Ministry of education and science of the Republic of Kazakhstan

Non-joint stock company
“Almaty University of power engineering and telecommunications”

K.K. Zhumagulov, S.B. Bukhina

DC MACHINES

Teaching guide

Almaty
AUPET
2016

UDC 621.313.2 (75.8)
Zh 62

Reviewers:
Head of electric drive and automation of technological complex department,
Candidate of technical sciences, associated professor,
Kazakh Innovation Technical University named after K.I.Satpayev
E. Khidolda,
Doctor of technical sciences, Professor of Department of “Electric drive and automation of industrial installations”, AUPET
P.I. Sagitov
Candidate of philological sciences, head of foreign languages department, AUPET
V.S. Kozlov.

Recommended to publication by Academic Council of Almaty University of power engineering and telecommunications (minutes № of 2016).

Zhumagulov K.K., Bukhina S.B.
Zh 62 DC machines: Teaching guide (for students of higher educational institutions majoring in specialty “Electric power engineering”)/K.K. Zhumagulov, S.B. Bukhina. – Almaty: AUPET, 2016. – 104 p.: 100 figures, references – 7.

ISBN

The teaching guide deals with the course "DC machines ". The principle of operation and design of DC machines are considered there. The physical phenomena occurring in DC machines in various operating modes as well as their mathematical description and the main characteristics of the machines are spoken in detail.

The teaching guide is developed for students, bachelors majoring in electric engineering. It can be used as a manual for the course "Electrical machines".

UDC 621.313.2 (75.8)

ISBN

Zhumagulov Kuanysh Kaltayevich
Bukhina Svetlana Borisovna

DC MACHINES

Teaching guide

Editor V.S. Kozlov

Signed for publication_____ 11. 2016
Edition 100 copies. Format 60x84 $_{1/16}$

Typographical paper № 2
Volume 6.44 quires

Order № ____ Price 3220 tenges

Non-Profit JSC “AUPET”
126, Baytursynov st., Almaty

Copying-duplicating bureau of
Non-Profit Joint Stock Company
“Almaty University of power engineering and telecommunications”
050013, 126, Baytursynov str., Almaty

Content

Introduction

Brief historical information about electrical machines and transformers.

Electrical engineering began to develop from the middle of the XIX century. The study of electromagnetic fields, carried out by scientists at that time, allowed to proceed to the creation of models for practical applications.

The works of French physicist A. Ampère, English physicist M. Faraday as well as Russian scientists E. Lentz, B. Jacobi and M. O. Dolivo-Dobrovolsky were of outstanding values. Their works gave a powerful impetus to the use of alternating current. By the beginning of the XX century some advantages and great possibilities to use electrical energy in the national economy became quite obvious. Such remarkable properties of electricity as ease of generation, conversion, transformation, distribution and transmission over long distances have been proved and almost realized.

For a long period of time electric generator and electric motor developed independently from each other, and only in the 70s of the XIX century they started to develop together.

DC machines underwent four stages of development:

a) magneto-electric machines with permanent magnets;

b) machines with electromagnets with independent excitation;

c) electric machines with self-excitation and elementary armatures;

d).electric machine with improved armatures and multi-pole systems.

The initial period of the development of electric machines is mainly associated with direct current. It is down on the fact that consumers of electric power were installations powered exclusively by direct current (arc lamps, electroforming installations, etc.).

The development of electric railways has significantly driven up demand for electric motors and generators. There was the need to transmit electric power over a distance in the 80s of the XVIII century. The first experiments on the transmission of electricity on direct current were carried out in 1882. However, high voltage in DC generators worsened the collector operation and often led to accidents.

A big merit in the development of alternating current belongs to Russian scientist P. N. Yablochkov who used a transformer to power invented electric candles in 1876. P. N. Yablochkov's transformer had an open core. Transformers with a closed magnetic circuit, currently used, appeared much later, in 1884. With a transformer being invented, there appeared a technical interest to alternating current, which until that time had no application.

In 1889, an outstanding Russian electrical engineer M. O. Dolivo-Dobrovolsky proposed a three-phase AC system. He created the first three-phase asynchronous motor and three-phase transformer. M.O. Dolivo-Dobrovolsky demonstrated experienced high-voltage alternating current transmission 175 km long in 1891 at the electrical exhibition (at Laufen in Frankfurt on the Main). The three-phase generator had a capacity of 230 kVA at a voltage of 95 V. With the help of three-phase transformers the voltage of the generator at Laufen was increased up to 15 kV and decreased in Frankfurt on the Main to 65 V (phase value); the three-phase asynchronous motor was powered with this very voltage value for a pumping plant of 75 kW. During further experiments, the voltage of a transmission line was increased up to 28 kV through serial connection of highest voltage windings of two transformers. The efficiency of power transmission was 77, 4% and was then considered high.

Later, oil transformers began to be used, as it was found that oil is a good insulator and a good cooling medium for power transformers. The last century is characterized by a rapid growth of industry and transport based on electrification. Transformers and electrical machines had to meet higher requirements: increased efficiency, reduction of weight and dimensions. Extensive study of electromagnetic and thermal processes occurring during the operation of transformers and electrical machines was carried out, as well as the search for new insulating materials and improving properties of electrical steel.

General information about electric machines and transformers.

An electric machine, which is based on the use of electromagnetic induction, is intended for converting mechanical energy into electrical energy, or electrical energy into mechanical energy, or electrical energy into electrical energy of another kind of current, different voltages, different frequencies.

An electric machine that converts mechanical energy into electrical one is called a generator. All electrical power is produced by AC generators (synchronous) installed at power plants. The conversion of electrical energy into mechanical energy is done by motors. Any electrical machine can be used both as a generator and as a motor. The property of electrical machinery to change the direction of converted energy is called reversibility.

If a conductor is placed in a magnetic field of permanent magnets poles or electromagnets (figure 1) N and S and replaced by force F1, electric motive force (EMF) will occur in it.

$$e = BlV \sin\alpha = Blv,$$

where

B is magnetic induction at the location of the conductor;

l – length of the conductor (its part located in a magnetic field);

V – velocity of the conductor moving in a magnetic field;

α – angle between the vectors of maximum magnetic induction and movement speed of the conductor (in the case under consideration $\alpha = \pi/2$, i.e. $\sin\alpha=1$).

The direction of EMF induced in a conductor is determined according to the right-hand rule (from the viewer behind the plane of the drawing). If the conductor is closed to any resistance of a power receiver, the resulting circuit under the action of e. m. f current I flows, whose direction coincides with the direction of EMF of the conductor. The interaction between the current conductor and the magnetic field of the poles creates electromagnetic force $F_{em} = lBI$, the direction of which is determined by the left-hand rule. This force is directed oppositely to the force F_1 and if $F_{em} = F_1$ the conductor moves at a constant speed. Thus, mechanical energy spent on moving the conductor is converted into electric energy, given to resistance of an external receiver of electrical energy, i.e. the machine will operate in generator mode.

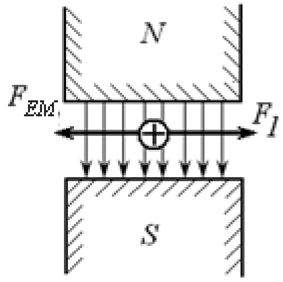


Figure 1 - Principle of operation of electric machines

If electrical current flows from an external source through a conductor the interaction between the current in the conductor and the poles of a magnetic field creates an electromagnetic force F_{em}. Under the action of this force the conductor will move in a magnetic field, overcoming a braking force of any mechanical energy receiver, i.e. the machine will work as a motor. Thus, because of the generality of the laws of electromagnetic induction and electromagnetic forces, any electric machine can operate both in generator mode and in motor mode.

Electrical machines are divided into direct current (DC) machines and alternating currents (AC) machines. A rotating magnetic field occurs in AC machines. Its rotary speed depends on the frequency of network current.

Any electrical machine consists of two main parts: a stationary part - stator and a rotating one - rotor.

AC machines can be divided into single-phase and multiphase (usually three phase) ones, as well as depending on principle of operation – synchronous and asynchronous. The process of energy conversion occurs at a synchronous speed in synchronous machines, i.e. at the frequency of rotor rotation which is equal to the rotation frequency of the magnetic field. Synchronous machines are widely used as generators; generators of this type produce all the generated electric energy. The use of synchronous motors is limited by a relatively small circle of special assignments (constant frequency, increasing $\cos \varphi$, etc.). The process of energy conversion occurs in asynchronous machines with non-synchronous (asynchronous) frequency, i.e. at the frequency of rotor rotation that is not equal to the rotation frequency of the magnetic field. Due to a number of significant advantages asynchronous machines used as engines, are the most common type of electrical machines.

In addition to synchronous and asynchronous AC machines, there are collector ones, used as AC motors and those allowing economical speed regulation in wide range. Their adjusting characteristics are close to characteristics of DC motors.

Electrical machines used to convert electrical energy into electrical energy of another kind of current (other voltages, number of phases, frequency) are called transducers. Electrical machines used as regulators and amplifiers of electrical signals are called respectively electric motor controllers and amplifiers.

Transformers are electrical machines due to common physical phenomena. They are static electromagnetic transducers of alternating current of one voltage into alternating current of another voltage. The operation principle of transformers is based on using the phenomenon of mutual induction between two (or more) windings placed in a closed steel magnetic circuit. Transformers are used to transmit electric power over long distances and distribute it among consumers, as well as in various transducers, measuring, protective and other devices.

Materials used for electrical machines and transformers.

To manufacture electrical machines and transformers one can use materials, which can be divided into active, insulating and structural ones.

Active materials. Such materials are magnetic and conductive (current), ensuring normal conditions for electromagnetic processes in electric machines and transformers. Conductor materials include primarily copper possessing low resistivity. Contact rings and collector plates are made of copper. Along with copper, aluminum is also used, and in some cases alloys of brass and bronze. Wires of round and rectangular cross sections for windings of electrical machines and transformers are made of copper and aluminum.

Electrical steel of different grades (GOST 802-58) is applied as magnetic material for cores in electric machines and transformers. The grades' letters and numbers mean the following: letter e is electrical steel; the first digit after the letter is the degree of alloyed steel (1 – low-alloyed; 2 – medium alloyed, 3 – enhanced alloyed, 4 – higher-alloyed steels). The second digit means guaranteed electromagnetic properties of steel (1 – normal, 2 – lower, 3 – low specific losses in steel at the frequency of 50 Hz; 4 – normal specific losses at the frequency of 400 Hz; 5 – normal and 6 – enhanced permeability in fields of less than 0.01 A/cm; 7 – normal; 8 – enhanced magnetic permeability in fields from 0.1 till 1 A/cm; 0 – cold rolled steel). The letter A after the number means very low specific losses. For example, «E330A steel» means enhanced alloyed steel, cold-rolled, with very low specific losses.

Losses in steel magnetic circuit consist of eddy currents losses and hysteresis (reversal magnetization). To reduce eddy currents losses magnetic circuits of transformers and electrical machines are made of separate plates isolated from each other. Insulating layers highly resisting vortex (eddy) currents limit the sphere of current activity in small areas and thereby considerably reduce losses of electrical energy. In addition, to reduce eddy currents losses magnetic circuits are composed of sheets of higher alloyed steel, which specific electrical resistance is much greater than that of conventional steel.

Hysteresis and eddy currents losses

$$R_{st} = pG_{st},$$

where p is a ratio of specific losses that depends on steel, thickness of steel sheets, frequency and maximum magnetic induction, W/kg;

G_{st} is the mass of magnetic circuit, kg.

Cold-rolled steel differs from hot-rolled one not only by fewer losses, but also by a high magnetic permeability, the value of which depends on the direction of magnetic lines. The magnetic permeability of cold rolled steel is more in the direction perpendicular to the rolling direction; the magnetic permeability is less than that of hot rolled steel. Therefore, magnetic circuits of electrical machines and transformers should be produced so that their magnetic flux enclose along the direction of rolling steel sheets or strips. The use of steel with higher magnetic permeability allows to increase magnetic induction and reduce the cross section of magnetic circuit and its mass.

Insulating materials. This is one of basic elements of electrical machines and transformers, as the reliability of their work largely depends on insulation quality. Insulation must provide reliable operation of electric machines or transformers under operating conditions with significant temperature fluctuations. Depending on thermal resistance heat insulating materials (GOST 8865-70) are divided into classes with following maximum allowable temperatures: Y class - 90°C, A class - 105°C, E class - 120°C, B class -130°C, F class - 155°C, H class - 180°C, C class - over 180°C.

Cellulose or silk fibrous insulating materials, which are not impregnated and not immersed in a dielectric fluid, are included into Y class. Organic polymeric dielectrics (polyethylene, polystyrene, etc.) with a softening temperature no less than 90 to 100°C also belong to this class. Cellulose or silk fibrous insulating materials, which are impregnated and immersed in a dielectric fluid, enamel wire insulation, based on oil or polyamide varnishes; wood and wood laminates are included into A class. Impregnating agents for materials of A class are transformer oil, oil varnishes, bituminous compositions. Molding compositions, enamel wire insulation based on polyvinyl acetale, polyester, epoxy and polyurethane resins as well as synthetic materials are included into E class. B class includes insulating materials based on inorganic dielectrics (mica, asbestos, fibrous glass) impregnated with varnishes or resins of high heat resistance, as well as plastic with an inorganic filler. Insulating materials made of inorganic dielectric and impregnated with varnishes or resins, as well as modified silicone compounds are included into F class. H class includes inorganic insulating materials impregnated with a silicone varnishes or resins. Such materials do not contain organic binding materials with thermal resistance lower than 180°C. C class includes inorganic insulating materials prepared without organic linking devices.

Windings structure of electrical machines and transformers must ensure their good cooling so that the temperature does not exceed the limits established for the respective classes of insulation. During normal operation of electric machines or transformers winding insulation must withstand prolonged influence of alternating electric fields, transient over-voltage occurring under operating conditions, as well as the mechanical effects during assembly process, operating conditions and short circuits.

Construction materials. They are used to manufacture those parts and components for electric machinery and transformers, which mainly serve for the transmission and perception of mechanical stresses. Cast iron, steel, non-ferrous metals and their alloys as well as plastics are used in electrical machines. Currently cast iron (simple, nodular) is rare used for magnetic cores, due to poor magnetic properties. As for steel (cast, forged) it is used for cores of DC machine frame, the rims of rotors of synchronous machines, etc.

Heating and cooling electrical machines and transformers.

The mode of operation of electrical machines or transformers under the conditions for which they were intended by the manufacturer is called nominal. This mode is characterized by nominal values listed on the factory plate on machines or transformers. Usually electrical machines and transformers are designed for continuous operating regime, in which they can work with established exceeding temperature of their separate parts over an ambient temperature not exceeding the permissible standards.

When operating electrical machinery and transformers have losses of converted energy. These losses consist of the following types:

a) electric losses (in windings) running for heating wires by currents flowing in windings, the resistance of transitional contacts on the commutator or slip rings;

b) hysteresis losses occurring in reversal magnetized ferromagnetic parts of machines or transformers;

c) eddy currents losses in the parts of machines and transformers in variable magnetic fields. Usually hysteresis and eddy currents losses are estimated jointly, as losses in steel depending on the steel grade, the thickness of sheets or tape, insulation quality, frequency of reversal magnetization and magnetic induction;

d) mechanical losses, running for friction in the bearings on the air (or gas), rotating machine parts, brushes on the collector or slip rings;

e) losses required for fan rotation located on the shaft of the machine.

In addition to these losses there are also additional ones, because of uneven distribution of magnetic fields and currents as well as dielectric losses at higher voltages. Losses of energy occurring during operation of electrical machines and transformers are transformed into heat, warming their separate parts. The heat needs to be dissipated into the environment so that the temperature of individual parts of electrical machines and transformers does not exceed the permissible limits.

According to the cooling method, electrical machines are divided into:

a) machines with natural cooling without special cooling devices. These machines are low power, since the heat dissipation in them is low intensive;

b) machines with self-ventilation, on the shaft of which a fan is placed, vacuuming or pumping air into the machine during rotation of the rotor and cycling it through the internal cavity of the machine.

Depending on the direction in which the cooling air moves through the rotor, there are two main systems of ventilation: radial and axial. In radial ventilation, cooling medium is moved in the radial direction from the shaft to the periphery of the rotor through the spaces between the packets of steel sheets forming the rotor core. In axial ventilation, axial channels are organized in the rotor core through which the air is passed parallel to the machine shaft.

Radial ventilation system is simple structural sense and reliable. Ventilation power losses are small and heat transfer is uniform. However, it is not compact and stable in relation to the amount of air flowing through the machine. The best results are obtained with axial ventilation in machines of small and average capacity; and it is radial ventilation that is used in the machinery of medium and high capacity.

Machines with outside cooling in which cooling air (or hydrogen) is passed through the pipes by a fan. This cooling is used for machines of large capacity.

Transformers use air and oil cooling. In dry transformers, heated surfaces of windings and magnetic core give off heat to surrounding air by convection and radiation. In oil-immersed transformers, thermal energy is transferred to the environment by special transformer oil, poured in a metal tank that contains a transformer.

Transformer oil is a good coolant medium and a good insulating material that provides high electric strength of a transformer with relatively small insulation intervals. The latter property allows creating the compact design of windings and magnetic core, and oil cooling makes it possible to apply higher electromagnetic loading of active materials (current density and magnetic induction) and to make transformers with lower weight of these materials.

By the protective method from influence of external environment, one can distinguish open, protected, splash proof, waterproof, hermetic and explosion-proof machine production. A machine is open if it has rotating and live parts having no protective devices. There are special protective devices preventing the penetration of foreign items into the machine, as well as protecting against accidental contact with live or rotating parts in a protected machine.

Splash-proof machine possesses a special protective device that protects against water drops falling at any angle up to 45° to the vertical. Waterproof machine is the one that is closed on all sides (not hermetically tight) and can withstand the test of pouring water. In a hermetic machine, tightly closed housing prevents moisture from entering the vehicle when it is immersed in water. Explosion-proof machine needs to withstand the explosion of gas inside the machine and not to transfer it to the external environment.

1 Principle of operation and design of electric machines

1.1 Operation principle of DC machines

The simplest DC generator may be a coil of conductor in the form of a frame rotating in a magnetic field between two permanent magnets N and S (figure 1.1).

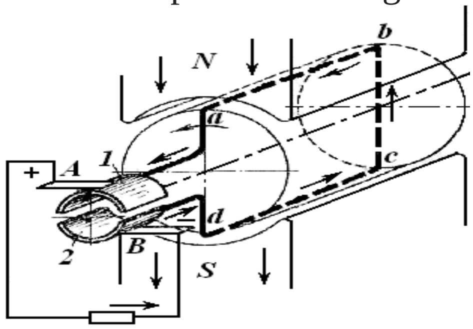


Figure 1.1 - Scheme of DC machines

The ends of the coil *abcd* are connected with two copper commutator plates, and isolated from each other and from the shaft they are placed on. There are stationary brushes *A* and *B* placed on the plates, which are attached to the external circuit consisting of some receivers of electricity. During the rotation of the coil with constant frequency conductors *ab* and *cd* intersect magnetic lines; an EMF is induced in the conductors at this time. If a magnetic field is uniform in the space of EMF of the conductor

$$e = E \sin \omega t, \tag{1.1}$$

where $\omega = 2\pi f$ – angular frequency;

f – frequency of EMF.

Thus, if a magnetic field is uniform, variable sinusoidal EMF is induced in the coil (figure 1.2, a). The direction of the induced EMF is determined by the right hand rule, i.e. when the conductor *ab* moves under the north pole, EMF is induced in it directed from the plane of the drawing. However, when it passes under the south pole, e. m. f. is directed behind the plane of the drawing. Thus, an EMF, variable in time, is induced in conductor *ab* changing its direction twice for one revolution of the coil.

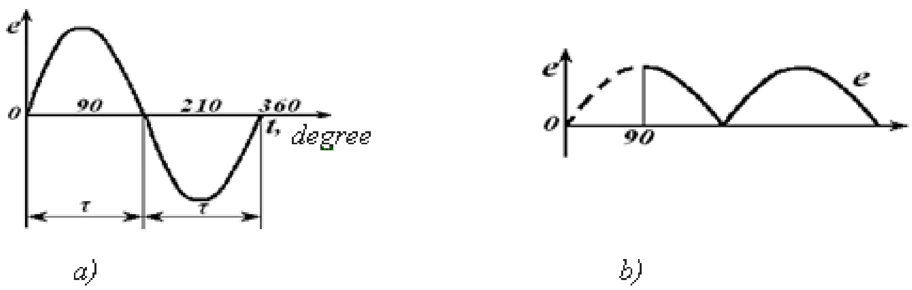


Figure 1.2 - EMF induced in the coil *(a)* and in the external circuit *(b)*

The time T for which EMF changes is called a period. The number of periods per second is called a frequency. Generally, when a machine has p pairs of poles, the frequency of induced EMF increases proportionally to p, i.e., $f = pn$, where n is the rotation frequency of the coil per second.

For normal operation of a generator, it is necessary to put brushes so that the induced EMF in the coil could be equal to zero at the moment of transition of the brush from one plate to another. Each of the brushes will be in contact only with the commutator plate and, consequently, with that of the conductors which are under the pole of a given polarity. For example, at the time, shown in figure 1.1, brush *A* gets in touch with plate *1* and has a positive potential, since it is supplied by the EMF from conductor *ab* under the north pole.

When the armature rotating on 90°, the coil will be located so that the conductors move along the magnetic field lines without crossing them. Therefore, the EMF induced in the coil is zero. The brushes connect the collector plates between them and thereby close the coil short. When the coil rotating on 180°, brush *A* is in contact with plate *2*, but still it has a positive potential, since it is supplied by the EMF from conductor *cd*, replacing conductor *ab* under the north pole. Similarly, we can see that brush *B* has always a negative potential. Thus, alternating current flows through coil *abcd*; wherein the current flows through the external circuit in one direction only, namely from positive brush *A* towards the negative brush *B*, i.e. the variable EMF induced in the coil is rectified into a pulsing EMF in the external part of the circuit (figure 1.2, b).

As seen from the figure, the curve of EMF contains a large variable component in addition to the permanent one, called EMF pulsation. To decrease it, you should increase the number of collector plates. If, for example, two coils are placed in a magnetic field the poles axes of which are shifted on 90° in space, and the ends of these windings are connected with four commutator plates, induced EMF will be shifted on phase by angle $\pi/2$ during the rotation of coils. The brushes in such a machine should be placed so that they contact with the plates of that coil, EMF of which has the greatest value at the given moment, and brushes EMF pulsation will be much less than with two commutator plates. Pulsation will decrease further with the increase of commutator plates and it will become less than 1% with 16 plates for a pair of poles.

To increase the EMF (voltage) in the brushes electric machines are produced with multiturn windings of the armature. Figure 1.4, a) shows a diagram of a two-pole DC generator, the armature winding of which consists of four coils, as well as a diagram of current flowing in the wires of the winding.

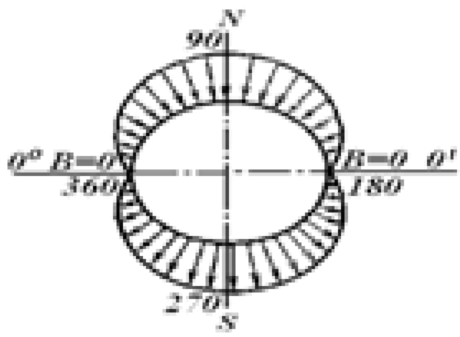


Figure 1.3 – Diagram of magnetic induction distribution under the pole

A commutator of the generator has four plates and there are two stationary brushes on them, with the help of which the armature winding is connected with the external circuit. Two total e. m. f are applied in parallel to these two brushes: one EMF of wires *7, 8, 1, 2,* the other from wires *6, 5, 4, 3,* the EMF of wires *7, 8* and wires *1, 2* being shifted on 90° with respect to each other. The EMF of wires *6, 5* and. *4, 3* are also shifted on 90°. Figure 1.4, *b)* and *c)* shows graphs of EMF changing in parallel circuits of armature windings, depending on time.

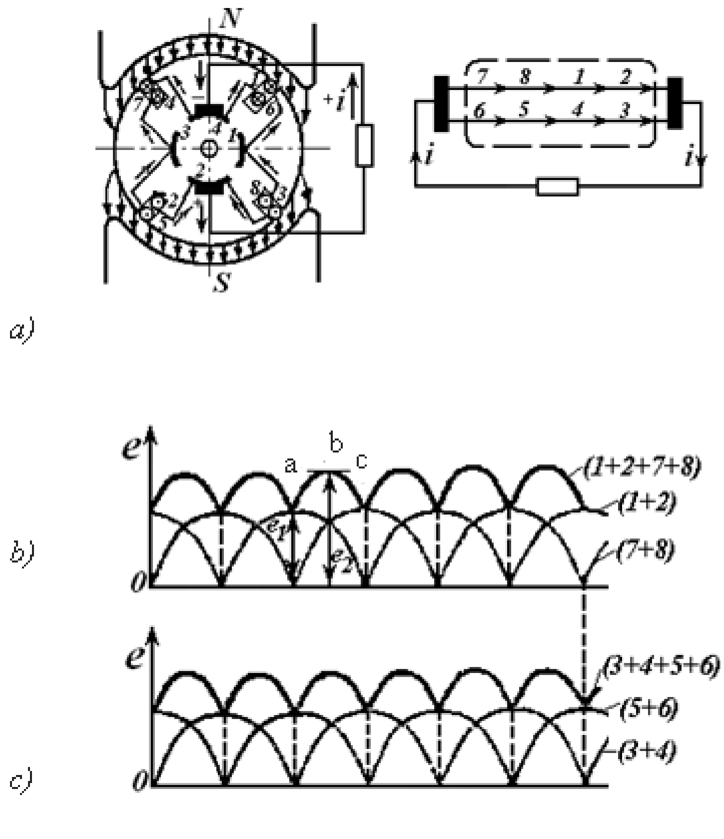


Figure 1.4 - DC generator with an armature winding and four coils

If you increase the number of collector plates and the number of wires (turns) of the armature winding, the resulting curve of the EMF becomes close to a straight line with insignificant pulsation. Thus, the commutator in DC generator acts as a converter of a variable EMF induced in the armature winding into a constant one on brushes, i.e. it carries out rectification of the EMF.

Electric machines are often produced multipolar ones. Figure 1.5 shows a diagram of a four-pole DC generator. A line perpendicular to the axis of poles and passing between the opposite poles is called geometrical neutral, and a part of the circumference of the armature corresponding to one pole – pole pressure. The simplest machine under consideration can operate as a motor if its armature winding is powered by direct current from an external power supply.

DC machines consist of a stationary part, a stator, and a rotating one - the armature, in which the process of converting mechanical energy into electrical energy (generator) or electrical energy into mechanical energy (motor).

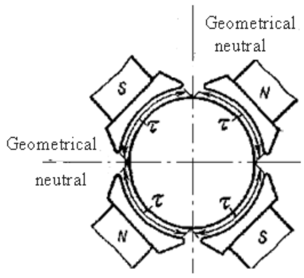


Figure 1.5 - Diagram of a four-pole generator

1.2 Design and basic elements of DC machines

There is a gap between fixed and rotating parts. The fixed part (figure 1.6) consists of a frame *3*, the main poles, designed to create the main magnetic flux, additional poles *2* that are used to achieve non-sparking operation of brushes on the collector (improved commutation). Bearing shields, main and additional poles are fixed with bolts to the frame.

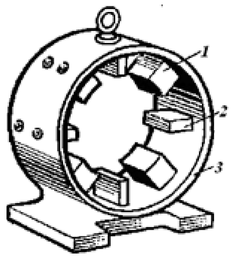


Figure 1.6 – Fixed part of DC machine

The main (general) pole (figure 1.7, a) has a core *4*, made from electrical steel sheets 0.5 – 1 mm thick, tighten with studs. Two coils of excitation windings *2* are mounted on the core. The lower part of the core, pole tip, is made so that the air gap was increased from the pole center toward its ends. This is done in order to reduce the distortion of the field under the armature reaction and scattering of the main field in switching area. The grooves for compensation winding are done in pole tips in compensated DC machines. The number of main poles is always even, the north and south poles alternating, which is achieved by appropriate connection of the winding coils of poles. The coils of all poles are connected in series. The poles are attached to the frame *1* with bolts or studs.

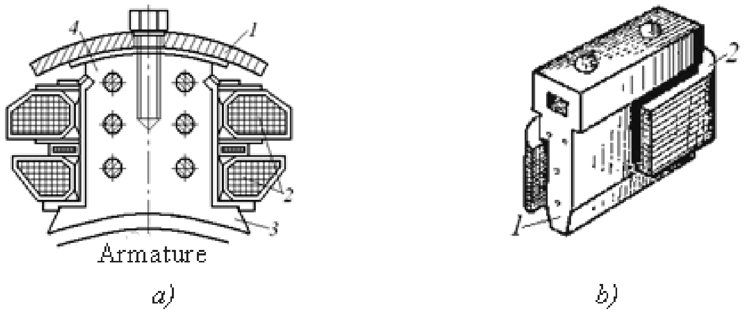


Figure 1.7 - Main *(a)* and additional *(b)* poles

An additional pole (figure 1.7, *b*) consists of a core *1* made of steel, and a winding *2*, made of copper bars with rectangular cross section. Windings of additional poles are connected in series with the armature windings, the poles being between the main ones and attached to the frame with bolts. The air gap under the additional poles is much more than under the main ones. Cross-section of additional poles is widened toward the frame. This increases the gripping surface of an additional pole to the frame, which gives great stability.

Brushes attached to the brush holder are installed to create an electrical contact with the commutator surface in DC machines. The brush holder (figure 1.8) consists of the pressure plates *1*; spring *2* transferring pressure to the brush *3*; the cage *4*.

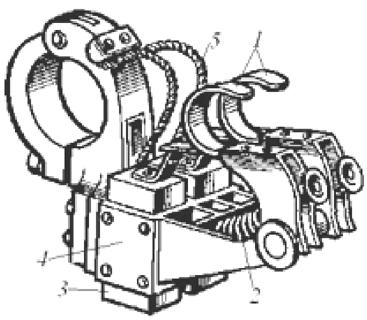
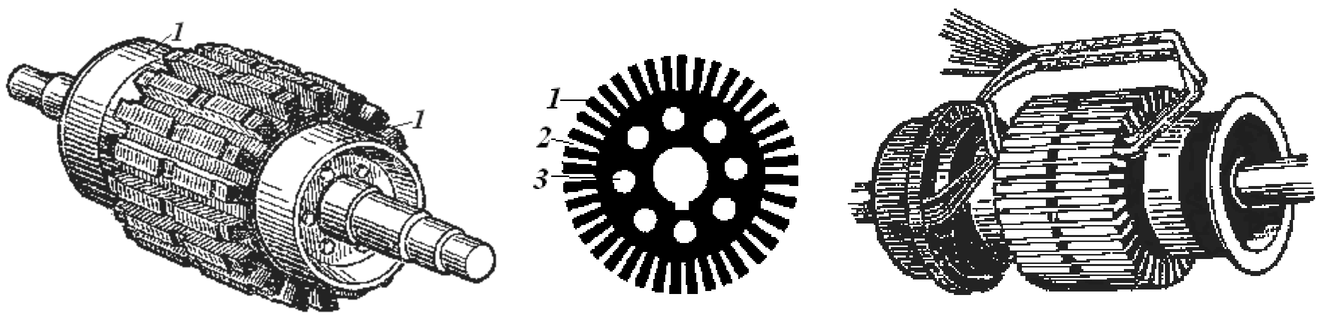


Figure 1.8 - Brush holder

To join elements of electric circuit of a machine to the brush the latter is provided with a flexible copper cable *5*. All brush holders of similar polarity are interconnected by busbars that are attached to the machine terminals. The brush holders are fixed on the traverse.

DC machine armature comprises an armature core with winding, a commutator, a fan and a shaft with a ball bearing or roller bearing.

The armature core (figure 1.9, *a*) of the machine is a package of electrical steel sheets 0.5 mm thick, which are isolated from each other with varnish to reduce losses caused by eddy currents. The package is placed on the armature shaft and is held in a compressed state with pressure washers *1*. Ventilation channels are designed in armature cores for better cooling of the machine. Each sheet of the package (figure 1.9, *b*) has teeth *1*, 2 and ventilation holes *3*. Conductors of armature winding are placed in the grooves the core (figure 1.9, *b*).



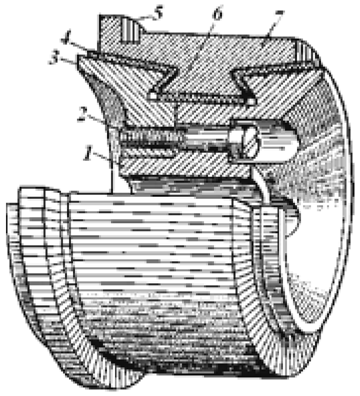
a) *b)* *c)*

a – armature without winding; *b* – steel sheet of the armature core; *c*–non wound armature of a DC machine.

Figure 1.9 - Armature core

The armature windings are attached to collector plates. Figure 1.10 shows a commutator assembled from plates *7* of hard – drawn copper, insulated from each other and from the armature shaft by micanite linings *4* and rings. The commutator consists of a housing *1*, bolts 2, pressure rings *3*, and micanite linings *4*. Commutator plates *7* are performed in the form of a "swallow tail" *6* to ensure the strength of attachment and ease of mounting. Commutator plates are connected with wires of the armature winding with the help of "necks" *5*, which are slotted for installation and sealing in them the ends of the sections of armature winding.

Figure 1.11 shows the construction of DC machines.



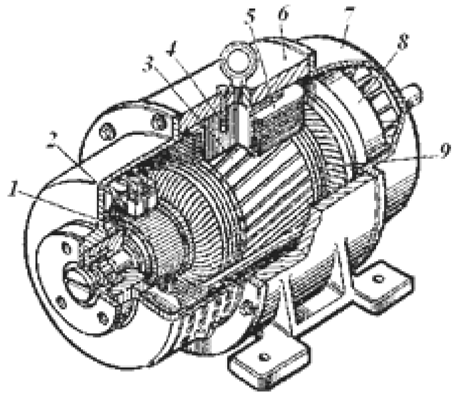


Figure 1.10 - Commutator design

Figure 1.11 – Design of DC machine

1.3 Ventilation system of electrical machines

Main poles are attached to the frame *6* with bolts. Main poles consist of the core *4* and exciting coil *5*. Frame side plates *7* are attached at flank sides of the frame by bearings holding the shaft of the machine. The armature of the machine includes the core *3*, the windings *9* and the commutator *1*. The fan *8* is fixed on the shaft of the armature; stationary brushes *2* are placed on the commutator. Depending on the method of cooling electrical machines are subdivided into the machines with natural cooling and those with self-ventilation. The machines with natural cooling have no special devices to enhance the cooling efficiency. Natural ventilation is used in machines of low capacity, since the conditions of cooling are relatively easy.

A fan (propeller) in machines with self-ventilation is used for cooling. The self-ventilation can be internal, when the air passes inside the machine, and outside when the fan is placed outside and blows the outer ribbed surface of the frame. Depending on location of the fan in relation to the cooling air flow inner-ventilation can be exhaust or pressure. Due to axial exhaust ventilation (figure 1.12, *a*) the fan *A* creates rarefaction of air: under atmospheric pressure, air enters the machine and is then released out of it. In case of axial pressure ventilation (figure 1.12, *b*) the fan *A* breathes air, pumps it in the machine, and then pushes it out.

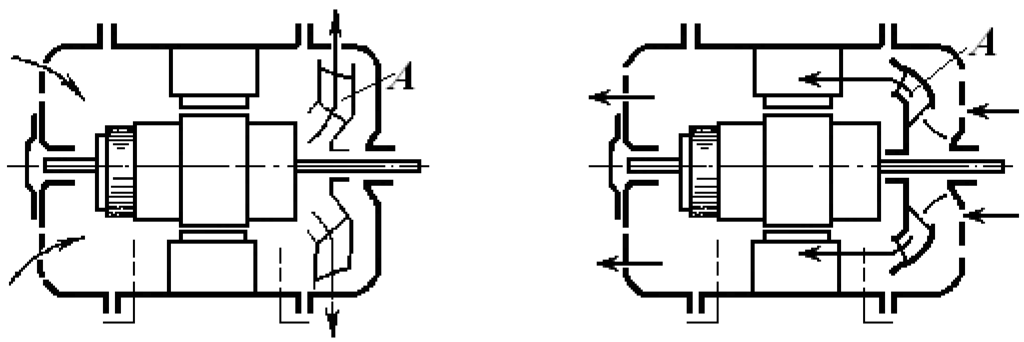
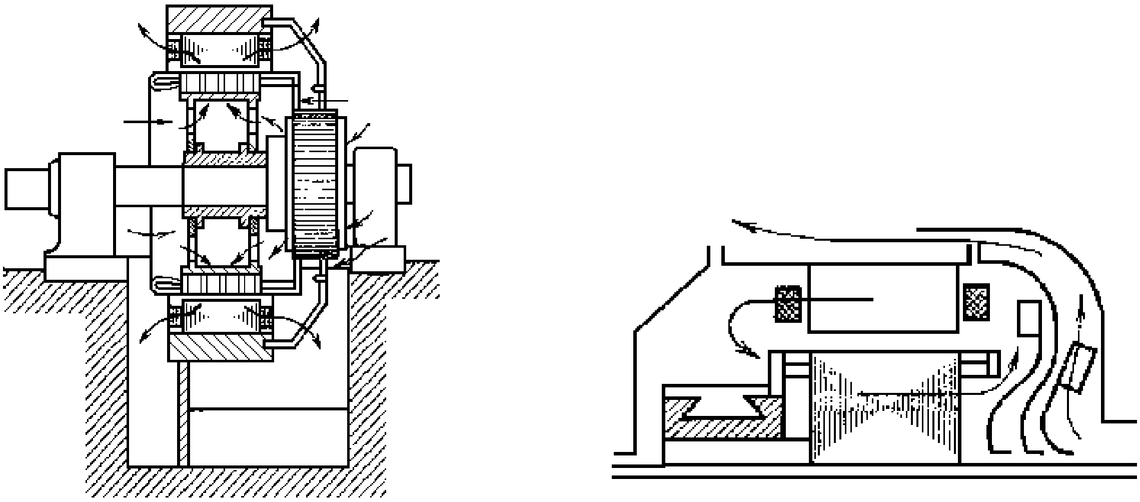


Figure 1.12 - Self-ventilation axial systems in DC machines

Due to axial ventilation cooling air passes through the inside ventilation channels in parallel to the shaft axis, but in case of radial ventilation it passes perpendicularly (figure 1.13, *a*). The disadvantage of self-ventilation is that fan performance decreases rapidly by reducing rotation speed of the machine, resulting in deteriorating the cooling intensity of the machine. Figure 1.13, *b* shows a diagram of ventilation with external airflow of the machine housing.



a) *b)*

Figure 1.13 - Machines with a radial cooling system *(a)* and a ventilation system with housing external airflow *(b)*

Machines with independent cooling. In such machines, the air comes from the fan, which operates independently from the machine. Ventilation can be closed or broaching. Due to broaching ventilation system, cold masses of air are brought from outside, pass through the machine and then are released out of it into the surrounding atmosphere. The drawback of this system is that dust and dirt, which are always in the air, can accumulate on the inner surfaces of the machine. This causes deterioration of cooling conditions of the machine. This may be the cause of troubles.

Using filters on air intake is inefficient because they often need cleaning; moreover, filters increase the resistance to air movement.

In case of a closed ventilation system (figure 1.14), the cooling air passes through a closed circuit through air coolers *AC*. Due to such a ventilation, the machine is protected from dust. Not only air but also hydrogen are allowed to be used as coolant. In case of hydrogen cooling ventilation, losses are almost ten times less, and insulation service life increases as oxidation processes are excluded. To eliminate an explosion if a detonating gas appears inside the machine, carbon dioxide is made to pre-pass through it. Then the machine is filled with hydrogen under pressure above atmospheric, to prevent air entering into the machine.

2 Armature windings of DC machines

2.1 Winding design

Armature winding is the most important element of the machine, meeting the following requirements:

a) the winding should be designed for predetermined values of voltage and load current corresponding to nominal rating power, and have the necessary electrical, mechanical and thermal strength, ensuring a long life period of service (up to 20 years);

b) winding design must ensure satisfactory conditions of current collecting from a commutator without harmful sparking;

c) material consumption for given operating parameters (efficiency, etc.) should be minimal;

g) technology of winding manufacture should be as simple as possible.

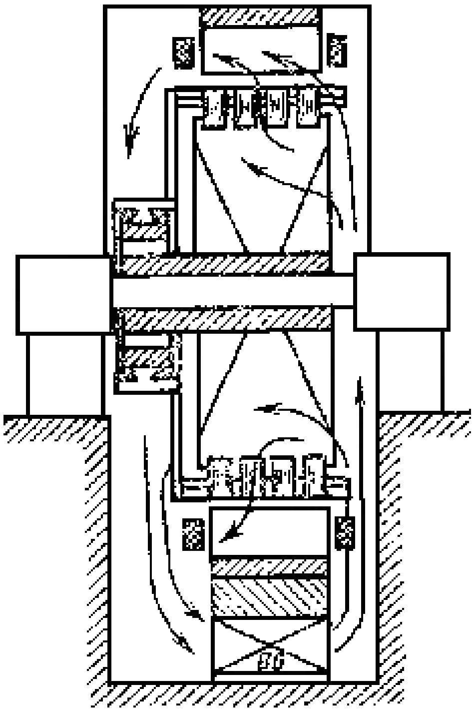


Figure 1.14 - Diagram of a closed ventilation system

In modern DC machines, armature winding is placed into grooves on the outer surface of the armature (figure 2.1), which simplifies the technology of its manufacture, increases the use of wire and makes the winding more reliable. The winding consists of several series-connected sections, each having two active sides placed in the grooves of the armature. On the frontal sides of the armature core the active sides are connected with facing wires. In order to avoid the intersection of facing connections, i.e. that they do not lie in one plane, the windings are performed double-layered (figure 2.2). Active sides are in grooves *1* between teeth *2* and from the frontal sides they are fastened with facing connections *3*. One active side of each section lies in the upper part of the groove and the other in the lower part (figure 2.3). Each active side of the section *2* is isolated and is placed in the groove *3*, which is pre-insulated. After laying all active sides, the groove is blocked with a non-magnetic wedge bar *1*. To stabilize the armature from mechanical point of view the windings are drawn tight with steel bands.

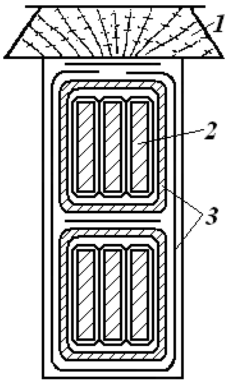


Figure 2.1 - Scheme of active sides on the armature core with winding

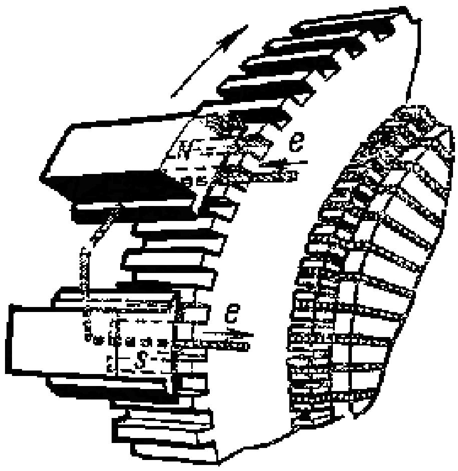


Figure 2.2 - Two-layer location of the armature winding

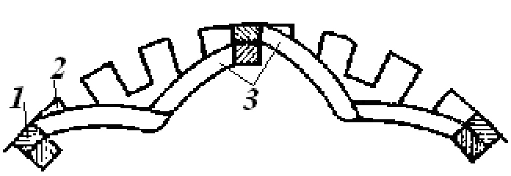


Figure 2.3 - Cross- section of the groove

Sections of DC machines windings may be of single-turn (figure 2.4 *a*), which consist of two active wires, and multiturn ones (figure 2.4 *b*).

Armature winding of DC machines are divided into loop (parallel), wave (serial) and combined ones (parallel-serial).

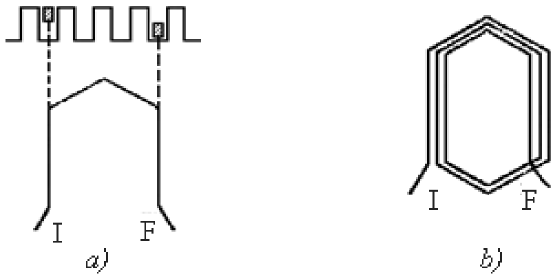
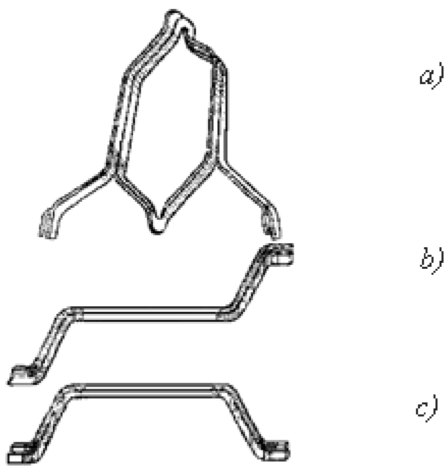


Figure 2.4 - Sections of armature windings

The windings may be simple and complex (multiple), the latter being formed of several simple windings. Figure 2.5, *a* shows a section (coil) of multiturn wave windings. Half-coil of two identical half-sections of wave winding is shown in figure 2.5 *b*, and loop winding in figure of 2.5 *c*. On deployed schemes of windings, the section sides located in the upper layer are drawn with continuous lines, and the sides located in the lower layer with dashed lines (figure 2.6).



a) Coil; *b)* Half-coil of wave winding; *c)* Half-coil of loop winding section – Figure 2.5 – Coil of multiturn wave windings

The winding sections are connected with each other in series so that the beginning of subsequent section is joined together with the end of the previous section to the common commutator plate. Because each section has two ends and each commutator plate is also attached to the ends of two sections, the total number of commutator plates K is equal to the number of winding sections S;

$$K=S=N/(2\omega),$$

where N is the number of active wires of the armature winding;
ω is the number of turns in the section.

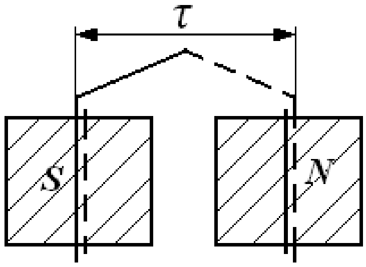


Figure 2.6 - Section image on the deployed scheme

In the simplest case, there are two sectional sides in the groove– one side is in upper layer and the other one in lower layer. The number of grooves of the armature Z=S. To reduce the pulsation of rectified voltage, and also to avoid excessive voltage between adjacent commutator plates, the number of grooves should be large enough. However, the production of armatures with a large number of grooves is impractical because in this case the grooves will be narrow, therefore, a significant portion of their area will be occupied by section isolation. There is not enough place for conductors, resulting in the loss of power. For these reasons, there are usually several ($u_n=2, 3, 4, 5$) sectional sides (figure 2.7) in each layer of a groove. $K=S=u_nZ$. In this case, we say that each real groove has u elementary grooves. That is why there is one sectional side in each layer of a groove. It is obvious that the total number of elementary grooves of the armature is $Z_E=u_nZ=S=K$. There are $Z_E/2p$ elementary grooves in one pole division τ. But often Z_E is not divided exactly by $2p$, so the fractional amount ξ is introduced with the help of which the step size is rounded to the nearest whole number

$$y \approx \tau = \frac{Z_Э}{2p} \pm \xi \quad . \tag{2.1}$$

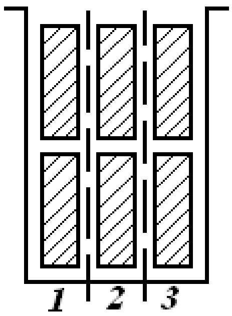


Figure 2.7 – Division of a real groove into elementary ones

2.2 Loop winding

Simple loop winding. A simple loop (parallel) armature winding is called winding, where the ends of each section are connected to two adjacent commutator plates (figure 2.8).

If winding is performed, an end section is attached to the commutator plate, located to the right of the original one, this winding is called right - hand or non - intersecting winding. When shifting to the left side the winding is called left – hand or intersecting winding. Left – hand windings do not find practical application, since they increase the consumption of winding wire. Figure 2.8 shows the steps of the winding y_1; y_2; y, which will be determined by the number of elementary grooves.

The first partial step $y_1 = Z_E/(2p) \pm \xi$ defines the distance along the surface of the armature between the initial "I" and final "F" sides of the section: ξ is a value, smaller than the one unit, subtracting or summing up which it is possible to get a step y_1, that is an integer number.

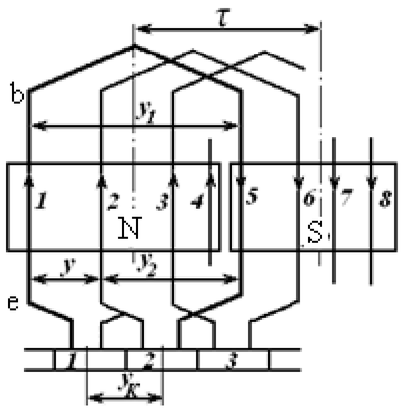


Figure 2.8 - Deployed scheme of a simple loop armature winding
H – the beginning of the wire;
K – the end of the wire;

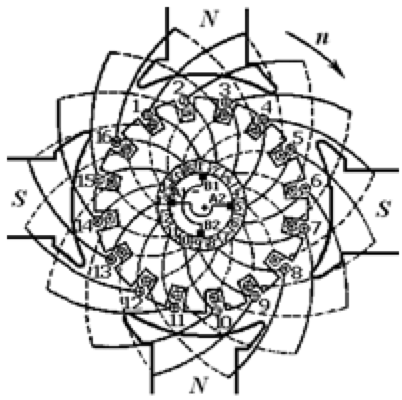


Figure 2.9 - Radial scheme of a simple loop winding
$2p=4$; $S=K=16$

The second partial winding step y_2 determines the distance between the last side of this section and the primary side of subsequent one. The resultant winding step y defines the distance between the initial sides in this section and subsequent one.The step along the commutator y_c defines the distance in commutator divisions between the commutator plate's middles, which are attached to the ends of the section. The step along the commutator is always equal to the resulting winding step: $y_c=y$. In a simple loop winding the step along the commutator $y_c=1$.

For example, in figure 2.9 one can see a radial scheme of a simple loop winding with the following data: $2p=4$; $S=K=Z_E=16$. Then $y_1=S/(2p)\pm\xi$; $y_1=16/4-0=4$; $y=y_c=1$; $y_2=y_1-y$; $y_2=4-1$; $y_2=3$. To facilitate diagrams drawing it is convenient to mark with the same numbers sectional sides, grooves and commutator plates with which they are connected. The implementation of construction begins with the connection of section sides forming sections in accordance with the first step. Thus, it is necessary to connect the upper side *1* of the section with the lower side, located at a distance of four intervals from side *1*, i.e. with the bottom side *5*. The initial part of the first section (side *1*) is connect with a commutator plate *1'*, and the end of the first section (bottom side *5*) with commutator plate *2'*, which is also connected 2 the initial part of the second section. The second section is formed by side 2 and 6, and its end is attached to plate *3'*, etc. When the armature rotates in a clockwise direction, the EMF (according to the right-hand rule) in conductors is shown in figure 2.9 with points and crosses. When the winding traverses the construction, one can see that for the considered position of the armature commutator plates *1'*, *5'*, *9'* and *13'* are nodal points, to which the sections are attached having an opposite direction of EMF. These commutator plates divide the entire winding into areas with the same direction of EMF in sections. If the brushes are placed on these plates, brushes *A1* and *A2*, from which electric current is transmitted into the external network, are considered as positive, and brushes *B1* and *B2* – as negative. The brushes of the same polarity are interconnected in parallel. For the characteristics of a winding, it is necessary to know how its sections are located in a magnetic field and how they are connected. In the winding diagram the cylindrical surface of the armature, cut along the machine axis in any place, for convenience takes place on a plane and is represented by a rectangle. Detailed winding scheme discussed above is shown in figure 2.10.

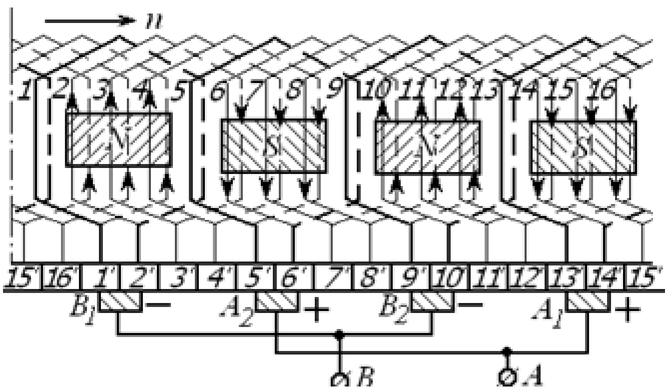


Figure 2.10 - Detailed scheme of simplex loop winding
2p=4; *S=K=16*

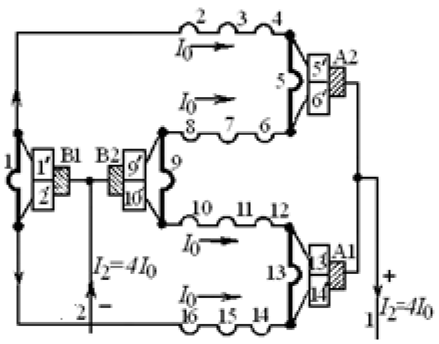
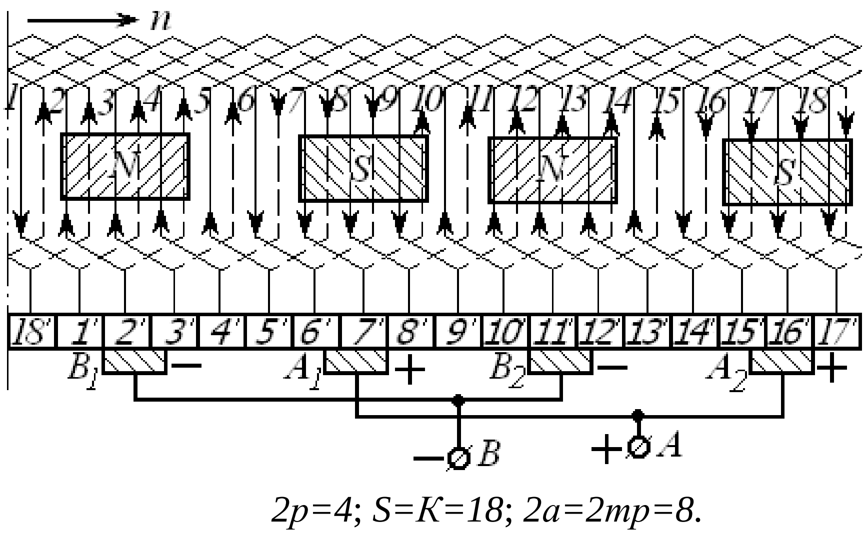


Figure 2.11 - Parallel branches of simplex loop winding

Two parallel branches of the winding go in opposite directions from each brush and end at the nearest brushes. The sections of a parallel branch are placed under a pair of adjacent poles, and due to the double layer winding there are two parallel branches for each pair of poles. Thus, the total number of parallel branches of the winding $2a=2p$. For greater clarity, considered winding parallel branches are shown in figure 2.11. In this example, four-pole machine winding forms four parallel branches, the current of one parallel branch I_0 flows in each one, and in the external circuit is $I_2=4I_0$.

Complex loop winding. Complex or multiple loop winding can be considered as a combination of several ($m=2,3,4...$) simple loop windings. Such a winding is also referred to a complex parallel one. In the winding under consideration the sections and commutator plates m of simple windings alternate circumferentially, and to divert the current from the winding it is necessary that the width of brushes is not less than m commutator divisions. Thus, m simple windings are included using the brushes in parallel and the number of parallel branches of a complex loop winding $2a=2pm$. The resulting step at the elementary grooves and the step along the commutator of a complex loop winding $y=y_c–m$. Steps y_1 and y_2 are determined in the same way as for a simple loop winding. The possibility of obtaining a large number of branches without increasing the number of poles in complex windings is the most distinctive feature of these windings. They are used in powerful machines of low-voltage with high-current armature, for example in generators for electrolysis.



$2p=4$; $S=K=18$; $2a=2mp=8$.

Figure 2.12 - Detailed diagram of a complex loop winding

For example, a detailed diagram of a complex loop winding is shown in figure 2.12 for $2p=4$; $5=k=18$; $m=2$. Here $y=y_c=m=2$; $y_1=18/4–2/4$; $y_1=4$; $y_2=y_1–y$, $y_2=4–2$; $y_2=2$. Here we note that if K/p is equal to an even number, such a complex loop winding is called symmetric, if *K/p* is equal to an odd number, - non-symmetric one. The implementation of a deployed scheme of the winding starts with the plates and sections *1*, then we go around all the odd sections and plates and return to plate *1'*, closing the first turn of the winding. Starting the second turn with the plate *2'* and sections *2*, we will go to all the even sections and plates and go back to the plate *2*, closing the second turn of the winding. Thus, we have a combination of two separate windings combined on the armature and operating in parallel. This is a complex loop double-closed winding. In our case, we have $2a=2\cdot4=8$ branches. The number of brushes is equal to the number of poles $2p$, but the width of each brush should be such that both windings could run simultaneously.

2.3 Wave winding

Simple wave winding. Simple wave (serial) winding is obtained by series connection of sections under different pairs of poles. The ends of the wave winding are connected to commutator plates, remote from each other at a distance of one step of winding along the commutator $y_к=y=(K\pm1)/p$ (figure 2.13).

To traverse the armature one should connect in series as many sections and as many pairs of poles as the machine has. Thus, traversing the winding around winding circumference, we get into the commutator plate located next (left) to the one from which the traverse started.

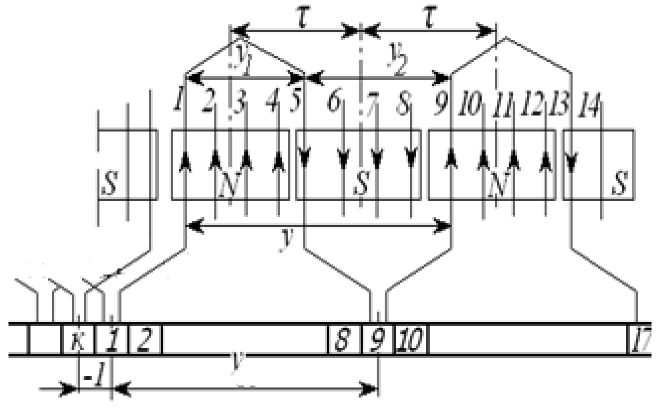


Figure 2.13 – Scheme of a simple wave armature winding

Then the second, third and subsequent traverses are done, until all wires are connected among themselves in one closed winding, the end of which is attached to the first commutator plate. Such a winding is called left-hand lead winding. If this plate is located at the right of the initial, one the winding is called right-hand lead winding. For the right-hand lead winding it is required higher consumption of winding wire**.** The feature of a simple wave winding is that the number of parallel branches does not depend on the number of poles and is always equal to two: $2a=2$. The resulting step y of wave windings is equal to the sum of partial steps y_1 and y_2, i.e. $y=y_1+y_2$. The sections of each parallel branch are evenly distributed under all the poles of the machine. In such a winding only two brushes could be used. However, in this case, winding symmetry would be broken, as the number of sections in parallel branches would be different. Therefore, one should install as many brushes, as main poles there are in the machine. This allows reducing current capacity needed for each brush. But in some cases, only two brushes are installed to make available for inspection and changing brushes not the entire circumference of the commutator, but only a part of it. In a simple wave winding, the step along the commutator must be equal to an integer number. If this requirement is not met, the number of elementary grooves is reduced by means of non-attaching one section to the commutator. This section is called a "dead" section.

A detailed diagram of wave winding with a "dead" section is shown in figure 2.14.

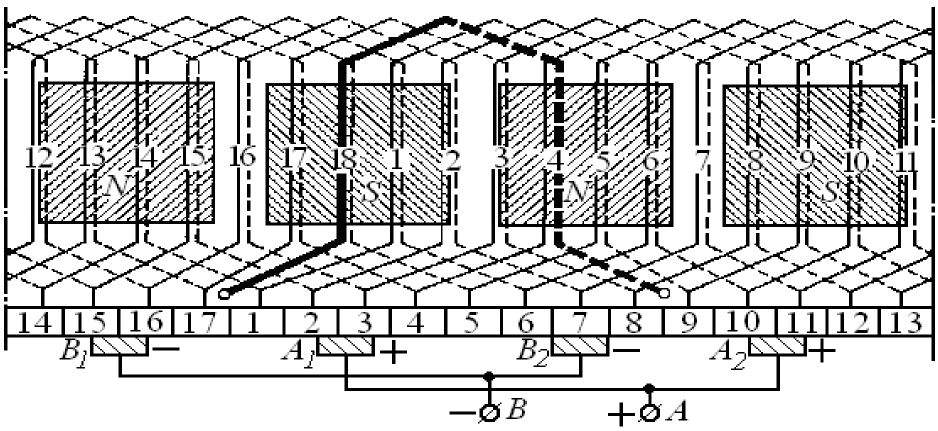


Figure 2.14 - Detailed diagram of wave winding with a "dead" section

However, the presence of winding asymmetry causes some complications in switching in the zones of a "dead" section, so it is recommended to avoid the use of wave windings with the "dead" section.in powerful machines with stressful switching conditions.

For example – The radial diagram of a simple wave winding according to $2p=4$; $S=K=15$ is shown in figure 2.15. When performing the winding we connect: commutator plate *1'*, the initial part of section *1* into groove *1*, the end is in the groove $1+3=4$ and commutator plate $1'+7'=8'$. Then we go to the initial part of section *8* in the groove *8*, to its end in the groove *11*, to the commutator plate $8'+7'=15'$, etc. The diagram of the same winding in details is shown in figure 2.16. The sections closed short by brushes are shown with bold lines.

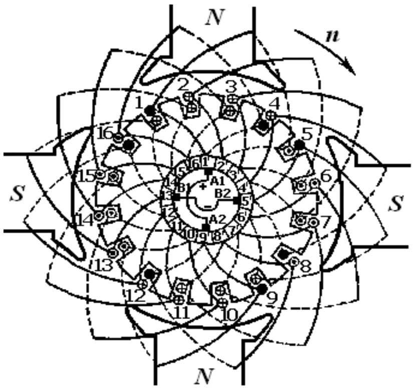


Figure 2.15 – Radial diagram of a simple wave winding $2p=4$; $S=K=15$

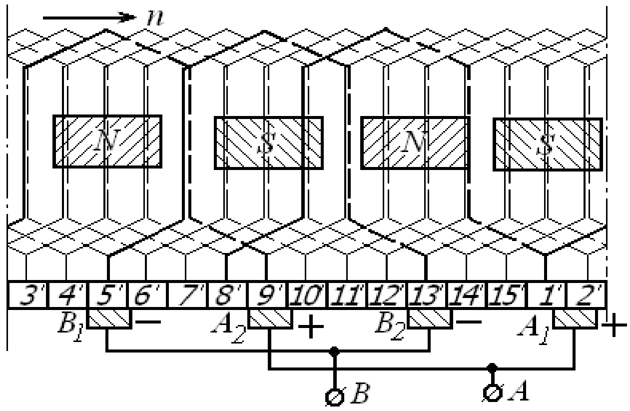


Figure 2.16 – Detailed diagram of winding $2p=4$; $S=K=15$

Thus, we have only two parallel branches, although the number of poles is $2/p=4$. The diagram of paths of current flow inside the winding or branches diagram are shown in figure 2.17. Since each of the branches of the wave winding is under all the poles, the inequality of flows of poles does not cause inequality of EMF and currents of parallel branches. Therefore, a simple wave winding does not need equalizing connections.

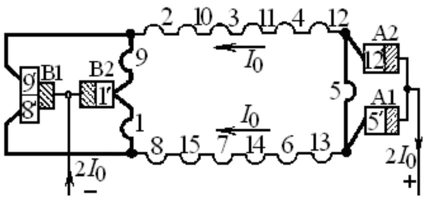
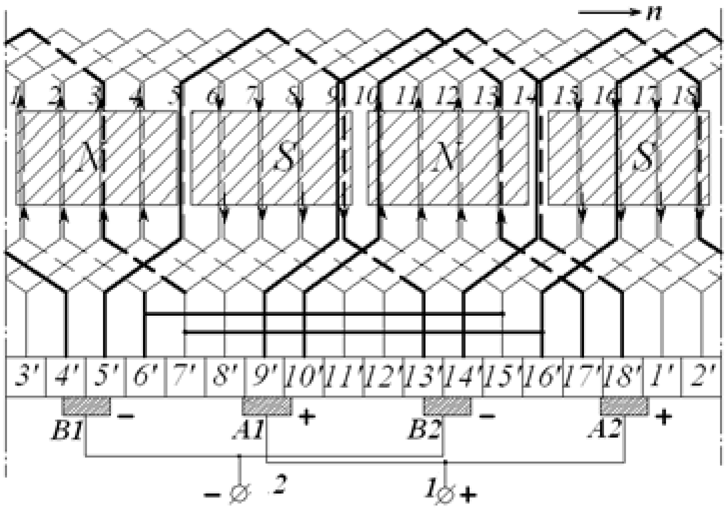


Figure 2.17 – Parallel branches of a wave winding

Complex wave winding. Complex wave winding consists of several simple wave windings laid in the grooves of the same armature. Since each simple wave winding has two parallel branches, complex wave winding will have the number of parallel branches $2a=2m$, where m is the number of simple wave windings constituting the given complex wave winding. These windings are connected between themselves in parallel by conductors – equalizing connections as well as brushes on the commutator. It is desirable that the number of plates, overlapping by the brush should be more than the number of pairs of parallel branches a. The step of winding on the commutator is $y_c=y=(K\pm m)/p$ R. When implementing complex wave windings after one traverse p of armature sections connected in series, the end of a section is attached to the commutator plate, separated from the initial one by m plates, leaving space for placing sections of other simple windings. Complex wave windings can be singly reentrant when one simple winding is a continuation of the other, as well as repeatedly closed windings when each simple winding is closed on itself.

For example, figure 2.18 shows a diagram of duplex double-reentrant wave winding of four-pole machine $S=K=Z_E=18$; $y_K=y(K\pm m)/p=8$; $y_1=K/(2p)\pm\xi=4$; $y_2=y-y_1=4$.



2p=4; Z=S=K=18.

Figure 2.18 - Diagram of a duplex double-reentrant wave winding

The winding construction begins by commutator plates *1'*. After the first traverse, during which sections *1* and *9* are connected, the end of the ninth section is attached to the commutator plate *17'*, i.e. do not reach the first plate for two commutator divisions. In further implementation, the windings are connected according to the scheme, all odd sections and commutator plates, thus, we obtain a closed simplex winding. Even sections and commutator plates form the second simplex winding. Both windings are connected in parallel with brushes and form a duplex double-reentrant wave winding.

2.4 Conditions of windings symmetry

The main requirement that the armature winding must meet is that EMF of its parallel branches at any position of the armature are equal. Otherwise, in the armature winding a current appears that occurs when the machine runs idle. This current, caused by the difference in EMF of parallel branches, is called the equalizing current. The equalizing current heats the armature windings, increases the current density under the brushes causing sparking on the commutator. In order to eliminate the possibility of equalizing current appearance and achieve the equality of parallel branches EMF of the armature winding, it is necessary to observe certain conditions when selecting the number of grooves Z and commutator plates K of the armature winding. These conditions are called conditions of symmetry of the armature winding, and they consist in the following:

a) the number of conductors in all grooves must be the same, i.e. $S=N/Z$ is equal to an integer;

b) each pair of parallel branches must have the same number of grooves, i.e., Z/a is equal to an integer;

c) each pair of parallel branches must have the same number of sections, i.e. $S/a=K/a$ is equal to an integer;

d) each side of the section belonging to one pair of parallel branches must be corresponded sections sides by other pairs of parallel branches, located in similar magnetic conditions. It is required that $2p/a$ should be equal to an integer.

2.5 Equalizering connections

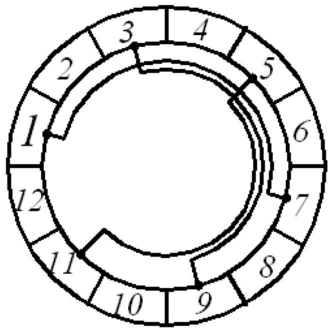
The experience of operating machinery with loop windings shows that equalizing currents occur even if there are symmetry conditions. The reason is magnetic asymmetry of machines (uneven gaps under different poles, inaccuracy of the assembly, and the presence of shells in the casting of the frame, etc.). In case of the loop winding, each pair of parallel branches is located under the pair of poles. Due to magnetic asymmetry, different e. m. f. in these will be induced there. In case of wave winding, parallel circuits cover all poles of the machine and this phenomenon is not observed. The equalizing currents summing with the load current, cause uneven loading of parallel branches, increasing electric losses, and pass from one parallel branch of the winding to the other through brushes. As a result, at normal loading the machine, the current density under the brushes is higher than normal, which causes sparking at the commutator. For currents not to be closed through the brushes, simple loop windings are provided with special equalizing compounds. In this case, points on the armature winding having theoretically equal potentials are connected electrically. So, equalizing currents are closed inside the winding without going to the brushes and connecting buses. These equalizing currents cause the magnetic flux of such direction that tends to reduce magnetic unbalance of the machine. Equalizing compounds balancing the asymmetry of the magnetic system of the machine are called first kind balancers. Typically, such balancers connect equal potential points from the commutator side (figure 2.19).

$$y_n=K/a=S/a=K/p.$$

The number of equal potential points, which we can find in the symmetrical winding, $a=p$. The distance between two adjacent equal potential points is called a potential (equalizing) step measured by the number of commutator divisions or the number of sections corresponding to one pair of branches.

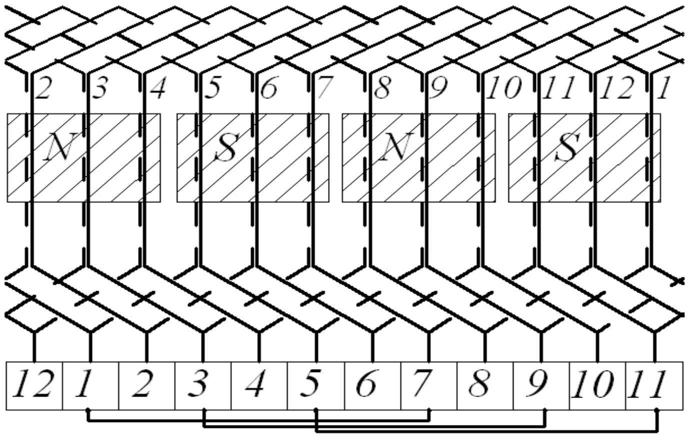
The total number of first kind equalizing connections Neq, which can be used in the winding, $Neq=K/a$. However, such number of equalizing connections are used only in heavy-duty machines, for example, in electric motors of rolling mills.

a)



a) detailed diagram of the winding

b)



b) view from the commutator side

c)

Figure 2.19 – First kind equalizing compounds

In order to save copper and simplify the design of the machine an incomplete number of balancers of copper wire with a cross section equal to ½, ¼ that of the conductor of armature winding is usually used. If simple wave windings do not require any equalizing connections, complex wave windings can work well only when you run them with equalizing connections.

Neighboring commutator plates in a complex wave winding belong to different simple wave windings that constitute it. If the transition resistance between the brushes and commutator plates belonging to different windings are not equal, the currents in separate wave windings are not also equal. The uneven current distribution will result in unequal voltage drops in the windings, whereby the voltage between adjacent commutator plates can greatly increase.

To eliminate this drawback, one should connect such simple points of wave windings with equalizing wires, which should theoretically have equal potential.

Equalizing compounds adjusting unbalance of voltage distribution on the commutator are called second kind balancers (figure 2.20).

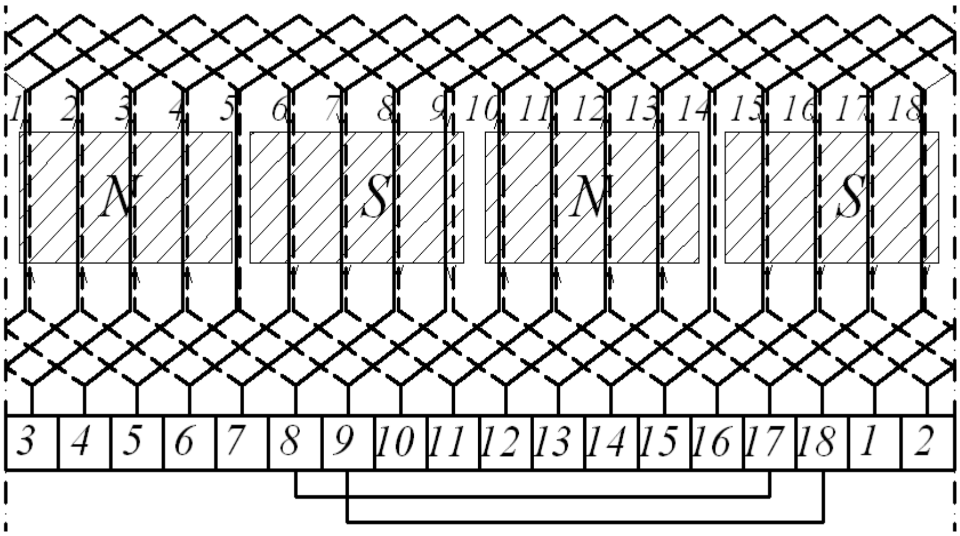


Figure 2.20 – Second kind balancers in complex wave windings

2.6 Winding of a mixed type

A mixed (frog) armature winding is sometimes used in DC machines of large capacity. This winding is a combination of a simple loop and complex wave windings located in the same grooves of the armature in four layers and connected to a common commutator. In this case, four conductors are soldered to each plate.

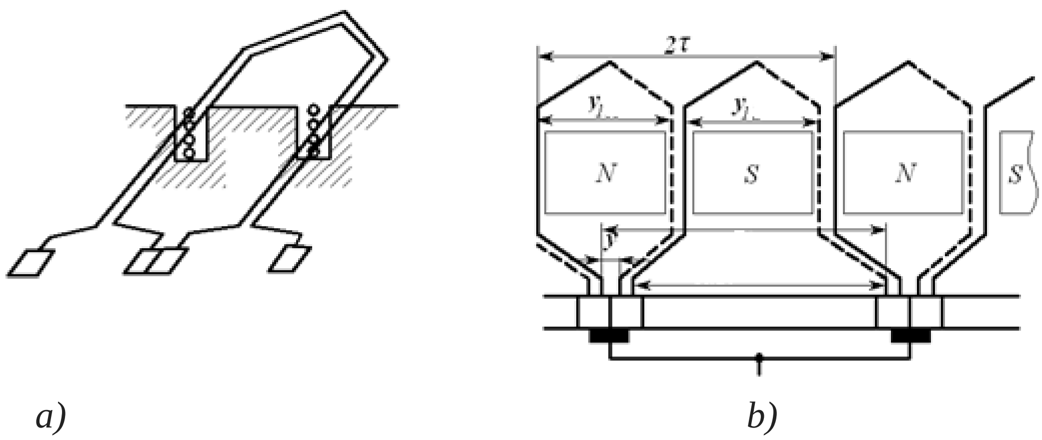


Figure 2.21 – Winding of a mixed type

Figure 2.21, *a)* shows a detailed diagram of the winding of a mixed type. The location of one section of the winding in the grooves is shown in figure 2.21, *b)*. The main advantage of this winding is that it does not require equalizing connections. It is a wave winding that performs functions of the first kind equalizing connections for the loop winding, while the loop winding performs functions of the second kind equalizing connections for the wave winding. The steps of windings on the armature consisting the mixed winding, are done similar: *y1loop=y1wave*. A step of winding is equal to the sum of steps of windings*: y1loop+y1wave = Ze/(2p)+Ze/(2p). As Zэ = K y1loop+y1wave= K/p*. A potential step to the commutator is $y_n = K/p$.

For example – Determine the step and the number of equalizing connections of simple loop winding in which *2p = 6; k =162*.

Solution. A step of equalizing connections is equal to $y_n=S/a=K/a=162/3=54$. The number of points connected by one balancer is $n_n=a=3$. Assuming that every third plate of the commutator is connected by the balancer, we find the number of commutator plates connected by equalizing connections $K_y=K/3=162/3=54$. The number of equalizing connections is $n_y=K_y/n_n=54/3=18$. The following commutator plates are connected together: 1-m by a balancer 1-55-109-1; 2-m by a balancer 4-58-112-4; 3-m by a balancer 7-61-115-7, etc.

2.7 Electromotive force of armature winding

In a symmetrical winding EMF of parallel branches are equal and there is common EMF of armature winding. The value of EMF of a parallel branch is determined on the basis of the law of electromagnetic induction.

An air gap δ between the main poles and the armature surface due to the shape of the tips of the poles is done much more on their edges (figure 2.22, *a)*, whereby a distribution curve of magnetic induction in the air gap has a trapezoidal nature, with a height equal to $B\delta$ (figure 2.22 *b*). Replacing the trapezium by a rectangle with equal area with width *b* and height H_{av}, we can assume that magnetic induction in the magnetic gap is constant. In this case, each conductor of the armature winding will cross the same number of magnetic lines per a unit of time while rotating.

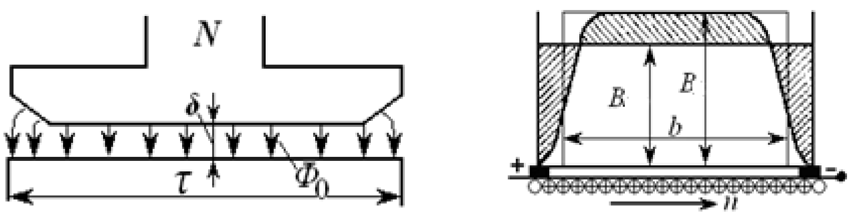


Figure 2.22 – Distribution of magnetic induction in the air gap of the machine when the armature surface is smooth

Let us assume that the armature winding consists of *N* active conductors and forms *2a* parallel branches. So, the number of conductors connected in series in each branch is equal to *N/(2a).* The sum of electromotive forces induced in these conductors will be the EMF of the armature winding of the machine. The average value of EMF induced in a single conductor, defined by the law of electromagnetic induction is

$$E_{av} = B_{av} e \upsilon \ . \tag{2.1}$$

Total electromotive force induced in all conductors of a parallel branch of the winding is

$$E_{armature} = e_{av}\ N/(2a) = B_{av} e \upsilon N/(2a). \tag{2.2}$$

Linear velocity of armature rotation is

$$\upsilon = \pi Dn/60, \tag{2.3}$$

where *n* – frequency of armature rotation;

D is the diameter of the armature.

Circumference surface of the armature equal to πD can be defined as the product of the pole division the τ by the number of poles of the machine *2p:* $\pi D = \tau 2p$, then

$$\upsilon = \frac{\tau 2pn}{60}, \qquad E_{Я} = B_{cp} l \tau \frac{2pn}{60} \cdot \frac{N}{2a}.$$

The product lτ is the plane that is permeated by the magnetic field lines (figure 2.23). The product of the plane and the magnetic induction gives a magnetic flux *f* in the air gap of the machine, which is coupled with winding turns of the armature: $f = B_{av} l \tau$. Substituting the last expression into the formula of EMF and making cuts in it, we get

$$E_{Я} = \frac{p}{60} \cdot \frac{N}{a} n \Phi . \tag{2.4}$$

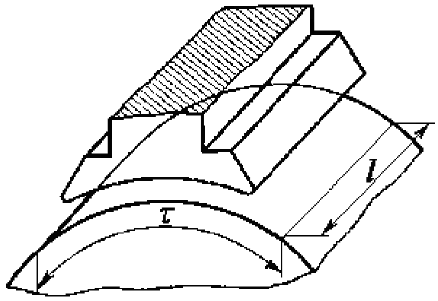


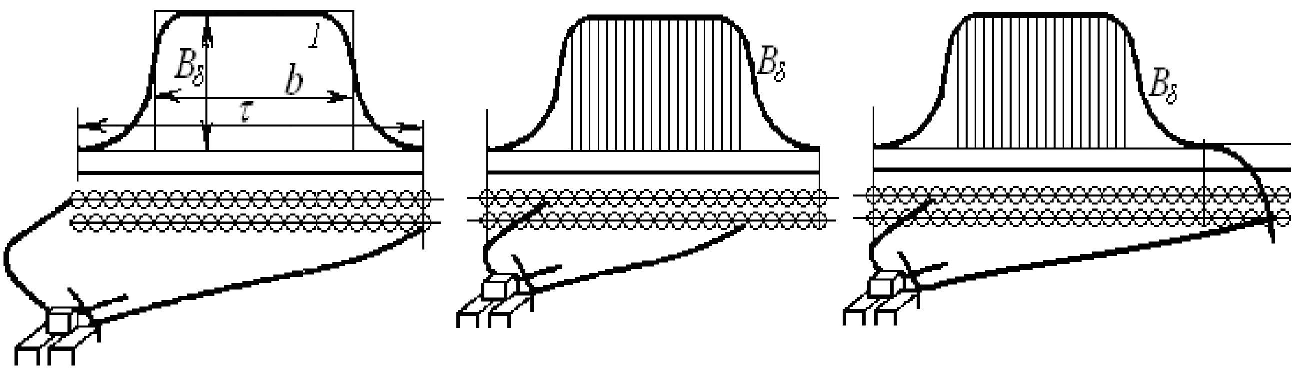
Figure 2.23 – For EMF formula derivation of armature winding

For each machine *p, N, a* are unchanged, so (2.4) can be written in the following simplified form

$$E_{armature} = k_E n f \, , \tag{2.5}$$

where $k_E = pN/(60a)$ is a constant coefficient.

Electromotive force of parallel branches depends on their position regarding the main poles, which is determined by the installation of brushes on the commutator. If the brushes are installed on commutator plates connected to nodal points (the transition through which changes the direction of EMF in the section), the EMF of parallel branches becomes the greatest one (figure 2.24 *a*). Here $y_1 = \tau$. When the brushes are shifted from this position, the sections will be included into the parallel branch with EMF of opposite direction and the total EMF of the parallel branch will be smaller (figure 2.24 *b*). If you produce the winding with the step lower than pole division $(y1<\tau)$, the section will be connected with a smaller magnetic flux (figure 2.24) and EMF of the machine will be reduced.



a) *b)* *c)*

Figure 2.24 – EMF of the armature winding

For example – Determine the EMF of a DC machine, if the number of armature conductors is *N=360*, the number of pole pairs *p=2*, the number of pairs of parallel branches of the armature winding *a=2*, the rotation frequency of the armature is *n=2000 rev/min*. The magnetic flux of the poles *F=0,01 Bδ*.

Solution. The value of EMF according to (2.4) is

$$E_{Я} = \frac{p}{60} \cdot \frac{N}{a} n\Phi = \frac{2 \cdot 360}{60 \cdot 2} 2000 \cdot 0{,}01 = 120\ B$$

2.8 Comparative characteristics of various types of windings

For the same power of DC machines, voltage reduction can be achieved by increasing current, and vice versa. This ratio is fundamental when choosing the type of armature windings. Let us suppose that machines of low power are up to *50 kW*, of average power – up to *50-500 kW*, of large power – more than *500 kW*. DC machines of low voltage are up to *24 kV*, of lower voltage – *60-80V*, normal voltage - *110-220 V*, high – *440-600 V* and higher – more than *750 V*. The loop (parallel) winding is used for higher values of current. The wave (serial) winding is applied for elevated values of voltage. If these types of the windings do not satisfy the required power, it is necessary to apply the complex loop, or complex wave winding or that of a mixed type. For machines with normal and high voltage, the wave winding is applied as there is the highest number of conductors of parallel branches connected in series in this winding. The simple loop winding is widely used in the machines of small and average power at normal voltage; the complex wave winding in machines of average and big capacity at high voltage; the complex loop winding mainly in machines of low voltage at a large current value; the mixed winding in the heavy-duty trucks. In technical and economic comparison of options of the windings one should consider the influence of the type of armature winding on the weight and size parameters of the machine. In this case, it is very significant to account the rotation frequency of the armature. It should also be noted that the choice of type of winding is greatly influenced by the average value of voltage between the commutator plates, the value of which depends on non-sparking work of the commutator.

3 Magnetic circuit of DC machines

3.1 Procedure for calculating the magnetic circuit of electric machines

Magnetomotive force of excitation winding of DC machines creates a magnetic field, the magnetic lines of which are closed through the sections of the machine, forming its magnetic system. The path of the magnetic flux is shown in the cross-section of the machine (figure 3.1). The entire magnetic flux F_n of a pole is divided into two unequal parts. A larger part of the main magnetic flux $F\delta$ penetrates through the air gap into the armature and is divided inside its core, then approaches to adjacent poles and closes through the housing.

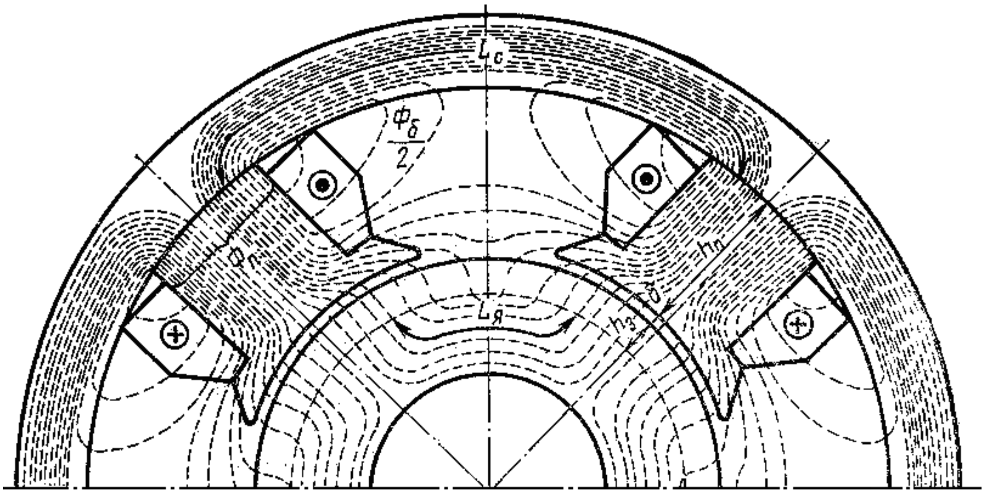


Figure 3.1 – Magnetic circuit of DC machines

The main magnetic flux of DC machines is the flux in the gap Fδ on the area corresponding to one pole division τ, when idling the machine. A smaller part of the dispersion flux Φσ is closed between the poles, bypassing the anchor. Then the magnetic flux of the pole is:

$$\Phi_{\Pi} = \Phi_{\delta} + \Phi_{\sigma} = \left(1 + \frac{\Phi_{\sigma}}{\Phi_{\delta}}\right)\Phi_{\delta} = k_{\sigma}\Phi_{\delta};$$

$$k_{\sigma} = \left(1 + \frac{\Phi_{\sigma}}{\Phi_{\delta}}\right)\Phi_{\delta} = k_{\sigma}\Phi_{\delta},$$

where dispersion factor of the main poles.

For DC machines, $k_{\sigma}=1,12 \div 1,25$. The path of the main magnetic flux in the machine consists of closed magnetic circuits, each of which covers a couple of poles. Due to magnetic symmetry, separate magnetic circuits of a multipolar machine are identical, and magnetic fluxes (as well as their components Fδ and Fσ) are equal; therefore, one can consider a magnetic circuit of one pair of poles. The segments of a magnetic circuit are different from each other due to both their geometrical dimensions and physical properties. By the law of total current for closed circuit, magnetization of one pair of poles is

$$F=I_B\omega_B=\Sigma Hl=\Sigma I, \qquad (3.2)$$

where I_B is the excitation current;

ω_B is the number of turns of excitation winding;

H – magnetic field intensity depending on magnetic induction, and determined by magnetization curves (figure 3.2);

l– the average length of a given section of the magnetic circuit.

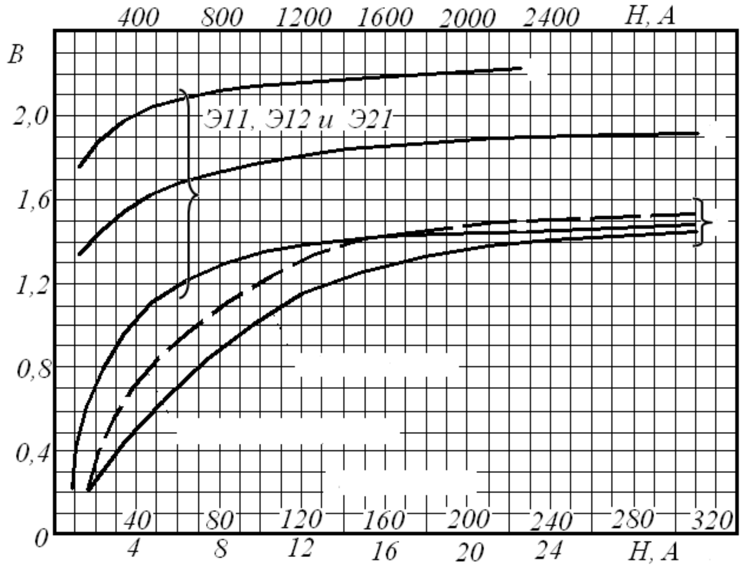


Figure 3.2 – Characteristics of magnetizing electrical and cast steel as well as rolled steel

In magnetic circuits of electrical machines, the intensity of a magnetic field changes at the boundary of different materials. On this basis, the magnetic circuit of DC machine can be divided into five sections, the characteristic values of the magnetic circuit of which are given in table 3.1.

Table 3.

Section	Section flux	Section induction	Ccross section area	Magnetic field intensity	Path length for a pair of poles	Magnetomotive force of a pair of poles
gap	F_0	B_δ	S_δ	H_δ	2δ	F_δ
Teeth layer (teeth)	F_0	B_t	S_t	H_t	$2h_t$	F_t
Armature core	$F_{ar}=0,5F_0$	B_{ar}	S_{ar}	H_{ar}	L_{ar}	F_{ar}
Core of a pole terminal	$F_p=k_\sigma F_0$	B_p	$S_П$	H_p	$2h_p$	F_p

Housing (frame)	F_h=0,5F_p	B_h	S_h	H_h	L_h	F_h

Here F_δ is for double gap; F_t – for double teeth zone of the armature; $F_{armature}$ for the armature core; F_p – two poles; F_h –heelpiece (frame).

Designed for a pair of poles magnetomotive force of the machine is equal to:

$$F_0=F_\delta+F_t+F_{ar}+F_p+F_h. \quad (3.3)$$

This equation shows that to determine the magnetomotive force it is necessary to find corresponding magnetic field intensity H for each of the five sites and multiply it by the length of the flow path in this area. The size of magnetic circuit sections are either known (in a designed machine), or installed over suggested magnetic inductions (while designing machine). Therefore, the induction can be defined for the required magnetic flux in all sections of the magnetic circuit by the formula: $B=F/S$, where F is the magnetic flux in the section; S –cross section area. In accordance with figure 3.1, the magnetomotive force of the machine is:

$$F_0=H_\delta 2\delta+H_t 2h_t+H_{ar}L_{ar}+H_p 2h_p+H_h L_h, \quad (3.3)$$

where δ is the length of the air gap, m

h_t– the height of the armature teeth, m;

h_p– the height of the main poles, m;

$L_{armature}$ – the length of the section along the armature core, m;

L_h – the length of the area along the frame (housing), m;

H – magnetic field intensity of a circuit section, A/m.

Let us assume that the nominal value of the main flux corresponds to the nominal voltage and frequency of the machine rotation: $F_0=1$. If we have the values of the main flow: $0,5F_0$; $0,8F_0$; $1F_0$; $1,2F_0$, we can calculate F_0 for each of them.

Magnetomotive force of the air gap. The air gap has the greatest resistance to the magnetic flux. In a gear armature is the magnetic field in the gap is distributed unevenly: the density of the magnetic lines at the surface of the teeth is more and it is less in the grooves (figure 3.3), since the magnetic resistance is less at the area with a tooth than with a groove. Figure 3.4 shows the distribution of magnetic induction in the air gap in the transverse and longitudinal sections of the machine. Because the magnetic induction in the gap varies both on armature circumference and along its length, so we can speak here about calculated induction in the gap using the method of reduction. The essence of this method consists in the following. The complex curve of magnetic induction distribution in the gap is replaced by an identically equal rectangle with height H_δ. The basis of such a rectangle in the first case gives the estimated pole arc b', and in the second case, the calculated length of the armature l'. The ratio $b/\tau=\alpha'$ is called the estimated coefficient of pole overlapping, the value of which depends on the maximum value of voltage between the commutator plates. In DC machines with additional poles $\alpha'=0,62–0,72$ the estimated length of the armature $l''=(l_П+l')/2$ is determined with sufficient accuracy, where l_p is the length of the pole on the axis of the machine; l' is the length of the armature without ducts. If b_h is the width of a ventilation duct, and n_h is the number of channels, $l=l_{ar}–n_hb_h$, where l_p – length of the armature in the axial direction. Using the estimated values H_δ, b', l', we define the main magnetic flux of the machine $F_0=H_\delta b'l'=H_\delta\ \alpha'\tau l'$, where $H_\delta=F_0/(\alpha'\tau l')$. To simplify the calculation, the tooth armature is replaced by a smooth one by increasing the effective quantity of the air gap δ to the calculated one $\delta'=\delta k_\delta$, where $k_\delta=(t_1+10\delta)/(b_{t1}–10\delta)$ –the coefficient of the air gap $t_1=\pi D_{ar}/z$ –tooth step; b_{t1}– width of the top of a tooth around the circumference of the armature; $D_{armature}$ is the diameter of the armature.

Therefore the necessary magnetizing force to conduct a magnetic flux through the gap is:

$$F_\delta=2H_\delta\delta'/\mu_0=2H_\delta\delta k_\delta/\mu_0. \tag{3.5}$$

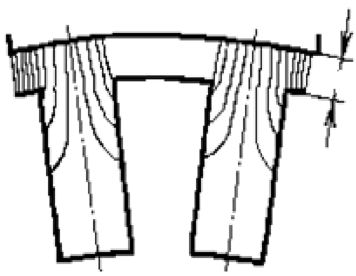
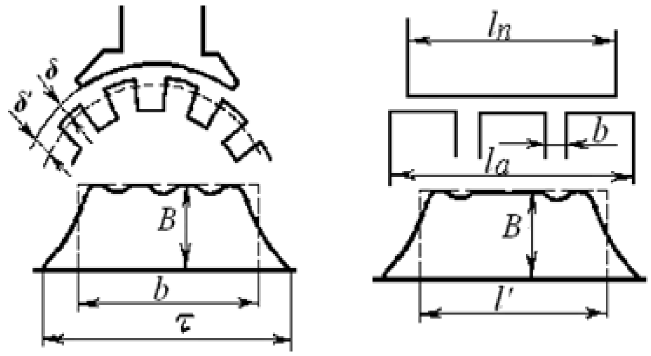


Figure 3.3 – Magnetic induction in the gap of toothed armature



a – on a pole division;
b –along the length of the pole.

Figure 3.4 – Distribution of magnetic induction under the pole

Magnetomotive force of teeth layer. When determining the magnetic induction in the teeth of the armature on can consider two cases: first, when $H_t<1,8$ *Тл* and when $H_t>1,8$ *Тл*. Let us accept that in the first case, the entire flow passes through the teeth, the second portion of the flow passes through the grooves.

The second case is more common. The calculation of magnetomotive force in this case will be done for one tooth step. The magnetic flux per one tooth step is: $F_t=B_\delta t_1l'=F_3+F_{gr}$, where F_t, F_{gr} fluxes in a tooth and a groove, respectively. The calculated magnetic induction is:

$$B_t'=B_t+B_pk_t, \tag{3.6}$$

where $B_t=F_t/S_t$ –a valid induction in a tooth;
$B_{gr}=F_{gr}/S_{gr}$ – groove induction;

c_t –tooth coefficient defined by geometric dimensions of the tooth and groove.

Using (3.6) and a drawing of the tooth and groove of the armature, we will find the value of magnetic induction in the upper, middle and lower sections of the tooth (figure 3.5). Depending on these values of the induction curves of teeth magnetization $B_t=f(H_t)$ (figure 3.2), we can determine the teeth magnetic field intensity of upper, middle and lower sections. For teeth the calculated value of magnetic field intensity is: $H_t=(H_{t1}+4H_{t.ф}+H_{t2})/6$, the value of magnetomotive force is $F_3=H_t2h_t$.

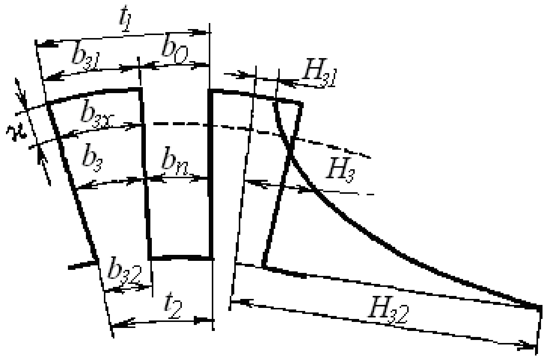


Figure 3.5 – Magnetomotive force of teeth

Magnetization of armature core, pole and basis. The magnetic flux in the armature core is $F_{ar}=0{,}5F_0=B_{ar}S_{ar}$. The cross-sectional area of the armature - $S_{ar}=h_{ar}lk_C$ where $S_{ar}=h_{ar}lk_C$ is the height of the armature core, $k_C=0{,}88\div0{,}93$ is a fill factor of steel. For the armature core magnetic induction is $B_{ar}=F_0/(2h_{ar}lk_C)$. According to magnetization curve for the steel brand under consideration we can find the field strength of the armature $H_{armature}$, and then the magnetomotive force of armature core is $F_{ar}=H_{ar}L_{ar}$, where L_{ar} is the length of an average magnetic line in the armature core. In the pole core magnetic induction is $B_p=F_p/S_p=F_0k_\sigma/S_p$, where F_p is the flux of the pole; S_p is the cross section of the pole. According to the magnetization curve of pole steel we find the field intensity of the H_p and then the magnetomotive force of the pole is $F_p=H_pL_p=H_p2h_p$, where h_p is height of pole core. The magnetic flux is $F_h=0{,}5F_p=0{,}5F_0k_\sigma$, and induction is equal to $B_h=F_h/S_h=F_0k_\sigma/(2S_h)$ in the housing. Cross section S_C is determined by geometric dimensions of the housing. According to the characteristic of magnetization for the material of the housing we find the field intensity H_C, then the magnetomotive force is $F_h=H_hL_h$,

$$L_C=\frac{\pi}{2p}\left(D+2\delta+2h_П+h_C\right),$$

where   is the length of average magnetic line in the housing.

3.2 Characteristics of machine magnetization

The dependence $F_0=f(F_0)$ drawn in rectangular coordinates, is called the magnetization curve of the machine or magnetic characteristics (figure 3.6). In the initial part, the magnetic feature has a straightforward character, since due to small values of flow F_δ the steel of the machine is weakly saturated and the magnetization is used to conduct a flow through the gap. The continuation of the straight part of the curve allows to use the magnetomotive force for the gap at various values of the flow F_δ (line *0b*), i.e. to get the dependence $F_\delta=f(F_\delta)$. With increasing magnetic flux, the great part of magnetization is required for conducting a flow through the steel sections. This part of the magnetomotive force corresponds to the segment *bc*. By the ratio $k_H=ac/ab$, called the load factor, it is possible to judge the degree of loading of the magnetic circuit when the value of flow F_δ is given. To perform a machine with loaded magnetic circuit is disadvantageous, as this material will be underutilized and the machine will get heavy.

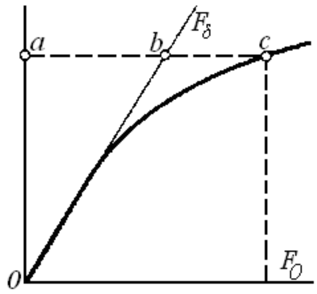


Figure 3.6 – Characteristic of magnetization

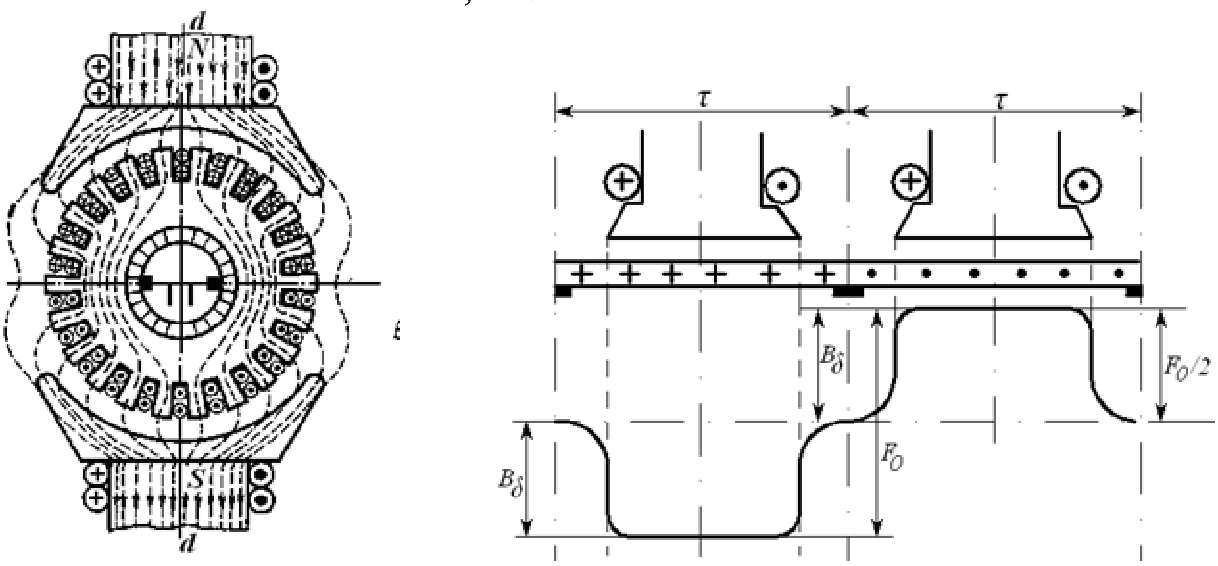
An extremely charged magnetic circuit is also inappropriate, as in this case, you need to make a powerful excitation coil with high consumption of copper or aluminum and with large power losses for excitation. For these reasons, electric machines are made with moderate loading in the nominal mode. The working point is somewhat above the bend of the magnetic characteristic. Typically $k_H=1,1\div1,35$ and in some cases $k_H\approx1,7\div2$.

4 Reaction of DC machine armature

4.1 Concept of armature reaction

When the machine is in idle mode, i.e. there is no current in armature windings, the only source of the magnetic field in the machine is the magnetomotive force of excitation winding creating the main flow *F*. At the load in addition to the main magnetic flux, there are magnetic fields of armature windings when the current occurs in the circuit of the armature, which consists of several windings (armature, additional poles, serial excitation and compensation). Therefore, the magnetic flux in the air gap and the spatial distribution of the magnetic field under load will be determined by the joint action of the magnetomotive force of poles and armature circuit. Thus, the magnetic flux that exists in the machine when running under load should be considered as the net flux created by the resulting magnetomotive force. The effect of armature magnetomotive force on the magnetomotive force of main poles is called armature reaction. When analyzing this phenomenon, we will use the superposition method to create a separate distribution of the main field of poles and that of the armature, and then combine them in a resulting magnetic field of the machine. This method gives correct results in that case, when overlapping, the parameters of the machine do not change. One of such parameters is the degree of loading of the magnetic circuit of the machine, which we assume as a constant value. To derive the expression of magnetomotive force of the armature the concept of a linear load is introduced. For this purpose, a tooth armature is considered as smooth one with a calculated air gap and a layer of conductors evenly distributed around the circumference of the armature.

Linear load of the armature is called the number of wires per 1 cm of the circumference of the armature, $A=NI_{ar}(\pi D)$, where N is the number of all conductors of the winding; I_{ar} – current in the conductor of the armature winding, and D is the diameter of the armature, cm.



a) *b)*

Figure 4.1 – Main magnetic flux of the machine in idle mode (*a*)
and a curve of distribution of magnetomotive force and induction under the main poles (*b*)

The distribution of the main flow in a double-pole machine in idle mode shown in figure 4.1, *a*, has the symmetrical character both regarding the centerline *dd* of the main poles and the geometric neutral, which occupies a fixed position in space. The distribution of magnetic induction in the gap under the pole is a trapezoidal curve (figure 4.1, *b*). Due to the rotation of the armature in a clockwise direction, electric motive forces are induced in the winding in the directions shown in figure 4.1, *a* by crosses and dots, but there is no current in the armature winding, as the circuit is open.

Figure 4.2, *a* shows the distribution of the magnetic field of the armature. The machine is not excited and the armature is fixed: $I_B=0$ and $n=0$. Brushes are installed on the line of geometric neutral; the current is conducted to them from some external source of DC current in such direction that the direction of currents in the branches of winding coincides with the direction of the EMF shown in figure 4.1, *a*. In this case, the magnetic field lines of the armature, the direction of which we determine according to the corkscrew rule go out of the armature at the left and enter at the right.

Since magnetic lines leave the north pole and enter the south one, the left side of the armature has a north polarity and the right side has a south polarity. Such a field is called the armature transverse field and is determined by a transverse magnetomotive force of the armature F_{arq}. As seen in figure 4.2 *b*, the armature is an electromagnet, the axis of which coincides with the line of brushes. Armature magnetomotive force along the line of geometric neutral has a maximum value as the respective magnetic line covers the largest current (curve 1), but magnetic induction from the flux of the armature at these points has a small value (curve 2) due to the higher magnetic resistance to the flow of the armature in the interpolar space. The graph of armature magnetic field induction has a saddle-shaped form; the induction is equal to zero under the middle of the poles and reaches the highest value under the edges of the pole terminals.

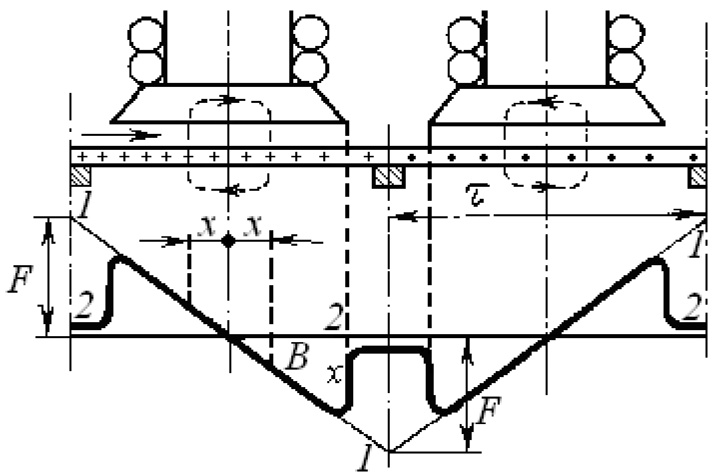
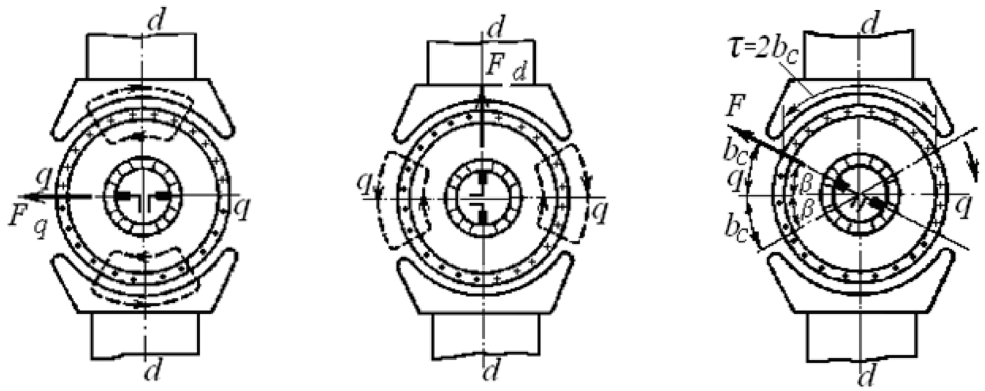


Figure 4.2 - field of the armature (a) and the curve of magnetomotive force of induction of the armature field (*b*)

4.2 Transverse and longitudinal magnetizing forces of the armature

If brushes are on the geometrical neutral line *qq* (figure 4.3 *a*), the armature field is directed at an angle of 90°, i.e. crosswise of the centerline of main poles *dd*. Such an armature field is called transverse and determined by a transverse magnetomotive force of the armature F_{arq}. The position of the brushes along the geometrical neutral line is their first major position.



a) *b)* *c)*

Figure 4.3 –Direction of armature magnetomotive force

With the shift of the brushes from the neutral to angle ±90°, the axis of the armature field is established along the axis of the poles *dd* up or down from the x-axis (figure 4.3 *b*). Such a field of the armature is called longitudinal and determined by the longitudinal magnetomotive force of the armature F_{ard}. The position of the brushes along the centerline of poles is the second main position. In the common case, the brushes can be shifted from the neutral to angle β or, respectively, around the circumference of the armature on the arc *bc* (figure 4.3 *b*). In these conditions, it is possible to consider the armature as two combined electromagnets. One of the electromagnet formed by a part of the winding and located in the double angle 2β, creates a longitudinal magnetomotive force of the armature $F_{ard}=2Ab_C$, and the other formed by the rest of the winding along the arc $\tau–2bC$, creates a transverse magnetomotive force of the armature $F_{arq}=A(\tau–2b_C)$.

There will be a resultant magnetic field when running the machine (figure 4.4). This pole is not symmetrical relative to the axis of the poles. The cause of magnetic field deformation is that the direction of transverse magnetic field lines of the armature and the field of poles under the trailing edge of the pole coincide, causing a resultant field under the trailing edge of the pole increases.

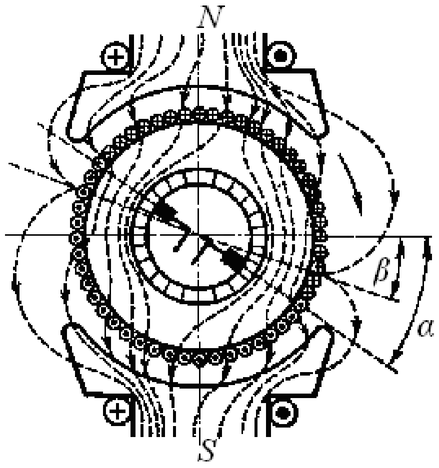


Figure 4.4. – Resulting magnetic field of the machine

However, under the leading edge of the pole these fields are directed oppositely, so the resulting field decreases. The result of the distortion of the magnetic field distribution is the displacement in the direction of rotation of a physical neutral at a certain angle *β*, the value of which depends on the load of the machine. Physical neutral is called the straight line passing through the center, and points on the circumference of the armature with zero magnetic induction, i.e. the straight line, perpendicular to the axis of the resultant magnetic field. To obtain satisfactory operation of brushes (without sparking) in machines without additional poles we have to move the brushes from geometric neutral in the same direction at angle *α*, which is a slightly larger than angle *β*.

4.3 Armature reaction

The armature reaction in the generator. To define what effect the armature magnetomotive force has on the poles magnetomotive force in the generator, let us assume that the armature rotates clockwise with a constant frequency, and the brushes are on the neutral. A pair of poles in expanded form is shown in figure 4.5, *a*. In all cases, they create the main field depicted as trapezoidal curve *1*. When the armature rotates in a given direction, electric motive forces directed behind the drawing plane are induced in the left branch of the armature winding, and those induced in the right branch are directed in the opposite direction. Currents pass through the windings in the same direction. This allows drawing a curve of the armature field *2*. To get the curve *3* of the resulting field, you need add up the ordinates of curves *1* and *2* at each point. We see that the armature field under the trailing (left) edges of the poles *N* and *S* tends to weaken the main field, i.e. to demagnetize it. But under leading (right) edges the armature field strengthens the main field, i.e. magnetizes it. Demagnetizing and magnetizing actions are mutually compensated, therefore the resulting flux of the machine does not differ in size from the main flux of the poles, if the magnetic circuit of the machine is not loaded, but it is distorted, i.e. it ceases to be symmetrical relative to the axis of the poles. Thus, points *a* and *b*, where the resulting field passes through zero, are shifted relative to the geometric neutral at a certain angle α in the direction of armature rotation. The physical neutral passes through these points. Usually the induction under the trailing edge of the pole increases so that the steel of poles and teeth in this area is quite saturated. As a result, the magnetic resistance of the area is increased and the distribution of induction is shown by curve *4*, passing below curve *3* under the trailing edge of the pole. We see that the field of the armature weakens largely the main field on the leading edge of the pole, and amplifies it on the trailing edge, resulting in a decrease in the main field.

If you move the brushes from the neutral position in the direction of rotation of the armature at angle $+\beta$ (figure 4.5 *b*), the curve *2* of the armature field will move at angle β in the direction of rotation of the armature, and the curve *1* of the main field remains in the same place. Adding the ordinates of curves *1* and *2*, we get curve *3* of the resulting field.

It is well seen that the field of the armature not only distorts the main field, but also weakens it. Due to the displacement of the brushes, the direction of current changes to the reverse in that part of the armature that is located between the geometric neutral position and each of the brushes. Thus, the magnetomotive force of the armature reaction of the generator, the brushes of which are shifted from the neutral in the direction of rotation of the armature, has two components: a longitudinal demagnetizing force that weakens the magnetic field of the poles, and transversal magnetomotive force distorting it.

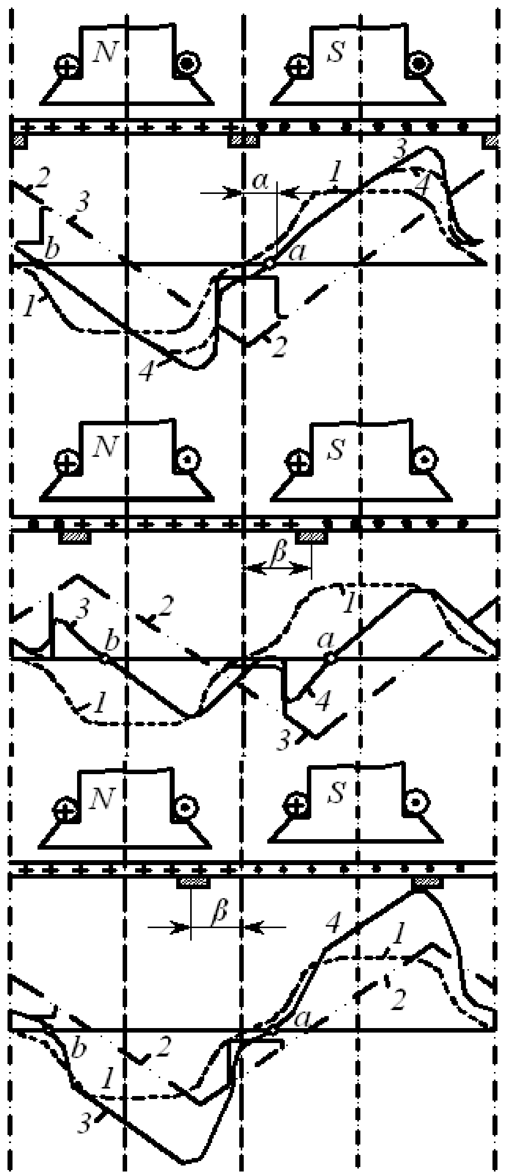


Figure 4.5 – Magnetization and induction of the resulting field

Accordingly, a longitudinal magnetomotive force of the armature reaction occurs when the brushes are shifted against the direction of rotation of the armature. The curves of fields that match this case are shown in figure 4.5, *c*. However, it should be noted that the shift of the brushes in the generator against the direction of rotation of the armature is not allowed, as it dramatically worsens the conditions of non-sparking operation.

The armature reaction in engine. Electromotive forces induced in the generator and motor have the same direction when the polarity of the poles and the direction of armature rotation are given, but the currents pass through the armature windings in different directions. Therefore, the polarity of the armature magnetic field changes in motors, and the reaction of the armature affects on the main magnetic flux in motors differently than in generators:

a) when brushes are located on the geometric neutral line the transversal magnetomotive force of the armature distorts the main field, weakening it on the trailing edge of the pole and increasing at the leading one;

b) when brushes are shifted from the neutral on rotation of the armature, the longitudinal magnetomotive magnetizing force occurs in the motor. However, the shift of brushes in the motor is done only against the direction of rotation of the armature.

5 Commutation

5.1 Essence of commutation process

The commutation is a set of phenomena related to the change of current in conductors of the armature winding when sections are transferred from one parallel branch to another when these sections are closed by brushes. The commutation process is very important in the theory of electric DC machines, as sparking that occurs at the commutator of these machines, mostly occurs due to improper behavior of this process. Figure 5.1 presents the distribution of currents when switching one section of a simple loop winding for five armature positions following each other at intervals of time $Ts/4$, where Ts is a period of commutation. The brush width bb is equal to bc – commutator division, the thickness of insulation between the commutator plates is not considered. It is assumed that the load of the machine is constant and the current in each parallel branch is equal to $I_{ar.}$ A short circuit under consideration begins at the moment of $t=0$ and ends at $t=Ts$. For the first period of time the brush touches only the commutator plate *2*, and the commutation section is among sections of the left parallel branch of the winding and current $i=I_{ar}$ flows in it. Currents in the wires connecting the commutator and winding for this time are: $i_1=0$ and $i_2=2I_{ar}$ (figure 5.1, *a*); they correspond to the beginning of commutation. In the next moment (figure 5.1 *b*) during the commutator rotation plate *2* gradually trails the brush and in its place plate *1* leads.

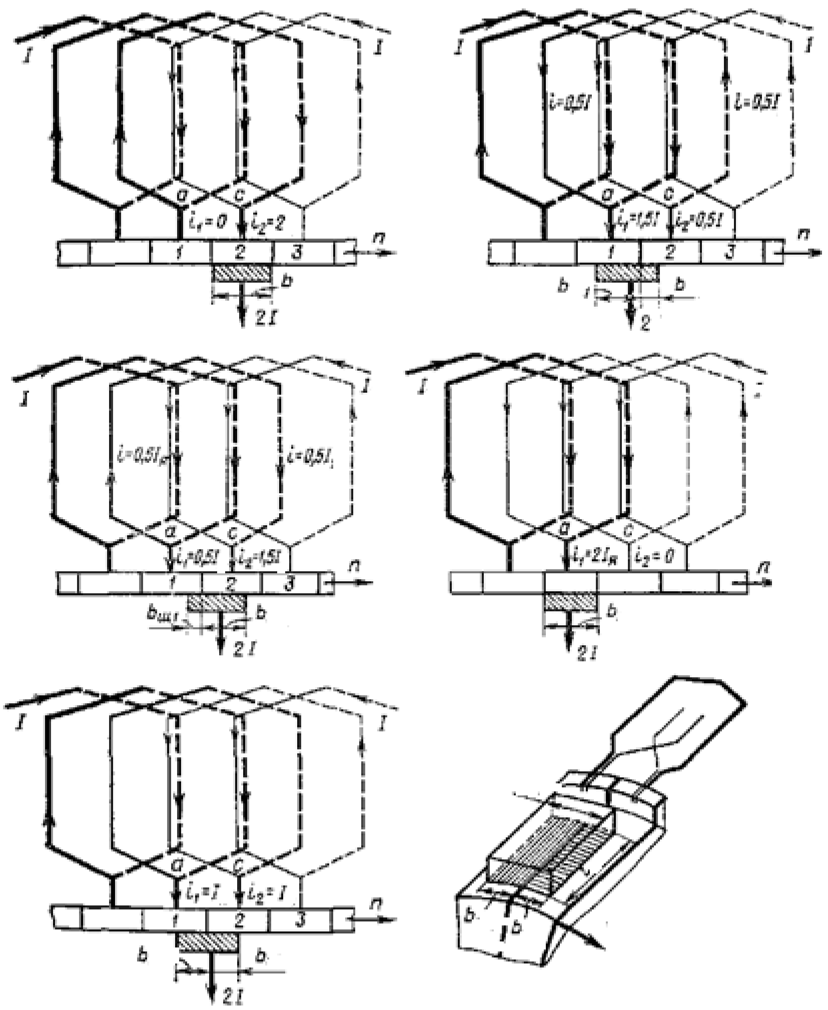


Figure 5.1 - Mutual position of the brush and commutator in commutation process

In our example, the left edge of the brush is called leading, and the right one – trailing. As soon as the brush comes into contact with a commutator plate *1*, the switching section will be closed short-circuited by the brush and the current will gradually decrease in it. Therefore, current $I_1=0,5I_{ar}$ will pass through commutator plate *1* and greater current $I_2=1,5I_{ar}$ flows through plate *2*, as the contact area of plate *2* with the brush is more, and that is why contact resistance between the brush and commutator plate is less. The current in the commutation section will have the same direction as before the commutation, but its value will be smaller than $I_{ar}(I=0,5I_{ar})$. When the brush contact surface evenly covers both commutator plates $R_{b1}=R_{b2}$ (figure 5.1, *c*), the current in the commutation sections will become equal to zero $I=0$, since $I_1=I_2=0,5I_{ar}$ For the subsequent point in time (figure 5.1, *d*) currents in the connecting wires will take the values: $I_1=1,5I_{ar}$, $I_2=0,5I_{ar}$. At the end of commutation for the fifth time point (figure 5.1, *e*) the brush is fully touch commutator plate *1* and the brush does not close the commutation section short. However, it will belong to the first parallel branch of the armature winding, and the current in it will $_r$ become equal to I_{ar}, but oppositely directed to the current at the beginning of the commutation. Currents in connecting wires are $I_1=2I_{ar}$ and $I_2=0$. The total current is equal to $2I_{ar}$. Thus, during the transition of the brushes from commutator plate *2* to the plate *1* there is a change of current in the switched section from $+I_{ar}$ to *0* and from *0* to – I_{ar}. This change of current is very fast *0,0003-0,001 sec.* Figure 5.1 *f* shows the position of the brushes on commutator plates during the commutation process.

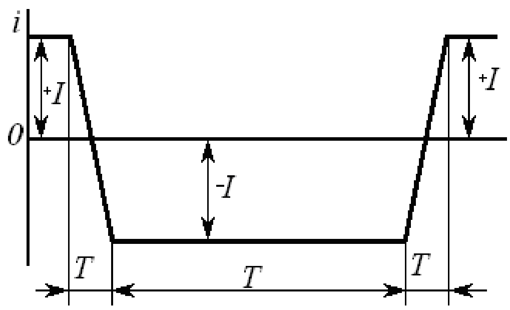


Figure 5.2 – Graph of section current change in time

In figure 5.2 a graph of current change in time in the section is shown when moving it twice from one parallel branch to another. The period of time T_K, during which the process of commutation occurs in a section is called the commutation period. During the time *T* the sections move between the brushes of different polarity. Short circuit (figure 5.1, *b*) consists of sections, two commutator plates and a brush; one can neglect the resistance of the section and connecting conductors between the section and commutator plates, since they are negligible compared with the resistance of transition contact between the brush and commutator plates. Denoting the resistance of transition contacts of trailing and leading edges of the brush as R_{b2} and R_{b1} let us make the equation according to the second law of Kirchhoff: $\Sigma e=0$. This assumption corresponds, for example, if $n \approx 0$ or to the complete balancing of the entire amount of electric motive forces in the section circuit:

$$\Sigma e=R_{b2}i_2 - R_{b1}i_1=0. \tag{5.1}$$

Besides, for nodes *a* and *c* according to the first law of Kirchhoff:

$$i_1=I_{ar}-i\ ; \quad i_2=I_{ar}+i, \tag{5.2}$$

where i is the current in the commutation circuit.

The current change in the section i is determined only by the change of R_{b1} and R_{b2}, that is why this case is called commutation resistance. At the considered moments of time the brush covers across the width the sections of commutator plates: $b_{b1}=\upsilon_c t$; $b_{b2}=\upsilon_c(T_K-t)$; $b_b=\upsilon_c T$, where υ_c is the circumferential speed of the commutator. Contact areas of the brush with commutator plates *2* and *1* will be: $S=b_{b1}l_{b1}$; $S_2=b_{b2}l_b$; full contact area is $S_b=b_b l_b$, where l is the length of the brushes. Taking into consideration the fact that the contact resistance is inversely proportional to the contact area, the expression for the transition resistance between the brush and the commutator plate can be written in the following form:

$$\frac{R_{br1}}{R_{br}}=\frac{S_{br}}{S_1}=\frac{l_{br}v_{cl}T_{cl}}{l_{br}v_{cl}t}=\frac{T_{cl}}{t};$$

$$\frac{R_{br2}}{R_{br}}=\frac{S_{br}}{S_2}=\frac{l_{br}v_{cl}T_{cl}}{l_{br}v_{cl}(T_{cl}-t)}=\frac{T_{cl}}{(T_{cl}-t)},$$

where

$$R_{br1}=\frac{R_{br}T_{cl}}{t}; \quad R_{br2}=\frac{R_{br}T_{cl}}{(T_{cl}-t)}. \tag{5.3}$$

Substituting (5.1) the values of currents i_1 and i_2 from (5.2) and resistances R_{b1} and R_{b2} from (5.3), we obtain:

$$i=I_{ar}\frac{R_{br1}-R_{br2}}{R_{br1}+R_{br2}}=I\left(1-\frac{2t}{Tcl}\right). \tag{5.4}$$

The commutation that corresponds the changes of current in (5.4) is called linear, as the current in the closed loop section varies on a straight-line law. Figure 5.3 shows a graph of current in the commutated section $i=f(t)$, drawn according to (5.4). Linear commutation is the most favorable, because only in this case there is one of the basic conditions of brushes operation without sparking, namely, the uniform current density under the brushes

$$i_{br1}=\frac{i_1}{S_{br1}}=\frac{2I_{ar}}{l_{br}b_{br}}; \qquad i_{br2}=\frac{i_2}{S_{br2}}=\frac{2I_{ar}}{l_{br}b_{br}}. \tag{5.5}$$

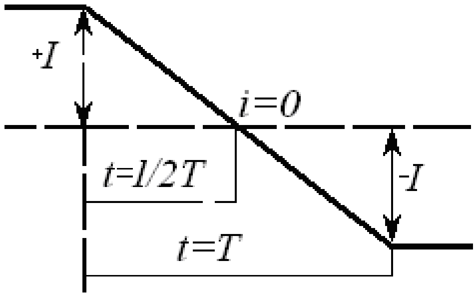


Figure 5.3 – Graph of linear commutation

5.2 Delayed and accelerated commutation

In fact $\Sigma e \neq 0$. In the commutated section, there are electric motive forces of self-induction e_L, mutual induction e_m and rotation e_K.

Electric motive force of self-induction e_L. Since the commutation period is very small (≈10-4 s), EMF of self-inductance occurs in the commutated section $e_L=-L(di/dt)$ (L – inductance of the section), which tends to slow down the commutation, as due to the self-induction the change of current always slows down in the circuit.

Electric motive force of mutual induction e_m. Usually the brush overlaps several commutator plates, i.e. $b_b>b_c$. Therefore, the commutation occurs simultaneously in several sections, which may be both in the same groove and in adjacent ones, hence, electric motive forces of mutual induction e_m occur in commutated sections : $e_m = -M(di/dt)$, where M is the mutual inductance in sections commutated simultaneously. Electric motive forces of self-induction and mutual induction create a resultant reactive electric motive force $e_r=e_L+e_m$, which hinders the process of changing the current in the commutated section.

Electric motive force of rotation e_K. In addition to the electric motive forces of self-induction and mutual induction in a short-circuited section during the rotation of the armature, an EMF of rotation e_K is induced; this force is caused by the fact that the sides to a short-circuited section cross the external magnetic field, which can be excited in the zone of commutation. The field of armature reaction and the external field generated by additional poles, form a commutating field in the zone of commutated sections. This field induces electric motive force of rotation. The direction of this force depends on the direction of the magnetic field lines and that of armature rotation: $e_K=2B_C l \upsilon \omega_C$,

where B_C is magnetic induction of the commutating field; l is the length of the active sides of the section; υ – linear speed of the section movement; ω_s – number of turns in the section. Thus, there is a sum of EMF in the commutating section $\Sigma e=e_r+e_C$. Taking into account (5.1), (5.2) and (5.3) the current in the commutating section is:

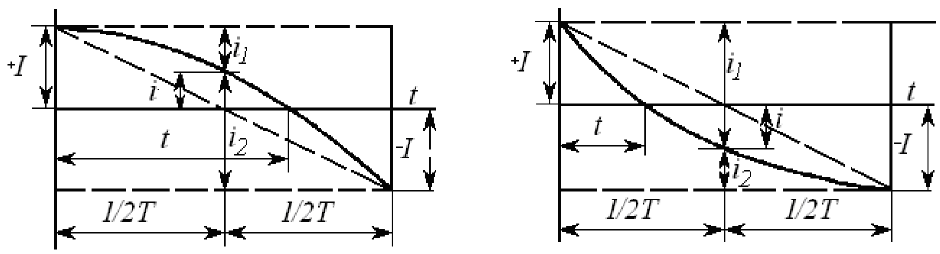
$$i = I_{ar}\frac{R_{br1} - R_{br2}}{R_{br1} + R_{br2}} + \frac{\sum e}{Ra_{br1} + R_{br2}} = I_{ar}\left(1 - \frac{2t}{Tcl}\right) + \frac{\sum e}{R_{br1}T_{cl}^2}(T_{cl} - t)t = i_l + i_{cl} \quad (5.6)$$

where $i_l = I_{ar}\left(1 - \frac{2t}{T_{cl}}\right)$ is the current of linear commutation.

$i_{cl} = \frac{\sum e}{R_{br1}T_{cl}^2}(T_{cl} - t)t$ is an additional current of the commutation.

The action of additional current of the commutation depends on the direction Σe. When $\Sigma e>0$ current t_c, adding with a linear current i_l, causes a slow process of commutation. When the current i passes through zero during the time elapsed from the beginning of commutation $t_c>T_c/2$, the current density under the trailing edge of the brush is more than that under the leading edge that may cause sparking under the trailing edge of the brush. Opening operation of short-circuited section is similar to circuit breaking with R and L.

Figure 5.4, *a* shows the graph of the curvilinear delayed commutation. For comparison, the same figure shows the graph of linear commutation. When $\Sigma e<0$ the additional current of commutation i_c has the opposite sign, and the character of change of currents will be accelerated (figure 5.4 *b*). In this case, currents i, i_1 and i_2 change quickly in the beginning of commutation and slowly at the end. The current and current density under the leading edge of the brush become large at the beginning of commutation. However, at the end of accelerated commutation, the current as well as current density under the trailing edge of the brush are small. Therefore, the circuit opening of the short-circuited section at such an accelerated commutation takes place in favorable conditions like the circuit opening with small current. Delayed commutation is unfavorable and unwanted; while slightly accelerated commutation, on the contrary, is desirable, therefore, in practice, such a commutation is preferable.



a) *b)*

Figure 5.4 – Curvilinear commutation

5.3 Causes of sparking of brushes

According to GOST 183-74 the degree of sparking at the commutator should be evaluated according to a scale of sparking (commutation classes) given in table

5.1. The degree of sparking of commutator machines is given in standards for individual types of machines, and in the absence of standards in the technical specifications (TS) on these machines. If the degree of sparking is not given, it should be no higher than 1½ at normal operation of the machine.

The roughness of commutator surface, protrusion of the mica insulating strips between the commutator plates, vibration of the brush unit, improper location of brushes and uneven brush pressure, etc. are mechanical causes of sparking of brushes.

Causes of a potential character. The tests have shown that commutation runs fine, if the maximum value of voltage between commutator plates is *25÷35* V for machines of high and medium capacity and *50÷60* V for machines of low capacity. If this voltage is out of the specified range, sparking or even arc appears between the adjacent plates.

Table 5.1

Sparking degree	Characteristic of sparking degree	Condition of commutator and brushes
1	Absence of sparking	Lack of blackening on the commutator and carbon deposits on brushes
1 ¼	Weak sparking under a small area of the brush edge	
1 ½	Weak sparking under a greater area of the brush edge	Appearance of blackening on the commutator and carbon deposits on brushes easily removed by cleaning the commutator surface with gasolines
2	Sparking under the entire brush edge. It is allowed only at short-term load impact and overloading	Appearance of blackening on the commutator and carbon deposits on brushes that cannot be removed by cleaning the commutator surface with gasolines
3	Strong sparking under the entire brush edge with large and flying out sparks. It is allowed only at the moment of direct connection or machine reversing if the commutator and brushes are in a good working order	Heavy blackening on the commutator that cannot be removed by cleaning the commutator surface with gasolines as well as burning and fractional damage of brushes

The causes of electromagnetic character are determined by the value of electromagnetic energy supply of a commutated section $0,5L_C i^2$ at the time of its opening. It is the discharge of electromagnetic energy that is the cause of sparking. Thus, the causes of electromagnetic nature depend on the value of reactive EMF e_r and additional commutation current i_c caused by this EMF. Strong sparking can be transformed into a circular fire on the commutator, which causes the damage of the brush-commutator unit of the machine.

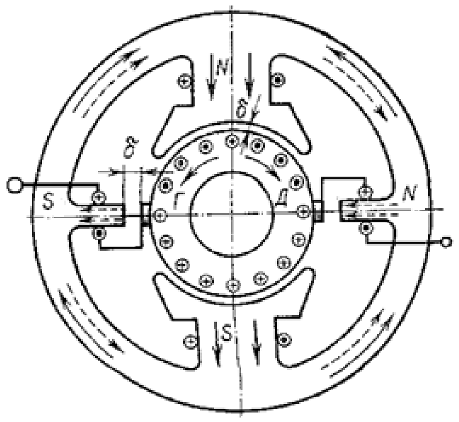
5.4 Main means of improving commutation

The main reason of poor commutation in DC machines is additional commutation current $i_c=\Sigma e/\Sigma R_c=(e_r \pm e_c)/\Sigma R_c$, where R_c – the sum of electrical resistances for additional commutation current i_c. The sum includes the resistance of the brush, sections and soldering in "commutator necks" as well as contact resistance between the brush and commutator. However, contact resistance and the brush resistance of these resistors have the largest value. the current decrease i_c can be achieved by the following ways: a decrease of reactive EMF - e_r; the creation of a magnetic field of such value in the commuting area and of such polarity that the EMF of rotation e_K would compensate EMF. e_r by the increase of resistance ΣR_c.. Reactive EMF - e_r can be reduced merely by constructive methods. While designing a machine it is necessary to provide the sections with a shortened step and as least as possible number of turns, reduce the speed of rotation and linear load of the armature, install brushes, commutator and sections with corresponding dimensions. However, these conditions can be limited due to the increase of machine size and therefore its cost.

To create a magnetic field that induces a compensating EMF of rotation e_c in the commutating zone, auxiliary poles are used in DC machines (figure 5.5). Magnetomotive force of auxiliary poles is to provide magnetic induction B_C in the zone of commutation of such a value that the EMF of rotation e_C would be equal to EMF e_r in value and opposite in direction, i.e. following equality $e_r – e_c=0$ would be satisfied for any moment.

Figure 5.6 shows the magnetomotive force of the generator with additional poles. Curve *1* represents magnetomotive force of main poles; curve *2* shows magnetomotive force of the armature; curve *3* – magnetomotive force of additional poles, curve *4* – resulting magnetomotive force of the generator with additional poles obtained by adding the ordinates of curves *1*, *2* and *3*.

In addition, the magnetic flux of additional poles should be directed towards the transverse flow of armature reaction, i.e. to compensate demagnetizing and distorting action of the transverse reaction of the armature in the area between the main poles.



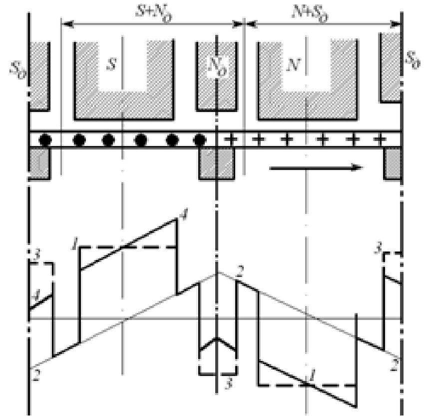


Figure 5.5 – Polarity of auxiliary poles of the machine with generator G and motor M

Figure 5.6 – Magnetomotive force of the generator with additional poles

Therefore, the polarity of an additional pole of the generator must be the same as the next main pole in the direction of rotation, and that of the engine – as the preceding main pole (figure 5.5).

Since the magnetomotive force of the transverse reaction of the armature and reactive EMF e_r is proportional to the armature current, the magnetomotive force of an additional pole and magnetic induction B_C must also be proportional to the armature current for their compensation. To meet this condition, the winding of additional poles are connected in series with the armature winding and additional poles are performed unsaturated at rated load of the machine. To do this, one should increase the gap under the additional pole compared to the gap under the main pole, make the induction in the core of an additional pole as many as 0.8÷1 *Тл,* for the steel saturation not to affect. The number of additional poles is usually equal to the number of main poles, and they are sometimes halved only in machines of low capacity. Auxiliary poles are placed between the main poles along the lines of geometric neutrals. Brushes are installed along the same lines and left in this position during all loads.

One can have the magnetic field necessary to create a compensating EMF of rotation by shifting the brushes from a geometric neutral in machines without additional poles (figure 5.7). Let us suppose that the machine operates as a generator and the armature rotates clockwise. If the brushes are installed on the geometrical neutral *1-1'* there is only one transverse field of the armature in the commutation zone. When rotated in this field of switched sections in them Electromotive forces directed similarly as they were directed before the introduction of sections in the zone of commutation will be induced in the field of commutated sections while rotating. Therefore, electromotive forces of rotation e_C, caused by armature transverse field will act in the same direction as the electromotive forces of self-induction e_L and those of mutual induction e_m and will slow down the commutation process.

If the brushes are displaced into area *2-2′*, where the armature field is fully compensated by the field of poles (natural neutral), the EMF of rotation e_C in commutated sections would be equal to zero, however, electromotive forces e_L and e_m would continue to slow the commutation process. In order to compensate these EMF it is necessary to displace the brushes even farther, position *3-3′*, where the resulting field in the air gap has a direction opposite to the direction of the field of those of the poles, under which the sections were before the commutation. As seen in figure 5.7 to create a commuting field, you should move the brushes from the geometric neutral in the direction of rotation of the armature in generator mode and against the direction of rotation in motor mode.

The disadvantage of the considered method is that the commutating field is not automatically changed proportionally to the armature current, and the required compensation of armature fields and EMF. e_L and e_m is obtained only at a certain load of the machine. At other loads, commutation conditions are less favorable. To implement an automatic change of brushes shift when the load changes is practically impossible.

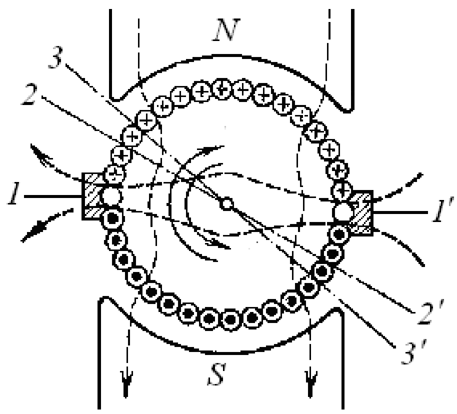


Figure 5.7 – Shift of brushes to improve the commutation

The increase in the resistance of commutated section circuit is possible in principle by performing "necks" with increased resistance. However, this leads to a decrease in the efficiency of the machine, as well as to the increase in current density at the trailing edge of the brush. In addition, these "necks" are unreliable in operation. The selection of brushes with proper characteristics and preservation of the oxide film on the surface of the collector is significant. When choosing a brand of brushes it is often necessary to find a compromise between contradictory requirements. For example, from the point of view of improving commutation it is profitable to choose hard types of brushes. However, this leads to increased wear of the collector as well as to increased size of the brush unit and the collector due to the lower admissible current density of these types of brushes. Currently, graphite brushes are widely used in machines of conventional design; carbon graphite and electro graphite brushes in machines of heavy-duty operation; copper or bronze graphite brushes are used in low-voltage machines. The chemical state of commutator surface has a great effect on the contact resistance between the brush and the commutator. In normal operation, the collector should be covered with a thin oxide film having high strength and electric resistance. Auxiliary poles will compensate the effect of armature reaction only in interpolar space (commutation zone). The armature reaction remains uncompensated directly under the main poles; this leads to a distortion of the main field and sharp difference between electromotive forces induced in the next sections of armature winding, resulting in sparking of potential character. To compensate armature reaction in the area of main poles the compensating winding is used (figure 5.8).

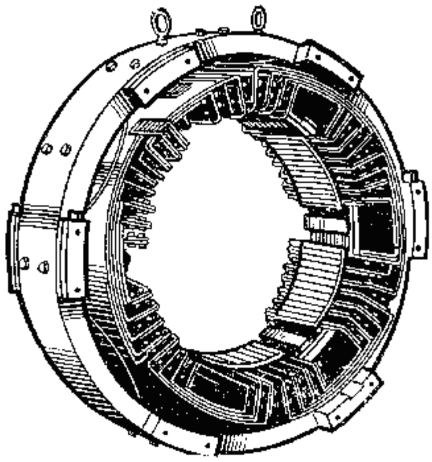


Figure 5.8 – DC machine housing with compensating winding

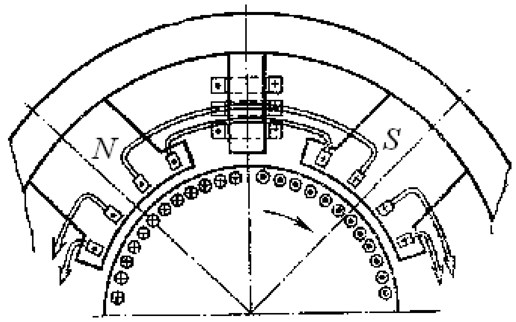


Figure 5.9 – Current direction in compensating winding

Insulated conductors are laid in the groove of pole terminals. The conductors are connected so that they form a winding with a magnetic axis coinciding with the geometric neutral (figure 5.9). Compensatory winding is connected in series with the armature winding. Magnetomotive force of the compensatory winding is distributed along the length of the pole arc. Its direction is opposite to the direction of the magnetomotive force of the transverse armature reaction and equal to it in value. The presence of compensation winding increases the reliability of machine operation, increasing its cost and losses in armature circuit. Therefore, it is used in low-voltage machines, operating in hard conditions (traction motors, cranes), as well as in machines of heavy-duty operation with sharp fluctuations of load (electric motors, rolling mills).

5.5 Armature commutation reaction

When the commutation trends from a straight, currents create an additional reaction of the armature in commutated sections. The armature commutation reaction means the effect of an electromotive force created by the currents of commutated sections upon the main flux of the machine. If the section current changes rectilinearly, in this position, the section does not affect the magnetic flux of the main pole.

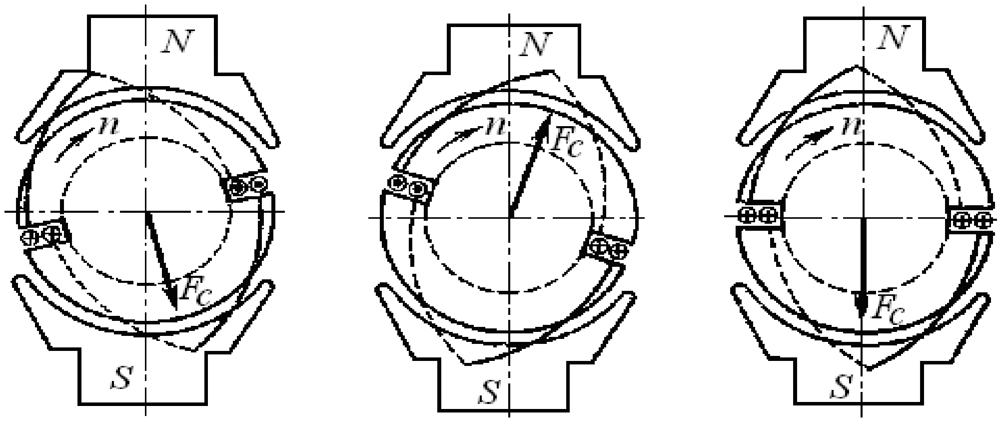


Figure 5.10 – Direction of magnetomotive force of a commutated section (in motor mode)

During the time 0<t<0.5 T_K the magnetic circuit F_s of a section is on one side of the geometric neutral (figure 5.10 *a*), and at $0{,}5T_K<t<T_K$ – on the other side (figure 5.10 *b*). The transverse component of magnetomotive force of the commutated section preserves a consistent direction and with magnetomotive forces of other winding sections generates the armature transverse reaction. The longitudinal component of the magnetomotive force of the commutated section at $t=0{,}5T_K$ reverses the direction, and its magnetizing action (in motor mode) for the first half commutation period is compensated by the demagnetizing action during the second half T_K. When the commutation is slowed down**,** during the greater part of the commutation period the current in the commutated section preserves its direction before the commutation. Therefore, the current transition point in the section through zero is shifted with accordance to armature rotation and the commutated section has a demagnetizing effect on the main poles in generator and magnetizing effect in motor (figure 5.10, *b*). When the commutation is accelerated the current in the commutated section reaches a value of zero for the period of time $t<T_K$ and the transition point of current in sections through zero is shifted against the rotation of the armature; in this case, the armature commutation reaction will be magnetizing in the generator and demagnetizing in the motor. During normal operation of the machine, the magnetomotive force of armature commutation

reaction is small compared to the magnetomotive force of excitation winding of the main poles and does not affect the magnetic flux of the machine. If the armature current is large, such as short-circuit in the generator, or when starting the engine, when, due to saturation of the magnetic circuit of auxiliary poles, the reactive EMF is dominated and commutation becomes very slow, the magnetomotive force of commutation reaction increases significantly and can have a significant impact on the machine operation.

5.6 Experimental verification and commutation adjustment

Due to the complexity of commutation process, the theory of commutation is based on several assumptions and simplifications. As a result one could not determine the exact number of turns of an additional pole, as well as to establish the exact size of the gap under the additional pole, etc. The practice of electric machine engineering shows that newly manufactured machines almost always need commutation adjustment, which consists primarily in the regulation of auxiliary poles, i.e. in changing resistance of the magnetic circuit or magnetomotive force of their excitation windings.

The most common method of experimental analysis of commutation is establishment of infeed curves of auxiliary poles. In 1934 V. T. Kasyanov and M. P. Kostenko developed a method of establishing a sparkless zone of machine operation at the plant "Electric Power" named after S. M. Kirov. The essence of the method is that the winding of additional poles is fed from a special DC power source and infeed curves are established that allow to identify the area of non-sparking operation and to determine the most advantageous number of turns of the additional pole as well as the size of gap δ with sufficient accuracy. To do this, the scheme is made as shown in figure 5.11, where *Ar* is the armature of a tested machine; W_1 W_2 – windings of auxiliary poles; *G* -DC generator of independent excitation for feeding additional poles; *S*– switch to change the polarity of generator *G*.

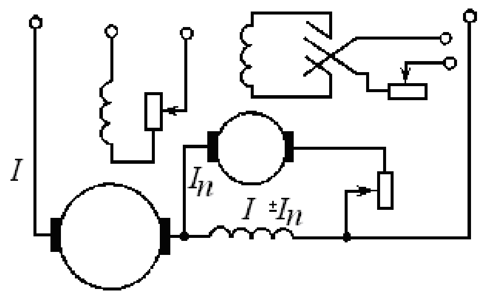


Figure 5.11 – Scheme for establishing infeed curves

When tested, the machine can operate in both a load mode and in the mode of short-circuit. The establishment of infeed curves starts with no-load operation ($I_{ar}=0$). Feeding auxiliary poles first in one direction and then in another, we can give the amount of current $\Delta I_P=\pm I_P 100\%/I_{NOM}$ at which the first visible sparking begins. The reason of sparking is an excessive e. m. f. $\Delta e=\pm e_K$, originating in the commutated section by the field of additional poles. If reactive and commuting EMF e_r and e_c were always in mutual equilibrium in the DC machine, infeed curves would have the form of two lines parallel to x-axis and located from it at the same distance. But since one cannot achieve full compensation of EMF e_r in the machines, the residual EMF increases with increasing load current I, at a certain value of which the machine starts to spark even if the number of turns of additional poles is properly selected.

Thus, the machine can be loaded only to such a limit current, at which it is impossible to obtain satisfactory commutation by any adjustment of additional poles. Infeed curves (figure 5.12) is not parallel to x-axis, but intersect at points C_1, C_2 or C_3 depending on the ratio between EMF e_r and e_c.

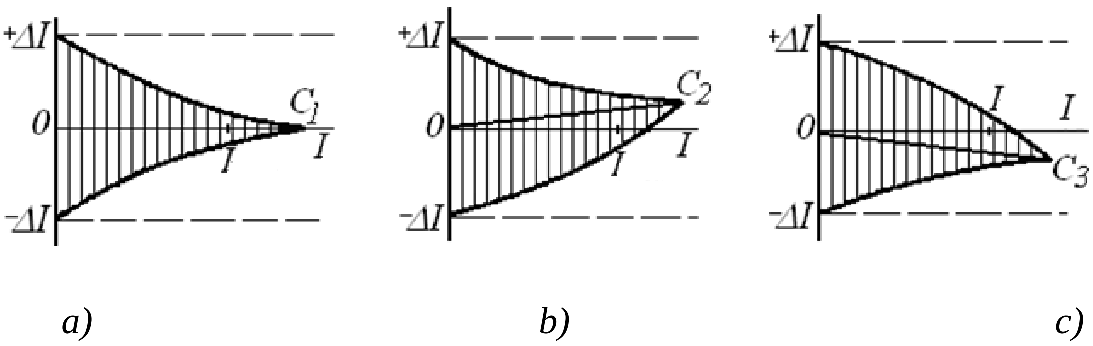


Figure 5.12 – Infeed curves while commutating

If they are compensated, i.e., the number of turns of additional poles is selected correctly, the infeed curves will intersect at point C_1 on x-axis and the middle line of the curves coincide with x– axis; C_1 is a linear commutation (figure 5.12 *a*). If the machine operates without feeding, reactive e. m. f. e_r dominates, and therefore, the commutation is slow, it is necessary to feed additional poles in the positive direction increasing the field they create in the zone of commutation. In this case, the middle line of the curves goes above x-axis and the point of intersection of curves C_2 is a slow commutation (figure 5.12 *b*). If e EMF e_c dominates you need to feed the additional poles in the negative direction, weakening the field they create. In this case, the middle infeed curve will go below x-axis toward the intersection point of the curves; C_3 is an accelerated commutation (figure 5.12, *c*). Comparing these curves, one can see that in the first case, the machine can run without sparking while over-loading than in the second one or third. Infeed curves allow to determine the most advantageous number of turns of an additional pole at a given size of a gap under an additional pole or most advantageous size of this gap for a given number of turns of the additional pole. The first method is usually used in machines of low and medium power, the second one for machines of large capacity with small number of turns of the additional pole. Furthermore, infeed curves permit to determine within certain limits conditions of commutation when you change the mode of machine operation.

5.7 Means of reducing interference

The commutation process of DC machines is accompanied by generation high frequency electromagnetic waves that cause interference in radio and television devices. The process of rectifying electromotive forces by using the commutator can also be a source of interference. However, the intensity of interference depends on the degree of sparking under the brushes, causing continuous crackling and noise in radio receivers. Therefore, the level of radio interference should not exceed the level of norms established by the standard. To reduce radio interference electrical filters are used, machines are shielded and windings are balanced connected in series with the armature. In some cases, to improve filtering of high-frequency voltages and currents one should use a filter consisting of capacitors, connected in parallel with the armature, and inductive coils connected in series (figure 5.13).

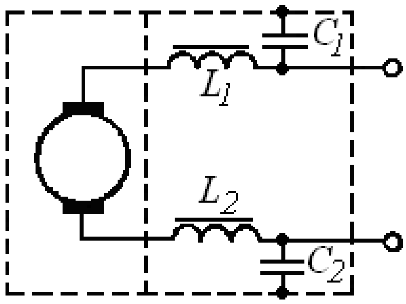


Figure 5.13 - Scheme of protection from interference in electric machines

6 DC Generators

6.1 General information about DC generators

In cases where high current is required or preferred by the conditions of production (enterprises of chemical and metallurgical industry, transport, etc.) it is generated by transforming AC into DC using converters. Engine-generator installations are widely used as converters. DC generators, as a source of energy, mainly operate in isolated installations (as exciters of synchronous machines), cars, airplanes, arc welding, trains lighting, ships, etc.

Thus, DC generators are quite widely used, and as a result, there are diverse requirements concerning power, voltage, speed, reliability, service life, etc. It is necessary that a magnetic field should be present while the rotor running. Depending on the method of creating magnetic field, generators are divided into independent excitation generators with electromagnetic excitation, with excitation by permanent magnets (magneto) and self-excitation, in which the current for excitation winding is supplied from the armature of the generator. During independent excitation, the generator winding is powered from an independent DC source. Magneto electric excitation is used only in low-voltage machines. There are three possible connections of excitation winding with the armature winding during self-excitation: parallel (shunt), serial (series) and mixed (compound). In accordance with this, there are generators with parallel, serial and mixed excitation with two excitation windings: one is connected in parallel and the other in series.

Characteristics of DC generator. The properties of generators are analyzed by means of characteristics establishing a relationship between the main values that determine the generator operation. They are EMF. E, terminal voltage of the generator U, excitation current I_e, current in the armature I_{ar} and frequency of rotation n. Since the generators often work with constant speed, the main group of characteristics is removed at a constant speed (n=const). Voltage U is of the highest importance because it determines the properties of the generator in respect of the network in which it operates. Therefore, the main characteristics are:

a) load $U=f(I_e)$ when I_{ar} is constant. In a particular case when $I_{ar}=0$, the load curve transforms into the characteristic of no-load operation being of great importance for the assessment of generator and establishing other characteristics;

b) external $U=f(I_{ar})$ when $R_e=const$;

C) adjusting $I_e=f(I)$ при $U=const$. In a particular case when $U=0$, adjusting characteristic is transferred into the characteristic of short circuit $I_K=f(I_e)$. The mode of operation of an electric machine under conditions for which it is designed, is called the typical (or rated) mode. The typical mode of operation is characterized by the values indicated on the nameplate as typical: voltage, power, current, speed. The rated power of DC generator is called a useful electrical power expressed in watts or kilowatts. The term "typical" can refer to the values which are not specified on the nameplate of the machine, but describing the typical operation: such as time, excitation current, efficiency.

Energy process and equation of e. m. f. of DC generator. The process of converting input mechanical energy into electrical energy is in the base of generator operation. Let us consider the process of energy transformation by the example of an independent excitation generator running at constant frequency (n=const). In the case of independent excitation power P_e required to cover the losses in the excitation circuit, is not included into the power P_1, supplied to the generator from the prime mover (figure 6.1). While transforming energy a part of power P_1, is spent on covering mechanical losses P_{MX} and losses in the steel P_s, and the remaining part is converted into electromagnetic power

$$P_{em}=E_{ar}I_{ar}=P_1-(P_{MX}+P_C).$$

Useful power $P_2=UI_{ar}$ given up by the generator in the network is less than power P_{em} by the amount of electrical losses P_m+P_{br} in the circuit of the armature and brush contacts

$$P_2=P_{em}-(P_m+P_{br}). \tag{6.2}$$

Since $P_2=P_{em}-(P_m+P_{br})$ is the resistance of all windings in the circuit of the armature and brush contact, $P_2=UI_{ar}=E_{ar}I_{ar} - I_{ar}^2R_{ar}$. After reduction of both parts of this equality by I_{ar} we obtain the equation of e. m. f. of the generator:

$$E_{ar}=U+R_{ar}\ . \tag{6.3}$$

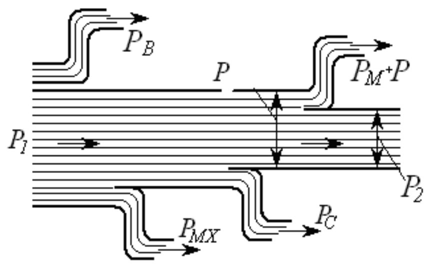


Figure 6.1 - Energy diagram of independent excitation DC generator

The equation of generator moments. Let us assume that the primary engine develops on the generator shaft moment M_0 making the generator rotate clockwise with a certain constant frequency n (figure 6.2). If the generator is excited, an EMF is induced in the conductor under the north pole, directed behind the plane of the drawing. If the generator is in no-load operation, we need a small moment M_0 to rotate the armature.

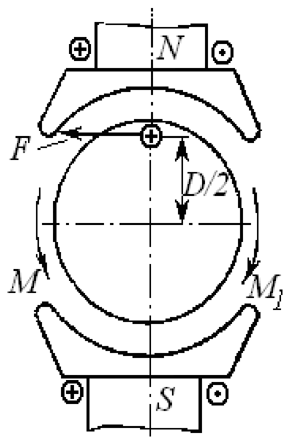


Figure 6.2 – Diagram of generator operation

This moment is expended to overcome friction in bearings of the brushes on the collector, air friction of rotating parts, as well as covering the losses of the armature core steel.

When a loaded generator operating, the current $i_{ar}=I_{ar}/(2a)$ appears in the armature winding. The current interacts with the main magnetic field of the machine. That is why a force acts upon each conductor of the armature winding

$$F_{em}=B_{av}li_{ar} \quad , \tag{6.4}$$

where B_{av} - average value of magnetic induction in the gap;

l - the length of the armature.

Having defined the direction of these forces according the "left-hand" rule, we realize that their magnetic moment is directed against the torque of the primary motor M_1. The value of electromagnetic torque (N·m) is:

$$M=F_{em}0,5DN=B_{av}li_{ar}0,5DN,$$

where N is the number of active conductors of the armature winding.

Keeping in mind that $i_{ar}=I_{ar}/(2a)$; $\pi D=2p\tau$; and excitation magnetic flux $F=B_{av}l\tau$, we get $M=B_{av}l(I_{ar}/2a)\cdot(2p\tau/2\pi)$; $N=pNI_{ar}\Phi/(2\pi a)$, or

$$M=C_M I_{ar} F \quad , \tag{6.5}$$

where $C_M=pN/(2\pi a)$ – a constant value for a given machine.

At a constant speed $(n=const)$ the torque of the primary motor M_1 is balanced by the sum of opposing moments: moment of no-load operation M_0 and electromagnetic torque M, i.e., $M_1=M_0+M$. This expression represents the equation of moments for the generator when $n=const$.

6.2 Independent excitation generator

Independent excitation is used quite widely in generators of low (4 – 24V) and high voltage (over 600 V), in machines of heavy-duty operation that require a wide voltage regulation (on ships in the steering electric drives, DC rowing electrical installations as the main generators and exciters, and other devices).

No-load characteristic. $U=f(I_B)$ when $I_{ar}=0$ and $n=const$. The scheme for no-load characteristic is presented in figure 6.3. Turning off the load by the breaker switch, we identify the rated speed. Then we gradually increase the current in the excitation winding I_{ex} from zero to $+I_{ex.MAX}=0a$ (figure 6.4) where voltage U_0 increases along curve *1* to $+U_{0.MAX}=(1{,}1\sim1{,}25)U_{NOM}$. Since $I_{ar}=0$, $U=E=c_enF=c_eF$, where c_e is a constant coefficient.

Thus, no-load characteristic $U=c_eF=f(I_{ex})$ represents in a different scale the characteristic of magnetization of the machine. When the excitation current is reduced up to $I_{ex}=0$, changing its direction, one can get curve *2*, called the descending branch of the characteristic. It is located in the first quadrant above the curve *1* due to the increase of residual magnetic flux. If we repeat the experience of changing excitation current in the opposite direction, we get curve *3*, called the rising branch of the characteristics of no-load operation. The descending and ascending branches form a hysteresis loop that defines the steel properties of poles and a housing. Having drawn middle line *4* between curves *2* and *3*, we will receive the calculated characteristics of no-load operation.

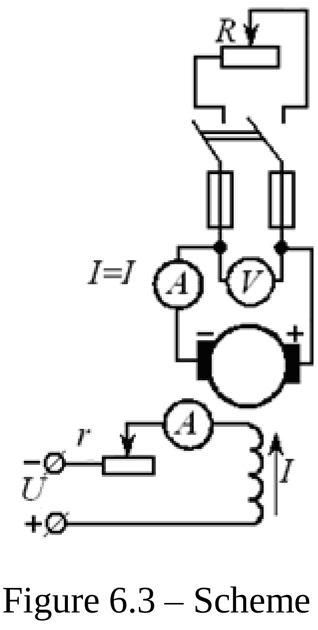


Figure 6.3 – Scheme of independent excitation generator

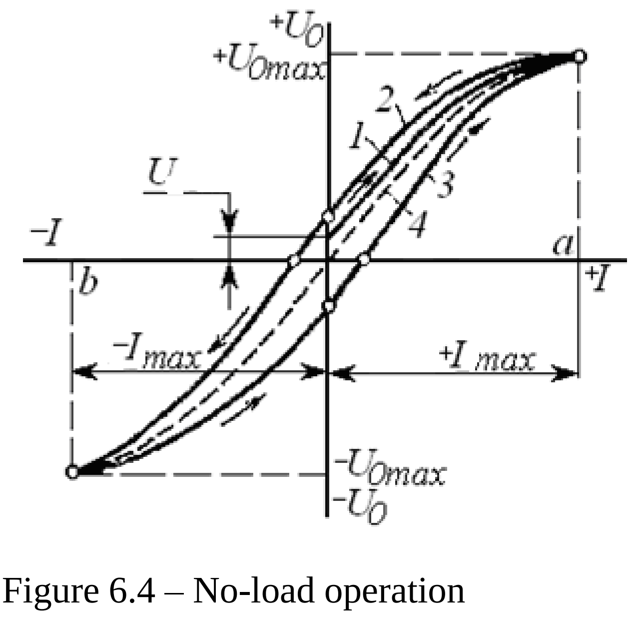


Figure 6.4 – No-load operation characteristics of independent excitation generator

The straight part of no-load operation characteristics corresponds to the unsaturated state of the magnetic system**.** In case of significant excitation currents, machine steel is saturated and the characteristic becomes curve. The point of rated voltage usually lies on the "knee" of the curve, as the machine operation on the straight part of the characteristic leads to significant voltage fluctuations and the operation in the area of saturation requires a large excitation current and limits the voltage regulation.

Load characteristics.

To relieve the load characteristics $U=f(I_{ex})$ when $I_{ar}=const$ the generator is excited and required load current I_{ar} is established by means of load regulator *R*. Then excitation current I_{ex} is gradually reduced and the value of load resistance is reduced so that whenever parameters I_{ex} and *U* are counted, the load current should remain unchanged. The generator voltage decreases under load due to voltage drop in the circuit of the armature $I_{ar}R_{ar}$ as well as demagnetizing action of armature reaction. Therefore, the load characteristic is below no-load operation characteristic and the lower it is the more load current I_{ar} is (figure 6.5).

To take into account the effect of these two factors on the decrease of generator voltage under load, let us consider the drawing characteristic triangle ***aвc***, using no-load operation characteristic and load one when $I_{ar}=I_{nom}$. Let point *c of* the load characteristic correspond to nominal voltage U_{nom} of the generator at excitation nominal current $I_{ex.nom}$ and load nominal current I_{nom}. If you disconnect the load, according to the characteristics of no-load operation, excitation current $I_{ex.nom}$ will correspond to voltage U_0. Therefore, segment *kc* characterizes the decrease of the generator voltage under load. Having measured the resistance of armature winding ΣR_{ar} and calculated voltage drop $I_{ar}\Sigma R_{ar}$ we can determine EMF of the generator at a given load current

$$E=U+I_{ar}\Sigma R_{ar} \quad , \qquad (6.6)$$

where $E<U_0$.

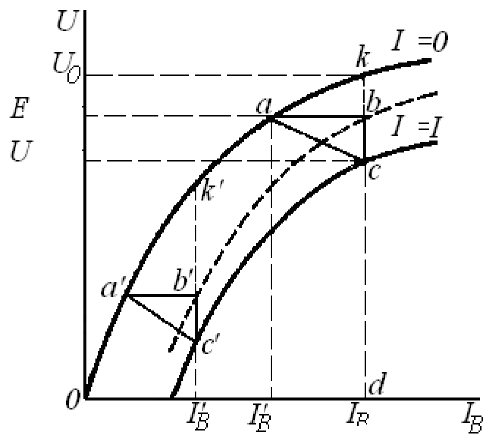


Figure 6.5 – Independent excitation generator load characteristic

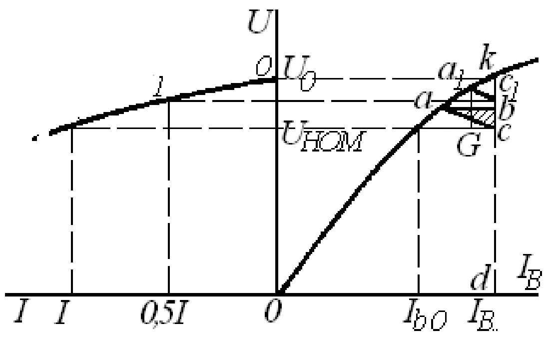
Segment *bk* characterizes the voltage drop due to demagnetizing action of armature reaction. The electromotive force E_{nom} corresponds to excitation current $I'_{ex.nom}$. Thus, if there were no demagnetizing action of armature reaction in the machine, it would be sufficient to conduct current $I'_{ex.nom}$ in excitation winding at which the generator would have nominal voltage U_{nom} at nominal load. In addition, to compensate the demagnetizing action of armature reaction it is necessary to install current $I_{ex.nom}>I'_{ex.nom}$ in the excitation winding. The value of segment $ab=I_{ex.nom}–I'_{ex.nom}$ characterizes the demagnetizing effect of armature reaction, and the value of segment *bc* depicts the voltage drop $I_{nom}R_{ar}$. Right triangle *abc* is called the characteristic triangle. The second characteristic triangle *a'b'c'* is built for a different value of excitation current I_{ex}. Side *c'b'* of the triangle is unchanged (*c'b'=cb*) because the load current does not change, but side *a'b'* decreased (*a'b'<ab*), because of the reduced demagnetizing effect of armature reaction.

External characteristics.

For removing external characteristics (figure 6.6 a) one can use the scheme represented in figure 6.3. Closing the circuit breaker, the generator is loaded, reducing the value of resistance *R* up to the nominal current $I_{ex}=I_{nom}$ at nominal voltage $U=U_{nom}$. Then the load is gradually reduced up to zero and the readings are taken. The resistance of excitation circuit R_{ex}, and hence excitation current $I_{ex}=U_{ex}/R_{ex}$ during the experience remain constant. The decrease of generator voltage under load occurs for two reasons: because of the voltage drop in the circuit resistance of the armature $I_{ar}R_{ar}$ and because of the demagnetizing action of armature reaction. The degree of slope of the external characteristic to the x-axis, i.e. the rigidity of the external characteristics is evaluated by changing the voltage of the generator at nominal load, called the nominal change of voltage. The relative change of voltage is the difference of voltage at no-load operation and voltage at nominal load in shares of nominal voltage: $\Delta U = (U_0–U_{nom})U_{nom}=\Delta U_{nom}/U_{nom}$. In case of short-circuit, generator voltage at its terminals falls to zero ($U=0$), and short-circuit current $I_{sh.c.}$ is many times greater than nominal. Therefore, short-circuit in the generator with any excitation is extremely dangerous.

The external characteristic can be drawn also by means of characteristics of no-load operation and the characteristic triangle. Let us draw a vertical straight line *dk* (figure 6.6, *b*), corresponding to a given excitation current $I_{ex.nom}=const$. So, $dk=0_{\Gamma 0}$ corresponds to U_0 if $I_{ar}=0$ and defines the initial point of external characteristics. The characteristic triangle *abc,* for current $I_{ar}=I_{nom}$ is located so that its top *a* should be on the characteristic, and other two sides *ab* and *bc* be parallel the first side to the horizontal axis, and the second one to y-axis. This determines the position of point *c* corresponding to voltage $U=U_{nom}$. To get intermediate points of the external characteristics, such as the one for current $I=0,5I_{nom}$, you need to halve each side of triangle *abc*. Instead, you can halve hypotenuse *ac* at point *G* and move segment *cG* parallel to hypotenuse *ac* to position a_1c_1. After that, from point

c_1 we draw the straight line parallel to x-axis, to the intersection with the ordinate 0,5 I_{nom} and get point $г_1$, and then using points $г_0$, $г_1$, $г_{nom}$ we draw an external characteristic.



a) *b)*

Figure 6.6. – External characteristic of independent excitation generator *(a)* and its drawing *(b)*

Regulating characteristics.

If the excitation current of the generator is regulated so that generator voltage remains constant and equal to the nominal one by increasing the current load, the corresponding curve of excitation current I_{ex} from the load current I_{ar} will represent the regulating characteristic, $I_{ex}=f(I_{ar})$ if $U=const$ and $n=const$. To relieve the regulating characteristics one can use the scheme shown in figure 6.3. When the circuit breaker is open one can establish the nominal voltage. Then the load is included and the current gradually increases up to I_{nom}. To maintain the generator voltage constant the excitation current is increased by reducing the resistance of the adjusting resistor. The regulating characteristic of independent excitation generator is shown in figure 6.7. The change of excitation current $\Delta I_{ex.nom}=(I_{ex.nom}–I_{ex0})/I_{ex.nom}$.

The regulating characteristic can be drawn according to the specifications of no-load operation and the characteristic triangle, as shown in figure 6.7 *b*. Let us draw the characteristic of no-load operation and line *ге* parallel to x-axis at a distance of *0г*. Having drawn characteristic triangle *abc*, for example, for nominal current I_{nom} we need to draw this triangle so that vertex *a* should be on the characteristics of no-load operation, and vertex *c*– on straight- *e*; this determines the required excitation current $I_{ex.nom}=o$ to create voltage $U_{nom.}$ Relocating point *ж* down from x-axis respectively to current I_{nom}, we get point *n* of a regulating characteristic for nominal load. Other points of regulating characteristics can be drawn either, for example point *m* for $I_{ar}=0,5I_{nom}$. For no-load we have $I_{B0}=O_0$. We draw the regulating characteristic through points $_0мн$.

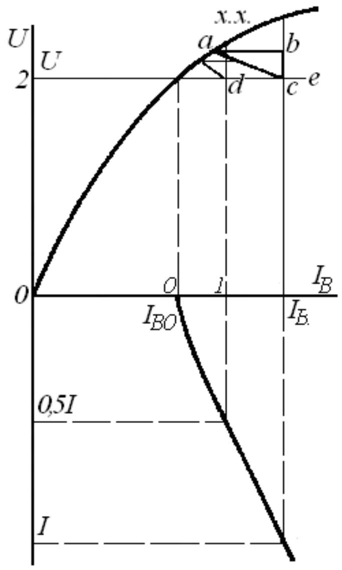


Figure 6.7 – Regulating characteristic of independent excitation generator *(a)* and its drawing *(b)*

6.3 Shunt generator

Self-excitation conditions.

The scheme of a shunt generator is shown in figure 6.8. A small flux of residual magnetization F_{res} (2-3% of the nominal one) is necessary for self-excitation of generator. When the armature of generator rotates a residual EMF $E_{res}=(2\text{-}3\%)E_{res}$ is induced in the windings by residual magnetic flux F_{res}. The residual EMF creates a small current in the excitation winding. Due to according direction of magnetizing and residual flows, this current will strengthen the magnetic flux of poles and will cause a corresponding increase of the EMF, induced in the armature winding. The increase of EMF will result in the increase of excitation current and, hence, magnetic flux of main poles, etc. As the exciting current changes continuously, the following electromotive forces act in the exciting circuit:

1) voltage U_{ex} at the terminals of exciting circuit, which at the same time is the voltage at the terminals of the armature;

2) voltage drop $I_{ex} R_{ex}$;

3) EMF of self-induction – $L_{ex}(dI_{ex}/dt)$, where L_{ex} is the inductance of exciting circuit.

Thus,

$$U_B - L_B \frac{dI_B}{dt} = I_B R_B \quad \text{or} \quad U_B = I_B R_B + L_B \frac{dI_B}{dt}. \qquad (6.7)$$

Usually the process of self-excitation occurs in case of no-load operation and $R_{ex}=const$. Then the dependence $U_{ex}=f(I_{ex})$is depicted as a curve of no-load operation (curve *1* in figure 6.9), the dependence $I_{ex}R_{ex}=f(I_{ex})$ is determined by straight line *2*, and $L_{ex}(dI_{ex}/dt)$ by the segments of ordinates between curve *1* and straight line *2*.

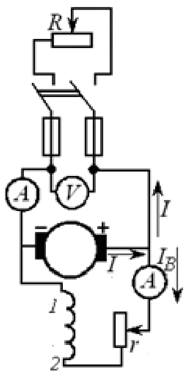


Figure 6.8 –Scheme of a shunt generator

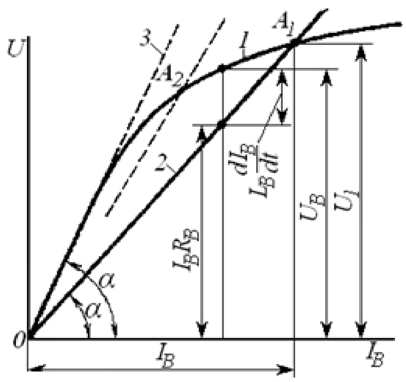


Figure 6.9 – Self-excitation of a shunt generator

At point A_1 of intersection of curve *1* and straight line *2* the EMF of self-induction is $L_{ex}(dI_{ex}/dt)=0$, and since I_{ex} is a finite quantity, $dI_{ex}/dt=0$ and therefore $I_{ex}=const$. Thus, at point A_1 the process of self-excitation is terminated. To get this point we draw a straight line at angle α, the tangent of which at a given scale is proportional to the value of total resistance of the excitation circuit, $tg\alpha=U/I_{ex}=R_{EX}$, where R_{EX} is the resistance of excitation winding and a regulating rheostat. If we increase the resistance R_{EX}, i.e. angle α, the point A_1 will move along the characteristic of no-load operation in the direction of *0*. If R_{EX} increases to such a degree that line *2* will be tangent line to the initial part of the characteristics of no-load operation. (straight line *5*), in these conditions the generator is not excited. The resistance of excitation circuit, which stops the self-excitation of generator, is called critical resistance $R_{EX.CR}$, and angle α corresponding to this resistance, is called critical angle. Therefore, self-excitation of a shunt generator is possible under the following conditions:

a) magnetic system of the machine needs to have residual magnetism;

b) magnetic flux generated by excitation winding must coincide in direction with the flow of residual magnetism;

c) resistance of the excitation circuit should be less than critical: $R_{ex}<R_{ex.cr}$;

d) load resistance should not be too small.

Characteristic of no-load operation.

As a shunt generator is excited by itself only in one direction, the characteristic of no-load operation $U_0=f(I_{ex})$ if $I=0$ and $n=const$ can be taken also only in one direction (figure 6.10).

Since the voltage drop in the armature from the excitation current I_{ex} can be neglected, the characteristics of no-load operation and load characteristics virtually coincide with similar characteristics of the generator of independent excitation.

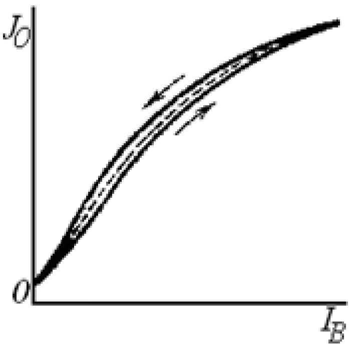


Figure 6.10 – Characteristic of no-load operation of a shunt generator

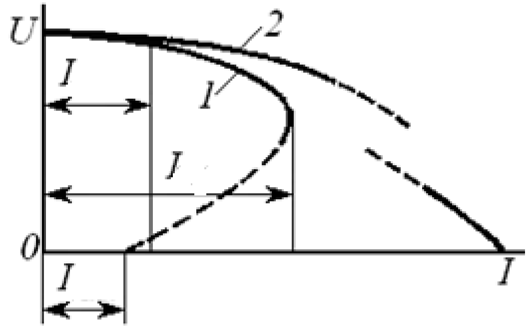


Figure 6.11 - External characteristics of a shunt generator – *1* and independent excitation generator - *2*

External characteristics.

These characteristics have the following form: $U=f(I)$ under $R_{ex}=const$ and $n=const$. If the excitation current remains unchanged in independent excitation generator, it changes with load change in the shunt generator. When the load increases the voltage at the terminals under the influence of armature reaction and voltage drop in the armature circuit is reduced. The voltage reduction causes the decrease of excitation current $I_{ex}=U/R_{ex}$. In its turn, the decrease of I_{ex} causes weakening the main magnetic flux, and, consequently, reducing EMF and voltage at terminals of the generator. If voltage decreases, excitation current I_{ex} decreases too. Under these circumstances, magnetic system of a generator is gradually demagnetized. The load current in a shunt generator increases only up to a certain critical value I_{cr}, exceeding the nominal one by no more than 2-2.5 times. The value of load current depends on two factors: value of generator voltage and load resistance. With the load increasing, the voltage at the terminals of the generator decreases (figure 6.11). In the beginning, when the magnetic system is saturated, demagnetizing is slow and the voltage U changes slightly, whereby the current in the armature circuit increases. However, with further current increase the degree of saturation of magnetic system decreases sharply, and voltage begins to drop rapidly. Reducing the resistance will be predominant but not lowering the voltage.

Therefore, the current reaching its critical value starts to decrease. In case of short-circuit $I_{ex}=0$, because $U=0$. The value of $I_{sh.c.}$ will be determined only by the value of EMF of residual induction: $I_{sg.c.}=E_{res}/R_{ar}$. So, short circuit caused by gradual decrease of load resistance is not dangerous for the shunt generator. But in case of a sudden short circuit the magnetic system of the generator does not have time to demagnetize immediately, and the current of short circuit $I_{sg.c.}$ reaches dangerous values for the machine. With such a sharp increase of current on the generator shaft there is a great braking torque, and there is strong sparking on the commutator, transforming into a circular fire.

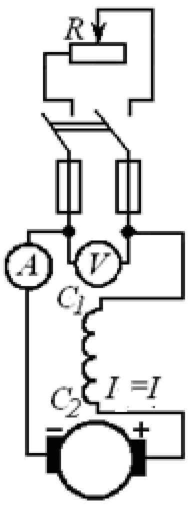
Regulating characteristics.

Regulating characteristics of shunt generator $I_{ex}=f(I)$ if $U=const$ and $n=const$ has the same form as those of independent excitation generator.

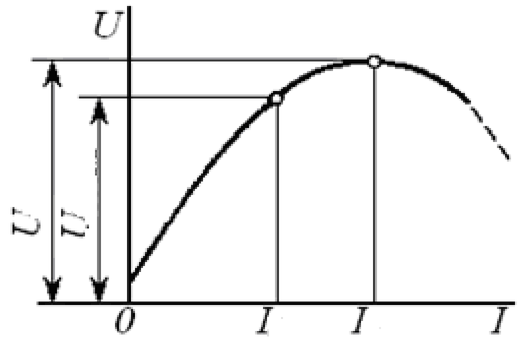
6.4 Series generator

In series generator excitation current $I_{ex}=I_{ar}$ (figure 6.12 *a*), and therefore the properties of this generator are determined only by external characteristics (figure 6.12 *b)*.

All other characteristics of the generator can be removed only when you enable it on an independent excitation. The external characteristic of series generator shows that with the increase of the load current from zero to nominal voltage at generator terminals at the beginning, when the magnetic circuit is not saturated yet, the voltage grows almost in direct proportion to the load current.



a)



b)

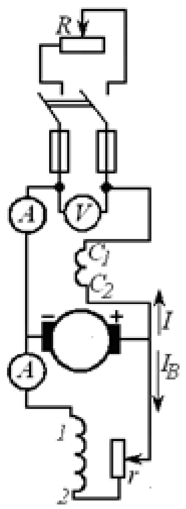
Figure 6.12 – Scheme *(a)* and external characteristic *(b)* of a series generator

Then the increase of voltage gradually decreases and finally stops. The reason is that I_{ar} is also excitation current I_{ex}, and the steel saturation occurs with load increase. However, timed with the increase of the armature current both demagnetizing effect of armature reaction increases and voltage drop in the circuit resistances of the armature and excitation winding, causing a decrease in voltage at terminals of the generator. With a large saturation of steel of the magnetic circuit of the machine, the increase of magnetic flux of EMF is practically terminated. At the same time, the voltage drop and the armature reaction will continue to increase. In case of short-circuit the generator voltage will be zero and short circuit current will exceed much the nominal current of the machine. Series generator has no practical application because it does not meet the requirements of most users with regard to constant voltage.

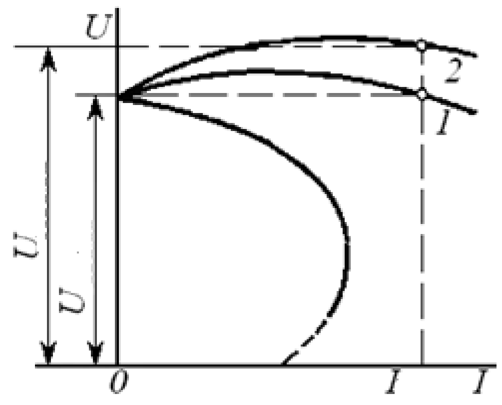
6.5 Compound – wound generator

As the compound – wound generator has a parallel and serial excitation windings (figure 6.13, a) it combines the properties of both types of generators. The flow of excitation is essentially created by a parallel winding and a serial winding is turned on according to the parallel one (in order that magnetomotive forces of windings were summed up).

The properties of a generator depend on the ratio of magnetomotive forces in these windings. If the load is connected to the circuit of the armature, the current appears and the excitation of the generator is carried out simultaneously by the action of magnetomotive forces in parallel and series windings.



a)



b)

Figure 6.13 – Scheme *(a)* and external characteristics of a compound – wound generator *(b)*

The form of external characteristics of a compound – wound generator (figure 6.13, *b*) depends on the ratio of turns of excitation windings. With appropriate selection of turns in armature windings of series excitation, its magnetomotive force can compensate the voltage drop of the generator and action of armature reaction, but the voltage at terminals of the generator with load changing remains almost constant (curve *1*). In order to maintain the constant voltage at consumer terminals (end of line), one have to compensate the voltage drop in wires of the line. In this case, the series excitation winding is reinforced, so that the external characteristic should have the shape of curve *2*.

In case of subtractive polarity the voltage of generator decreases sharply with load current increasing (curve 3), owing to demagnetizing effect of series excitation winding, magnetomotive force of which is directed toward to that of parallel winding. Subtractive polarity is used in generators of special purposes, for example in welding generators, where you need a steeply dipping external characteristic for limiting short-circuit currents. Load characteristics of the compound – wound generator $U=f(I_{ex})$ if $I=const$ and $n=const$ have the same form as the corresponding characteristics of a shunt generator. But in case of strong series winding they can be located above the characteristics of no-load operation. Constant voltage at generator terminals is usually supported by regulating the current in windings of parallel excitation. The form of regulating characteristic depends on the ratio of a magnetomotive force of the winding of series excitation with demagnetizing reaction action and voltage drop in the armature circuit. Figure 6.14 shows the regulating characteristics in case of normal excitation (curve *1)* and under over excitation (curve *2*).

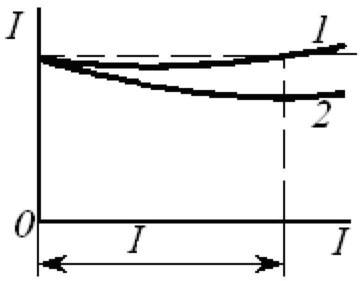


Figure 6.14 – Regulating characteristics of a compound – wound generator

6.6 Parallel operation of DC generators

Several generators are typically installed at DC power plants. They are connected in parallel on common buses. The total capacity of these generators must correspond to the power of their consumers. In addition, in case of breakdown of one of the generators or maintenance shutdown a standby generator is required. Installing multiple generators instead of a single one of total power provides a more efficient use of aggregates. So, in case of load decrease, several generators can be turned off, so that the others should work at full capacity, and therefore with a higher efficiency Shunt generators are often used in parallel operation. In this case, it is necessary to fulfill a number of conditions and provide the possibility of load transfer from one generator to another.

Parallel operation of generators.

Of two generators (figure 6.15) one generator G_I is connected to the network, i.e., circuit breaker *B1* is closed. To connect generator G_{II} to the same circuit one should create such conditions that the current in the armature circuit of the second generator G_{II} was minimal. For this, the sum of electromotive forces in the closed circuit formed by armature circuits of generators and a section of the circuit between them must be equal to zero, i.e. $E_{GI}+E_{GII}=0$. From this formula $E_{GI}=-E_{GII}$, i.e., electromotive forces of generators must be equal and directed oppositely. Using a special switch, one can alternately measure the voltage of the generator and network by means of voltmeter *V*. If the generators polarity is proper, the voltmeter needle deflects in one direction. If the needle deflects in different directions it is necessary to change polarity of a generator being turned on. The EMF of generator G_{II} is regulated by a rheostat connected in the excitation circuit. Typically, the generator G_{II} is turned on by circuit breaker *B2*, when generator G_I is already loaded. In this case $U_{NET}=E_{GI}-I_{GI}R_{GI}$; to connect generator G_{II} one has to perform the proper polarity and to create such current in the excitation circuit by a rheostat that electromotive force of the generator was equal to the voltage in the network $E_{GII}=U_{NET}$.

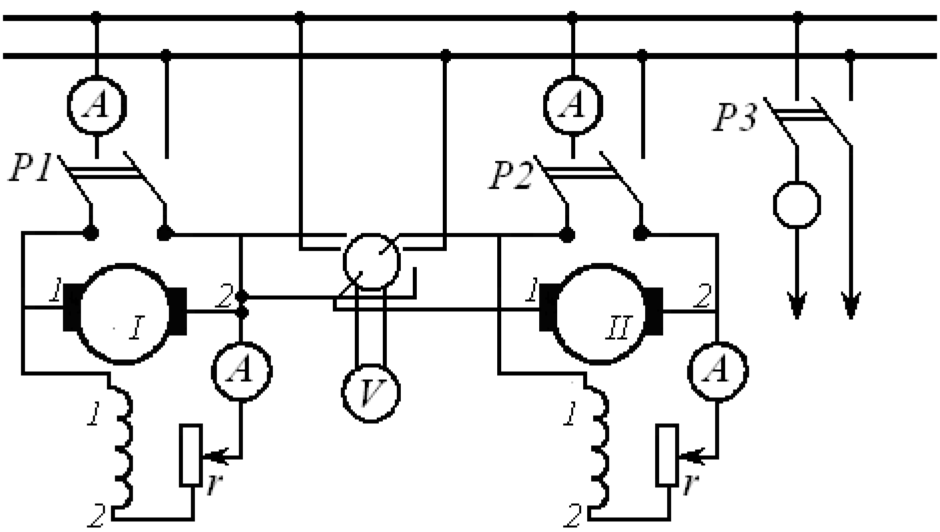


Figure 6.15 – Scheme of shunt generators during parallel operation

Distribution and load transfer.

During parallel operation, generators voltage at their terminals must be the same, as they are connected to a common network with voltage U_{NET}. From the equations of DC generator electromotive forces equilibrium:

$$U_{NET.}=E_{GI}–I_{GI}\,R_{GI}\,; \qquad U_{NET.}=E_{GII}–I_{GII}\,R_{GII},$$

where

$$I_{I}=(E_{GI}–U_{NET.})/R_{GI}, \qquad I_{II}=(E_{GII}–U_{NET.})/R_{GII}. \qquad (6.8)$$

Having connected generator G_{II} to the network, it is necessary to transfer the load from generator G_{I} to generator $G_{II.}$ One should increase its EMF E_{GII} by increasing the excitation current. In this case, current I_{GII} will flow in the armature circuit of generator $G_{II,}$ and current I_{GI} will decrease in armature circuit of generator G_{I} and it results in the voltage increase, which may disturb the normal operation of electric users. It is necessary to increase simultaneously the excitation current in generator G_{II} and reduce the excitation current in generator G_{I} for the network voltage to remain unchanged during load transfer. So, one can transfer loads from one generator to another by changing the excitation current of generators operating in parallel and thus, maintain constant voltage in the network.

Before disconnecting G_{I} it is necessary to transfer its load to G_{II} i.e. to fulfill the condition $I_{GI} = 0$ by reducing excitation current of G_{I} and the simultaneous increase of the excitation current on generator G_{II}. In case of a large change of EMF E_{GI} difference $E_{GI}–U_{NET}$ may become negative and current I_{GI} will change the direction regarding e. m. f. $E_{GI,}$ i.e. generator G_{I} will work as a motor consuming energy from generator G_{II}. That two engines are located on one shaft can lead to breakdown, and therefore generators circuits are provided with a protection that disconnects the generator when the direction of armature current changes.

If generators operate in parallel without excitation current regulation, the load distribution between them depends on the tilt of their external characteristics.

Figure 6.16 shows the external characteristics of generators G_{I} and G_{II}. If generators are put into parallel action in case of no-load operation, the characteristics emanate from a single point U_{0} on the y-axis.

If you then connect the load to the generators, the voltage will drop to some value U_{NET} which is common to both generators. And generator G_{I} having a characteristic with a larger tilt than generator G_{II} will be loaded with lower current I_{GI}. Therefore, it is desirable that the generators of equal capacity, connected in parallel, should have the same external characteristics, and the generators of various capacities - the same voltage changes at nominal load.

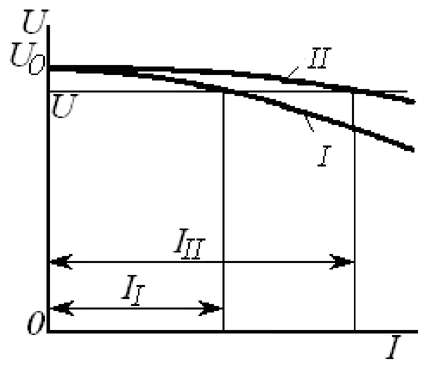


Figure 6.16 – Current distribution between generators

Parallel operation of compound – wound generators.

Diagram of compound – wound generators in parallel operation is shown in figure 6.17.

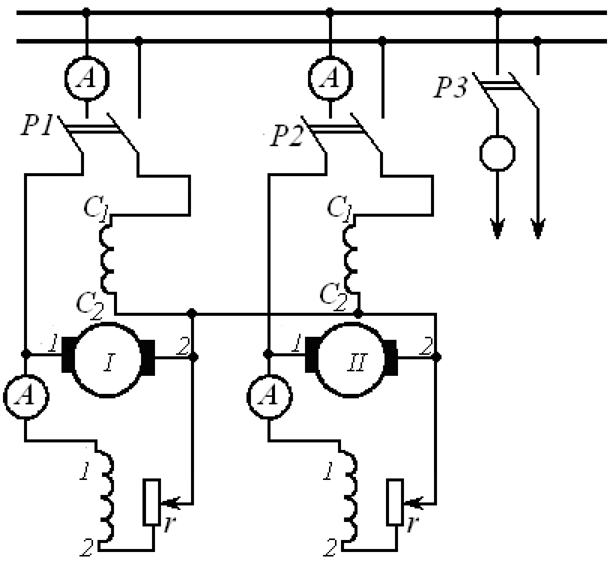


Figure 6.17 – Scheme of compound – wound generators in parallel operation

Its distinguishing feature is that point *C2C2* in which series windings are connected to similar terminals of the armature are connected by an equalizing wire. If there is no equalizing wire the stable parallel operation is not possible. Let us admit that current I_{GI} of the first generator for any reason (for example, due to the increased speed) slightly increases. So, the magnetic field of series excitation winding of the generator will increase, its EMF E_{GI} will increase. It will cause a further increase in current I_{GI}, etc. At the same time, current I_{GII} and EMF E_{GII} of the second generator will continuously decrease. As a result, one generator will be loaded and second unloaded; their parallel operation becomes unstable. But if there is an equalizing wire the parallel work will proceed normally, as a random increase of the armature current of one generator will be distributed between series excitation windings of the two generators and will increase electromotive forces of the generators. The load from one generator to another is transferred in the same way as the shunt generators.

7 DC motors

7.1 General information about DC motors

DC motors find a wide application in industrial, transport, crane and other installations where you want a wide smooth speed control. The same electric machine can operate both in generator mode and in motor mode. This property of electric machines is called reversibility.

Let us assume that the motor is supplied with voltage $U_{NET.} = const$. At a given (figure 7.1) poles polarity as well as current direction I_{ar} in the armature (the armature winding is drawn with only one wire) a driving moment M (or a torque) is created on the motor shaft; it is directed counterclockwise. Due to the action of this torque the motor rotates in the direction of the torque with constant frequency n.

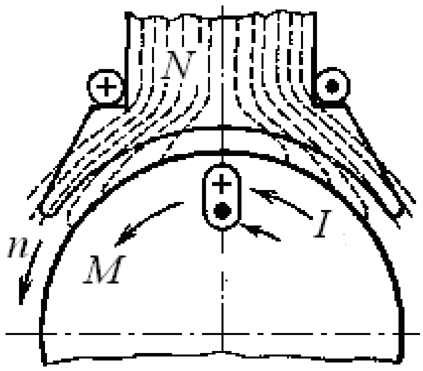


Figure 7.1 – Moment direction and counter electromotive force of motor armature winding

Applying the right-hand rule, we find that an electromotive force e_{ar}, is induced in armature conductor (winding). The EMF. is directed oppositely relative to armature current, and therefore it is called counter-electromotive force of the armature and it is considered as an electromagnetic counteracting of the motor relative to voltage of the network $U_{NET.}$.

For engine with constant speed, we can write the equation for EMF:

$$U_{NET.}=E_{ar}+I_{ar}R_{Яar},$$

where E_{ar} is electromotive force and I_{ar}–current corresponding to steady-state operation;

$I_{ar}R_{Яar}$ –voltage drop in the resistance of armature circuit of the motor.

The equation of moments of the engine. The electromagnetic torque of the motor:

$$M=(1/\pi)NI_{ar}p\ F\ /(2a)=C_M I_{ar}\ F \quad (7\ 2)$$

is created by interaction of the main magnetic field F and the current in the armature winding I_{ar} , as well as used to overcome braking torques: (retarding moments)

a) moment of no-load operation M_0;

b) net torque M_2;

c) dynamic moment M_j.

Moment of no-load operation M_0 exists in any mode of engine and is determined by the friction in bearings, friction of brushes on the collector, ventilation losses and losses in steel. Net torque M_2 is determined by the properties of the working machine and the nature of production process. Dynamic moment occurs at any change of rotational speed of the engine

$$M_j=\pm J(d\omega/d), \quad (7.3)$$

where J is the moment of inertia of all rotating parts;

ω – angular velocity of armature rotation.

If the engine speed increases, moment E_j is positive and adding moments M_0 and M_2, increases the braking torque on the motor shaft. With n decreasing, moment M_j is negative and reduces the total braking torque. The law of moment equilibrium determines the dependence between the torque and braking moment on the engine shaft: these points are in mutual equilibrium in any condition of engine operation, i.e. equal to each other in value but directed in opposite directions. At $n=const$ the moment $M_j=0$ and

$$M=M_0+M_2=M_{ST}\ , \quad (7.4)$$

where M_{ST}– is a static moment on the motor shaft.

Consequently, the engine runs steadily and rotates with constant frequency, if the developed torque and driving moment is equal to opposing moment $M=M_{ST}$ The point of steady-state operation of the engine is the intersection point of mechanical characteristics of an electric motor $M=f(n)$ and actuator $M_{ST}=f(n)$.

If the engine and the driven actuator have mechanical characteristics $M=f(n)$

and $M_{ST}=f(n)$ (figure 7.2,*a*) in case of a random increase in speed from *n* to *n*' the equality of moments will be disturbed.

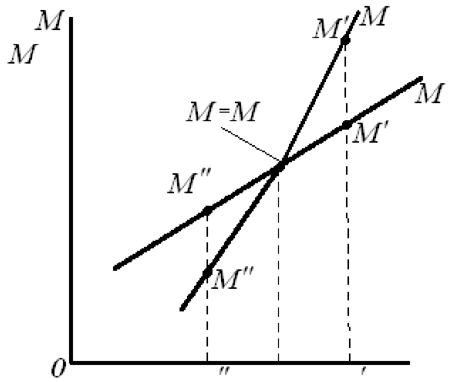


Figure 7.2 - To the concept of operational stability of the engine

The torque developed by engine will decrease and become less than a braking one $(M'<M_{ST})$. Therefore, the engine will slow down to value *n*, wherein $M=M_{ST.}$ On the contrary, in case of an accidental decrease in frequency *n* to value *n''* the motor torque *M''* becomes greater than opposing torque M''_{ST}, and the engine armature accelerates, returning it to the starting frequency *n*. Thus, in the case under consideration, the engine operation is stable, because $(dM/dn)<(dM_{ST}/dn)$. If mechanical characteristics $M=f(n)$ and $M_{ST}=f(n)$ have the form shown in figure 7.2 *b*, the motor operation becomes unstable.

Indeed, in case of a random change of the rotational speed from *n* to *n'* redundant torque of the motor *M'* causes a further increase of speed. If there is a change of speed from *n* to *n''*, the redundant opposing torque causes a further speed reduction, therefore, the engine operation will be unstable, because $(dM/dn)>(dM_{ST}/dn)$.

The engine energy diagram. Figure 7.3 depicts the energy diagram of a shunt motor operating in the steady mode, i.e. at $n=const$. The engine is supplied with power $P_1=U_CI$, which covers losses in the excitation circuit R_{ex} and electrical losses in armature circuit $I^2_{ar}R_{ar}$. And its remaining part is the electromagnetic power of the armature $P_{EM}=E_{ar}I_{ar}$ converted into mechanical power of the motor $P_{M.}$ Useful mechanical power at the motor shaft P_2 is less than the total mechanical power P_M by the value of power P_0 required to cover losses in steel P_S and mechanical losses P_{MECH}, i.e.

$$P_2=P_M-(P_S+P_{MECH}).$$

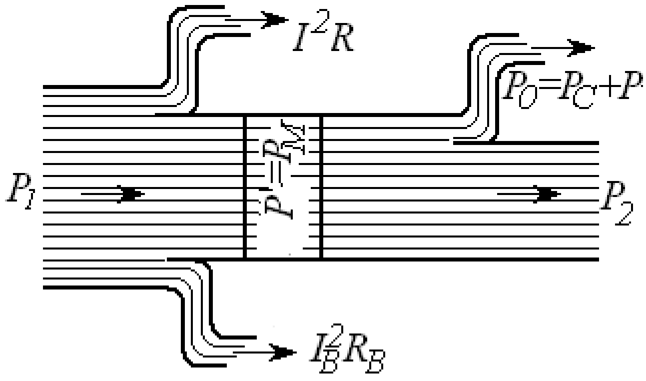


Figure 7.3 – Energy diagram of a shunt motor

7.2 Classification and characteristics of DC engines

Depending on the method of incorporating the excitation winding and the armature winding, there are the following types of DC motors:

a) shunt-motors;

b) series motors;

c) dual-field motors in which there are two excitation windings: parallel and serial. DC motors are evaluated by a group of the following characteristics: starting, operating, control and mechanical.

Starting characteristics.

Starting characteristics are determined by following values:

a) starting current I_{START} characterized by ratio I_{START}/I_{NOM} ;

b) starting torque M_{START}, characterized by ratio $M_{START}/M_{NOM;}$

c) smooth starting operation;

g) time of start up t_{START};

d) efficiency of operations determined by the cost of starting equipment.

At the initial moment of starting the engine, the armature is immovable, a counter- EMF in the armature winding is equal to zero and the current in the armature of the motor is $I_{AR}=U_S/R_{AR}$. The resistance of the armature circuit is small, so, the starting current exceeds the nominal one 20 or more times. A sharp current step at start-up creates on the shaft of the motor a large starting torque, which may cause mechanical destruction of both engine and actuator, to cause a sharp drop in voltage as well as intense sparking under brushes. Therefore, when starting up the engine one can use starting rheostats to limit the starting current. The starting rheostats are connected in series to the armature circuit (figure 7.4). With increasing frequency of rotation (speed) of the armature, counter- EMF increases but the armature current decreases. That is why the rheostat resistance should be reduced so that at the end of starting it was fully eliminated, and that starting current should exceed the nominal one no more than two or three times.

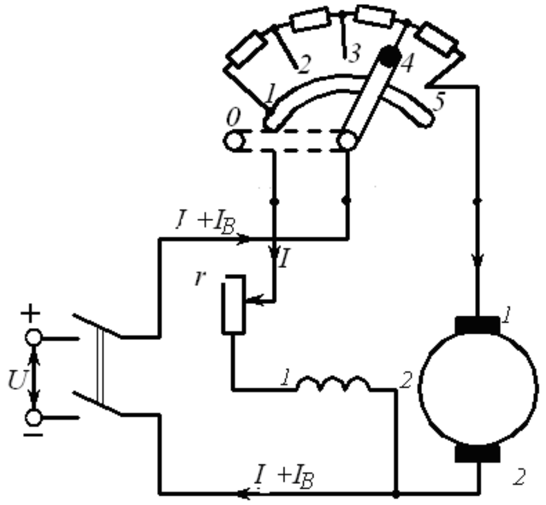


Figure 7.4 - Scheme of connection of a starting rheostat in the circuit of shunt motor

Running characteristics.

Running characteristics are the dependences of speed, torque and efficiency on useful power on the shaft or the armature current n; M and $\eta=f(P_2)$ или $f(I_{AR})$ if $U=U_{NOM}=const$ and nominal excitation current. The rotational speed n is determined from the equation of EMF $U_C=E_{AR}+I_{AR}R_{AR}=c_enF+I_{AR}R_{AR}$, where $n=(U_C–I_{AR}R_{AR})/(c_eF)$. So, $U_C=const$, the form of the frequency characteristic depends only on the voltage drop $I_{AR}R_{AR}$ and change of flow F.

Regulating characteristics.

These characteristics determine the properties of motors when speed control. They include:

a) limits of regulation, determined by the ratio $n_{MAX}/n_{MIN;}$

b) economical operation of regulation (initial equipment costs and subsequent maintenance costs);

c) nature of regulation, smooth or stepped;

g) easy of regulating equipment and operations for speed regulation. DC motors possess diverse and flexible regulating characteristics and are therefore indispensable in installations with widely variable speed.

Mechanical characteristics. Mechanical characteristics are very important for electric drive of industrial mechanisms. They represent the dependence $n=f(M)$ at ???=*const* and constant resistance in the armature circuit (provided the current control in the excitation circuit of the motor is not performed).

7.3 Shunt motor

To start up DC motors one may use two-, three - and four-terminal starter rheostats. Figure 7.4 presents the scheme of turning on three-terminal starter rheostat for the shunt engine.

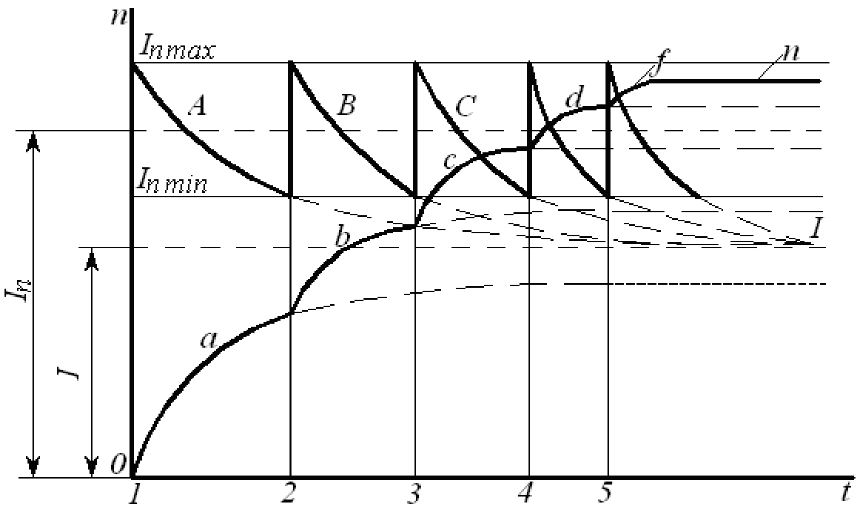


Figure 7.5 – Diagram of motor start-up process

The rheostat has six contacts: five working ones (1, 2, 3, 4, 5) and a dead contact (zero 0); three terminals, L, W, I, which are respectively connected to the line, excitation winding and armature. A sliding contact of the rheostat moves along fixed contacts and the contact arc D, through which the excitation winding is on full voltage. The regulating rheostat in the excitation circuit of $r_{P\Gamma}$ should be turned off, as in this case, excitation current I_{ex}, magnetic flux F and the motor torque reach the maximum value that facilitates engine starting up. Starting rheostat is designed for operation conditions of short duration, when the number of sections is determined by terms of smoothness of engine start-up. As in the first moment of the start, $n=0$, and counter electromotive force $E_{AR}=0$, and $I_{start.MAX}=U_C/(R_{AR}+\Sigma R_{start})$, where R_{start} is the sum of resistances of all sections of the starter rheostat.

The starter rheostat can be calculated so that the series shutdown of its sections the starting current should be varied from $I_{start.MAX}$ to $I_{start.MIN}$. In this case, I_{start}=0,5 ($I_{start.MAX}+I_{start.MIN}$). Figure 7.5 shows the diagram of rheostat starting of the motor. After increasing the speed, the starting current is reduced to value $I_{start.MIN}$, the handle of rheostat is transferred to the second contact, thereby turning off the resistance of the first section. The starting current increases again to $I_{start.MAX}$, after which the engine speed starts to rise along curve b, and the current decreases along curve *B*. Then the starting process goes in the same order, until the entire rheostat will be turned off, and then the engine will run in steady mode at current *I* and frequency of rotation *n*. The engine is stopped by quick movement of the starting rheostat handle to zero position and by disconnection of the circuit breaker *BR* (figure 7.4).

Engine running characteristics.

They have following forms n; M; $\eta=f(I_{AR})$ if $U=U_{NOM}=const$ and $T_{EX}=const$.

A diagram of the motor is shown in figure 7.6 *(a);* the rheostat in the excitation circuit of $r_{рг}$ needs to be adjusted so that the engine should develop nominal power P_{NOM} at nominal voltage U_{NOM}, current I_{NOM}, and the frequency of rotation n_{NOM}. In this position, the rheostat should remain in the same position. The running characteristics are shown in figure 7.6 *b*. The frequency of rotation of the armature is $n=(U-I_{AR}R_{AR})/(c_eF)$; as, by assumption, values U and I_{AR} are constant, then under these conditions, the engine speed is slightly affected by two things: the voltage drop in armature I_{AR} and armature reaction. In case of the increase of the load current I_{AR}, the voltage drop increases and rotational speed decreases. Simultaneously, the armature reaction demagnetizes the motor, i.e. it results in decreasing the magnetic flux of main poles and therefore, tends to increase its frequency of rotation.

Thus, these facts have the opposite effect on the frequency of rotation of the armature, and depending on the predominance of one of these factors a reduction or an increase in the frequency of the rotation occur under loading of the engine. It is necessary to put the stabilizing winding on main poles for the operation of shunt engines to be stable even when the armature reaction predominates. The stabilizing winding is connected in series with the armature winding and is activated in accordance with a parallel excitation winding. In this case, while increasing the load current the demagnetizing effect of armature reaction is compensated by a magnetizing action of stabilizing winding.

Thus, the external characteristic of a shunt motor $n=f(I_{AR})$ has the form of a nearly straight line, slightly inclined to the x-axis. The change of the rotational speed while increasing the load from zero to nominal is 2÷8%. Such external characteristics is one of the most distinctive properties of the shunt engine; this characteristic is called hardening. Knowing the character of the dependence $n=f(I_{AR})$ it is easy to explain the characteristic of the torque $M=f(I_{AR})$. According to the equation of moments at the steady mode of operation: $M=c_MI_{ar}F=M_0+M_2=M_{ST}$. At no-load operation $M=M_0=c_MI_0F$. If the flow of excitation remained constant, characteristic $M=f(I_{AR})$ would represent a straight line.

In fact, when current I_{AR} increases flux F decreases a little due to demagnetizing action of the transverse armature reaction, so, characteristic $M=f(I_{AR})$ deviates somewhat from a straight line to the axis of the current. The characteristic of useful moment $M_2=f(I_{AR})$ must go lower characteristic $M=f(I_{AR})$ by the value of idling torque M_0, which is almost independent of the load. Figure 7.6 *b* presents also the curve dependence of efficiency on the load $\eta=f(I_{AR})$. The efficiency increases rapidly in the range from $I=I_0$ up to $I\approx0,25I_{NOM}$, it reaches its maximum at about $I\approx0,5I_{NOM}$ up to $I\approx I_{NOM}$, and then within load change from $I\approx0,5I_{NOM}$ up to $I\approx I_{NOM}$ remains almost constant.

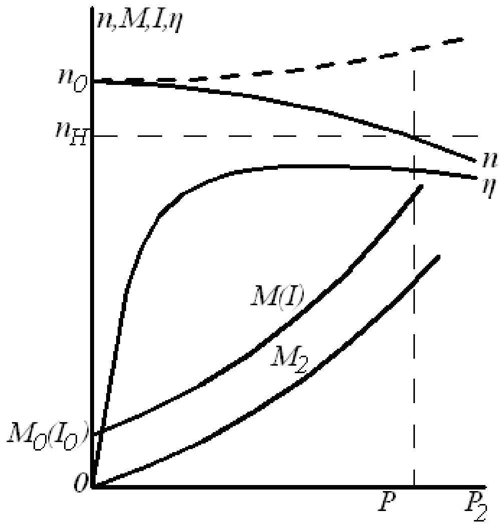


Figure 7.6 – Scheme of a shunt motor *(a)* and its running characteristics *(b)*

As seen from the graph of the efficiency, to run the motor with high efficiency, we must strive to its nominal load. Usually, in engines of low power $\eta=75\div85\%$, average engines and more power $\eta=85\div94\%$.

Regulating characteristics.

One of the main advantages of DC motors is the possibility of smooth speed control over a wide range. In general, the armature circuit of the engine can be turned on by adjusting the rheostat $R_{pг}$. Then from the formula $n=[U–I_{AR}(R_{AR}+R_{pг})]/(c_eF)$ it follows that the speed of DC motors can be controlled by:

a) voltage change U;

b) voltage drop change in the resistances of armature circuit $I_{AR}(R_{AR}+R_{pг})$;

c) the change of the excitation flow and, consequently, the change in the excitation current I_{AR}.

The first method is possible only in special installations, allowing regulation of voltage U. Rheostat $R_{pг}$ in the armature circuit should be chosen so that one could regulate the speed in the desired range. Let us assume that the voltage and the excitation current remain constant, i.e. $U=const$ and $I_{AR}=const$, in addition, static torque $M_{ST}=M_0+M_2$ does not depend on the engine speed. When rheostat $R_{pг}$ is not turned on a steady-state mode of engine operation is characterized by torque M_2, rotational speed n_1, and current in the armature circuit I_{21}. Immediately when rheostat $R_{pг}$ is turned on, the speed and counter EMF remain unchanged due to the considerable mass moment of inertia of the armature and the current in the armature circuit is reduced to a value I_{21}'. The torque of the engine will be correspondingly reduced.

The excess load torque over the torque results in decreasing frequency of armature rotation, reducing counter EMF and increasing current in the armature circuit (figure 7.7). The new value of current I_{22} and rotational speed n_2 are installed at equal torque of the motor and load torque of the driven mechanism. If the excitation current and load torque M_2 are constant, the steady-state value of current in the armature circuit is $I_{22}= I_{21}$ and the frequency of armature rotation $n_2=n_1[U–I_{21}(R_{AR}+R_{pe})]/(U–I_{21}R_{AR})$. The installed power of the motor is $P_1=U(I_{AR}+I_{EX})$ in steady state modes remains unchanged. The useful power $P_2=M_2\omega=M_2 2\pi n_2/60$ is reduced in proportion to the rotation speed. Disadvantages of this method of speed control is low efficiency and deterioration of cooling conditions, so it is used mainly for speed control of low power motors. If the engine operates in steady state at constant voltage at the terminals of the armature and current in the excitation winding, according to the relevant operating characteristics for the desired torque M_2 one can determine rotation frequency n_1 and current I_{21} in the armature circuit, as well as one can calculate counter EMF E_{21}. When excitation current reduces to value $I_{EX2,}$ the magnetic flux decreases. Due to high mass moment of inertia of the armature, its rotation frequency remains the same immediately after changing the excitation current, a counter-e. m. f. decreases to value E_{21}' proportionally to the magnetic flux, the circuit current of the armature increases to value $I_{21}' = (U–E_{21}')/R_{AR..}$ Since the voltage drop in the armature circuit is a small part of the network voltage, the relative increase of current $(I_{21}'–I_{21})/I_{21}=(E_{21}–E_{21}')/(U–E_{21})=(E_{21}–E_{21}')/I_{AR}R_{AR}$ significantly exceeds the relative decrease of the magnetic flux. This results in increasing the torque and accelerating the armature rotation. The counter-e. m. f. in the armature winding increases, the current decreases, until the equilibrium between the motor torque and load torque of the driven mechanism occurs under new steady-state values of current I_{22} and the rotation speed n_2 (figure 7.7). Power supplied to the motor $P_2=U(I_{AR}+I_{EX})$ and useful power $P_2=M_2 2\pi n/60$ increase in the same measure. Therefore, the efficiency of the engine does not practically change using this method of speed control. The dependence of the rotation frequency n on the value of excitation current I_{EX} is expressed by regulating characteristic of the engine $n=f(I_{EX})$ if $I_{AR}=const.$ and $U=const$. Figure 7.8 shows the two regulating characteristics of the engine, taken at various values of armature current: if $I_{AR}<I_{NOM}$ and $I_{AR}=I_{NOM}$. As seen from these characteristics at low values of the excitation current and the open circuit excitation $I_{EX}=0$ the rotation frequency increases indefinitely, that results in engine "overrun".

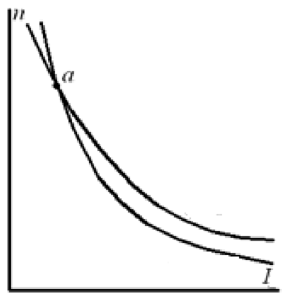


Figure 7.7 – Regulating process of rotational frequency by a rheostat in the armature circuit *(a)* and excitation circuit *(b)*

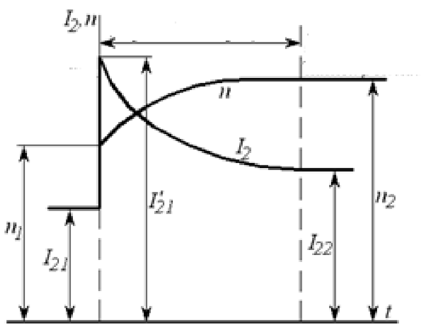


Figure 7.8 – Regulating characteristic of the motor

7.4 Series motor

Figure 7.9 shows a diagram of a series motor. Startup of this engine is carried out by using two-terminal starting rheostat R_{ST}, as the shunt engine.

Engine ratings.

They have the form n; M and $\eta=f(I_{EX})$ if $U=U_{NOM}=const$. In series engines the armature current is simultaneously the excitation current ($I_{AR}=I_{EX}=I$), so the magnetic flux F at different loads of the machine changes greatly, and this is its feature. From the equilibrium equations of the EMF we have the same formula of the rotation frequency as that for shunt engine: $n=(U–I_{AR}R_{AR})/(c_eF)$. With the series engine, the change of the main magnetic flux of the poles has a principal value, if not to take into account the voltage drop $I_{AR}R_{AR}$ and armature reaction.

At low and medium loads the motor magnetic circuit can be considered unsaturated and in this case $F=k_{\Phi}I_{AR}$, therefore, $n=(U–I_{AR}R_{AR})/(c_ek_{\Phi}I_{AR})$. The coefficient of proportionality k_{Φ} in a significant range of loads at $I_{AR}<I_{NOM}$ is almost constant and only if $I_{AR}>(0,8\div0,9)I_{NOM}$ of k_{Φ} begins to slightly decrease due to the saturation of the magnetic circuit.

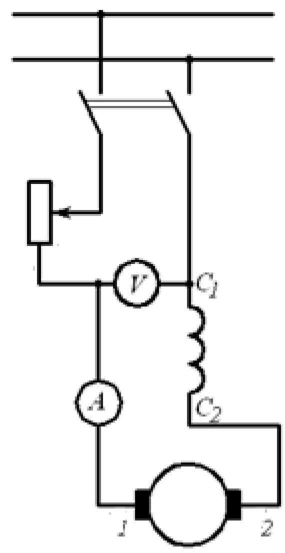


Figure 7.9 – Scheme of series engine

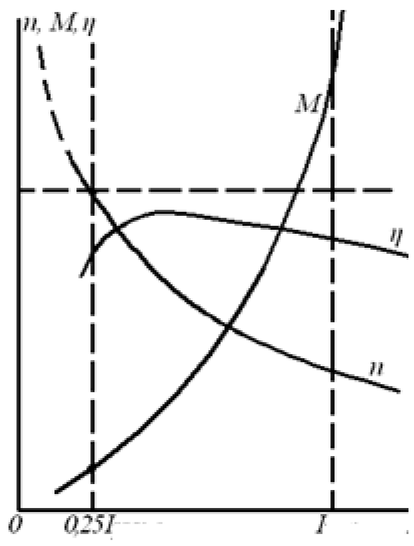


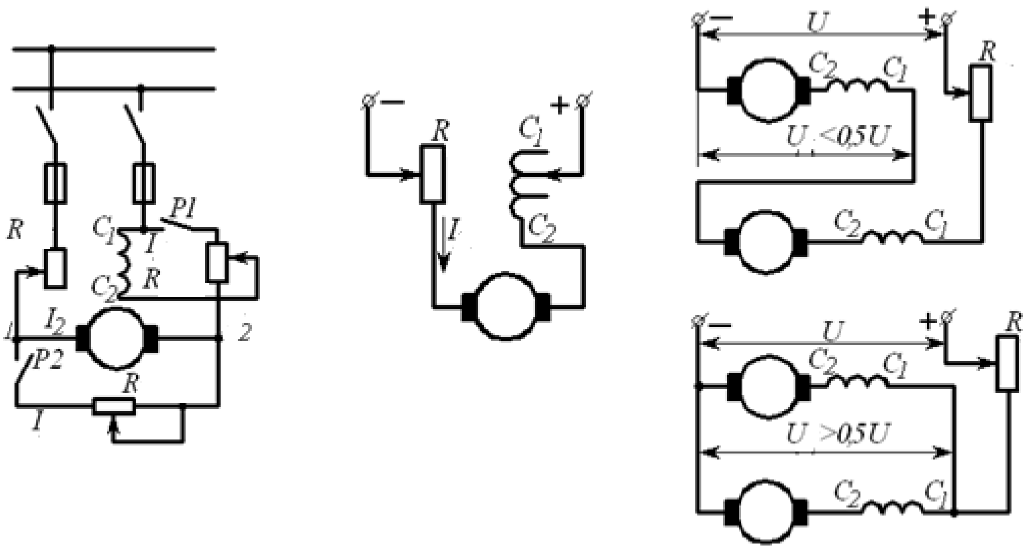
Figure 7.10 – Series engine ratings

Figure 7.10 shows the series engine ratings. The characteristics of rotation frequency is soft, i.e., the rotation frequency abruptly changes when the load changes, and has a hyperbolic character. However, with a significant decrease of load, the engine starts to develop an increasing rotational speed or, as they say, "to overrun" that can result in destructing the machine. Therefore, the series engine should be placed in such operation conditions in which neither start up without load, nor idle operation would be impossible. These engines are designed to withstand without harmful effects the speed increase by 20% over the highest one specified on the factory plate, but no more than 50% over nominal. Characteristic $M=f(I_{AR})$ if $U=U_{NOM}=const$ of series engine with a weak saturation of steel is a parabola. Since $F=k_{\Phi}I_{AR}$, and $M=c_M I_{AR} F$, so $M=c_M' I_{AR}^{2.}$ When current I_{AR} increases, the motor is saturated, i.e. $F=const.$ does not depend on current I_{AR} and the characteristic of torque straightens. Under these conditions, the torque varies almost proportionally to the current, as the shunt motor: $M=c_M I_{AR} F$. The property of series engine to develop a torque proportional to the square of current is very important in the cases where a high starting torque is needed (cranes, locomotives), as well as a large overload capacity of the motor. With the increase in load, useful power $P_2=M_2\omega=M_2 2\pi n/60$ increases slower than the torque, due to considerable reduction of rotational frequency. Supplied power $P_1=UI$, proportional to the motor current also increases slower than the torque. Characteristics of the efficiency has the same form as for the shunt engines.

Regulating engine characteristics.

The rotational frequency of series motors is also regulated by voltage change. One can regulate the speed of shunt engines by means of this method. The considered method is used in traction installations (cranes, subways, trams etc.), where several engines are installed; they are connected in series at slow speeds, and in parallel at large ones, simultaneously using connection of regulating rheostat $R_{рг}$, as shown in figure 7.11.

The control of rotational speed by means of changing the excitation magnetic flux. During normal turning on the motor winding, the current in excitation winding is equal to the armature current. If you close circuit breaker *B1* (figure 7.11, *b*), the excitation current will decrease, increasing the frequency. When the frequency of rotation increases, switching conditions deteriorate and confine the upper limit of rotational frequency of the armature, which does not exceed *1.4* of nominal. To evaluate this method of speed control, the concept of coefficient of field extinction $c_{f.e.}=R_{SH.EX}/(R_{EX}+R_{SH.EX})$ is introduced, where $R_{SH.EX}$ – shunt resistance of parallel excitation winding. A similar increase in rotational frequency of the armature can be obtained if the excitation winding is tapped, i.e., to make the taps on some excitation windings turns and make changes of the magnetomotive force of this winding (figure 7.11, *b*). The resistance change of regulating rheostat in the armature circuit also allows you to adjust the motor speed (U_M – motor voltage).



a) *b)* *c)*

a) – changing the circuit of turning on;
b) – changing the excitation current;
c) - sectioning the armature winding.

Figure 7.11 – Schemes of regulating rotational speed of series engine

7.5 Dual-field motor

Dual-field motor has two windings, one *W* of which is connected in parallel with armature winding, and the second *C* –in series (figure 7.12).

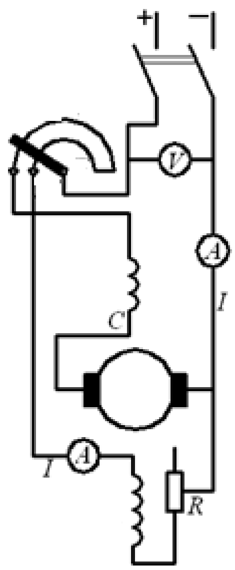


Figure 7.12 – Scheme of turning on of dual-field engine

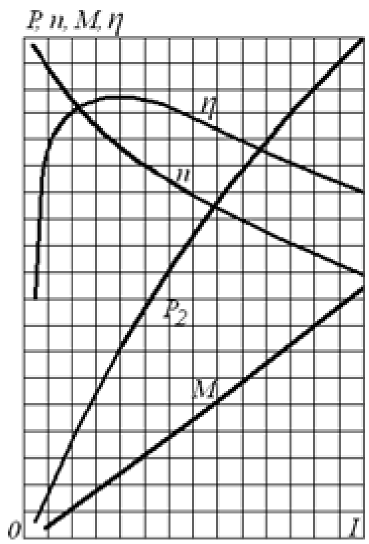


Figure 7.13 – Dual-field engine ratings

The ratio of magnetomotive forces of windings may be different, but usually one of the windings creates a great magnetomotive force, it is called principal. The engine speed is $n=(U–I_{AR}R_{AR})[c_e(F_1±F_2)]$, where F_1, F_2 are magnetic fluxes of parallel and serial excitation windings, respectively. The plus sign corresponds to additive polarity of the excitation windings, when magnetomotive forces of windings are added. Therefore, as the load increases the magnetic flux increases too, which results in decreasing engine speed. With subtractive polarity of windings when you increase the load, magnetic flux F_2 demagnetizes the machine (minus sign), increasing the frequency of rotation. At starting dual-field motor with subtractive polarity of windings, magnetic flux of serial winding F_2 can significantly weaken the resulting flow of the engine and this can complicate the start-up process. To avoid this, serial windings of such motors are sometimes shorted during all the time of start-up.

Dual-field motor ratings (figure 7.13) become similar to the characteristics of shunt or series engine according to which winding plays a major role. This engine has a number of advantages compared with series engine. It can run idle, as the flow of parallel winding F_1 restricts the engine speed during no-load operation and eliminates the danger of "overrun". The rheostat in the circuit of parallel winding adjusts the frequency of rotation. The dual-field motor is used when you need a considerable starting torque, fast acceleration at the start-up and relatively large speed variations are admissible when the load changes. In this regard, the dual-field motor is used to drive DC compressors, machine tools, rolling mills, lifts, electric traction etc.

8 Losses in DC machines and their efficiency

8.1 Types of losses

While operating the electrical machine loses a part of consumed energy. This energy is lost uselessly and dissipated as heat, warming the individual parts of the machine. Losses in electrical machines are divided into basic and additional. Main losses result from basic electromagnetic and mechanical processes, whereas additional processes occur due to direct-axis pulsations of the flow caused by the stepped appearance of the armature, as well as due to the uneven distribution of the main magnetic flux in the groove, etc. Despite the mode in which the machine (generator or motor) operates, the basic losses are divided into electrical, magnetic, or losses in steel and mechanical.

Electrical losses.

Electrical losses in each winding are $P_{el}=I^2R$. Winding resistance depends on its temperature. Therefore, GOST 2582-72 determines losses in the windings at rated temperature of 75°C for A classes of windings insulation; 115°C for E and B classes of insulation; 130°C for F and H classes. Usually one should calculate the losses in the armature circuit $P_{EL.AR}=I_{AR}^2R_{AR}$ and in the excitation circuit $P_{EL.EX}=U_{EX}I_{EX}$ (parallel winding). At the temperature θ the resistance of winding will be:

$$R_\theta=R_0[1+\alpha(\theta-\theta_0)], \quad (8.1)$$

where R_0 is the resistance of winding at temperature θ_0;

α – temperature resistance coefficient (for copper α=0,004).

Electrical losses include losses in brush contacts. Two brushes of different polarity the value of losses is $P_{EL.BR}=\Delta U_{BR}I_{AR}$, where ΔU_{BR} is a transient voltage drop at the brushes taken into accordance with the brand of brushes: for carbon and graphite *2 V*, for metallographite *0.6 V*.

Magnetic losses.

Magnetic losses include hysteresis and eddy currents losses caused by the reversal magnetization of steel. The value of magnetic losses depends on magnetic induction and frequency of reversal magnetization of the armature core *f*; since $f=pn/60$ and does not depend on the load of the machine, so, at $n=const$ they can be considered constant. The hysteresis losses (*W/kg*) are:

$$P_H=\sigma_H fB^2 100 \,, \quad (8.2)$$

where σ_H=3,2÷4,4 is a coefficient-dependent of the steel grade;

$f=pn/60$ is the frequency of reversal magnetization;

B is the highest value of magnetic indu σ_{EDDY} ction in the steel.

Eddy currents losses.

$$P_{EDDY}=\sigma_{EDDY}(fB/100)^2 \,, \quad (8.3)$$

where σ_{EDDY} – coefficient that depends on the brand and thickness of steel sheets (for low-and medium-alloyed steel grades $\sigma_{EDDY}=3,6\div2,9$, for high-alloy $\sigma_{EDDY}=1\div0,6$).

Mechanical losses.

Mechanical losses P_{MECH} consist of losses in bearings, friction of the brushes on the commutator and ventilation losses (air friction losses of rotating parts of the machine). The losses in the bearings depend on the type of bearings, the condition of bearing surfaces, type of lubricant, etc. When the machine operates, these losses, depend only on the speed and do not depend on the load. Losses in bearings $P_{BE}=c_{FR}F_{BE}\upsilon_{SH}$, where c_{FR} is the coefficient of friction; F_{BE} – pressure on the bearing; υ_{SH} – frequency of rotation (speed) of the shaft journal. Friction losses of the brushes $P_{FR.BR}= c_{FR}\ f_{BR}S_{BR}\upsilon_C$, where f_{BR} – specific pressure on the brush; S – contact surface of all brushes; υ_C - peripheral speed of the commutator. Ventilation losses P_{VEN} depend on the machine design and type of ventilation. In self-ventilated machines with built-in fans ventilation losses are $P_{VEN} =c_{VEN}Q\upsilon^2$, where c_{VEN} is a coefficient; Q– the amount of ventilated air, m^3/s; υ – speed of the fan at outer circumference, *m/s*. General mechanical losses are $P_{MECH} = P_{BE} + P_{FR.BR} + P_{VEN}$. The sum of the magnetic and mechanical losses is the loss of no-load operation $P_0=P_C+ P_{MECH}$.

Additional losses.

It is difficult to evaluate additional losses. These are losses in pole terminals due to the rotation of the armature and its serration, as well as losses in armature steel caused by distortion of the main field by armature reaction and others. Therefore, in machines without compensating windings, the value of additional losses is taken equal to *1%* of useful power for generators or *1%* of input power for engines. In machines with compensating windings, the value of additional losses is equal to *0.5%*.

8.2 Efficiency

If we know the losses in the machine, it is possible to determine the coefficient of performance (efficiency) of the machine. As you know, the generator efficiency is the ratio of useful electrical power to mechanical power on the shaft: $\eta=P_2 100\%/P_1$. Here $P_1=P_2+\Sigma P$, where ΣP is the sum of all losses in the machine; $P_2=UI$ for generator; U is the voltage at terminals of the generator; I – current given to the network. So, for the generator:

$$\eta_\Gamma = \frac{P_2}{P_2+\sum P} = \frac{UI}{UI+\sum P} = 1-\frac{\sum P}{UI+\sum P} \quad . \qquad (8.4)$$

The input power in engines is $P_1=UI$, where U is the voltage at motor terminals, I is the current used by the motor. So, for the engine

$$\eta = \frac{P_1-\sum P}{P_1} = \frac{UI-\sum P}{UI} = 1-\frac{\sum P}{UI} \qquad (8.5)$$

Since the efficiency of the machine depends on the sum of losses, it is a constant value, i.e. it depends on load. At no-load operation when useful power is zero, $\eta=0$. While the load is increased the efficiency of the machine increases rapidly. It has the highest value when the load is equal to $(0,8–1)P_{NOM}$, when constant losses are equal to variable ones. Under significant overloading due to losses increase, the efficiency decreases again in the resistances of the armature circuit.

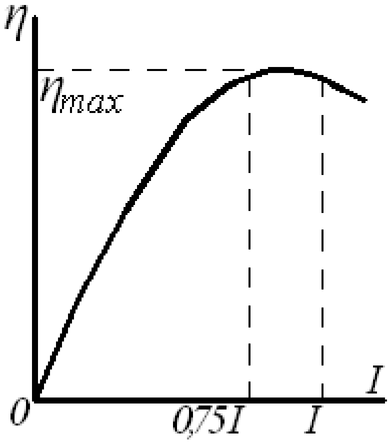


Figure 8.1 – Efficiency dependence on load

Figure 8.1 shows the efficiency dependence of the machine $\eta=f(I)$ if $U=U_{NOM}=const.$ and $n=n_{NOM}=const$. Modern electrical machines have high efficiency So, for DC machines of *10 kW* efficiency $\eta=0,83\div0,87$; ones of *100 kW* $\eta=0,88\div0,93$; of 1000 kW $\eta=0,92\div0,96$. Machines of small capacity have the lowest efficiency value, for example, for *10 W* engine $\eta=0,3\div0,4$. The methods of experimental determination of efficiency are divided into direct and indirect. There are several methods of direct determination of the efficiency by using experimental values P_1 and P_2:

a) mode of engine-generator, in which two identical machines are connected on the same shaft, one of them acting as an engine and the other as a generator;

b) mode of calibrated machine in which the test machine serves as a motor and causes the rotation of calibrated electric motor;

c) mode of engine, wherein the tested machine operates in motor mode. The direct method of determining efficiency can provide significant inaccuracy, because, firstly, P_1 and P_2 are close values, and secondly, their experimental determination is associated with errors. Therefore, GOST 11828-72 prescribes for machines with $\eta>70\%$ an indirect method of determining the efficiency at which experimental data is used to determine losses ΣP.

9 Special DC machines

9.1 Amplifiers in electric machines

The system of continuous automatic regulation and control is widely used in modern industrial electrical installations. One of the main elements of this system is a power amplifier. There are different types of amplifiers: electronic, electromagnetic and ones for electrical machines. The latter are a special kind of electric machine generators, which are rotated by drive motors with *n=const*. These machines allow obtaining a lot of power at quite low output power control due to the power derived from the drive motor. One of the main characteristics of electromagnetic amplifiers (EMA) is the power gain equal to the ratio of the output electric power P_2 to the control power P_C

$$g_P = P_2 / P_1. \qquad (9.1)$$

An important requirement for the control system is minimum time of control signal transmission, but EMA has an electromagnetic inertia due to the excitation flow. The operation of EMA is determined by electromagnetic time constant of windings

$$T = L/R, \qquad (9.2)$$

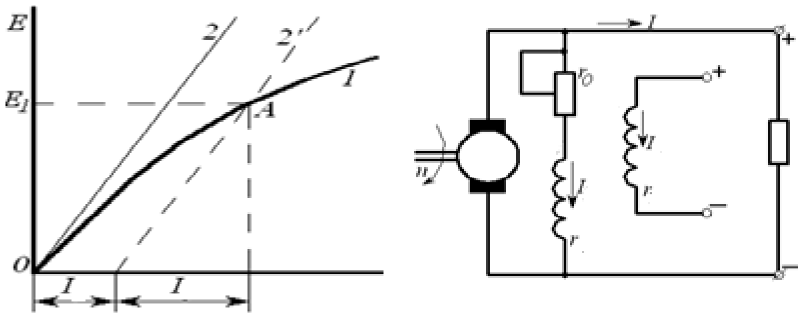
where L and R are inductance and active resistance of control windings.

If the power gain increases, the time constant of the amplifier also increases. One can compare amplifiers with different power gain g_P and time constant T by the quality factor f_Q

$$f_Q = g_P / T \qquad (9.3)$$

and call them single staged. A serial multiple power amplification occurs in multistage amplifiers. According to the mode of excitation, one can distinguish electromagnetic amplifiers (EMA) with longitudinal and transverse flow. The main flow of excitation is directed along the longitudinal axis of the machine in amplifiers with a longitudinal field.

Structurally, a single stage electromagnetic amplifier with a longitudinal flux (figure 9.1, *a)* is a generator of parallel excitation with a single winding of independent excitation, which is called the control winding. Self-excitation circuit of an electromagnetic amplifier with a self-excitation winding has the resistance equal to or somewhat greater than the critical one by condition for the appearance of self-excitation process. The voltage at the output of the amplifier as a generator with self-excitation is zero, since the voltage-current characteristic *2* crosses the characteristic*1* of no-load operation at central point of coordinates (figure 9.1 *b).* If current I_C flows in the control winding, due to its magnetomotive force the generator will quickly self-excite to the point *A* of no-load operation characteristic. In this case, the straight line will be in position *2'*.



a) *b)*

Figure 9.1 – Scheme of an electromagnetic amplifier with a longitudinal field *(a)* and its no-load operation characteristic *(b)*

Electromagnetic amplifiers with transverse field are the most common. They are usually made with smooth poles *2p=2*. In a conventional DC machine cross-reaction of the armature distorts the main field of poles and often breaks commutation, therefore, measures are taken to mitigate the cross reaction of the armature. In electromagnetic amplifiers with a transverse field a transverse flow of the armature reaction is used to obtain the e. m. f. For this purpose an additional pair of vertical brushes *2* is placed on the commutator, the axis of which is perpendicular to the major axis of horizontal brushes *1* (figure 9.2).

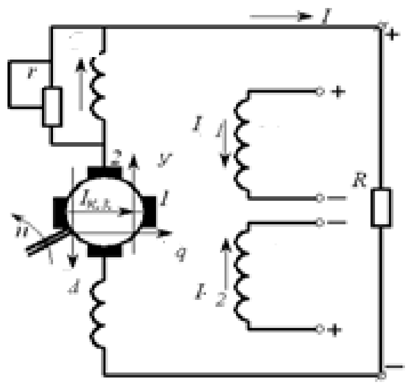


Figure 9.2 – Scheme of connection of electromagnetic amplifier with transverse flow

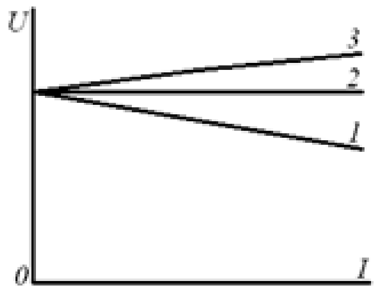


Figure 9.3 – External characteristics of an electromagnetic amplifier

After submitting the input signals on control winding, currents of these windings I_{CON} create magnetomotive force and the flow F_{CON}, which acts in the direction across the axis of short-circuited brushes *1*. Crossing the relatively small flow an e. m. f. is induced in the armature winding, which creates short - circuit current $I_{SC.}$ This is the first stage of amplification which is essentially a separately excited generator, operating in the mode of short-circuit. Short - circuit current I_{SC} creates a transverse flow of the armature reaction F_q, which is directed along the axis of horizontal brushes *1* and perpendicular to the axis of vertical brushes *2*. Under the action of flow F_q an EMF is induced in the armature winding applied between brushes *2*. If the load is connected to these brushes, there is a load current *I* in circuit of vertical brushes *1*. Therefore, the second stage of amplification by electromagnetic amplifiers (EMA) are the circuits of transverse and longitudinal brushes. The load current *I* creates a longitudinal flow of armature reaction F_d, the direction of which coincides with the axis of vertical brushes *2* and is a counter one against flow F_{CON} of a control winding. If you do not take measures to compensate flow F_d, the machine will be demagnetized and inoperative. That is why, there is an obligatory compensatory winding in the housing of EMA, the flow of which F_{COM} is directed towards the flow F_d. The precise regulation of compensation is carried out by rheostat r_{COM}, connected in parallel to the compensation winding. To improve the commutation over vertical brushes *2*, through which load current *I* passes, additional poles are mounted.

Due to the fact that the magnetic circuit of the amplifier is unsaturated, voltage *U* is a linear function of load current *I*, i.e. the outer characteristic of EMA is a straight line (figure 9.3). If there is an undercompensation of the armature reaction when load increases, the voltage of the amplifier drops (curve *1*). If the compensation is full, the voltage of EMA varies slightly, only due to the change of the voltage drop on the armature (curve *2*). If there is a significant overcompensation (curve *3*) a self-excitation of the amplifier can take place, i.e., an arbitrary increase in voltage at current constancy in the control winding. The total coefficient of amplification of EMA with a transverse field is in the range *2000÷10 000*, but sometimes reaches *100 000*.

9.2 DC machines with a smooth armature

Modern automatic control systems make stringent requirements to the executive DC engines: speed, maximum precision of speed control, high commutation reliability. Recently there have been engines in which the armature winding is placed directly on the armature core but not in the grooves. Machines with smooth armatures offer the following features: the armature winding has a relatively lower inductance than the winding placed in the grooves; lack of teeth makes it possible to increase significantly the magnetic inductance in the air gap.

Decreasing winding inductance reduces reactive EMF in commutated sections. The presence of a relatively large non-magnetic portion of the magnetic circuit of the machine reduces the armature reaction. Therefore, the engines with a smooth armature have straight resistant characteristics of speed and linear dependence of torque of the armature current even at high accelerations. Furthermore, due to the absence of teeth in the engine there is practically no pulsation of the main magnetic flux, which is important in the motor operation. The usefulness of a smooth armature is caused by the improvement of their characteristics in small capacity machines and by ensuring sufficient commutation reliability and improving the distribution of potential on the commutator in high-power machines. The armature winding is mounted directly on either the insulated core or a plastic layer.

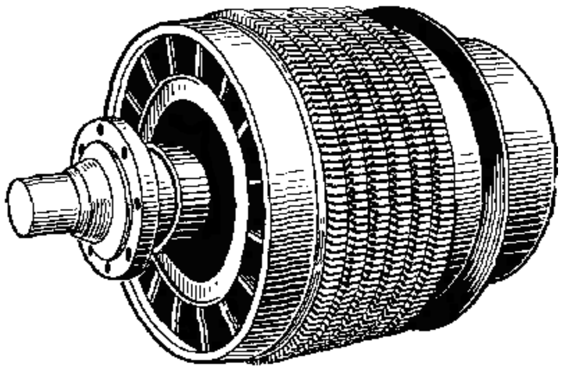


Figure 9.4 – Smooth – core armature with plastic segments before laying down a winding

In the first case, sections of the armature winding impregnated with epoxy resin are placed on the insulated core. A banding glass tape fixes these sections. In the second case, plastic segments are installed on the smooth surface of the armature core. The winding is placed in the grooves (figure 9.4). One of the main problems arising in the manufacture of machines with smooth armatures is the creation of the excitation winding to provide greater magnetomotive force if dimensions are limited. Such engines are used in drives that operate with a wide speed and load control (rolling mills, weight-handling devices).

9.3 Unipolar machines

Unipolar generators allow to obtain a large direct current (up to *500 000 A*) at low voltage (for example, in electrolysis plants). One of the schemes of a unipolar generator is shown in figure 9.5.

Massive steel rotor *1* rotates in a magnetic field that is generated by fixed toroidal coils of excitation winding *2*. Main magnetic flux *F* in the central active part of the machine has the same polarity around the entire circumference, hence the name of the machine. Induced EMF. $E=Blv$ in the terminals of the rotor winding when it rotates in a magnetic field also has the same direction along the entire circumference. Stationary brushes *3* remove the current from the rotor. The use of unipolar generators has been limited due to difficulties of current drainage, as the brush machine turns bulky. Currently, the current is drained off the rotor by means of liquid metals (mercury, sodium).

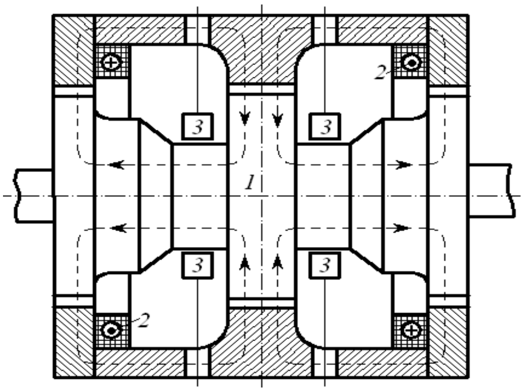


Figure 9.5 - Unipolar generator

Unipolar induction is also used in magneto hydrodynamic (MHD) generators. In these generators, the flow of hot ionized gases called "plasma" is used instead of a moving conductor.

9.4 Executive engines

The executive engines are called engines, which are used in automatic control systems and regulation of various automated equipment and which are designed to convert an electrical signal (control voltage) obtained from a measuring device or a sensor into mechanical movement (rotation) of a shaft to influence onto corresponding regulating or control unit. If the voltage and power of a signal are small to control the executive engine, so, intermediate power amplifiers are applied (magnetic or electronic). Nominal power of executive motors is usually small – up to 500÷600 W. The requirements for accuracy and quick operation are imposed to these engines: it is required that the dependence of torque M and rotational speed n on the signal voltage (control) should be possibly linear.

Figure 9.6 shows the executive DC motor with print armature winding. The armature of this engine has the form of a thin disk *5* of a nonmagnetic material (textolite, glass, etc.), on both sides of which the conductors of the armature winding *8* are applied by a printing method. The principle of operation of this motor is the same as motors with a cylindrical armature. When the engine is on, the current in the armature windings interacts with the magnetic field of excitation of permanent magnets *2* located on the motor stator and facing their pole terminals *3* to one side of the plastic disc of the armature.

On the other side of the disc, there is a ring *4* made of ferromagnetic material. This ring performs the same functions as the armature core in engines of conventional design, i.e. it is an element of the magnetic system of the machine, through which the main magnetic flux closes. The armature of the motor is fixed on the shaft *6* by a sleeve *7*.

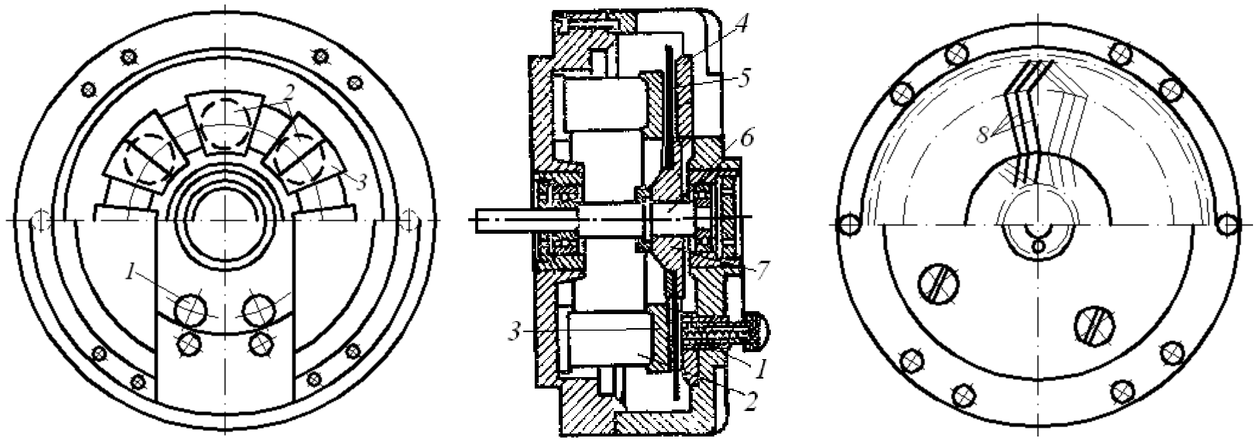


Figure 9.6 – Construction of DC engine with print armature winding

Turning on the motor is done through brushing contact with brush holder *1*. As the sections of print winding are single-turn, and the number of sections is limited by the surface area of the disk, the engines with print winding are usually manufactured for low voltage circuit.

9.5 Tachometer – generators

Tachometer – generators are electrical micro machines, operating in generator mode and used to convert the rotational speed into a proportional electrical signal. The proportion of conversion is determined by means of output characteristics of the tachometer, i.e. the dependence between the input value (shaft rotation frequency n) and an output one (voltage U_{OUT} in the output winding). Most of the tachometers have a conventional design of DC machines with independent excitation under $I_{EX}=const.$ or with permanent magnets, which have $F=const$. If the constancy of magnetic flow $E_{AR}=k_EnF=k_En$ .is the EMF of the generator, $E_{AR}=U+I_{AR}R_{AR}=U(1+R_{AR}/R)$, where $I_{AR}=U/R$ is the armature current of the generator; R is the resistance of external circuit, to which the generator is connected. Thus, $U=E_{AR}(1+R_{AR}/R)k_En/(1+R_{AR}/R)$, i.e., at constant load and armature circuit resistance the proportionality is maintained between the generator voltage and the frequency of rotation of the armature.

The characteristics of a tachometer – generator are shown in figure 9.7 for several values of *R*. As long as current I_{AR} of the armature increases, a demagnetizing effect of armature reaction begins to show itself. The value of the magnetic flux is reduced and the characteristic of the tachometer-generator deviates from a straight line down. The use of measuring instruments with large internal resistance reduces the nonlinearity of output characteristics.

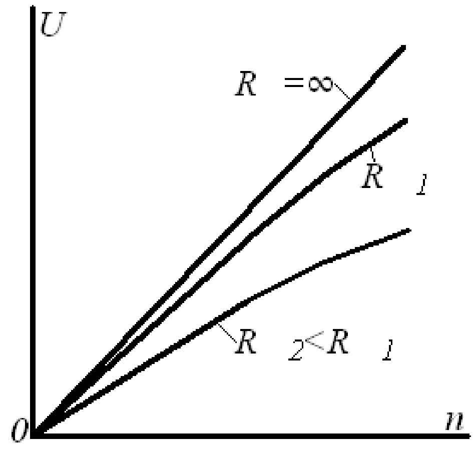


Figure 9.7 - Characteristics of a tachometer-generator

An important indicator of a tachometer – generator – the slope of the output curve, which is the ratio of the increment of the output voltage to the increment of the rotation frequency [*V/(r/min)*]: $e=\Delta U_{OUT}/\Delta n$, where ΔU_{OUT} – increment of the output voltage, V; Δn is the increment of the speed. In operation of tachometer–generators, the slope of the output curve can vary under the influence of temperature of excitation winding and transient voltage drop at the brush contact.

9.6 Traction motors

Traction DC motors drive the rolling stock in various types of transport: urban, suburban and mainline electric railways, water, in-plant, mine transport, etc. In accordance with that, traction DC motors are performed for different power and voltage. Compared to machines of a stationary type, working conditions of traction motors are much harder, as the size of the engine is limited by the diameter of drive wheels and track width.

Engine operation takes place in conditions of frequent start-up with a significant acceleration of the rolling stock and is accompanied by sharp changes in voltage at the motor terminals, current and speed.

Traction motors of a pulsating current.

The peculiarity of these engines is that they are supplied directly from AC system through the rectifier made of silicon diodes. The value of current pulsation is estimated by pulsation coefficient $c_{PUL}=(I_{MAX}-I_{MIN})/(I_{MAX}+I_{MIN})$. A significant disadvantage of pulsation current motor is hard potential conditions on the commutator, contributing to a circular fire on it.

References

1 Kopylov I. P. Electric machines.- M.: Logos, 2000.-606 p.

2 Sylkin M.I., Kalykov B.R. Electric machines.- Almaty, 2005.-178 p.

3 Bespalov V.Ya., Kotelenets N.F. Electric machines. - M.: Academia, 2006.-320 p.

4 Nabiyev F.M., Electric machines. – M.: RadioSoft, 2009.

5 Waldek A. I., Popov V.V. Electric machines. DC machines and transformers: Piter, 2007.-320 p.

6 Kopylov, I. P., Klokov B.K. Designing machinery. – M.: 2011.–767 p.

7 Aliyev I.I. Electric machines. –M.: RadioSoft, 2011. – 448 p.