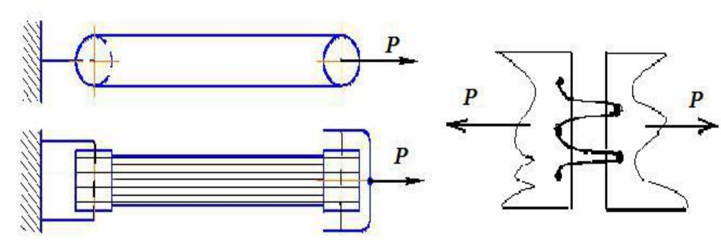


Figure 2.13 – Non-stick indicator to determine high effort

2.4 Thermoelectric converters (thermocouples)

The principle of operation of thermocouples is based on a physical phenomenon, when two dissimilar conductors (or semiconductors) are in contact with each other at the atomic level, there is a difference in electrical potentials. If the edges of this connection are placed in an environment with different temperatures, then a thermo-EMF will appear in the circuit of these conductors (Fig. 2.14). Conductors A and B are called thermoelectrodes, and their places of pressure and 2 are called junctures. Free or cold is a juncture whose temperature is maintained relatively constant. Hot is the juncture in the medium whose temperature is measured.

From the point of view of electronic construction of metals, the physical essence of thermo-EMF is explained by the fact that in different metals free electrons have different energies and velocities.

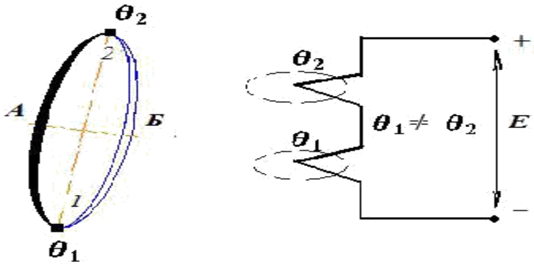


Figure 2.14 – Thermocouple. Schematic diagram and thermo-EMF

Due to this phenomenon, when they connect, the free electrons of one penetrate the other and the metal with greater activity of free electrons acquires a positive potential (due to the loss of some electrons), and with less activity - a negative potential. Thermo-EMF is a measure of temperature difference. More precisely the output voltage of the thermocouple can be written as a power series from the temperature difference (θ- θ_0), where θ_0 is a certain set calibration temperature:

$$E=\alpha 1\cdot(\theta-\theta_0)+\alpha_2\cdot(\theta-\theta_0)^2+\ldots+\alpha_n\cdot(\theta-\theta_0)^n. \qquad (2.11)$$

Each combination of two metals in a thermocouple is characterised by its own series of temperature-independent coefficients α_1 ($i = l...n$) [1, 15, 25]. If the junctures are at the same temperature, the current in the circuit does not flow, because in both junctures there is the same magnitude, but opposite in sign to the thermo-EMF. Millivoltmeters are connected to thermocouples to measure thermo-EMF.

For example, between electrodes A and B, as shown in Fig. 2.15 a, the point 1 indicates the hot juncture; and points 2, 3 - cold junctures. Figure 2.15, b shows millivoltmeter which is included in the gap of the electrode B, point 1 is marked - hot juncture; point 2 - cold juncture; and dots 3 - neutral junctures. The differential pair shown in Fig. 2.15, c, is used to measure the temperature difference at two points 1 and 2, which are hot junctures.

In this case, if $\theta_1 \neq \theta_2$ then a thermo-EMF will appear in the circle, the polarity of which will show where the temperature will be higher and where lower. To obtain a much larger thermo-EMF, thermocouples are used, the scheme of which is shown in Fig. 2.15, d. Due to the fact that the thermo-EMF, which is formed by one thermocouple is small, and for different thermocouples makes up from 0.01 mV to 0.07 mV per 1 C, it is necessary to sum all the EMF. It is believed that when using a thermopile with thermocouples in quantity n, the accuracy of temperature measurement will increase n times, accordingly.

It should be noted that the value of thermo-EMF depends only on the material of the thermoelectrodes and the temperature of each junctures, and does not depend on the temperature distribution along the thermoelectrons (if the juncture temperature remains constant), in addition, the inclusion of the measuring instrument in the thermoelectric circuit does not affect the value of the thermo-EMF. The materials, from which thermoelectrodes are made, must meet the requirements to retain their mechanical and chemical properties for a long time, have a relatively high thermo-EMF and good electrical conductivity.

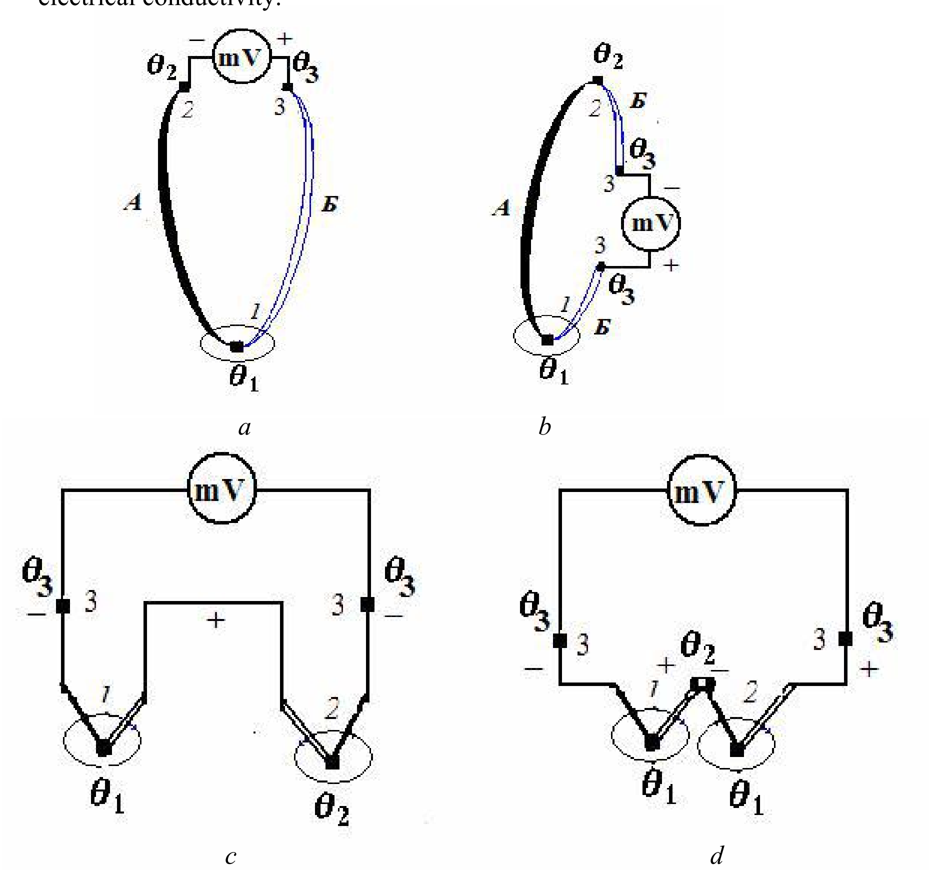


Figure 2.15 – Connection diagrams of measuring devicesto thermocouples

Thermocouples made of precious metals are usually used as a model or to measure high temperatures. For example, a platinum-rhodium thermocouple (one electrode is made of an alloy of 90% Pt + 10% Rn, and the other is made of pure platinum) at θ = 1600 ^{0}K has a thermo-EMF of 16.76 mV. It is used in the long mode for measurement of temperatures to θ = 1600 ^{0}K and short-term - to θ = 1900 ^{0}K. Or other platinum-rhodium thermocouple (one electrode is made of alloy 70% Pt + 30% Rn, and the second - from an alloy of 94% Pt + 6% Rn) at θ = 1800 ^{0}K has 10.82 mV thermo-EMF. It is used for short-term modes up to θ = 2100 ^{0}K.

In addition to the advantages (chemical resistance), these thermocouples have a disadvantage. At temperatures above 1000 ^{0}K in the long-term mode, thermoelectrodes can interact with the surrounding elements, as a result of which their characteristics will change.

Thermocouples from base metals are more common because of the low cost. For example, chromel-alumel thermocouple (one electrode is made of chromel 89% Ni + 9.8% Cr + 1% Fe + 0.2% Mn, and the second is made of alumel 94% Ni + 2% Al + 2.5% Mn + 1% Si + 0.5% Fe). Or chromel-copel thermocouple (one electrode is made of chromel, and the other - from a copel of 55% Cu + 45% Ni). Thermocouples made of semiconductor materials (thermogenerators) with a sensitivity of up to 1 mV per 1 ^{0}C are used to convert thermal energy into electricity within 700^0 K. For example, one electrode is made of bismuth (Bi) + antimony (Sb) + zinc (Zn), and the second - with (Bi + Sb), or (Sb + Zn). On the basis of semiconductor thermocouples, converters of solar energy into electricity are being developed.

Usually calibration of recording devices is carried out at a cold juncture temperature of θ_2 = 0 ^{0}C, but in practice it is difficult to meet such requirements, because it is necessary to place the cold juncture in a bath with melting ice, or place in a special thermostat. Therefore, it is easier to specify the real temperature according to the calibration curve (Fig. 2.16).

In addition, automatic correction of temperature errors is also used (Fig. 2.17), which is carried out by compensating the temperature of the reference contact, the temperature of which is measured by a resistive indicator R (θ) which is included in the bridge circuit. The circuit is connected in such way that the input voltage of the bridge and the EMF of the thermocouple compensate each other, and there is compensation for the temperature of the reference contact.

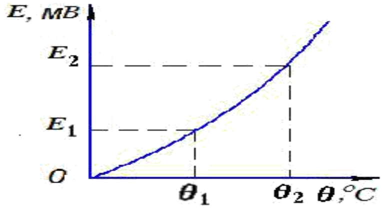


Figure 2.16 – Dependence of thermocouple EMF on temperature.Graduation curve of a thermocouple

The temperature sensitivity of the reference contact must be opposite to that of the bridge circuit. The object, the temperature of which is measured by the active contact AB, is most often located at a certain of the circuit.

The temperature sensitivity of the reference contact must be opposite to that of the bridge circuit.The object, the temperature of which is measured by the active contact AB, is most often located at a certain distance from the other elements of the circuit.

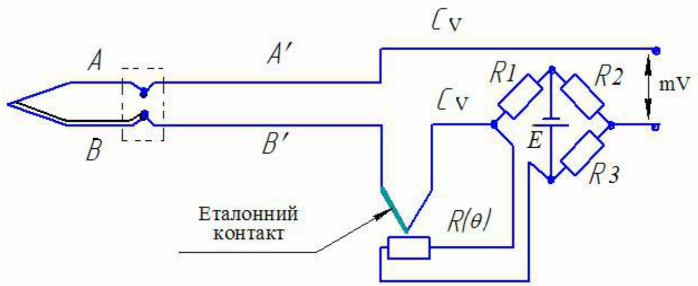


Figure 2.17 – Schematic diagram for temperature compensation due to the reference contact

The material in the thermocouple is too expensive to use as a long connecting wire, so use two cheaper wires A ′ and B ′. Moreover, no additional error will occur if these wires have thermoelectric characteristics similar to A and B. The connection cable between the two thermocouple contacts has the same thermoelectric characteristics and is called a compensation cable.

To calculate the temperature using a thermocouple, let us have a look at one of the following approximate methods. The value of thermo-EMF is determined by the formula:

$$E_{TR} = U_M \cdot \left(R_M + R_{EW} + R_{TR}\right) / R_M \quad , \qquad (2.12)$$

where U_M – voltage at the clamps of the millivoltmeter;

R_M – millivoltmeter resistance ;

R_{EW} – resistance of extension wires;

R_{TR} – thermocouple resistance.

The temperature difference θ_{dif} , which is the difference between the temperature of the hot and cold ends of the thermocouple $(\theta_1 - \theta_2)$ ^{0}K

$$\theta_{dif} = E_{TR} \cdot 100 / E_{TAB} , \quad (2.13)$$

where E_{TAB} – the value of thermo-EMF at temperatures $\theta_1 = 373$ ^{0}K and $\theta_2 = 273$ ^{0}K.

ETAB values for different thermocouples are given in the tables of reference literature [1, 15, 25]. The actual temperature is determined by:

$$\theta_1 = \theta_{dif} + \theta_2 , \quad (2.14)$$

where θ_2 – the temperature of the cold end of the thermocouple (usually the ambient temperature).

This temperature value is approximate because it is calculated on the assumption of a linear function between the thermo-EMF and the measurement temperature. For more accurate determination of temperature it is necessary to refer to the calibration tables [1, 15, 25]. Digital devices for temperature measurement by thermocouples in the range from 0 to 1800 ^{0}C with an interval of 0.1 ^{0}C have been developed (Fig. 2.18). The temperature is measured using a thermocouple TC made of two electrodes a and b, and then converted into a signal suitable for processing and analysis. The functional unit of the converter provides linearisation of the general transformation function [1, 15].

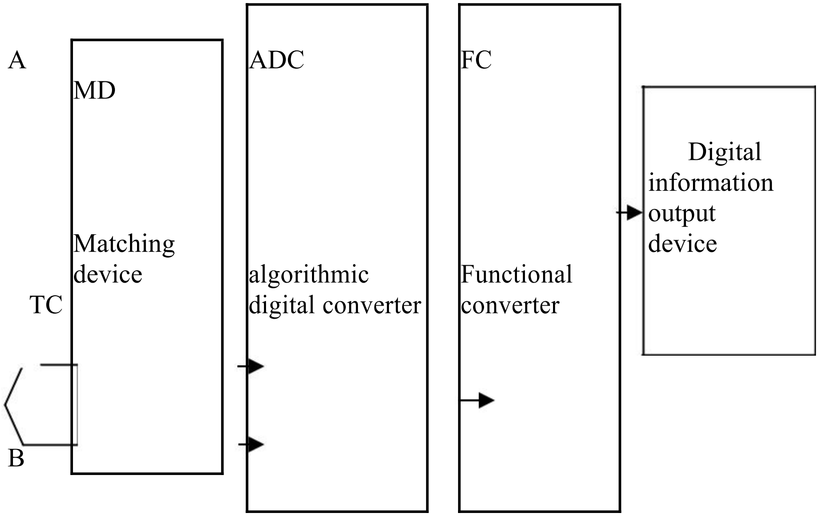


Figure 2.18 – Functional diagram of a digital device for measuring temperature

2.5 Inductive and transformer indicator

Inductive and transformer indicators are designed to measure the values of displacement and force. The principle of their operation is based on the change of inductance due to the movement of the motor element or the magnetic connection between the primary and secondary windings. Therefore, these indicators are distinguished by the initial parameters: with a variable coefficient of self-induction (inductive indicators) and with a variable coefficient of mutual induction.

2.5.1 Inductive indicators:

As noted, the principle of their operation is based on changing the inductance of the indicator system due to changes in the magnetic flux of the input value of the movable part. The inductance of the electromagnetic system is determined by the formula:

$$L = \frac{1}{I} \cdot \sum \Phi \cdot W \,, \tag{2.15}$$

where L – inductance of the electromagnetic system of the indicator ;

I - coil current;

Φ - magnetic flux;

W-is the number of turns of the winding.

If we neglect the scattering of the magnetic flux in a magnetic system containing a winding and a ferromagnetic core with a slight air gap, then $\sum \Phi_i \cdot W_i = \Phi \cdot W$. Given that $\Phi = I \cdot W / Z_\mu$, then we can get the following equation:

$$L = \frac{W^2}{Z_\mu}, \qquad (2.16)$$

where Z_μ – the total magnetic resistance of the magnetic circuit, which can be determined by the formula:

$$Z_\mu = \sqrt{(R_m + R_\delta)^2 + X_\mu^2}, \qquad (2.17)$$

Components which are as follows:

$$R_m = \frac{l}{\mu_a \cdot S}; \qquad (2.18)$$

$$R_\delta = \frac{1}{\mu_0 \cdot \Lambda}; \qquad (2.19)$$

$$X_\mu = \frac{P_{CT}}{\omega \cdot \Phi_2}; \qquad (2.20)$$

where R_m – active resistance of the magnetic circuit;

l – the length of the middle power line of the magnetic circuit;

μ_a – absolute magnetic permeability;

μ_0 – magnetic constant of air;

S – magnetic circuit crossing;

R_δ – magnetic resistance of the air gap;

Λ – air gap conductivity;

X_μ – reactive resistance of the magnetic circuit;

P_{CT} – losses in the core and in the leading structural elements;

ω– angular frequency.

Let us have a look at the principle of operation of an inductive indicator with a variable air gap and its area (Fig. 2.19). It consists of a magnetic circuit 1 on which the excitation winding 2 is wound, and a movable anchor 3. When evaluating the characteristics of the indicator, you can neglect the magnetic resistance of the steel parts of the magnetic circuit.

It should also be noted that when moving along the anchor in the X_1 direction, the air gap δ will change, when moving in the X_2 direction, the gap area S will change, and when moving in the X_3 direction, both δ and S will change. Change in working gap δ is limited to 10% of the nominal value to obtain a more satisfactory linearity of such an indicator. In addition, the output signal does not become zero at any value of X. Unilateral gravity acts on the anchor of the indicator:

$F = \frac{1}{2} \cdot I^2 \cdot \frac{dL}{dx}$, where I – current in the winding

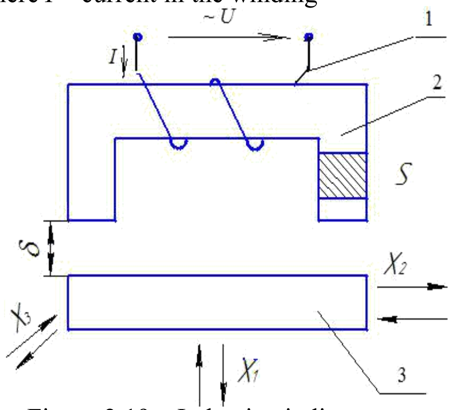


Figure 2.19 – Inductive indicator

Fig. 2.20 shows the characteristics of such an indicator , which reflect their nonlinearity

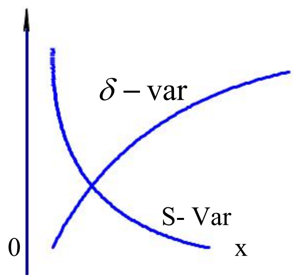


Figure 2.20 – Characteristics of the inductive indicator

To eliminate these shortcomings, differential and bridge switching schemes are used, which have better characteristics and, accordingly, have become more widespread.

2.5.2 Transformer indicators

Fig 2.21 shows the simplest transformer indicator.

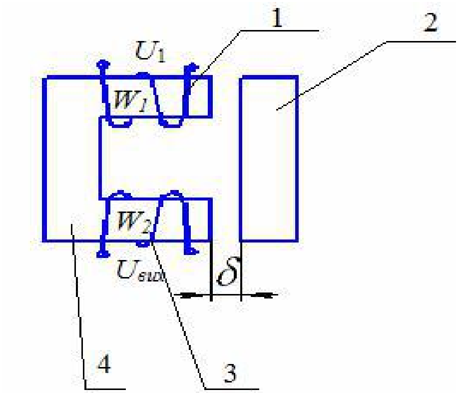


Figure 2.21 – Single transformer indicator

In these indicators, the input displacement (δ, x or α) changes the value of the inductive connection between two winding systems, one of which (primary - 1) is supplied with alternating current, and the other (secondary - 3) removes the output signal. The anchor 2 is attracted to the core 4.
The transient characteristic of such an indicator is equal to:

$$U_{out} = \frac{W_2}{W_1} \cdot U_1 = k \cdot U_1, \qquad (2.21)$$

where W_1 and W_2 – turns of input and output winding;
δ – the gap between the yoke and the indicator anchor;
k – transformation coefficient;
U_1, U_{out} – input and output voltage, respectively

Fig. 2.22 shows a more sensitive - differential transformer indicator, and its output voltage, accordingly , is equal to

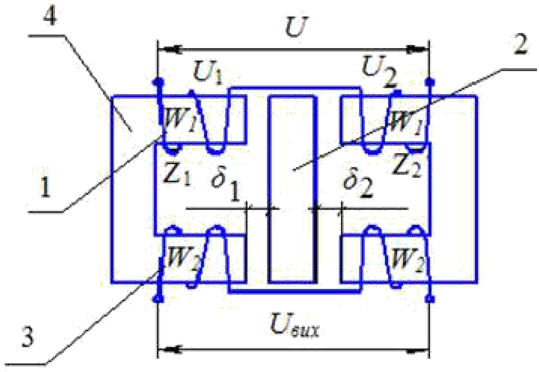


Figure 2.22 – Differential transformer indicator

$$U_{out} = k \cdot U_1 \frac{\delta_2 - \delta_1}{\delta_2 + \delta_1} \tag{2.22}$$

From the formula (2.22) we can see that the output voltage (Uout) is directly proportional to the difference in the length of the gaps (δ2 - δ1).

Figure 2.23 shows an indicator with a variable area of the gaps, in which the movement of the anchor will change the distribution of magnetic flux in the secondary windings.

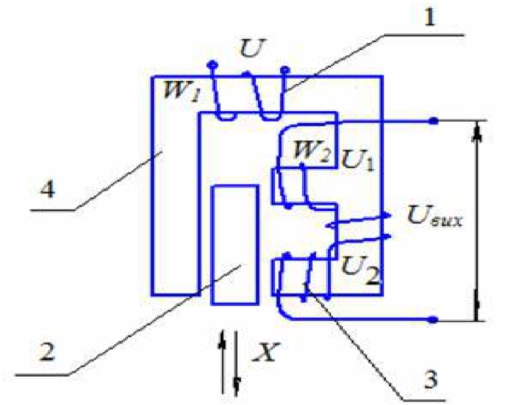


Figure 2.23 – Differential transformer indicator with a modified gap area

2.6 Capacitive indicators

Capacitive indicators (more precisely, capacitive shear indicators) are designed to measure displacement values, part sizes, fluid levels, and so on. The principle of operation is based on a change in the indicator capacitor by the influence of a certain input parameter, that is measured. Capacitance *C* is a function of the distance *d* between the electrodes of the indicator (or capacitor plates (covers)), the area of the electrodes *S* and the dielectric constant *ε* of the dielectric between the electrodes, ie $C = f(d, S, \varepsilon)$. Obviously, by changing *d, S* and *ε*, you can implement three types of capacitive indicators. For example, some designs and graphs of changes in their capacity are shown in the following figures: when changing the air gap between the plates of the condenser (Fig.2.24, a), when changing the area of overlap of the plates, when one plate of the capacitor is shifted relative to the second (Fig.2. 24, b), when changing the dielectric constant of the medium (Fig. 2.24, c). The first design variant has a characteristic that is close to hyperbolic, the other two design variants have almost linear characteristics. If you neglect all the edge effects, then the capacity of the indicator shown in Fig. a will be equal to:

$$C(x) = \frac{\varepsilon_0 \cdot S}{d}, \qquad (2.23)$$

where *x* – input value;
ε_0 – electric constant equal to 8,85 10^{-12} F/m;
S – the area which is covered by capacitor plates ($S = a \bullet b$); *d* – the distance between the plates of capacitor.

The characteristic which decreases with increasing distance between the plates means that with increasing magnetic flux, the direction of the induced current is opposite to that determined by the drill rule. However, the indicator is nonlinear and has a hyperbolic transmission characteristic. This indicator is used to measure small movements without contact with the measured object. The indicator characteristic can be linearised by using differential switching circuits.

The indicator shown in Fig. 2.24, b, has a transmission characteristic when changing the electrode overlap area.

$$C(x) = \frac{\varepsilon_0 \cdot (в \cdot R)}{d}, \qquad (2.24)$$

where *в* – indicator width;
R – the overlap length of the capacitor plates.

This indicator has a linear dependence on x. Usually its design is implemented in the form of a rotary capacitor for measuring angular displacements. The design with a rotary capacitor is also used as an output converter for measuring electrical voltage (capacitive voltmeter). The indicator shown in Fig c, is also linear, and is used when changing the position of the dielectric that have a relative electrical permeability of the material. If we accept that $C_0 = C_0 \frac{a \cdot b}{d}$, then the capacitance of the capacitor will be equal to

$$C(x) = C_0 \cdot \left\{ 1 + \frac{R}{a} \cdot (\varepsilon_M - 1) \right\}, \tag{2.25}$$

Most often it can be implemented in the form of two concentric cylinders and used to measure the liquid level in the tank. Moreover, the non-conductive liquid plays the role of a dielectric.

The measured object must apply a force *F (x)* to the capacitive indicator to move the electrodes to a value of x equal to:

$$F(x) = \frac{1}{2} \cdot U^2 \frac{dC(x)}{dx}, \tag{2.26}$$

where *U* – indicator supply voltage.

If the increase in x is taken as positive, then for the indicator (a) - the force will be positive, and for (b) and (c) - will be negative. In general, capacitive indicators are quite reliable and cheap in practice.

The general principle of their operation is to create an output signal of current, charge or EMF, which are equivalent to the effects of mechanical force, magnetic or light flux, and so on.

2.7 Active indicators

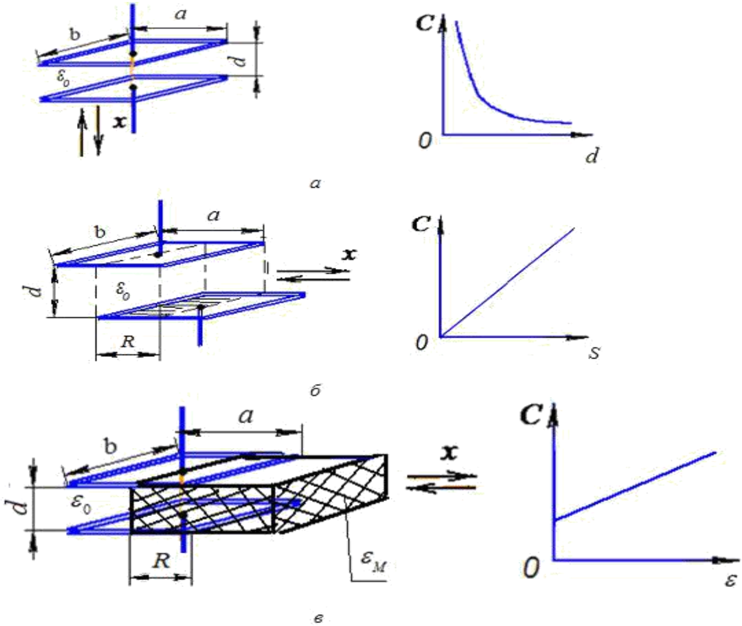


Figure 2.24 – Capacitive displacement indicator

The action of the active indicator can be represented by the ratio:

$$U = -B \cdot l \cdot V, \qquad (2.27)$$

where U – voltage induced in a moving conductor;

B – magnetic induction;

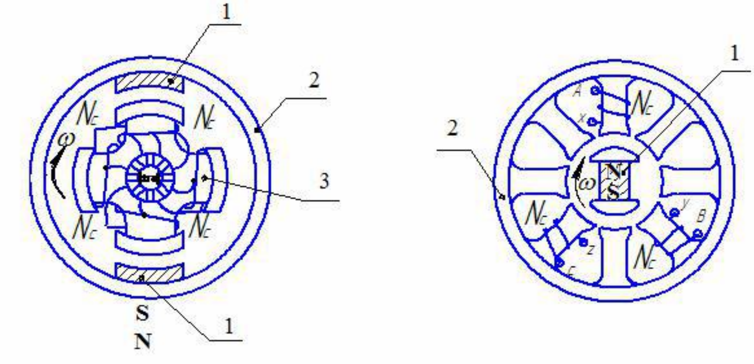
l – conductor length;

V – the speed of uniform movement of the conductor in a direction that is perpendicular to the lines of force.

Active sensors can be DC or AC, single-phase or multiphase, and are typically used to control speed, angular acceleration, angle of rotation, speed or acceleration of linear motion. The indicators can generate significant output signals on the power voltage in a wide range of changes of the controlled size, have practically linear characteristic, well resist short-term mechanical and electric overload, are easy to use.

2.7.1 Speed indicator - tachogenerator

A voltage proportional to the rotor speed is generated at the output of the speed indicator. Figure 2.25 shows the design of direct (a) and alternating (b) currents. The magnetic excitation flux is formed by a permanent magnet 1. When the rotor 3 (Fig. 2.25, a), or magnet 1 (Fig. 2.25, b) with an angular velocity ω in the signal windings Nc rotates, changes in EPM are induced. To rectify the generated voltage, collector and brushes are use in the circuit



a. b.

Figure 2.25 – DC and AC tachogenerators

To reduce the voltage between the adjacent lamellae of the collector, a desoldering is made from the middle of each winding, connected by a corresponding collector plate. Tachogenerators can control not only the speed but also the angle of rotation φ of the working mechanism. To do this, the indicator must be rotated at a constant frequency, and the output must connect an integrating device. The DC indicator does not require this device, if one of the brushes is mechanically connected to the working mechanism, and the rotor is rotated with a constant frequency. Then, as the working mechanism rotates, the position of the brushes and the voltage between them will change, and the voltage will change in proportion to the angle of rotation of the working mechanism.

2.7.2 Angular acceleration indicator

This kind of indicators is shown in Fig. 2.26. The magnetic excitation flux Φ_{exc} is formed by a permanent magnet 3. In the rotor 4 (made of copper or aluminum) the EMF is provided under the condition of its rotation. The currents will be distributed as in a normal coil

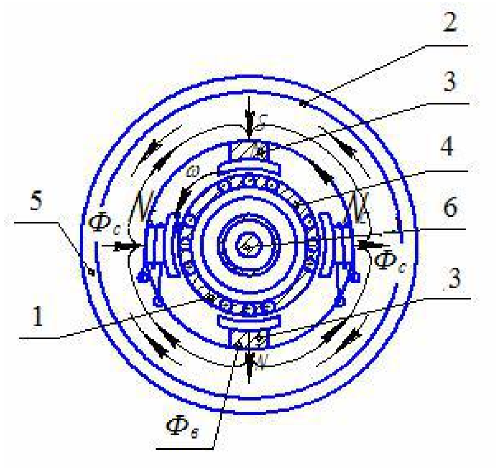


Figure 2.26 –Angular acceleration indicator: 1 and 2 - internal and external magnetic circuits; 3 - permanent magnets; 3- rotor, 5 - hull with bearing assemblies; 6 - shaft.

Therefore, the produced rotor currents form a signal magnetic flux Φs. Its direction will coincide with the direction of flow produced by the coil N when currents flow in its upper and lower parts. The flux Φs is orthogonal to the flux *Фexc*, and is directed along the magnetic axis of the signal windings N_c. If the rotor rotates at a constant angular velocity ω, the EMF in the signal windings will be zero, because according to the law of electromagnetic induction, the EMF is always zero under constant flux.

Any changes in the speed of the rotor (acceleration or deceleration) lead to a change in the EMF and currents in the rotor, equivalent to an increase or decrease in the flow Φs, and ultimately to the induction of the EMF in the signal windings. The resulting output EMF will be equal to the sum of the EMF of each signal winding, and is proportional to the angular acceleration ξ. If you replace the permanent magnets with electromagnets, connect them to an AC source, then when the indicator is running, the output EMF will be proportional to the angular speed ω of rotation of the rotor.

2.7.3 Wiegand sensor (indicator)

The Wiegand sensor (Fig. 2.27) is used to determine the speed of the working mechanism [1, 16]. As the operating mechanism rotates (not shown in the figure), the associated magnetic switch 4 changes position.
Therefore, the magnetic fluxes from the permanent magnets 1 or 2 are closed through the signal winding Nc and the magnetic circuit 3. As a result, an alternating signal *ec* is induced in the signal winding N_c .

The frequency of rotation of the working mechanism can be judged by the number of pulses *ec* (positive), or by the average value of the output EMF.

These indicators have certain advantages, ie they do not require a third-party power supply, have a sufficiently large output signal (up to 5 V, duration from 15 to 50 μs), intrinsic safety, in addition, the amplitude and the pulse duration does not depend on the rate of change of the magnetic field, which allows the use of sensors at speeds close to zero.

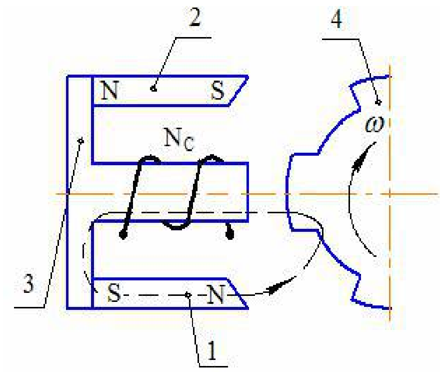


Figure 2.27 – Wiegand sensor

2.8 Features of design and technological characteristics of electromagnetic indicators

In the development of electromagnetic indicators, the choice of materials and components are important. In the considered systems of indicators, the basic elements are magnetic conductors, winding wires and bearings. Therefore, it is recommended to implement such technical and technological solutions as:

1)Magnetic conductors are recommended to be made of high nickel materials (permalloy and sendast), which have the highest values of magnetic permeability in weak fields and corrosion resistance.

In addition, from a technological point of view, they are easy to process on metal-cutting machines (Table 2.1). The disadvantage of permalloy is the sensitivity of its magnetic properties to mechanical stresses during machining. But it can be reduced by high-temperature firing in vacuum or water. Permalloy is the most suitable for use in electromagnetic indicators of groups 1, 2 and 6.

2) Winding wires (except special and expensive silver and gold) made of copper are used, with low resistance and high elasticity (relative elongation at break - 15%) in comparison with aluminum (relative elongation at break - 5%), and operating temperature range from - 60 ^{0}C to +150 ^{0}C. For example, wires of the ПЕВ-1 and ПНЕТ-IMIд brands.

Figure 2.1 – Qualitative comparative characteristics of permalloy

Group	Alloy grade	Basic properties
1	79 НМ, 8 НСХ, 81 НМА, 83 НФ	The highest magnetic permeability in weak fields
2	50 НХС	high magnetic permeability and electrical resistivity
3	50 НП, 68 НМП, 34 НКМП	Rectangular hysteresis loop
4	27 КХ, 47 ХФ, 49 К2Ф, 49 К2ФА	High magnetic induction of technical saturation
5	47 НК, 47 НКХ, 64 Н, 40 НКМ	low residual magnetic induction and constancy of magnetic permeability
6	16 Х, 36 КНМ	High corrosion resistance

3)The bearings are subject to both radial and axial loads, and the deflection of the shaft under the action of these loads is small, and does not cause angular displacement of the shaft axis relative to the axis of the seat, so you need to choose radial single row ball bearings or electromagnetic suspensions.

They have the lowest friction losses, and provide the highest accuracy and speed. Bearings must have an inner diameter within 3… 5 mm, radial beating - within 5 ... 7 μm; duration of work - not less than 10^{-7} turns ; operating temperature range from - 60 ^{0}C to +150 ^{0}C, as well as moisture resistance. Magnetic or electromagnetic suspensions are used to unload friction units, including bearings.

2.8Test questions and tasks

1)Indicators of control and regulation. Purposes. Classification.
2) Contact indicators. Advantages and disadvantages.
3) Potentiometric indicators. Sensitivity. Electrical resolution of the potentiometer. Special types of potentiometers.
4) Ohmic strain gauges. Advantages of foil over wire. Strain sensitivity. Temperature error compensation. Non-adhesive strain gauges.
5) Thermoelectric indicators.
6) Thermocouples. Basic switching schemes. Thermocouples made of precious and non-precious metals. Heat generators. Automatic correction of temperature errors.
7) Inductive indicators. Principle of action. Mathematical relations from which the ideas of construction of these indicators follow.
8) Inductive indicators with variable clearance and area. Switching circuits.
9)Transformer indicators. Principle of action.
10) Capacitive indicators. Their three types.
11) Active indicators. Principle of action. DC and AC tachogenerators.
12) Angular acceleration indicator .
13) Wiegand sensor.
14)Features of design and technological characteristics of electromagnetic indicators.
15)**Task 1.**
Calculate the rheostat displacement indicator and sketch it with the following data: winding length on the frame L = 40 mm, the lower limit of the hull temperature ϴ = - 20 ° C, the maximum ambient temperature ϴmax = 40 °C, the winding resistance R = 800 Ohm, the winding current I = 0,01 A, the winding material - nichrome X15H60.
16) **Task 2.**
Using a thermocouple, determine the temperature of the measuring medium, if known: voltage at the claps of the millivoltmeter U_M, the resistance of the millivoltmeter R_M, the extension wire R_w and thermocouples R_{TC}, E_{TABL} - the value of thermo-e.m.f. for a specific thermocouple (given in the reference tables).

3 ELECTROMAGNETIC AND MAGNETIC COUPLINGS

Electromagnetic and magnetic couplings are units of mechanisms of rotation, in which the torque itself is directly transmitted by electromagnetic or magnetic forces [5, 15, 17, 29]. These devices are designed for remote clutch, disengagement, switching, reversing of kinematic circuits, as well as a brake or force limiter. In addition, inductive electromagnetic couplings (IEMC) with variable slip allow you to adjust the speed of the shaft, which is followed by the main (leading), to smooth the pushes and high-frequency torsional vibrations.

Electromagnetic and magnetic couplings are distinguished by:

1) manufacturing principle:
- electromechanical (powder);
- magnetic (friction, induction, hysteresis, etc.).

2) functions performed:
- safety;
- damper (German. Dampfer - muffler, including mechanical vibrations);
- special;

3) transmission of motion:
- clutch;
- uncoupling;
- switching;
- braking;

4) mode of operation:
- relay (without slipping of the leading and the conducted, elements);
- sliding;

5) the connection between the leading and the ongoing elements:
– rigid (hard);
– soft;

6)kind of excitation:
– electromagnetic unipolar (unipolar, in which the axes of the electromagnetic clutch and the excitation winding coincide);
- multipolar (axes of the electromagnetic coupling and winding are parallel, perpendicular, or tangential).

3.1 Friction electromagnetic couplings

In friction electromagnetic couplings (FEMC), two or more friction surfaces touch each other and are compressed by the force generated by the electromagnet (Fig. 3.1).

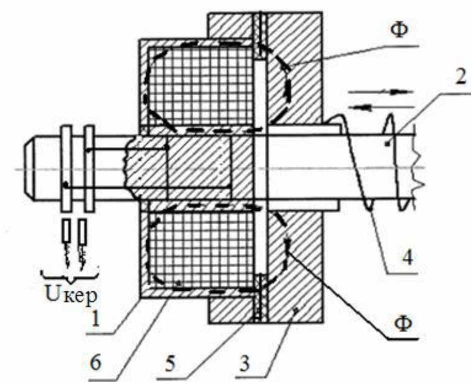


Figure 3.1 – Design of friction electromagnetic coupling

If it is necessary to turn on the coupling, control voltage U_{contr} is applied to its conductive part (1)- (exciting winding-6) due to which a magnetic flux Φ is formed which closes through the friction ring (5). As a result, between the main part and the part of the magnetic circuit (3), which is movable relative to the driven shaft (2), there is an electromagnetic force. As can be seen in Fig. 3.1 the coupling operates due to the moment of friction of M_{fr}. Fig. 3.2 shows the friction element with the designations: R_{in} - inner and R_{out} - outer radii of the annular friction element.

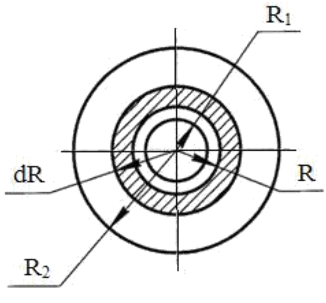


Figure 3.2 – The element of friction is ring. Schematic diagram

Let us have a look at an elementary annular friction element with an average radius R and a width dR. Then the increase in friction:

$$dF_{FR} = K_{FR} \cdot P_{SP} \cdot dS_{T} , \tag{3.1}$$

where K_{FR} – coefficient of friction between working surfaces;
P_{sp} – specific pressure between them:

$$P_{SP} = \frac{P_F}{S_T} \quad (3.2)$$

where P_F– final force when the current in the control winding reaches the nominal
dS_T – the area of the elementary annular friction element:

$$dS_T = 2 \cdot \pi \cdot R \cdot dR \,, \quad (3.3)$$

Then:

$$dF_{FR} = 2\pi \cdot K_{FR} \cdot P_{SP} \cdot R \cdot dR. \quad (3.4)$$

The increase in friction moment will be defined as the ratio:

$$dM_{FR} = dF_{FR} \cdot R = 2\pi \cdot K_{FR} \cdot P_{SP} \cdot R^2 \cdot dR \,. \quad (3.5)$$

From the above, the moment of friction will be determined by the formula:

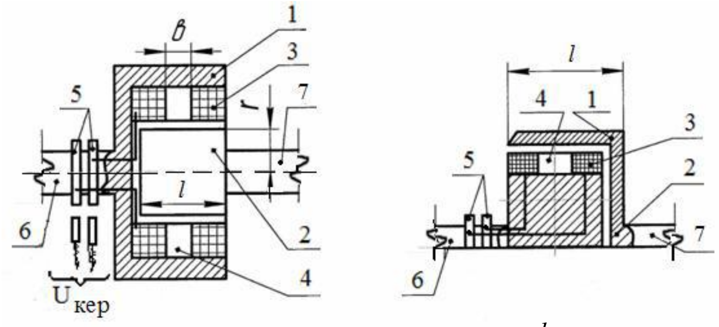
$$M_{FR} = \int_{R_{vt}}^{R_{zsh}} dM_{FR} = \frac{2}{3} \cdot \pi \cdot K_{FR} \cdot P_{SP} \cdot R_{ZSH}^3 \cdot \left(1 - \beta^3\right) \quad (3.6)$$

where $\beta = \frac{R_{vt}}{R_{zsh}}$

For normal operation, the moment M_{fr} must be greater than the moment of loading M_d driven axis (which is consistent with the axis of the coupling), ie, more than the counteracting moment. Friction surfaces are made as two, or several disks, or conical. The so-called conical couplings, in comparison with disk couplings, have smaller dimensions when transmitting the same moments, less compression force, greater reliability of adhesion with less wear of friction surfaces, but have significant requirements for manufacturing accuracy. Friction discs are made of steel, cast iron or bronze with a specific compressive pressure P_{sp} = 0.4…. 0.6 MPa, or metal-ceramics (the most advanced) - with P_{sp} = 0.8… 1.0 MPa, and operating temperature - up to 200 ^{0}C. The turn-on time $t_{turn\text{-}on}$ is in the range from 0.07s to 0.3s, depending on the dimensions of the coupling, electromagnet time constant, the course of the anchor, or the number of disks.

3.2 Inductive couplings

Inductive electromagnetic couplings (IEMC), or sliding couplings - are an inductor with an excitation winding (3) DC and an anchor (2), not mechanically connected (Fig. 3.3). The principle of their operation resembles the operation of an induction motor with a short-circuited rotor, and differs in the magnetic field that rotates is formed by an inductor on the main shaft (6) after applying the control voltage *Ucontr* to the current collector (5).



a *b*

Figure 3.3 – Designs of inductive couplings with internal (a) and external (b) anchors

The excitation windings (3) with the poles (4) are inside the magnetic circuit of the inductor (1). The anchor (2) is made either short-circuited (so-called "squirrel cage"), or in the form of a massive ferromagnetic rotor. If the anchor is massive, then the torque of the coupling is formed due to the eddy currents of the anchor. The torque is transmitted to the driven shaft (7). Figure 3.4 shows the mechanical characteristics of the IEMC with a massive rotor.

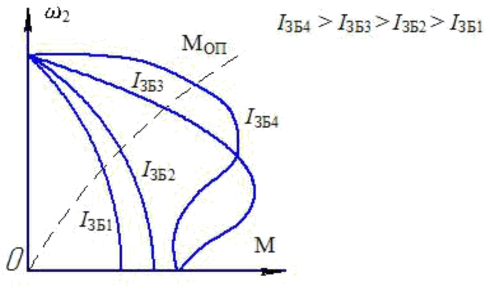


Figure 3.4 – Mechanical characteristics of IEMC

If you adjust the excitation current I_{exc} (I_{exc1}… I_{exc4}) and, accordingly, the magnetic flux Φ, you can smoothly and in a wide range to adjust the speed ω_2 of the driven shaft, as well as the moment M transmitted by the coupling. The larger the I_{exc}, the greater the magnetic flux Φ, the steeper the mechanical characteristics, as shown in Fig. 3.4, provided $I_{exc4} > I_{exc3} > I_{exc2} > I_{exc1}$ and the operation of the coupling in steady state.

If during the operation of the coupling the speed ω_2 and the moment of resistance M_{res} of the main shaft change (ie the counteracting moment changes), the speed of the driven part of the coupling and the moment of resistance can also be unstable. To stabilise the frequency, usually introduce special control devices. If the inductor moves relative to the conductive surface of the massive rotor, it will be induced EMF:

$$E=-B \bullet l \bullet V,$$

where l – geometric size (see Fig. 3.3, a);

B – induction of coupling material;

V – sliding speed.

This EMF gives the current a value of $i= e / R$, where R is the current loop resistance, which is determined by the geometric dimensions (pole thickness), the depth of magnetic flux penetration into the body of the massive rotor and coefficient of increase in resistance due to part of the surface.

Electromagnetic force F_{EM}, which affects the driven surface of the anchor:

$$F_{EM} = B \cdot l \tag{3.7}$$

Then the electromagnetic moment will be defined as:

$$M_{EM} = F_{EM} \cdot r, \tag{3.8}$$

where r – the average radius of the coupling.

The power transmitted by the coupling is equal to:

$$P_2=M_{EM} \bullet \omega_2, \tag{3.9}$$

where ω_2 – coupling speed which is being driven.

If $M_{EM} \approx M_{res}$ then $P_2 - M_{EM} \cdot \omega_2 \approx M_c \cdot \omega_2$,the losses will be determinate $\Delta P= Mres \bullet \omega$, ($\omega = \omega_1 - \omega_2$ – the frequency of sliding of one part of the coupling relative to another).

Electromagnetic processes in the anchor of the type "squirrel cage" proceed in the same way (or similarly) as in asynchronous motors. The coefficient of sliding of IEMC makes 1… 3%. Efficiency (eff) of couplings with a massive anchor reaches 0.94, couplings with a short-circuited anchor reaches 0.96… 0.98. Inductive electromagnetic couplings, compared to friction couplings, do not wear surfaces, have a flexible connection, and due to the lack of mechanical contact allow significant overloads.

3.3 Electrostatic (powder) couplings

Powder electrostatic couplings with magnetic connection (PECM) are essentially capacitors with movable covers, which perform the function of a power element (Fig. 3.5). One cover is the main (leading), the other - led (which is conducted). The space between the covers is filled with a semi-liquid mixture consisting of a solid base (magnesium oxide, gypsum, gelatin, etc.) and a liquid component (transformer or organosilicon oil, kerosene, etc.).

If a voltage of U is applied to the plates of such a capacitor, chains of grains of a solid component (so-called "non-rigid mechanical connection") are formed between them. An electrostatic force occurs between the plates:

$$F_{ES1} = \frac{U^2}{2} \cdot \frac{dC}{d\delta}, \qquad (3.10)$$

where *FES1* – electrostatic force;

U – voltage between the plates;

C – coupling capacity;

δ – the distance between the covers (plates).

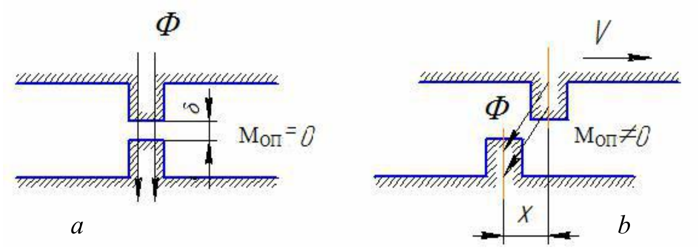


Figure 3.5 – The principle of operation of the electrostatic coupling at $M_{res} = 0$ (a) and at $M_{res} \neq 0$ (b)

The transmitted electrostatic force F_{ES} is equal to:

$$F_{ES} = \mu_x \cdot F_{ES1}, \qquad (3.11)$$

where μ_x – the viscosity coefficient of the filler, depending on the composition and concentration of the component.

Then the electrostatic transmitted moment M_{st} is equal to:

$$M_{ST} = F_{ES} \cdot r, \qquad (3.12)$$

where *r* – the average equivalent radius of the coupling.

Figure 3.6 shows the mechanical characteristics of the electrostatic coupling; we can see that the M_{st} does not depend on the rotational speed, but changes with the change of current (I_{exc3}> I_{exc2}> I_{exc1}) excitation. We can say that it has a rigid mechanical characteristic, ie the transmitted moment does not change from sliding friction at constant control current. Powder couplings, in comparison with friction and inductive couplings, use less power (at the same moments that are transmitted). They have significant speed, quiet, easy to operate, and almost no surface wear.

But the electrostatic coupling has certain disadvantages, which include the following: the starting moment of the coupling is zero and, therefore, in order to start - it must be accelerated to a speed close to synchronous; compaction of the filler under the action of centrifugal forces or due to its subsidence (caking) in non-working couplings and ,therefore, these are irreversible changes in its physicochemical properties, i.e. aging.

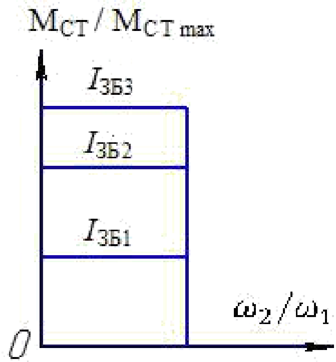


Figure 3.6 – Mechanical characteristics

These couplings are used for automatic control for: smooth adjustment of the transmitted moment or rotation frequency (for example, in belt mechanisms); smooth clutch and disengagement; limitation of the transmitted moment; reverse of the driven shaft, with the unchanged direction of rotation of the drive motor during a shock-free time-controlled start-up; as well as to perform the function of an electromagnetic power amplifier (with a push-pull coupling, the power gain can reach 3500), or an electromagnetic brake.

3.4Test questions

1.Electromagnetic couplings. Purposes. Classification.
2. Friction electromagnetic couplings. Determination of friction moment.
3. Inductive couplings (sliding couplings). Construction. Characteristic. Power transmitted by the coupling.
4. Electrostatic couplings (powder). Construction. Determination of electrostatic moment. Characteristic. Usage example.

4 ELECTROMAGNETIC AND MAGNETIC SUSPENSIONS AND SUPPORTS

In the construction industry due to the increase in speed and increase the requirements for the accuracy of the devices, there is an urgent problem to reduce the friction of support nodes and suspensions, which with little effort (about 0.1… 0.5 N) contributes to large errors and affects the quality of indicators, relays, etc. In addition, also to reduce friction, wear, etc. electromagnetic and magnetic suspensions are used in other fields of technology, for example, in railway transport [15, 25, 33].

In suspensions, the weight of the body that is suspended, as well as the forces acting on it, are balanced by the forces of the magnetic or electric field, which in electrical engineering are called ponderomotive forces. It uses the phenomenon of levitation, ie "free flight" of the body in neutral equilibrium relative to other bodies. This principle is used in the development of devices for measuring force, pressure, flow, density, etc. The main problem is to ensure their stability.

It is known that metals are divided into ferromagnets with strong magnetic properties; para-magnets, in which the magnetic properties are weakly expressed; diamagnets, in which there is a magnetisation that is directed toward the magnetising field, and this in turn - to repel only diamagnetic bodies from the poles of the magnet. It should be noted that diamagnetism is inherent in all substances without exception, but ferromagnetism and paramagnetism can overlap diamagnetism. Only those made of diamagnets can be stable suspensions. The best of them are bismuth (Bi) and pyrolytic graphite, as well as superconductors in which $\mu = 0$, ie in superconductors the magnetic field decreases to zero, and thus form on their surfaces something like a screen through which the magnetic field does not penetrate. However, stable suspensions can be created at $\mu > 1$ in alternating magnetic fields, if you control the force of gravity (repulsion) of the electromagnet depending on the position of the body, ie using automatic control systems and indicators.

4.1 Brief classification of existing suspensions

Elementary magnetic suspensions are suspensions on permanent magnets. They are divided into "magnet-magnet" and "magnet-ferromagnetic" systems. To ensure stability, they are used together with supports of adjustable type, or with partial unloading. Figure 4.1 shows a brief classification of suspensions.

Electromagnetic suspensions with non-adjustable magnets have a high overload capacity compared to permanent magnets. Diamagnetic suspensions have a small lifting force, even when using the best diamagnet - pyrolytic graphite. Superconducting (cryogenic) suspensions work with superconductors using low temperatures. Inductive supports have a small load capacity and significant exciting moments, which create instability. Conductive suspensions are stable magnetic suspensions that use electrodynamic interaction (magnetic fields and current-carrying conductors, or two current-carrying conductors). They have quite simple designs. However, the need to excite currents directly on the suspended body is a disadvantage.

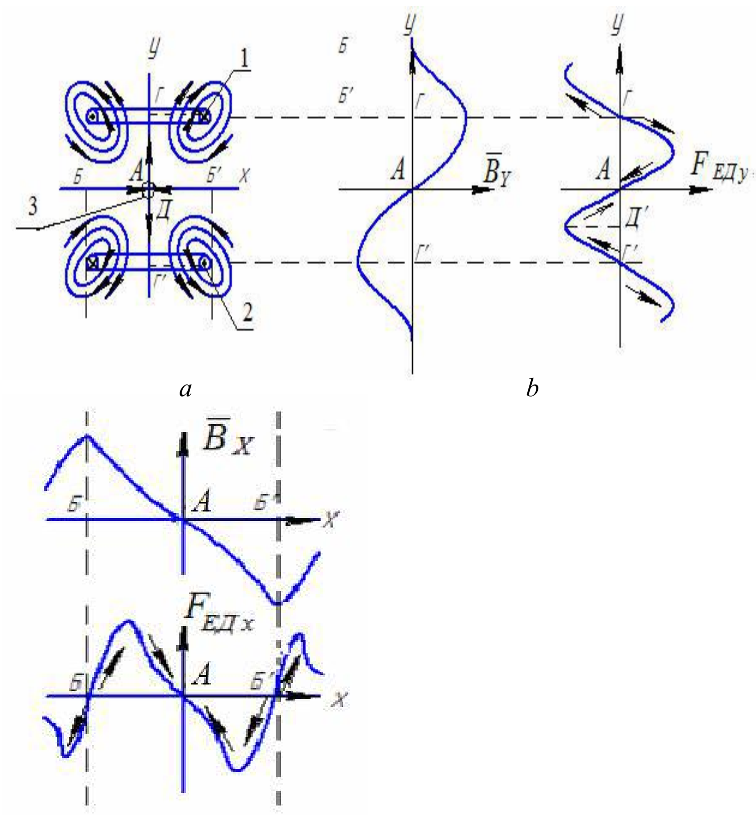
Adjustable electromagnetic suspensions use the phenomenon of ferroresonance of voltage or currents in series or parallel L-C circuit. The use of microelectronic feedback technology in these systems allows the development of electromagnetic suspensions with better performance. Active are the suspensions that are used in self-regulation (external SAR and indicators). If the regulation of the current in the suspensions is a function of individual parameters of the circuit when moving the center element, then the suspensions are called passive.

4.2 Inductive electromagnetic suspensions and supports

Figure 4.2 shows a system of two coaxial (1 and 2), but not coplanar turns, through which sinusoidal currents flow that are equal in amplitude and opposite in phase. As we can see, separatrix and graphs of the distribution of magnetic induction components and electrodynamic force are along the axes y and x, respectively, of the induction system.

Assuming that a weightless non-ferromagnetic conductive body 3 is located between points Б and Б 'on the x-axis, or points Г and Г'
on the y-axis. Then an electrodynamic force will act on the body (F_{ED} x, or F_{ED} y) which will aim to return it to point A, where the magnetic induction is zero.

Therefore, point A for a weightless body is a point of stable equilibrium. Points Б, Б ', Г and Г' are points of unstable equilibrium, although the electrodynamic force F_{ED} is zero in them. In real conditions, the force of gravity acts on the body 3. We place the body 3 at point A, and because in it $F_{ED}=0$, the body will go down at a point Д. There are two options here: either in the area А-Д (Fig. b) the increasing force will balance the force of gravity (then there will be - levitation), or the body will "slip" the point Г 'and fall further.



c

Figure 4.2 – System of turns of electromagnetic supports

Let us have a look at an Inductive suspension with a stable equilibrium along the vertical axis (Fig. 4.3). The device consists of a magnetic circuit 1, an alternating current winding 3 and an electrically conductive non-ferromagnetic disk 2 (short-circuited turn), as well as a central rod of the magnetic circuit 4. When current flows through the winding, an electrodynamic force acts on the disk, directed towards decreasing the flux linkage of the winding with the disk, i.e. up.

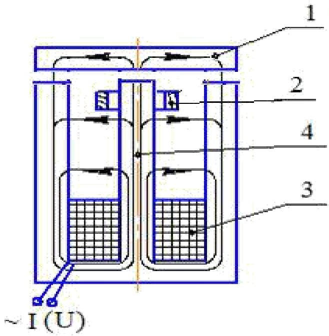


Figure 4.3 – Inductive suspension on the vertical axis with a stable equilibrium

The disk rises because of this. This system is economical, because it implements the properties of the electromagnetic connection of the field source and the conductive body due to the magnetic circuit. But levitation (spreading) is not realised here since stable equilibrium of the disk is possible only in the vertical plane (axis), and along the horizontal it is limited by the central rod of the magnetic circuit.

Uniaxial resonant suspension (Fig. 4.4) is a system where the body is suspended. In a uniaxial resonant suspension system, the suspended body is centered by regulating the current in the support magnets. If we neglect the protrusion and scattering fluxes and the power losses in the magnetic circuit, and also assume that all magnetic supports are concentrated in the air gap (the magnetic circuit is saturated), we obtain:

$$\begin{cases} i_1 = i_0\left(1+K_1X\right) \\ i_1 = i_0\left(1+K_1X\right) \end{cases}; \begin{cases} \Phi_1 = \Phi_0\left(1+K_2X\right) \\ \Phi_1 = \Phi_0\left(1+K_2X\right) \end{cases}; \qquad (4.1)$$

where i_0 and Φ_0 – the current and flux of the magnetic system, respectively, in the absence of a shear of the body that is centered;

$X = \Delta x/\delta_0$ – relative deviation of the center body;

Δx – absolute linear displacement of the center body;

δ_0 – half the size of the initial air gap;

K_1 and K_2 – current and flux gain.

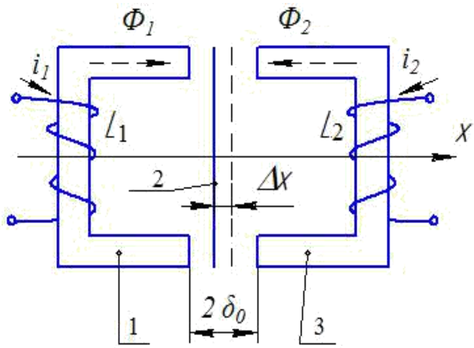


Figure 4.4 – Uniaxial resonant suspension

The necessary condition for stability is the value of the coefficients K_1> 1 and K_2> 0, which is provided by passive or active methods, ie the laws of regulation of currents in the windings. Passive suspensions operate only on alternating current, and are called magnetic resonance and electromagnetic suspensions with internal (parametric) feedback. This is ensured by adjusting the parameters of the circuit at resonant modes, ie due to the fact that in this case there is a greater dependence of the current on the parameters of the circuit. Current and voltage resonance are used.

Figure 4.5 to the windings L_1 and L_2 of the two electromagnets 1 and 3 are connected to the tuning capacitors C_1 and C_2, which ensure operation on the required segment of the resonant characteristic. The principle of operation of such a scheme is based on the change of inductances L_1 and L_2 windings with a shift of the center body 2. The technique also uses biaxial and triaxial magnetic resonance suspensions, which differ from uniaxial only in the number of electrical circuits.

4.3Magnetic ferrofluid supports

In magnetic ferrofluid supports, ferrofluid (colloidal solution of ferromagnets) is introduced between the two surfaces to magnetically seal the shaft (fig. 4.6).

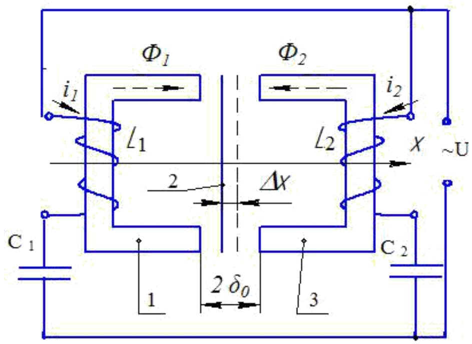


Figure 4.5 – Scheme of magnetic resonance suspension with LC – circuit

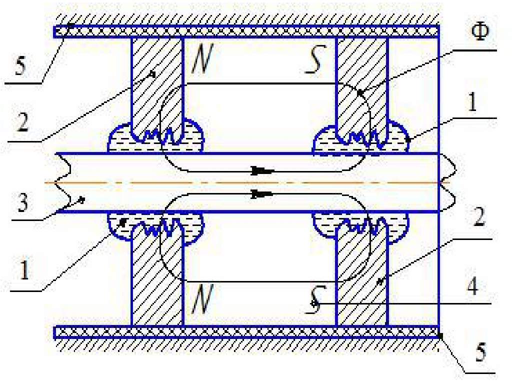


Figure 4.6 – Scheme of magnetic ferrofluid support

Ferrofluid 1 in the gap between the toothed surfaces of the annular ferromagnetic poles 2 and the ferromagnetic shaft 3, and is retained in these gaps by a magnetic field formed by an annular permanent magnet 4. Ferromagnetic poles 2 and permanent magnets 4 are fixed by a stationary magnetic hull 5.

4.4 Test questions

1.Electromagnetic and magnetic suspensions. Purposes. Ponderomotive forces and levitation phenomena.
2. Describe the suspensions on permanent electromagnets and magnets. Suspensions with partial compensation of the weight of the suspended body. Give their examples.
3. Suspensions on permanent electromagnets.
4. Inductive electromagnetic supports.
5. Uniaxial resonant suspension.
6. The principle of operation of the magnetic ferrofluid support.

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SNIGIROV Volodymyr Maksymovych
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Zaporizhzhia Polytechnic National University
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