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ALMATY UNIVERSITY OF POWER ENGINEERING AND TELECOMMUNICATIONS

Department of Power supply and renewable energy sources

ELECTRIC DEVICES

Lecture notes for specialty
5B071800 - Electrical power engineering

Almaty 2018

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Lecture notes have been prepared in accordance with the educational-methodical set of disciplines "Electric devices" for speciality 5B071800 – Electical power engineering.

Lecture notes for bachelor-students by speciality 5B071800- Electrical power engineering.

Reviewer: Candidate of Economic Sciences, Tuzelbayev B.I.

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Content

1 Lecture №1. Introduction to the discipline course

Content of the lecture: classification of electric devices. The main requirements imposed to electric devices. The main materials applied in an instrument - making. Literature.

The purpose of the lecture.

To acquaint students with functions and place of electric devices in power industry. Terminology and literature for the course.

The electrotechnical devices used in power industry can be conditionally divided into three big groups:

- electric machines;
- electric networks;
- electric devices;
- basics of electrotechnical theory.

Electric devices are the integral component in the system of creation, distribution and use of the electric power.

Purposes of teaching the course on electric devices:

- to provide future experts in the field of power industry with basic knowledge about electric devices, understanding of physical bases and provisions of the general theory of electric devices;
- to study the designs of the main devices of common industrial use on the basis of the general theory;

Under the electric devices we usually understand electrotechnical devices intended for management, regulation and protection of electric circuits and machines and also for control and regulation of various nonelectric processes.

1.1 General information about electric switching devices

The main purpose of electric switching devices is to turn on or off electric circuits, and to provide a path for the current during their being on state. They are of greatest importance in 50 or 60 Hz electric power systems. The main power electricity is at frequency of 50 Hz in Europe, Russia and Central Asia, but it is at frequency of 60 Hz in North America and Japan. Not only do they make the transmission of electric power possible, but their failure can lead to losses – due to the interruption of power distribution, or damage of valuable equipment – many times higher than their own value. Therefore, electric switching devices must be reliable, and owing to their large quantity in electric power systems, their manufacturing must be cost effective. To achieve efficient transmission of electric power, different voltage levels are utilized in power systems. The higher is the transmitted power or longer the distance of transmission, the higher is the rated voltage of the system (V r=0.4; 6; 10; 35; 110; 220; 500; 750 kV). Obviously, the rated voltage of the electric switching devices has to exceed that of the network, in which they are installed. Consequently, the rated voltages of high voltage equipment are 6, 10, 35, 110, 220, 500 and 750 kV respectively.

Similar to the electric grid, the switching devices can be classified as “low”, “medium”, “high”, “very high” and “ultra high” voltage types (figure 1.1). However, more general is a simpler classification: low voltage (LV; <0.4 kV), medium voltage (MV; 6, 10, 35 kV) and high voltage (HV; 110, 220, 500 and 750 kV).

Electric switching devices are rarely standalone units, usually several of them are installed together at specific points of the electric systems, forming – together with connecting elements – switchgears. Switchgear is a general term covering switching devices and their combinations with associated control, measuring, protective and regulating equipment, also assemblies of such devices and equipment with associated interconnections, accessories, enclosures and supporting structures.

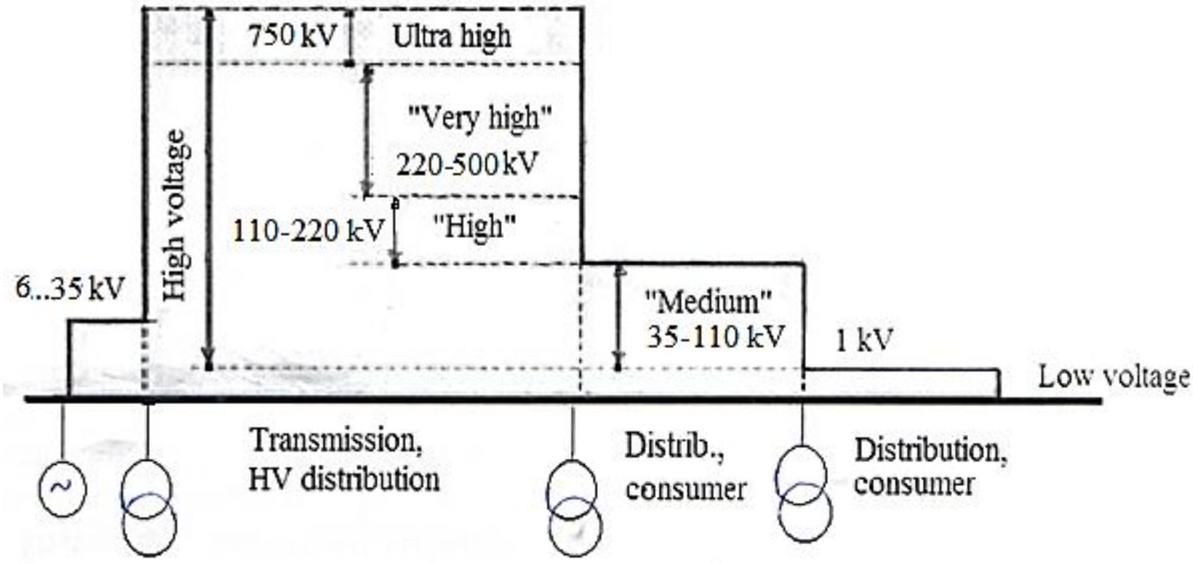


Figure 1.1 - Rated voltages of electric switching devices

Besides their rated voltage, electric switching devices must be appropriately selected according to their purpose and function. In accordance with their function, we shall first discuss the normal operating, rated, overload, and fault (short-circuit) currents occurring in normal and faulty states of the electric systems. These system states can be made or terminated by electric switching devices, but they can be caused unintentionally by faults (short-circuit or disruption) as well.

Turning on or off consumer loads correspond to the normal operation of three-phase systems. Although, sometimes the elements of electric power systems have to make switching operations during no-load conditions, too (e.g. turning on/off a transformer or transmission line which is not in use).

Switching operations may occur in a faulty state of the system as well, like during overloads or short-circuits. For instance, turning on a faulty piece of equipment can result in making a short-circuit current. The electric switching devices are responsible for the automatic disconnection (interruption) of this excessive current.

1.2 Classification of electric devices

We shall discuss the characteristic currents of different system states by means of simplified single-phase models of the symmetrical three-phase systems.

For convenience of studying, devices are classified by various features.

a) by purpose devices are subdivided into the following groups:

- switching, intended for inclusion and shutdown of electric circuits;
- protective, intended for protection and disconnection of electric circuits from overloads, currents of short circuit and other abnormal modes;
- starting and regulating, intended for start-up and regulation of speed of electrical machines;
- controlling (relays), intended for control of the set parameters of an electric circuit;
- regulating, intended for automatic continuous stabilization or regulation of the set parameter of an electric circuit or system;

b) by the principle of work there are distinguished contact and contactless devices.

The first have mobile contact parts, and the impact on the operated circuit is carried out by contacting and breaking of these contacts. Existence of a contact system is a weak point of such devices. Contactless devices do not have disconnected or sliding contacts. These devices exercise control by changing the electric parameters;

c) contact devices can be automatic and non-automatic.

The first come into action from the set operating mode of a circuit or a machine. Non-automatic devices act upon the will of the operator.

Within one group or type devices are distinguished:

a) by voltage – low voltage (to 1000V) and high voltage (over 1000V);

b) by the nature of current - a direct current, alternating current of industrial frequency and alternating current of the increased frequency;

c) by the nature of protection against environment - open execution, splash-proof, explosion-proof, etc.;

d) by way of operation – electromagnetic, magnetoelectric, thermal, inductive, etc.;

e) by some other factors (speed, a way of arc suppression, etc.).

2 Lecture №2. The main requirements and materials for constructing electric devices

Content of the lecture: the main requirements imposed to electric devices. The main materials applied in the instrument-making.

The purpose of the lecture: discuss the main requirements and materials for constructing electric devices.

2.1 The main requirements imposed to electric devices

Qualifying standards to electric devices are rather sufficient and depend on the purpose, conditions of application and operation of the device.

Except the specific requirements relating to a particular type of the device, all electric devices have to meet the general requirements:

a) each device working under electric current heats up. In this case a device temperature should not surpass some certain admissible level established for this device and its details;

b) in each electric circuit there may occur abnormal (overload) or an emergency (short circuit) operating mode. The current passing through the device in these modes can exceed rated current of the device considerably. Thus, the device is exposed to big thermal and electrodynamic influences. However, it has to sustain these influences without any deformations affecting its further work;

c) each electric device works in a circuit with a certain voltage where overvoltage may also take place. But electric isolation of the device must ensure reliable functioning of the device at preset values of overvoltage as well;

d) contacts of devices should be capable of switching on and disconnecting all currents of operating modes, other devices and currents of emergency operation;

e) particular demands are required to each electric device with the view of reliability and the accuracy of work, and also a certain speed;

f) it is desirable that any electric device had the smallest possible dimensions, weight, cost, could be simple in design, convenient in service and technological in production.

2.2 The main materials applied in instrument-making

The materials applied in instrument-making can be divided into the following groups:

a) conducting materials – mainly copper, aluminum, steel, brass, etc.;

b) ferromagnetic materials – alloys may be used for magnetic conductors;

c) insulating materials – for electric isolation of current carrying parts from each other and from the grounded parts;

d) arc-resistant insulating materials – asbestos, durable porcelain, gypsum, ceramics, quartz sand, plastic for arc-extinguishing chambers;

e) alloys of high resistance – for production of various resistances;

f) contact materials - silver, bronze, copper, gold, metal ceramics for ensuring high wear resistance of contacts;

g) bimetals, that are applied in the automatic devices using linear lengthening of bodies when heated by electric current;

h) constructional materials – metals, plastic, insulating materials for shaping the devices and its details into particular forms and for production of details whose primary value is transfer and perception of mechanical efforts.

Technical progress in instrument-making is considerably defined by quality of the above materials.

3 Lecture №3. Electrodynamic efforts in devices

Content of the lecture: calculation of electrodynamic efforts on the basis of the Biot-Savart law and on change of a stock of electromagnetic energy of a contour. Electrodynamic efforts in rounds and coils of devices. Electrodynamic efforts between the conductor with current and ferromagnetic weight. Electrodynamic efforts in conductors of a variable section.

The purpose of the lecture.

To acquaint students with the electrodynamic efforts operating in electric devices and the existing methods of their calculation.

3.1 Basic concepts

At short circuit in a network currents many times exceeding the rated current of the device may flow through current carrying parts of the device. At interaction of these currents with a magnetic field of other current carrying parts of the device electrodynamic efforts (EDE) are created. These efforts seek to deform both conductors of current carrying parts, and insulators on which they are fixed. This circumstance demands carrying out calculation on electrodynamic firmness of the device, i.e. on the ability of the device to sustain passing of short circuit current without damage. Calculation of EDE is conducted usually either on the basis of the Biot-Savart law, or on change of store of magnetic energy of the system. Let's consider application of the specified methods for calculation of EDE**.**

It is known that the conductor with the current located in a magnetic field is affected by the mechanical force which can be found from the expression:

$$F = I \cdot L \cdot B \cdot \sin\beta, \tag{2.1}$$

where I - the current flowing through the conductor;

L - length of the conductor;

B - induction of a magnetic field;

ß - a corner between the direction of induction and the direction of current.

The direction of force action can be found:

a) by the rule of the left hand;

b) by the method of a lateral thrust and contraction of magnetic lines;

c) in a carrying current conductor direction of force is defined from the following general position: forces affecting the conductor seek to change a contour configuration so that the magnetic flux covered by a contour increases.

3.2 Calculation of EDE on the basis of Biot-Savart's law

Let the task be set for us: to find forces affecting the current carrying conductor in a magnetic field, created randomly by the current carrying conductors located in space.

To use the formula (2.1) and to find forces affecting the current carrying conductor it is necessary first to find the value of the induction created by sources of a magnetic field in the location of our conductor. The value of induction is just defined on the basis of Biot-Savart's law, known from the course of physics.

According to this law (Biot-Savart), in the absence of ferromagnetic environments the elementary induction created by the element of a linear wire dL through which the current I flows, in the point at distance ρ from a current element will be equal:

$$dB = \frac{\mu \cdot I \cdot dL \cdot \sin\alpha}{4 \cdot \pi \cdot \rho^2}, \tag{2.2}$$

where α - the corner between the vector ρ and the direction of current.

The resulting induction in the considered point from all wire:

$$B = \frac{\mu \cdot I}{4 \cdot \pi} \cdot \int_L^0 \frac{dL \cdot \sin\alpha}{\rho^2}. \tag{2.3}$$

Similarly induction in the space point that is of interest to us is defined from all available conductors with currents.

After the definition of induction, EDE is calculated using the formula (2.1).

The above described method of EDE calculation is universal. However, in some cases, for finding electrodynamic forces it is simpler to apply the second method which bears the name of the power method.

3.3 Calculation of electrodynamic forces by the change of electromagnetic energy storage of the contour

The electromagnetic field around conductors and current carrying contours possesses energy storage. Electromagnetic energy of the streamlined contour I is equal to:

$$W = L\frac{I^2}{2}. \tag{2.4}$$

In turn, electromagnetic energies of two streamlined contours I_1 and I_2 are equal to:

$$W=L_1 \cdot \frac{i_1^2}{2} + L_2 \cdot \frac{i_2^2}{2} + M \cdot i_1 \cdot i_2, \quad (2.5)$$

where L - inductance of a contour;

M - mutual inductance of contours.

Any deformation of a contour or change of a relative positioning of contours leads to the change of electromagnetic energy storage.

As it is known, work of forces in any system is equal to the change of energy storage in this system:

$$A=Fdx=dW, \quad (2.6)$$

where dW is the change of energy storage in the system at its deformation in the direction of axis X under the influence of force F.

It is on this law - the law of energy conservation, that the second method of EDE definition in contours is based, which received the name of the power method of EDE calculation.

When using this method electrodynamic force in a contour or between contours, acting in the direction of axis X is equal to the speed of change of energy storage in the system at its deformation in the same direction, i.e. its derivative in this direction:

$$F=dW/dx. \quad (2.7)$$

It is convenient to apply this method when the formulas connecting inductance and mutual inductance of contours with their geometrical parameters are known, i.e. in rounds and coils of electric devices and transformers.

3.4 Electrodynamic efforts in a turn, a coil and between coils

According to the researches, the force acting in a current carrying turn is proportional to the square of current and to the diameter of the turn. This force affects a rupture of a turn. If the coil consists of ω streamlined turns, then inductance and the disruptive force will increase by ω 2 times. Forces in the coil are directed so that its flux linkage increases. They seek to squeeze the coil on height and thickness and to increase its average diameter.

3.5 EDE between the current carrying conductor and ferromagnetic mass

When the conductor approaches the ferromagnetic wall, the magnetic field is distorted, the magnetic lines of force tend to close along the mass, and forces arise that tend to attract the conductor to this mass, that is, there appear attractive forces which are not dependent on the direction of the current in the conductor.

This property is used for retraction of an electric arc in the arc-suppression steel lattice applied in many low-voltage devices in which there is an effective suppression of an arch.

3.6 Electrodynamic efforts in conductors of variable cross-section

If the cross section of the conductor varies, which always happens in the place of the conductor contacts, then in the place of the change in the cross section, due to the curvature of the streamlines, longitudinal EDE arise (figure 3.1) tendng to breaking-off a transition place along the axis of the conductor and being directed towards a larger section. These forces reduce the force of pressing the contact springs of the devices which leads to an increase in the contact resistance of the contacts and at high short-circuit currents - to their welding.

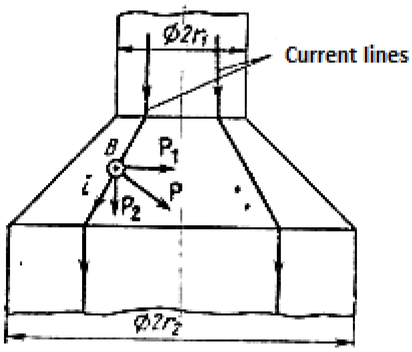


Figure 3.1- EDE in conductors of a variable cross-section

4 Lecture №4. Thermal calculations of electric devices

Content of the lecture: bases of thermal calculations. Losses in conductors. Heat transfer from a heated body**.** Heat conductivity, convection, radiation. Thermolysis at steady-state conditions.

The purpose or the lecture.

To acquaint students with bases of thermal calculations of electric devices.

4.1 Bases of thermal calculations

4.1.1 Losses in the streamlined conductors.

The power P being lost in the conductor when passing through it of electric current is equal to:

$$P=I^2 \cdot R ,$$

where I - effective value of current;

R – resistance of the conductor.

At direct current R corresponds to ohmic resistance

$$R_0 = \frac{\rho \cdot I}{s}.$$

At alternating current losses turn out to be bigger, than at direct current. This increase of losses happens due to superficial effect and effect of proximity, and is taken into account by the coefficient of additional losses $C_{al} > 1$. Resistance at alternating current due to the above mentioned effects is more ohmic, and it bears the name of active resistance

$$R=R_0 \cdot k_д.$$

Active resistance is a fictitious resistance of the conductor which, being multiplied by a square of effective value of current, gives the losses which are really available at alternating current.

4.1.2 Superficial effect.

The alternating magnetic field encompassing the conductor with current induces EMF in this conductor, which is directed towards the applied voltage. As the central layers of the conductor are crossed by a bigger magnetic flux than external, so EMF will be the greatest on the wire axis. This EMF leads to reduction of current density in the central layers of the conductor in comparison with current density in external layers. Influence of this phenomenon can be perceived as reduction of effective section of the conductor and respectively increase in resistance. Influence of the superficial effect grows with growth of current frequency, conductivity and magnetic permeability of the conductor material.

4.1.3 Effect of proximity.

In this case change of current distribution by the conductor cross-section and change of resistance arises due to the influence of the magnetic field of the adjacent conductors with current.

4.2 Heat transfer from a heated body. Heat conductivity. Convection. Radiation

Transfer of heat always goes from more heated bodies to less heated bodies and continues until temperatures of the bodies become even. The higher is the temperature of a heated body, the more intensive is the process of heat transfer.

Three types of heat transfer are distinguished: heat conductivity, convection and radiation.

4.2.1 Heat conductivity.

The process of heat transfer from one particle of a body to another or from one body to another when these particles or bodies adjoin with each other is called heat conductivity. Heat conductivity in metals occurs due to the thermal movement of electrons, and in other cases – molecules. Heat conductivity is characteristic for solid bodies. A necessary condition of heat conductivity is the difference of temperatures.

At calculation of heat transfer through a body due to heat conductivity an often applied expression is:

$$\tau = \Phi \cdot R_T,$$

where τ is the difference of temperatures on the internal and external walls of the material;

θ is the thermal stream passing through the walls of adjoining bodies;

R_T - thermal resistance of a body.

$$R_T = \frac{\delta}{\lambda \cdot S}, \tag{3.1}$$

where λ is the heat conductivity coefficient numerically equal to the amount of heat transferred through the surface area of 1 m^2 for 1 second at the temperature drop in 10°C.

The equation (3.1) is similar to the Ohm's law for electric circuits, and it is called the thermal Ohm's law. Thermal resistance is in direct proportion to the length of the way of the thermal stream δ and in inverse proportion to the section of this way and coefficient of heat conductivity.

As appears from (3.1) amounts of heat transferred from one body to another due to heat conductivity is in direct proportion to the difference of temperatures between them and in inverse proportion to the thermal resistance of R_T of the body through which heat is transferred. If the thermal stream passes through a number of walls with various thickness and coefficient of heat conductivity, the resulting thermal resistance of all walls will be equal to the sum of these resistances.

4.2.2 Convection.

The process of heat transfer by movement of particles of liquid or gas is called convection. At natural convection the movement of the cooling gas or liquid occurs at the expense of difference of density of heated and cold volumes. At artificial convection the cooling environment is set in motion by means of fans or pumps.

Amount of heat given by a body due to convection:

$$Q = \alpha \cdot \tau \cdot S,$$

where α is thermolysis coefficient at convection determined by heat which is removed for 1 sec. from a surface in 1sq. m at a difference of temperatures in 10°C;

τ is the difference of temperatures between a heated body and the cooling gas or liquid environment;

S - body surface.

4.2.3 Thermal radiation.

A heated body gives part of its energy to the surrounding space by radiation of electromagnetic waves (ultra-violet, infrared).

This way of a thermolysis is called thermal radiation, emission or radiation.

Heat given by a heated body due to radiation can be calculated with the help of the equation of Stefan-Boltzmann:

$$Q = k \cdot \left[\left(\frac{T_2}{1000} \right)^4 - \left(\frac{T_1}{1000} \right)^4 \right] \cdot S.$$

The amount of the given heat depends on the difference of the fourth degrees of absolute temperatures of its heated surface and the environment. The total amount of heat given by all types of heat exchange is in complex relation with the body temperature and its geometrical sizes. Therefore in each case there are first estimated the intensity of all types of heat exchange and considered those which prevail. For example, for the conductors dipped into oil only convection is considered; for long buses heat conductivity is neglected, and only convection and radiation are considered.

4.3 Thermolysis in the preset mode

Heat transfer from the surface of a body occurs simultaneously with convection and radiation. Though, it is difficult to determine what part of heat is transferred to the environment by convection, and what part – by radiation. Therefore, the concept of coefficient of thermolysis C_t is introduced, which defines the amount of heat given to the environment for 1 sec. by all types of a thermolysis with 1sq.m. surfaces at a difference of temperatures of a heated body and surrounding space in 1 degree Celsius. The coefficient of heat transfer (or heat exchange) can be found empirically.

Then the amount of heat given by a heated body to the surrounding space will be equal to:

$$Q = k_T \cdot \tau_Y \cdot S.$$

In the set mode, when all losses of P emitted in the conductor are sent to the surrounding space, it is possible to write down:

$$P = k_T \cdot \tau_Y \cdot S.$$

From where the excess of temperature of a heated body over the ambient temperature Θ_o is just found:

$$\tau_Y = \frac{P}{k_T \cdot S}.$$

And then also the temperature of a heated body:

$$\Theta_T = \Theta_O + \tau_Y.$$

5 Lecture №5. Operation of devices in the transitional modes

Content of the lecture: heating and cooling of devices at a long operating mode. Heating and cooling of devices at a short-term operating mode. Heating and cooling of devices at a repeated and short-term operating mode.

The purpose of the lecture.

To acquaint students with features of heating and cooling of electric devices depending on duration of an operating mode of the device.

5.1 Heating and cooling of devices at a long operating mode

5.1.1 Equation of the device heating.

After turning on the device the temperature of its elements does not instantly reaches the established values. The heat of the device is partially sent to the surrounding space, partially goes for increase of its temperature.

The equation of thermal balance looks as follows:

$$P \cdot dt = k_T \cdot S \cdot \tau \cdot dt + C \cdot dt, \tag{4.1}$$

where P - the power of thermal losses in a body;

C - a body thermal capacity:

$$C = M \cdot c,$$

where c – heat capacity;

M – body mass.

In the equation (4.1) the left member of the equation is the energy consumed by the device from a circuit for the period dt. The first member of the right part of the equation is the amount of heat given by a body to surrounding space during dt time. The second member is the amount of heat taken by a body at changing its temperature on dt.

The solution of the differential equation (4.1) relative to dt will be equal to:

$$\tau = \tau_Y \cdot (1 - e^{-t/T}) \ , \tag{4.2}$$

where τ_y - the established excess of body temperature over ambient temperature, is found by the formula:

$$\tau_Y = \frac{P}{k_T \cdot S}.$$

T- a constant of time for a body heating, is determined by the formula:

$$T = \frac{c \cdot M}{k_T \cdot S}.$$

The heating time constant physically represents the time for which the body will heat up to the established temperature in the absence of thermolysis in the environment.

5.1.2 Equation of the device cooling.

To make a conclusion for a cooling equation in the equation (4.1) we will assume

$$P \cdot dt = 0.$$

In this case the equation will look as follows:

$$0 = k_m \cdot S \cdot \tau \cdot \cdot dt + C \cdot d\tau .$$

From where

$$\tau = \tau_0 \cdot e^{-t/T},$$

where τ_0 – excess of body temperature at the time of the beginning of the process of cooling.

The curve of cooling is the mirror image of a curve of heating.

Curves of heating and cooling of the device are given in figure 5.1. Time t is taken in T shares. The established body temperature usually is reached over time equal to (3+5) T.

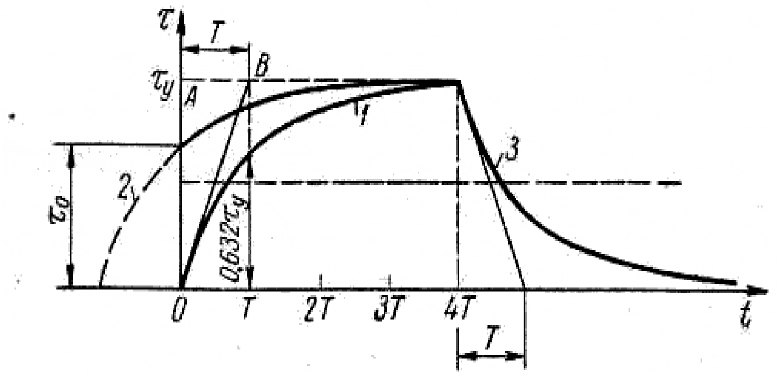


Figure 5.1 - Curves of the processes of heating and cooling the device at a long operating mode

5.2 Heating and cooling of devices at a short-term operating mode

At a long operating mode the permissible load (P_d) is defined so that the steady-state excess of temperature τ_y equals to admissible excess $\tau_{\mathbf{d}}$. Excess of temperature in this case changes on the curve 1 (figure 5.2).

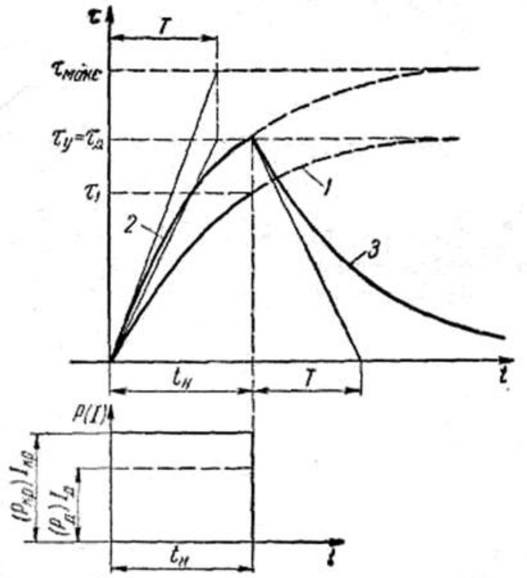


Figure 5.2 – Curves of the processes of heating and cooling of the device at a short-term operating mode

At the same loading in a short-term operating mode in time $\tau_{н}$ excess of temperature would reach the value τ_1, i.e. the device would not be completely used on heating. Therefore at the short-term mode it is possible to increase loading so that excess of temperature would change on the curve 2, and by the end of the mode (in time $\tau_{н}$) reach admissible temperature. For the characteristic of the short-term mode the concept of coefficient of an overload is introduced:

$$p = \frac{I_{кр}}{I_{дл}},$$

which shows how many times it is possible to increase a permissible load on current at the short-term mode in comparison with the long-term mode:

$$p = \frac{1}{\sqrt{1 - e^{-t_{кр}/T}}}. \tag{4.3}$$

The analysis (5.3) shows that the coefficient of an overload grows with the increase of time constant. In this regard in the devices, household appliances working in the short-term modes it is recommended to increase time constant which allows to raise loading on current. The increase of the time constant is basically reached at the expense of increase in mass of the material involved in the heating process.

5.3 Heating and cooling of devices at a repeated short-term operating mode

The operating mode is called repeated and short-term, when loading periods $t_{nominal}$ alternate with pauses t_{start}. Full period $t_{nominal} + t_{start}$ is called a cycle t_{center}.

The mode is characterized by switching duration (SD%) and switching speeds - number of cycles per hour.

SD % - represents the ratio of loading duration in percentage to the duration of all cycle:

$$SD\% = \frac{t_{nominal}}{t_{center}} \cdot 100\%.$$

Curves of the processes of heating and cooling of the device are represented in figure 5.3.

In this mode the periods of heating and cooling alternate and, since some moment, there comes the state when excess of temperature fluctuates between some maximum t_1 and a minimum t_2. If the device is loaded with the current corresponding to switching duration of the device (SD%), excess of temperature will be equal to admissible excess of temperature (curve 1).

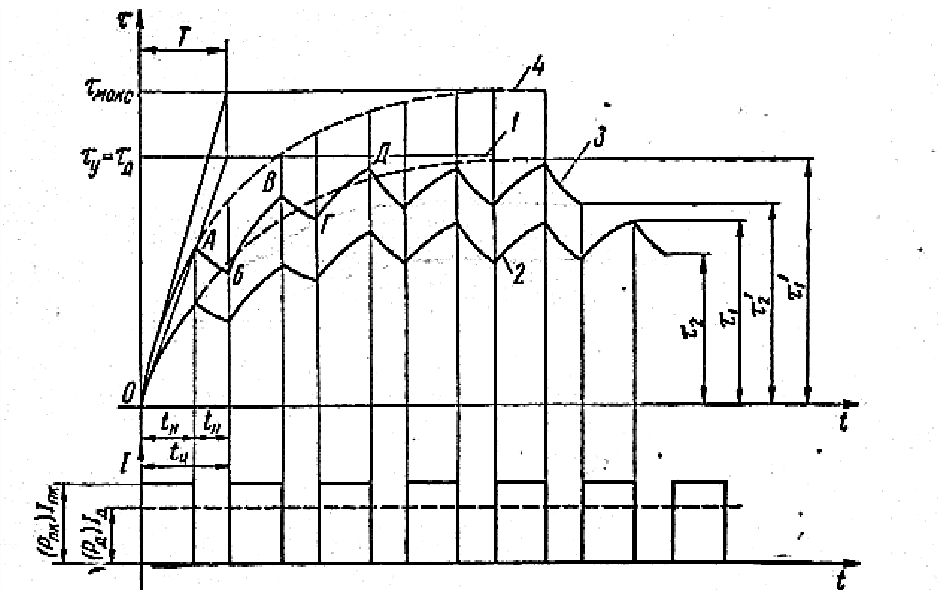


Figure 5.3 – Curves of heating and cooling processes of the device at a repeated and short-term operating mode

If the device, at this value of current, is left switched on for a long period of time, excess of temperature will be more than it is admissible, and the device will break down.

6 Lecture №6. Thermal stability of electric devices

Content of the lecture: heating of devices at a short circuit. Thermal stability of devices. Maximum permissible temperatures of heating of conductors and devices. An indirect method of definition of the established excess of temperature and a time constant of heating the device.

The purpose of the lecture.

To study relations between rated currents of the device elements (or the conductor) and their maximum permissible temperatures.

6.1 Heating of the device at short circuit

Short circuit is characterized by big current and small duration which are determined by reaction time of the maximum current protection. As the researches have shown, if duration of heating does not exceed 0,1 T, it is possible to neglect return of heat in surrounding space and to suggest that all energy emitted at short circuit goes for heating of the device.

The equation of thermal balance (4.1) in this case will look like

$$P \cdot dt = k_m C \cdot d\tau$$

from where $$d\tau = \frac{P \cdot dt}{C}$$

then $$\tau_{K3} = \frac{I_{K3}^2 \cdot t_{K3} \cdot R}{C} + \tau_0,$$

where τ_0 – excess of temperature of the device at the time of the beginning of short-circuit.

Heating of the device at short-circuit happens practically in a straight line (figure 6.1)

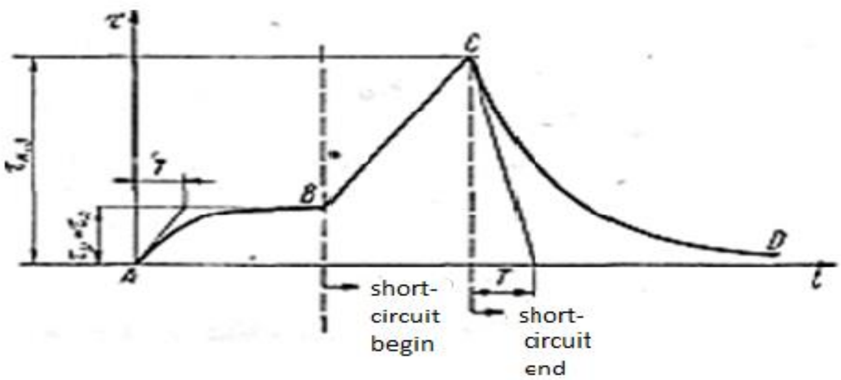


Figure 6.1 - Heating of the device with short circuit and cooling it after shutting down

6.2 Thermal stability of devices

Thermal stability of devices means the ability to withstand without damage and overheating above the norms the thermal action of short-circuit currents of a certain duration. In their catalogs manufacturers of devices preset current of thermal stability and the time during which the device can pass this current without overheating and without being damaged.

The devices and electric circuits protected by the safety locks having small endurance of reaction time (less than 5ms) are not usually checked for thermal and electrodynamic stability.

6.3 Maximum permissible heating temperature of conductors and devices

For ensuring reliable operation of the device the temperature of its conductors and details should not surpass some certain value. The temperature at which reliable operation of the device is guaranteed and the influence of which conductors and devices can withstand without decrease of the electric and mechanical properties is called maximum permissible temperature.

Two permissible temperatures are normalized:

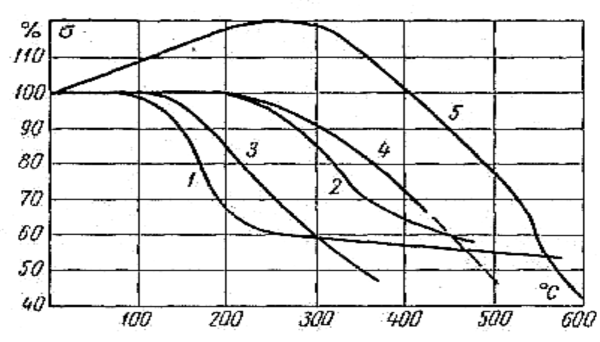
- at a nominal long-term mode;
- at a short circuit.

Short circuit is a short-term mode, therefore there can be admitted a higher heating by short circuit currents, than at a long-term mode. However, this heating should not lead to decrease of electric and mechanical properties of isolation and wires.

For aluminum maximum permissible temperature for the short circuit mode is admitted equal to 200^0 C, and for copper 300^0 C.

Maximum permissible temperature for the isolated conductors is defined by properties (an isolation class) to which the conductor adjoins.

Maximum permissible temperature for bared (uninsulated) conductors is defined by the mechanical durability of conductors which sharply decreases with the growth of temperature (figure 5.2).



1 - copper; 2 - silver; 3 - aluminum; 4 - bronze 5 - steel.

Figure 6.2 - Dependence of the tensile strength of metals on the heating temperature at stretching

Maximum permissible temperature for the conductors having contact connections sharply decreases in comparison with the whole conductors and is defined by the temperature of the beginning of intensive oxidation of contact surfaces. Practice shows that if the temperature of contact connections does not exceed 70 degrees, their reliable and long-term functioning is ensured. And, on the contrary, if temperature of the wire having contact connections exceeds 70 degrees, then, as a result of oxidizing processes, resistance of contacts increases, and thermal losses in them increase simultaneously. Contacts overheat and collapse. Reliability of power supply worsens.

Maximum permissible temperature for non-current-carrying details: bearing, fixing, protective, etc. is defined from service safety conditions (exclusion of burns at contact with them).

6.4 An indirect method of determining the established temperature excess and a constant of time of the device heating

In practice, it is often required to find the value of a constant of heating time and the steady-state temperature excess of the device, experimental obtaining of which demands much time (10 — 20 hours) which, naturally, causes considerable inconveniences.

In this case the steady-state established temperature excess is defined on the basis of the partially taken curve of heating.

$$\tau = f\left(\frac{d\tau}{dt}\right).$$

The method is based on the fact that the dependence represents by itself a straight line. The construction is conducted as follows (figure 5.3):

a) during identical, relatively short time intervals Δt, corresponding to them temperature excess values $\Delta\tau$ are found;

b) to the left of the coordinate axis, at a randomly chosen scale at the level of the corresponding value τ segments are marked: $\frac{d\tau_i}{dt_i}$;

c) the ends of segments are connected by a straight line.

The point of intersection of a straight line with an ordinate axis will determine the steady temperature rise, τ_y, and the segment at the intersection with the abscissa axis will be equal to the ratio $\frac{\tau_y}{T}$. Thus, it is possible, by a curve piece of heating, to determine the wanted values τ_y and T.

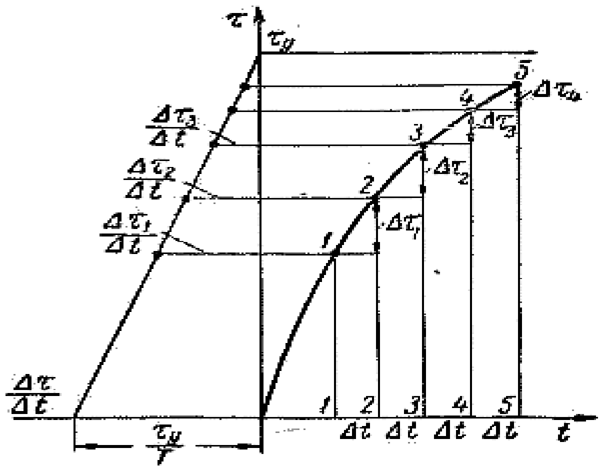


Figure 6.3 –To the determination of a constant of time and the steady-state temperature excess by the indirect method

7 Lecture №7. Electric contacts

Content of the lecture: Basic concepts. Terminology. Transitional resistance of contact. Temperature of a contact platform. Dependence of transitional resistance on a condition of contact surfaces.

The purpose of the lecture.

To study the basic concepts about contacts, to estimate an important role which contacts play in ensuring reliable operation of electric devices and electric networks.

7.1 Basic concepts. Terminology

The concept of an electric contact encompasses both a place of metal contact of conductors, and the conductor itself. The purpose of contact is to continue a way of current from one conductor to another.

By the way of connection of conductors with each other contacts are subdivided into 3 groups:

a) closed (not disconnected) contact connections;

b) open (disconnected) contact connections;

c) sliding contact connections.

The conductors which are rigidly connected among themselves belong to the first group. They include: bolted connections of buses, connection of conductors to plugs, etc. In the second group there are conductors intended for switching of electric circuits. They are switches, contact breakers, etc. Brush contacts of electrical machines, rheostats, etc. belong to the third group.

In electric contacts, it is necessary to distinguish the seeming and physical areas of contact.

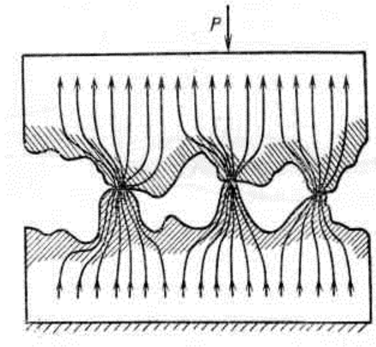


Figure 7.1 – Contact of surfaces

However carefully contact surfaces are polished, they will always have microscopic hillocks or roughness therefore physically two surfaces will adjoin not at the complete seeming area, but only at separate microscopic platforms (figure 7.1).

The quantity of contact platforms depends on geometrical forms of the adjoining contacts.

By the type of touch there are distinguished 3 types of contacts:

a) a point contact – provided only in one microscopic platform – a point. For example: sphere-to-sphere, sphere-plane, etc.;

b) linear contact - the seeming contact occurs on the line. For example:

cylinder - plate, coil-coil, etc. Physically contact happens on a number of the platforms (at least two) located on the line;

c) superficial contact – the seeming contact happens on a surface, and physically - on a number of the elementary platforms (at least three) located on this surface.

The sizes of elementary platforms of contact are proportional to the contact pressing force and depend on resistance of the material of contacts to crumpling:

$$S_э = \frac{P}{\sigma} , \tag{7.1}$$

where P - force squeezing contacts;

σ - temporary resistance of material to crumpling (from the reference book).

However, with growth of compression force growth of the sizes of platforms is slowed down because of shrinkage of the area of contact.

7.2 Transitional resistance of contact

In the zone of current transition from one conductor to another there is large electric resistance called the transitional resistance of contact.

Physically the nature of transitional resistance is an electric resistance of microscopic hillocks on which there is a contact of conductors among themselves. Transitional resistance of the contact can be presented as the result of sharp increase of current density in contact platforms in comparison with current density in a contact body.

The value of transitional resistance of contacts is determined using experimental data, on the following expression:

$$R_{nep} = \frac{\varepsilon}{P^n}, \qquad (7.2)$$

where ε is a certain quantity depending on the material, the form, the way of processing and the condition of the contact surface;

P – contact compression force;

n – the exponent characterizing the type of contact and the number of common platforms.

Experimentally defined values of ε considerably depend on the condition of the surface of contacts, nature of their processing and, especially, on the level of oxidation.

According to the experiments carried out, the transitional resistance of contacts quickly decreases with growth of force of contacts compression (figure 7.2).

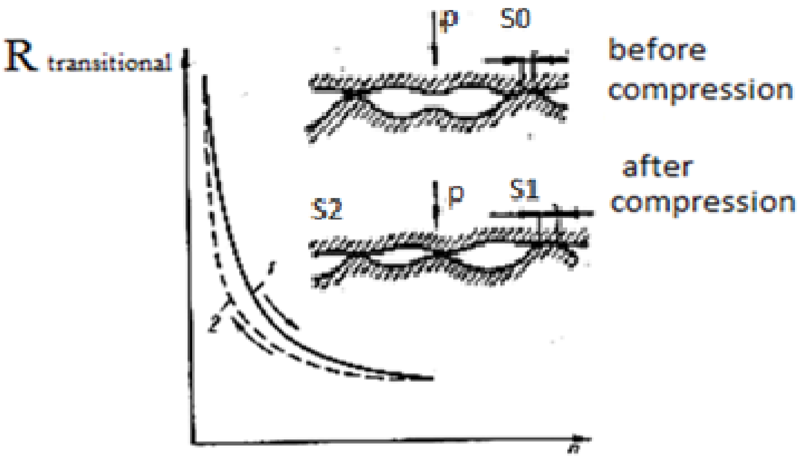


Figure 7.2 - Dependence of transitional resistance of the contact on the force of compression

7.3 Dependence of transitional resistance on temperature

As contact resistance represents the resistance of metal of the conductor, so it also increases with growth of temperature.

However, with the increase of temperature the structure of hillocks and elementary contact platforms change due to the value of resistance to crumbling.

Therefore with growth of temperature transitional resistance grows in the beginning (figure 7.3), and then there is a sharp decrease of mechanical strength of material, for example, transitional resistance of copper at 200^0 also falls sharply. Further growth of temperature repeatedly entails linear growth of transitional resistance up to the material melting temperature at which contacts are welded, and the transitional resistance reduces almost to zero.

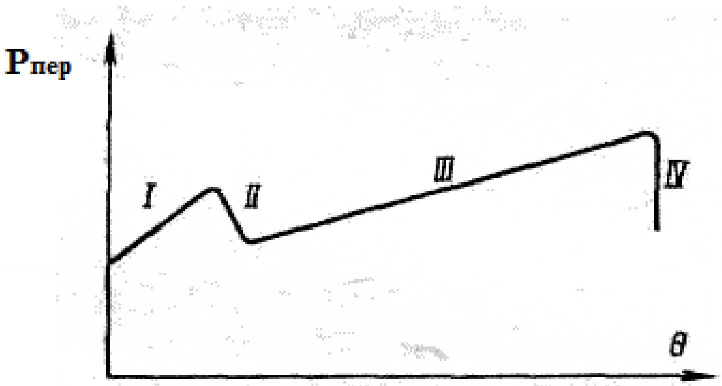


Figure 7.3 – Dependence of transitional resistance on temperature

7.4 Dependence of transitional resistance on the condition of contact surfaces

The results of carried out experimental researches showed that the transitional resistance of contacts is extremely sensitive to oxidation of surface. Oxidic films are especially dangerous to contacts on small currents when forces of pressing are small. The process of formation of a film begins right after the contact of the protected surface of contacts with the air around them. Transitional resistance can thus increase tens of thousands times. In this regard contacts on small currents (small pressing) are produced from the precious metals which are resistant to oxidation (gold, platinum, etc.). In high-current contacts the film collapses either thanks to big pressing, or due to slipping of one contact relative to another. In the course of work the transitional resistance of contacts does not remain constant. Under the influence of oxygen, other aggressive gases, the increased temperature intensity of formation of a film grows. Thus the transitional resistance of contact, drop of voltage on it and its temperature increase. At certain values of voltage and temperature there occurs an electric breakdown of film, then the contact resistance falls. This phenomenon is called fritting.

8 Lecture №8. Operating modes of contacts

Content of the lecture: operating modes of contacts at switching and breaking of an electric circuit. Work of contacts in the switched-on state in the nominal mode and in the short-circuit mode.

The purpose of the lecture.

Consideration of the physical phenomena occurring during the work of contacts of electric devices.

Let's consider the processes connected with work of contacts in the following modes:

a) work of contacts at circuit closing;

b) work of contacts in the closed-in state;

c) work of contacts at circuit break.

8.1 Switching of a circuit

At turning on the electric devices there may take place the following processes in their contact systems:

a) vibration of contacts;

b) erosion of contact surfaces.

8.1.1 Vibration of contacts.

The processes arising at vibration, will be considered on the example of the contact system of the contactor a simplified scheme of which is given in figure 8.1.

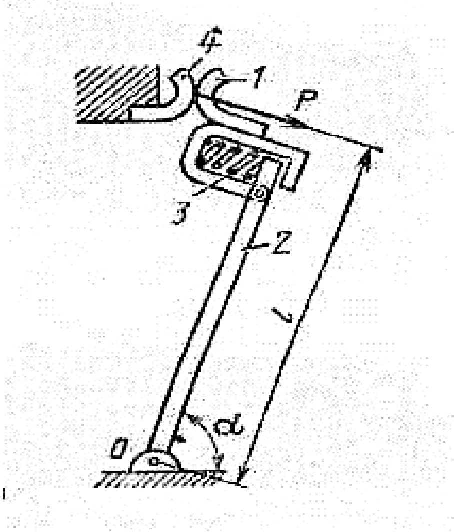


Figure 8.1 – Contact system of the contactor in the course of switching

Mobile contact 1 is connected with the contact lever 2 and a contact spring 3. Motionless contact 4 is rigidly fixed on a support. At switching of the contactor its electromagnet affects the lever 2 movement of which leads to joining contacts 1 and 4. At the time of contact there happens a blow which results in deformation of crumbling of contacts and a kick of contact 1 to the right. Between contacts a gap is formed, and under the influence of voltage applied to them there appears an electric arch. The movement of contact 1 to the right will stop when the energy received by it at blow turns into the energy of compression of the spring 3. After that contact 1 under the influence of spring 3 will start moving to the left. There will be a new blow and new kick-off of the contact. This phenomenon is called vibration of contacts.

Vibration of contacts leads to repeated formation of an electric arch which results in their strong wear because of melting and dispersion of the material of contacts. For reduction of vibration preliminary deformation of the contact spring 3 is created. In this case, at the time of contacts touch the effort of pressing increases not from zero, but from previously established pressing value P_{start}. The preliminary tightness of a contact spring is created by failure of a mobile contact.

The failure (follow-through) of contact is understood as distance on which the mobile contact will move if the motionless contact is removed.

Then:

$$P_{start} = c \cdot \Delta l_{wire},$$

where c - rigidity of a contact spring;

Δl_{wire} - contact failure size.

With creation of a failure of contact and increase in initial pressing of a contact spring the transitional resistance of contact decreases, and, that is very important, vibration also decreases. However at excessively big initial effort vibration can sharply increase at the insufficient power of the switching electromagnet.

At the same time the increase in the traction moment leads to the increase in the speed of the mobile contact, its kinetic energy results in growth of the kick-off amplitude. So, as we see, an optimum ratio of power of the switching electromagnet and size of a failure of contacts is required.

At switching of contacts on the existing short circuit vibration of contacts increases because of emergence of the rejecting electrodynamic forces in contact points. In order that there was no melting of contacts at the time of their contact, the effort of a preliminary tightness of a contact spring has to compensate electrodynamic forces of rejection and create such pressing by which falling of voltage on transitional resistance will not cause melting of a point of a contact and welding of contacts.

8.1.2 Erosion of contact surfaces.

In the course of switching, as contacts move closer to each other, intensity of electric field between them increases, and at a certain distance (100-th parts of a millimeter) there is an electric breakdown of an air interval between contacts. At breakdown electrons bombard the anode, and its material passes to the cathode, being set on it in the form of thin needles.

Wear of contacts as a result of transfer of material from one contact on another, i.e. evaporation of material in surrounding space without change of composition of material is called physical wear or erosion.

8.2 Work of contacts in the switched-on state

In this mode we will consider 2 cases:

a) nominal current passes through contacts;

b) short-circuit current passes through contacts.

8.2.1 Mode of rated current.

As it was previously noted, transitional resistance of contacts is characterized by two temperature points:

Temperature of a softening of material and temperature of melting.

For reliable work of contacts it is necessary that at rated current power failure on transitional resistance was equal to:

$$I_{nominal} \cdot R_{contact} = 0,5 \div 0,8) \cdot U_{contact1} \ , \qquad (8.1)$$

where $U_{contact}$ is power failure in contact at which the temperature of contact is equal to the temperature of contact material softening (it is shown in reference books).

At calculations of contact systems of devices at the set rated current and the known power failure for contact material from the formula (8.1) transitional resistance is defined, and then by the formula (8.2) the required contact pressing P is found.

8.2.2 Mode of short circuit.

At short circuit current 10-20 times exceeding nominal rates passes through contacts. Because of a small constant of heating time the temperature of a contact platform rises almost instantly and can reach melting temperature.

It is also necessary to remember that at short circuit, due to push-off forces arising in contact platforms, contact pressing weakens, and transitional resistance increases, thermal losses and heating of contacts increase, which may cause their welding.

8.3 Breaking of a circuit

In the course of disconnection of contacts contact pressing decreases, transitional resistance increases, and at the expense of it temperature of points of a contact grows. At the moment of disconnection microledges of contacts heat up to melting temperature, and between contacts there appears a bridge of liquid metal. At the further movement of contacts the bridge breaks and, depending on parameters of the disconnected circuit (voltage and current), there occurs an arc or smoldering discharge, followed by high temperature.

High temperature leads to intensive oxidation and dispersion of material in surrounding space, to transfer of material from one electrode on another and to formation of an oxidic film on contacts. All this involves wear of contacts.

The wear connected with oxidation and formation of films of chemical compounds of material on contacts with environment is called chemical wear or corrosion.

The erosion and corrosion of contacts reduce service life of devices. The direction of erosion and a form of wear of contacts depend on a type of the discharge and value of current. For emergence of the arc discharge it is necessary that values of voltage and current exceeded some minimum U_0 and I_0 values, characteristic for the given material of contacts. For example, for copper U_0= 12,3

V, and I_0 = 0,43 A. If current in a circuit is less than I_0, there will be a smoldering discharge or a spark between contacts, if it is more – there will be an arc discharge.

Service life of contacts depends on material of contacts, their weight, number of switches and current strength of the switched circuit.

The following measures are used against erosion of contacts:

a) reduction of duration of an arch burning by means of arc-suppressing devices;

b) elimination of vibrations of contacts at switching;

c) use of arc-resistant materials for contacts.

9 Lecture №9. Materials for electric contacts

Content of the lecture: materials for contact connections.

The purpose of the lecture.

Studying of physical properties of the main conduction materials applied as contact connections.

9.1 Materials for contact connections

The contact material strongly affects its service life and reliability of work, and respectively reliability of operation of devices and power supply of consumers in general.

The following requirements are imposed to contact materials:

- they have to possess high conductivity and heat conductivity;
- to be resistant to corrosion and to have a conducting oxide film;
- to be arc-resistant, i.e. to have high temperature of melting and evaporation;
- to be hard for reduction of mechanical wear at frequent on/off switches, mechanically strong and responsive to machining;
- to have high values of current and voltage necessary for arc-formation;
- to have low cost.

The listed requirements are sometimes inconsistent, and it is impossible to find material which would meet all the requirements.

For contact connections are applied:

- copper;
- silver;
- aluminum;
- tungsten;
- metal ceramics.

Let's consider merits and demerits of these materials.

Copper

The most widespread contact material.

Copper meets almost all requirements except for a corrosion resistance. Oxides of copper have bad electric conductivity.

Positive properties of copper:

a) high specific electric conductivity and heat conductivity;

b) sufficient hardness that allows to use it at frequent on/off switches;

c) high enough values of current and voltage necessary for an arc-formation;

d) simplicity of technology and low cost.

There are also some disadvantages of copper:

a) at an outside work copper becomes covered by a layer of the strong oxides having high electric resistance;

b) demands big forces of pressing.

For protection of copper against oxidation the surface of contacts becomes covered by an electrolytic way with a silver layer 20-30 microns thick. In contacts on big currents silver plates are sometimes placed. (In the devices which are rarely switched on). Because of low arc resistance application in devices disconnecting a powerful arch and having a large number of switches in an hour is undesirable. In the contacts which do not have mutual sliding because of a film of oxides use of copper is not recommended. It is applied both for not disconnected, and to the disconnected contact connections. In not disconnected connections corrosion-resistant coatings of contact surfaces are applied, namely: silvering, tinning, nickel plating and galvanizing, and also a covering of the smoothed-out copper contact by neutral greasing with the subsequent seal of seams.

Silver

Positive properties of silver:

a) high electric conductivity and heat conductivity;

b) the film of oxide of silver has small mechanical durability and quickly collapses when heating a contact point;

c) contact of silver is steady due to low bearing stress;

d) weak pressing is enough for work.

Stability of contact and small transitional resistance of contact are characteristic properties of silver.

To disadvantages of silver may be referred: small arc resistance and insufficient hardness which interferes with its application in the presence of a powerful arch and frequent switches and breakings.

It is applied in relays and contactors at currents up to 20A.

At big currents it is used as material for the main contacts working without arch.

Most often silver is applied in the form of slips – in a place of the contact made of copper a silver slip is welded, and it is also used as a second component at creation of contacts from metal ceramics.

Aluminum

Positive properties of aluminum:

a) high electric conductivity and heat conductivity;

b) small density of material that allows to reduce the mass and weight of the device.

To disadvantages may be referred:

a) formation on air of films with high resistance and with high mechanical strength;

b) low arc resistance (temperature of melting is much less, than that of copper and silver);

c) small mechanical strength.

Because of existence of moisture and oxides in the air copper and aluminum contacts form a galvanic cell.

Under the influence of the EMF of this element there occurs electrochemical destruction of contacts (electrochemical corrosion). In this regard at connection with copper aluminum must be covered in the electrolytic way by a thin layer of copper, or both metals should be covered with silver. Aluminum and its alloys (dural, silumin) is applied mainly as material for bus bars and constructional details of devices. It is not applied in disconnected contacts.

Tungsten

Positive properties:

a) high arc resistance;

b) big firmness against erosion and welding;

c) high hardness allows to apply it at frequent on/off switches;

d) high temperature of melting.

And disadvantages are:

a) high specific resistance;

b) small heat conductivity;

c) formation of strong oxidic and sulphidic films.

Due to the formation of films and their high mechanical durability tungsten contacts require big pressing.

They are applied as arc resistance contacts at the disconnected currents up to 100 kA and more, on small and average currents as working contacts with high frequency of switch-offs.

Metal ceramics

Main properties of contact connection: high electric conductivity and arc resistance - cannot be received due to alloys of such materials as silver and tungsten or copper and tungsten as they do not form alloys.

Therefore a method of powder metallurgy is applied for receiving the materials possessing necessary properties. Metal ceramics is received by agglomeration of mix of powders of various metals one of which possesses the increased electric conductance, and the other has high arc resistance.

The materials received in such a way keep physical properties of the metals which are part of them. Arc resistance of metal ceramics is provided with such components as tungsten and molybdenum. Low transitional resistance of contact is reached by use of silver or copper as the second component. Metal ceramics unites high arc resistance with rather good conductivity. The most widespread compositions of metal ceramics are: silver-tungsten, silver-graphite, silver-molybdenum, copper-tungsten, copper-molybdenum, etc. Metal ceramics is used for arc-suppression contacts on average and the big disconnected currents and also as the main contacts on rated currents up to 600 A in devices with a large number of switches.

10 Lecture №10. Bases of the theory of burning and suppression of an electric arch

Content of the lecture: the processes arising at ionization of an arc interval. Thermionic and autoelectronic emission. Collisional and thermal ionization. The processes arising at deionization of an arc interval. Recombination and diffusion of charged particles.

The purpose of the lecture.

Studying of the physical phenomena occurring at emergence of an electric arch between the dispersing contacts of the device.

Disconnection of an electric circuit at somewhat considerable currents and voltage, as a rule, is followed by an electric discharge between the dispersing contacts. The air interval between contacts is ionized and becomes conducting for some time. In it there emerges an arch leading to undesirable consequences for contacts and the device as a whole. For effective fight against negative influence of an electric arch it is necessary to have ideas of the modern theory of emergence of an electric arch, of the physical processes accompanying this phenomenon.

10.1 The processes arising at ionization of an arc interval

In usual conditions air is a good insulator: for example, for breakdown of an air interval in 1 cm it is necessary to put voltage not less than 30 kV. To become a conductor the air interval should obtain a certain concentration of charged particles: electrons and ions.

The process of separation from a neutral particle of one or several electrons and formation of free electrons and positively charged ions is called ionization. Ionization of air can happen under the influence of light, X-rays, high temperature, under the influence of electric field and some other factors. For the arc processes taking place in electric devices the greatest value take: at the processes happening at electrodes – thermionic and autoelectronic emission, and from the processes happening in an arc interval - collisional and thermal ionization.

10.1.1 Thermionic emission.

The phenomenon of emission of free electrons from the surface of a cathode having high temperature is called thermionic emission.

At a divergence of contacts the transitional resistance of contact and density of current sharply increases in the last contact platform. This platform is warmed up to melting and at a further divergence of contacts is torn, with formation of vapors of metal in air. On a negative electrode the cathodic spot (the heated platform) is formed which is the basis of an arch and the center of radiation of electrons at the first moment of divergence of contacts.

Density of current of thermionic emission depends on temperature and material of contact. It is small and can be sufficient only to start emergence of an arch, but not for support of its burning.

10.1.2 Autoelectronic emission.

The phenomenon of emission of electrons under the influence of a strong electric field is called autoelectronic emission. In the process of divergence of contacts intensity of a field between them increases and passes through values exceeding 10^9 V/m sufficient for evaporation of electrons from the cold cathode. Current of autoelectronic emission is also small and can serve only as the beginning of emergence of an arch. Thus, the initial stage of emergence of the arc discharge at the dispersing contacts is explained by existence of thermionic and autoelectronic emission of free electrons into an arc interval.

After emergence of an arch and formation of positive ions and electrons each of them will move towards the electrode: positive charges - to the cathode, and electrons - to the anode. Due to positive ions thermionic and autoelectronic emission increases. Thermionic emission increases due to rising of temperature of the cathode as a result of bombardment of the cathode by positive ions, and autoelectronic emission - due to strengthening of electric field between a layer of positive ions and the negative cathode.

10.1.3 Impact ionization.

If the free electron at the movement in electric field gets sufficient speed and, respectively, kinetic energy, then at collision with a neutral particle it can knock-out an electron from this particle, i.e. ionize this particle. The newly appeared electron can ionize the following neutral particle, etc. There will be an avalanche increase of a stream of electrons in an arc interval.

Condition for collisional ionization is existence of electric field and sufficient length of free run necessary for acquisition by an electron of the demanded energy for ionization of molecules in an air interval. Speed of electrons depends on a potential difference on the length of its free run. Therefore it is used to indicate not the speed of the movement of electrons, but that minimum value of a potential difference which is needed at the end of a free way, so that the electron could get the necessary speed. This potential difference has the name of potential of ionization. The higher is the pressure and density of gas, the less length of free run the electron has, and the less energy will the electron obtain. Ionization of an air interval will be complicated, there might no arc arise. Availability of vapors of the metals in an air interval having the potential of ionization lower, than that of the air considerably reduces the energy of ionization and facilitates formation of the arc discharge.

10.1.4 Thermal ionization.

It is the process of ionization under the influence of high temperature. Support of an arch after its emergence, i.e. providing the arc discharge with sufficient number of free electrons, is actually explained by almost the only type of ionization – thermal ionization. Temperature of a trunk of an arch reaches 4-7 thousand degrees Kelvin. At such high temperature quickly increases both the number of quickly moving molecules, and their speed. At collision of quickly moving molecules and atoms their major part collapses, with formation of charged particles. The main characteristic of thermal ionization is the extent of ionization representing the relation of number of the ionized atoms in an arc interval to the total number of atoms in this interval. Vapors of metal are much quicker ionized, than air, which is explained by their lower potential of ionization.

10.2 The processes arising at a deionization of an arc interval

Along with processes of ionization in an arch there are return processes, i.e. reunion of charged particles and formation of neutral particles. This process carries the name of deionization.

At emergence of an arch ionization processes prevail. In steadily burning arch both processes are equally intensive, and at prevalence of processes of a deionization the arch dies away. The deionization occurs, mainly, at the expense of recombination and diffusion.

10.2.1 Recombination.

The process at which variously charged particles, coming to mutual contact, form neutral particles is called recombination. Intensity of recombination increases with reduction of temperature of the arch and increase in pressure. In the electric arch burning close to surfaces of an arc-suppression chamber recombination of the main carriers of charges in an arch – electrons with positive ions happens in the following way: electrons charge the chamber wall surface to some negative potential at which positive ions are attracted to this surface and, having attached an electron, form a neutral particle.

At recombination, part of energy is released in the form of radiation of quanta of light (photons).

10.2.2 Diffusion.

It is carrying out of charged particles from the area of burning of an arch in environment. Thereby conductivity of an arch decreases.

Diffusion is caused by both electric, and thermal factors. Density of charges increases in the trunk of an arch on the way from the periphery to the center. Therefore, electric field arises, forcing ions to move from the center to the periphery and to leave the arch area. Difference of temperatures of a trunk of an arch and surrounding space also act in the same direction. The charged particles which have left the arch area are finally recombined out of this area. In freely burning arch the role of diffusion is insignificant. However, its role increases in the arch blown by compressed air and in an open moving arch. The number of the phenomena facilitating clearing of an arch include dissociation (decomposition) of neutral molecules of gases on separate atoms. The dissociation of molecules of gas is followed by absorption of thermal energy. Arch temperature thus goes down, the process of a deionization will prevail over the process of ionization, and conditions for arc-suppression improve.

As arc-suppression gas, hydrogen is most often applied. It is emitted in arc-suppression chambers at decomposition under the influence of high temperature of an arch of transformer oil, fiber, plexiglass.

11 Lecture №11. Conditions of suppression of an electric arc

Content of the lecture: volt-ampere characteristic (VAC) of an electric arc. Static and dynamic VAC. Conditions of suppression (quenching) of an arch of direct and alternating current.

The purpose of the lecture.

On the basis of the analysis of the VAC arc, to consider ways of clearing of an arc on direct and alternating current.

11.1 Volt-ampere characteristics of an arc

The most important characteristic of an arch is its volt-ampere characteristic (VAC) representing dependence of voltage on an arc on current.

With increase of current in a circuit, and, consequently, of the number of electrons in an arc interval, arc temperature time increases accordingly, thermal ionization is amplified, the number of the ionized particles increases in an arch and, respectively, the electric resistance of an arc falls.

And, resistance of an arch falls so sharply that voltage on it falls, too, despite growth of current. Upon transition of current from one value of current to another the thermal condition of an arch does not change instantly, as it possesses thermal inertia. If the current is changed slowly, thermal inertia of an arch has no effect. VAC, received at slow change of current, is called static. If current is changed quickly, VAC will depend on the speed of change of current. Such VAC is called dynamic.

Static VAC of an arc depends on the length of an arc, material of electrodes, parameters of the environment and refrigerating conditions.

Voltage decreasing on an arc interval is equal to:

$$U_{arc} = U_{electron} + E_{arc} \cdot l_{arc},$$

where $U_{electron}$ - sum of near-electrode voltage drops;

E_{arc} - intensity of electric field inside the arc;

l_{arc} - arc length.

$$U_{electron} = U_{cathode} + U_{anode},$$

where $U_{cathode}$- near-cathode voltage drop, equal to 10 – 20V;

U_{anode}- near-anode voltage drop, equal to 5-10V.

Intensity of electric field in an arc depends on current and conditions of burning of an arc: the more intensive is cooling of an arc and the higher is the pressure of the environment in which the arc burns, the greater is the intensity of electric field in an arch and the higher is its VAC. And rise of VAC, as we will further see, promotes clearing of an arch.

Let's consider conditions of clearing of an arc of direct current.

11.2 Conditions of arc-suppression

To extinguish an arc of a direct current, it is necessary to create such conditions under which in an arc interval at all values of current from initial to zero the processes of deionization would surpass the processes of ionization.

For the circuit represented in figure 11.1a, containing resistance R, inductance L and an arc interval with voltage drop U_{arc}, to which U current source voltage is applied, for any time point the equation will be fair:

$$U = i \cdot R + L\frac{dI}{dt} + U_{arc},$$

where $L \cdot \frac{dI}{dt}$- The EMF arising on inductance at change of current in a circuit.

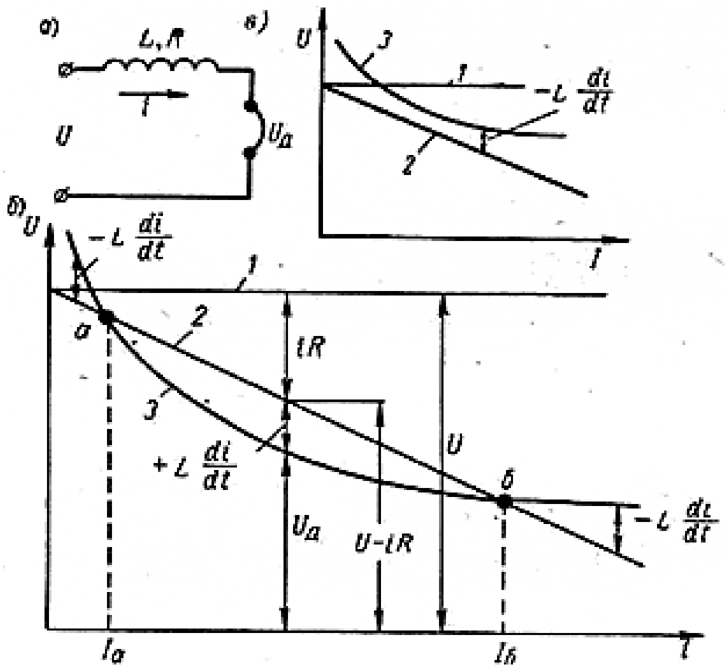


Figure 11.1 - To the condition of short-circuit suppression of an arc of direct current

At steadily burning arc when processes of ionization and deionization are in an equilibrium state:

$$\frac{dI}{dt}=0 \quad \text{and} \quad U=i\cdot R+U_{arc}.$$

If $\frac{dI}{dt}>0$, in an arc the process of ionization prevails over the process of a deionization, i.e. the amount of newly formed charged particles will be more than those disappearing in the result of recombination.

If $\frac{dI}{dt}<0$, the processes of deionization in the arc prevail, the number of charged particles decreases and the arc is suppressed.

Therefore, for clearing of an arc it is necessary that current in it should constantly decrease , i.e. $\frac{dI}{dt}<0$, and, therefore:

$$U_{arc}>U-i\cdot R. \tag{11.1}$$

Thus the inequality (11.1) must take place at all values of current. The graphic solution of the task is shown in figure 11.1b.

In this drawing the straight line 1 represents U voltage source, a straight line 2 - the rheostatic characteristic of a circuit $U-i\cdot R$, and the curve 3 - VAC of the arch. Segments between the rheostatic characteristic and VAC correspond to $L\frac{dI}{dt}$. In points «A» and «B» the condition is fulfilled: $\frac{dI}{dt}=0$, i.e. in these points the equilibrium state takes place. However, in the point «B» it is stable equilibrium, and in the point «A» – it is not.

At currents $I<I_A$, $U_{arc}>U-i\cdot R$ and on inductance there is negative voltage $L\frac{dI}{dt}<0$, testifying the increase of deionization in the arch. Under the influence of this voltage current will decrease to zero. If for any reason $I>I_{A}$, on inductance there will be positive voltage $L\frac{dI}{dt}>0$, confirming the ionization process increase, and the current will increase to value $I_Б$.

The point "B" is a point of stable equilibrium: at any changes of current under the influence of voltage on inductance the system will revert to the original state.

In electric devices all measures are taken to ensure that the arch is suppressed in the shortest period of time. Obviously, for this purpose it is necessary, that $U_{arc}>U-i\cdot R$. It is possible either at the expense of raising VAC, or at the expense of increase in resistance of the circuit. VAC can be lifted as a result of increase in length of an arch, intensity of cooling and increase of pressure of the environment in which the arch burns.

At the closed contacts the arc is absent and current in the circuit is equal to $I_{contact} = \frac{U}{R}$ (figure 11.2). At divergence of contacts there appears an arc between them with current I_2. If the length of the arc and voltage of the source are invariable, then, at increase of resistance, the current in the circuit will start decreasing, accepting values I_3, I_4. At further increase of resistance conditions for clearing of an arc are created. Current and resistance at which there come conditions for clearing of an arch, are called critical.

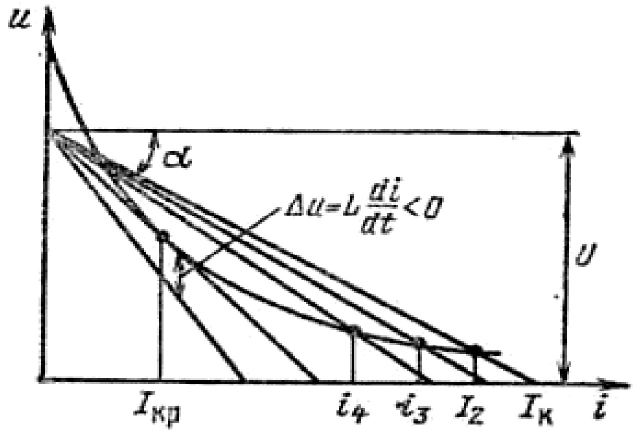


Figure 11.2 - Current in a circuit at various resistance R and existence of an arch

If at invariable current to increase voltage or at an invariable voltage to increase current, the rheostatic characteristic $U_{arc} > U - i \cdot R$ will rise up. But then for observance of conditions of clearing of an arch it is also necessary to lift the VAC of the arc. Therefore, with increase of voltage of the source and with growth of the disconnected current conditions of shutdown become harder.

11.3 Features of burning and clearing of an arc of alternating current

If for suppression of an arch of a direct current it is necessary to create conditions under which current would reduce to zero, then at alternating current, the current in the arch irrespective of extent of ionization of the arc interval passes through zero each half-cycle, i.e. each half-cycle the arch dies away and emerges again. The problem of quenching in this case consists in creating conditions under which current would not be restored after passing through zero.

For quenching of an arc of alternating current at a voltage up to 1000V the phenomena occurring at the cathode at transition of current through zero have crucial importance. At the time of transition of current through zero in near-cathode area in time about 0.1 microseconds isolation of an air interval is restored up to the size U_0= 150-250V i.e. in order that there was an arch it is necessary to put voltage above the specified sizes.

12 Lecture №12. Ways of suppression of an electric arc

Content of the lecture: ways of suppression of an electric arc. Magnetic blasting. Suppression of an arch with high pressure. Application of arc-suppression lattices on direct and alternating current.

The purpose of the lecture.

Consideration of the physical phenomena occurring when suppressing an electric arch between the dispersing contacts of the device in different ways.

The purpose of arc-suppression designs of devices consists in providing suppression of an arch:

a) for short time with admissible level of over-voltage;

b) at small wear of current-carrying parts of the device;

c) at the minimum volume of the heated gases;

d) with minimum sound and light effects.

For quenching of an arch of a direct current it is necessary that the VAC of arcs proceeded above the rheostatic straight line, i.e.:

$$U_{arc} > U - i \cdot R,$$

and as

$$U_{arc} = U_{electron} + E_{arc} \cdot l_{arc},$$

then raising of the characteristic can be achieved through:

a) increasing the length of an arch l_{arc};

b) intensity of the electric field in an arch column E_{arc};

c) using near-electrode power failure.

Raising VAC at the expense of increase in length of an arch is ineffective as it demands significant increasing the sizes of devices.

It is possible to increase intensity of electric field in an arch E_{arc}:

a) by effective cooling of an arch;

b) due to the rise in pressure of the environment in which the arch burns.

Cooling of an arch is usually carried out:

a) moving an arch in relation to the environment in which it is, using a magnetic field (magnetic blasting) for this purpose;

b) driving the arch by means of magnetic blasting in a narrow crack of an arc-suppression chamber the sides of which have high heat conductivity and arc resistance. The arch in process of retraction in a crack gets a zigzag form, due to which the length of an arch increases. Cooling of an arch is achieved in the result of close contact of an arch with colder (compared to the arch temperature) ceramic walls of the crack.

12.1 Movement of an arch under the influence of a magnetic field

Electric arch, being a peculiar conductor with current, can interact with a magnetic field. As a result the arch will be affected by force, the so-called magnetic blasting moving the arch.

Most often the magnetic field is created by the coil which is in-series connected with the switch-based circuit. The force affecting a unit of length of the arc in a magnetic field is equal to:

$$F = I \cdot H ,$$

where I – arc current;

H - intensity of the magnetic field created by the arc-suppression coil in the zone of an arch burning.

As for the in-series coil $H \equiv I$ that $F \equiv I^2$.

Thus, the force operating on an arch is proportional to the square of the current.

At small currents this force is small, therefore for obtaining force sufficient for suppression of small currents it is necessary to increase the number of coils in the winding, and, as the winding is flowed round by rated current of the device, then the section of its rounds has to correspond to this current. It leads to a big consumption of copper.

By means of magnetic blasting the arch is driven with a force into narrow cracks of the arc-suppression lattices made of refractory materials. As a result the arch is sharply cooled on lattice walls. Deionization processes quickly increase, and the arch dies away. It is applied in contactors with a heavy operating mode at the number of switches more than 600 per hour.

12.2 Arc-suppression with high pressure

Conductivity of an arc interval depends on extent of ionization of gas. At an invariable temperature extent of ionization falls with growth of pressure. It means that for carrying the same current at high pressure it is necessary to apply higher voltage.

With growth of pressure heat conductivity of gas also increases, which leads to strengthening of heat removal and cooling of an arch. Finally, with growth of pressure voltage on an arch increases.

Suppression of an arch by means of high pressure created by the arch itself in hermetically closed chambers is used in fuses and some other devices. In these devices all energy emitted in an arch is given to the gas which is in limited volume. At initial approach the ratio is fair:

$$\rho \cdot \vartheta = \frac{2}{3} \cdot W_{arc} ,$$

where W_{arc} - energy of an arch;
υ - volume;
ρ - pressure.

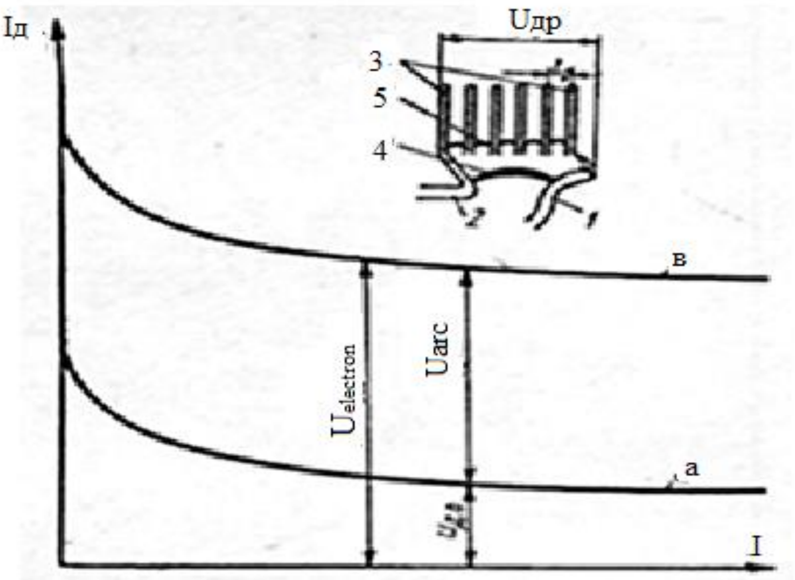
As a result, the arch may be extinguished in small thoroughly closed chambers, and the devices made absolutely safe in regard of fire.

12.3 Suppression of an arch in an arc-suppression lattice

The above considered ways of arc-suppression were related to the impact on its trunk.

The arch can be extinguished, using near-electrode power failures. For the first time this essentially new way of suppression was offered by Dolivo-Dobrovolsky.

Over the dispersing contacts 1 and 2 of the device (figure 12.1) there are installed fixed metal plates 3 isolated from each other forming an arc-suppression lattice. The arch 4 arising at shutdown is driven into this lattice where it breaks into a number of connected in- series short arcs 5.



a - open; b - in an arc-suppression lattice.
Figure 12.1 – Arc-suppression lattice and static volt-ampere characteristics of an arch

Each plate of a lattice has a near-electrode drop of voltage. Suppression of an arch happens at the expense of the sum of near-electrode falls of voltage.

Direct current

At the number of plates m the number of short arcs will be $m+1$ and as much will be near-anode U_{anode} and near-cathode $U_{cathode}$ drops of voltage. The voltage on the whole arch in a lattice will be equal:

$$U_{arc_{discharge}} = U_{electron} \cdot (m+1) + E_{arc} \cdot l_{arc},$$

where $U_{electron} = U_{anode} + U_{cathode}$ is the sum of near-electrode drops of voltage;

$l_{arc} = l_O \cdot (m+1)$ - arc length;

l_O - distance between lattice plates.

VAC of an arc in an arc-suppression lattice is expressed by the same form of the curve, as VAC of an open arch, but removed for the sum of near-electrode drops into the area of higher voltage.

To extinguish the arc, it is necessary that the number of plates of a lattice met the condition:

$$m > \frac{U_C}{U_Э},$$

where $U_{cathode}$- circuit voltage;

$U_{electron}$- near-electrode drop of voltage.

Alternating current

When suppressing an arch of alternating current in an arc-suppression lattice the main role is played by the processes at the cathode at the time when current passes through zero. At the moment of current passing through zero insulation the near-cathode area restores up to the value $U_{electron} = 150 - 250B$.

As on direct current $U_{electron} = 20 - 25B$, which is much less than on alternating current, then the required number of plates in an arc-suppression lattice on alternating current is respectively much less. The arc-suppression lattice on alternating current acts 7-8 times more effectively than on a direct current. It explains its broad application on the alternating current and limited application on the direct current.

The arc-suppression lattice allows to reduce strongly the sizes of an arch and to extinguish it in limited volume at faint lighting and sound effect. This provided its broad application in arc-suppression devices of contactors and automatic switches.

Plates of an arc-suppression lattice are made of magnetic material (steel). Attraction forces arising between an arch and ferromagnetic plates promote fast entry of an arch into space between the plates and splitting of the arch into a number of short arches connected in-series. A disadvantage of the arc-suppression lattice consists in burning-out of plates in the repeated short-term mode at current 600 A and above. For reduction of corrosion the plates are covered with copper or zinc.

13 Lecture №13. Electromagnetic mechanisms

Content of the lecture: electromagnet attraction force. Maxwell's formula. Electromagnets of alternating current. A short-circuited winding as a measure of fight against noise and vibration in devices of alternating current. Delay and acceleration of action of an electromagnet.

The purpose of the lecture.

To supply students with the main information on the electromagnets which are electromechanical converters of energy in many devices.

Electromagnetic mechanisms are applied for actuating many devices. As we noted earlier, work of an electromagnet has an effect on normal work of contacts of devices, existence or lack of vibration of contacts, possibility of a comparison welding of contacts at SC, etc. That, in turn, is provided with creation of the electromagnet attraction force, necessary for normal operation of devices.

13.1 Electromagnet traction force

In engineering calculations electromagnet traction force is usually calculated by Maxwell's formula:

$$P = \frac{B_\delta^{\ 2} \cdot s_\delta}{2 \cdot \mu_0},$$

where B_δ - magnetic induction in a working gap;

S_δ - equivalent section of an air gap;

μ_0 - magnetic permeability of air.

The formula can be used if the induction in an air gap is distributed0 evenly. It is sometimes convenient to find traction force of an electromagnet through a magnetic flux:

$$P = \frac{\Phi^{\ 2}}{2 \cdot \mu_0 \cdot s_\delta}.$$

13.2 Electromagnets of alternating current. Short-circuited winding

At sinusoidal alternating current the flux changes under the law:

$$\Phi = \Phi_m \cdot sin\omega t.$$

Traction force of an electromagnet will be in that case equal:

$$P = \frac{\Phi_m^2 \cdot sin^2 \cdot \omega t}{2 \cdot \mu_0 \cdot s_\delta} \ .$$

Let's designate

$$\frac{\Phi_m^2}{2 \cdot \mu_0 \cdot s_\delta} \cdot P_m.$$

Then

$$P = P_m \cdot \sin^2 \omega t = \frac{P_m}{2} \cdot (1 - \cos 2\omega t)\,,$$

i.e. traction force P pulses in size with a double frequency of the circuit, without changing thus the sign (figure 13.1b)

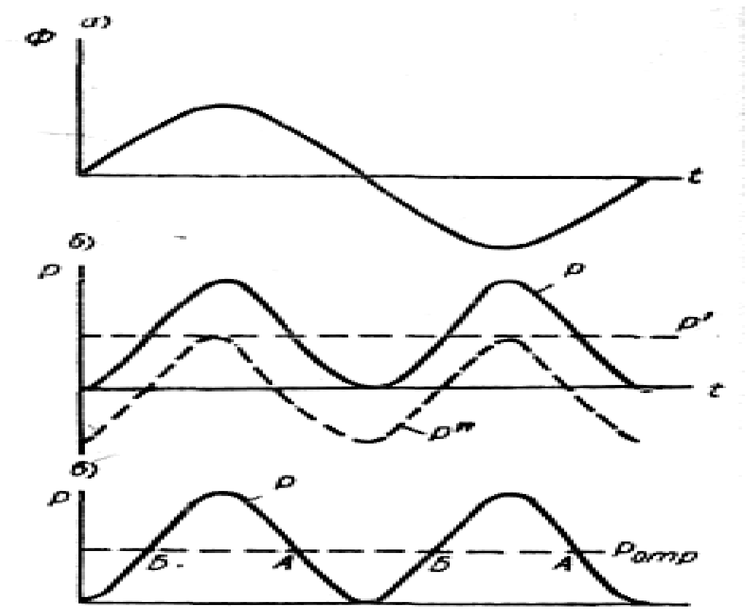


Figure 13.1 – Curve of changes of force of an attraction of an electromagnet of alternating current without short-circuited round

Traction force can be presented in the form of two components: a constant in time:

$$P_1 = \frac{P_m}{2}\,,$$

and the variable changing in time under the law of a cosine:

$$P_2 = \frac{P_m}{2} \cdot \cos 2\omega t.$$

The average for the period value of force P will be equal $P_m / 2$.

If the detachable effort of an electromagnet is $P_{reflection}$ (figure 13.1), then twice for the period in the point «A» the anchor of an electromagnet will start detaching, and in the point «B» – will again be attracted, i.e. will vibrate with a double frequency. Vibration results in wear of magnetic system and is followed by buzz.

The traction force of the electromagnet P will in this case be combined of two pulsing, but shifted on a phase, forces P_1 and P_2. Each of the forces P_1 and P_2 can be presented in the form of two components:

$$P_1 = \frac{P_{1m}}{2} - \frac{P_{1m}}{2} \cdot Cos 2\omega t \quad \text{and} \quad P_2 = \frac{P_{2m}}{2} - \frac{P_{2m}}{2} \cdot Cos 2\omega t ,$$

and full force

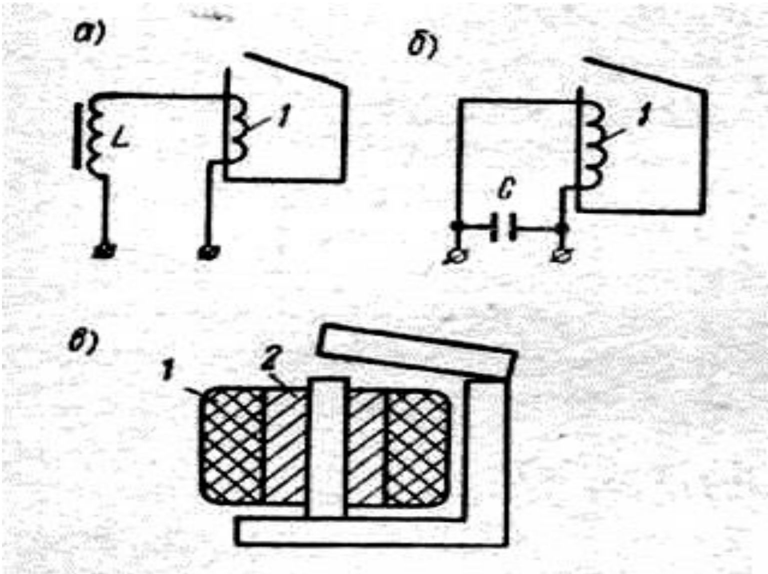
$$P = \frac{P_{1m}}{2} + \frac{P_{2m}}{2} - [\frac{P_{1m}}{2} \cdot Cos 2\omega t + \frac{P_{2m}}{2} \cdot Cos(2\omega t - 2\varphi)] .$$

Thanks to the shift of phases the resulting force P pulses much less, and the minimum value of this force remains above the detachable effort P_o, just by which the vibration of an anchor is excluded.

13.3 Delay and acceleration of action of an electromagnet

In some cases in practice it is necessary to slow down or accelerate action of an electromagnet. Delay of action of an electromagnet of a direct current can be reached (figure 13.3).

The short-circuited winding slows down increase of a flux at switching of an electromagnet. At switching of capacity increase of voltage on the coil proceeds gradually in the process of charging the condenser. Acceleration of action of an electromagnet can be reached due to reduction of a constant of time. In this case the existence of a short-circuited winding, the massive parts of a magnetic conductor, metal frameworks of the coil and any short-circuited turns formed of the fixing and other details lying on the way of a stream is inadmissible as they will increase time of action of an electromagnet. The laminated magnetic conductor also leads to acceleration of action of an electromagnet. Still greater acceleration can be received at switching of the electromagnet according to the scheme presented in figure 13.4.



a) increase in a constant of time of the coil; b) inclusion parallel to the coil capacity;
c) reaching small electric resistance by means of the short-circuited round.

Figure 13.3 – Schemes of delay of operation of an electromagnet

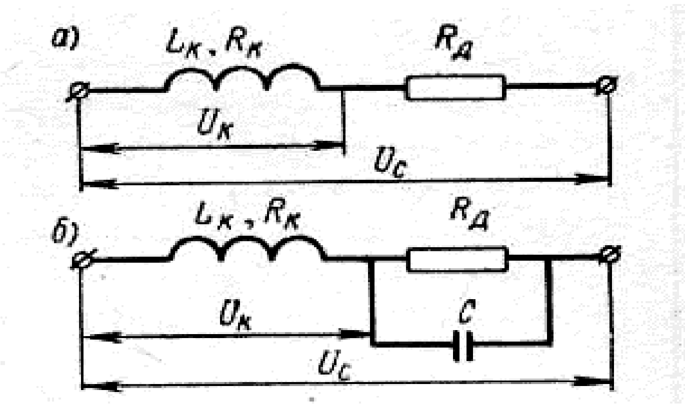


Figure 13.4 – Schemes acceleration of actuation of an electromagnet of a direct current

Literature

1 Chunikhin, A.A. Electric devices. – M.:Alliance, 2008. – 720 p.

2 Electric and electronic devices. Godgello A.G., Y.C. Rozanova. – M.: Center «Academy», 2010. - T.1. Electromechanical devices. – 352 p.

3 Electric and electronic devices. Godgello A.G., Y.C. Rozanova. – M.: Center «Academy», 2010. - T.2.Electronic devices. – 352 p.

4 Clayn R.Y.Electric and electronic devices. Уч. пособие. Part.1 «Physical phenomena in electrical devices».–Tomsk: TPU, 2000 . – 97 p.

5 Clayn R.Y. Electric and electronic devices.– Tomsk: 2009. - Part. II: Electromechanical devices.– 161 p.

6 Nabatov C.A., Afonin B.B..Tambov: TGTU, 2007.– 96 p.

7 Fadeyev V. B. the Electronic handbook at the choice of high-voltage switches. - Almaty: AIPET, 2006.

Additional training materials and aids

8 The electric phenomena in gases. An educational movie for higher education institutions.

9 High-voltage switches of Siemens company. Educational video.

10 Vacuum switches of the company Tavrida Electric. Educational video.

11 Fadeyev, V. B. The Electronic handbook on the choice of low-voltage protective devices and cables. – Almaty : AIPET, 2005.

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