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Renewable Energy Systems

Oleksii B. Ivanov, Fedir P. Shkrabets, Jan Zawilak

ELECTRICAL GENERATORS DRIVEN BY RENEWABLE ENERGY SYSTEMS

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CONTENTS

INTRODUCTION

The book is devoted to electrical generators used for conversion of energy obtained from renewable energy sources such as wind, water and geothermal heat. About 18 % of total generated electricity worldwide is obtained from renewable energy sources. Only wind power generation gives in many regions from 14 to 40 % of the produced electric power.

In some countries the share of power obtained from renewable energy sources is much greater. So, the share of power from renewables in Sweden is 54 %, in Austria – 62 %, in New Zealand – 65 %, in Brazil – 85 %. In Iceland almost 100 % of the power is got from renewable sources.

Renewable energy is derived from natural processes that are replenished constantly. In its various forms, it is got directly from the sun, or from heat generated deep in the earth. Renewable energy replaces conventional fuels in power generation, obtaining hot water, space heating, production of transport fuels, and rural energy provision.

The renewable solar, wind, ocean, hydropower, biomass and geothermal resources are a reservoir for receiving electrical power and heat. Biofuels and hydrogen are also derived from renewable resources.

Wind can be used to run wind turbines which may have power capacity of 600 kW to 5 MW of rated power. For commercial use turbines with rated power of 1.5–3 MW are now common.

The power output of a turbine depends considerably of the wind speed, so as wind speed increases, power output increases dramatically. Areas where winds are stronger and more constant are preferred locations for wind farms.

The ratio of actual energy production in a year to the theoretical maximum is called the capacity factor. Typical capacity values for the wind power farms are in the range of 20-40%. The upper values of the capacity are obtained at particularly favorable sites such as offshore and high altitude areas.

Nowadays conversion of the wind power into electricity is realized mainly with use of alternating current generators. The wind-driven power plant may be used as a self-contained fully independent power unit, as a power unit operating in parallel with other units including diesel-driven generators or as working in parallel with powerful system.

Technical potential of wind energy is assessed as five times total current global energy production, or 40 times current electricity demand. Such high-scaled use of the wind energy requires large amounts of land for wind turbines accommodation. It could become a problem for areas of high wind potential.

At offshore areas average wind speeds are about 90% greater than that of favorable land areas. Therefore, the offshore regions can provide substantially more energy.

It is very important that wind power does not produce greenhouse gases such as carbon dioxide and methane.

Energy stored in flowing water is widely used. This energy store is significant, which is explained by much greater water density in comparison with air. Therefore, even a slow flowing stream of water, or moderate sea swell can yield considerable amounts of energy. Hence, there are hydroelectrical power stations differing in size and design. The most powerful stations include large dams that are needed to provide storing of large amount of water potential energy which transformed into kinetic form and after that it is converted into electrical energy with the help of electrical generators. At these stations the installed generators capacity reaches several thousands MW. Much smaller hydroelectrical power installations have a capacity of several tens kW and are used in remote areas rich in water resources. In the last decades the damless hydropower stations of relatively small power capacity are applied to get electric power from the flowing river water utilizing its kinetic energy. In recent time power systems for utilization of energy of the oceans and seas are developed. These systems use kinetic energy of marine currents and tides, and thermal energy of sea water.

Geothermal energy derived from heat in the Earth's core may be used for conversion to electricity. Three types of electric power stations carry out such a conversion. The stations using dry steam obtained from the fractures in the Earth’s core have turbines, driven directly by this steam which conveys mechanical energy to electric generators. At another type of power plants, hot water taken from the underground hot sources at temperature about 200 °C is boiled, and the obtained steam is used to drive a generator turbine. There are binary plants at which the hot water flows through heat exchangers, boiling an organic fluid that spins the turbine. To increase the amount of the heat obtained from the earth the condensed steam and remaining geothermal water is often injected back into the hot rocks for following use. Geothermal power sources exist in some geologically unstable parts of the world. For example, Iceland produced near 170 MW of geothermal power and heated 86% of all houses in the year 2000 through geothermal energy. There is also the potential to generate geothermal energy from hot dry rocks. Holes at least 3 km deep are drilled into the earth. Some of these holes pump water into the earth, while other holes pump hot water out.

Solar powered electrical generation relies on photovoltaics and heat engines. Biomass is as a sort of natural battery for storing solar energy. As long as biomass is produced sustainably, with only as much used as is grown, the battery will last indefinitely. Liquid biofuel becomes increasingly used fuel for internal-combustion engines.

According to Renewable 2010 Global Status Report, during 2004 through 2009 years renewable energy capacity grew worldwide at rates of 10–60 percent annually. For wind power and many other renewable technologies, growth accelerated in 2009 relative to the previous four years. More wind power capacity was added during 2009 than any other renewable technology. Grid-connected power voltaics increased the fastest of all renewables technologies, with a 60-percent annual average growth rate for the five-year period.

Although now the construction of power installations using renewable power sources and electric energy production is expensive, renewable energy will become essentially cheaper than electricity obtained from burning fossil fuels. The main reasons for that are cost-free sources of renewable power that become important after building the renewable infrastructure, improvement of renewable energy technologies that facilitates the increase of the efficiency of renewable energy and reduction of cost, speeding up the innovation process leading to the reduction of the cost of windmills and a solar panels.

1. BASIC PRINCIPLES OF ELECTRICAL MACHINES

1.1. The concept and classification of electrical machines

Use of energy resources needs conversion of some forms of energy into other ones. Devices in which such conversion occurs are the energy transducers. Transducers in which mechanical motion and mechanical energy take part are energy-converting machines. An energy-converting machine can transform an energy form or transform a set of parameters of the same form of energy to another its parameter set. So in a heat engine thermal energy released at fuel combustion is transformed into mechanical energy, i.e. the form of energy changes. In the case of hydraulic machine, in which mechanical energy of a liquid translational motion transforms into mechanical energy transmitted trough a rotating shaft, the form of energy remains unchanged.

Certain part of energy stored in nature in the forms of chemical energy, nuclear energy, as the energy of moving water of rivers and seas, as the energy of winds, the sun energy, etc people convert to electric energy as it is easily transmitted over any required distance, distributed among consumers and converted again to mechanical, heat or chemical energy used for practical purposes.

Immediate conversion of thermal, chemical or nuclear energy to electricity is performed with considerable losses, low efficiency and is not cost-effective. Therefore such a conversion as a rule includes an intermediate stage: the energy of prime carrier is previously converted into mechanical one, and after that the obtained mechanical energy is converted into electric energy.

The energy transducer transforming mechanical energy into electric energy or vice versa is called the electric machine.

The electric machine intended to transform mechanical energy into electric energy is called the generator. And the machine intended to transform electric energy into mechanical energy is called the motor.

An electric machine is an electromagnetic device that includes interdependent magnetic and electric circuits. The magnetic circuit consists of stationary and moving magnetic cores separated by the air gap. The machine electric circuits having two or more windings may move relatively one another together with the cores at which they are located.

Every electric machine is a reversible energy transducer. That is, the same machine can realize any of the both energy transformations: it can be used as either a generator or a motor. The energy conversion that a machine carries out depends of conditions in which it operates. If mechanical energy is supplied to its moving part, the electric machine operates as a generator of electric energy. In the case when electric energy is supplied to the machine, its moving part executes mechanical work, and the machine operates as a motor.

Electric machines can be classified in different ways. Any strict formal classification was not established. At the same time frequently the classification given below can be accepted.

Electric machines can be classified by the criteria of their functions, current type, operation principles, voltage magnitude, rated power, rotational speed, type of construction, etc.

By functional area electric machines can be divided to motors, generators and machines of special purposes. The functions of generators and motors were discussed above. The special purpose machines are used as controlling and controlled devices in various automatic and cybernetic systems, information technology and electrotechnology.

By the current type are distinguished electric machines of direct current (DC machines) and of alternating current (AC machines).

DC machine is a machine incorporating an armature winding connected via a commutator to a direct current system and having magnetic poles which are excited from a source of direct or undulating current or from permanent magnets.

AC machine is a machine which has an armature winding intended for connection to an alternating current system.

Considering principle of electric machines operation they can be divided into machines, which use magnetic field and which operation is based on the electromagnetic induction, and machines that use electric field and which operation is based on the electric induction. The most machines use magnetic field and electromagnetic induction because such machines have essentially less dimensions and cost.

Alternating current machines by their principle of operation are divided into two types – synchronous an asynchronous. In a synchronous machine the frequency of generated voltage and the speed of the machine are in a constant ratio. In an asynchronous machine the speed on load and the frequency of the system to which it is connected are not in a constant ratio.

By the voltage level the machines can be classified as machines of high (more than 10,5 kV), standard (6,3 kV to 220 V) and low (less than 110 V) voltage.

By the rated power the electric machines can be sorted to machines of micro (less than 0,5 kW), small (0,5 – 20 kW), medium (20 – 250 kW), great (250 – 10 000 kW) and ultimate (more than 10 MW for DC and more than 1000 MW for AC) power.

High-speed machines have the rotational speed of 3,000 – 100,000 rpm, medium speed – of 500 – 3 000 rpm, and low-speed machines – of 500 – 1 rpm.

There are other approaches to classification of electric machines. Such classifications may be founded in standards that determine types of machine construction, methods of their mounting, degree of protection against environmental conditions, form of cooling, continuous duty rating.

Use of renewable power sources, such as wind, flowing and waste water, systems of power co-generation, require application of electric generators, mainly synchronous and asynchronous types of different construction.

1.2. Basic designs of electrical machines

Independently of the kind of current (direct or alternating current), electric machines may be divided by their magnetic circuit construction for salient pole and non-salient pole types.

In non-salient pole machines the air gap between the stator and rotor magnetic cores is uniform in any point of the gap circle. The stator and rotor windings are distributed in the slots arranged on the core surfaces (Fig. 1.1 a).

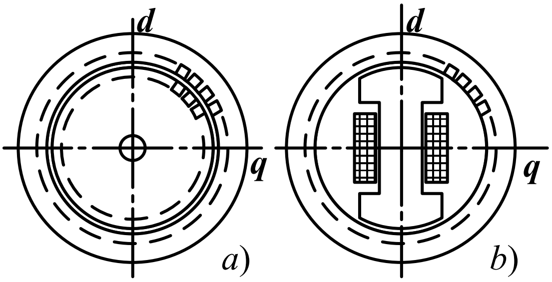


Fig. 1.1 Salient (a) and non-salient (b) pole machines

In salient pole machines the field poles project from the frame yoke or hub towards the air-gap (Fig. 1.1 b). As it is understood, the concentrated field winding can be placed as on the rotor as on the stator. In machine having salient poles and concentrated field winding, the direct and quadrature axes of the magnetic circuit are clearly determined. The air gap and reluctance in the directions of the direct and quadrature axes have essentially different values.

Machines which construction is shown in Fig 1.2 have the most application.

The asynchronous machines have as a rule a non-salient magnetic system (Fig. 1.2 a).

Such type of the system have too a non-salient pole synchronous machine. In the machines with non-salient poles rotor has cylindrical shape. A machine having a cylindrically shaped rotor the periphery of which may be provided with slots which accommodate the coil sides of a winding is called the cylindrically rotor machine.

In the most cases salient pole synchronous machine has a salient pole magnetic system on its rotor (Fig. 1.2 b).

Commutator DC machines have magnetic system with salient poles on the stator (Fig. 1.2 c).

The magnetic circuit of an inductor-type, or parametric, generator has salient poles on the stator and a toothed rotor (Fig. 1.2 d). Electromechanical energy conversion is performed in such a machine due to periodical variation of the air gap reluctance.

A machine magnetic circuit member (the stator or the rotor core) is made laminated, i.e. assembled of steel laminations insulated from one another, if variable magnetic flux is passing through the core. Such a measure provides decrease of magnetic losses caused by the eddy currents. When the magnetic flux does not vary in time the magnetic core can be made of solid steel.

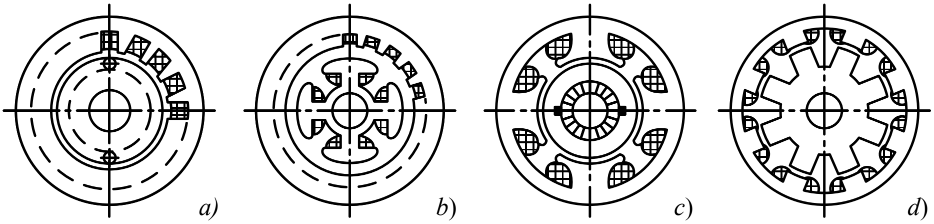


Fig. 1.2 Main types of electrical machines design

In asynchronous machine both the stator and rotor cores are subjected action of variable magnetic field and therefore are made laminated.

In synchronous machines the rotor magnetic field is constant. Therefore cylindrical rotor magnetic core of the non-salient pole synchronous machine is produced of solid steel, and the field winding coil sides are imbedded into slots milled on its cylindrical surface.

In DC machines the frame of soft steel flat solid slab rolled into cylindrical shape serve at the same time as magnetic circuit yoke. The yoke can be made of cast iron. The magnetic circuit of a DC machine is completed by the armature core placed on rotor built up of punched steel laminations. The laminations have slots and teeth punched in them. Enough of laminations are assembled on the shaft to give the necessary armature core axial length. The armature winding is connected to the commutator segments. Brushes made of a carbon-based mixture are stationary and pressed against the exterior surface of the commutator. They provide the external connection to the rotating armature winding and also enable commutation between the particular coils of the rotating winding.

In some applications DC machines may have a rotating field winding, and synchronous machines – a stationary field winding. Such machines are said have reverse construction.

One of used constructions is so called disc-type machines, i.e. machines having a rotor in the form of a disc and axial air-gap. Usually stator and rotor of such a machine has the shape of disks (Fig. 1.3). In these machines the magnetic field energy is concentrated in the air gap between the discs.

A reluctance machine is modification of the synchronous machine in which one member, usually stationary, carries armature and excitation windings or permanent magnets effectively disposed relative to each other, and in which the other member, usually rotating, is without windings but carries a number of regular projections. The reluctance machines have many variations of construction. One of the constructions is a machine with two stator *2* and two rotor core stacks *1* (Fig. 1.4). The field winding is a ring coil *3* encompassing the machine shaft. Each the stator have the armature winding *4*. The cores of rotors and stators have teeth. The stator and rotor tooth axes coincide on different parts of air gap circle depending of a rotor angular position. The rotor core rotation causes variation of reluctance for the magnetic fluxes, and the fluxes linked to the armature windings vary too. Armature windings flux linkages variation produce alternating voltage in them.

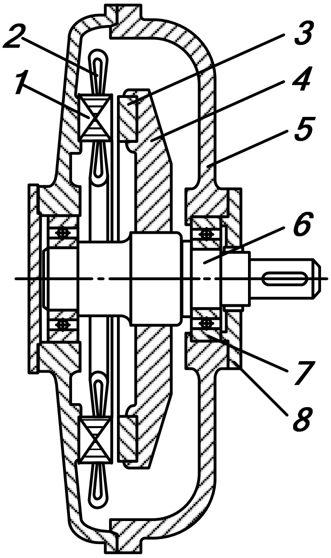


Fig. 1.3 Frontal disc-type machine: 1 – stator core, 2 – stator winding, 3 – permanent magnets, 4 – rotor core, 5 – end shields, 6 – shaft, 7 – bearings, 8 – bearing caps

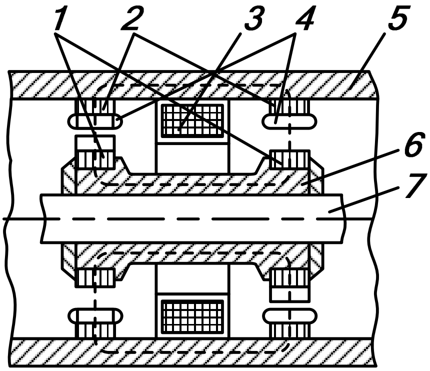


Fig. 1.4 Reluctance (inductor-type) electric machine

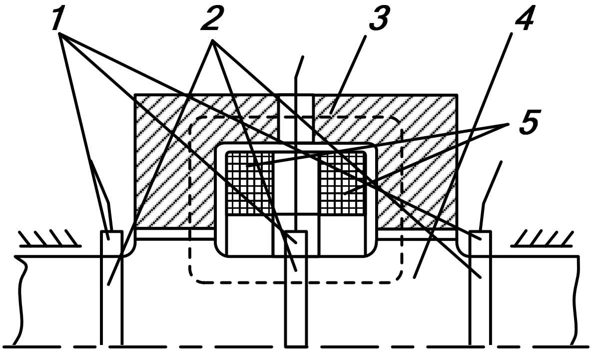


Fig. 1.5 Homopolar generator

To produce direct current of great values the homopolar DC machines are used. Such machines have no a commutator, but they can not operate without sliding contact in principle. An example of homopolar generator is shown in Fig. 1.5. The magnetic flux shown as the dashed line *3* is produced by the field current flowing in the field winding *5* and is closing in the path including the magnet frame, the solid rotor and two air gaps. The direct currents generated in the solid rotor are collected with the brushes from the slip rings *1*. To reduce resistance losses in the rotor, slots may be made on its surface, copper bars are inserted in them. The bars are welded to the slip rings, forming a cage winding.

1.3. The magnetic field of electrical machines

Magnetic field of an electrical machine is produced by currents flowing through their windings. In the case of use permanent magnets in machine magnetic circuit they also produce magnetic field.

If the member of the machine has a winding supplied with direct current, the field produced by it is constant in time and stationary relatively the member core (Fig. 1.6). If the core moves, the magnetic field travels with it.

The windings supplied by alternating current may produce or pulsating field that alternates one space axis only or rotating field, which poles are moving along the air gap circle, depending on the winding structure.

In the case of a single-phase winding the pulsating magnetic field is obtained (Fig. 1.7).

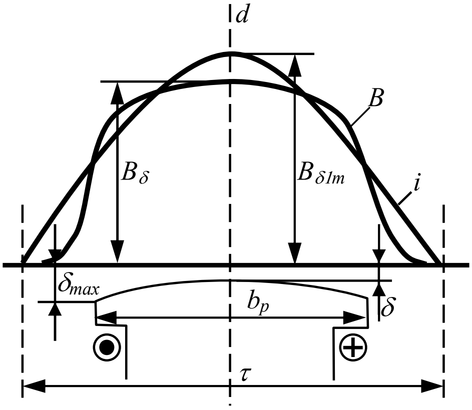


Fig. 1.6 Magnetic flux density of field produced by direct current of salient pole winding

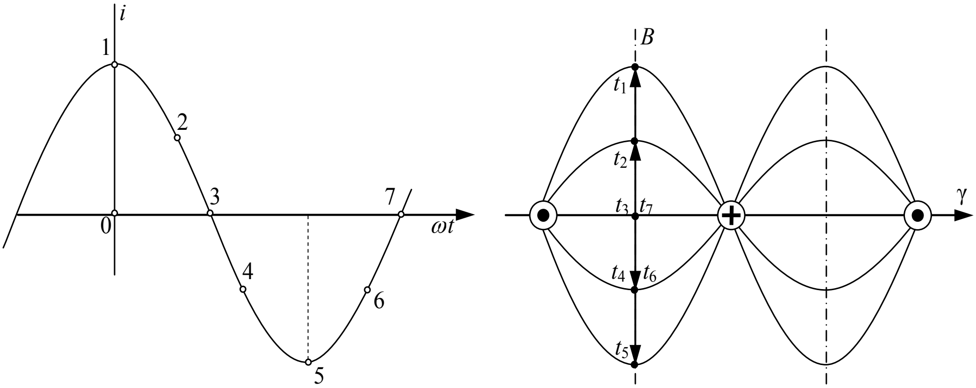


Fig. 1.7 Curves of current and magnetic flux produced by single-phase winding distribution

If there is a multi-phase winding supplied with multi-phase alternating currents the field rotates in space (Fig. 1.8).

The rotating field has constant magnitude if phases of the multi-phase winding are similar and settled symmetrically around the air gap and are fed with balanced multi-phase current system. The vector of flux density on a pole axis (or any axis fixed at a point of the flux density distribution curve) of rotating field describes a circle (Fig. 1.9). Such a rotating field may be called the circular field.

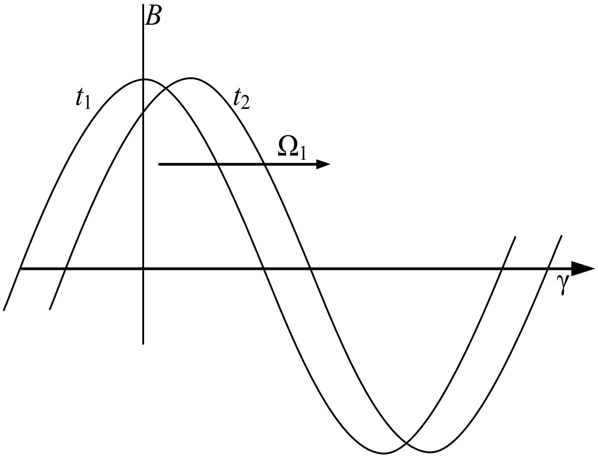


Fig. 1.8 Flux of rotating magnetic field distribution

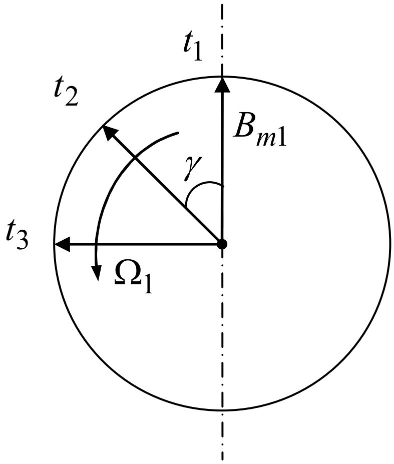


Fig. 1.9 Vector of magnetic flux density describes a circle

At any irregularity of multi-phase winding symmetry or unbalancing of the multi-phase currents the vectors of rotating field describe ellipses (Fig. 1.10) and the rotating field is elliptic.

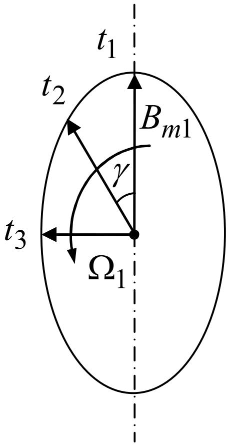


Fig. 1.10 Elliptic rotating flux

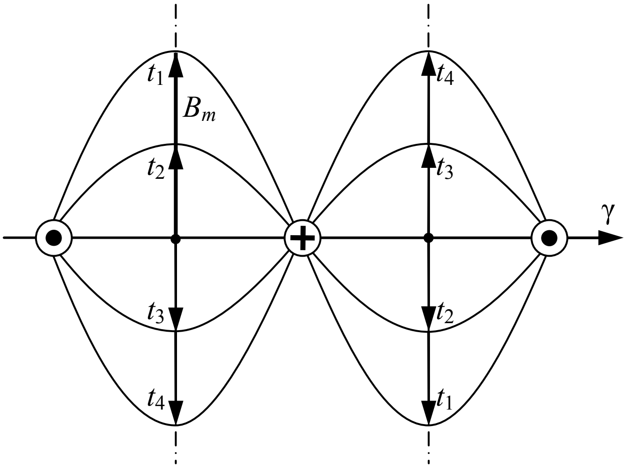


Fig. 1.11 Vectors of pulsating field describe straight lines

Any vector of the pulsating flux density describes a straight line not changing it angular position (Fig. 1.11), this vector direction changes at change of the single-phase winding current direction of flow. The extreme case of asymmetry is a single-phase winding fed by a single-phase current.

In fact the magnetic flux density is distributed along the air gap circle by non-sine curve due to discrete location of the winding conductors inserted to the slots. Usually, it distinction from the sine curve is little, and the fundamental of actual non-sinusoidal periodic curve of the flux density may be in many cases taken into consideration as it is done in Fig. 1.7 and 1.8. Harmonics of the flux cause additional power loss, undesirable distortion of a machine characteristics and worsening of it running ability. Therefore it is always desirable to have the flux density distribution very close to sine curve.

The magnetic flux and magnetic flux density distribution along the air gap define important properties of electric machines. The flux is determined by the machine winding currents and parameters of magnetic circuit.

The magnetic flux density at points of the air gap may be found on the basis of calculation of the magnetic field strength. For this, the magnetomotive force (*mmf*) along the closed path, coinciding with the strength vector line, is determined taking into account that according to Ampere's Law it is equal to the total electric current through the surface bounded by that path.

To simplicity consider firstly magnetic circuit of a non-salient pole alternating current machine with a single-phase stator winding. Admit that the winding is concentrated so that one coil is available for one pair of magnetic poles, the width of a coil y (the coil pitch) equals the length of the air gap circle part suited with one pole τ (the pole pitch) and a coil sides are set in the slots in one layer (one-layer winding). In such a case it is said that there is a single-phase concentrated full pitch winding. For it there is $y = \tau$. The number of the coil turns denote as w_c. The instantaneous value of the current flowing trough the coil turns denote as i_c. Develop the air gap circle into the straight line and show the part of developed machine magnetic circle according to one pair of poles or two pole pitches (Fig. 1.12). As the magnetic field induced by the winding varies along the air gap periodically with period of 2τ, the magnetic field in the bounds of one pole pair will repeat at the other pairs which are available if the total field pole pair number p is more than one. The number of poles in heteropolar machines is always even and equals $2p$.

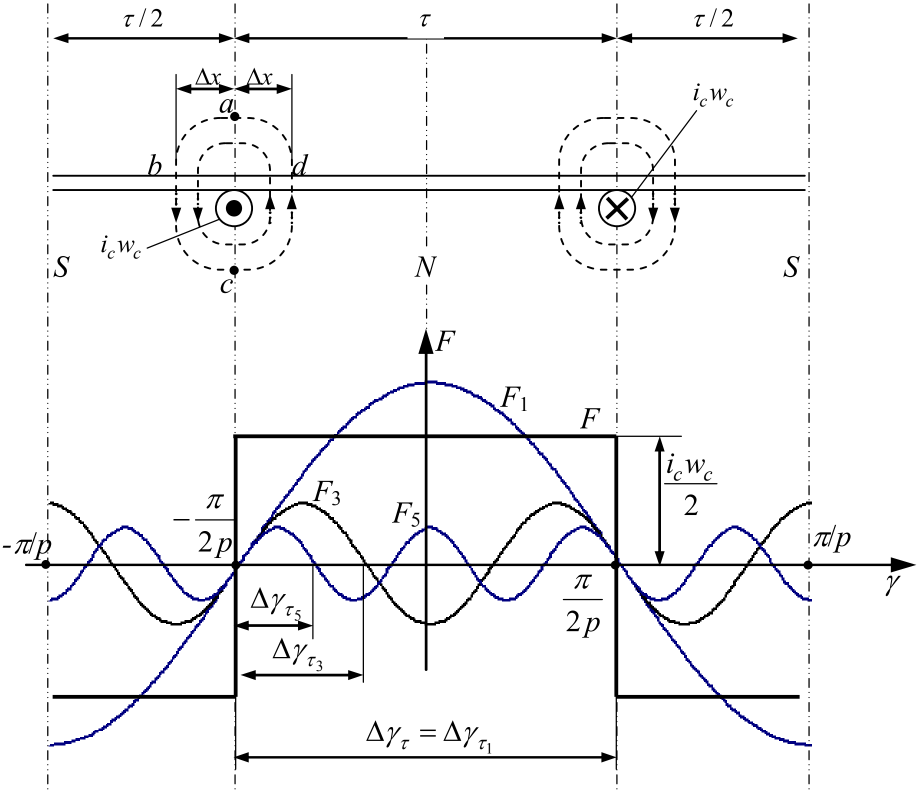


Fig. 1.12 Developed magnetic circuit of a non-salient alternating current machine

A magnetic strength line has width $2x$. At $x=0$, it does not encompass conductors , and the current through the surface bounded by this line is zero. When it widens and becomes equal to half of the slot width ($x=b_s/2$) and wraps the coil side conductors the current through the bounded surface becomes equal $\sum i = i_c \cdot w_c$. After wrapping the coil side, further widening the line till $x=\tau/2$ does not change the current trough the surface.

Proceeding from the Ampere's Law, integrate along the chosen path and write:

$$\oint \overline{H}\overline{dl} = \sum i \tag{1.1}$$

where $\overline{H}$ is magnetic field strength, $\overline{dl}$ is the vector representing the path element dl which direction coincides with circulation about the path. Taking into account the strength lines symmetry in relation the axis *ac* have:

$$\int_{abc} \overline{H}\overline{dl} + \int_{cda} \overline{H}\overline{dl} = 2\int_{abc} \overline{H}\overline{dl} = 2F \tag{1.2}$$

and

$$\int_{abc} \overline{H}\overline{dl} = F \tag{1.3}$$

where $F = \frac{\sum i}{2}$ The quantity F is called the winding *mmf* and is a function of x.

Admitting that the slot width is $b_s = 0$, have for any value of x:

$$F = \frac{i_c w_c}{2} \tag{1.4}$$

As magnetic field strength at the left and right of the coil side are opposite the values of F should be taken with opposite signs. Admit that in the area of north pole it is positive, and of south pole is negative.

Plot the graph of dependence $F = f(\gamma)$ where γ is the angle counted around the air gap circle from the north pole axis of (Fig. 1.12).

The graph of single phase concentrated full pitch winding is symmetrical rectangular curve having the height of $\frac{i_c w_c}{2}$ and the period of $\frac{2\pi}{p}$. It may be developed into the Fourier series along γ-axis as it is shown in Fig. 1.12. As the curve of the winding *mmf* is symmetrical relative the γ-axis, it includes only odd harmonics. Also pay attention that the single phase winding induces pulsating magnetomotive force and pulsating magnetic flux. This regards as to rectangular curve of the winding *mmf* as to fundamental and harmonics of the Fourier series to which the rectangular curve is developed.

So using the Fourier series and accounting symmetry of the curve about ordinate the periodical curve of phase *mmf* is represented with the expression:

$$F = \sum_{\nu=1}^{\infty} F_\nu = \sum_{\nu=1}^{\infty} F_{\nu\,\max} \cos(\nu\gamma p) = \sum_{\nu=1}^{\infty} F_{\nu\,\max} \cos(\nu\alpha) \qquad (1.5)$$

where ν is the harmonic number, F_ν is $\nu - th$ harmonic of the series, $F_{\nu\,\max}$ is the amplitude of the $\nu - th$ harmonic at any given time instant. The angle γ is spatial angle. The angle α is called the electrical angle because it enters to the functions of time expressing link fluxes, induced voltages and other electrical quantities.

Let the coil current varies in accordance with the cosine law:

$$i_c = I_{c\,m} \cos \omega t \qquad (1.6)$$

where $I_{c\,m}$ is amplitude of the current, ω is the current angular frequency.

Then the amplitude of the $F_{\nu\,\max}$ *mmf* harmonic at any given time instant equals

$$F_{\nu\,\max} = F_{\nu\,m} \cos \omega t \qquad (1.7)$$

where $F_{\nu\,m}$ is the largest maximum value of the $\nu - th$ *mmf* harmonic fitting the current amplitude.

Calculation the Fourier series factors of the rectangular *mmf* of a single phase winding gives the following expression for the largest maximum value of the $\nu - th$ *mmf* harmonic:

$$F_{\nu\,m} = \frac{4}{\pi\nu} F_m = \frac{2\sqrt{2}}{\pi\nu} I_c w_c \qquad (1.8)$$

where F_m is the height of the rectangular *mmf* curve of a single phase winding, I_c is *rms* value of the coil current, w_c is the coil turn number.

The phase winding may have one or several parallel branches. In the case of one branch the coil current is full current of the phase, i.e. $I_c = I$. If there is several identical branches the phase current divides equally among them. Denoting the number of branches as a receive for general case:

$$I_c = \frac{I}{a} \tag{1.9}$$

where I is the *rms* of the phase current.

The winding being now considered is a concentrated full pitch single phase winding inducing the magnetic field having p pole pairs. It consists of p coils which may form identical parallel branches which possible number depends on the total number of coils. In many cases it is possible to realize different ways of connection giving different number of branches. The total number of turns of the coils that appear in any of the parallel branches is equal to

$$w = \frac{w_c \cdot p}{a} \tag{1.10}$$

The parameter w is called the number of turns of the phase winding.

Taking into account (1.9) and (1.10), after substitution the proper expressions of I_c and w_c into (1.8) receive:

$$F_{\nu\, m} = \frac{2\sqrt{2}}{\pi p \nu} Iw \tag{1.11}$$

In particular, the maximum amplitude of the *mmf* fundamental for the concentrated full pitch one layer phase winding is

$$F_{1\, m} = \frac{2\sqrt{2}}{\pi p} Iw \tag{1.12}$$

The permeability of electrical steel is many times grater than of the air which is approximately equal to the magnetic constant. On this reason, the magnetic field strength at the steel part of the machine magnetic circuit is much less than in the air gap and sometimes is negligible. To make understanding of interrelation between the *mmf* and the magnetic field easier we may on this stage of consideration assume that the magnetic field strength in the steel of a machine equals zero. Then have roughly on the basis of (1.3) the following:

$$\int_{abc} \overline{H}\,\overline{dl} = H_\delta \cdot \delta = F \tag{1.13}$$

where H_δ is the magnetic field strength in the air gap, δ is the air gap amount. Hence, the magnetic field strength equals

$$H_\delta = \frac{F}{\delta} \tag{1.14}$$

The magnetic flux density in the air gap is

$$B_\delta = \mu_0 H_\delta = \mu_0 \frac{F}{\delta} \tag{1.15}$$

where μ_0 is the magnetic constant.

From (1.14) and (1.15), it follows that the air gap field strength and flux density are defined by values as of the *mmf* as of the air gap amount. For a non-salient pole machine, neglecting variations of the air gap along the circle due to alternation of teeth and slots at the stator and rotor core surfaces, it may be assumed $\delta = const$. It permits to consider that the curves of the magnetic flux density and of the magnetic field strength variation along the air gap circle (the curves of these quantities distribution) repeat the shape of the curve of *mmf*. In reality the neglected parameters affect the magnetic field and properties of electric machines. In particular the magnetic tension on the steel parts, the steel magnetic saturation and the cores teeth structure may noticeably contribute to the field distribution in the air gap and to other characteristics of electric machines. But the assumed simplification permits to understand easier the major relationships taking place in the machines.

The considered phase winding produces the *mmf* and magnetic field in which harmonics with $\nu > 1$ are strongly expressed, i.e. have their amplitudes commensurable with the fundamental amplitude that adversely affects the machine properties.

In fact, the windings of AC electric machines are some more complicated that is necessary to reduce the harmonics essentially.

For one layer windings the major way to reduce harmonics of their mmf and magnetic field is the winding distribution. In the distributed windings each the coil of the concentrated winding is replaced with several (q) coils, placed to adjacent slots, which have the full pitch (or average these coils pitch is full). For that the number of slots should be increased by q times. The indicated several coils compose a group of coils replacing one coil of the concentrated winding.

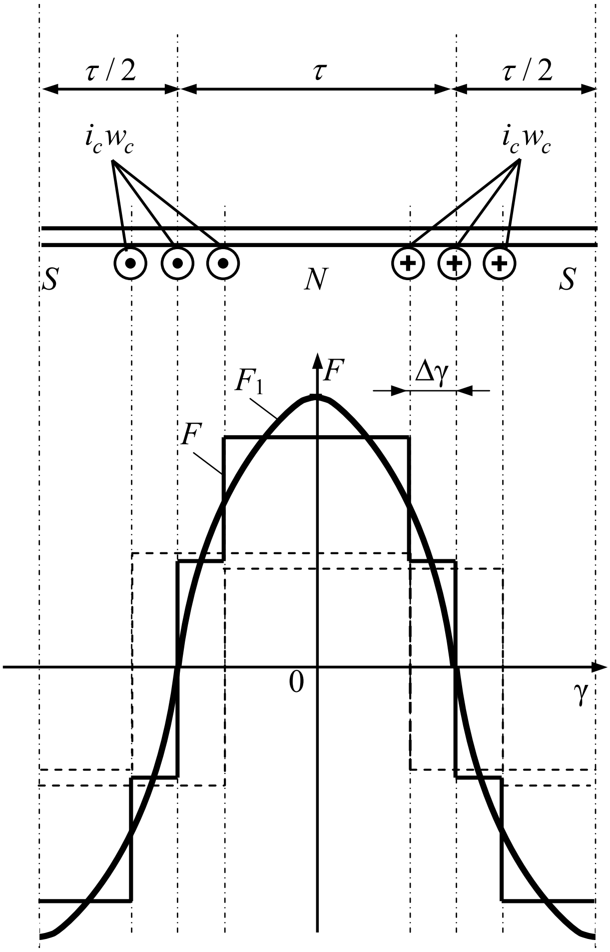


Fig. 1.13 Plotting curve of distributed winding *mmf*

Such a winding have p groups of coils, each the group per one poles pair. The distributed winding is equivalent to q concentrated windings placed on the same core with displacement for one tooth pitch one to another. The curve of its *mmf* may be obtained by adding ordinates of the *mmf* curves of q displaced concentrated windings (Fig. 1.13). The resulting *mmf* of distributed winding varies along the air gap by step curve. Its ordinates differ from the fundamental ordinates not so much as in the case of the rectangular curve of the concentrated winding. Therefore amplitudes of harmonics of the distributed winding are smaller, and the mmf curve is closer to the sine function. The harmonics content decreases with increase of q .

Consider influence of a winding distribution on the *mmf* harmonic amplitude. For simplicity, find at first amplitude of the fundamental taking into account that the added components are cosine curves displaced by spatial angles $\Delta\gamma$ (Fig. 1.14).

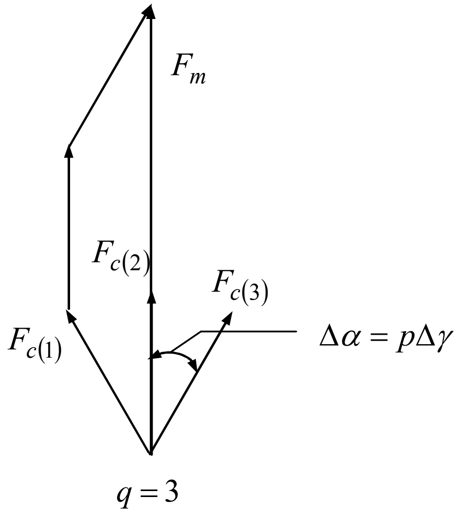


Fig. 1.14 Determination of mmf for group of coil section

The amplitude of the resulting curve is less than arithmetic sum of the components amplitudes. Therefore, F_m is $F_m < \sum F_{c\,m} < qF_{c\,m}$ where $F_{c\,m}$ is the component amplitude. The ratio

$$\frac{F_{m\,1}}{qF_{c\,m1}} = \frac{\sin q\dfrac{\Delta\alpha}{2}}{q\sin\dfrac{\Delta\alpha}{2}} = k_d \tag{1.16}$$

where $\Delta\alpha = p\Delta\gamma$ is called the distribution factor. The distributed single phase winding *mmf* maximum amplitude of the fundamental is calculated by the formula:

$$F_{m1} = qF_{cm1}\cdot k_d = \frac{2\sqrt{2}}{\pi p} Iw\,k_d \tag{1.17}$$

The distribution factor for fundamental not so much less than unity, and the winding distribution insignificantly reduce it.

The maximum amplitude of harmonic depends on it number ν and is found as

$$F_{\nu m} = \frac{2\sqrt{2}}{\pi p \nu} Iw\, k_{d\nu} \tag{1.18}$$

where $k_{d\nu}$ is the distribution factor for $\nu - th$ harmonic:

$$k_{d\nu} = \frac{\sin\left(\nu q \frac{\Delta\alpha}{2}\right)}{q \sin\left(\nu \frac{\Delta\alpha}{2}\right)} \tag{1.19}$$

As the number of poles of the $\nu - th$ harmonic is directly proportional to its number $p_\nu = \nu p$ the electrical angle of adjacent slots $\Delta\alpha = p\nu\Delta\gamma$, and the distribution factor for different harmonics is different and reduces with the harmonic number increase. Due to that and to inverse variation with the harmonic number the amplitude of mmf harmonic reduces with its order, and a winding distribution is efficient way for mmf harmonics suppression. Exclusion is so called teeth harmonics which period is commensurable to the tooth pitch. For any such a harmonic the distribution factor is the same as for fundamental, therefore winding distribution does not directly cause reduction of teeth harmonics. But as the numbers of teeth harmonics increase with increase of q, and amplitude of teeth harmonics may be essentially decreased by proper selection the number of coils q in a group. For that purpose the number of coils in a group is taken $q \geq 3$.

Further reduction of a machine magnetic field harmonics is provided by using coils with shortened span (pitch) $y < \tau$. Such a winding is called the short pitch winding. Short pitch may be realized in two layer windings which coil sides arranged into the slots in two layers: the upper layer located closer to the slot opening (closer to the core surface) and the bottom layer located deeper at the slot bottom (Fig. 1.15). The two layer winding has $2p$ groups of coils per phase. The relative coil pitch in per unit is $\beta = y/\tau < 1$. Usually it is taken in the limits of 0,8 … 0,86. In multi-phase machine there is the winding with m phases. The number of slots is m times as much as it is needed for placement of coils of one phase. The total number of slots required for placement of m-phase winding is

$$z = 2pmq \tag{1.20}$$

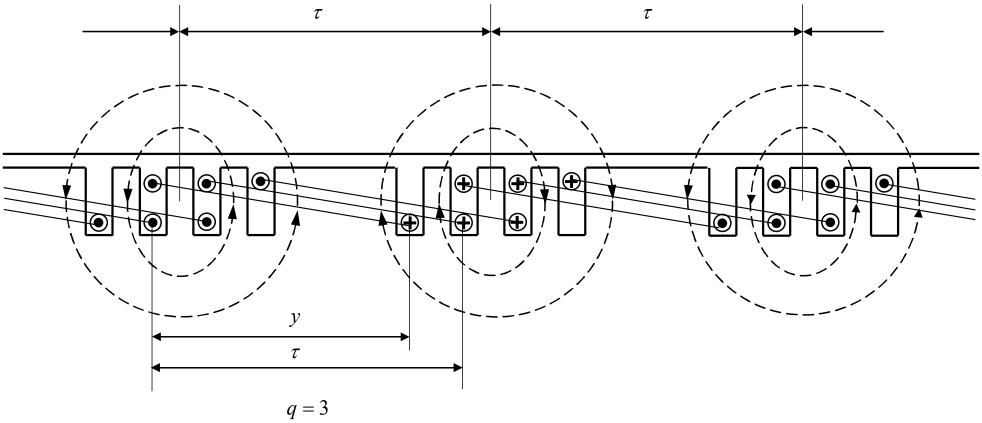


Fig. 1.15 Two layer short pitch distributed winding

The quantity $q = z/(2pm)$ is usually called the number of slots per pole and per phase.

The phase *mmf* curve of two layer winding may be obtained by addition of ordinates of two identical single layer windings displaced spatially by the angle $\Delta\gamma_s = \frac{\pi}{p}(1-\beta)$. As the result a step curve is obtained. This curve is closer to sine than the curve of the single layer full pitch distributed winding, and therefore it contains harmonics with smaller amplitudes. Use of two layer distributed short pitch windings provides much more efficient harmonics suppression. Influence of shortening the pitch on the *mmf* harmonics may be assessed with account of summation of sine curves of two full pitch one layer windings displaced spatially by the angle $\Delta\gamma_s$ (Fig. 1.16).

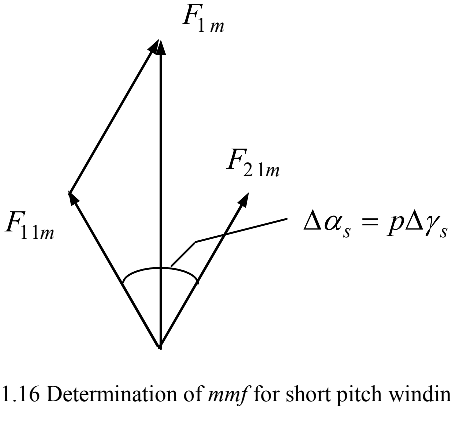


Fig. 1.16 Determination of *mmf* for short pitch winding

In the figure summation is made for fundamentals. The resultant *mmf* of the short pitch winding is less than arithmetic sum of the summands representing full pitch components. The ratio

$$k_{p_1} = \frac{F_{1m}}{2F_{H\,m}} = \sin\left(\beta \pi\!/\!_2\right) \tag{1.21}$$

is called the pitch factor. It permits to account influence of pitch shortening on the winding *mmf* harmonics and the induced voltage. For the fundamental of the short pitch winding the pitch factor insignificantly less than 1, for harmonics it is significantly less than unity excluding the teeth harmonics for which the pitch factor value is the same as for the fundamental. In particular, the $\nu - th$ *mmf* harmonic amplitude of a distributed short pitch phase winding is found as

$$F_{\nu\, m} = \frac{2\sqrt{2}}{\pi p \,\nu} Iw \cdot k_{d\nu} \cdot k_{p\nu} = \frac{2\sqrt{2}}{\pi p\, \nu} Iw\, k_{w\nu} \tag{1.22}$$

where $k_{d\nu}$, $k_{p\nu}$ and $k_{w\nu} = k_{d\nu} k_{p\nu}$ are distribution factor, pitch factor and winding factor for $\nu - th$ harmonic correspondingly.

A multi-phase symmetrical winding consists of m identical phase windings shifted by spatial angles of $\frac{2\pi/m}{p}$ (in the case of $m > 2$) around the circle. Summarizing all phases *mmfs* find that the multi-phase winding *mmf* rotates in the direction of phase sequence with the angular speed equal to $\Omega_1 = \frac{\omega}{p} = \frac{2\pi f}{p}$. The same direction of rotation and the speed value also take place for the fundamental of *mmf.* When a multi-phase winding is fed by balanced multi-phase current system the fundamental rotating *mmf* as the produced rotating magnetic field are circular.

In the case of three-phase winding ($m = 3$) phases spatial displacement is $\frac{2\pi/3}{p}$, and they are fed by three-phase current system. This winding *mmf* fundamental is circular if the current system is balanced. The rotating *mmf* of three-phase symmetrical winding fed by balanced three-phase currents does not contain the third harmonic and harmonics which numbers are divisible by three as these harmonics disappear at summarizing the pulsating *mmfs* of the winding phases. Harmonics of a three-phase winding *mmf* at these conditions also are rotating and circular and produce rotating circular magnetic field components.

The speed of rotation of any three-phase winding *mmf* harmonic is

$$\Omega_{\nu} = \pm \frac{2\pi f_1}{p} = \pm \frac{\Omega_1}{p} \tag{1.23}$$

where sign "+" or "-" is selected on the following rule.

If a harmonic number equals $\nu = 6n + 1$ where $n = 0, 1, 2, 3, \ldots$, i.e. $\nu = 1, 7, 13, 19, \ldots$, the sign "+" is taken. For harmonics with numbers $\nu = 6n - 1$ where $n = 1, 2, 3, \ldots$, i.e. $\nu = 5, 11, 17, 23, \ldots$, it is necessary to take the sign "-". The sign "+" means that the harmonic rotates at the same direction as the step curve of the three winding *mmf*, i.e. at the direction of sequence of phases on the surface of the machine member core. In the case of negative sign the rotation is at the opposite direction. Pay attention that the speed of the fundamental is positive.

The harmonic rotational speed is inversely proportional to the harmonic order. The more the harmonic number is the slower the harmonic rotates.

The amplitude of a rotating harmonic of three-phase winding *mmf* is determined by the expression:

$$F_{\nu\, m} = \frac{m\sqrt{2}}{\pi p \nu} I w\, k_{p\nu} \tag{1.24}$$

where $k_{w\nu} = k_{d\,\nu} k_{p\,\nu}$. For non-salient pole machines with smooth-faced core surfaces in absence of magnetic saturation, amplitudes of rotating magnetic flux density harmonics are found from the expression:

$$B_{\nu\, m} = \mu_0 \frac{F_{\nu\, m}}{\delta} \tag{1.25}$$

Dependence of the rotating *mmf* on time and the space angle which describes its distribution along the air gap at any time instant is expressed as:

$$F_{\nu} = F_{\nu\, m} \cos(\omega t \mp \nu p \gamma) = F_{\nu\, m} \cos(\omega t \mp \nu \alpha) \tag{1.26}$$

where $\alpha = p\gamma$, the sign "+" is applied for harmonics $\nu = 6n + 1$ and "-" for harmonics $\nu = 6n - 1$.

In the case of three phase winding electromagnetic irregularity, its rotating *mmf* becomes elliptic. The extreme irregularity is the case of single phase winding which *mmf* is pulsating.

For a pulsating and elliptic *mmf* harmonics, the double-revolving method may be applied. This method lies in resolving the pulsating or rotating elliptic *mmf* harmonic into two circular rotating in opposite directions *mmf* having the speed equal to $\Omega_\nu = \pm \frac{\Omega_1}{\nu}$:

$$F_\nu(t, \alpha) = F_{\nu\, dir} + F_{\nu\, rev} = F_{\nu\, dir,\, m} \cos(\omega t - \nu\alpha) + F_{\nu\, rev,\, m} \cos(\omega t + \nu\alpha) \quad (1.27)$$

where $F_{\nu\, dir}$ and $F_{\nu\, rev}$ are direct and reverse components accordingly, $F_{\nu\, dir,\, m}$ and $F_{\nu\, rev,\, m}$ are their amplitudes. In the case of pulsating curve the direct and reverse harmonics amplitudes are:

$$F_{\nu\, dir,\, m} = F_{\nu\, rev,\, m} = \frac{F_{\nu\, m}}{2} \quad (1.28)$$

Resolving of pulsating and elliptic fields is presented in Fig. 1.17 where vectors of *mmf* fundamentals on the pole axes for direct and reverse components and for actual resulting field are shown.

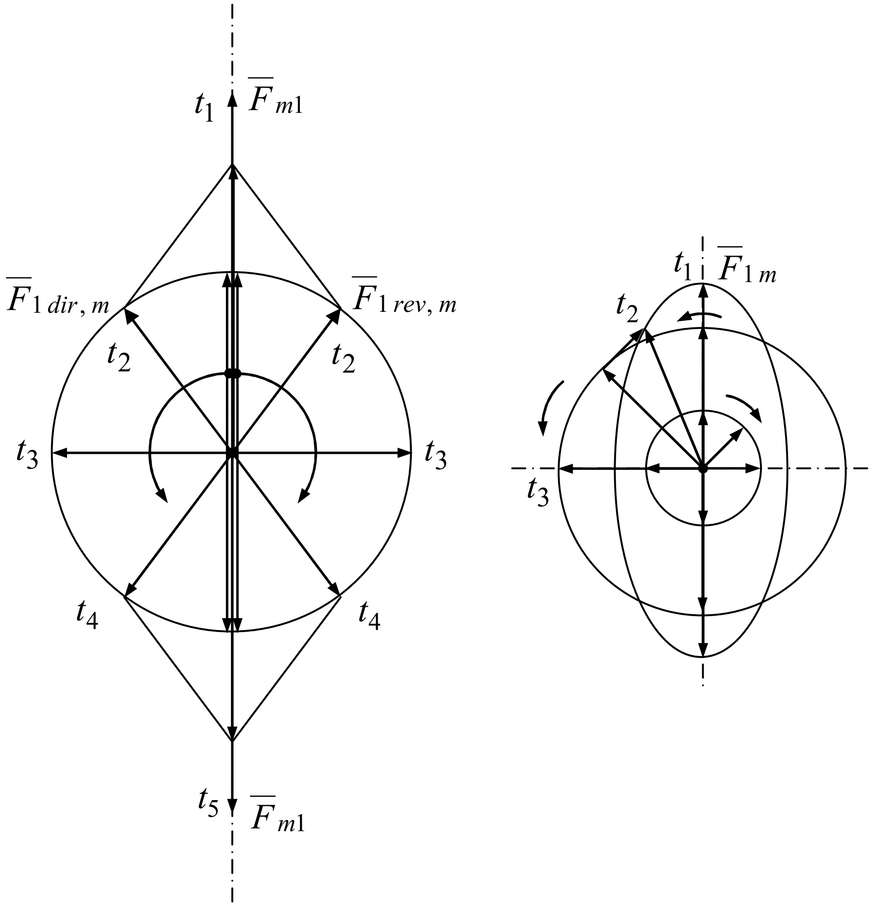


Fig. 1.17 Pulsating and elliptic magnetic fields

1.4 Voltage induced in electrical machine windings

Rotating magnetic field rotates relatively the winding conductors embedded into slots. These conductors are coil (or else coil section) turns sides. The coil being the basic element of a winding has two embedded sides placed in the slots and two end parts connecting the embedded sides. The number of turns of a coil is w_c. Therefore number of active conductors placed at magnetic field and belonging to the embedded coil side accommodated at one slot is too w_c. Each the coil section has two active sides embedded into different slots, being apart at the distance y (coil pitch or else coil span). The coil pitch is smaller than or is equal to the pole pitch (short or full pitch).

The rotating magnetic field cuts the embedded conductors inducing voltage in them. The voltage induced in a coil due to electromagnetic induction is defined as

$$e_{c1} = -\frac{d\psi_c}{dt} \tag{1.29}$$

where ψ_{c1} is the linked flux of the coil.

Consider the fundamental of the rotating magnetic flux. The linked flux of the coil formed by this flux is

$$\psi_{c1} = \psi_{c\,m1} \cos(\omega_1 t - \alpha_c) \tag{1.30}$$

where $\psi_{c\,m1}$ is the coil linked flux amplitude, $\alpha_c = p\gamma_k$ is electrical angle between the coil and the rotating flux north pole at the initial time instant $t = 0$.

The linked flux amplitude equals

$$\psi_{c\,m1} = w_c \Phi_{c\,m1} = w_c \Phi_{m1} k_{p1} \tag{1.31}$$

where $\Phi_{c\,m1}$ is maximum flux bounded by the coil that occurs at coinciding the coil and the pole axes, $\Phi_{c\,m1}$ is the flux of fundamental through the pole pith area.

Finding the coil induced voltage by (1.29) with account of (1.30) and (1.31) obtain:

$$e_{c1} = E_{c\,m1} \cos(\omega_1 t - \alpha_k - \pi/2) \tag{1.32}$$

where the amplitude of the voltage induced in the coil is

$$E_{c\,m1} = \omega_1 \cdot \psi_{c\,m1} \tag{1.33}$$

Rms value of the induced voltage equals

$$E_{c1} = \frac{\omega_1}{\sqrt{2}} \psi_{c\,m1} = \pi\sqrt{2} f_1 w_c \cdot \Phi_{m1} k_{p1} \approx 4.44 f_1 w_c \Phi_{m1} \cdot k_{p1} \tag{1.34}$$

The winding phase comprises several groups of coils. In the group q coils, displaced by the angle γ_z that corresponds to the tooth pitch, are connected in series.

Therefore the *mmfs* of these coils are displaced by phase at the angles $\alpha_z = p\gamma_z$. The task of calculation of the induced voltage across the group of coils leads lie in addition of q sine curves displaced by equal angles α_z as it was done at calculation of *mmf* of a distributed winding. After addition obtain the group of coils induced voltage:

$$E_{q1} = qE_{c1} \cdot k_\alpha = q\pi\sqrt{2} f_1 w_c \Phi_{m1} k_{w1} \tag{1.35}$$

Connection of coil groups provides arithmetical summation of the groups induced voltage of a parallel branch. As the result obtain the following expression for the voltage induced across the phase winding terminals by the rotating field fundamental:

$$E_1 = \pi\sqrt{2} f_1 w \Phi_{m1} k_{w1} \tag{1.36}$$

where number of turns of the winding phase for one layer winding equals

$$w = \frac{w_c z}{2ma} \tag{1.37}$$

and for two layer winding it is

$$w = \frac{w_c \cdot z}{ma} \tag{1.38}$$

The voltage induced in the phase winding by rotating harmonic of the three-phase winding field has the same frequency that the voltage induced by the field of the fundamental, i.e. $f_\nu = f_1$. This is explained by different rotational speeds of harmonics of the three-phase winding field as it follows from the expression

$$\Omega_\nu = \pm\frac{\Omega_1}{\nu} \tag{1.39}$$

If the voltage is induced by the field of rotating field winding of synchronous machine, the magnetic field harmonics have the same rotational speed $\Omega_\nu = \Omega_1$ and different harmonics induce the voltage of different frequencies, i.e. $f_\nu = \nu f_1$.

In general the voltage induced in the phase winding by the $\nu - th$ harmonic of rotating magnetic field is determined by the equality:

$$e_\nu = E_{m\nu} \cdot \cos(\omega_\nu t - \nu\alpha) \tag{1.40}$$

where $E_{m\nu} = 2\pi f_\nu w \Phi_{m\nu} k_{w\nu}$.

The rms value of phase winding voltage induced by higher harmonic of the rotating magnetic field equals

$$E_\nu = \pi\sqrt{2} f_\nu w \Phi_{m\nu} k_{w\nu} \tag{1.41}$$

As it is seen from the expressions (1.33), (1.34), (1.35) and (1.40) distribution of the winding and an shortening the coil span decrease the voltage induced by the magnetic field higher harmonics in the electric machine alternating current winding.

But, as it was explained at consideration of the magnetic field, these measures do not affect the winding factors of the tooth harmonics, hence these harmonics of the magnetic field are not reduced at distribution and the pitch shortening. Also are not reduced the voltage induced by them in the winding.

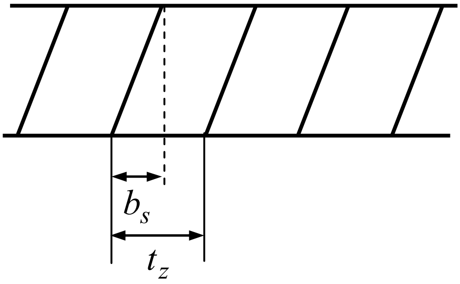


Fig. 1.18 Skewed slots

For improvement of asynchronous machine properties, reduction of tooth harmonics by skewing rotor slots Fig. (1.18) is often used.

The tooth harmonic number is defined as

$$\nu_z = \frac{kz}{p} \pm 1 = 2mqk \pm 1 \tag{1.42}$$

where $k = 1, 2, 3 \ldots$.

Influence of skewing the slots on the voltage induced by magnetic field harmonic is accounted with the help of the skew factor determined by the formula:

$$k_{s\,\nu} = \frac{\sin\left(\nu \frac{b_s}{\tau} \frac{\pi}{2}\right)}{\nu \frac{b_s}{\tau} \frac{\pi}{2}} \tag{1.43}$$

where b_s is the size of slot skew.

Usually the slot skew size is taken about the tooth pitch size t_z.

With account of slots skew the rms of the phase winding voltage induced by a magnetic field harmonic is calculated as

$$E_\nu = \pi\sqrt{2} f_\nu \cdot w\,\Phi_{m\,\nu} \cdot k_{w\,\nu} \cdot k_{s\,\nu} \tag{1.44}$$

Slots skew provides essential reduction of the voltage induced by tooth harmonics and has weak influence for the voltage induced by fundamental and other non-tooth magnetic field harmonics.

An effective measure of reduction induced voltage from tooth harmonics is the winding distribution taking great enough number of slots per pole and per phase as was explained above.

1.5. Parameters of electrical machines

As parameters, resistance and reactance of windings and rotor moment of inertia are usually referred.

As a rule the electrical parameters are defined per one phase.

The resistance is determined by the expression:

$$R = \rho_\theta \frac{l}{S} k_R \tag{1.45}$$

where l is the wire length, S is its cross-section area, k_R is the factor accounting increase of resistance due to non-uniform current flowing through the conductor cross-section distribution, ρ_θ is the conducting material resistivity at specified temperature. Values of resistivity are given in Table 1.1.

Table 1.1 Resistivity of conducting materials

Winding type	Material	Resistivity, OhmMm, at temperature (ºC)		
		20	75	115
Wound-type winding	Copper	$0{,}01754 \cdot 10^{-6}$	$0{,}02128 \cdot 10^{-6}$	$0{,}02439 \cdot 10^{-6}$
Cage winding	Aluminum bus	$0{,}02857 \cdot 10^{-6}$	$0{,}03571 \cdot 10^{-6}$	$0{,}03846 \cdot 10^{-6}$
	Cast Aluminum	$0{,}03333 \cdot 10^{-6}$	$0{,}04167 \cdot 10^{-6}$	$0{,}04545 \cdot 10^{-6}$

Factor 136 is the ratio of the resistance values at non-uniform and at uniform current distribution and is greater than unity. It accounts influence of skin-effect caused by eddy currents induced by the leakage flux in a conductor inserted into a slot. To reduce resistance, conductors of great cross-section area are split to several parallel conductors of cross-section not more than 16 … 18 mm^2 which are laid flatly in a slot (Fig. 1. 19). The conductor height should not be more than 2,5 mm. In large machines the conductors are transposed by the slot height to provide different position of the conductor by height that equalizes the voltage induced in the conductors the leakage flux.

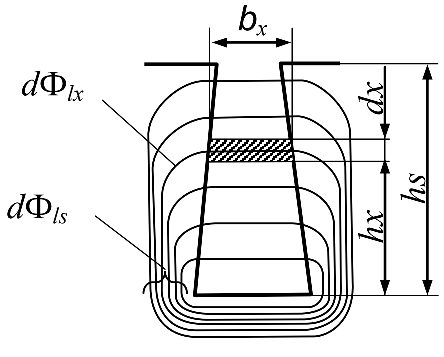


Fig. 1.20 Picture of slot leakage flux

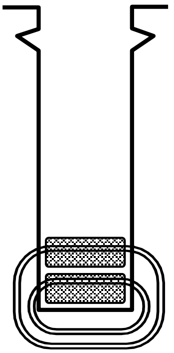


Fig. 1.19 Layout of rectangular conductors in slot

Reactance of windings of electric machines is defined by self-induction and mutual induction. Inductive reactance caused by mutual induction of the machine windings is a characteristic of the machine principal magnetic field which magnetic flux is linked with both machine windings. Methods of the reactance caused by mutual reactance are different for different types of machines. Inductive windings reactance caused by self-induction are called leakage reactance and characterize leakage magnetic fluxes linked with turns of only one of the windings.

At the leakage reactance determination the leakage flux of a winding is divided into three parts – the flux of embedded coil sides (slot leakage flux), end winding linked flux (end connection leakage flux) and differential leakage flux. For calculation the leakage reactance, the leakage permeance is determined for each of these leakage flux parts.

For each part of the leakage flux the specific permeance, i.e. permeance per unity of the leakage magnetic field length l_l. So the coefficient of specific permeance of slot leakage for embedded conductor element of height dx (Fig. 1.20) is defined as:

$$\lambda_s = \int_0^{h_s} \left(\frac{N_x}{N_s} \right)^2 \frac{dx}{b_x} \tag{1.46}$$

where N_x is the number of conductors beneath the selected element, N_s is the total number of conductors in the slot, b_x is the element width.

Taking into account that the phase winding occupies z/m slots and expressing N_s by the number of phase winding turns have:

$$x_{ls} = 2\pi f \mu_0 N_s^2 \lambda_s = 4\pi f \mu_0 \frac{w^2}{pq} \lambda_s l_s \tag{1.47}$$

Depending on the slot shape expressions for calculation the coefficients of specific permeance for slot leakage flux have been obtained on the basis of (1.45) and are given in reference tables.

Determination of the coefficients of specific permeance for the end connection leakage flux λ_e is more complicated because complicated end connections geometry. Therefore it calculation is carried out by empiric expressions obtained as the result of numerous experiments which are given for different winding constructions in reference books.

The differential leakage flux is the sum of fluxes of magnetic field harmonics in the air gap which do not contribute in producing the torque. Flux linkage of these harmonics increase the winding reactance that is accounted with the help of the coefficient of specific permeance of the differential leakage flux λ_{dif}.

With account of all the components of leakage flux the phase leakage reactance is calculated by the following expression:

$$x_l = 4\pi f \mu_0 \frac{w^2}{pq} l_s \left(\lambda_s + \lambda_e + \lambda_{dif} \right) \tag{1.48}$$

The moment of inertia J determines in considerable part dynamic processes of electric machine operation at transients. It is the sum of products of the elementary volume masses of the rotor and squares of their distance to the axis of rotation. The moment of inertia equals

$$J = \int_V \gamma \rho^2 dV \tag{1.49}$$

where ρ is the distance of the element to the axis, dV is the elementary volume, γ is the material density.

At calculation, the rotor is conventionally divided into parts having simple shape and consisting of the same material, calculate these parts moment of inertia and find the total rotor moment of inertia as the sum of the parts moments.

At the same mass of the rotor the moment of inertia for rotor which has the radius less and the length greater is less. If the driving torque pulsates it is expedient to use the machine with greater moment of inertia that is provided by increase the radius and making the length shorter. Increase of the moment of inertia of hydro-generators improves their stability at parallel operation.

Test questions

1. What kind of energy transducer is called the electric machine?
2. In what case an electric machine works as a generator and in what case – as a motor?
3. What does the principle of electric machine reversibility mean?
4. By what criteria may the electric machines be classified?
5. What are salient and non-salient pole machines?
6. What is the principle of a reluctance machine construction?
7. In what cases is a core of electric machine member made laminated?
8. Describe construction of a disc-type machine.
9. What alternating current windings produce pulsating and circular rotating magnetic field?
10. In what case the circular rotating magnetic field becomes elliptic?
11. Explain a concept of the winding of electric machine magnetomotive force.
12. What shape has the curve of a single phase concentrated AC winding?
13. What for the AC winding of electric machine is made distributed?
14. What positive result does the AC winding pitch shortening?
15. What is accounted with the help of the winding factor?
16. How is the maximum amplitude of a single-phase winding determined?
17. What are single layer and two layer windings? What useful properties a two layer winding has?

18. How the rotating wave of three-phase winding mmf is expressed, and how can be a rotating mmf harmonic amplitude found?
19. By what is the rotational speed of three-phase winding magnetic field harmonic defined?
20. What harmonics are contained in three phase winding rotating mmf and which of them rotate in positive and negative direction?
21. What is the double-revolving method and how it is applied to the pulsating and rotating elliptic magnetic fields?
22. What is interrelation between the winding mmf and its magnetic field?
23. Write expressions for instantaneous and rms values of voltage induced in a phase of AC winding by rotating magnetic field.
24. What quantities are considered as parameters of electric machine?
25. How is the electric machine winding resistance defined?
26. To what parts the leakage flux of a winding is divided when the leakage reactance is calculated?
27. What is the electric machine moment of inertia? In what cases is reduction and in what cases increase of the moment of inertia expedient?

2. WINDINGS OF ELECTRICAL MACHINES

2.1. Basic elements of winding

In electric machines windings of alternating current are placed in slots disposed on inner surface of a stator core or on external surface of a rotor. Shape of teeth and slots of alternating current machines depend on their types and nominal power. In machines of great power windings are made of conductors of rectangular cross-section, and in this case the slots with parallel sides are used (Fig. 2.1 a, b and 2.2). Such slots provide the best conductors placement and their reliable insulation. In machines of small and medium power stator and rotor windings are made of round wire (Fig. 2.1 c, d). In such machines semi-closed oval and trapezoidal slots are used. In a number of cases when the conductors have rectangular cross-section the semi-open slots are used that reduces reluctance of core teeth compared with the open slots. Electrical micromachines often have slots of round shape that permit to make their punching simpler and cheaper.

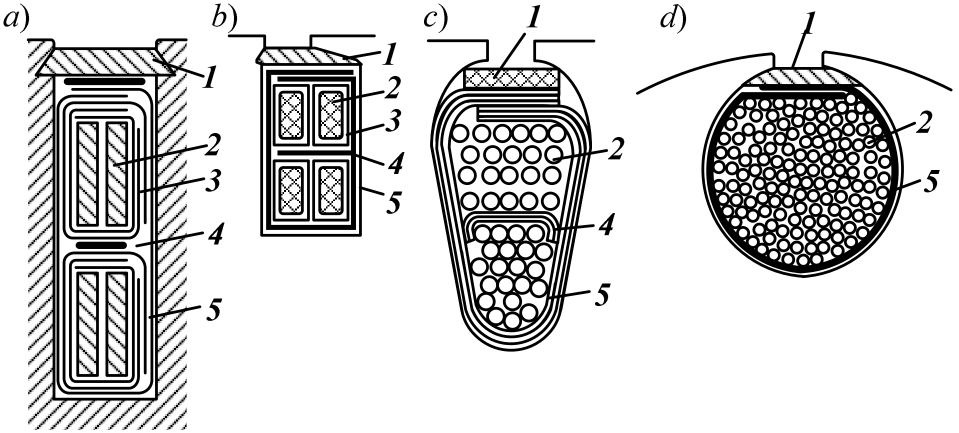


Fig. 2.1 Rotor slots of alternating current machines - open (a), semi-open (b), semi-closed (c, d): 1-wedge, 2 – conductors, 3 – coil insulation, 4 – layer insulation, 5 – slot insulation

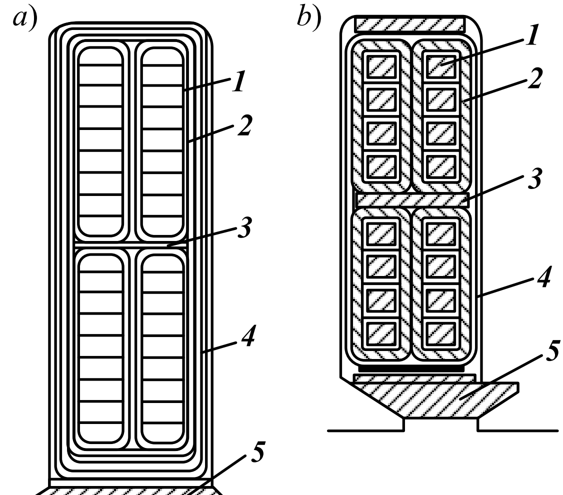


Fig. 2.2 Stator slots - open (a), semi-open (b): 1 – conductors, 2 – coil insulation, 3 – layer insulation, 4 – slot insulation, 5 – wedge

At the conductor insertion to the slots, the slot bottom and sides are covered with insulation using glass cloth, varnished fabric, synthetic fibre, mica, etc. The upper and bottom layers are also insulated from one another. The conductors are fixed in a slot with wedges. The rotor winding end coil sides are too fixed with bands. In some cases the bindings are accommodated in several places along the rotor core.

Connection of a rheostat to the rotor winding and the current leading in the rotor circuit the slip rings are fixed on the shaft. At the three-phase rotor winding it is needed three slip rings. In the case of a cage winding the sip rings are not necessary. Current collection from the slip rings is made with the help of brushes which are rectangular bars made by sintering of coal, graphite and metal powder (copper and lead) mixture. The brushes are held in position with the brush holders. The brushes pressure against the slip rings is maintained with springs.

Consider the principles of polyphase windings.

Conductors embedded in slots are connected between them with the end winding conductors constituting a number of coils which have definite number of turns (Fig. 2.3 a). The coils occupying several neighboring slots, relating to one phase and pole pair and connected in series constitute a group of coils. Each of the winding phases have in common case a number of groups of coils connected in series or in parallel. Parallel connection is used at great currents or necessity of switching separate group of coils. Elementary unit of a winding is a turn, consisting of two conductors embedded in slots, which situated at the distance from one another. This distance is called the coil span or pitch or the winding pitch. It is comparable with the pole pitch which is the peripheral distance between corresponding points on two consecutive poles:

$$\tau = \frac{\pi D}{2p} \tag{2.1}$$

where *D* is the rotor or the stator bore diameter, *2p* is the number of poles.

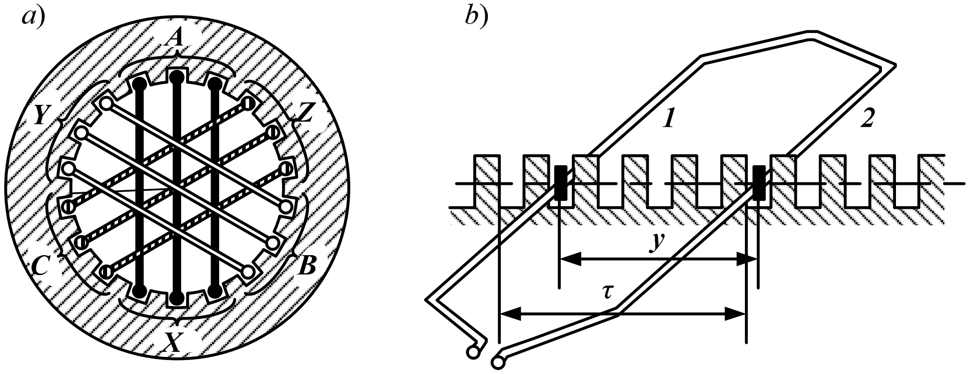


Fig. 2.3 Placement of three-phase winding coils on stator (a) and formation of turn of two active conductors (b)

The pole pitch is expressed not only as a length but often as a number of tooth pitches (or a number of slots):

$$\tau = \frac{Z}{2p} \tag{2.2}$$

where Z is total number of tooth pitches (or slots) of the stator or rotor.

If $y=\tau$, it is said that the coil pitch is full. In the case of $y<\tau$ there is a short coil pitch and when $y>\tau$ – a long coil pitch. The coil pitch is often expressed in per units as $\beta=y/\tau$ or in per cent as $\beta=100\, y/\tau$ [%].

Situated in neighboring slots coil sides of one group of coils occupy q slots taking the angle $\alpha=2\pi pq/Z$. The number of slots per pole and per phase is equal to

$$q = \frac{Z}{2pm} \tag{2.3}$$

where m is the number of phases.

Usually the turns located in the same slots are integrated into one or two coils. The coils are inserted into slots so that one slot is completely occupied with a side of one coil, or two sides of two different coils occupy the slot above one another. Respectively recognize single layer and two layer windings (Fig.2.4).

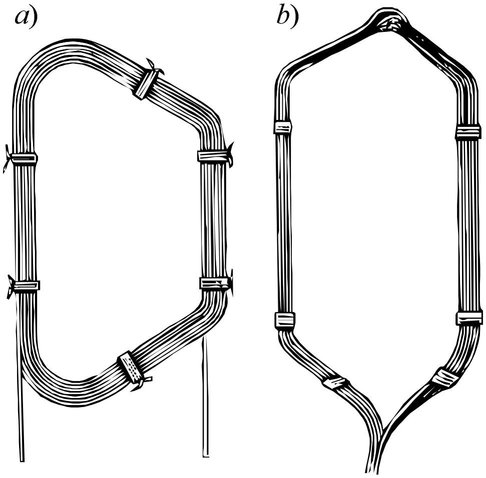


Fig. 2.4 Coils of single layer (a) and two layer (b) windings

In the winding shown in (Fig. 2.3) a each of the phases consists of three coils which sides are situated into three adjacent slots, i.e. this winding has $q=3$. In common case $3q$ slots of a three-phase winding lie at one pole pitch.

If $q=1$, only one coil side per phase lies under each the pole. Such a winding is called the concentrated winding. In the case of $q>1$ a winding is called the distributed winding.

In most cases the windings have integral number of slots per one pole and one phase. In three-phase machines the angle occupied by the sides of coils belonging to a group of coils equals $\pi/3$ or $2\pi/3$, in a single phase machine when 2/3 slots are filled with winding – $\alpha=2\pi/3$, in two-phase machine – $\alpha=\pi/2$.

Depending on coils design the windings are divided in two groups: windings fed-in-windings and form-wound windings. Fed-in-windings are usually random wound windings, in which the individual conductors are fed into each slot through the slot opening. Their coils are wound of round wire. For initial shaping these coils are wound to a bobbins and then inserted into semi-closed slots through the slot openings (Fig. 2.1 c, d). The layer linings are placed after the bottom layer insertion. The coils are fixed in the slots with wedges or coverings. The end windings are formed after the winding placing. Then the winding is impregnated with varnish. The fed-in windings manufacturing is as a rule completely mechanized.

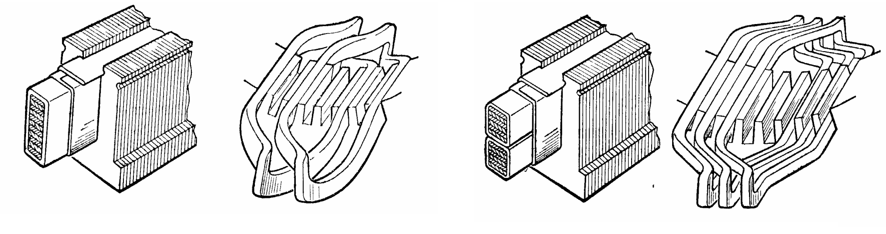
Form-wound windings are assembled of coils (half-coils) which are given their shape before being assembled into the machine. Simultaneously they are covered with coil, slot and layer insulation. After that the coils are placed to open or semi-open slots (Fig. 2.1 a, b and 2.2), fixed and impregnated.

The form-wound windings have the following advantages:

- application of rectangular conductors improves the slot space utilization,
- higher winding reliability as the slot is filled with ready made and revised coils which take less deformation.

There is why the fed-in windings are used mainly in machines of rated voltage till 1000 V power of lower than 100 kW. In mote powerful machines the form-wound windings of rectangular conductors are used.

Depending of disposition the coils in a slot single-layer and two layer winding are distinguished.



a) *b*)

Fig. 2.5 Single layer (a) and two layer (b) windings

The single-layer windings (Fig. 2.5 a) are the most suitable for mechanization of wounding as for that the winding should be concentric and both coil sides are inserted into the slots simultaneously. But the end windings in this case have greater length and coils wire consumption increases. Such windings have full pitch, and therefore the magnetic field curve contain greater higher harmonics, additional magnetic losses increase, torque-speed curve dip arise and noise produced by working machine intensifies. Still due to their simplicity and cheapness such windings are widely used for machines of lower power less than 10…15 kW.

Two layer windings (Fig. 2.5 b) can be performed as short pitch windings that improve the magnetic field distribution along the air gap circle due to reduction of higher harmonics. The voltage induced by the magnetic field higher harmonics is also reduced. The two layer windings have simpler shape of the end windings that makes assembling of the winding easier. Such windings have form-wound coil sections and are used in machines of nominal power greater than 100 kW. They are placed into the slots by hand.

Consider the principle of three-phase single-layer winding arrangement taking for example four-pole machine ($2p$=4) with number of slots per pole and per phase q=2. In such a case the conductors belonging to one phase are placed under a pair of neighboring poles in four slots (Fig. 2.6). One phase occupies eight slots: $2pq$=4*2=8. Total number of slots in the machine equals to Z=$2pmq$=4*3*2=24 . In Fig. 2.6 instantaneous directions of the induced voltages of different phase conductors for the instant when the induced voltage in phase AX is maximum and positive.

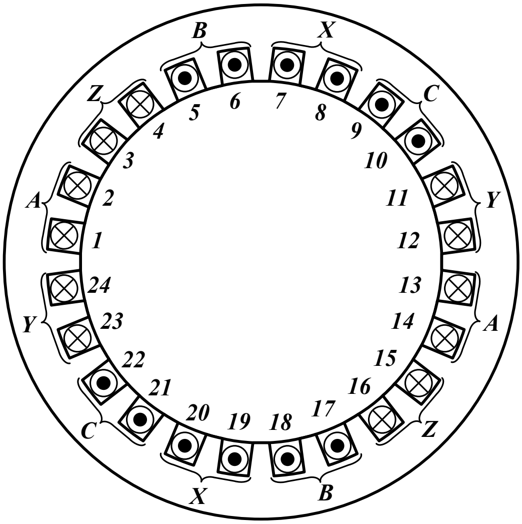


Fig. 2.6 Disposition of single layer winding coils in slots of three-phase machine stator

2.2. Diagrams of alternating current machine windings

In Fig. 2.7, 24 slot lines lying on the developed cylindrical core surface are shown. The lines are divided into four groups corresponding to the pole pitches. Each pole pitch contains τ=Z/2p=24/4=6 tooth pitches. Mark the slots at each pole pitch in which coil sides belonging to different phases lie. As the winding is balanced there is equal number of different phases coil sides onto each pole pitch that equals to the number of slots per pole and per phase. Instantaneous directions of currents in the coil sides at one pole pitch are the same at given time instant (see slots 1-6, 7-12, 13-18 and 19-24). In slots of neighboring pole pitches the current directions are opposite.

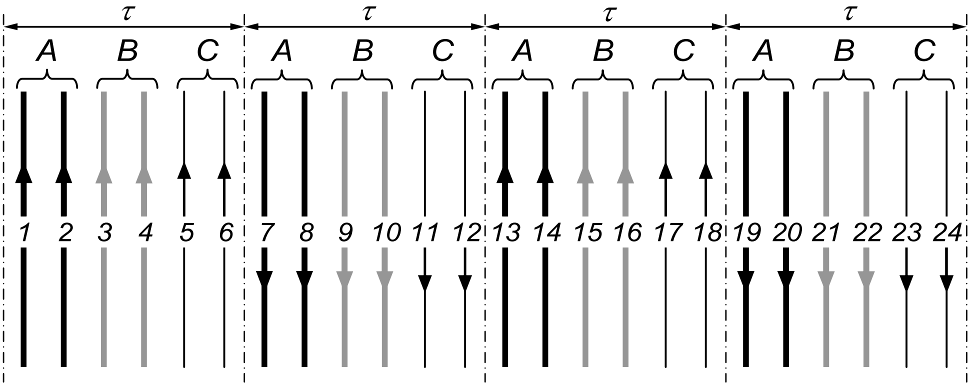


Fig. 2.7 Coil sides of three-phase single layer winding

Fig. 2.7 represents embedded coil sides or slot portions of the winding. The end windings should be made so that the current directions would correspond to shown in Fig 2.7. They may be carried out in several different ways giving different types of single-layer windings that are called concentric, spool and chain windings.

Consider concentric single layer windings. A developed diagram of a concentric winding is given in Fig. 2.8 where the same numeration of slots as in Fig. 2.7 is applied. The winding is distributed one. The winding pitch is equal to the pole pitch though the spans of different coils of each group are not equal, one of them is shorter and another is longer compared with the pole pitch. In concentric winding the coils of a coil group are located concentrically inside one another. The end windings of different phases intersect and can not be located in the same plane. Therefore peripheral extremities of different phase end windings are placed in two or three different planes i.e. are bi-planar or triple planar (Fig.2.9).

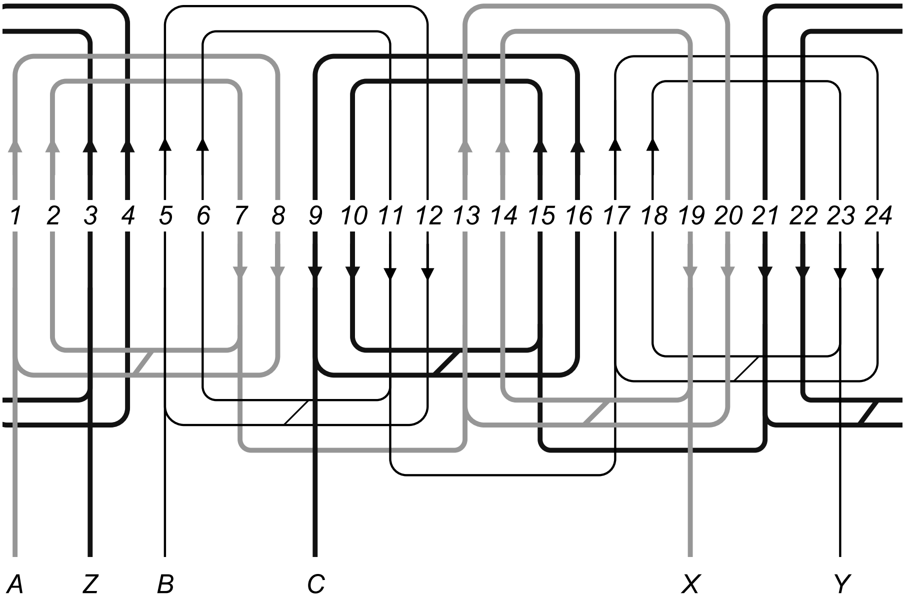


Fig. 2.8 Single layer concentric winding, Z=24, $2p$=4

The windings of each of thee phases are identical but displaced around the circle to the same direction by 2/3 of the pole pitch or 120 electrical degrees.

For the distributed single layer winding the winding factor equals as the pitch factor is 1.

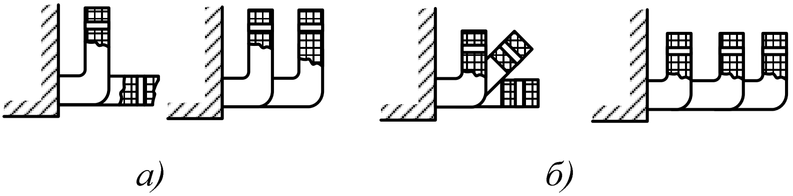


Fig. 2.9 End connections of single layer windings placed in two planes (a) and in three planes (b)

The single layer concentric winding range of application becomes nowadays wider as their manufacturing and placing into slots can be easier mechanized in comparison with two layer ones.

Consider two layer windings. Two layer winding have found their application in wide range of alternating current machines beginning from nominal power of 15 kW.

Only some unique turbo-generators of great power have direct cooled single layer windings that is explained by complicated construction and special features of great machines winding having small pole number.

Main advantage of two layer winding is possibility to use shortening of the coil pitch for decrease of the magnetic field higher harmonics and voltage induced by them in the winding. Besides the two layer windings provide more options for obtaining the winding parallel paths, forming winding with fractional number of slots per pole and per phase. They provide more uniform placement of the end windings.

Usually the two-layer winding have the coil pitch of y=(0,8-0,86)τ at which the fifth and seventh harmonics are suppressed considerably.

In Fig 2.10 lay-out of a two-layer winding conductors in stator slots of four-pole machine having the same data that the machine with single layer winding was shown in Fig. 2.6 (2p=4, q=2, Z=24). The winding pitch is assumed equal to y=0,833τ =0,833*6=5. In each the slot the coil sides are arranged in two layers. Conductors of the same phase in upper and bottom layers are displaced by one tooth pitch. The conductors are connected in coils so that induced in them voltages add together. With account of the voltage direction a phase (AX in the figure) has eight coils embedded in slots (in figure that are slots1-6, 2-7, 7-12, 8-13, 13-18, 14-19, 19-24, 20-1). One side of each the coil is placed in the upper layer, and another – in the bottom layer.

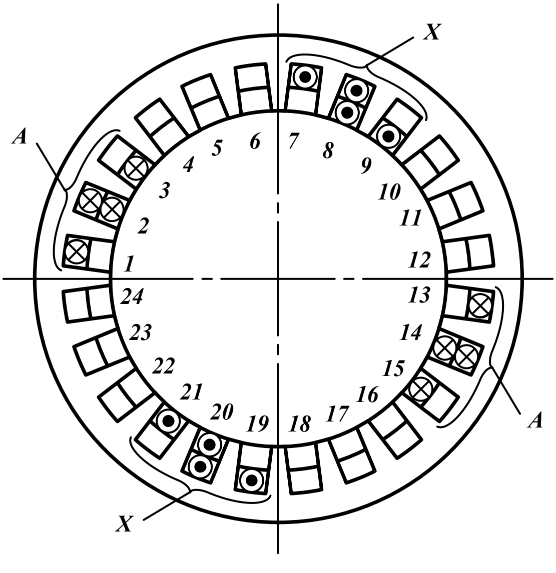


Fig. 2.10 Disposition of two layer winding coils in slots of three-phase machine stator

In the developed diagram of a two layer winding (Fig. 2.11) all the conductors of each slot layer, i.e. each coil side, is shown as a line. A coil side of upper layer is shown as a full line, a coil side of bottom layer – as a hatch line.

As in one-layer three-phase winding, in a two-layer one the windings of all thee phases are identical but displaced around the circle to the same direction by 2/3 of the pole pitch or 120 electrical degrees.

The total number of coils at a two layer winding is twice as much as at a single layer winding that makes the winding some more complicated and expensive. But due to shortening the pitch, consumption of the conductor material reduces. All the coils have the same shape and dimensions that permits to mechanize their manufacturing.

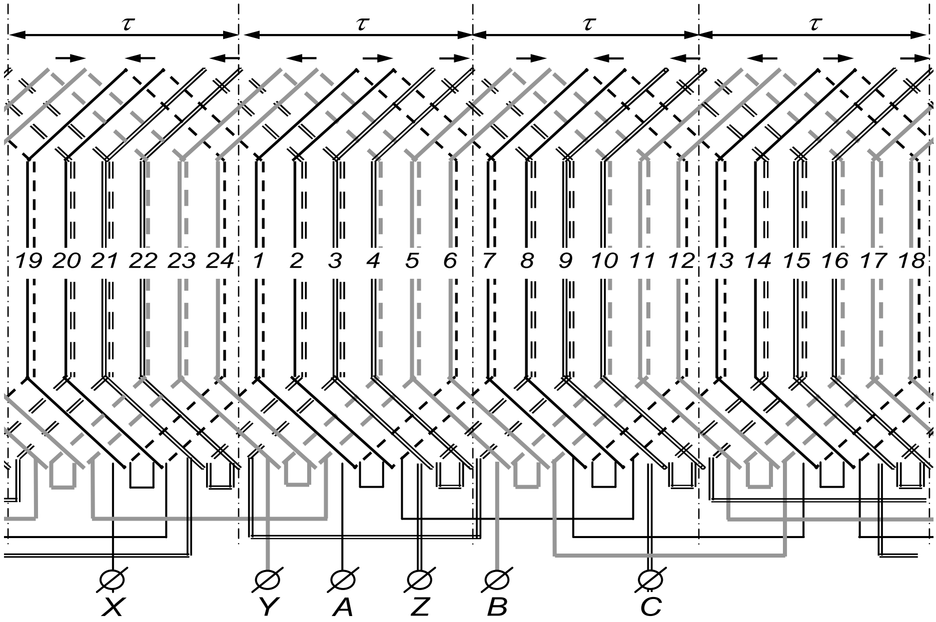


Fig. 2.11 Developed diagram of short pitch two layer winding: Z=24, 2p=4, q=2, τ=6, y=5

In the two-layer winding in Fig. 2.11 all the turns lying under one pair of poles are connected in sequence and the groups of coils lying under successive pairs of main poles are connected to one another in the same sequence as those pole pairs. Such a winding is called the lap winding. Sometimes stator windings of large machines are carried out as wave windings. The wave winding is a two layer winding in which the sequence of connections is such that consecutive coil sections lie under adjacent pole pairs in one direction around the machine. A coil section of a two-layer wave winding is sown by hatch lines in Fig 2.12. Comparing section of lap and wave windings it is seen that they differ by direction of the end connections bending. The wave windings are mainly used when the number of coil section turns is unity. The first sides of the winding successive coils are displaced by two pole pitch distance. So, following the winding coils path, the wave movement occurs. Passing all the machine poles the wave tour is made. To prevent the winding closing, the next circle wave tour begins one slot before (or after) the initial slot of the first tour. In this way q wave tours around the machine circle are made, and as a result we obtain a half of a phase winding. The second half is received in the same way but the wave tours begin at the slot displaced for one pole pitch to the first slot of the previous phase winding part. It is understood that the wave winding of a phase consists of two similar parts, and they may be connected in series or in parallel forming one or two paths of the winding. The connection should be made so that proper succession of current direction in conductors is provided. The lap and wave windings electrically and magnetically are identical. In the case of great number of poles and the coil number of turns equal to unity the wave winding can provide saving of conductor material at the expense of shorter end connections. The wave winding may be executed with full and sort pitch. Full pitch wave windings find their application mainly in wound rotors of asynchronous machines. The number of paths of the wave winding (at each of the phases) may be obtained equal to one or two.

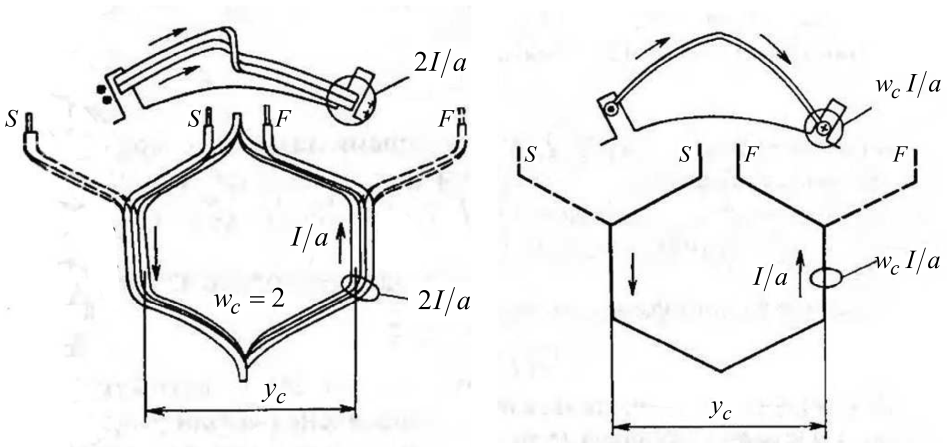


Fig. 2.12 Coil sections of two layer lap (full line) and wave (hatch line) windings: a – coil view, b – schematic symbol

Sometimes combined single and two layer windings are used. In common two-layer winding some part of slots are filled with coils of the same phase (slots number 3, 5, 7 and so on in Fig. 2.11 and other slots – with coil sides that belong to two different phases of winding. In the combined single and two layer winding, one large single layer coil section having doubled number of turns is inserted to the slots having in common winding coil sides of the same phase, and by two small coil sides of different phases are inserted in two layers to the remaining slots at which they are in the usual winding (Fig 2.13). Such a winding consists of concentric coil sections. The number of coil groups is equal to the number of poles. One group of coils comprises one large and (*q* -2) small coils, total number of coils in a group is (*q* -1). The pitch of a large coil is ($y_g=\tau$-1) and of small coils – ($y_{s1}=y_g$-2), ($y_{s2}=y_g$-4) and ($y_{s3}=y_g$-6) and so on. Such a winding can be fulfilled only at $q>2$. The coil pitch of the winding having one large coil in a group of coils should be taken equal to $\beta=2(q+1)/3q$. The combined single and two layer winding can be too carried out with two great coils in a coil group. In this case the number of coil in a group is q_{gr} =2, and the winding pitch should be taken equal to $\beta=(q+2)/3q$. Such a winding may be carried out at $q>4$.

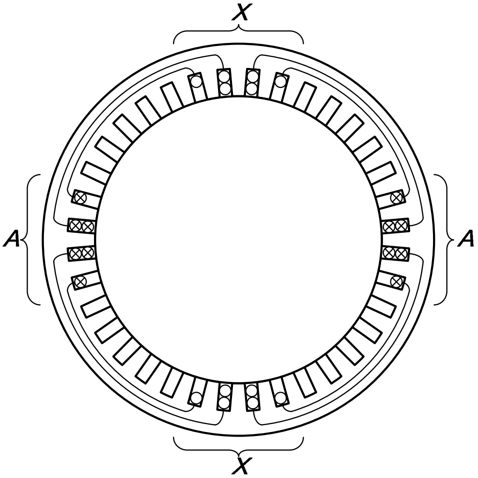


Fig. 2.13 Disposition of one phase coils in slots of three-phase machine stator $2p=4$, $q=3$, $Z=36$

Fractional slot winding is a distributed winding in which the number of slots per pole and per phase q is a fraction. Fractional slot windings are applied in multi-pole machines, for example in such as hydro-generators and slow-speed motors, which due to limited value of the pole pitch the number of slots per pole and per phase can not be taken great enough. Such windings permit to obtain induced voltage varying by law close to sine curve at relatively small number of slots. In such a winding group of coils of the same phase, that are situated under successive poles and connected in series, are shifted a little that promotes reduction of higher harmonics.

To get balanced fractional slot winding, i.e. the winding phases induced voltages to be equal and displaced by phase to one another by 120º, it is necessary that $z/3t$=integral number.

where t is the greatest common divisor of the total number of the machine slots Z and the number of pole pairs p.

Distribution the slots and, consequently, the coils and the groups of coils between the phases can be made in the following way.

The fractional value of q is represented as an improper fraction:

$$q = \frac{N}{d} = b + \frac{c}{d} \tag{2.3}$$

where $N=(b\,d+c)$ is the fraction numerator, b is the fraction integral part and c and d, ($c<d$), are the numerator and denominator of its fractional part respectively.

Consider a diagram of a simple fractional slot windings for which Z=0, $2p$=4, m=3, and $q=Z/2pm$=2½. The developed diagram of one phase is shown in Fig. 2.14. Using the assumed notations it may be written: b=2, c=1, and d=2. Then have N=2*2+1=5.

Pay attention to some peculiarities typical for all the fractional slot windings. The group of coils can not consist of fractional number of coils. Therefore the number of coils in the groups is chosen so that the average number of coils of the group was equal to q. On this reason in the phase winding are present "great" and "small" group of coils. A great coil group has the number of coils greater per unit in comparison with small one. The great and small groups alternate with some periodicity.

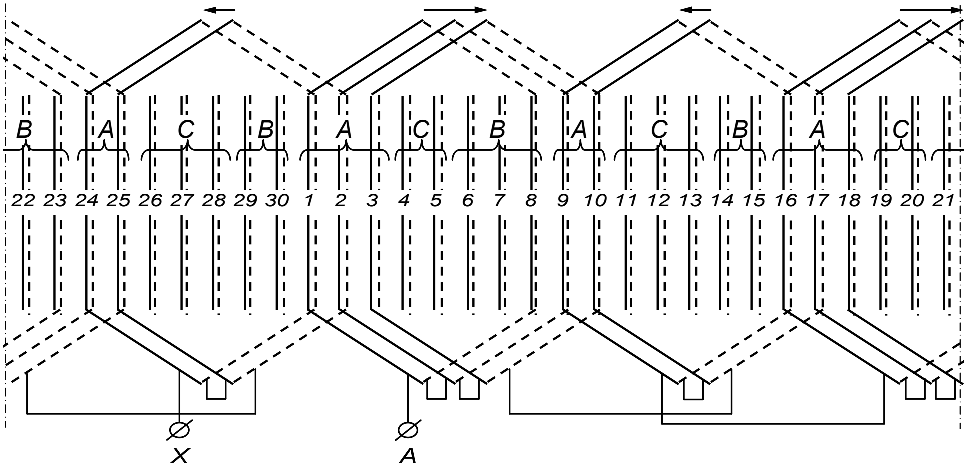


Fig. 2.14 Developed diagram of fractional slot winding for one phase

The winding under study comprises equal numbers of great and small group of coils. These croups have respectively three and coils each (average number of coils in a group is 2½). The number of coils in a small group is always equal to b and in a great – (b+1). Alternation of the number of coils in great and small groups along the core circle may be written as a sequence of integral figures indicating the number of coils in each group. For the winding we consider such a sequence is /3,2/3,2/3,2/3,2/3,2/3,2/ that means that beginning of the reference point the first group is great comprising three coils, the second one is small comprising two coils, the third one is great again of three coils, an so on. The alternation has strictly definite periodicity for each given winding. In the winding under study in each the period there are two coil groups including (3+2=5) coils in total. In general a fractional slot winding has d groups of coils in a period by N coils per the period. Under this condition the average number of coils in a group equals q.

The coils in each group are connected in series. The distribution factor for a fractional slot winding is determined as

$$k_d = \frac{\sin\left(\frac{\pi}{m}\nu\right)}{N\sin\left(\frac{\pi}{2mN}\nu\right)} \tag{2.4}$$

As it is seen a fractional slot winding makes possible to reduce the higher harmonics as in the case of an integral slot winding requiring greater number of slots.

Diagram of coil groups connection (conventional winding diagram)

In many cases conventional diagrams showing sequence order of the winding coil groups and their connection are useful.

Fig. 2.15 presents such a diagram for the winding which developed diagram is given in Fig. 2.11. Each rectangular box represents a group of coils. In the boxes the figures above its diagonal are the group sequence numbers, and the figures below the diagonals are numbers of coils in groups. In the diagram of the specified winding the winding pitch should be indicated because the conventional diagrams of full pitch and short pitch windings are the same.

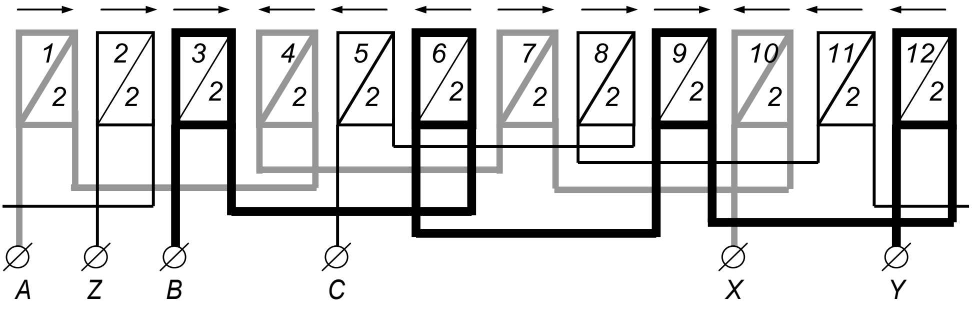


Fig. 2.15 Conventional diagram of winding at Z=24, $2p$=4, q=2, τ=6, y=5

Parallel paths of winding and coil group interconnection

The cross-sectional area of winding conductors is selected by the allowable current density at operating the machine at its rating. Usually the current density is assumed in the range of J=4…6 A/mm^2. At the rated power and current a conductor cross-sectional area increases. By conditions of coil sections manufacturing and their insertion to the slots restrictions are imposed on value of a conductor cross-sectional area and it may not be taken too much. Therefore at great cross-section conductors are divided into several strands of smaller conductors. The total cross-section area of the strands should be equal to the needed cross-section area of the conductor. The fed-in-windings are wound with round wire of diameter not more than 1,7 – 1,8 *mm*. In such windings the conductor may be assembled of several strands which number as a rule should not be more than five.

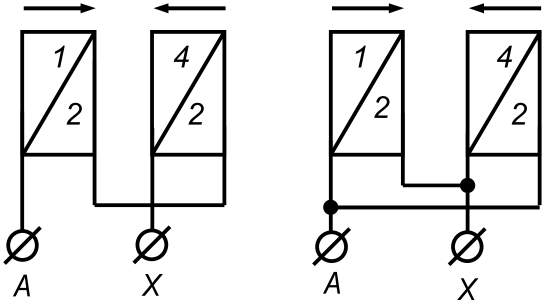
When a winding is produced from rectangular conductors, the strand or the whole conductor cross-section area should not be more than 17…20 mm^2 to reduce eddy-current loss. The conductor is divided to strands at its cross-section area exceeding the indicated. If solving the problem in this way is impossible the winding is made with several parallel paths. Increase of the paths number decreases, and consequently the conductors cross-section area decreases too. To obtain a phase winding with a parallel paths its groups of coils are divided for a equal parts. As the number of groups of coil equals $2p$ at two-layer winding and p at single-layer winding, the number of parallel paths a should be equal to $2p$ and p respectively.

Division of coil groups for parallel paths is made so that resistance and reactance of the paths were equal and their induced voltages were equal in magnitude were in phase. Under these conditions the phase current will divide for parallel paths in equal parts.

In Fig 2.16 a, a conventional two-layer winding diagram of one phase at a=1 for two-pole machine is shown. Direction of path-tracing the coil group by the current, that conditionally indicates polarity of the poles, is shown by arrows. When the number of paths is changed the poles polarity must remain unchanged. Therefore the arrows above the rectangles must not change their directions. The two-pole two-layer winding may be too connected for obtaining a=2. This case is shown in Fig. 2.16 b.

Tree-phase windings of alternating current machines may be connected in star or in delta. For large machines star-connection is preferable.

In many cases three-phase induction motors destined for operation at supply by two different mains voltages that differ by $\sqrt{3}$ times (for example, 220/380 V, 380/660 V).In such a case six terminals are set in the terminal box. Depending on the linear voltage value the winding of phases are connected in delta or in star.



a) b)

Fig. 2.16 Connections of two-pole phase winding at different number of paths: a – at a=1, b – at a=2

2.3. Pole-switching three-phase windings

Comparison of single and two speed machines

Multi-speed pole changing machines have usually two, three or four rotational speed. In most cases multi-speed machines are accomplished with a cage rotor because for wound-rotor multi-speed machine additional switch for changing pole number of the rotor winding be needed. In such machines the stator winding is usually two-layer one which leads connected to a pole switch. Such a winding does not differ from common alternating current machines stator windings, and their manufacturing is made by the same technology. The output power of a machine having several separate windings is appreciably reduced in comparison with the machine with a single winding which uses the same magnetic core. On this reason multi-speed machines with more than two separate windings are not in use.

Comparison of alternating current machines of the same rated power having one and two windings show that for two winding machine consumption of copper is greater by 40…50 % and steel by 30…40 % than for machine with one winding. Besides two winding machines have less efficiency and power factor. On the other hand two winding multi-speed machines have simpler pole switching circuit and smaller switch than machines with one winding because of less number of the winding leads to be commutated. In the case of two windings technical properties of the machine may be made closer to needed for operating at every speed.

When the speeds are switched with the ratio of 1:2 in the case of two windings it is necessary to switch among six leads because at star connection there are three leads from each winding. The same number of leads is available in the case of one pole-switching winding at switching by widely spread the schemes *Δ/YY*, *YY/□Δ*, and *YY/Y* with the pole ratio of 1:2. Therefore for machines with speed ratio 1:2 one winding is always applied. Two speeds with another ratio and also three and for speeds are obtained with the help of either one or two separate windings. If three speeds are needed one winding for two speeds with the ratio of 1:2 and the second winding for the third speed are taken. At this the number of leads to be switched is nine: six leads of two-speed winding and three leads of one-speed winding connected by star. At use of one winding for three speeds the leads number may be from nine to eighteen depending on switching circuit and the speeds ratio. To get four speeds two windings with the ratio of 1:2 for each are applied. Number of the switched leads is from 12 to 16 depending on the switching scheme.

In a four-speed machine with two windings may be obtained two pairs of speed value in which the speeds relate as 1:2. For example: 500/1000/750/1500 or 500/1000/1500/3000 rpm. In other cases the number of switching leads increases greatly.

Requirements to windings

There are the following main requirements to pole-switching (or multi-speed) windings:

- maximum power recovery at the lowest speed so that useful power of the machine differ from the power of a single-speed machine of the same frame limit and pole number as less as possible,
- optimal electrical and mechanical characteristics of the machine at every magnetic field rotational speed,
- the less as possible number of switched leads of the winding needed for switching to every speed,
- maximum reliability of the winding,
- construction of the lead switch should be of the less complexity and it should have the less dimensions as possible,
- manufacturing the winding and its repair should be not more complicated than of common single-speed winding.

Depending on a multi-speed machine service conditions different of the requirements may be of greater importance. The most frequent requirement is maximum machine power recovery at the lowest speed. Worsening active materials utilization in multi-speed alternating current machine in comparison with single-speed machine at the same other conditions, such as current and magnetic loads, filling the slots with conductors, the main influence quantities are the winding factor and worsening power indices. Therefore for better machine power recovery at the lowest speed it is necessary:

- to have maximum winding factor for multi-speed winding,
- efficiency and power factor should not be other than these quantities of analogous by rated power pole number winding of single-speed machine.

To provide motor optimal characteristics at every rotational speed it is necessary to possible schemes of multi-speed windings for the given machine operating conditions. Selection of winding scheme that fits the operating conditions of a two-speed machine with speed ratio of 1:2 does not cause difficulties. The more complicated problem is development of circuit for three or four-speed winding. The best reliability and minimum switch dimensions are provided by the circuits which have minimum number of the winding leads to be switched at changes of rotational speed. Complexity of the switch depends not on total number of the winding leads connected to the switch but by the total number of commutations realized at all speed changes, i.e. by number of leads commutated at all switch positions.

The multi-speed windings diagram may be divided into following groups:

- diagrams at which a motor or generator can develop the same useful power at any rotational speed,
- diagrams at which shaft torque remains constant, and shaft power varies in proportion to the speed,
- diagrams at which the shaft power increases more quickly than the speed,
- diagrams at which the useful power at higher speed decreases in comparison with the power at lower speed.

In practice the windings of the first two groups are mostly applicable. The winding of the third group are applied not so often, the fourth group of windings is used rarely.

The simplest winding permitting to change the number of poles twice, is shown in Fig. 2.17 (in the figure only one phase is represented). Each winding phase is divided into two parts that are switched from series to parallel connection.

When the coils 1-2 and 3-4 are switched for parallel connection the number of poles decreases twice, therefore the magnetic field rotational speed increases two times. After the switching the number of turns connected in series in each phase decreases two times but as the rotational speed increases twice the voltage induced in a phase does not vary. Hence, the machine at every of two speeds may be connected to the network with the same voltage.

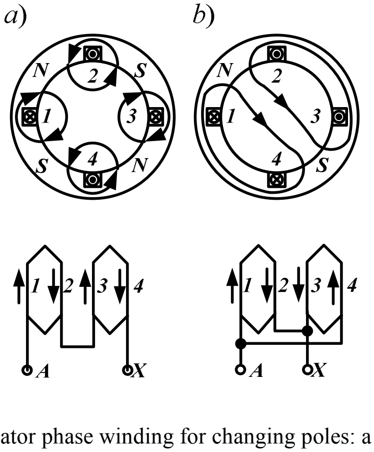


Fig. 2.17 Switching of stator phase winding for changing poles: a – at $2p$=4, , b – at $2p$=2

Consider two layer winding (Fig. 2.18). Each stator phase of two-speed motor with the ratio of poles of 2:1 consists of two parts in which the numbers of coil groups are equal. When through these parts conductors the currents flow in the same direction, magnetic field has larger number of poles (Fig 2.18 a). When direction of current in one of the parts changes to opposite, the number of poles decreases two times (Fig. 2.18 b). Such switching should be done in all the phase windings simultaneously. At this the switched parts may be connected either in series (Fig. 2.18 b) or in parallel (Fig. 2.18 c).

The length of an arc of a circle occupied by sides of a coil group remains the same at both pole numbers. But the pole pitch changes twice.

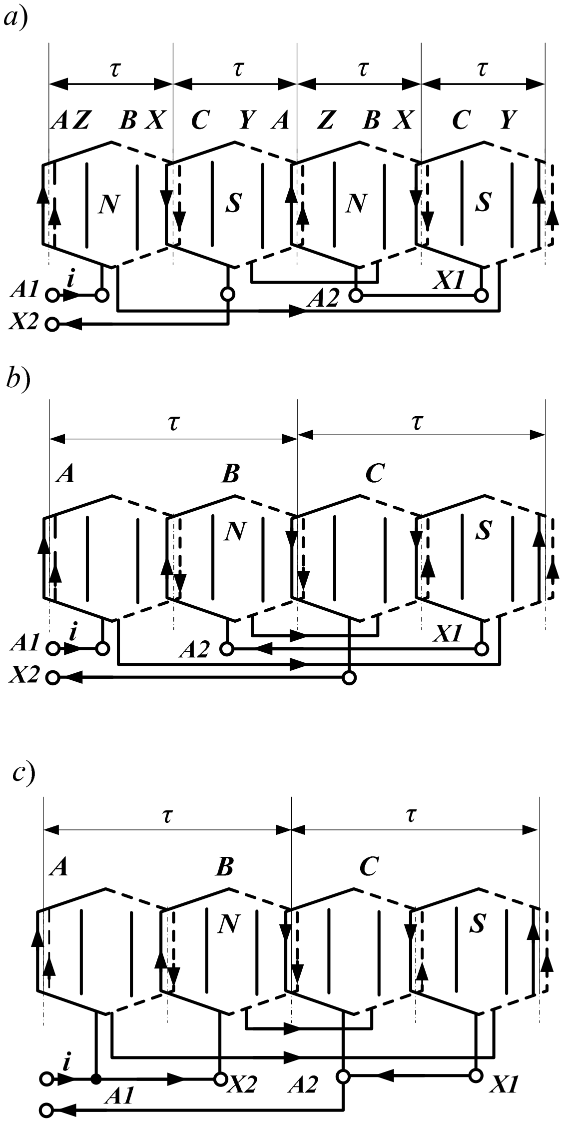


Fig. 2.18 One phase of pole-switching winding: a – $2p=4$, b, c – $2p=2$

In Fig 2.19 the alternation of phases of the pole-switching winding with the pole ratio of 2:1 for different rotational speeds is represented. As it is seen, to obtain the same direction of rotation it is necessary to change places of two phase winding start leads (for example start leads of phases *B* and *C*).

The winding pitch at greater number of poles is taken equal to the pole pitch $y=\tau$. In this case the *mmf* distribution is close to sinusoidal. At the less number of poles have y=0,5 τ, and even higher harmonics arise of which the second and the fourth are most appreciable. This causes dips in the machine torque speed curve and increases the magnetic noise at unfavorable proportion of number of stator and rotor slots. It also worsens the energy datum of a machine in comparison with the case of normal phase zone $\alpha=60^{\circ}$ and y=(0,8…0,86)τ.

The mostly often used stator winding circuits for switching pole number with ratio of 2:1 (Dalander's circuits) shown in Fig. 2.20 represent switching between star and double star (Fig. 2,20 a and b) and between delta and double star (Fig. 2.20 c and d). Switching between star and double star (*Y/YY*) provides constant torque at both speeds, and switching delta to double star (*Δ/YY*) provides approximately constant power.

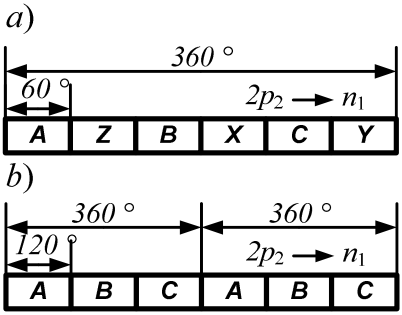


Fig. 2.19 Alternation of phase areas of pole-switching winding at pole ratio 2:1

Transition from the lower to greater speed brings change direction of the currents in the half of the half-windings. To remain the same direction of rotation it is necessary to exchange connection of two phases leads (in the figure that is made for the phases *B* and *C*).

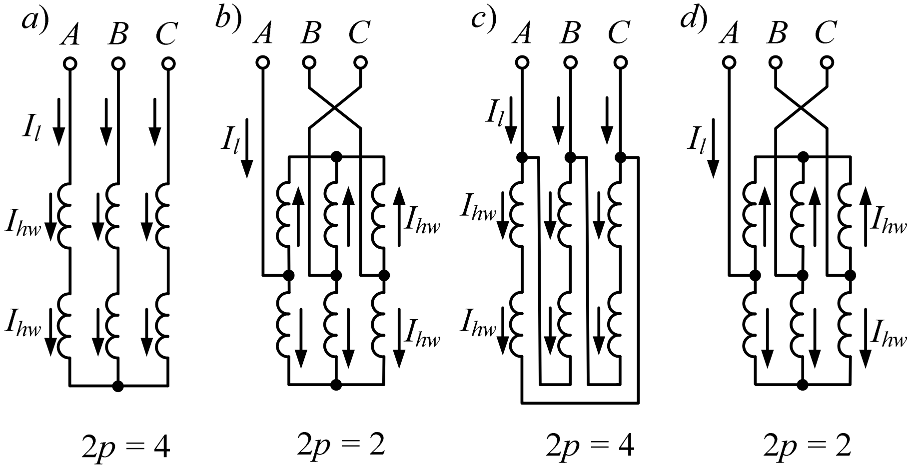


Fig. 2.20 Circuits of pole-switching windings at pole ratio 2:1

Consider relations of the consumed power P_1 and of the torques M for considered circuits assuming that line-to-line voltage $U_{l\text{-}l}$, the current I_{hw} in each the half-winding, efficiency η and power factor $\cos\varphi$ remain unchanged.

For the circuits in Fig. 2.20 a and b have

$$\left.\begin{aligned} \frac{P_{12}}{P_{11}} &= \frac{\sqrt{3}U_{ll}I_{l2}\cos\varphi}{\sqrt{3}U_{ll}I_{l1}\cos\varphi} = \frac{\sqrt{3}U_{ll}2I_{hw}\cos\varphi}{\sqrt{3}U_{ll}I_{hw}\cos\varphi} = 2 \\ \frac{M_2}{M_1} &= \frac{P_{22}}{\Omega_{22}}\bigg/\frac{P_{21}}{\Omega_{21}} = \frac{P_{12}}{\eta\Omega_{22}}\bigg/\frac{P_{11}}{\eta\Omega_{21}} = \frac{P_{12}}{P_{11}}\cdot\frac{\Omega_{21}}{\Omega_{22}} = 1 \end{aligned}\right\}. \tag{2.5}$$

For the circuits in Fig. 2.20 c and d the relations are

$$\left.\begin{aligned} \frac{P_{12}}{P_{11}} &= \frac{\sqrt{3}U_{ll}I_{l2}\cos\varphi}{\sqrt{3}U_{ll}I_{l1}\cos\varphi} = \frac{\sqrt{3}U_{ll}2I_{hw}\cos\varphi}{\sqrt{3}U_{ll}\sqrt{3}I_{hw}\cos\varphi} = 1.15 \approx 1 \\ \frac{M_2}{M_1} &= \frac{P_{22}}{\Omega_{22}}\bigg/\frac{P_{21}}{\Omega_{21}} = \frac{P_{12}}{\eta\Omega_{22}}\bigg/\frac{P_{11}}{\eta\Omega_{21}} = 0.575 \approx 0.5 \end{aligned}\right\}. \tag{2.6}$$

In equalities (2.5) and (2.6) index "1" relates to the lower speed, and index "2" – to the higher. At switching by circuits 2.20 c and d as a rule is indicated the same power for both speed values, i.e. assume that $P_{12}=P_{11}$ and $M_2=0{,}5M_1$.

Switching the speed with the ratio not equal to 2:1 is made using the windings having circuit "triple star" with connections to the neutral points. The switching is executed by the principle of amplitude modulation (pole amplitude modulated winding).

In the circuit with the triple star and connection to the neutral points (Fig.2.21) the phase windings coils are connected in three parallel paths – in the triple star. A coil of each the parallel path produces pulsating magnetic field with strongly expressed spatial higher harmonics. These harmonics disposition in space is such that the winding parts connected to phases *A*, *B* and *C* and through which equal currents flow form a balanced system. At that their joint action strengthens one of the magnetic field harmonic components and deletes the component having another number of poles.

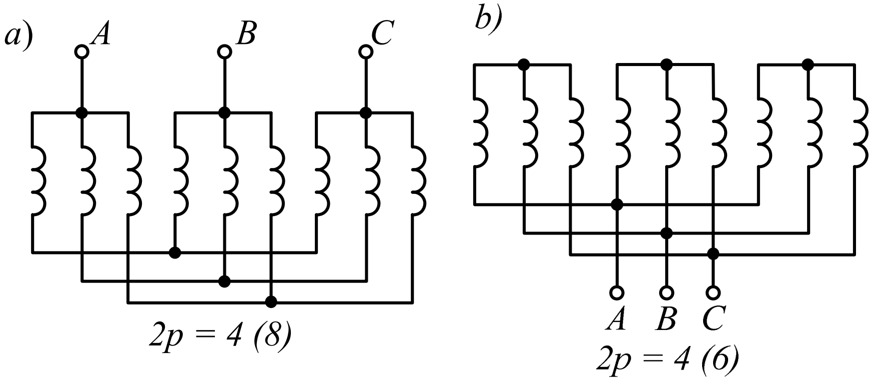


Fig. 2.21 Pole-switching winding with triple star and connection to the neutral points

The Kharitonov's pole switching winding consists of two parts (Fig. 2.22) – two-layer winding 1 connected in delta at $2p=4$ and in double star at $2p=6$. For receiving $2p=2$ the winding 2 is used additionally. In the windings with pole switching by the principle of pole amplitude modulation, changing current direction in a part of coils is necessary. At this the *mmf* distribution along the air gap circle is varied that provides change of the poles number.

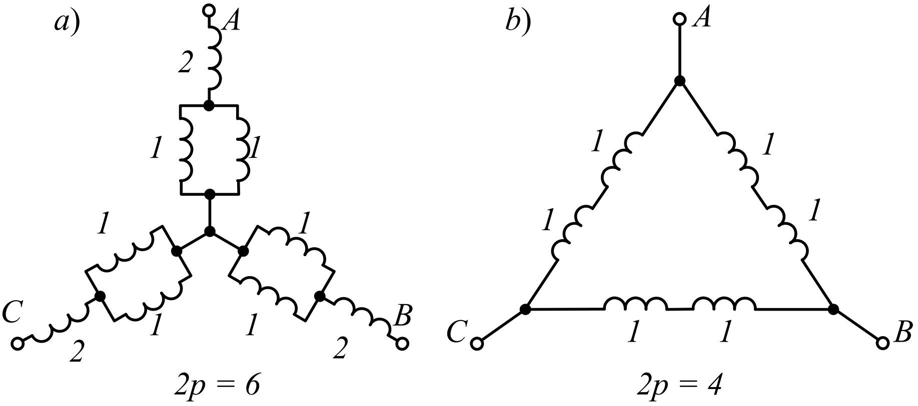


Fig. 2.22 Kharitonov's pole switching winding

2.4. Excitation windings of synchronous machines

Field windings construction

Excitation or field windings of salient pole synchronous machines are made as coils that are placed on the pole cores.

These coils are as a rule made of non-insulated flat wire by wounding on-edge. Thanks to this method of wounding more number of turns may be placed in one layer, conditions of cooling of such a windings becomes better, as the coil has great enough cooling surface. In Fig. 2.23, cross-section of asynchronous machine pole with a field coil. Wounding of coil on the conductor edge needs use of special winding machine. If there is lack of space between the adjacent poles, the stepped coils are carried out. The turns located closer to the rotor are made from the copper conductors of smaller width than the turns of upper coil part. Jointing the wires is made by soldering with silver. Passing from one conductor cross-section area to another is recommended to do smoothly to provide greater surface of connection in the joint. In large machines comber-type edge-profile is made for increase of cooling surface as it is shown in Fig. 2.24.

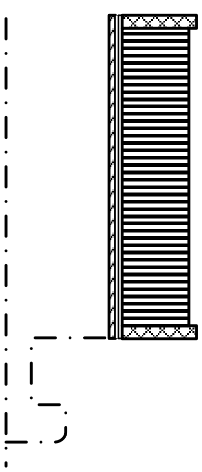


Fig. 2.23 Pole of synchronous machine with field coil

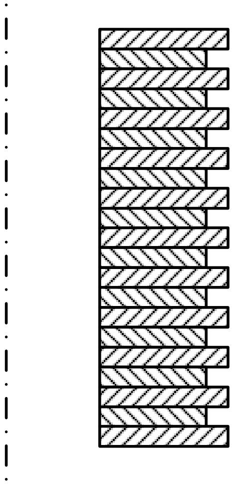


Fig. 2.24 Comber-type field coil

Wounding of field coils is made to the same direction, and they are connected in series. For connection to a current conductor the input plates are soldered to the coil ends. The adjacent coils are joint with buckles and soldered.

In rear cases, aluminum bus-bar wire instead of copper. Exchange copper for aluminum is possible only when distance between pole cores is great enough to place the coils from wider flat conductors. Increase of the conductor width is necessary due to smaller conductivity of aluminum. Leads of aluminum coils are made of copper that is welded to the end turns.

In aluminum coils insulation of the turns is provided by the oxide film. To make this film ticker aluminum is treated with process of oxidation, and after that the coil is baked in furnish to make it monolithic.

Insulation of field coils

The field coils are put on the insulated pole core. Normally the core insulation consists of four-five layers of electric-grade cardboard 0,4…0,5 mm thick. Between the turns at each conductor side electric cardboard 0,2 mm thick is glued with varnish. From above and below the coil, disks of saturated wood or hardened bakelite paper are put to insulate the coil from the pole face and the rotor body. The disks thickness is about 10 mm.

To receive heatproof class B insulation the pole core is insulated with two or three layers of asbestos paper and two-three layers of flexible mica 0,4 – 0,5 mm thick. Between the layers asbestos paper 0,25-0,5 mm thick is fixed with varnish. Between the wooden disks the disk of asbestos cloth about 1 mm thick is put. Common type insulation of a field coil is shown in Fig. 2.25, and heatproof insulation – in Fig. 2.26. After the field coil jamming on the rotor the field coil should be tightly pressed against the rotor rim and the pole face. For that the equalizing distancing disks of electrical paper are put under the lower insulating disks. With time it is possible some weakening of a field coil fixation at a pole. To prevent movement of the insulating disks, springs are put into nests into rotor body.

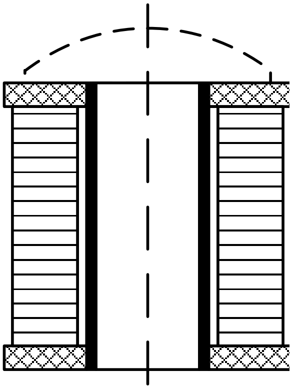


Fig. 2.25 Common type insulation

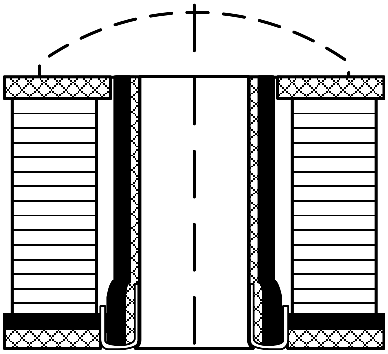


Fig. 2.26 Heat-proof insulation

Field winding of non-salient pole machines

In turbo-generators (Fig. 2.27) distributed field winding consisting of several concentric coils for each pole is applied. The coils are inserted into the rotor slots, and the coils of a group are connected in series. Each the coil group is one pole winding.

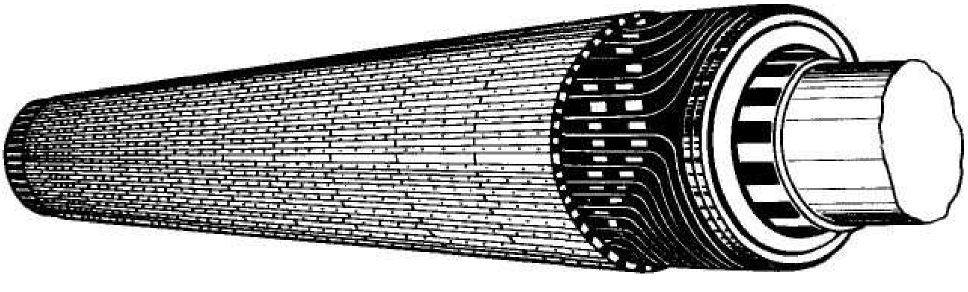


Fig. 2.27 Field winding of turbo-generator

2.5. Asynchronous machine rotor windings

Wound-rotor windings

By their construction and circuits wound rotor windings of asynchronous machines differ something from stator windings of alternating current. For rotors of machines with nominal power till 80 – 100 kW two layer winding are usually applied.

By construction they differ only with displacement of end windings and with use of binding bands on them. Difference of the winding circuits lies in selection of phases start and end points. Distance between stator winding start points is taken minimally possible for more compact layout of leading ends. On a rotor they are intended to be placed evenly around the circle to save balanced placement of rotating mass.

At increase of a machine dimensions, number of turns of the stator winding reduces. At this, number of turns of the rotor winding should be also decreased. If not, the voltage across the slip rings increases, and insulation breakdown can occur. On this reason the rotor conductor cross-section area in large machines becomes great, and the winding is changed for bar-wound with only two active conductors per slot. The number of winding turns decreases, the rotor phase current has great value, and the rotor winding conductor cross-section area is much greater than of stator winding.

The bar-wound rotor winding is commonly executed as wave because of less number of intergroup connections which are hardly executed at use of heavy conductors.

Consider an example of rotor wave winding that has Z_2=24 slots and $2p_2$=4 poles. The lines of slots are drawn in Fig. 2.28. The pole pitch is $\tau_2=Z_2/2p_2=6$, the number of slots per pole and per phase equals $q=Z_2/2p_2w_2=2$. Indicate direction of currents in phase A bars and build up the winding diagram beginning from the upper bur placed to the second slot. The winding has full pitch.

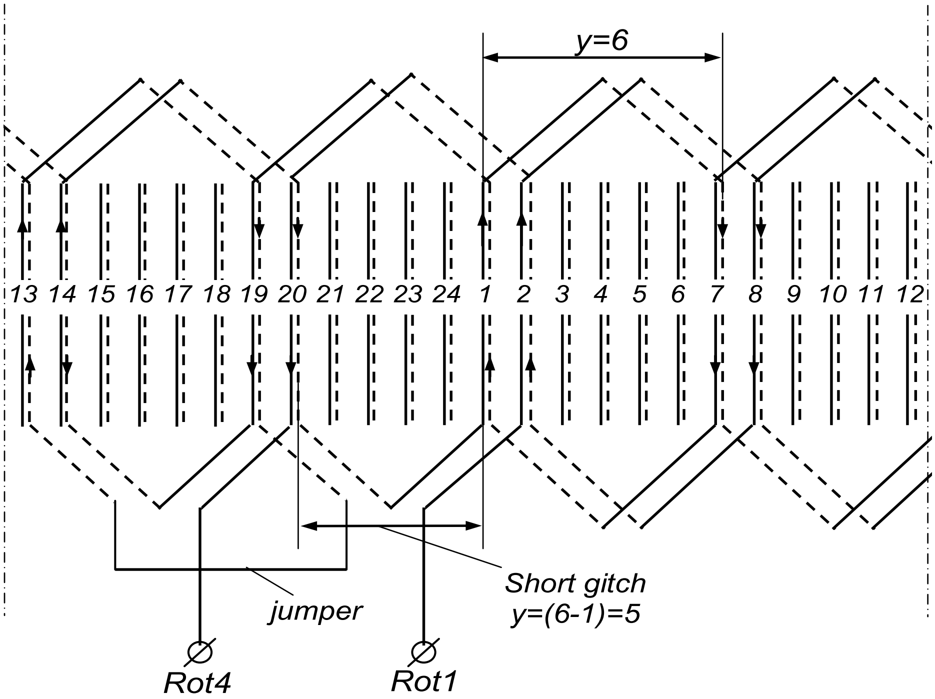


Fig. 2.28 Principle of rotor wave winding

For convenience, simultaneously show consequence of wounding in a winding table (Fig. 2.29). After completion the wave tour around the machine circle begin the next wave tour for one slot before the previous. The next wave tour may begin for one slot later, but in this case crossing in end winding near slot ends takes place.

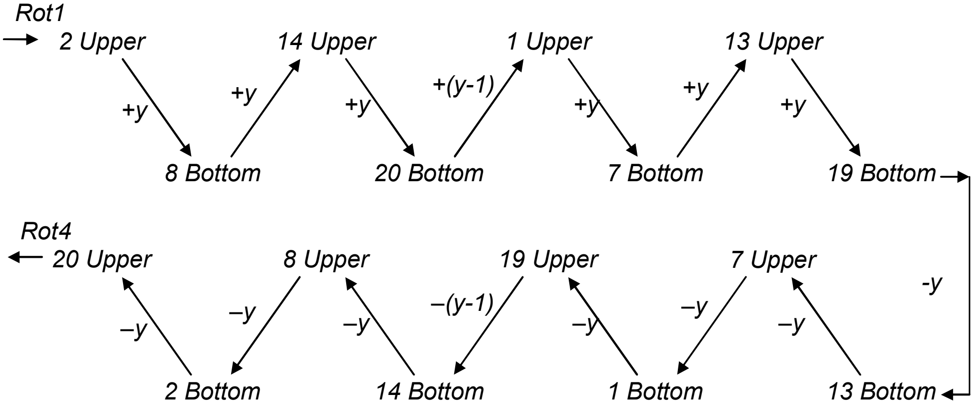


Fig. 2.29 Rotor wave winding table for phase A at Z_2=24, y=6

The first part of the winding finishes in the 19-th slot. Filling the slots by the second part bars is carried out in the opposite order after return for one pole pitch backwards. The second part is finished after executing two more wave tours around the rotor in the opposite direction relative movement at the first part execution.

The start points of the phases are placed symmetrically at distance of $2q_2p_2$ slot pitches, i.e. the start points are shifted for 1/3 rotor circle.

Full developed diagram of the winding is given in Fig. 2.30. The phases start at 2nd, 10th and 18th slots. The described winding is typical for bar-wound rotors.

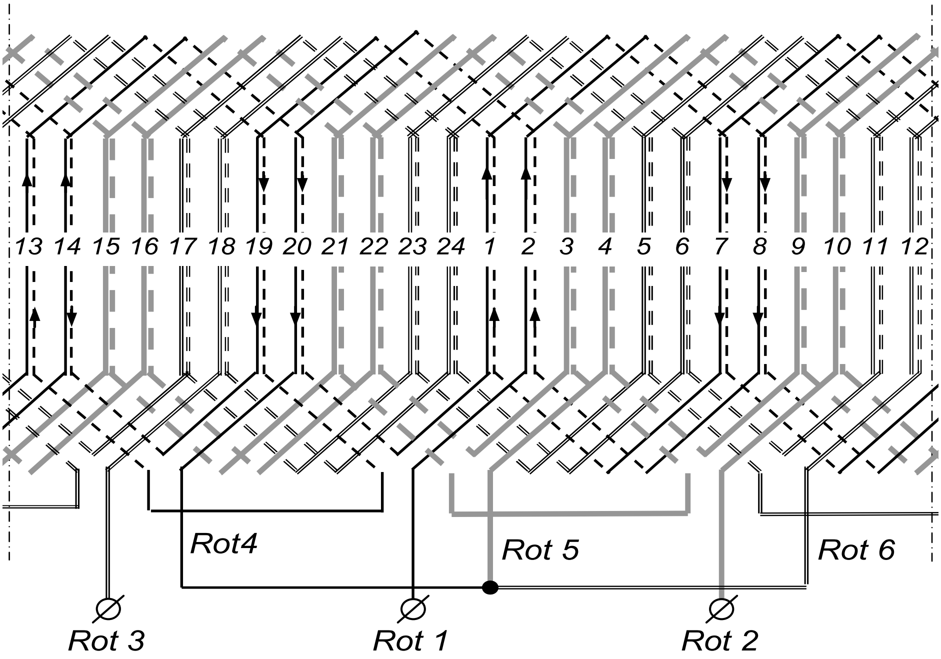


Fig. 2.30 Rotor bar-wound winding: Z_2=24,$2p_2$=4,q_2=2

A wave winding has only one jumper per phase regardless the pole number, whereas the lap winding should have ($2p$-1) jumpers between coil groups per phase. This simplifies the winding connection especially in multi-pole machines.

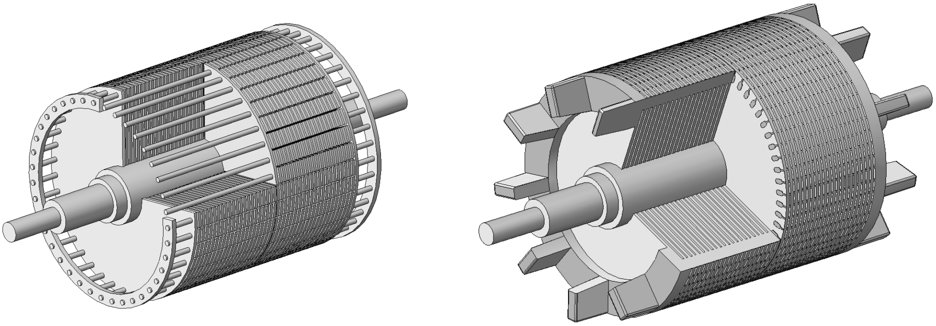
At symmetrical phases starts disposal the phase finishes and jumpers are also symmetrically disposed. If the start of a phase is in the upper slot layer, the phase finishes also in the upper layer, and jumper connects bars placing in bottom layers.

The bar-wound wave windings have mostly one path, and more rarely with two parallel paths.

Cage windings

Cage windings are widely used in rotors of asynchronous and synchronous machines. In synchronous machines they serve as damper winding. Such windings have no insulation between the conductors and slot sides.

Cage (or squirrel cage) windings may be welded or casted (Fig. 2.31).



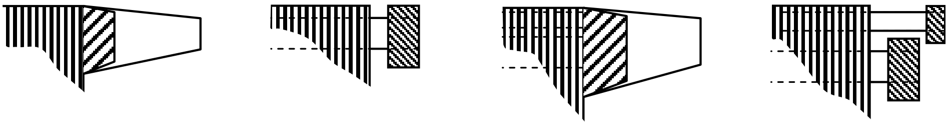
a)

b)

Fig. 2.31 Rotors of asynchronous motors with welded (a) and casted (b) cages

In welded and brazed constructions copper, or brass bars are inserted into the slots and short circuited on the ends by end rings. The connection of the bars to end rings is made by welding or brazing. The cast cages are made of aluminum or aluminum alloys, the bars and end rings are casted as integral parts. At the end rings are simultaneously casted the projecting vanes to fan the air against the end connections of the stator winding and so to aid in cooling the machine.

The end rings may either abut with the rotor core end surfaces or be at some distance of them. In rotors with cast cages the end rings always abut the core (Fig. 2.32 a, c). In this case they not only fan the air but keep the rotor laminations tightly together pressing them. In rotors with inserted bars the end rings are disposed at some distance of the core (Fig. 2.32 b, d).



a)

b)

c)

d)

Fig. 2.32 End rings: single cage (a – casted, b – welded), double cage (c – casted, d – welded)

The slots shape and the rotor construction are defined by the machine power and requirements to the machine characteristics. The mostly used shape of slots is given in

Fig. 2.33. For improvement a motor starting properties the rotors may have a double cage (Fig. 2.33 h, i). A welded double cage has usually separate end rings for each the cage. The starting cage has bars of smaller section. It bars are placed closer to the air-gap surface and is often made of brass. The other, with greater section of the bars, is embedded deeply in the rotor and serves at rotation with normal speed after start. It bars and the end rings are made of copper. Brass is used for the starting cage because of its greater specific resistance and heat capacity in comparison with copper.

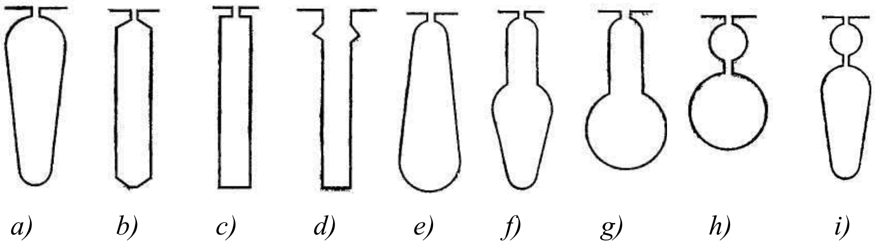


Fig. 2.33 Shape of cage induction machine rotors

Increase of the starting cage specific heat capacity is important for machines in the case of heavy starting conditions as during the start the cage may be heated to high temperature due to great losses in the rotor during the start.

Machines with casted double cage are widely spread (Fig 2.33 i). In such machines outer and inner cages are casted of the same metal. The end rings are common for both cages and abut with the core (Fig. 2.32 c).

Damper windings of synchronous motors (Fig. 2.34) are of welded construction. They are more powerful than of generators as they are used at start too. The bars have mostly round cross-section and are placed in slots of pole shoes. Damper windings of generators are made of copper, and of motors – of brass. As a rule the end rings do not abut the pole shoes being at some distance of them.

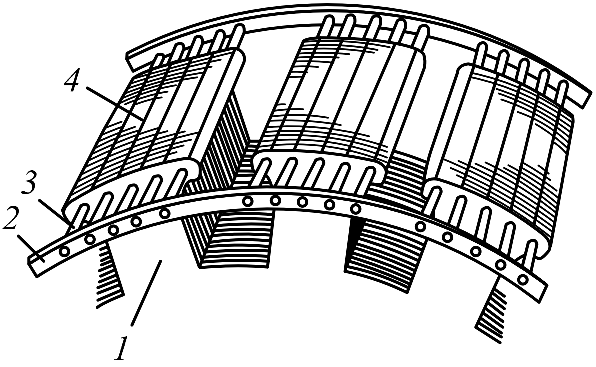


Fig. 2.34 Damper winding of synchronous generator:
1 – rotor poles, 2 – end rings, 3 – cage bars, 4 – pole shoes

Test questions

1. What shape of slots is applied in electric machines when coils are made of round and rectangular wire?
2. How is the pole pitch defined?
3. What is the number of slots per pole and per phase and how it relates with the distributed winding structure and properties?
4. What is single and two layer winding. In what cases each of these types is preferred?
5. What is concentric single layer winding? How are end connections of these windings arranged in two and three planes?
6. What are the lap and wave windings? in what cases the wave winding is expedient to use?
7. What is combined single and two layer windings?
8. How fractional slot windings are built and in what cases it is preferable?
9. How are parallel paths formed in an AC winding of electric machine? How to find possible number of the winding parallel paths?
10. What is the conventional winding diagram? Give examples of such diagrams for a single layer and double layer windings.
11. What are possible ways of providing several speeds of electric machine rotating magnetic field at constant frequency of supply voltage?
12. What circuits of pole switching are used in multi-speed machines at the speed ratio of 2:1?
13. How is the pole switching realized at the pole ratio different than 2:1?

14. How is the speed by pole change at constant power and at constant torque realized at the pole ratio of 2:1?
15. What is the field winding of a synchronous machine construction? In what cases is use the field of comber –type preferred?
16. How the fields of non-salient pole machines arranged?
17. What types of windiness are used for rotors of asynchronous machines.
18. In what case the wave winding is preferable for the rotors?
19. Describe the cage rotor windings. What is double cage winding?
20. What shapes of slots are used for cage induction machines? On what machine parameters and characteristics they may affect?
21. How the damper winding of synchronous generator is arranged?

3. SYNCHRONOUS GENERATORS

3.1. The principles of operation and construction

Consider the synchronous generator or alternator using its bipolar model (Fig. 3.1). In the figure, it is shown the alternator which magnetic system consists of the stator core having three-phase a.c. winding placed in the slots at it inside surface and the rotor core with salient poles having excitation or field d.c. winding. The stator a.c. winding serves as the machine armature winding and therefore the stator of such a synchronous generator is called the armature. When the field winding is connected to a source of direct current it produces the principal magnetic field of a machine. As this field is produced by direct current it is stationary with respect to that winding and the rotor as a whole.

Assume that the principal magnetic field (i.e. the value of its magnetic flux density) varies around the air gap by the sine curve (Fig.3.2). In this case, when the rotor is brought into rotation by some driving motor, e.g. a windmill, the field lines cut the armature winding conductors and induce sinusoidal electromotive forces in them. The armature phase winding induced voltage rms value is equal to

$$E_f = 4{,}44 w_f f \Phi_f k_\mathrm{w} \tag{3.1}$$

where w w is the number of turns belonging to the armature phase and connected in series, $f=pn/60$ is the voltage frequency in Hz, p is the field pole pairs number, n is the rotor speed in revolutions per minute, Φ_f is the magnetic flux per pole in Wb, k_w is the armature winding factor.

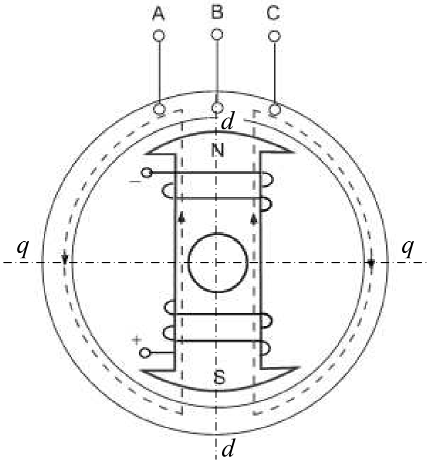


Fig. 3.1 Bipolar alternator

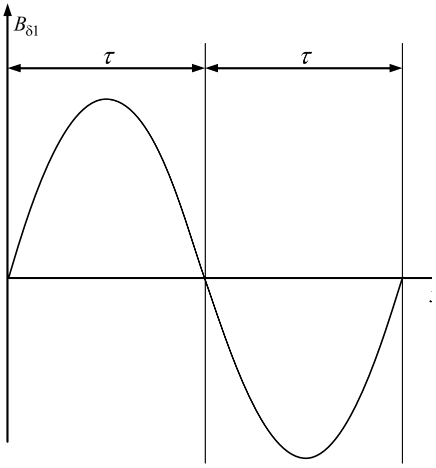


Fig. 3.2 Variation of magnetic flux density around the air gap

In accordance with expression (3.1) the armature induced voltage and, consequently, the voltages across the armature phase winding terminals vary depending on the following two factors:

- value of the magnetic flux Φ_f that can be varied by the field current,
- the rotational speed n.

To obtain the required generator output voltage frequency at given number of pole pairs the rotational speed should have values as indicated in Table 3.1.

Table 3.1 Required rotational speed of alternator, rpm

p	1	2	3	4	5	...
f=50 Hz	3000	1500	1000	750	600	...
f=60 Hz	3600	1800	1200	900	720	...

As the frequency produced by a generator, in the most cases, should not vary, the alternator output voltage can be controlled only by means of the field current variation. Sense of the rotor rotation has to provide the positive phase sequence on the armature winding terminals *A*-*B*-*C*.

In general synchronous machines could be made as with stationary as with rotating armature. Large synchronous machines are made with stationary rotor to simplify electric power takeoff or input to the armature winding (Fig. 3.3 a). As power consumed by the field winding is small as compared to the power in the armature circuit (about 0,3 – 2%), power input to the field winding by means of two slip rings does not meet any considerable problems. Small synchronous machines are made as with stationary as with rotating armature. In the synchronous machine with rotating armature and stationary field system (Fig. 3.3 b) the load is connected to the armature winding via three slip rings.

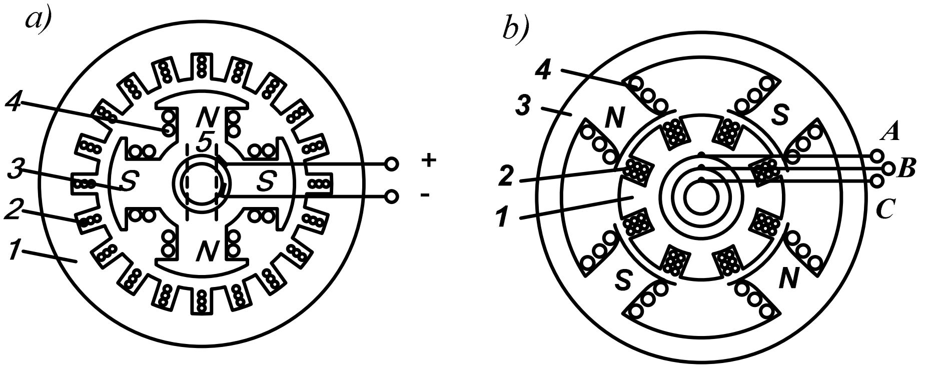


Fig. 3.3 Synchronous machines with stationary (a) and rotating (b) armature: 1 – armature core, 2- armature winding, 3 – field system poles, 4 – excitation (field) winding

Rotor construction

There are two different types of rotor field system construction – salient pole (Fig. 3.4 a) and non-salient pole (Fig. 3.4 b).

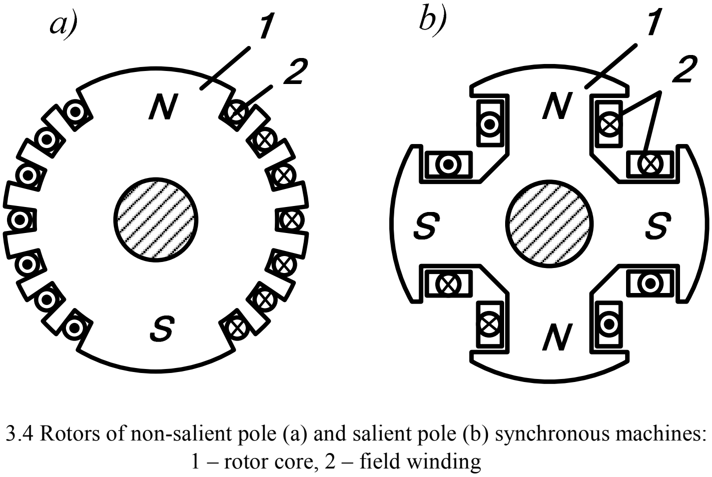


Fig. 3.4 Rotors of non-salient pole (a) and salient pole (b) synchronous machines: 1 – rotor core, 2 – field winding

Bipolar and four-polar machines of large rated power operating at rotational speed of 3000 or 3600 rpm are made as a rule with the non-salient-pole rotor. Use of salient pole construction for such machines is generally impossible due to difficulty of the poles and the field winding fixation mechanical strength providing.

The salient pole field system is usually applied for machines having four poles and more (Fig. 3.5). In this case the field winding consists of coils having rectangular cross-section which are placed on the pole cores and fixed with the help of pole shoes. The rotor, poles and pole shoes are made of electrical steel laminations.

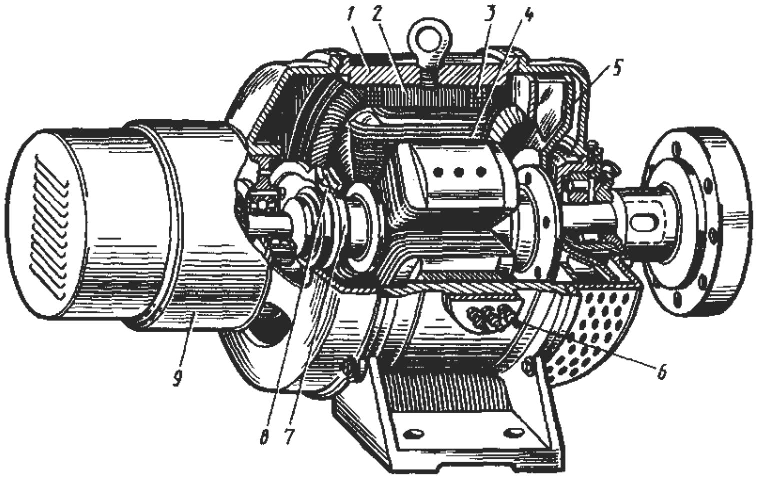


Fig. 3.5 Salient pole machine: 1- machine frame, 2 – armature core, 3 – armature winding, 4 – rotor, 5 – fan, 6 – termination, 7 – slip rings, 8 - brushes, 9 - exciter

Salient pole machines pole faces are usually shaped so that the air gap is minimal on the pole axis and maximal at the pole edges. Owing to that the magnetic flux density varies around the air gap closely to sine curve.

3.2. The concept of a synchronous generator operation

In a synchronous generator under load, two magnetomotive forces act in the machine magnetic circuit. One of them is *mmf* of the field that is always coincides by direction with the pole axis and rotates together with the rotor and another is the armature winding *mmf* which rotates synchronously with respect to the field *mmf* and which direction depends of phase displacement between the induced voltage produced by the principal magnetic field and the armature current. So the resultant magnetomotive force of a generator under load, which is a sum of the magnetomotive forces of the field and armature windings, differs of the machine magnetomotive force at no load. Effect produced by the armature *mmf* on the machine resultant *mmf* and its resultant magnetic field when the machine operates under load is called the armature reaction. In synchronous machines the armature reaction causes the armature terminal voltage variation at operation under load as compared with no load operation. The voltage change appeared as the result of load application expressed in per cent of rated armature voltage is called the voltage regulation. The armature reaction has also some other consequences.

In the most cases a synchronous generator load is lagging or leading with the power factor between unit and zero. To understand effect of the armature reaction on a synchronous machine operation consider the cases of lagging and leading zero power factor and the case of unit power factor. At this we will take into account that the voltage induced in the armature winding by the field magnetic flux, lags behind this flux by 90 degrees.

Armature reaction at unity power factor (active load)

In Fig. 3.6, *a* the stator and rotor of a bipolar generator are shown. The rotor has salient poles. It rotates counterclockwise. At the given time instant the rotor is in vertical position, and the induced voltage in phase *A* has maximum value. As at active load the current is in phase with the voltage, the current in phase *A* circuit has maximum value too. Representing the exciting magnetic field and the armature magnetic with lines of force it is seen that the armature *mmf* vector $\underline{F}_a$ is at right angle to the field *mmf* $\underline{F}_f$. It is too confirmed by the vector diagram plotted for this case. So, at active load, the armature *mmf* produces cross-magnetizing effect. Order of the diagram construction is the following. In accordance with spatial rotor position, the field *mmf* vector $\underline{F}_f$ is plotted. Then the vector of the armature induced voltage $\underline{E}_f$ lagging the field *mmf* $\underline{F}_f$ by 90° is constructed. The vector $\underline{I}_a$ representing the armature current is shown being in phase with the voltage induced in the armature winding. In the case under consideration, the armature *mmf* causes the resultant machine magnetic field distortion. The resultant field is weakened under the leading pole tips and is strengthened under the trailing ones (Fig. 3.7). Due to saturation of the magnetic circuit in the area of the trailing pole tips, the resultant machine magnetic field is somewhat reduced as compared to no-load.

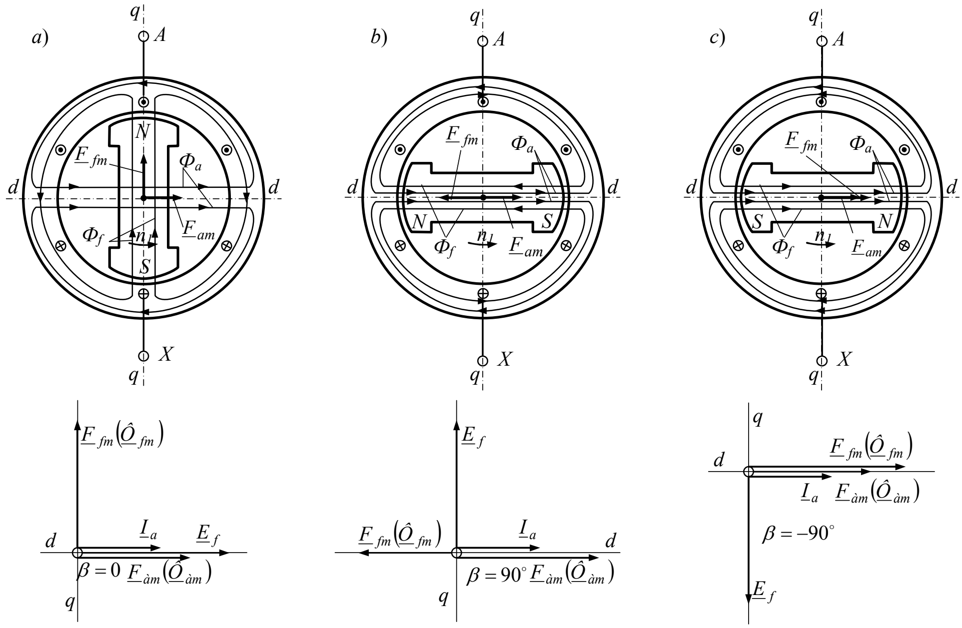


Fig. 3.6 The synchronous generator armature reaction at active (a), inductive (b) and capacitive (c) loads

It is explained by the fact that demagnetization of the leading pole tips and armature core teeth under them occurs easily, but magnetization the trailing pole tips and the teeth under them is restricted by magnetic saturation. As the result the machine magnetic flux is reduced, i.e. the magnetic system is demagnetized to some extent. The reduction of the magnetic flux causes decrease of the armature induced voltage.

Armature reaction at zero power factor, lagging (purely inductive load)

At purely inductive load the armature current $\underline{I}_a$ lags the induced voltage $\underline{E}_f$ by 90°. Therefore it reaches maximum value just when the rotor turns forwards by 90° relative to its position at which the induced voltage reached its maximum (Fig. 3.6 b). At that the armature magnetomotive force $\underline{F}_a$ is directed along the pole axes in direction opposite to the field *mmf* $\underline{F}_f$. We can too be convinced of that by plotting the vector diagram.

Such effect of the armature *mmf* reduces the machine field. The armature reaction in a synchronous generator at purely inductive load is direct-axis reaction because the armature *mmf* is directed along the machine direct-axis and is demagnetizing because its direction is opposite the field *mmf* and its action appears in reduction the resultant magnetic field. So the armature reaction in the case of purely inductive load is called direct-axis demagnetizing.

Unlike the case of purely active load, the resultant magnetic field at purely inductive load is not distorted.

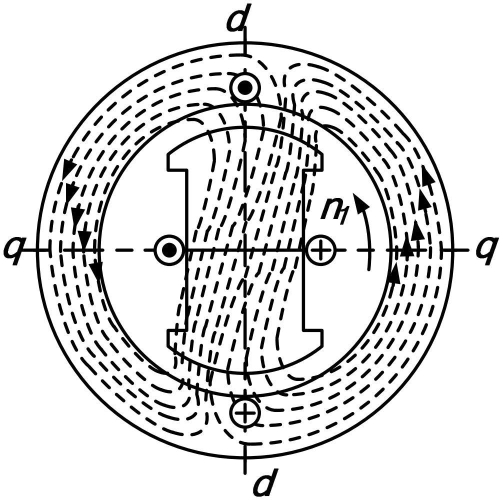


Fig. 3.7 The magnetic field of a synchronous generator at active load

Armature reaction at zero power factor, leading (purely capacitive load)

As the armature current $\underline{I}_a$ in the case of capacitive load leads the induced voltage $\underline{F}_f$. by 90°, it reaches its maximum value sooner than $\underline{F}_f$. when the rotor occupies the position shown in Fig. 3.6 c. As in the previous case, the the armature magnetomotive force is directed along the pole axes but in direction that is the same that of the field *mmf* $\underline{F}_f$.

The armature *mmf* increases the machine field. The armature reaction in a synchronous generator at purely capacitive load is direct-axis reaction because the armature *mmf* is directed along the machine direct-axis and is magnetizing because its direction coincides with the field *mmf* and its action appears in increase of the resultant magnetic field. So the armature reaction in the case of purely capacitive load is called direct-axis magnetizing.

As in the case of purely inductive load, there is no distortion in the resultant field at capacitive load.

Armature reaction at non-unity and non-zero power factor

When the power factor is neither unity nor zero, the armature current $\underline{I}_a$ is displaced in relation to the induced voltage $\underline{E}_f$ by angle ($-90^o<\beta<+90^o$). To clear up the question of the armature reaction affect on the generator magnetic field at such a load use the diagram of *mmf*, given in Fig. 3.8.

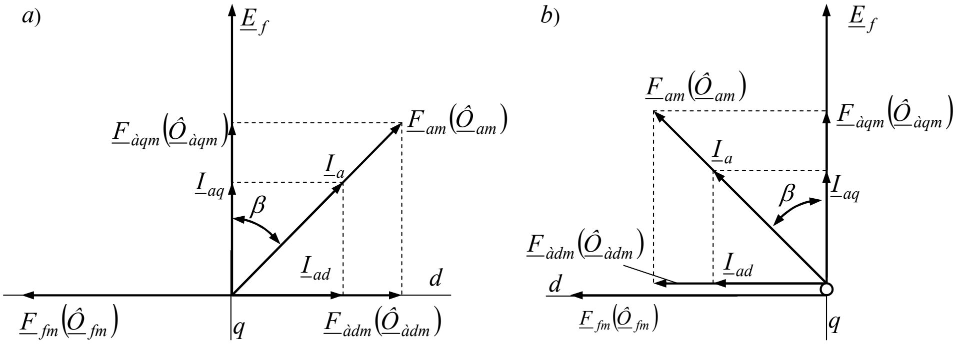


Fig. 3.8 Armature reaction at non-unity and non-zero power factor

In the case of lagging power factor (Fig. 3.8 a) vector, $\underline{F_a}$ lags the armature voltage, induced by the field flux, by the angle ($0^o < \beta < 90^o$).

For salient-pole machines, having different reluctances in directions of direct- and quadrature-axes, two reactions method is applied. This method lies in the following. Divide vector $\underline{F_a}$ into two components – the direct-axis component $F_{ad}=F_a \sin\beta$, and quadrature-axis component $F_{aq}=F_a \cos\beta$. The same can be too made in the case of leading power factor (Fig. 3.8, *b*). The quadrature-axis component of the armature *mmf* is directly proportional to the quadrature -axis armature current component $I_{aq}=I_a \cos\beta$, and the diret-axis armature *mmf* component is directly proportional to the direct-axis armature current component $I_{ad}=I_a \sin\beta$. If the direct-axis current component I_{ad} lags the voltage E_f (in the case of lagging power factor), the *mmf* component F_{ad} demagnetizes the generator. If the direct-axis current component I_{ad} leads the voltage E_f (in the case of leading power factor), the *mmf* component F_{ad} magnetizes the generator magnetic system. Direction of the vector $\underline{F_{ad}}$ relatively $\underline{E_f}$ is defined by armature reaction character which in the case of armature current $\underline{I_a}$ lagging the induced voltage $\underline{E_f}$ is demagnetizing, and in the case of leading armature current is magnetizing.

The armature reaction direct-axis component $\underline{F_{ad}}$ and quadrature-axis component $\underline{F_{aq}}$ produce the armature reaction magnetic fluxes. Their fundamentals are:

direct-axis component

$$\Phi_{ad} = \frac{F_{ad}}{R_{md}} = \frac{F_a \sin\beta}{R_{md}}, \tag{3.2}$$

quadrature-axis component

$$\Phi_{aq} = \frac{F_{aq}}{R_{mq}} = \frac{F_a \cos\beta}{R_{mq}} \tag{3.3}$$

where R_{md} and R_{mq} are the synchronous machine reluctances for the magnetic fluxes fundamentals by the direct and quadrature axes.

The armature reaction magnetic fluxes, linking the armature winding, induce voltages in it:

Due to the direct-axis flux of armature reaction

$$\underline{E}_{ad} = -j\underline{I}_{ad} X_{ad} \tag{3.4}$$

and due to the quadrature-axis flux of armature reaction

$$\underline{E}_{aq} = -j\underline{I}_{aq} X_{aq} \,. \tag{3.5}$$

Here X_{md} and X_{mq} are the direct-axis and quadrature-axis inductive reactance of armature reaction which play role of the main armature winding inductive reactance. In salient pole synchronous machines the values of reluctance R_{md} and R_{mq} for fundamentals of the magnetic flux by the direct and quadrature axes differ from one another ($R_{md} < R_{mq}$). The reactances may be defined as

$$X_{ad} = 2\pi f L_{ad} = 2\pi f \frac{\Psi_{ad}}{\dot{i}_{ad}} \tag{3.6}$$

$$X_{aq} = 2\pi f L_{aq} = 2\pi f \frac{\Psi_{aq}}{\dot{i}_{aq}} \tag{3.7}$$

where L_{md} and L_{mq} are the direct-axis and quadrature-axis armature inductances, ψ_{md} and ψ_{mq} are the linked direct-axis and quadrature-axis fluxes of armature reaction. Due to inequality of the appropriate reluctances these reactances are unequal, so ($X_{ad} > X_{aq}$).

Voltage on the generator leads under load differs of the voltage at no load operation. It is explained by several reasons which are the armature reaction, the leakage magnetic flux, the voltage drop in the armature winding resistance. Under load the machine magnetic circuit is affected by several *mmf* which interaction produce resulting magnetic field. Considering the factors affecting the synchronous generator voltage, it is assumed in some cases that these *mmf* acts independently (superposition principle), i.e. each the *mmf* produces its own magnetic flux independently. But such understanding does not exactly fit physical nature of the phenomena, because magnetic materials saturation can influence conditions of the generator magnetic field. But now, to make understanding the phenomena easier, we will count that components of the resulting magnetic field are independent, that is, that principle of superposition is true for a synchronous generator magnetic circuit conditions.

Summarizing action of the magnetomotive force components for a salient pole generator operation we observe the following:

- magnetomotive force F_f produced by current in the field winding causes the field magnetic flux Φ_f, that is the machine main flux, which link with the armature winding varies in time, and through what this flux induces the voltage E_f in the armature winding;
- Armature reaction magnetomotive forces by the direct-axis F_{ad} produce the magnetic flux Φ_{ad} inducing in the armature the direct-axis voltage component E_{ad} (3.4). This voltage is directly proportional to the inductive reactance of armature reaction by the direct-axis X_{ad}. This reactance accounts degree of the direct-axis armature reaction affect for the synchronous generator operation. If the magnetic system is saturated, the flux Φ_{ad} is less as compared to the case of non-saturated system, because this flux passes not only the air gap part but all the steel parts of the machine magnetic circuit. By this reason, magnetic saturation of the steel parts causes noticeable growth of the magnetic circuit reluctance and the inductive reactance X_{ad} is reduced.
- Armature reaction magnetomotive forces by the quadrature-axis F_{aq} produce the magnetic flux Φ_{aq} inducing in the armature the quadrature-axis voltage component E_{aq} (3.5). This voltage is directly proportional to the inductive reactance of armature reaction by the quadrature-axis X_{aq}. The inductive reactance of armature reaction by the quadrature-axis does not practically depend on magnetic saturation as in a salient-pole machine the flux Φ_{aq} overcomes a longer path through the air gap in the space between the poles.
- The armature leakage flux Φ_{la} induces the leakage voltage in the armature winding E_l which is proportional to the winding phase leakage reactance X_l:

$$\underline{E}_{a\sigma} = -j\underline{I}_a X_l \tag{3.9}$$

- Current I_a causes an armature voltage drop in the armature resistance R:

$$\underline{U}_R = \underline{I}_a R \tag{3.10}$$

A vector sum of the above indicated voltages induced in the armature phase winding minus the resistance drop determines output generator voltage:

$$\underline{U} = \sum \underline{E} - \underline{I}_a R = \underline{E}_f + \underline{E}_{ad} + \underline{E}_{aq} + \underline{E}_{a\sigma} - \underline{I}_a R \tag{3.11}$$

In this equation $\sum \underline{E}$ is the resulting voltage induced in the armature phase winding by the magnetic field produced by jointly acting magnetomotive forces F_f, F_{ad}, F_{aq} and the leakage flux Φ_{la}.

Synchronous machines of medium and large power have small enough resistance R, and the resistance drop I_a R, even under rated load, is so small that it may be neglected. Then equation (3.11) can be written as

$$\underline{U} = \underline{E}_f + \underline{E}_{ad} + \underline{E}_{aq} + \underline{E}_{a\sigma} \tag{3.12}$$

or

$$\underline{U} = \underline{E}_f - j\underline{I}_{ad}X_{ad} - j\underline{I}_{aq}X_{aq} - j\left(\underline{I}_{ad} + \underline{I}_{aq}\right)X_l = \underline{E}_f - j\underline{I}_{ad}X_d - j\underline{I}_{aq}X_q \tag{3.13}$$

where X_d=X_{ad}+X_l is called the direct-axis synchronous reactance and X_q=X_{aq}+X_l is called the quadrature-axis synchronous reactance.

In non-salient pole machines the air gap around the circle does not vary. Therefore the reluctances by direct and quadrature axes are equal to one another (R_{md}= R_{mq}=R_m). Therefore, there is no need to apply the two reactions method. The armature reaction magnetic flux induces the voltage in the armature winding:

$$E_a = -jI_aX_a \tag{3.14}$$

where $X_a = 2\pi fL_a = 2\pi f\psi_a/i_a$ is the reactance of armature reaction.

The armature reaction flux Φ_a and the armature leakage flux Φ_{la} are produced by the same current I_a, and the reactance X_a and X_l may be considered as total inductive reactance X_s:

$$X_s = X_a + X_l\,. \tag{3.15}$$

that is called the synchronous reactance of a non-salient pole generator. Subject to that, the voltage E_a and the voltage E_l should be considered as a vector sum

$$\underline{E}_a + \underline{E}_l = -j\underline{I}_aX_a - j\underline{I}_aX_l = -j\underline{I}_aX_s \tag{3.16}$$

which represent the total synchronous voltage induced in armature of a non-salient machine. With account of the above-said, the voltage equation of a non salient pole synchronous generator takes on form:

$$\begin{aligned}\underline{U} &= \Sigma\underline{E} - \underline{I}_aR_a = \underline{E}_f + \underline{E}_a + \underline{E}_l - \underline{I}_aR = \\ &= \underline{E}_f - j\underline{I}_aX_a - j\underline{I}_aX_l - \underline{I}_aR = \\ &= \underline{E}_f - j\underline{I}_aX_s - \underline{I}_aR\end{aligned} \tag{3.17}$$

or, neglecting the armature resistance

$$\underline{U} = \underline{E}_f - j\underline{I}_aX_s\,. \tag{3.18}$$

3.3. The vector diagram of a synchronous generator

Using equation (3.11), plot the vector diagram of a salient pole generator working under load with lagging power factor. In such a case the current I_a lags the voltage E_f. For plotting the diagram the following data are required: the induced voltage E_f at no-load operation, the load current I_a, the displacement angle β between E_f and I_a, the armature reactance X_{ad} and X_{aq}, resistance of the armature winding phase R. At the generator balanced load the diagram is plotted for one phase.

According to equation (3.11), in arbitrarily selected direction plot the vector $\underline{E}_f$ and the vector $\underline{I}_a$ lagging it by the angle β (Fig. 3.9 a). Divide into the components – direct axis $\underline{I}_d$ and quadrature-axis $\underline{I}_q$. To the vector $\underline{E}_f$ add the vectors of induced voltages $\underline{E}_{ad}=-j\underline{I}_{ad}X_{ad}$, $\underline{E}_{aq}=-j\underline{I}_{aq}X_{aq}$, $\underline{E}_l=-j\underline{I}_aX_l$ and subtract the voltage drop $\underline{I}_aR$. Connecting the beginning of $\underline{E}_f$ with the end of the vector $-\underline{I}_aR$, obtain the phase voltage vector $\underline{U}$. The vector $\underline{E}_{ad}R$ has in this case the opposite direction to the vector $\underline{E}_f$ as at lagging power factor armature reaction demagnetizes the machine system.

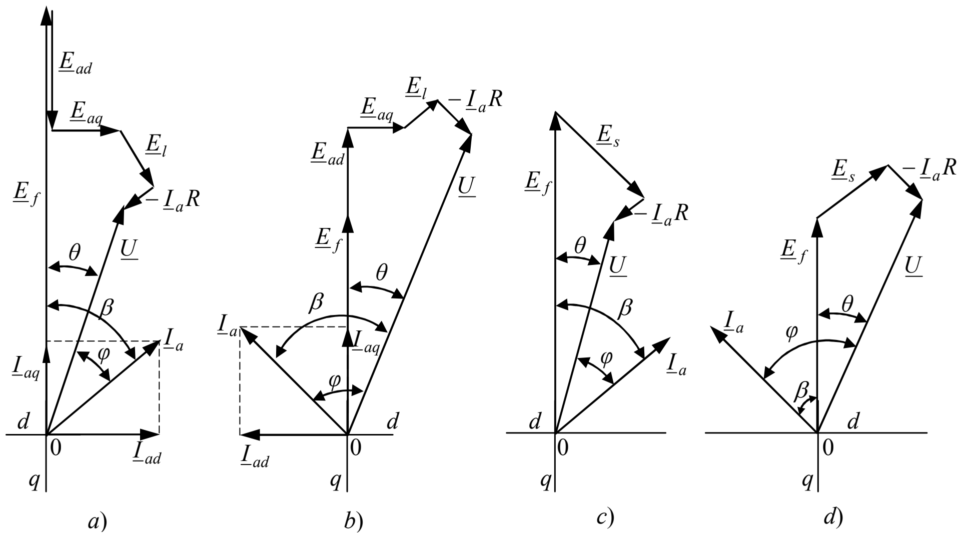


Fig. 3.9 Vector diagrams for salient pole (a, b) and non-salient pole (c, d) synchronous generators: a and c – at lagging power factor, b and d - at leading power factor

Plotting the diagram for a salient pole generator working under load with leading power factor, the vector $\underline{I}_a$ is placed to the left of the vector $\underline{E}_f$ (Fig. 3.9, *b*). The vectors $\underline{E}_{ad}$ and $\underline{E}_{aq}$ directions are taken in accordance with directions of the vectors $\underline{I}_d$ and $\underline{I}_q$ respectively so that the vectors of voltages induced due to armature reaction lag the corresponding vectors of the current components. The vector $\underline{E}_{ad}$ has in this case the same direction that the vector $\underline{E}_f$ as at leading power factor armature reaction magnetizes the machine system.

The vector diagram for a non-salient pole generator (Fig. 3.9 c and d) is plotted by equation (3.18).

It is necessary to pay attention that the diagrams in Fig. 3.9 do not account influence of the magnetic circuit saturation. Therefore they just illustrate qualitative side of processes. At the same time they make possible to come to the following conclusions. The main factor influencing a generator voltage regulation under load is the direct-axis component of the armature reaction flux that produces the induced voltage $\underline{E}_{ad}$. When a generator operates with lagging power factor the voltage on the generator leads reduces with load current increase because of demagnetizing effect of the armature reaction (Fig. 3.9 a and c). At leading power factor the voltage increases with load current growth as the armature reaction magnetizes the machine magnetic system (Fig. 3.9 b and d).

3.4. The isolated operation of a synchronous generator

Major characteristics of a synchronous generator operating as an independent unit without connection its armature circuit to a source of alternating voltage are its voltage regulation characteristics and field current-armature current curves.

The voltage regulation characteristics of a synchronous generator are the relationships between the armature winding voltage U and the load current I_a of a generator under constant field current I_f, rotational speed n and power factor $\cos\varphi$.

The field current-armature current curves are the relationships between the field current of a generator and the armature current under constant values of U, n and $\cos\varphi$ These curves show how the field current must be varied to maintain the voltage constant when the generator load varies.

The voltage regulation characteristics and field current-armature current curves are represented in Fig. 3.10.

At no-load operation the generator voltage equals the induced voltage, i.e. $U=E_f$. Voltage regulation under load is mainly determined by the armature reaction. At unity power factor the armature reaction is generally quadrature-axis which demagnetizing effect is very slight. The voltage regulation characteristic for this case is slightly inclined to the current axis (curve 2 in Fig. 3.10 a).

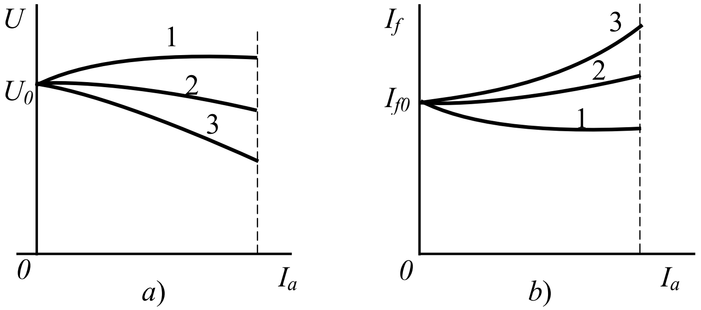


Fig. 3.10 Voltage regulation characteristics (a) and field current-armature current curves (b) of a synchronous generator

At mixed active and inductive load the power factor $90° > \varphi > 0$ and demagnetization is stronger than at unity power factor. The voltage regulation characteristic, therefore, has greater slope and lie below the curve for active load (curve 3 in Fig. 3.10 a).

In both above cases to maintain the voltage under load constant the field current have to be increased (curves 2 and 3 in Fig. 3.10 b).

At mixed active and capacitive load the power factor $0 > \varphi > -90$ the armature reaction magnetizes the generator magnetic system and the regulation characteristic lies between curves 1 and 2 (Fig. 3.10 b). At enough noticeable capacitive load component the voltage at loading is increased (curve 1 in Fig. 3.10 a), and for maintaining the voltage constant the field current have to be reduced (curve 1 in Fig. 3.10 b).

At use synchronous generators for practical applications the voltage stabilization is provided by special field regulators.

One of important parameters of synchronous generator is its short-circuit ratio that is defined as the ratio of the field current for rated armature voltage on open-circuit to the field current for rated armature current on sustained symmetrical short-circuit, both with the machine running at rated speed:

$$SCR = I_{f0} / I_{fsc} \tag{3.19}$$

SCR value is one of the parameters that determine synchronous generators operational properties. The greater *SCR* value, the more stable is a generator operation as variation in load causes less voltage regulation. But generators with greater value of *SCR* are more expensive due to greater specific copper and steel consumption per kW of rated power. Reduction of *SCR* strengthens affect of armature reaction, but such generators consume less copper and steel for their manufacturing.

3.5. The power flow diagram of a synchronous generator

Synchronous generators convert input mechanical power P_1 into electric power P_2 that is over to the load. Consider this process using the power flow diagram (Fig. 3.11).

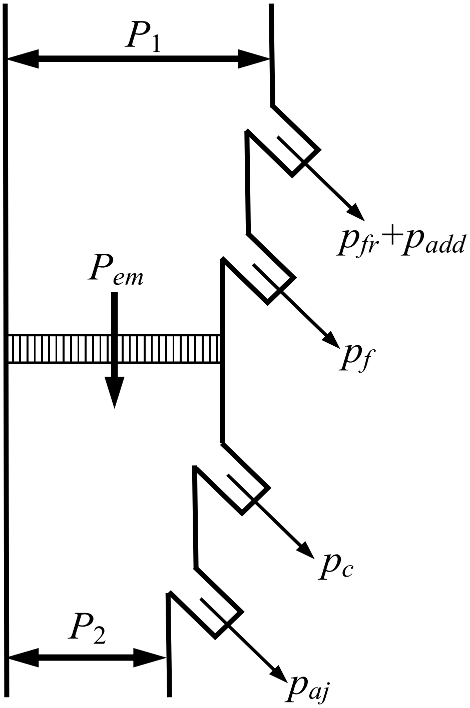


Fig. 3.11 The power flow diagram of a synchronous generator

While the mechanical energy conversion, the following power losses arise in the rotor:

- the no-load losses $P_0=p_{fr}+p_{add}$ where p_{fr} is the friction and ventilation (mechanical) losses, p_{add} is additional eddy-current losses caused by the space ripples in the flux wave and the tooth eddy-current losses caused by non-sinusoidal field flux distribution;
- the field winding loss p_f due to Joule effect; $p_f=U_f I_f$ where U_f and I_f are the field voltage and current correspondingly.

The remaining part of the input power

$$P_{em} = P_1 - \left(p_{fr} + p_{add} + p_f\right) \tag{3.20}$$

is transferred to the armature by means of electromagnetic field and is called, therefore, the electromagnetic power.

In the armature some part of the electromagnetic power p_c is lost in armature core as the magnetic losses caused by the field flux due to eddy currents and hysteresis. Besides, in the armature the winding Joule loss $p_{aj}=mI_a^2R$, where m is number of the winding phases, arises.

The rest of the power, P_2, that is active electric power, is given to the generator load (the armature winding terminal output):

$$P_2 = P_{em} - \left(p_c + p_{aj}\right) \tag{3.21}$$

The synchronous generator efficiency is defined as $\eta = P_2/P_1$. The input power may be found as $P_1=P_2+\sum p$ where $\sum p = p_{fr}+p_{add}+p_f+p_c+p_{aj}$ is total loss, each component of which may be found by test.

So the efficiency may be calculated by the equality

$$\eta = \frac{P_2}{P_2 + \sum p} \tag{3.22}$$

The efficiency of up-to-date synchronous machines is 90% and more, it increases with rise of a machine rated power.

3.6. The operation of a synchronous generator in parallel with power network

When the parallel operation of a synchronous generator with a power network is studied the questions of great importance are methods of the generator switching in parallel with the bus system supplied by other sources, and active and reactive power control.

Assume that the network is much more powerful than the generator, and the network voltage U_s and frequency f_s cannot be varied. Before switching the generator in parallel with the network the following conditions, called the conditions of synchronization, must be fulfilled:

1. the generator phase rms voltage E_f must be equal to the network phase *rms* voltage, i.e. $E_f = U_s$,
2. the generator frequency f_f must be equal to the network frequency, i.e. $f_f = f_s$,
3. the generator and network voltages are to be in phase,
4. the phase sequence of the generator and the network must be the same.

If these conditions are fulfilled its switching the generator to the common busses is not accompanied by inrush of a current. In the case when of the above requirements are not executed the following consequences appear:

- if $E_f \neq U_s$ and the third condition is fulfilled, the equalizing current will flow through the armature winding at switching the generator to the busses. It is caused by the voltage vector difference $\Delta\underline{E} = \underline{E}_f - \underline{U}_s$. The equalizing current is reactive by its character, and the generator does not take load on itself. By magnitude this current can be large causing the armature winding overheating,
- if $f_f \neq f_s$ then the voltage difference $\Delta\underline{E}$ assume a character of beating, and the equalizing current varies continuously by value and by phase in regard to $\underline{E}_f$ and $\underline{U}_s$. This current causes the armature winding heating and alternating-sign mechanical beats on the shaft,
- if $\underline{E}_f = \underline{U}_s$ the vectors $\underline{E}_f$ and $\underline{U}_s$ rotate synchronously but are not in phase or antiphase, the equalizing current has an active component. In the time of switching on the generator, mechanical push that can be of great value appears,
- if the phase sequence of the generator and the network does not agree, their parallel operation is impossible. In such a case switching on the generator in parallel to the grid can cause a heavy failure due to great equalizing currents and alternating-sign mechanical pushes.

Fulfillment the measures providing realization the above listed conditions (items 1 – 4) are called synchronizing. In practice at synchronizing, first the needed generator rotational frequency is established that gives approximate the frequencies f_f and f_s equality which is later made more exact. After that the equality $E_f = U_s$ is achieved by variation the generator field current. The phase displacement between $\underline{E}_f$ and $\underline{U}_s$ is checked wit the help of a synchroscope. In most cases the synchronizing is made automatically without assistance of service personnel.

The synchronous generator reactive power at its parallel operation with the network is possible by variation of its field current. After synchronizing and switching the generator for parallel operation the armature current is zero as $\Delta\underline{E} = \underline{E}_f - \underline{U}_s = 0$ (see Fig. 3.12 a).

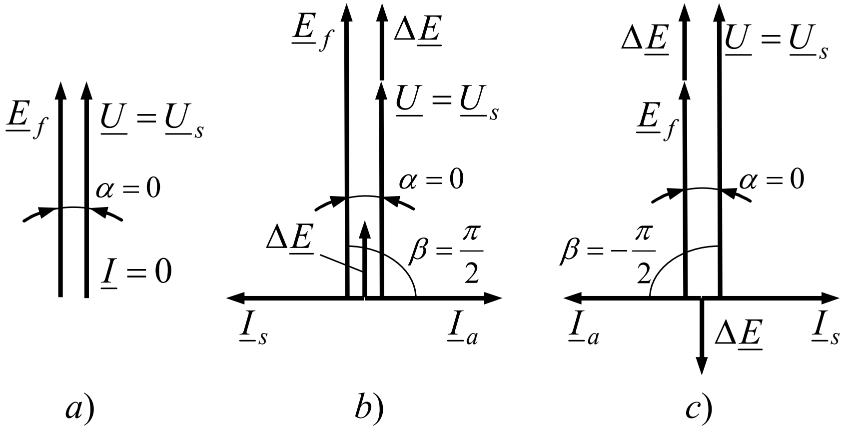


Fig. 3.12 The control of a synchronous generator switched to network reactive power at no-load

In these conditions the synchronous machine floats idly on the line, it does neither deliver electric power to the grid nor draws it. The loss in the field winding is covered by power supplied by an exciter.

When a generator operates in parallel with a network supplied by a source of large power capacity, it terminal voltage U remains constant and equal to the grid voltage. Because of that, the generator resulting magnetic flux does not vary its magnitude.

Increase of the field current with regard to the value at which the machine was synchronized and switched to parallel operation with zero armature current (the machine overexcitation) causes increase of armature voltage U_f, induced by the field flux, and appearance the current

$$\underline{I} = \frac{\underline{E}_f - \underline{U}_s}{jX_s} = \frac{\Delta\underline{E}}{jX_s} \tag{3.23}$$

This current lags the vector $\Delta\underline{E}$ and, in this case, the vector $\underline{E}_f$ by 90^0 (Fig. 3.12, b) as the armature resistance may be neglected, and only the synchronous inductive reactance may be taken into consideration (X_s in the case of non-salient machine). This current causes direct-axis demagnetizing armature reaction because of which the resulting magnetic flux remains constant. For the sources supplying the network the current I_a that appears under overexcitation is leading with regard to the network voltage U_s, i.e. the generator delivers reactive power to the network, reducing the reactive power generated by the network power source. Further increase of generator field current does not change in this case the armature current phase but calls forth its magnitude further increase. The power factor of the generator equals zero, and phase displacement φ between $\underline{U}$ and $\underline{I}_a$ is 90^0 or $\pi/2$ rad.

Decrease of the field current with regard to the value at which the machine was synchronized and switched to parallel operation (underexcitation) makes E_f less than the terminal voltage U, the vector $\Delta\underline{E}$ changes its phase by 180^0 and has the opposite direction with respect to the voltage $\underline{U}$. The armature current becomes leading relative to $\underline{E}_f$ and, hence, lagging relative to the network voltage $\underline{U}_s$ (Fig. 3.12 c). So the generator operating at underexcitation conditions draws reactive power from the network, increasing the reactive power generated by the network power source.

Note that reactive armature current does not cause either driving or retarding torque, and therefore, active power at variation of the field current is neither consumed nor generated by a synchronous machine.

Vector diagrams of a synchronous generator under control of active and reactive power are given in Figures 3.13 and 3.14. In order that generator switched on parallel operation delivered active power to the network it is necessary to increase the driving torque produced by its prime mover. As the result the rotor pole axis moves forward with respect to the axis of the armature rotating field leading it by the angle $\theta > 0$, and the vector $\underline{E}_f$ shifts forward with respect to the voltage $\underline{U}$ leading it by the same angle.

Armature current get active component $\underline{I}_{aact}$, and this indicates that the generator delivers active power to the network. At the same time the generator produces the retarding torque counterbalancing the driving torque of the prime mover.

Further increase of the driving torque at constant field current the vector $\underline{E}_f$ not changing its length, will turn counterclockwise in leading direction with respect to $\underline{U}$ angle θ will increase. The vectors $\Delta\underline{E}$ and $\underline{I}_a$ will grow in length, and the generated power will increase. At the same time the reactive power will somewhat increase, therefore, to provide the needed operating conditions of the generator switched in parallel with the network it is necessary to control the field current.

The generated power and the generator torque will be so much greater as the greater the driving torque and angle θ is.

Variation of the field current both under load and no-load causes only variation the reactive power.

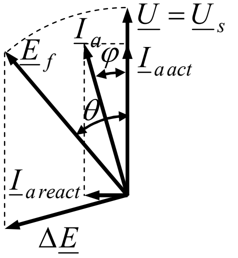
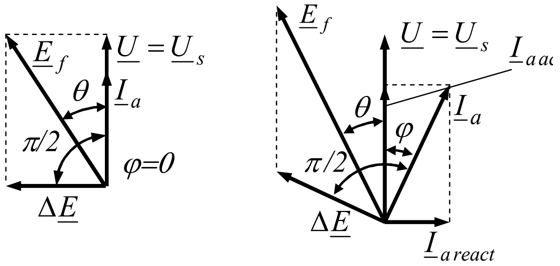


Fig. 3.13 The control of a synchronous generator switched to network active power



a) *b*)

Fig. 3.14 The control of a synchronous generator switched to network active power under load

So the synchronous generator operating at conditions shown in the Fig. 3.13 has demagnetizing reactive current I_{areact} i.e. consumes reactive power. If the current I_f is somewhat increased, conditions at which $I_{areact}=0$ can be obtained (Fig. 3.14 a). Such conditions are called full or normal excitation.

Further rise of the field current causes appearance leading reactive current (Fig. 3.14 b), and the generator becomes a source of reactive power.

3.7. The V-curve and load angle characteristics

Relationships $I_a=f\,(I_f)$ for a synchronous machine between the armature winding current and the excitation current obtained for constant values of armature winding voltage U and active load P are called V-curve characteristics. Three such characteristics for the cases when $P_2=0$ (no-load operation), $P_2=P_{2(1)}>0$ and

P_2=$P_{2(2)}$> $P_{2(1)}$ are plotted in Fig. 3.15. It follows from the vector diagrams (Fig. 3.12 – 3.14) that that right branches of V-curves fit the machine overexcitation, and left branches fit its underexitation. The curve 1 shows variation of the armature current at no-load. Minimum values of the armature current determined by the curves 2 and 3 (Fig.3.15) include only the active current component at relevant loads and therefore the generator operates in the lowest points of these curves with unity power factor. The dashed-line curve from the left in Fig.3.15 represents the limit of stability occurring for a given load at reduction of the field current.

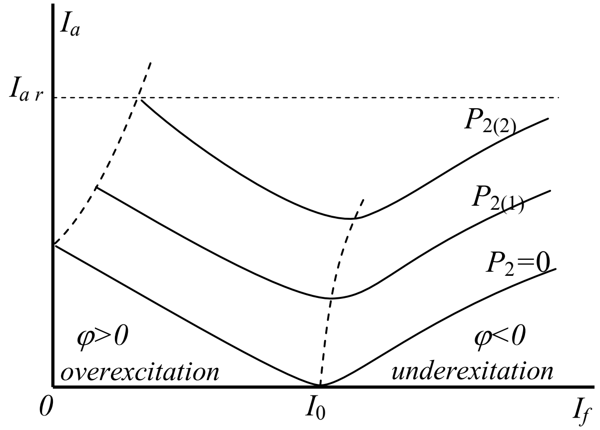


Fig. 3.15 The V-curves of a synchronous machine

For study of parallel operation of a synchronous generator with a power network, it is convenient to express the power via the voltages $U=U_s$, E_f and the angle θ between the vectors $\underline{U}$ and $\underline{E_f}$ which is determined by displacement between the axes of the rotor and the resulting rotating magnetic field. If $\underline{U}$, f and $\underline{E_f}$ are constant, the electromagnetic power P_{em} depends only on θ. The relationship between these two quantities is called the load angle characteristic. This characteristic is plotted for definite given value of the field current.

Load angle characteristic of non-salient pole generator

Neglecting the losses, we may assume that $P_{em} \approx P_2$, and may use the equation:

$$P_{em} \approx P_2 = mUI_a \cos\varphi \tag{3.24}$$

From vector diagram given in Fig. 3.9, using additional geometrical constructions, it can be easily found that

$$I_a X_s \cos\varphi = E_f \sin\theta \tag{3.25}$$

hence

$$I_a \cos\varphi = \frac{E_f \sin\theta}{X_s} \tag{3.26}$$

Inserting (3.26) into (3.24) receive:

$$P_{em} = \frac{mUE_f}{X_s} \sin\theta \tag{3.27}$$

According to equation (3.27) in Fig. 3.16 is plotted the load power-angle characteristic $P_{em} = f(\theta)$.

The electromagnetic torque is determined from the equation:

$$M = \frac{P_{em}}{\Omega} = \frac{mUE_f}{\Omega X_s} \sin\theta \tag{3.28}$$

Using appropriate scaling factor values the curve of power-angle characteristic is at the same time the characteristic of the electromagnetic torque plotted against the angle θ. From relationship (3.27) and Fig. 3.16 it follows that for a non-salient pole generator the maximum values of the electromagnetic power and electromagnetic torque take place at $\theta = 90^0$ and are equal to:

$$P_{emm} = \frac{mUE_f}{X_s} \tag{3.29}$$

$$M_m = \frac{mUE_f}{\Omega X_s} \tag{3.30}$$

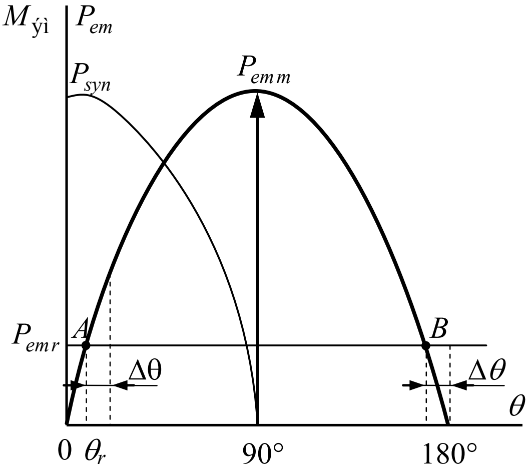


Fig. 3.16 The load angle characteristic of a non-salient generator

Thus limiting power of a generator depends on U, E_f, , and X_s. The terminal voltage is defined by the network conditions. The voltage E_f induced by the field flux is defined by the field current value. Electromagnetic power and torque is produced only in excited salient pole synchronous generator.

In Fig. 3.16 the power supplied to the generator trough its shaft is shown with the horizontal line. At steady-state operation the rated electromagnetic power of a generator may be assumed equal the power P_1 supplied by the prime mover (point A in Fig. 3.16).

The ratio of the pull-out electromagnetic load to the rated electromagnetic load

$$K_{oc} = \frac{P_{em\,m}}{P_{emr}} \tag{3.31}$$

may be called the overload capacity. For non-salient pole synchronous machines

$$K_{oc} = \frac{1}{\sin\theta_r} \tag{3.32}$$

where θ_r is the angle θ value corresponding the rated operation conditions.

Load angle characteristic of salient pole generator

For a salient pole synchronous generator the electromagnetic power is determined by the relationship:

$$P_{em} = \frac{UE_f}{X_\alpha}\sin\theta + \frac{mU^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin 2\theta \qquad (3.33)$$

The first member of the above equality

$$P_{em1} = \frac{mUE_f}{X_d}\sin\theta \qquad (3.34)$$

defines the major component of the power depending on as the network voltage as the field current (or the induced voltage E_f).

The second member

$$P_{em2} = \frac{mU^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin 2\theta \qquad (3.35)$$

defines additional power that does not depend on the excitation and takes place only in a salient pole machine.

In a non-salient pole machine $X_d = X_\mathrm{q}$, therefore $P_{em2}=0$.

The electromagnetic torque of a salient pole synchronous machine also consists of two components:

- the major one

$$M_1 = \frac{mUE_f}{\Omega X_d} \qquad (3.36)$$

- additional torque caused by different reluctance by the axes *d* and *q*

$$M_2 = \frac{mU^2}{2\Omega}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin 2\theta \qquad (3.37)$$

The power P_{em2} and torque M_2 appearing only in a salient-pole machine make possible rotation of the rotor after it pulling in synchronism synchronously with the armature field in absence of excitation due to non-equal reluctances by the machine axes that cause inequality of the synchronous reactance $X_d > X_q$.

The load angle characteristic of the salient pole generator having $R=0$ for E_1=const and *U=const* is shown in Fig. 3.17. It is assumed that parameters X_d and X_q do not vary too. Point of maximal power of the salient pole generator is shifted to the left with respect to the maximum point of the curve $P_{em2}(\theta)$and takes place at $\theta<90^0$. In a salient pole generator maximum point of electromagnetic power curve is usually obtained at $\theta=70\quad 80^0$. Maximum value of P_{em} is some greater than such a value of

P_{em1}. The overload capacity of a salient pole generator is greater than a non-salient one.

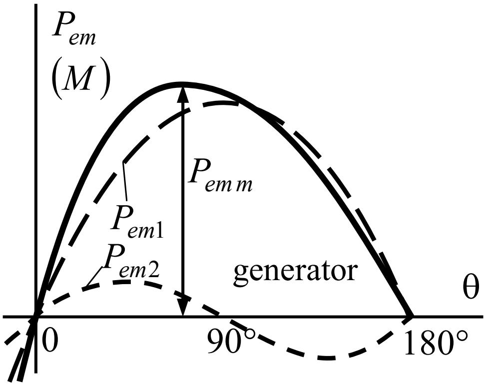


Fig. 3.17 The load angle characteristic of a salient pole generator

3.8. The static and dynamic stability of a synchronous generator parallel operation with a network

The overload capacity K_{oc} defines the static stability of a generator at parallel operation, i.e. its capacity to operate not pulling out of synchronism under gradually changing load.

Parallel operation of a synchronous generator with a network is stable if positive (negative) change of electromagnetic power ΔP_{em} is obtained at positive (negative) change of the load angle $\Delta\theta$ hence at

$$\frac{\Delta P_{em}}{\Delta\theta} > 0 \tag{3.38}$$

The limit of this ratio

$$p_{syn} = \frac{\partial \mathrm{P}_{em}}{\partial\theta} = m\frac{UE_f}{X_s}\cos\theta \tag{3.39}$$

is called the synchronizing power coefficient. We shall denote it as p_{syn}.

Physically the synchronizing power coefficient determines the force which holds the machine in synchronism during its parallel operation with the network, i.e. elastic electromagnetic linkage between the rotor and rotating magnetic field poles. Such a linkage is similar to action of elastic springs which would couple these poles. If by any reason the angle θ exceeds 90^0, the magnetic coupling gets broken that is equivalent to the springs breaking.

The synchronizing power coefficient may be interpreted as the specific synchronizing power which is spent when the rotor poles are displaced relative to their equilibrium position with regard to the rotating field poles. The synchronizing power may be found as

$$P_{syn} = p_{syn}\Delta\theta \tag{3.40}$$

By analogy with the synchronizing power coefficient, the synchronizing torque coefficient m_{syn} may be introduced:

$$m_{syn} = \frac{\partial M}{\partial \theta} = \frac{mUE_f}{\Omega X_s}\cos\theta \tag{3.41}$$

The synchronizing torque tends to return rotor to equilibrium position relatively the rotating field in the case of the rotor angular displacement. It is determined as

$$M_{syn} = m_{syn}\Delta\theta \tag{3.42}$$

The synchronizing power and torque appear at parallel operation of synchronous generators. Therefore these concepts are unacceptable for a generator off-line operation.

The dynamic stability is a generator property to take sudden and great disturbances (changes of load, driving torque, field current) without pulling out synchronism.

In the process of a generator operation short-circuit in the connected network can occur. At short-circuit the voltage and electromagnetic power reduce and the generator can pull out of synchronous rotation. To prevent this, the generator is equipped with fast excitation system that automatically increase rapidly and the field current when the voltage falls down. Increase of the field current causes increase in the electromotive force E_f providing maintenance of the electromagnetic power in the sufficient limits.

The generator damping winding situated on its rotor facilitates improvement of generators parallel operation dynamic stability. This winding produces asynchronous braking torque promoting the rotor oscillations decay. In non-salient rotors part of damping winding is performed by the rotor core of solid steel. Eddy-currents generated in the solid core due to the rotor oscillations produce the braking torque like the currents in damping winding of a salient rotor.

Test questions

1. How are the salient and non-salient pole synchronous machines with electromagnetic excitation arranged?
2. What is the dependence that determines the synchronous machine speed of rotation (the rotational frequency and angular velocity)?

3. What is the armature reaction? What is influence of the armature reaction on the synchronous generator magnetic field at different load power factor?
4. Plot vector diagrams of mmfs for synchronous generator for the cases of zero, lagging and leading power factors.
5. With what speed is it necessary to rotate the generator to get te output voltage of the given needed frequency?
6. Explain application of two reactions method to salient pole synchronous generators. Why this method is not applied to non-salient pole generators?
7. How to calculate voltage induced in armature by direct-axis and quadrature-axis fluxes of armature reaction using direct-axis and quadrature-axis reactance of synchronous generator?
8. What is direct-axis and quadrature-axis reactance of synchronous machine and its relation to the linked direct-axis and quadrature-axis fluxes of armature reaction?
9. What is the leakage reactance of synchronous generator?
10. Write down the voltage equation of non-salient pole synchronous generator.
11. Write down the voltage equation of salient pole synchronous generator.
12. Explain what synchronous reactances of salient pole and non-salient pole synchronous generators are.
13. Plotting vector diagram for salient pole synchronous generator at lagging and leading power factor, show that the load angle of a generator is positive.
14. Plotting vector diagram for non-salient pole synchronous generator at lagging and leading power factor, show that the load angle of a generator is positive.
15. Explain voltage regulation characteristics and field current-armature current curves of synchronous generator.
16. Explain a concept of the synchronous generator short-circuit ratio.
17. Draw the power flow diagram of synchronous generator and explain the power loss and flow of power that occur at generator isolated operation.
18. How to find the efficiency of a synchronous generator?
19. What are the conditions of switching synchronous generator in parallel with a network?
20. How is it possible to vary active power delivered by a generator to the network?
21. How is it possible to vary reactive power of a generator operating inn parallel with the network?
22. Explain V-curves of a synchronous generator. What are underexcitation and overexcitation of a generator?
23. How to calculate the electromagnetic torque for a non-salient pole generator?
24. How to calculate the electromagnetic torque for a salient pole generator?
25. How is additional torque caused with different reluctance by the salient pole machine axes defined?
26. Plot and explain load angle characteristics of non-salient and salient pole generators.
27. How are synchronizing power and synchronizing torque of synchronous generator defined?

4. PERMANENT MAGNET SYNCHRONOUS GENERATORS

4.1. The construction of permanent magnet generators

Brushless electric machines with permanent magnets that may be too called the permanent magnet electric machines were the first type of electromechanical energy convertors. After Faraday's discovery of electromagnetic induction many constructions of electric machines with excitation from permanent magnets for generation of alternating current were suggested. Later such machines were substantially replaced with machines with excitation windings because the permanent magnet machines of those days had less power efficiency, greater materials consumption and dimensions. In the last ten years permanent magnets with much greater specific energy density made on the basis of alloys of iron, cobalt, molybdenum, chrome, nickel and other materials. In further period production of high-coercivity permanent magnets made of rear metals and inter-metallic compounds began. By their energetic parameters, mass and overall dimensions the permanent magnets made of the rear metals often out-perform the electromagnets.

The brushless machines with permanent magnets have simpler circuit diagram, do not consume power for excitation, have higher efficiency and reliability, and are less sensitive to the armature reaction in comparison with conventional machines. Disadvantage of the brushless machines is their limited adjustability stipulated by impossibility to vary the permanent magnets flux in wide range. But in many cases this limitation is not determinative and does not prevent wide application of the permanent magnet machines as generators and motors.

Advantages of permanent magnet synchronous generators lie in high reliability, simplicity of construction and maintenance due to absence of sliding contacts and rotating field winding, higher efficiency due to elimination of loss for excitation.

Most of the used permanent magnet synchronous generators have magnetic system with rotating permanent magnets. Magnetic systems of these generators distinguish from one another mainly with their rotors design. The stator is practically the same as of common generators. As a rule it consists of cylindrical laminated steel core on which internal surface slots for the armature winding are arranged. The air gap of such machines is taken minimally acceptable by technological requirements. The rotor design is substantially determined by magnetic and other physical properties of magnetically hard material.

Rotor with a cylindrical magnet

The simplest is construction of rotor with a solid ring-shaped cylindrical permanent magnet (Fig. 4.1 a). The magnet 1 is casted from, for example, neodymium- iron-boron or samarium-cobalt alloy. Sometimes ferrite magnets are used. The magnet is fixed to the shaft via aluminum bush 2. The magnet is magnetized radially on a multi-pole installation. As mechanical strength of magnets is low, in high-speed machines it is inserted into a band of non-magnetic material.

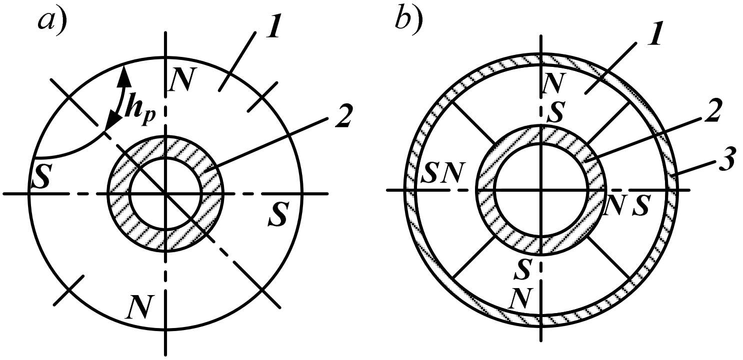


Fig. 4.1 Rotors with a cylindrical magnet

Another construction is cylindrical rotor assembled of separate segments 1 with non-magnetic steel envelope 3 (Fig. 4.1 b). The radially magnetized segments are placed to the bush 2 made from magnetically soft steel and fixed to it. Such a construction permits to obtain the induced voltage close by its form to sine curve.

Disadvantage cylindrical rotor design is little use magnet material due to small average length of field line h_p in the pole. The length h_p decreases with the poles number growth and use of the magnetic material volume become worse. Cylindrical rotors are applied for generators with rated power till about 300 VA.

Rotors with star-shaped magnet

The star-shaped salient pole rotors without pole shoes are widely used in permanent magnet synchronous generators of rated power till about 5 kVA (Fig. 4.2 a). The star-shape magnet 1 is fixed to the shaft with the help of casting by non-magnetic alloy 2. The magnet may too be casted immediately at the shaft. To lower demagnetizing affect of armature reaction at surge short-circuit currents damper system 3 is provided. In high-speed machines a band of non-magnetic material is built up to the magnet. The star-shaped rotor provides good utilizing the magnetic material volume. But on the reason of low magnetic permeability of the magnet and noticeable leakage of magnetic flux between the poles, good magnetizing the magnet back is difficult. Under conditions of the generator overload the armature reaction may cause nonsymmetrical magnetization of the pole tips that distort the field distribution along the air-gap circle and the induced voltage curve.

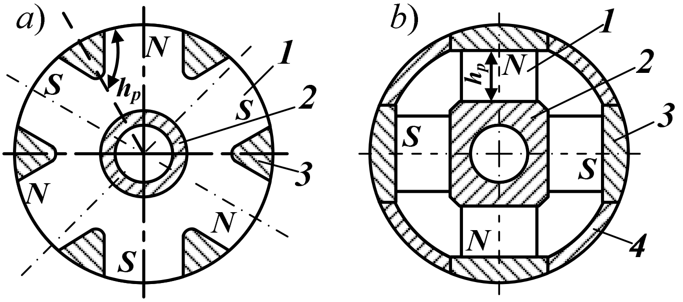


Fig. 4.2 Star-shaped rotors: a - without pole shoes, b – assembled with pole shoes

One of the ways to reduce affect of armature reaction the magnet field is application of pole shoes made of magnetically soft steel. Choosing the pole shoes width the pole leakage flux varies, and optimum usage of the magnet may be obtained. Variation of the poles shape the needed air gap flux density distribution is received. In Fig. 4.2, *b* the design of assembly star-shaped rotor with prismatic permanent magnets and pole shoes is presented. Radially magnetized magnets 1 are placed on the bush 2 of magnetically soft steel. On the poles the shoes of magnetically soft steel are applied. Mechanical strength of the shoes they are welded to non-magnetic insertions 4 that form a band. Space between the magnets may be filled with aluminum or compound. Prismatic shape of the magnets makes possible use of high-coercivity anisotropic materials. Rated power of permanent magnet synchronous generators reaches 100 kVA. Disadvantages of the star-shaped rotors are their complicated construction and less filling the rotor volume with magnets.

Rotor with claw-shaped poles

In generators having large number of poles is frequently used the rotor with claw-shaped poles. The claw-shaped poles rotor (Fig. 4.3) consists of cylindrical magnet 1, magnetized in axial direction and placed to the non-magnetic bush 2. On both sides of the magnet two flanges 3 and 4 made of magnetically soft steel and having claw-shaped projections forming the poles are settled.

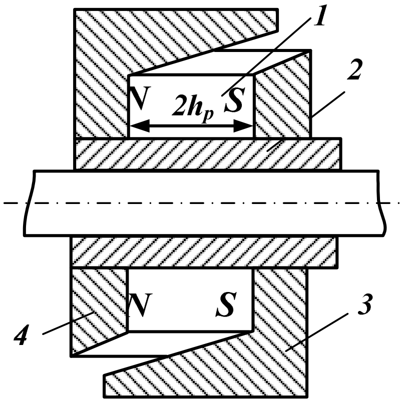


Fig. 4.3 Claw-shaped rotor

All the left flange projections are north poles. The projections of the right flange are south poles. Projections of the flanges alternate around the circle forming the multi-pole excitation system. The projections play also the part of the pole shoes. In generators with claw-shaped rotor the magnetic flux passes in axial and radial directions. Therefore the magnet cross-section area must be enough for passing the total flux of all the pole projections having the same polarity. A simple magnet shape makes possible application of high-coercivity materials with columned structure. Rated power of a claw-shaped rotor permanent magnet synchronous generator does not exceed 5kVA. It may be essentially increased by use of module concept when several claw-shaped magnets are settled on one shaft.

Disadvantages of a claw-shaped rotor are complication of structure, difficulties arising at magnetizing of assembled rotor, risk of bending the projections ends at high speed, low infilling the rotor volume with magnetic material.

Rotors with magnetic flux concentration

The above described rotors structure make possible to reach comparatively low values of magnetic flux density in the synchronous generator air gap about $B_\delta \approx 0{,}2...0{,}5\ T$. Higher values may be obtained using rotors with concentration of permanent magnets magnetic flux (Fig. 4.4). In such a rotor, that may be called a rotor of collecting type, prismatic permanent magnets 1 magnetized tangentially are used. The magnets abut against non-magnetic bush 2 with their inner flanks and against the segments 3 of magnetically soft material with their sides. From outside it is encompassed with the rim 4, 5 of non-magnetic steel. In such the collecting type rotor the magnetic flux produced by neighboring magnets is concentrated in the segment poles.

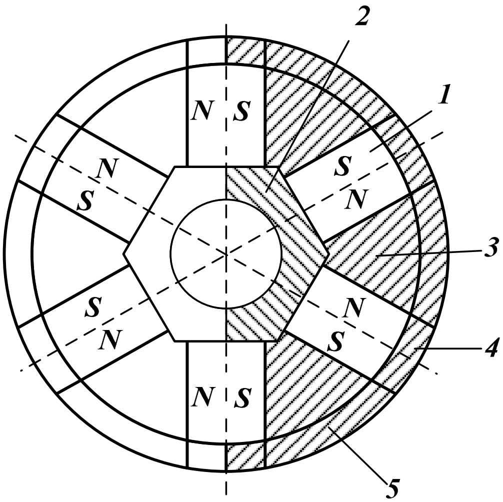


Fig. 4.4 Collecting type rotor

To obtain high values of the magnetic flux density in the air gap the magnet width b_m should be more than a half of the pole segment width $b_m = \alpha_p \tau$. Neglecting the leakage flux the air gap flux density is $B_\delta = K_\delta B_m$ where B_m is the magnetic flux concentration factor and $K_\delta > 1$ is the magnetic flux density inside the magnet.

If $K_\delta > 1$ that can be easily obtained when $2p > 4$ the magnetic flux density is $B_\delta > B_m$. So, application of the rotors with magnetic flux concentration provides the output synchronous generator power increase.

Disadvantages of collecting type rotors are complexity of the structure, small part of magnets in the rotor volume and availability of additional air gaps between magnets and pole segments.

The above rotor types are most applicable but also other constructions of permanent magnet synchronous generators are in use. In view of the high-coercivity rear metal magnets made of samarium-cobalt, neodymium-iron-boron alloys, etc., use of permanent magnet generators with smooth-core armature, outer rotating field system, disc-type rotor and others is perspective.

When a permanent magnet synchronous machine serves as independent single-phase source of AC voltage, a damping winding is arranged. For effective suppression of the backward armature magnetic flux the damping winding is made of copper bars and conducting rings of great cross-sectional area. In Fig. 4.5 design of a rotor with permanent magnet of neodymium-iron-boron alloy is shown. Four permanent magnets form alternated succession of magnetic poles on the rotor surface. The stator is typical for synchronous generators.

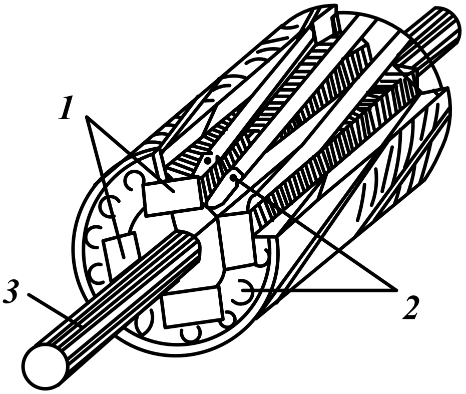


Fig. 4.5 The design of a rotor with neodymium-iron-boron magnets: 1 – magnets, 2 – squirrel-cage, 3 - shaft

There are rotors with different combination of permanent magnets. That is rotors with series and parallel connection of the magnets *mmf*, with voltage control by means of axial shifting of the rotor relatively the stator, with combined excitation system controlled by permanent magnets and field winding, etc.

4.2. Generators for wind-electric sets

For gearless windmills the best decision is application of multi-pole synchronous generators exited by permanent magnets. There is experience of designing and use of low-speed generators gearless windmills with rotational speed of 125 – 375 rpm.

As a gearless windmill requires low rotational speed of a generator, the generator outline dimensions is greater than of the same rated power high-speed generators. In the frame 1 (Fig. 4.6) is placed a common stator 2 with its winding 3. The rotor (inductor) 4 with pasted to it neodymium-iron-boron plates 5 is fixed to the shaft 6 mounted in the bearings 7. The frame is held by the base 8 fixed to the windmill support. The rotor is driven by the wind turbine. These generators have shown good serviceability and high reliability at their use in wind-electric sets.

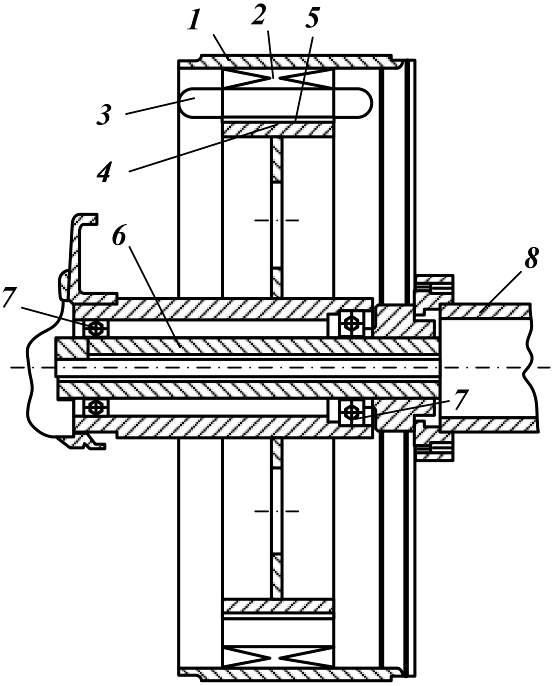


Fig. 4.6 A permanent magnet synchronous generator for gearless wind power installation: 1 – frame, 2 – stator, 3 – winding, 4 - rotor, 5 – plates of permanent magnet, 6 – shaft, 7 – bearings, 8 – base

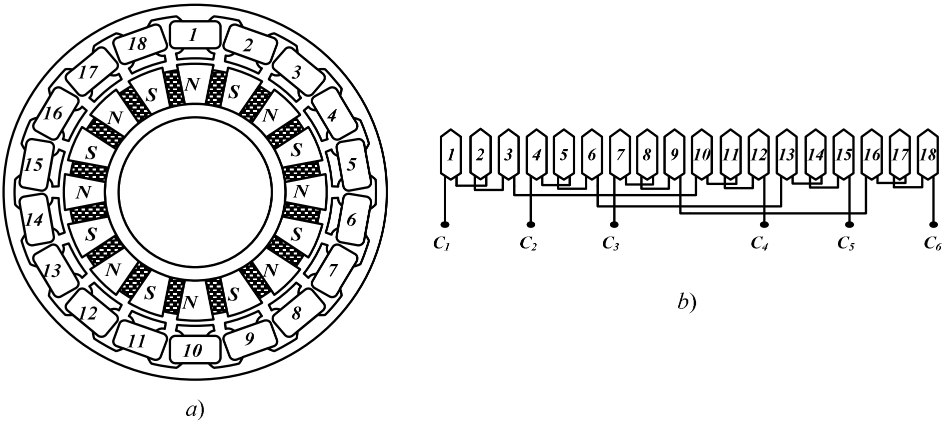
Application of low-speed, multi-pole synchronous generators with permanent magnets which rotational speed strictly match the speed of the wind turbine have considerable advantages in operation and cost being used in small-scale power mills.

Consider permanent magnet synchronous generators of lower-power having short pitch, fractional slot winding of the stator destined for small-scale power mills. Such a winding produces two *mmf* higher harmonics, either of the two may be taken as the generator operational speed.

In Fig. 4.7 the synchronous generator with $2p = 16$ poles and $Z_a = 18$ slots is shown schematically. In the slots 18 coils (by 6 per phase) are imbedded. The number of slots per pole and per phase equals $q = 3/8$. The produced higher harmonics of the *mmf* have numbers $\upsilon = 4$ and 5, the harmonics per unit magnitudes are $F_4^* = 0{,}957$ and $F_5^* = 0{,}766$ ($F_\nu^* = F_\nu / F_1$).

The multi-pole collecting type rotor of the generator have tangential arrangement of the magnets that provides the air-gap magnetic flux concentration and makes possible use cheaper permanent ferrite-strontium magnets. The voltage stabilization is provided by an active power regulator.

At low wind speed low – speed generators are applied. In these cases the wins power set often has no a gearbox and the wind turbine is directly connected to the generator shaft. In such cases the problem to receive high enough voltage and output power arises. One of the ways for its solution is use of a generator of great enough diameter.



b)

a)

Fig. 4.7 A multi-pole permanent magnet synchronous generator (a) and its winding connection diagram (b)

At this the generator rotor may be performed as permanent magnet one without any sliding contacts and brushes that improves reliability and increases duration of service without maintenance an repair. An electric generator with permanent magnet rotor may have designs differentiated by the windings and magnets layout. The magnets with alternated polarity are placed on the rotor and the winding on the stator. In the axial or disc-type generator the stator and rotor are the co-axial discs (Fig. 4.8). In the radial or cylindrical-type generators the stator and rotor are co-axial cylinders (Fig. 4.9).

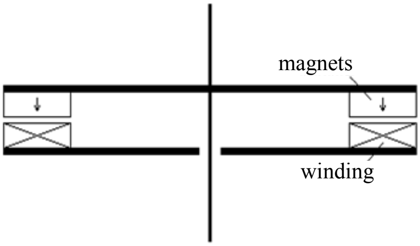


Fig. 4.8 Schema of an axial (disc-type) generator

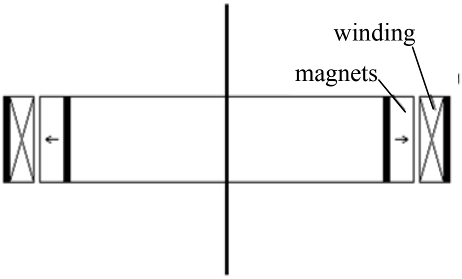


Fig. 4.9 Schema of a radial (cylindrical-type) generator

4.3. The features of brushless synchronous machines with permanent magnets

The synchronous machines with permanent magnets have some singularities compared with conventional machines.

In the permanent magnet machines field forcing is impossible. Therefore, in operational conditions when considerable overloading can appear, the permanent magnet machine should be designed for the increased power with regard to the machines that have electromagnetic inductor.

The machines with permanent magnets it is necessary to have minimal air gap whereas in the conventional synchronous machines the air gap must be large enough to provide small enough value of the direct-axis synchronous reactance X_d, at which the machine possesses the needed stability to demagnetizing armature reaction. The machine with permanent magnet excitation output power increases with the air gap decrease and small value of X_d is provided by low magnetic conductance by the direct axis *d* as magnetic permeability μ of the permanent magnet material is small. If the permanent magnets are made of the high-coercivity rear metals the air gap may be taken greater.

In conventional synchronous machines the leakage flux produces negative effect, and it is intended to be decreased. In the permanent magnet machines the leakage flux may produce a useful effect. So the flux leakage weakens effect of the magnet parameters worsening caused by demagnetizing armature reaction and makes its behavior more stable.

The next singularity lies in the fact that in the conventional machines always $X_d \geq X_q$. In the machines with permanent magnets, having pole shoes of magnetically soft material, as a rule the inequality $X_d < X_q$ is true. Really the magnetic lines of the direct axis armature flux, determining X_d, pass along the magnet having low magnetic conductance due to small magnetic permeability μ. At the same time the magnetic lines of the quadrature-axis armature flux pass through the wide pole shoes made of magnetically soft material (Fig. 4.10).

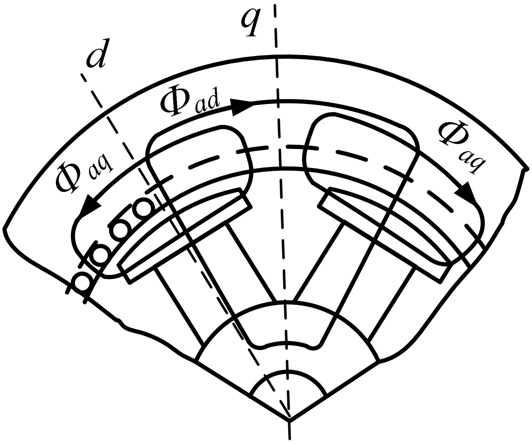
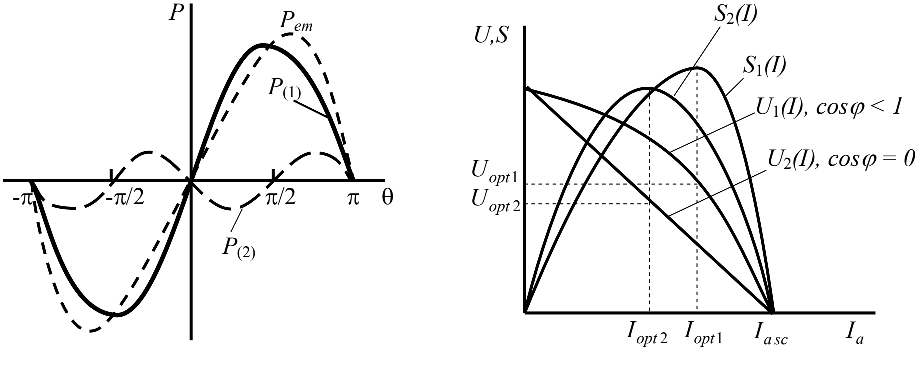


Fig. 4.10 Fluxes of armature reaction in a machine with pole shoes

On this reason we have $\Phi_{ad} < \Phi_{aq}$ and $X_d < X_q$. When the rotor has no pole shoes it is usually $X_d \approx X_q$. Change of the sign of the inequality, connecting X_d and X_q, causes change of the sign of additional electromagnetic power and torque appearing in salient pole machines.

In Fig. 4.11 the load angle curves $P_{em} = f(\theta)$, $P_{(1)} = f(\theta)$ and $P_{(2)} = f(\theta)$ for a synchronous machine with permanent magnets having $X_d < X_q$ are given. As it is seen extreme of the curve $P_{em} = f(\theta)$ for a permanent magnet synchronous machine shifts to greater by its modulus values of θ and the synchronizing power coefficient $p_{syn} = \frac{\partial P_{em}}{\partial \theta}$ is less than for common synchronous machines.

Affect of saturation in the permanent magnet machines, especially when magnets of rear metals having linear demagnetization characteristic are used, appears weaker than in common machines. This is explained by the fact that the permanent magnets occupy the considerable part of the machine magnetic circuit, and they have great reluctance and work on the linear descending branch of the magnetization characteristic. Therefore, saturation of the subparts of magnetically soft steel, exposed in series with permanent magnets and the air gap, and possessing small reluctance has an insignificant effect on the magnetic field. In the permanent magnet machines application of weakly saturated magnetically soft steel parts that provides the best utilization of the permanent magnets properties is a reasonable decision. The exception to this is the machines with the armature magnetic biasing when saturation of steel parts is used for variation of the magnetic flux within a wide range.



a) *b*)

Fig. 4.11 The relationship between the electromagnetic power of a permanent magnet synchronous machine and load angle (a) and voltage regulation and apparent power curves (b)

The voltage regulation characteristics for mixed active and inductive and for purely inductive loads are shown in Fig. 4.11 b. For each of these characteristics the relationship of the apparent power $S = mUI_a$ against the current may be plotted. Such a curve has maximum at the current $I_{a\,opt}$ and the voltage U_{opt}. Under the conditions of maximal apparent power we have

$$i_{aopt} = U_{opt} = \frac{1}{\sqrt{2(1+\sin\varphi)}}, \tag{4.1}$$

where $i_{aopt} = \dfrac{I_{a\,opt}}{I_{a\,sc}}$, $U_{opt} = \dfrac{U_{opt}}{E_f}$; and φ is the phase displacement angle.

Such operational conditions are not always practical due to great voltage reduction and currents values. On that reason in most cases the conditions

$$i_a = \frac{I_a}{I_{asc}} < i_{aopt}, \qquad u = \frac{U}{E_f} > U_{opt} \tag{4.2}$$

are realized. In this case the operating point is shifted to the no-load conditions ($u = 0{,}7....0{,}9\,, i = 0{,}2...0{,}4$) and $S < S_{\max}$.

4.4. Control and stabilization of a permanent magnet synchronous generator

The essential distinction of permanent magnet synchronous generators as compared to conventional types is difficulties at their output voltage control and stabilization. In a conventional type generator it is possible to vary the main flux and the voltage changing the field current. In a permanent magnet machine such possibility is not available as the magnetic flux Φ is in the limits of the descending branch of the magnetization characteristic and varies insignificantly. To control and stabilize the permanent magnet synchronous generator voltage special techniques are used.

In principle it is possible to control the permanent magnet generator voltage by means of the rotational frequency variation but this method is problematic as it is necessary to use an adjustable drive, the method is low-speed, and variation of the rotational speed causes variation of the generator frequency.

One of the possible ways of the voltage stabilization is implementation of capacitive components to the armature outside circuit causing direct-axis magnetizing armature reaction. At capacitive load the generator voltage regulation is small and the regulation curves can even have increasing portions. The capacitors providing the needed capacitive load impedance are connected in series to the load (Fig. 4.12 a, b) either directly or via step-up transformers decreasing the capacitors mass and dimensions thanks to increase their service voltage and reduction of the current. It is possible to connect the capacitors in parallel to the load too (Fig. 4.12 c).

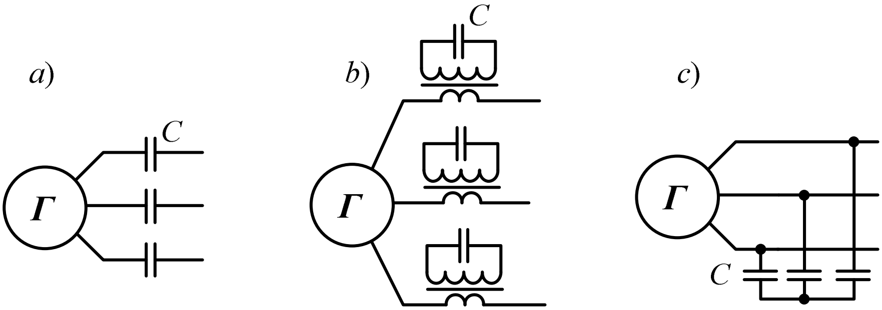


Fig. 4.12 Connections of stabilizing capacitors

If it is necessary to increase the output voltage stabilization accuracy, non-linear variable condensers may be used. The variable condensers are made of ferroelectric ceramics (for example, the barium titanate), which permittivity ε is strongly dependent against the applied voltage as AC U as DC $U_=$. Typical curves $\varepsilon = f(U)$ and $\varepsilon = f(U_=)$ for ferroelectric ceramics are given in Fig. 4.13. As the condenser capacity is directly proportional to ε the relationship $\varepsilon = f(U)$ permit to choose parameters of the variable condensers so that the generator voltage variation will cause such variation in capacitance which provides the voltage stabilization. Dependence $\varepsilon = f(U_=)$ permits to control the variable condenser capacitance by applying auxiliary DC voltage. The auxiliary voltage is produced by a control system responding the service voltage deviation of the specified value. The structural diagram of such a system is shown in Fig. 4.14.

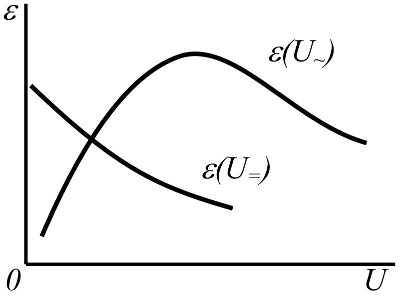


Fig. 4.13 The curves of ferroelectric ceramics permittivity as a function of AC and DC voltage

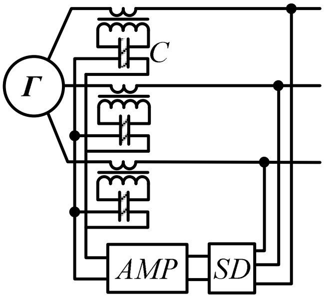


Fig. 4.14 A structural diagram of a voltage regulator with ferroelectric ceramics variable condensers

The sensing device SD detects the voltage deviation of the specified value and produces the signal delivered to the amplifier AMP. The amplifier output DC voltage is supplied to the variable condensers. The condensers capacitance is changed under the voltage impact, and stabilization of the generator voltage is reached. Though the ferroelectric ceramics variable condensers possess good regulating properties the have worse mass and dimensions characteristic than condensers of common type. There are limitations for their working temperature.

Satisfactory stabilization of permanent magnet generator output voltage may be obtained with the help of the tuned circuit that includes the capacitor C and the saturated-core reactor L. The resonance circuit is connected in parallel to the load as it is shown in Fig. 5.15 a in single phase representation. As the result of the core saturation the coil inductivity falls down at the current increase. The voltage across the inductive coil depends nonlinearly on the coil current (Fig. 5.15 b). At the same time the voltage across the capacitor U_C depends linearly as a function of current I_C. In the point of the curves $U_{L=}f(I_L)$ and $U_{C=}f(I_C)$ intersection fitting the rated voltage U_{rated} current resonance takes place. At the voltage lowering $U' < U_{rated}$ and $I'_C < I_L$, i.e. the resonance circuit draws capacitive current from the generator. At this the magnetizing direct-axis armature reaction promotes the voltage growth. If U then

$I_C < I_L$ and the resonance circuit takes inductive current. The demagnetizing direct-axis armature reaction causes the voltage U reduction.

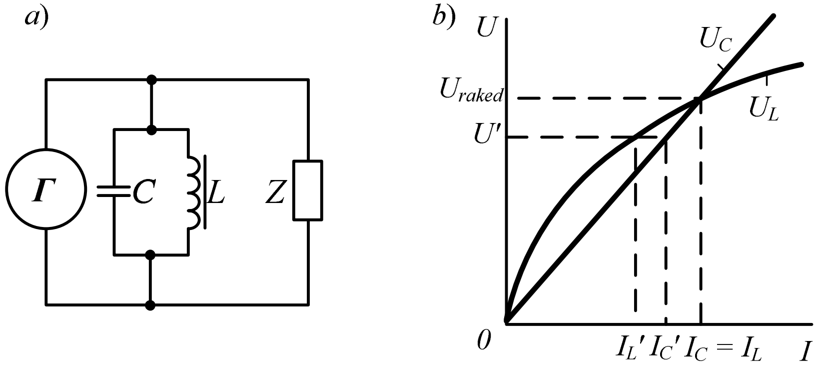


Fig. 4.15 Stabilization of the permanent magnet voltage with a resonance circuit: connection the circuit (*a*), voltage-current characteristics (*b*)

Sometimes the magnetically biased with reactors are used for generators voltage stabilization. Such reactors are biased with direct current produced by a voltage control system (fig. 4.16 a). With the voltage decrease the control system increases the bias current that causes reduction of the rector inductivity. The demagnetizing effect of direct-axis armature reaction weakens, the voltage drop on the reactor decreases, and the output generator voltage is recovered.

Voltage control and stabilization of permanent magnet generators could be efficiently performed with a semiconductor converter. The circuit of such a converter is shown in Fig. 16.4 b. In each phase of the converter there are two anti-parallel connected thyristors T1 and T2. Each the half-wave of the voltage $u_1 = f(wt)$ meets direct polarity of one of the thyristors. If the system supplies the initiate signal with some delay fitting the switching on angle α, the output converter voltage $u_z = f(wt)$ is determined by the hatched area boundary in Fig. 4.16 c which *rms* value is

$$U_2 = \sqrt{\frac{1}{\pi}\int_{\alpha}^{\pi}\left(\sqrt{2}U_1 \sin wt\right)^2 dwt} = U_1\sqrt{\frac{\pi - \alpha + \frac{\sin 2\alpha}{2}}{\pi}} . \quad (4.3)$$

With α growth the voltage U_2 decreases (Fig. 4.16 d). At the rated conditions the angle is $\alpha = \alpha_{rated}$. When the voltage U_1 decreases, the angle α decreases so that the voltage remains $U_2 \approx \text{const}$. Such a converter makes possible not only stabilization but also the voltage wide range control by means of the angle α variation. The system disadvantage is the output voltage worsening caused by appearance of higher harmonics in the curve $u_2 = f(wt)$.

The above described methods of the voltage control and stabilization require additional auxiliary equipment. It is possible to carry out the task with arrangement additional d.c. biasing winding in the generator.

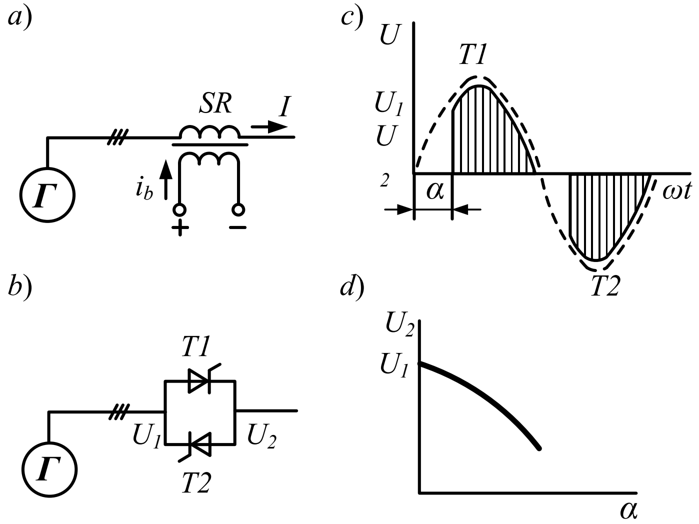


Fig. 4.16 The output voltage of a permanent magnet generator stabilization by means of a saturated-core reactor (*a*) and semiconductor converter (*b*). Output voltage of the converter: the curve of instantaneous values (*c*) and of *rms* value as a function of angle α (*d*)

This winding changes degree of the generator steel core saturation and hence the armature core permeance.

Effect produced by the biasing winding is illustrated in Fig. 4.17 a where curves: $\Phi_m = f(F_m)$, $\Phi_l = f(F_m)$ and $\Phi_\delta = f(F_m)$ are shown. The magnetizing lines of external with regard to the permanent magnets circuit part are inclined at the angles of $\alpha = arctg\Lambda_{ext}$ with the axis F.

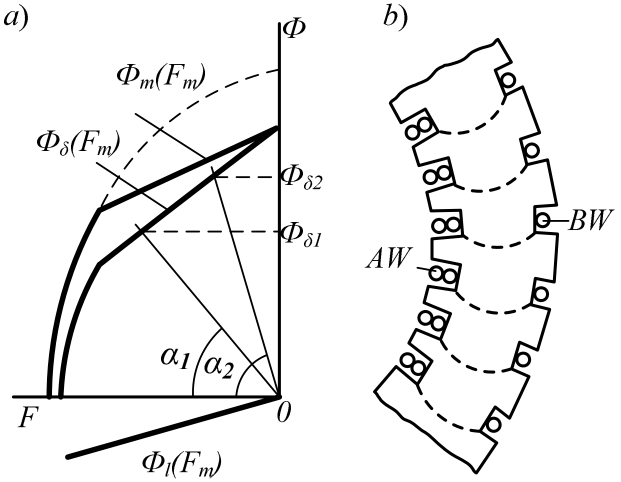


Fig 4.17 Changing of the magnetic flux in an air gap (*a*) and the arrangement of biasing winding (*b*)

Under the bias current variation, the steel core saturation, its permeability, permeance, the angle of the external core part magnetization lines inclination and the magnet working point change. It was assumed that under biasing the core steel permeability μ_c remains constant, and the relation $\Phi_{ext} = f(F_{ext})$ was represented as the angle arm, though actually the permeability μ_c varies, and the dependence $\Phi_{ext} = f(F_{ext})$ is not linear. If current of the biasing winding decreases so that the external permeance increases from $\Lambda_{ext1} = tg\alpha_1$ to $\Lambda_{ext2} = tg\alpha_2$, the air gap flux at no-load increases from $\Phi_{\delta 1}$ to $\Phi_{\delta 2}$.The biasing winding is wound around the armature core (Fig. 4.17 b), its internal conductors are imbedded to the same slots that the armature winding and external ones are placed to the armature core surface. In such a construction utilization of the slots becomes worse, and only the armature core yoke is biased.

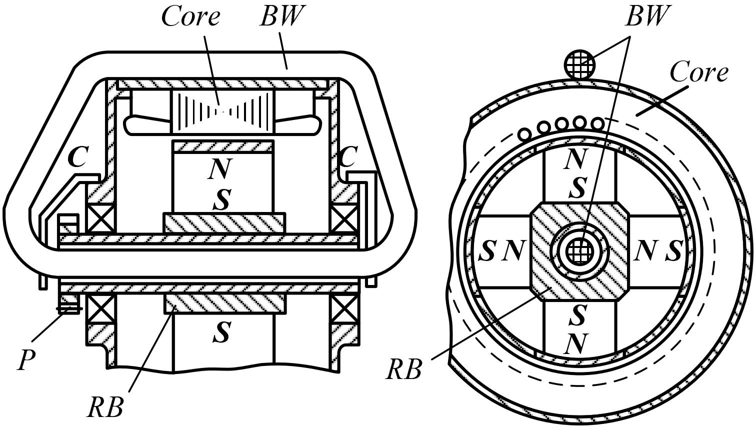


Fig. 4.18 A biasing winding with active conductors placed into a hollow shaft

It is possible to arrange the biasing winding so that its active wires are placed to the machine hollow shaft (Fig. 4.18). The winding is fixed to the stator with the clamp C. The rotor is brought to rotation with the help of the gear pinion P. In this construction the stator and rotor cores are saturated simultaneously, and the needed magnetomotive force is less than in the machine with the winding wrapping only the armature core. The biasing winding conductors placement into the hollow shaft makes the machine design much more complicated. Usually the winding is designed so that its current is maximal at no-load and is reduced at loading, causing the flux Φ_δ increase and the generator voltage stabilization.

Test questions

1. What are advantages and disadvantages of synchronous generators with permanent magnets?
2. Explain construction of permanent magnet synchronous generator with cylindrical rotor.
3. Explain construction of permanent magnet synchronous generator with star-shaped rotor.
4. Explain construction of permanent magnet synchronous generator with claw-shaped poles.
5. Explain rotor of permanent magnet synchronous generator with magnetic flux concentration.
6. Explain load angle characteristics of permanent magnet synchronous generators.

7. What are peculiar properties of permanent magnet synchronous generator voltage regulation curves and their influence on selection of operating conditions?
8. How is it possible to adjust the voltage of permanent magnet synchronous generator with the help of capacitance control?
9. Explain permanent magnet output voltage stabilization with resonant circuit.
10. How is the output voltage of permanent magnet synchronous generator stabilized by means of saturated reactor?
11. How is the voltage stabilization and control of synchronous generators with permanent magnets provided with use of additional biasing winding?

5 ASYNCHRONOUS GENERATORS

5.1. General characteristics and construction of asynchronous machines

Electric machine of alternating current in which the speed on load and the frequency of the system to which it is connected are not in a constant ratio is called the asynchronous machine. Operation of asynchronous machine is grounded on use of rotating magnetic field. The asynchronous machine rotor speed depends on load.

They are most widely-spread type of alternating current electric machines. Asynchronous machines are mostly used in the motor operating conditions. They are relatively simple by construction, serviceable and reliable, have high enough power efficiency and are cheaper than machines of other types. By this reason the application domain of asynchronous machines widens rapidly. Lately, application of asynchronous machines as generators supplying consumers of three-phase current and also of direct current through rectifying devices is of great interest. In definite conditions, self-contained asynchronous generators are preferable or even the single assumable decision, as for example in movable high-speed electric power units with gearless turbine prime mover having rotational frequency of 9 … 15 thousands rpm. As another example of efficient use of asynchronous generators, their use in small hydro-power stations may be taken.

Asynchronous generator requires minimum maintenance can be easily stitched to parallel operation. Its output voltage is closer to sine wave form than of a synchronous generator. They have less mass per unity power. Mass of asynchronous generators of nominal power up to 100 kW is about 1,3 – 1,5 times as less as synchronous generators and require less conducting materials. By construction asynchronous generators are the same as common asynchronous motors, and may be manufactured at the same plants as the asynchronous motors.

Disadvantage of asynchronous machines is consumption of considerable reactive power. The consumed reactive power of asynchronous machine can reach 50% of its apparent power. Consumption of reactive power provides creation of asynchronous machine magnetic field. The reactive power is supplied to asynchronous machine by the network or other source such as a capacitor bank, synchronous compensator or synchronous motor.

For improvement of asynchronous generator operational characteristics capacitors may be connected in series or in parallel to the load. The sources of reactive power should provide with it as the asynchronous generator as the load that have in most cases lagging reactive component. The capacitor bank or synchronous compensator mass and dimensions may exceed these parameters of the asynchronous generator. In the case of the load unity power factor they are comparable.

One of tasks to be solved is stabilization of output voltage and frequency of asynchronous generator as it has drooping voltage regulation characteristics. When the asynchronous generator is a part of wind power unit this problem becomes more complicated due to unstable rotational frequency of the rotor. At designing of Asynchronous generators for wind power stations the calculations are carried out on maximum efficiency in wide range of load and speed, and on minimum cost with account of control and regulation system. The generators construction should meet climatic conditions, acting external mechanical forces, and especially considerable dynamical and thermal impacts at transients caused by starts, supply interruptions, short circuits and also at wind gusts.

Construction of asynchronous machines may be considered by the example of widely spread induction motors. The stator and rotor cores are separated with the air gap. The core of each of the indicated peaces carries its winding. The stator winding is connected to the network and may be considered as the winding like the primary of a transformer. The rotor winding is like the secondary of a transformer because it receives electric power from the stator winding due to inductive coupling.

By construction asynchronous machines are divided into two types: machines with cage (or squirrel cage) rotor and machines with wound rotor.

The stator of an asynchronous motor (Fig. 5.1) consists of the frame 11 and the core 10 carrying a three-phase winding. The frame is casted from aluminum or cast iron or is welded of steel. The shown machine has enclosed construction and is cooled with an exterior fan. For better cooling the frame has longitudinal ribs increasing the cooling surface. To the frame the laminated magnetic core is attached. Punched thin sheets of electric steel, usually 0,5 mm thick, insulated by a varnish coating or by an oxide coating produced by heat treatment, are assembled into the stack the stack and are bound with clamps or by external longitudinal joint welds. Such a construction facilitates reduction of the eddy current losses produced at the core magnetization reversal by the rotational magnetic flux. On the inner stator core surface the axial slots are arranged to which the embedded winding coil sides are placed. The imbedded coil sides are connected in proper order by the coil ends lying outside the slots at the core end surfaces.

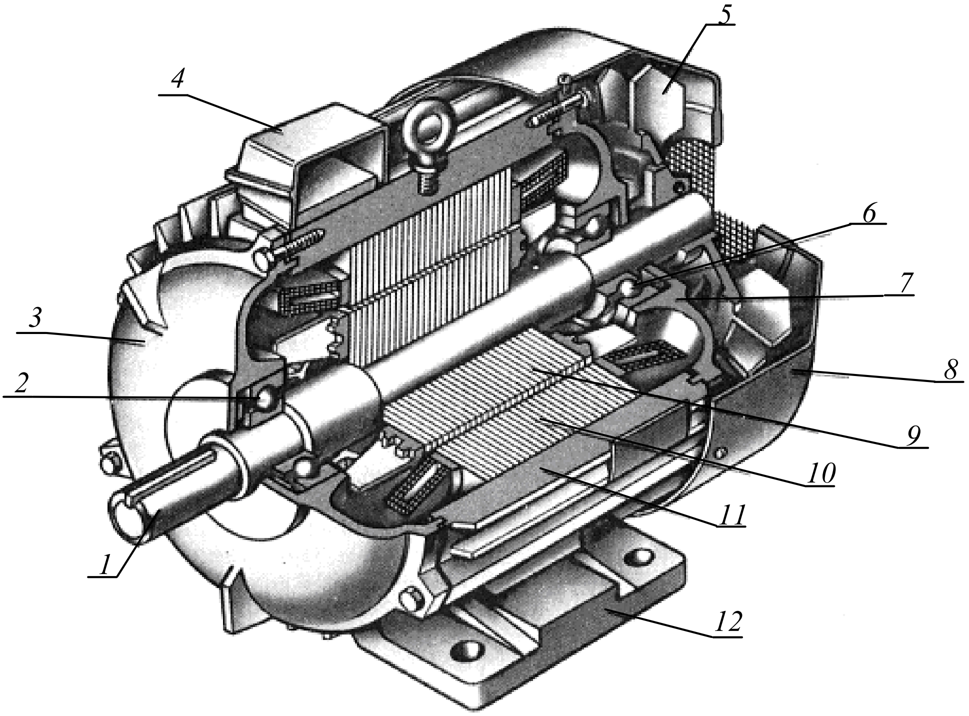


Fig. 5.1 A three-phase cage induction motor: 1- shaft, 2 and 6 –bearings, 3 and 7 – end shields, 4 – terminal box, 5 – fan, 8 – fan cover, 9 – rotor core with cage winding, 10 – stator core with winding, 11 – frame, 12 –feet

Inside the stator bore the rotor is placed. It consists of the shaft 1 and the core 9 with the cage winding. The cage or squirrel cage consists of a number of aluminum or copper bars which are placed into the rotor core slots and short circuited on the ends by end rings (Fig. 5.2). The rotor core is also laminated but its sheets are usually not covered with varnish but insulated by oxide. Eddy currents in the rotor core are small as this core magnetization reversal occurs at small frequency. At the supply frequency equal to 50 Hz frequency of the rotor core magnetization reversal is about 2…3 Hz.

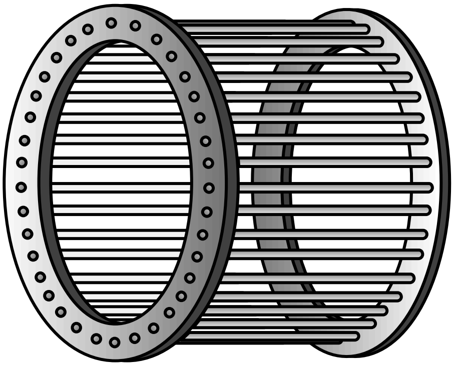


Fig. 5.2 A rotor squirrel cage

The shaft is installed with the help of the rolling bearings 2 and 6 placed in the end shields 3 and 7 (Fig. 5.1). Cooling of the motor is performed with centrifugal blower 5 providing the outer air flow. The ventilator has the cover 8. In the center of the cover there is an opening for outer air draw. If a motor has protected design the end shields have opening (jalousie) and a system of inner self-ventilation. The air is run by the inner ventilator trough the machine inner hollow. Mounting of a motor is performed or with the help of feet 12 or the adjusting flange which is made for this aim at the end shield on the side of the shaft extension. The feet and the flanges have holes for fastening bolts.

Construction of the wound-rotor asynchronous machines differs of the cage type mainly by the rotor design (Fig. 5.3). This type motor stator also consists of the frame 3 and the core 4 with the three-phase winding. It has the end shields 2 and 6 with the rolling bearings 1 and 7. The frame has feet 10 and the terminal box 9. But the rotor is more complicated. On the shaft 8 the laminated core carrying the three phase winding 5 made like the stator winding is fixed. This winding is star-connected, and its leads are connected to three slip rings 11 that are isolated from one another and from the shaft. To provide electrical connection of the rotating rotor winding with external circuit there is the current collecting set 12 consisting of brushes and brush-holders. The brush-holders are fixed to the insulated parts of the studs screwed into the end shield lug.

Though the wound-rotor asynchronous machines has more complicated construction an are less reliable they are more adjustable and possesses better starting abilities.

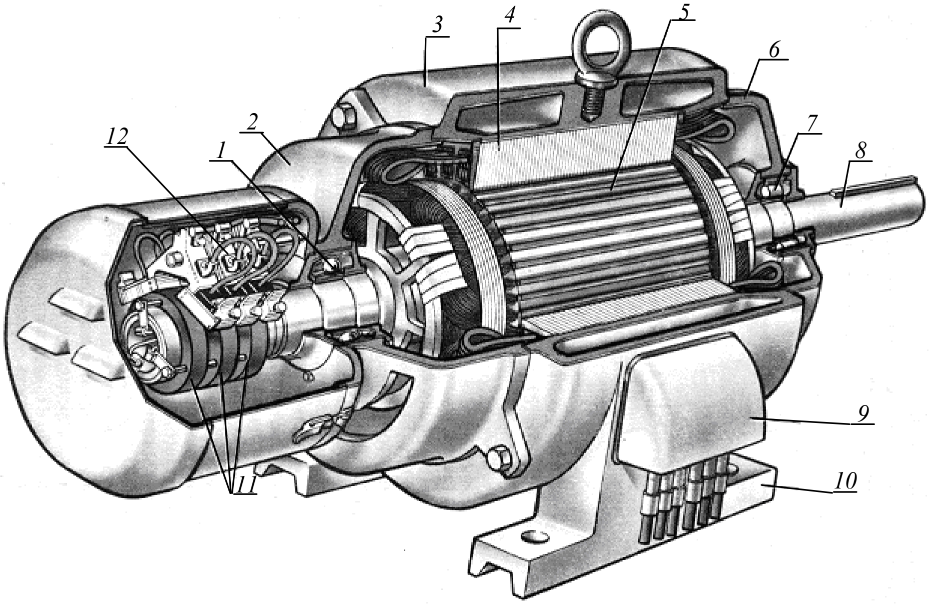


Fig. 5.3 A three-phase wound-rotor asynchronous machine: 1and 7 – bearings, 2 and 6 – end shields, 3 – frame, 4 – stator core with winding, 5 – rotor core with winding, 8 – shaft, 9 – terminal box, 10- feet, 11 – slip-rings, 12 – current collecting set

5.2. The operation and major relationships

Physical nature of energy conversion, relation of main parameters, equivalent circuit and vector diagram for asynchronous generator and motors are very similar. It is convenient to consider at first process of energy conversion in asynchronous motors.

In a three-phase asynchronous motor the rotating magnetic flux of constant magnitude (i.e. circular rotating field) is produced by the balanced three-phase currents flowing through the stator winding (Fig. 5.4).

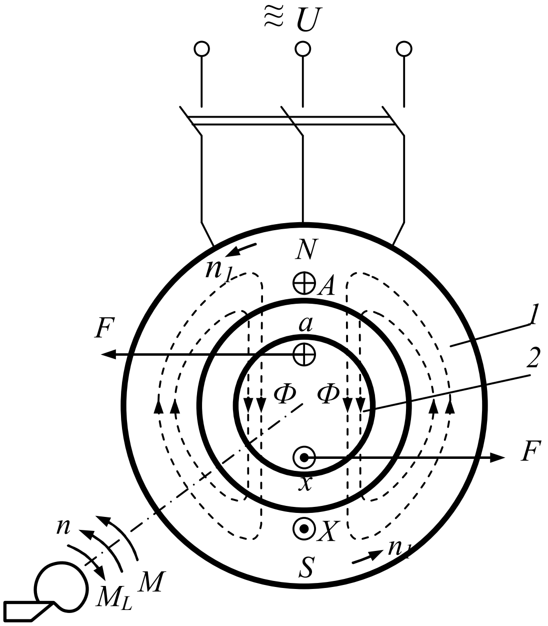


Fig. 5.4 How an asynchronous machine operates

This field cuts conductors of the stator and rotor windings and induces voltage in them that is about 180° out of phase to the voltage applied across winding terminals. The voltage induced in the stator winding confines the stator current and provides conditions for electric power consumption from the mains. Denote the stator phase induced voltage as e_1 and the voltage induced in the phase of rotor winding as e_2. If the rotor circuit is closed, the alternating current i_2 flows through the rotor winding. The active component of the rotor winding phase current is in phase with the induced voltage. Interaction between the rotor currents and the rotating flux causes the electromagnetic forces F_{em} acting on the rotor conductors. These forces produce the machine electromagnetic torque M. In a motor, electromagnetic torque direction coincides with direction of the magnetic flux rotation. If the electromagnetic torque is greater than the braking torque applied by the load to the motor shaft, the rotor begins to revolve, and the electric power consumed by the stator winding from the mains is converted to mechanical power that is conveyed through the shaft to the loading device connected to it.

The magnetic field produced by the stator winding currents has rotational frequency of $n_1 = f_1/p$ revolutions per second or $n_1 = f_1/p$ revolutions per minute (rpm). When the rotor is stationary, the rotating field flux speed relatively conductors of the stator and rotor windings is the same, and the voltages induced in the stator and rotor windings, and also the stator and rotor currents, have the same frequency $f_1 = pn_1/60$ that equals the frequency of the stator current and of the voltage applied to the stator winding. The rotor currents produce their own rotating *mmf* causing the rotor rotating flux which rotates with the same speed relatively stator and rotor as the flux produced by the stator currents. So, it is seen that when the rotor is stationary there are two rotating components of the machine magnetic flux having the same direction of rotation and equal speeds. There is no relative slippage of these fluxes. The stator and rotor magnetomotive forces, or the stator and rotor magnetic fields, rotate in synchronism with the same synchronous speed n_1. The stator and rotor *mmfs* rotating in synchronism summarize and form the resultant rotating *mmf* causing the resultant rotating magnetic flux having both the synchronous speed.

When the rotor is not stationary but rotates with speed (rotational frequency) n, slippage between the rotating field and the rotor occur. Difference between the rotational frequencies of the rotating flux and the rotor $n_s = n_1 - n$ may be called the slip rotational frequency or slip speed. Usually the slip speed is determined in per unit or in per cent as

$$s = \frac{n_1 - n}{n_1}, \; per\ unit\,, \; s = \frac{n_1 - n}{n_1}, \% \tag{5.1}$$

and is called the slip. If $n = 0$, the slip is $s = 1$.

The rotor speed may be expressed in terms of s and n_1 as

$$n = n_1 (1 - s). \tag{5.2}$$

At $s \neq 1$ or $n \neq 0$ the magnetic field rotating with synchronous speed induces in the rotor winding the voltage e_2 which frequency f_2 does not equal the stator voltage frequency f_1:

$$f_2 = \frac{pn_s}{60} = \frac{pn_1 s}{60} = f_1 \cdot s \tag{5.3}$$

where p is the number of pole pairs of the magnetic field, $n_s = n_1 - n = n_1 \cdot s$.

The rotational speed of the rotor magnetic field relatively the rotor winding is $n_{2r} = \frac{60 f_2}{p} = \frac{60 f_1 s}{p} = n_1 \cdot s$. Hence this field rotates relatively the stator winding with the speed $n_{2s} = n_{2r} + n = n_1$, i.e. at every rotor speed the stator and rotor fields rotate in synchronism being fixed one to another and producing the resultant magnetic field rotating with synchronous speed n_1.

Rms values of the voltage induced in the phase windings of the stator stationary rotor equal to

$$E_1 = \pi\sqrt{2}\Phi_m f_1 w_1 k_{w1} \tag{5.4}$$

$$E_2 = \pi\sqrt{2}\Phi_m f_1 w_2 k_{w2} \tag{5.5}$$

where Φ_m is the magnetic flux of the resultant magnetic field penetrating air gap within one magnetic pole, w_1 is the number of stator phase winding turns, i.e. the turns connected in series within a path of the stator phase winding, w_2 is the number of rotor phase winding turns, k_{w1} and k_{w2} are the winding factors of stator and rotor windings respectively.

The rotor induced voltage depends on the rotor speed, and hence, on the slip. In general case, the voltage induced in the rotor phase winding E_{2s} may be found as

$$E_{2s} = \pi\sqrt{2}\Phi_m w_2 f_2 \cdot k_{w2} = E_2 \cdot s \tag{5.6}$$

Let R_1 and R_2 denote the stator and rotor phase winding resistances respectively, X_{l_1} – the stator phase leakage reactance, $X_{l_{2s}}$ – the rotor phase leakage reactance at any given value of the slip. Stator and rotor leakage reactance may be expressed as

$$X_{l_1} = 2\pi f_1 L_{l_1}\ ;\ X_{l_{2s}} = 2\pi f_2 L_{l_2} = \omega_2 L_{l_2} = 2\pi f_1 L_{l_2} \cdot s = \omega_1 L_{l_2} s = X_{l_2} \cdot s = \omega_1 L_{l_1} \tag{5.7}$$

where L_{l_1} and L_{l_2} are stator and rotor leakage inductance respectively, ω_1 and ω_2 are stator and rotor voltage angular frequency, X_{l_2} is stationary rotor leakage reactance. From this, impedances of stator and rotor phase windings may be written as

$$\underline{Z}_1 = R_1 + jX_{l_1}\ ;\ \underline{Z}_{2s} = R_2 + jX_{2s} = R_2 + jX_{l_{2s}} = R_2 + jX_{l_{2s}} \cdot s \tag{5.8}$$

Using Kirchhoff voltage law write the equations for stator and rotor phase winding meshes:

$$\left.\begin{aligned} \underline{U}_1 &= -\underline{E}_1 + \underline{Z}_1 \cdot \underline{I}_1 = -\underline{E}_1 + R_1\underline{I}_1 + jX_{l_1}\underline{I}_1 \\ \underline{E}_{2s} &= \underline{I}_2\underline{Z}_{2s} = \underline{I}_2 R_2 + jX_{l_{2s}} \cdot \underline{I}_2 \end{aligned}\right\} \tag{5.9}$$

where $\underline{U}_1$ is the voltage across the stator phase winding leads. Note that sinusoidal quantities in these equations have generally different frequencies: the stator quantities vary with the frequency f_1, and the rotor quantities – with the frequency $f_2 = f_1 \cdot s$.

Remaining the rotor current phasor unchanged we can replace the rotating rotor winding for the stationary one. Formally this can be made by division of the second equation (5.9) by s Then receive:

$$\underline{E}_2 = \frac{R_2}{s}\underline{I}_2 + jX_2\underline{I}_2 \tag{5.10}$$

After this transformation of the rotor circuit voltage equation it is possible to consider the rotor circuit stationary ($n = 0$; $s = 1$) with the current $\underline{I}_2$, such as in the rotating rotor but having the same frequency that the stator current, and the voltage such as in stationary rotor. At this the rotor leakage reactance became equal to the reactance of the stationary rotor X_2 and the rotor resistance changed and became equal to R_2/s where s is the slip value the same that of the rotating rotor.

Let analyze consequences of such a replacement. As the rotor current phasor has not changed the rotor *mmf* magnitude remains the same as of rotating rotor. At this it rotational speed relatively the rotor changed for n_1 but this speed relatively the stator and the stator field remained unchanged. Therefore the resultant rotating magnetic field of the machine remained unchanged. Further, as ratio of reactance and resistance for rotating and transformed stationary rotor is the same, the angles of phase displacement between rotor circuit sinusoidal quantities also remained the same after the rotor transformation.

At the described rotor transformation active power dissipated in the rotor circuits changes. In the rotating rotor winding active power is $m_2 I_2^2 R_2$, at the stationary rotor obtained after transformation it became $m_2 I_2^2 \dfrac{R_2}{s}$, where m_2 is the rotor phase number. The power transmitted from the stator circuit to the rotor of asynchronous machine by means of magnetic field, further called the electromagnetic power P_{lm}, is spend to obtain mechanical power P_{mech} and for covering the resistance losses P_{R_2} in the rotor winding. So it may be represented as

$$P_{lm} = P_{mech} + P_R \tag{5.11}$$

Taking into account, that $P_{lm} = M\Omega_1$ and $P_{mech} = M\Omega$ where M is electromagnetic torque, Ω_1 and Ω are synchronous and rotor angular speed respectively, with account of (5.2) have:

$$P_{R_2} = m_2 I_2^2 R_2 = P_{lm} - P_{mech} = P_{lm} \cdot s \tag{5.12}$$

It is seen that the active power dissipated in the rotating rotator circuits equals the rotor resistance loss. At the same time the active power dissipated in the equivalent circuits of stationary rotor obtained at the transformation of real rotating rotor is summary power of mechanical power and resistance loss.

Presenting the equivalent rotor resistance as $\frac{R_2}{s} = R_2 + R_2 \frac{1-s}{s}$ find:

$$P_{mech} = I_2^2 R_2 \frac{1-s}{s} \tag{5.13}$$

So the mechanical power produced by the asynchronous machine may be found simply by calculating the active power consumed in the part of the equivalent rotor resistance $R_2 \frac{1-s}{s}$.

The above said shows that the processes of electromechanical energy conversion in asynchronous machine may be analyzed on the basis of the machine with equivalent stationary rotor.

The equivalent rotor winding parameters may be referred to the parameters of the stator winding as it is made in transformer when the secondary is referred to the primary winding parameters. At this, invariance of power, magnetic field and time phase relations should be provided. At the reduction of rotor winding to the reference conditions the referred rotor winding number of phases becomes equal to m_1, the rotor phase turns number – to w_1, and the rotor winding factor – to k_{w1}.

The rotor referred quantities are denoted by primed symbols, they are referred to the stator by the equalities:

$$\left.\begin{aligned} E_2' &= E_2 \frac{w_1 k_{w1}}{w_2 k_{w2}} \\ I_2' &= I_2 \frac{m_2 w_2 k_{w2}}{m_1 w_1 k_{w1}} = \frac{I_2}{k_i} \\ R_2' &= R_2 k_e k_i \\ X_{l_2}' &= X_{l_2} k_e k_i \end{aligned}\right\} \tag{5.14}$$

where $k_e = \frac{w_1 k_{w1}}{w_2 k_{w2}}$ and $k_i = \frac{m_1 w_1 k_{w1}}{m_2 w_2 k_{w2}}$ are the voltage and current transformation ratios.

Using the referred quantities the equivalent stationary rotor voltage equation is written as

$$\underline{E}'_2 = \frac{R'_2}{s}\underline{I}'_2 + jX'_{l2}\underline{I}'_2 = \underline{Z}'_2 \cdot \underline{I}'_2 + R'_2\frac{1-s}{s}\underline{I}'_2 \tag{5.15}$$

where $\underline{Z}'_2 = R'_2 + jX'_{l2} = \underline{Z}_2 \cdot k_e \cdot k_i$ is the rotor impedance referred to the stator.

Reference of the rotor quantities does not vary the machine magnetic field, active and reactive power of the stator and rotor circuits, machine electromagnetic and mechanical power and phase displacement angles between the phasors.

From the above it is understood that the magnetomotive force of the rotor winding referred to the stator is the same as of the actual winding, i.e.

$$\underline{F}'_{2m} = \frac{m_1\sqrt{2}}{\pi p}\underline{I}'_2 w_1 \cdot k_{w1} = \frac{m_2\sqrt{2}}{\pi p}\underline{I}_2 \cdot w_2 k_{w2} = \underline{F}_{2m} \tag{5.16}$$

When the slip of asynchronous machine $s \neq 0$ currents flow trough its both windings and its rotating magnetic field is produced by mutual action of stator and rotor windings magnetomotive forces. The resultant *mmf* causing the magnetic field equals

$$\underline{F}_{1m} + \underline{F}_{2m} \tag{5.17}$$

where $\underline{F}_{1m} = \frac{m_1\sqrt{2}}{\pi p}\underline{I}_1 w_1 k_{w1}$ and $\underline{F}_{2m} = \frac{m_2\sqrt{2}}{\pi p}\underline{I}_2 w_2 k_{w2}$ are complex amplitudes of stator and rotor *mmf* respectively.

At rotation of the rotor in synchronism with the magnetic field ($s = 0$) the rotor induced voltage and current equal zero, the electromagnetic torque and mechanical power are also zero, and machine is said operates at no-load. The rotating magnetic field at no-load is produced by only stator magnetomotive force. Denote stator rms current at no-load as I_0 and the machine *mmf* amplitude as F_{0m}. Then have:

$$\underline{F}_{0m} = \underline{F}_{1m0} = \frac{m_1\sqrt{2}}{\pi p}\underline{I}_0 w_1 k_{w1}, \tag{5.18}$$

where $\underline{F}_{1m0}$ is stator *mmf* at no-load.

The magnetic flux Φ_m may be found from (5.4). The voltage drop $Z_1 I_1$ in limits of rated load may be as a first approximation neglected, and the stator induced voltage is $E_1 \approx U_1$. If the voltage across the machine terminals remains constant, it may be assumed that the magnetic flux also remains constant at load variation. Then, based on the above, the machine magnetomotive force does not vary at the load variation, and the following equation is true:

$$\underline{F}_{1m} + \underline{F}_{2m} = \underline{F}_{0m} \tag{5.19}$$

From (5.19) with account of (5.14) and (5.16) obtain the relationship:

$$\underline{I}_1 = \underline{I}_0 - \underline{I}'_2 \tag{5.20}$$

With account of (5.9), (5.15) and (5.20) the complex equations of asynchronous machine is written as:

$$\left.\begin{aligned} \underline{U}_1 &= -\underline{E}_1 + jX_{l_1}\underline{I}_1 + R_1\underline{I}_1 \\ \underline{E}'_2 &= jX'_{l_2}\underline{I}'_2 + R'_2\underline{I}'_2 + R'_2\frac{1-s}{s}\underline{I}'_2 \end{aligned}\right\} \tag{5.21}$$

Assuming that the machine magnetization characteristic is linear, the no-load current at sinusoidal flux varies by sine law in time and have two components. One of them is the magnetizing current $I_{0\mu}$ leading the stator induced voltage by 90 electrical degrees and being in phase with the stator phase linked flux ψ_1. The other is the component I_{0a} being in phase with the stator voltage component $-\underline{E}_1$ that overcomes the steel losses at no-load. The no-load current maybe represented as

$$\underline{I}_0 = \underline{I}_{0\mu} + \underline{I}_{0a} \tag{5.22}$$

Proceeding by (5.22) the current I_0 may be imagined as the sum of currents flowing through two parallel branches: the current $I_{0\mu}$ flowing through the branch with inductive reactance $X_\mu = \omega_1 L_\mu$, where L_μ is inductance of the stator winding caused by the main magnetic flux, and the current I_{0a} flowing through the branch with resistance $R_\mu = \dfrac{m_1 E_1}{P_{st}}$, where P_{st} is steel loss in the stator core. The voltage across terminals of this parallel connection is $-\underline{E}_1$. As a rule the resistance R_μ is much grater than reactance X_μ.

The described parallel connection may be transformed into equivalent series connection with the same voltage $-\underline{E}_1$ between its terminals and parameters which values may be approximately found by equalities:

$$R_m \approx \frac{X_\mu^2}{R_\mu} >> X_\mu \qquad X_m \approx X_\mu \tag{5.23}$$

Taking into account the above the stator induced voltage may be expressed as

$$\underline{E}_1 = -jX_\mu \cdot \underline{I}_{0\mu} = -R_\mu \cdot \underline{I}_{0a} = -\underline{Z}_m \underline{I}_0, \quad \underline{Z}_m = R_m + jX_m \tag{5.24}$$

Using (5.21), (5.22) and (5.24) it is possible to express the input impedance of the asynchronous machine determined on terminals of the stator phase as

$$\underline{Z}_{in} = \frac{\underline{U}_1}{\underline{I}_1} = \underline{Z}_1 + \frac{\underline{Z}_m\left(\underline{Z'}_2 + R'_2\frac{1-s}{s}\right)}{\underline{Z}_m + \left(\underline{Z'}_2 + R'_2\frac{1-s}{s}\right)} = \underline{Z}_1 + \frac{\underline{Z}_m\left(\frac{R'_2}{s} + jX'_2\right)}{\underline{Z}_m + \left(\frac{R'_2}{s} + jX'_2\right)} \tag{5.25}$$

Structure of expression (5.25) permits to identify equivalent circuit of asynchronous machine as the series-parallel connection shown in Fig. 5.5 a.

At no-load ($s = 0$) the resistance $\left(R'_2\frac{1-s}{s} = \infty\right)$, and the right branch of equivalent circuit is open. The stator no-load current equals $I_1 = I_0$, electromagnetic torque is $M = 0$. At stationary rotor as at the initial instant of starting or at locked-rotor, the slip is $s = 1$. The part of rotor resistance depending on the slip is $R'_2\frac{1-s}{s} = 0$. By analogy with transformer this operation conditions are sometimes called the short-circuit conditions of asynchronous machine. At $s = 1$ the machine electromagnetic torque represents the initial starting torque. At no-load and at locked rotor the machine does not perform electromagnetic energy conversion.

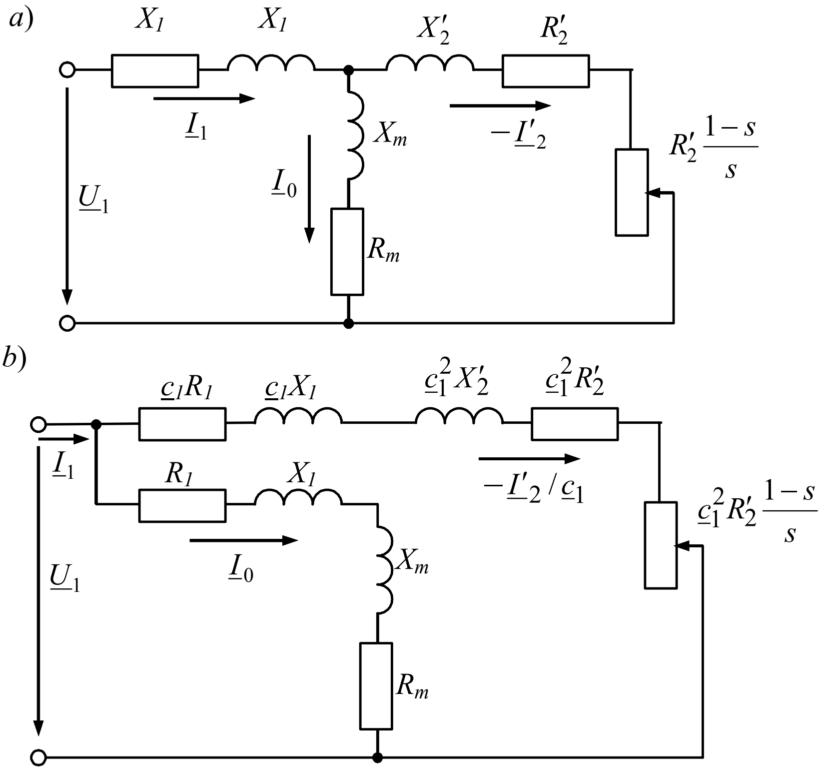


Fig. 5.5 Equivalent circuits of an asynchronous machine (*a*) and modified circuit (*b*)

Asynchronous machine carries out energy conversion operating as a motor at $0 < s < 1$, a generator at $s < 0$ and an electromagnetic braking at $s > 1$.

Sometimes it is convenient to modify the equivalent circuit so that the shunt path containing $\underline{Z}_m$ is directly connected to the input terminals (Fig. 5.5, b). The coefficient $\underline{c}_1$ is complex quantity $\underline{c}_1 = 1 + \dfrac{\underline{Z}_1}{\underline{Z}_m}$. In most cases it may be assumed the real quantity $c_1 \approx 1 + \dfrac{X_1}{X_m}$. For machines of more than 2 – 3 kW this coefficient is $c_1 = 1{,}02...1{,}05$. In many cases the simplified modified circuit, obtained assuming $c_1 = 1$, may be used. In this case errors of currents and other quantities determination do not exceed the acceptable values. So the rotor current is determined with error not more than 2 – 5 %.

Active reactive and apparent power consumed by the motor equal:

$$\begin{cases} P_1 = m_1 U_1 \cos\varphi_1, \ W; \\ Q_1 = m_1 U_1 \sin\varphi_1, \ var; \\ S_1 = m_1 U_1, \ V \cdot A. \end{cases} \tag{5.26}$$

Using the simplified modified equivalent circuit find:

$$I_2' = \frac{U_1}{\sqrt{\left(R_1 + R_2'/s\right)^2 + \left(X_1 + X_2'\right)^2}} \tag{5.27}$$

From (5.12), the electromagnetic power of the machine is found as

$$P_{em} = \frac{P_{e2}}{s} = \frac{m_1 I_2' \cdot R_2'}{s} \tag{5.28}$$

The electromagnetic torque is equal to

$$M = \frac{P_{em}}{\Omega_1} \tag{5.29}$$

where $\Omega_1 = \frac{2\pi f_1}{p}$ is the angular synchronous speed. After substitution of (5.27) the equation of electromagnetic torque is obtained:

$$M = \frac{m_1 p U_1^2 R_2'}{2\pi f_1 s\left[\left(R_1 + \frac{R_2'}{s}\right)^2 + \left(X_1 + X_2{}'\right)^2\right]} \tag{5.30}$$

The electromagnetic torque is directly proportional to square of the stator voltage and there is more complicated dependence on the slip and parameters of the stator and rotor. In Fig. 5.6 *a* the torque-slip curve of asynchronous machine $M = f(s)$ is drawn. Fig. 5.6 *b* shows the speed-torque curve $n = f(M)$ obtained on the basis of the torque-slip curve with account of (5.2).

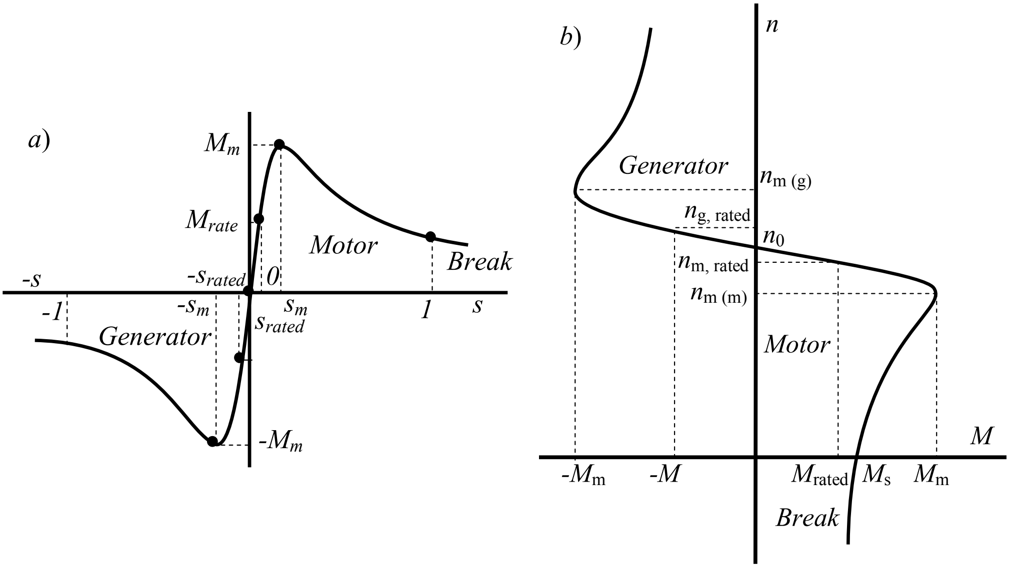


Fig. 5.6 Torque-slip (*a*) and speed- torque (*b*) curves

Specific points of the curves are the point corresponding to no-load at $s = 0$ ($n = n_1$), the points of maximum (breakdown) torque with coordinates ($s = s_m$; $M = +M_m$) or ($M = +M_m$; $n = n_{m(m)}$) and ($s = -s_m$, $M = -M_m$) or ($M = -M_m$, $n = n_{m(g)}$), and the starting point with coordinates ($s = 1$, $M = M_s$) or ($M = M_s$, $n = 0$).

The maximum torque is found from the equality:

$$\pm M_m = \frac{m_1 p U_1^2}{4\pi f_1 \left(\pm R_1 + \sqrt{R_1^2 + \left(X_1 + X_2'\right)}\right)} \tag{5.31}$$

The starting torque is

$$M_s = \frac{m_1 p U_1^2 R_2'}{2\pi f_1 \left[\left(R_1 + R_2'\right)^2 + \left(X_1 + X_2'\right)^2\right]} \tag{5.32}$$

5.3. An asynchronous generator switched in parallel to network

At $s<0$ the rotor induced voltage changes its phase for the opposite in comparison with that in a motor due to change of direction of the rotor movement relatively the stator. Therefore direction of the active rotor current component I_{2a} also changes to opposite, and the machine electromagnetic torque becomes braking as it is opposite to the rotor rotation. As the result direction of energy conversion changes, the machine converts mechanical energy, received through the shaft from external source, into electrical energy transferred to the network.

Calculation of quantities and parameters that define the asynchronous machine operation conditions is carried our on the basis of equations (5.21), (5.20) and (5.24) and the equivalent circuit (Fig. 5.5) corresponding with the concept of the machine with stationary equivalent rotor and the rotor parameters referred to the stator. Therefore, energy conversion and operation of asynchronous generator is considered using appropriate equations, formulas and parameters.

As it was said above the power dissipated in the resistance $R_2'\frac{1-s}{s}$ of the equivalent stationary rotor phases equals the mechanical power transferred through the shaft of asynchronous machine. The electromagnetic power transferred between the stator and rotor equals the power dissipated in the resistances R_2'/s. For the motor conditions $s>0$, and these resistances are positive.

When the machine operates at negative slip, i.e. as generator, R_2'/s and $R_2'\frac{1-s}{s}$ are negative. The angle β_2 of phase displacement between the rotor induced voltage and current is defined by the equality

$$tg\beta_2=\frac{X_2'}{R_2'/s}<0 \tag{5.33}$$

and

$$\pi/2<\beta<\pi \tag{5.34}$$

The vector diagram of asynchronous generator switched to the network (Fig. 5.7) shows that the phase displacement of the stator current I_1 with respect to the voltage U_1 is $\pi/2<\varphi<\pi$. Therefore, the active power of the machine $P_1=m_1U_1I_1\cos\varphi<0$ at negative slip is also negative that indicates transfer of electric power from the stator winding to the network.

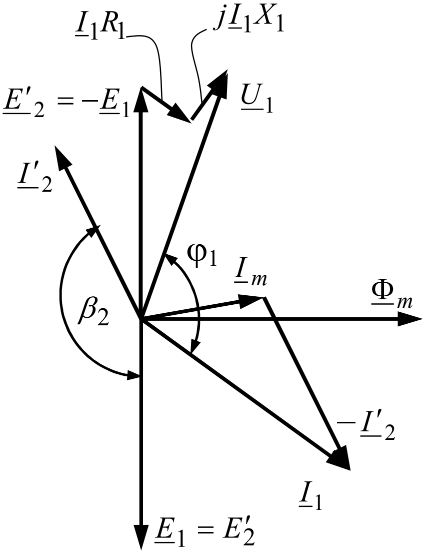


Fig. 5.7 A vector diagram of an asynchronous generator

Electromagnetic power $P_{em} = m_1 E'_2 I'_2 \cos\beta_2 < 0$ is negative too that indicates transfer of power by means of the magnetic field from the rotor to stator winding. Mechanical power $P_{mech} = m_1 I_2'^2 R'_2 \frac{1-s}{s} < 0$ at negative slip is also negative that indicates consumption of mechanical energy from external source through the shaft. This confirms that an asynchronous machine operates at negative slip, i.e. at speed above synchronous, as an electric generator. The reactive current of a generator is lagging as of asynchronous motor, i.e. asynchronous generator consumes reactive power that is needed for producing the magnetic field.

Full stator current of asynchronous generator has as the reactive magnetizing component as the active component corresponding to the active power that is supplied to the network consumers. At constant voltage the current is a function of the slip (Fig. 5.8). Minimum current at no- load ($s = 0$) is purely reactive magnetizing current.

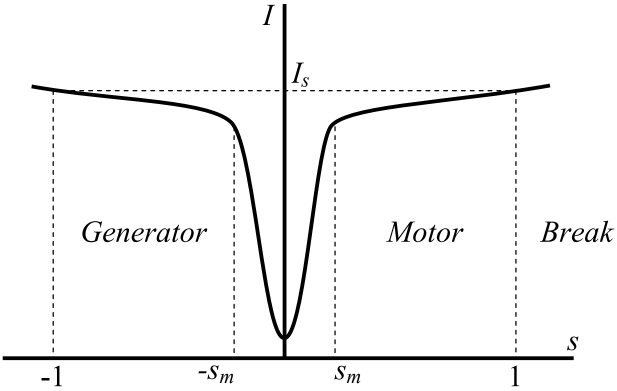


Fig. 5.8 Stator current as a function of slip

An asynchronous generator delivering active power to the network should receive reactive power from it. Therefore an asynchronous generator can work in parallel with the network which has its own sources of reactive power such as, for example, a synchronous generator. Asynchronous generator loses its excitation if the external source of reactive power disappears.

5.4. A comparison of synchronous and asynchronous generators parallel operation with network

For synchronization of synchronous generator with the network four conditions should be fulfilled: the *rms* values of the generator induced voltage and the network voltage must be equal, these quantities have to be in phase, the generator and network frequencies are to be equal, phase sequence of the generator and network must coincide. Violation of the first three requirements causes considerable electromagnetic overloads, power fluctuations, mechanical inrushes on the prime mover shaft, voltage beating. The fourth requirement violation may cause the generator breakdown.

Sort-circuit on the buses may be a reason for powerful transient with large surge current with magnitude $I_{surge} = (10\ldots20)I_{rated}$, hard electro-dynamic and thermal loading in windings and attachment points initiating hard consequences for a synchronous generator.

A wind power unit equipped with synchronous generator is exposed to action of pulsating torque of wind turbine caused by the wind flow variability that results in current and power components pulsating at parallel operation with the network. The turbine blades angle control system has considerable time constant being the cause of blades angle adjustment delay, and the synchronous generator operates under conditions of permanent transient accompanied with random fluctuation of the torque angle θ and the load. At strong wind gusts there is danger of synchronous generator pulling out of synchronism and going into asynchronous operation that may be cause of the damper winding break. The said leads to the generator reliability reduction and may cause it failure.

Asynchronous generators have advantages at their parallel connection to the network. They are the following.

Conditions of asynchronous generator switching for parallel operation with the network, another asynchronous or synchronous generator are much easier. It may be switched on even at considerable difference of the asynchronous generator and equivalent network generator rotational frequencies. The requirement that should be met is coincidence of the generator and the network phase sequence. Virtually the problems of synchronization and pulling out of synchronism disappear.

There is no need in asynchronous generator short circuit protection as the generator is de-excited in such a case as it loses the source of excitation.

Quality of output voltage of asynchronous generator is better than of synchronous.

In the case of asynchronous generator there is no need in self-excitation and the field adjustment.

In Fig. 5.9 the records of small generators parallel operation with the network, one of which is asynchronous and other is synchronous. Comparison of their output power curves shows that for roughly the same conditions at gusty wind the power pulsation of asynchronous generator is much less than of synchronous one. The power of asynchronous generator contains only low frequency fluctuations caused by slow variation of the wind speed. Maximum deviations took place only at prolonged wind speed increase and are explained by transient of the generator slip variation. Switching asynchronous generator on parallel operation is possible at practically any wind conditions. At the same time synchronous generator switching on in parallel to the network is difficult at gusty wind.

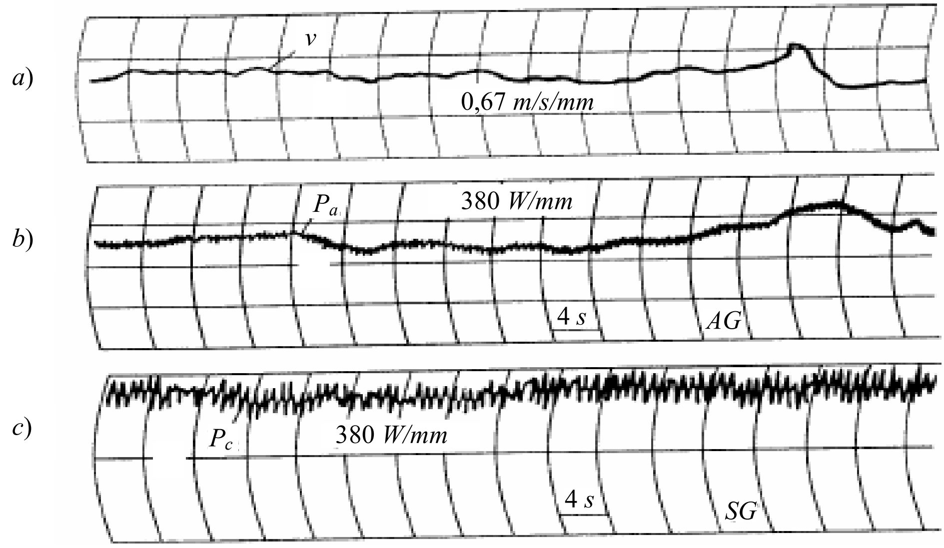


Fig. 5.9 Records of parallel operation with network: *a* – wind speed, *b* – power supplied by an asynchronous generator, *c* - power supplied by a synchronous generator

The rotor of synchronous generator has the same spatial orientation that the rotor of powerful network integrated equivalent synchronous generator, i.e. these generators are synchronized, and in the process of parallel operation displacement of the switched generator rotor occurs in narrow limits of load torque angle θ. At the angle θ greater than θ_m, synchronous generator pulls out of synchronism.

Rotor of asynchronous generator moving relatively the rotating field with the slip s is not strictly coupled with resultant magnetic field axis. At load variation, it speed vary too. On that reason the voltage beating reduces, and the amplitude of the power fluctuation is about three times as less as in synchronous generator. The transients at the interrupt load change are practically absent.

At switching asynchronous generator to network there is no need to coincide spatially rotating masses of switched and operating generators. Transient time reduces, arising currents and torques decrease considerably in comparison with synchronous generators. Characteristics of asynchronous generators appreciably depend on method of wind wheel control. When centrifugal governor acting on the blades hydraulic drive is used considerable regulator swinging occur that complicates the windmill parallel operation with network. Windmills equipped with asynchronous generator of great power better work at conditions of variable rotational speed depending on the wind speed. Such a method permits to increase factor of wind speed utilization and electric energy production.

5.5 Power flow diagram, losses and efficiency of an asynchronous generator

A generator carries out conversion of electric energy into mechanical energy. The input mechanical energy P_1 is supplied by a prime mover to the generator through its shaft and is converted into the useful active power delivered to the network (Fig. 5.10).

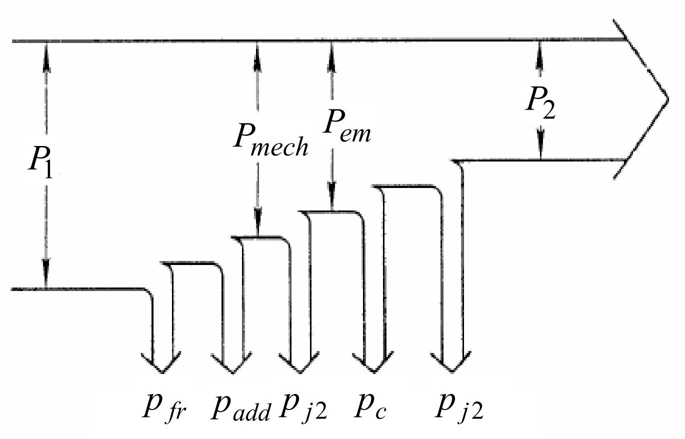


Fig. 5.10 A power flow diagram

The input power depends on the prime mover torque and the angular rotational speed:

$$P_1 = M_{pm} \cdot \Omega = M_{pm} \frac{\pi n}{30} \tag{5.35}$$

where the prime mover torque M_{pm} is measured in NMm, the shaft angular speed Ω in radians per second and the rotational frequency n in revolutions per minute (rpm).

Part of the input power p_{fr} is lost covering mechanical losses (for friction in bearings, ventilation, etc. Another part that is lost is the additional power loss p_{add} caused mainly by the field harmonics arising due to effect of windings *mmf* harmonics and teeth structure of the magnetic cores. The flux harmonics cause parasitic ghost torques and induce voltage and current in the windings which produce additional loss especially in rotor cage. This loss is difficultly calculated and is often assumed equal to $p_{add} \approx 0{,}05P_1$ at rated load. At other load it may be evaluated assuming it being directly proportional the square of the current.

The mechanical power being further converted in the machine equals

$$P_{mech} = P_1 - p_{fr} - p_{add} \,. \tag{5.36}$$

The rotor current causes Joule loss in the rotor winding resistance

$$p_{j2} = m_1 I_2'^2 \cdot R_2' \tag{5.37}$$

The remaining part of the power is electromagnetic power P_{em} transferred to the stator winding by means of the magnetic field:

$$P_{em} = P_{mech} - p_{j2} = \frac{p_{j2}}{s} \tag{5.38}$$

Taking into account that at small values of slip magnetization of the rotor core occurs with very small frequency all magnetic loss p_c of asynchronous machine usually referred as the loss covered on account of the electromagnetic power.

Joule loss in the stator winding is equal to:

$$p_{j1} = m_1 I_1^2 \cdot R_1 \tag{5.39}$$

Subtracting the magnetic loss and the stator Joule loss receive useful output power delivered by the generator to the network:

$$P_2 = P_{em} - \left(P_c + P_{\gamma 1}\right) \tag{5.40}$$

The input mechanical power may be expressed in terms of the output power and the losses as:

$$P_1 = P_2 + \sum P \tag{5.41}$$

where $\sum \Delta p$ is the sum of losses: $\sum \Delta p = p_{fr} + p_{add} + p_{j2} + p_c + p_{j1}$.

The efficiency of asynchronous generator is evaluated by the expression:

$$\eta = \frac{P_2}{P_1}\cdot 100 = \left(1 - \frac{\sum p}{P_1}\right)\cdot 100 = \left(1 - \frac{\sum p}{P_2 + \sum p}\right)\cdot 100\% \qquad (5.42)$$

and has value in the range of 70 … 95 %.

5.6. Isolated operation of the asynchronous generator

It was explained above that the asynchronous machine should consume reactive power needed for producing it magnetic field. At isolated operation in generator conditions, to provide supply of asynchronous generator with reactive power and the output voltage adjustment the capacitors X_c and X_{cs} are connected across and in series the stator output terminals (Fig. 5.11). For analysis of operation of synchronous machine in generator conditions is used the same equivalent circuit as for motor. The generator operates at negative slip, the speed of magnetic flux rotation is less than the rotor speed. Magnetic flux of asynchronous generator defining the windings electromotive forces depends on magnetizing *mmf* that equals the sum of the windings emf. Under the generator load variation the magnetic flux and the voltage drop across impedance of the stator winding vary and the output voltage across the stator terminals changes its value. If the generator magnetic circuit is saturated the magnetic flux Φ_m remains almost constant and load variation causes much less changing of output voltage U_1 and external characteristic of asynchronous generator becomes more flat.

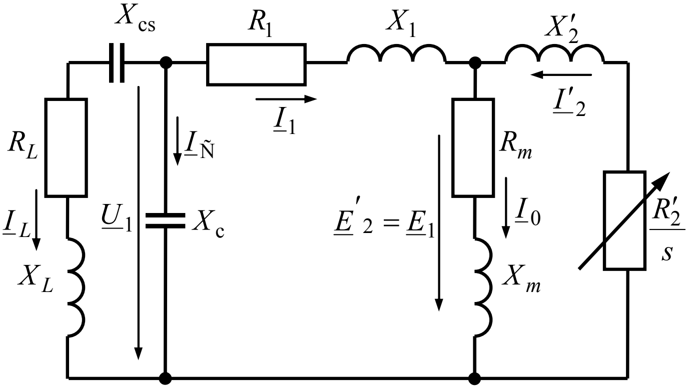


Fig. 5.11 The equivalent circuit of the asynchronous generator

The rotor speed of asynchronous generator is defined by (5.2) and for generator conditions is greater than the rotational speed of the magnetic flux. The reactive power for creation of the magnetic field is supplied by the capacitors connected to output terminals of the stator winding, and the active power is covered on account of input mechanical power delivered to the machine by the drive motor (prime mover) such as diesel engine, hydro-turbine, windmill, etc.

Asynchronous generator can not produce reactive power. Under conditions of isolated operation the capacitor connected across the generator terminals should cover reactive power consumed by the machine to produce magnetic field. In the case of inductive load the consumed by it reactive power must be too delivered by that capacitor (Fig. 5.12).

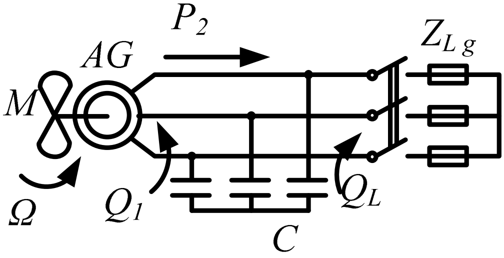
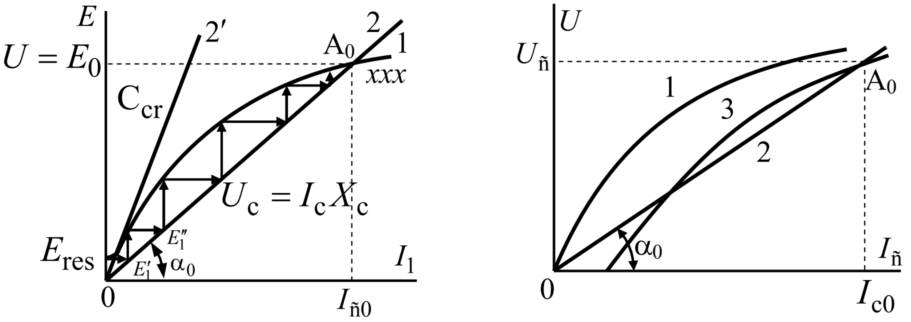


Fig. 5.12 Self-energizing of the isolated asynchronous generator

Self-energizing of asynchronous generator can take place under condition the residual flux Φ_{res} availability. When the rotor is driven by the mover the residual flux induces the voltage in the stator winding $E_{res} = (0{,}02\ldots0{,}03)U_{rated}$ causing the current in the capacitor circuit The current I_c leads the voltage U_1, and the current I_1 is lagging and magnetizes the generator stipulating the flux and the induced voltage increase. The process continue till the induced voltage reaches the value $U_1 = E_0$ that corresponds to the point A_0 of intersection of corves of the machine magnetization characteristic and the capacitor voltage-current characteristic (Fig. 5.12 a). The point A_0 defines steady operation conditions at no-load. The process of self-energizing finishes at no-load with coming the by generator to the steady state with the stator terminal voltage E_0 and the stator current I_{c0}. The generator voltage depends on the condenser capacitance. The more the capacitance is the higher is the voltage across the generator terminals. At small capacitance value C_{cr} the characteristic $I_c X_c$ do not intersect the no-load characteristic, and the generator does not become excited. In some cases the beginning of the process of self-energizing may be initiated by discharge to the winding previously charged capacitor bank.



a) *b*)

Fig. 5.13 Self-energizing of the asynchronous generator from capacitor bank

The angle α_0 is found on the basis of the relation

$$tg\alpha_0 = \frac{U_c}{I_{c0}} = \frac{X_{c0} I_{c0}}{I_{c0}} = X_{c0} = \frac{1}{\omega_1 C_0} \tag{5.43}$$

Self-energizing of asynchronous generator under load requires of the capacitance C increase that is illustrated by Fig. 5.12 b where curve 3 is asynchronous generator load saturation characteristic. The self-energizing finishes at the point A_r. At this

$$tg\alpha_r = \frac{U_c}{I_{cr}} = \frac{X_{cr} \cdot I_{cr}}{I_{cr}} = X_{cr} = \frac{1}{\omega_1 C_r} \tag{5.44}$$

As $tg\alpha_0 > tg\alpha_r$ then $C_r > C_0$. The capacitors reactive power equals total amount of reactive capacity of the generator and the load, that is

$$Q_c = m_1 I_c \cdot U_1 = Q_{gen} + Q_L = P_L \cdot tg\varphi_L + P_{gen} \cdot tg\varphi_{gen} \tag{5.45}$$

The needed capacitance may be found from the relation

$$X_c = \frac{1}{\omega_1 C} = \frac{U}{I_c} = \frac{m_1 U_1^2}{Q_c}$$

or

$$C = \frac{Q_c}{m_1 \omega_1 U_1^2} \qquad (5.46)$$

where $\omega_1 = 2\pi f_1$.

It is understood from the above that the capacitance must be adjusted at load variation. It is also relates to the load power factor variation. In practice electric machines exited with the help of the valve inverters, for example, self-excited voltage inverters, are in use.

5.7. The characteristics of an asynchronous generator operating for isolated load

The operating characteristics are meant relations of the current, power capacity, power factor and efficiency on the parameter depending on load - the slip. For asynchronous generator switched in parallel to network, these characteristics are given in Fig. 5.14.

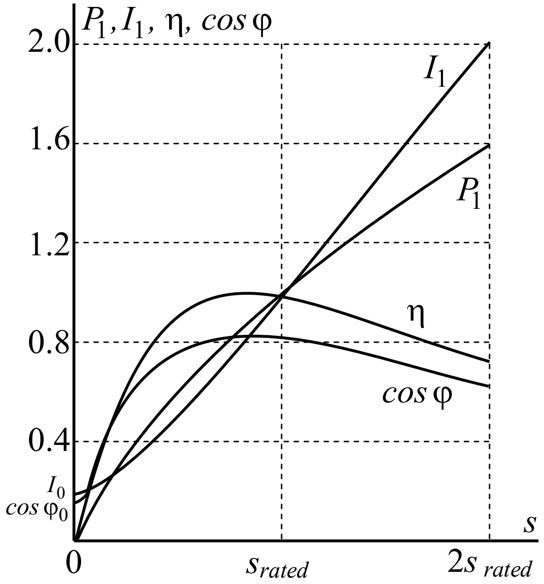


Fig. 5.14 Calculated operating characteristics of an asynchronous generator

The curve $\eta = f(s)$ is typical. The maximum value is obtained at the slip value close to the rated. Farther load increase brings the efficiency decrease.

The no-load power factor is in the range of 0,1…0,2 or some more. The maximum power factor of 0,7…0,85 is obtained at about rated load and at further load increase is falling down. The stator current at no-load, as the power factor, depends on the generator power capacity and pole number. At the slip values till the critical the stator current continuously increase.

The output power depends on the losses ratio.

For independently operating generator the most important is external or voltage regulation (Fig. 5.15 a) and adjustment characteristic (Fig. 5.15 b).

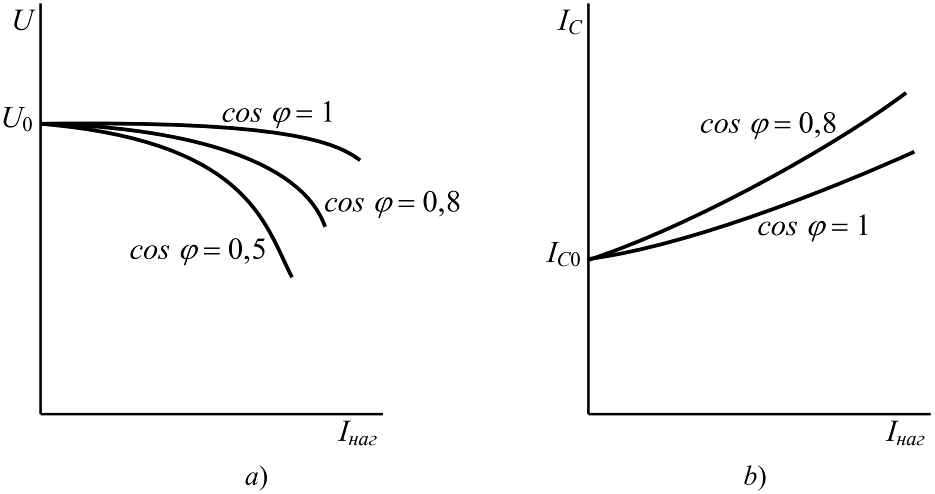


Fig. 5.15 Voltage regulation (*a*) and current adjustment (*b*) characteristics for different power factor values

The external characteristics represent dependence of the output voltage on the output power or the load current at constant values of frequency f_1, rotor speed n, power factor $\cos\varphi_L$ and capacitance C. The current adjustment characteristic represents dependence the capacitor current I_C or it capacitance C against load current I_L at constant values of U_1, f_1, $\cos\varphi_L$ and n.

Four kinds of independent operation conditions of asynchronous generator are possible:

- operation at constant rotational speed ($n = const$, $f_1 = var$)
- operation at stable frequency reached by the speed adjustment ($f_1 = const, n = var$)
- operation at variable n, and the frequency stabilization by means of the generator control
- operation at variable speed n and frequency f_1.

Variation of the frequency f_1 at changing from the no-load to full load is determined by the slip variation and is taken into account at determination of inductive and capacitive reactance of the generator elements which depend on the frequency.

Analysis of asynchronous generator independent operation leads to following conclusions:

- Stability of asynchronous generator voltage and overload capacity may be provided at conditions of great saturation of the generator magnetic circuit (the saturation factor of $k_\mu = 2{,}8\ldots4{,}0$); at minimally achievable resistances and leakage reactance which values in per unit have to be $X_1^* \approx X_2'^* < 0{,}08\ldots0{,}1$ and $R_1^* \approx R_2' = 0{,}01\ldots0{,}03$; at high value of the power factor $\cos\varphi_L$ close to unity.
- Increased saturation of the magnetic circuit has to be obtained by means of the rotor teeth and core saturation at minimum saturation of the stator.
- The needed degree of saturation may be obtained in asynchronous generators at $2p \le 4$. At $2p > 4$ the most saturation factor that may be received is $k_\mu \le 2{,}8$, the generator overload capacity and rated power decrease.
- Higher voltage stability and overload capacity are obtained for a generator with capacitive excitation supplying power to semiconductor rectifier.

5.8 The control of the independently working asynchronous generator frequency and voltage

Stabilizing of the output voltage of asynchronous generator may be carried out by adjustment the capacitance connected to the stator winding or to the wound rotor circuit, use of controlled reactor or non-linear capacitors, variation of the capacitors voltage, biasing the stator core.

For cage-type of asynchronous generators two methods of control are shown below.

The first is a circuit (Fig. 5.16 a) in which reactive power of asynchronous generator is regulated by means of the capacitor bank capacitance variation with the help of power transistor which works or in continuous or in pulse mode.

The method of stator yoke biasing (Fig. 5.16 b) require use for biasing winding placement 25…30 % of the stator slots area for the voltage stabilization in the limits of 0,5…1,25 generator rated power. This method causes distortion of the flux density distribution curve.

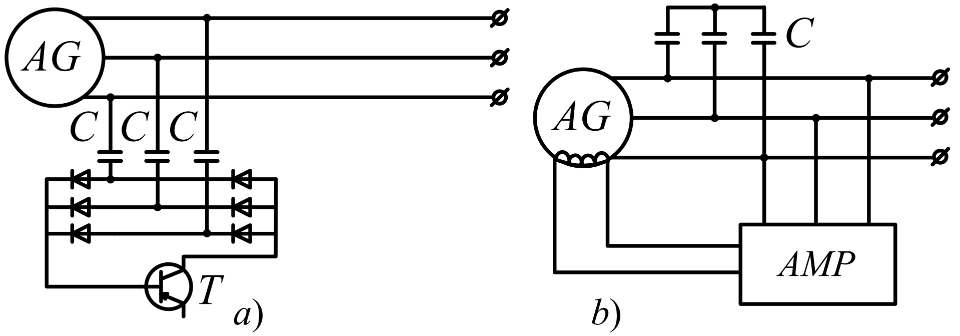


Fig. 5.16 The asynchronous generator control with the use of a power transistor (*a*) and biasing stator yoke (*b*)

One of possible ways of the capacitance regulation is use of non-linear voltage-controlled capacitors - varicaps (Fig. 5.17). The devices detecting the voltage and frequency and those quantities deviations send their signals to the amplifiers A1 and A2. The amplifiers outputs are rectified and applied to the varicaps producing reactive power. The frequency channel effects on the servo-motor SM acting upon the speed regulator.

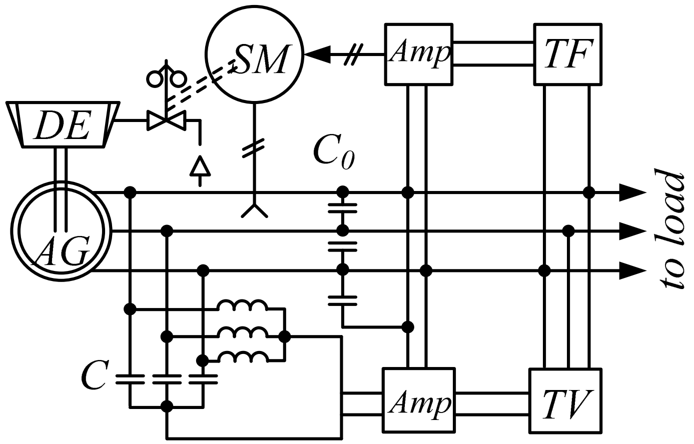


Fig. 5.17 Automatic control of a generator voltage and frequency with the use of voltage-controlled capacitors

Automation of switching the capacitors battery may performed by semiconductor switching elements that are controlled by a computing device and accomplish connection and disconnection of capacitors providing the voltage adjustment (Fig. 5.18)

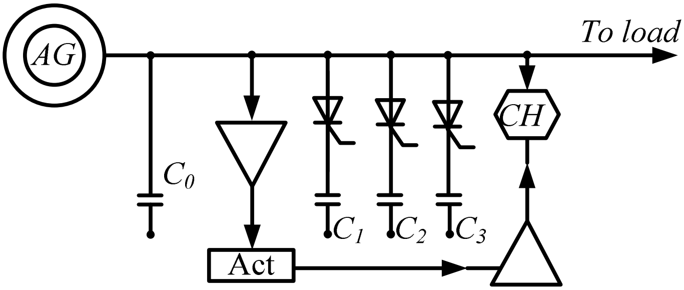


Fig. 5.18 The asynchronous generator automatic control by computer-controlled switching

Reduction of mass and dimensions of the capacitor bank may be achieved with use of a transformer with adjustable transformation ratio (Fig. 5.19). Disadvantages of this method are large dimensions and mass of the transformer at 50 Hz and necessity of the transformer reactive power compensation.

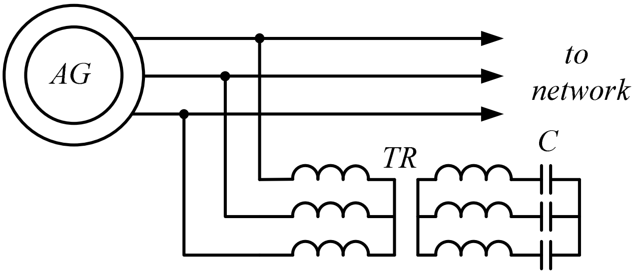


Fig. 5.19 Voltage stabilizing with the use of a regulated transformer

As alternators wound rotor asynchronous machines may be used. The capacitors may be connected either to the stator or to the rotor through slip rings. Decrease of the needed capacitance may be provided by application of a transformer or an autotransformer with adjustable transformation ratio.

Generation of reactive power may be realized with use of inverter exciting system (Fig. 5.20). The storage battery SB voltage is transformed by the inverter I into pulse voltage of the needed frequency providing the generator excitation. After excitation the inverter energizing is carried out by the generator output voltage. The controlled rectifying elements are switched on with leading relatively the instants of the phase voltage curves intersection that under condition of saving the conducting state duration by use of reinforced thyristor switching provides the reactive power for the generator excitation.

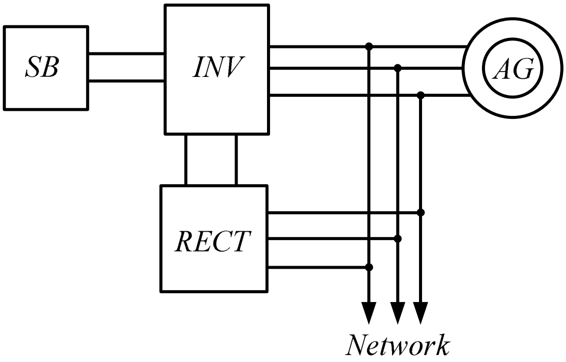


Fig. 5.20 Inverter excitation of the asynchronous generator

Test questions

1. What I called the asynchronous machine?
2. What are advantages and disadvantages of asynchronous machines?
3. What are main constructions of three-phase asynchronous machines?
4. What is difference of cage and wound-rotor asynchronous machine construction?
5. With what speed rotate the stator and rotor mmfs?
6. What is called the slip and what is the relationship between the rotor and synchronous speed?
7. In what limits is the sleep at different operational conditions?
8. What are the sleep values at the machine rotation?
9. To what are the induced voltage in the stator and stationary rotor equal?
10. What is relation between the rotating and stationary rotor induced voltage?
11. How are the stator and rotor leakage reactance determined?
12. Write down the equations for stator and rotor phase winding meshes.
13. What is the asynchronous machine with equivalent stationary rotor?
14. How is the mechanical power determined on the basis of the equivalent stationary rotor circuit analysis?
15. By what equalities are the rotor parameters referred to the stator winding?
16. Write down the equations of asynchronous machine with equivalent stationary rotor referred to the stator winding?
17. Draw up the equivalent circuits of asynchronous machine.
18. Write down the equation of electromagnetic torque of asynchronous machine.
19. Explain the torque-slip and speed-torque curves of asynchronous machine.
20. How are the maximum and starting torques of asynchronous machine determined?

21. What difference between the vector diagrams of asynchronous machine operating as motor and a generator?
22. What difference between synchronous and asynchronous machine conditions of switching on parallel operation?
23. What are advantages of asynchronous generator operating in parallel with a network?
24. Explain the power flow diagram of asynchronous generator.
25. Draw up the equivalent circuit of asynchronous generator supplying independent load.
26. How is reactive power provided at independent operation of asynchronous generator?
27. Explain characteristics of independently operating asynchronous generator.
28. What cases of operation conditions are possible at independent operation of asynchronous generator?
29. At what conditions may stability of asynchronous generator voltage and overload capacity be provided?
30. What methods are used for control of independently working asynchronous generator frequency and voltage?

6. BRUSHLESS ALTERNATORS WITH ELECTROMAGNETIC EXCITATION

6.1. General features of brushless synchronous generators

One of topic questions is designing generators of stable frequency working at varying rotational speed as it takes place at wind power plants. Perspective approach is use of valve synchronous induction generators, inductor-type synchronous machines, double fed electric machines and different cascade generator designs with integrated magnetic systems and windings and also machines with claw-shaped poles which have brushless excitation system without slip rings and brushes.

The contactless excitation system of classical synchronous generators is shown in Fig. 6.1. At the shaft of the synchronous generator, rotors of two additional electric machines of small power, the main exciter and pilot exciter, and the rotating rectifier supplying power to the synchronous machine field winding are mounted. The armature winding of the main generator (GA), the exciter field winding (MEF) and the pilot exciter armature winding (PEA) are located on the stator. On the rotor, the synchronous generator field winding (GF), the main exciter armature winding (MEA), rotating rectifier (RR) and the pilot exciter inductor with permanent magnets (PEI) are disposed.

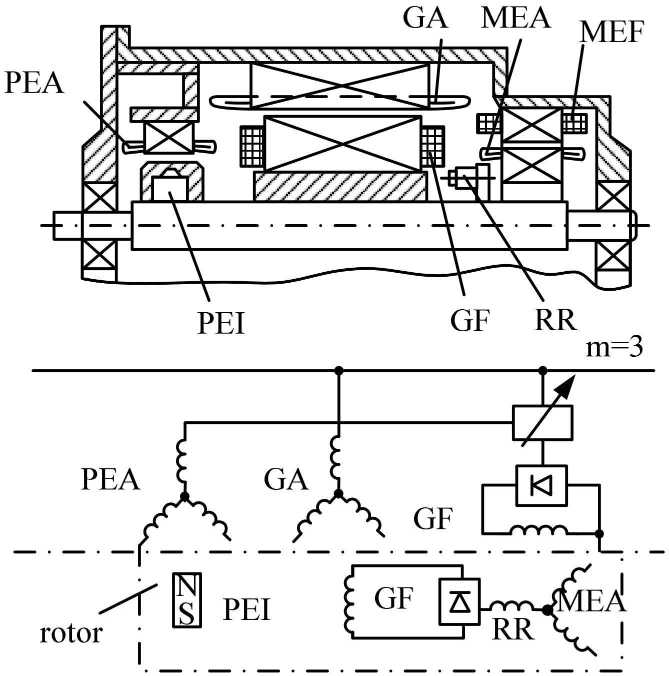


Fig. 6.1 The brushless excitation system of a common type generator

In this way the construction integrates three machines. At the rotor revolution the voltage is induced in the pilot exciter armature winding causing the current that is rectified and supplied to the MEF. The current induced in the MEA being rectified by the RR is supplied to the generator field GF. As the result the voltage is induced in the generator armature. The rectifier has three-phase bridge circuit or sometimes is made as six-phase circuit with neutral point. The rotating rectifier may be arranged inside the hollow shaft.

In smaller brushless generators simpler excitation systems are used. So the generator with claw-shaped poles has no a rotating field winding, and an exciter is not needed. Therefore, reliability of the generator increases. The magnetic flux produced by the stationary field after passing the air gap with the help of claw-shaped poles changes its direction to axial and closes its path through the axial part of magnetic core. This part may be located out of the armature, inside it or as cantilever. Special feature of such generators lies in increased leakage fluxes which may reach of 30 – 50 % of the main flux. On that reason the total flux may be 1.5 times as much as the flux in the air gap, and dimensions and mass of the axial part of magnetic circuit conducting the full flux increase. The output voltage control at its variation caused by the load change is made changing of the field current.

6.2. Inductor alternators

Inductor machine is a machine in which the magnetic flux density in any point of the air gap varies only by magnitude but its direction remains unchanged. So the flux density pulses and includes variable (working) and constant (nonworking) components.

The generator field winding is stationary. Voltage in the stator winding is induced due to its linkage with the pulsing magnetic field that varies periodically because of variation of air gap portions reluctance at rotation of rotor having regular projections.

These machines have simple rotor design possess higher reliability, are well controlled and serviceable at hard climatic conditions such as take place in wind electric power installations.

Principle of an inductor generator operation may be explained with the help of Fig 6.2.To the bore of the magnetic core, the rotor with regular projections is placed. The core has a field winding supplied with direct current. The number of rotor tooth pitches is integer. The stator teeth are semi-closed, their pitch equals a half of the rotor tooth pitch.

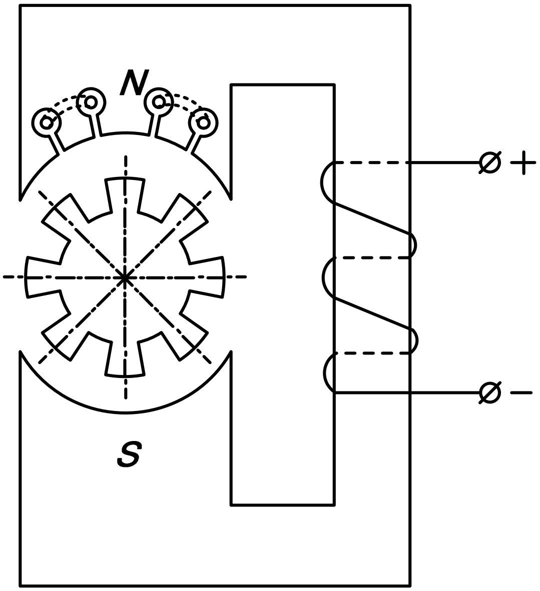


Fig. 6.2 A diagram of the inductor generator

Current of the field winding produces magnetomotive force F_1. It causes the flux $\Phi = \frac{F_1}{R_m}$, where R_m is reluctance of the magnetic circuit equal to sum of the magnetic circuit sections reluctances. At the rotor rotation the magnetic circuit full reluctance is unchanged.

The voltage that may be induced in a coil in consequence of electromagnetic induction is defined by the equation:

$$e = -\frac{d\Phi}{dt} \cdot w, \tag{6.1}$$

where w is the number of turns.

As at every rotor position the reluctance of the total air gap is the same, integer and equal number of teeth and slots is always located under the pole. Hence, at constant *mmf* the magnetic flux penetrating the core cross-section will remain constant. Independently of the rotor position greater flux part will go through the teeth and only insignificant part of it will go through the slots.

In the process of rotor revolution the rotor teeth position will change relatively position of the stator teeth. The flux going through each the stator tooth will vary periodically by magnitude between some maximum value, taking place when under this tooth locates the rotor tooth, and minimum value when rotor slot locates under the stator tooth.

In Fig. 6.3 five positions of the rotor teeth relatively the stator teeth is shown. The stator teeth are filled with turns of the stator winding. The field line distribution in the air gap for every rotor position is given.

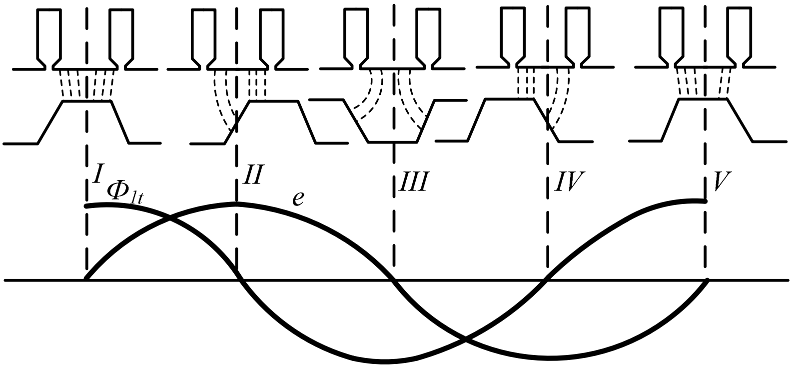


Fig. 6.3 Positions of rotor and stator teeth

In position I the flux linked with the winding coil is maximal. During the rotor movement it decreases and reaches minimal value in position III. Then the flux linked with the coil begins to increase and in position V have maximal value again. Further the process continues in the same order. So the flux linked with the winding varies periodically between maximum and minimum values, and alternating voltage is induced in the winding.

It is expedient to note that voltage is induced in the winding at the linked flux variation independently of the reason of its variation. Such a reason may be movement of winding coils relatively the field or movement of magnetic field relatively the winding or changing the magnetic field direction or variation the magnetic flux by any other reason.

By character of magnetic field produced by the field winding the inductor generators are divided homopolar and heteropolar types. The main distinctive feature of induction machines is availability of ferromagnetic rotor with explicit teeth and slots.

In homopolar generators (Fig. 6.4) the field winding of ring type is used. It produces axial magnetic flux. The stator core 1 may have one (Fig. 6.4 a) or two (Fig. 6.4 b) core stacks. The stator winding 2 is placed into the stator slots. The yoke 3, flange 5 and rotor bush 6 are manufactured of magnetically soft steel and are parts of the machine magnetic system. The field winding coil 4 is placed on the stator. The rotor and stator cores having teeth are assembled of electrical steel laminations.

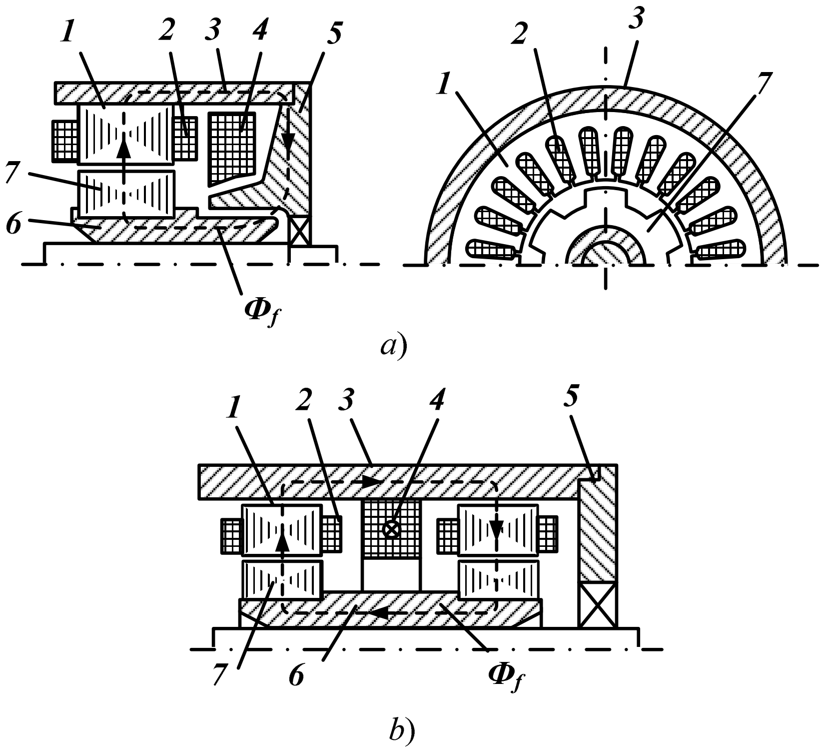


Fig. 6.4 The homopolar inductor synchronous generator: *a* – single stack core, b – two stack core

Feeding the field winding with direct current, homopolar magnetic flux Φ_f in the air gap is obtained. Its major part passes the rotor teeth and minimal gap δ_{min}, and the less part – the slots and maximal gap $\delta_{\max}$. During the rotor revolution the magnetic flux density varies between $B_{\min}$ and $B_{\max}$ at any point of the air gap. The period duration of the flux density variation corresponds with turning the rotor by one tooth pitch $t_{z_r} = \pi D / z_r$. Therefore the number of pole pairs in such a machine may be assumed equal to the number of rotor teeth $P = z_r$.

If the stator winding has the pitch equal to

$$y = \tau_1 = t_{z_r} / 2 \tag{6.2}$$

the frequency of the voltage induced in it at the rotor (inductor) angular speed Ω_r is

$$f = z_r \cdot \Omega_r / 2\pi \qquad (6.3)$$

In a generator with two stack stator core the magnetic flux passes the stator 1 and rotor 7 cores twice successively, so being used twice. Flanges 5 are made, in this case, from constructional non-magnetic material. To obtain the voltage close to sinusoidal skew of the inductor slots by 0,5…0,7 of stator slot pitch is provided.

Construction of heteropolar inductor generator is shown in Fig. 6.5. Part of stator 1 slots that is filled with the field coils 2 is made of greater size. To small slots the armature winding 3 is placed. The rotor core 4 having teeth is always made laminated. The field winding produces heteropolar magnetic field in the air gap. To provide the magnetic flux linked with the field winding constant, at the ark of the stator bore between the large slots integer number of rotor tooth pitches find room. Otherwise, the pulsing flux will induce voltage in the field winding causing additional loss, and the output voltage curve will be distorted. The magnetic field distribution at the arc portion between the large slots is the same that in the homopolar machine. The frequency of voltage induced in the armature winding does not depend on the field winding and determined by the rotor teeth number and the rotational frequency.

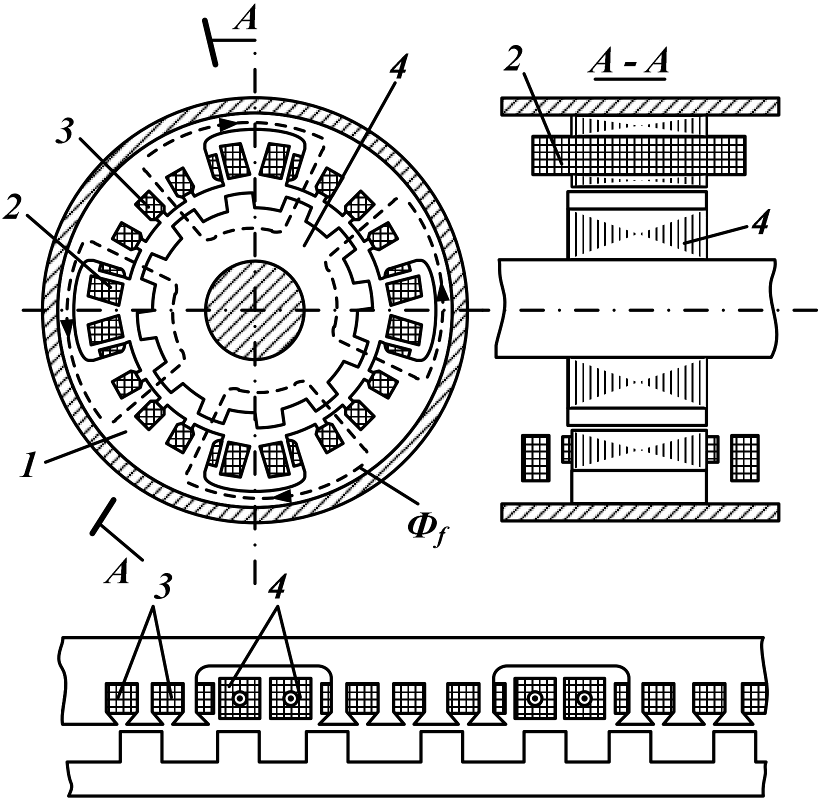


Fig. 6.5 The heteropolar inductor generator

For improvement of the voltage curve form ad obtaining minimal size of stator teeth, short fractional pitch armature windings with $q = z_s/(2pm_1)$ are applied for inductor generators. The pole pitch is determined by the rotor teeth number: $\tau_1 = \pi D/2p = \pi D/z_r$.

Spatial distribution of the flux density and the flux produced by the field *mmf* for homopolar induction generator are defined by the relations:

$$B_{\delta f} = B_{f0} + B_{fr}\cos(z_r\alpha - z_r\Omega_r t) \tag{6.4}$$

$$\Phi_{f\tau} = B_{f0}l\tau_1 + \frac{2}{\pi}B_{fr}l\tau_1\cos(\Omega_r z_r t) = \Phi_{f0} + \Phi_{fr}\cos\omega_1 t \tag{6.5}$$

where $\alpha = \frac{\pi x}{\tau_1 z_r}$, τ_1 is the pole pitch, l is the active conductor length, Ω_r is angular speed, z_r is the number of rotor teeth, Φ_{f0} and B_{f0} are constant components of the flux and flux density, Φ_{fr} and B_{fr} are harmonics of the flux and flux density caused by teeth structure of the core.

The voltage induced by fundamental flux component is

$$e_0 = \sqrt{2} E_0 \cdot \sin \omega_1 t \tag{6.6}$$

where $E_0 = 4.44 f_1 w_1 k_{w1} \Phi_{fr}$ is *rms* value at no-load.

The magnetic flux zero-frequency component Φ_{f0} does not participate in producing the voltage e_0. But it increases the total flux worsening use of magnetic material. The efficiency of the magnetic flux of synchronous inductor generator utilization is assessed with the help of utilization factor

$$k_{ut} = \Phi_{fr} / 2\Phi_{f0} = B_{fr} / (\pi B_{f0}) \tag{6.7}$$

which has value of $k_{ut} < 0,5$ for existing machines. This means that at the same voltage and power capacity an inductor generator should have larger magnetic system and hence larger dimensions and mass than conventional synchronous generator.

The maximal flux passing the rotor teeth equals

$$\Phi_{f\max} = \Phi_{f0} + \Phi_{fr} \tag{6.8}$$

and the tooth minimal flux is

$$\Phi_{f\min} = \Phi_{f0} - \Phi_{fr} \tag{6.9}$$

Magnetization characteristics for the portions of teeth and slots differ (Fig. 6.6).

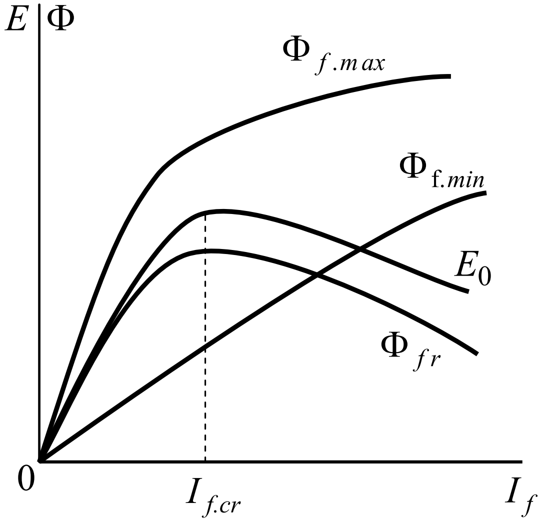


Fig. 6.6 Magnetization and no-load characteristics of the synchronous inductor generator

Difference of these characteristics ordinates equals

$$\Phi_{fk} = 0{,}5\left(\Phi_{f\max} - \Phi_{f\min}\right) \tag{6.10}$$

and it is proportional to variable part of the flux.

At increase of the field current the steel saturates, and the flux Φ_{fr} reduces. According to the curve $\Phi_{fr} = f\left(I_f\right)$ the no-load characteristic $E_0 = f\left(I_f\right)$ is plotted. If the field current exceeds the critical value $I_{f\,cr}$, the induced voltage decreases. Remember that in conventional synchronous generators increase of the field current always causes the voltage increase. The indicated feature worsens regulating properties of inductor generators. To widen the range of the voltage control the inductor generator magnetic system is made low saturated increasing its dimensions.

At balanced load the armature currents produce the armature magnetomotive force rotating at synchronous speed:

$$F_1 = F_{1m}\cos\left(z_r\alpha - w_1 t - \beta\right) \tag{6.11}$$

where β is the phase displacement between the no-load voltage E_0 and the current.

As for conventional generator this *mmf* is divided in the direct-axis and the quadrature-axis components:

$$F_{d_1} = F_{d_{1m}} \cos\left(z_r\alpha - \omega_1 t\right) \tag{6.12}$$

$$F_{q_1} = F_{q_{1m}} \sin\left(z_r\alpha - \omega_1 t\right) \tag{6.13}$$

where $F_{d_{1m}} = F_{1m} \sin\beta$, $F_{q_{1m}} = F_{1m} \cos\beta$.

The magnetic flux density components are determined by equalities

$$B_{ad_{1m}} = \lambda_{ad_1} F_{d_{1m}}, \; B_{aq_{1m}} = \lambda_{aq_1} F_{q_{1m}} \tag{6.14}$$

where λ_{ad_1}, λ_{aq_1} are values of specific permeance by the direct and the quadrature axes.

The armature reaction induced voltage:

$$E_{ad_1} = \pi\sqrt{2} f_1 \omega_1 k_{\omega 1} \tau_1 l B_{ad_{1m}}, \tag{6.15}$$

$$E_{aq_1} = \pi\sqrt{2} f_1 \omega_1 k_{\omega 1} \tau_1 l B_{aq_{1m}} \tag{6.16}$$

and relevant reactance

$$X_{ad} = E_{ad_1} / I_d, \; X_{aq} = E_{aq_1} / I_q \tag{6.17}$$

Resistance and leakage reactance of the armature winding is calculated as for conventional alternating current machines. Using the machine parameters the vector diagram of voltage and current and characteristics of an inductor generator may be calculated and plotted. The inductor generators have less flatted characteristics than conventional types, and to stabilize their voltage it is necessary to vary the field current in wider range. To flatten the external voltage-current characteristic capacitive compensation by connection capacitor across the machine terminals is sometimes used.

The magnetic fields produced by excitation and armature windings of an inductor generator may contain as odd as even harmonics. The even harmonics are removed by taking the armature winding pitch close to the pole pitch and fractional number of slots per pole and per phase with odd denominator. The excitation winding field odd harmonics induce the same harmonics in the armature, cause distortion of the output voltage and current curves and additional power loss. The odd harmonics of the armature field are taken into account as in conventional machines with the help of the leakage reactance.

6.3. Synchronous generators with claw-shaped poles.

Synchronous machines with claw-shaped poles distinguish from the conventional machines by construction of inductor magnetic circuit and the field winding. The rotor magnetic core consists of three parts (Fig.6.7): back core 2, disc 1 with claw-shaped projections forming north poles, disk 3 with claw-shaped projections forming south poles. The ring shaped field winding 4 locates between the discs 1 and 3 with projecting poles and is supplied from exciter trough slip rings. The magnetic lines of flux coming out of the north poles cross the air gap then pass the armature core linking with the armature winding, cross the air gap again and return into the rotor north poles. These lines represent the magnetic flux of mutual inductance.

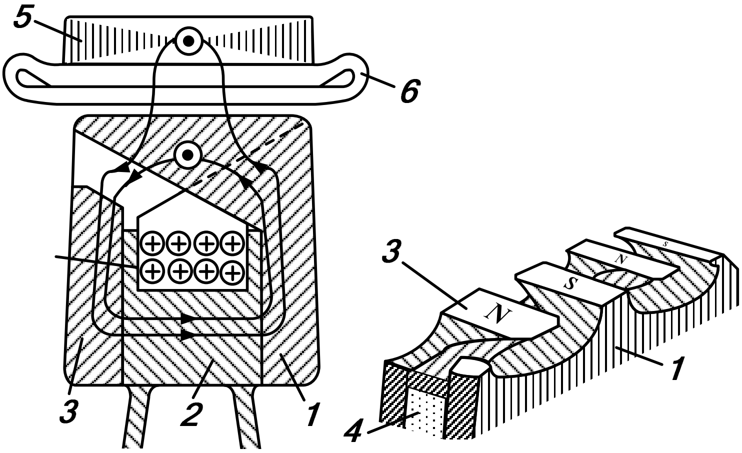


Fig. 6.7 The synchronous generator with claw-shaped poles

The magnetic lines of leakage flux being smaller part of the machine magnetic field cross the space between the poles without linking with the armature winding.

Such a construction is used only for small machines. More acceptable are claw-shaped machines with stationary field winding which current supply does not need sliding contact and brushes. Nowadays there are many different constructions of claw-pole machines, which can be divided into three groups: machines with claw-shaped armature, machines with claw-shaped inductor and machines which both members - armature and inductor, are claw-shaped.

Claw shaped poles are also used in machines with external closing the magnetic flux and with frontal parts disposition.

The frontal machines are made as inductor machines of two types: with heteropolar pole systems placed at both sides of frontal armature and with concentric armature and field winding.

The machines with external poles are divided into machines with

- external field coil that is co-axial to the armature and may be or rotating or stationary,
- inner field coils placed at sides of armature core,
- lateral field coil and alternate poles of unequal length.

The numerous by construction types are machines with inner claw-shaped inductor. They are divided to machines with inner and external core.

The machines with inner core may have field system on the rotor that revolves with it, and with stationary field system.

Inductor placed on the rotor, depending on type of excitation may be:

- with electromagnetic excitation provided by rotating field winding (with single and multiple claw-shaped pole system),
- with excitation by cylindrical permanent magnet (there are similar as above variations),
- with compound system provided by permanent magnet and additional winding (the same variations).

Machines with external core may be divided in two basic modifications – with electromagnetic and compound excitation. Systems with electromagnetic excitation may be designed so that the flux is repeatedly used and may have claw-shaped inductor. The machines with compound excitation may have one-sided and bilateral disposition of the field winding. in the last case the permanent magnet may of cylindrical or star shaped.

A brushless synchronous generator with claw-shaped poles and inner closing the magnetic flux path is given in Fig. 6.8. Its rotor is shown in Fig. 6.9.

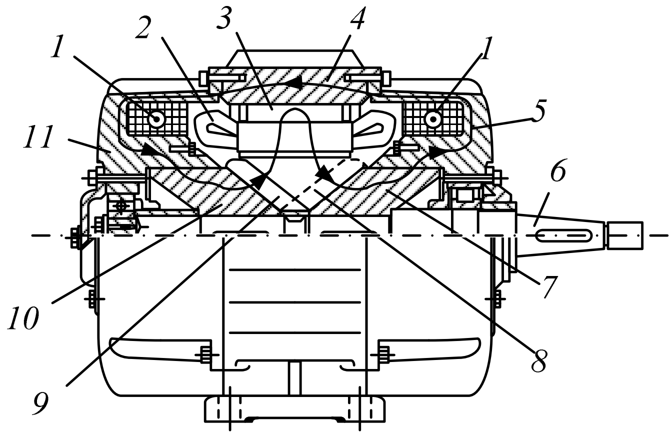


Fig. 6.8 Brushless synchronous generator with external magnetic flux closing

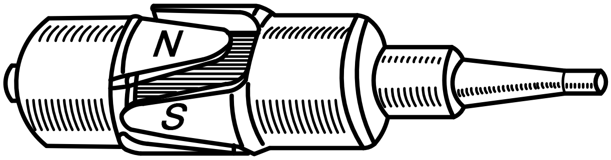


Fig. 6.9 The claw-shaped rotor of a brushless synchronous generator

The field winding consists of two stationary ring-shaped coils 1 that are placed in deepening's of the shield ends 5, 11. Lines of the principal magnetic flux produced by these coils currents close by the path including the north poles 9, the air gap, the armature 3 core teeth, the armature core, the air gap one more time, the south poles 8, the back core of the south poles 7, the gap between the core 7 and the shield end 5, the shield end 5, the yoke 4, the shield end 11, the gap between the shield 11 the back core 10 of the north poles, the core 10, and the north pole again. The flux of the field winding, excluding the leakage flux, is linked with the armature winding. At the shaft 6 together with the pole cores 7, 10 and the poles 8, 9 the flux linkage of the armature winding varies periodically and the voltage is induced in it.

Such brushless generators may have advantages at their use as wind generators when maintenance of remote units is difficult and at the same time high service reliability is required.

Constructional scheme of the brushless synchronous generator of Secsin type is shown in Fig. 6.10.

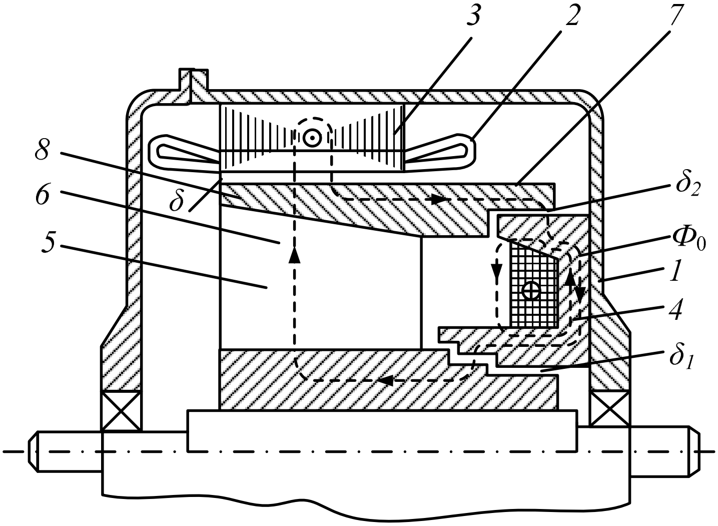


Fig. 6.10 A brushless generator with inner flux

The direct current field winding 1 and the armature winding 2 are located on the stator. The armature winding is inserted to the armature laminated core 3. The inner core 4 abuts the field winding. The rotor has central steel bush 5 with radial projections 6, and cylinder 7 with axial projections (claws) 8 which are located between the projections 6. The bush 5, protions 6 and cylinder7 with claws 8 are made of magnetically soft steel. The space between the projections 6 and claws 8 is casted with non-magnetic alloy 9. All the electric elements of the brushless generator are placed on the stator, and the rotor is just mechanical element.

The magnetic flux Φ_0 produced by the winding 1 close by the path with minimal magnitude of air gap: inner core 4, additional air gap δ_1, rotor bush 5, projections 6, the working gap δ, stator with the armature winding 3, the air gap δ, the claws 8, the cylinder 7, the additional gap δ_2, the clamp 4.

As it is understood the projections 6 and the claws 8 have opposite magnetic polarity relatively the armature. In Fig The projection 6 are the north poles because the flux starts from them, and the claws 8 are the south poles as the flux enters them.

At rotation the flux Φ_0 in the core 3 rotates and induces the voltage in the armature winding 2. Besides the leakage flux Φ_l not linked with the winding 2 exists.

The generator frame is not a part of magnetic circuit and may be manufactured of light metallic alloy. The field winding has small diameter, therefore its mass and loss in it are little. Generators with inner flux are lighter and more compact than generators with external flux.

Often generators with inner closing of the flux have two-sided excitation system, so as generators with external flux closing. Generators with inner flux have considerable leakage flux. The leakage factor is about 1,5…1,6. Magnetic flux density under poles may differ essentially that causes that the magnetic field becomes unbalanced in relation to the armature winding, and the generator external (regulation) characteristic acquire great slope that makes the generator voltage stabilization more difficult.

In brushless generators with frontal disposition the claw-shaped pole projections are radial and are separated from frontal armature with axial air gap. One of designs is given in Fig. 6.11 a. The armature winding is imbedded to radial slots at frontal steel ring-type core surface 2. The slots are milled after the core wounding or are punched in the process of wounding. The frontal armature view is shown in Fig. 6.11 b. The ring-type field winding 5 is fixed in the frame 6 made of magnetically soft steel. The rotor has the steel bush 7 with radial pole projections forming the inner star-like construction. Between the poles 8 are the inside directed poles of exterior star bounded with steel rim 4.The inner and exterior stars are joint with welded insertion of non-magnetic steel or casted of non-magnetic alloy. The main magnetic flux produced by the winding 5 passes the following path: The frame 6 – additional air gap δ_1 between the frame and the rotor – the bush 7 – the poles 8 – the main air gap δ – the armature – the air gap δ – the poles 3 – the additional air gap δ_2 between the rim and the frame – the frame 6. So the poles 3 and 8 acquire opposite polarity relative the armature.

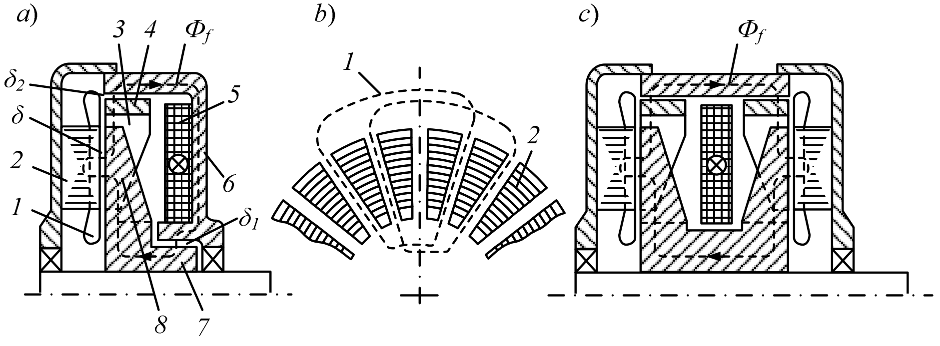


Fig. 6.11 Frontal single-package (a, b) and two package brushless machines

The frontal two package brushless synchronous machine (Fig. 6.11 c) has better flux utilization and less specific mass. In it one more armature and the rotor pole system is placed instead of the side part 6 of the frame. Such a machine is symmetrical relatively the middle cross-section and less number of additional air gaps.

At considerable power capacity, from hundreds to thousands kVA, two-package frontal brushless construction with internal armatures may be applied (Fig. 6.12).

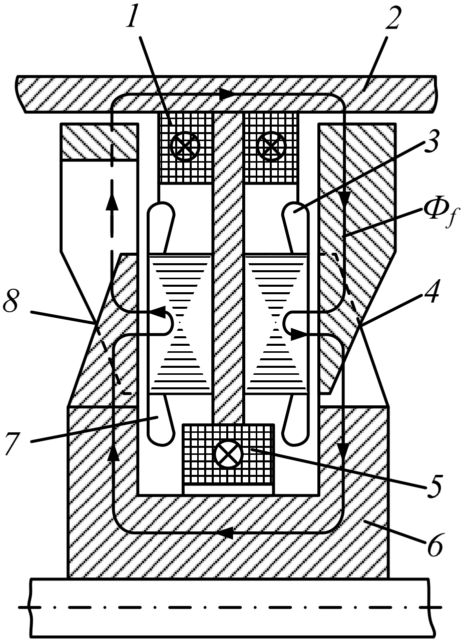


Fig. 6.12 Frontal brushless two-package machine with internal armatures

The flux is produced by two concentric field windings 1 and 5. Between them two armature packages with the windings 3 and 7 are placed. To them, two pole systems 4 and 5 each consisting of internal and external stars, as in the machine by Fig. 6.11, abut. The external frame 2, placed between the rotor pole systems, and the bush 6 are made of magnetically soft steel. The main magnetic flux Φ_f path, wrapping both field windings with aiding current directions is shown in the figure.

Frontal brushless synchronous generators have considerable advantages. Firstly, they have short rigid rotor with continuous external rim and radially oriented pole projections. Therefore, the rotor toughness is high, and the claw-shaped projections are not subjected to bending strains at their rotation. Secondly, the lines of magnetic flux have relatively not large length. Therefore, such machines have specific mass about 1,5…2 times as less, as the machines with externally closing magnetic flux, their specific mass is near to conventional synchronous machines. Third, field windings of frontal machines take comparatively small volume and cause small power loss. Fourth, possibility of placing windings at periphery is favorable for intensive cooling of frontal synchronous machines including good conditions of self-cooling.

Disadvantages of frontal synchronous machines consist in possible imbalance of magnetic stress forces, especially in single-package constructions, and necessity of using in many cases combined journal and thrust bearings, in increased moment of rotor inertia, and in non-uniform distribution of the magnetic field by radius due to unsymmetrical leakage fluxes at internal and external cylindrical surfaces of the armature.

6.4. Brushless synchronous generators with a disc-type rotor

In synchronous generators with claw-shaped rotor the cross-section of a pole projection should provide conduction of magnetic flux following from the collecting bush to radial pole part that causes necessity to avoid undue increase of flux density in axial parts of the magnetic circuit by taking proper geometrical dimensions of the machine active area. Availability of heavy external steel frame, that is a part of the magnetic circuit, and considerable leakage fluxes are also disadvantage of these machines.

The indicated disadvantages are not available at brushless synchronous machine with disc-type rotor. Such a machine (Fig. 6.13) consists of the stator 1 having stationary core 2 with toroidal field winding 3, armature units 4 – 8, and disc-type rotor 9. The disc-type rotor have main disc – distributor of magnetic flux and intermediate disc-type rotors 11 and 12 rigidly mounted on the shaft 13. Frontal end shields 14 and 15 are stationary non-magnetic discs in which the bearings 16 and 17 are mounted. The end shields 14 and 15 are joined by longitudinal bars 18, forming the machine frame.

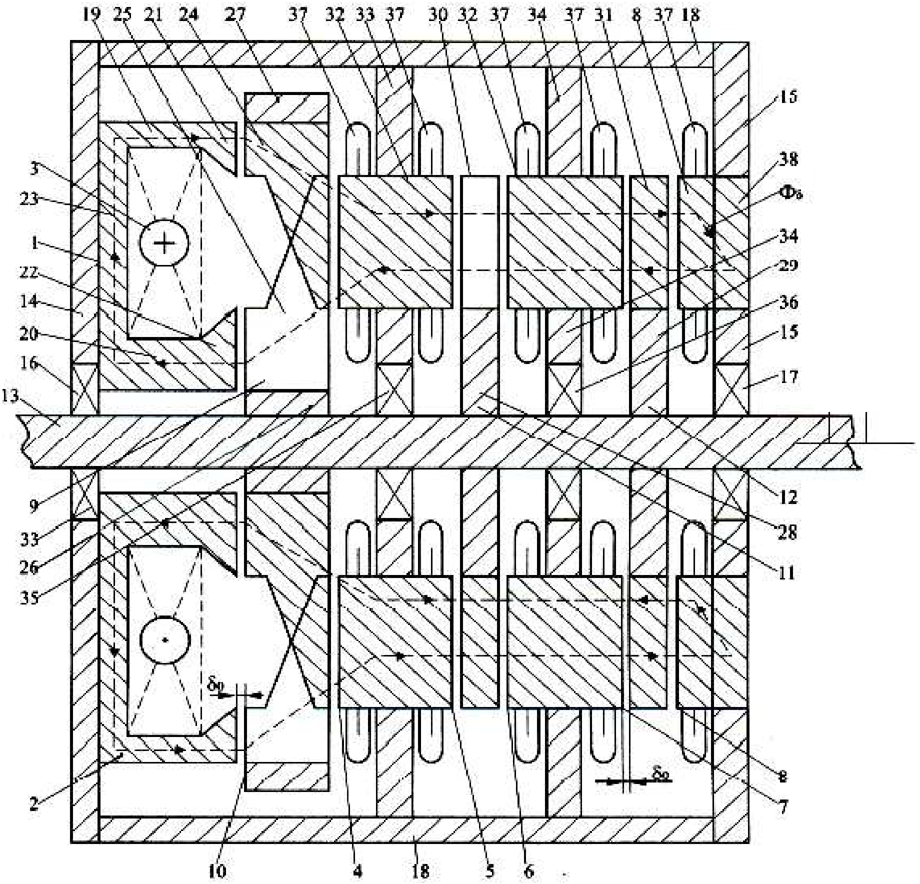


Fig. 6.13 A brushless synchronous machine with a disc-type rotor

The stationary core 2 consists of external 19 and internal 20 cylindrical ferromagnetic tubes with pole shoes 21 and 23 joint by common ferromagnetic base in the form of round ring which is the poles yoke. In the space between the tubes 19 and 20 the toroidal field coil 3 is placed.

The stationary core 2 is rigidly fixed to the shield 14. Between the pole shoes 21, 23 and p claw-shaped poles 24 and 25 there is additional air gap δ_0.These poles are joint by external 27 and internal 26 non-magnetic discs. The disc 26 is fixed on the shaft. System of poles 24 and 25 constitutes the disc distributor 10. Each of the intermediate discs 11 and 12 consists of non-magnetic discs 28 and 29 carrying $2p$ ferromagnetic poles 30 and 31, each of the poles is made as a part of a round ring. The non-magnetic rings 29 and 29 are fixed on the shaft, and together with the disc distributor 10 represent the disc-type rotor 9.

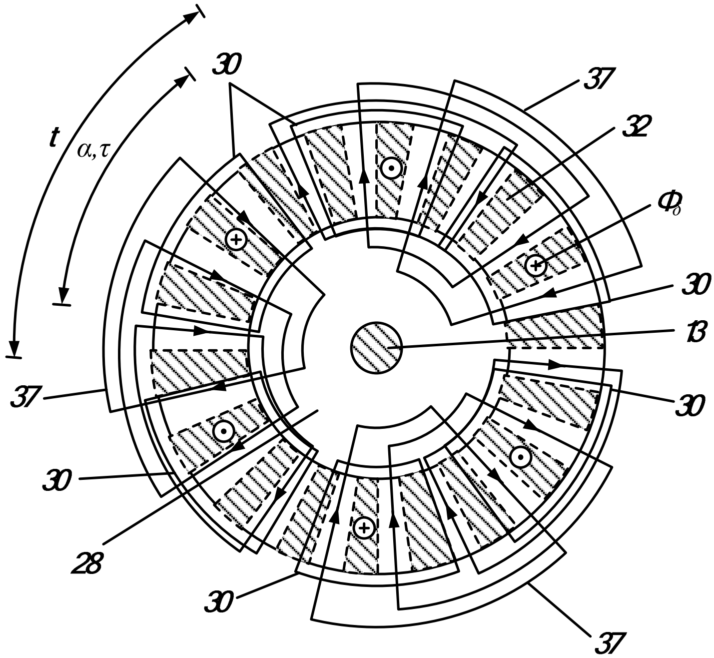


Fig. 6.14 The path of the magnetic flux

The path of the magnetic flux is shown for a pair of the disc rotor poles. The armature units 4 – 8 have the same construction and contain ferromagnetic not connected magnetically bar teeth 32 mounted on the non-magnetic discs 33, 34 and 15 which are set on the bearings 35, 36 and 17.

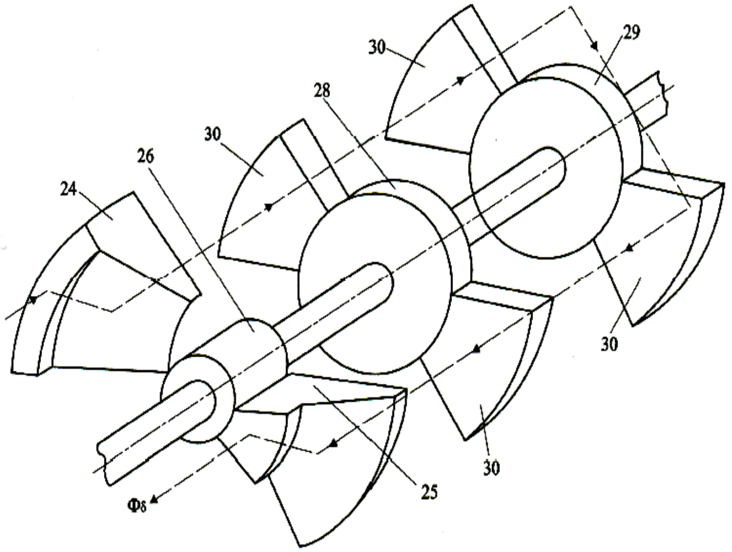


Fig. 6.15 The elements of the disc-type rotor

Between the bar teeth 32 (Fig. 6.14) of each armature unit, the armature winding coils 37 are inserted. Elements of the disc rotor 9 are separated from the armature units by working air gaps δ_1.

6.5. The brushless generator with combined winding

Brushless cascade generator with combined winding there are armature and field windings with different number of poles. The windings are placed on the stator and can not move relatively one another. Electromagnetic coupling of the windings is realized via a closed winding set on the rotor. At this the armature and field windings may be integrated into one combined winding that makes easier its manufacturing, decrease consumption of the wire and increase the generator efficiency. The principle of integration of windings and the generator and exciter magnetic fields in one mutual magnetic system permits to get a self-contained machine.

The combined $2p_1/2p_2$ pole winding, where $2p_1$ is the number of poles produced by three-phase alternating current, and $2p_2$ is the number of poles of the field produced by the field current, has high winding factor for the field with $2p_2$ poles. This field is distributed around the air gap circle by sine law. The winding circuit is formed as two sub-circuits each connected by star. One of the stars is formed by the groups of coils of two phases producing odd pole pairs and the groups of coils of the third phase producing even pole pairs. The second star is formed by the remaining groups of coils. Special feature of the combined winding is placing the end windings of one of the phases in the direction opposite the direction of placing the end windings of two other phases. The null points of the stars are used to supply the field current. So the winding includes a tree-phase winding with number of pole equal to $2p_1$ and a single-phase winding with number of poles equal to $2p_2$ integrated in one thee-single-phase winding (Fig. 6.16).

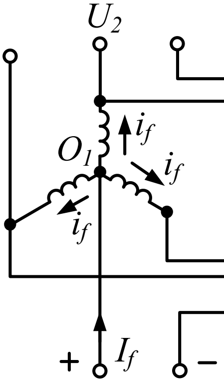


Fig. 6.16 The circuit of the combined winding

According to the accepted rule, the number of pole pairs p_1 and p_2 of the combined three-single-phase winding should be in relation $0{,}5p_1 < p_2 < 1{,}5p_1$. The combined winding with $2p_1 = 8$, $2p_2 = 12$, $(p_2 = 1{,}5p_1)$ and $q_1 = 0{,}5$ is shown in Fig. 6.17. The coil pitch is $y = \frac{2}{3}\tau$, and the number of teeth on the core surface is $z_1 = 2p_2 = 12$.

Each the phase includes $p_1 = 4$ coils and have two or p_1 parallel paths. They form two three-phase stars with two zero points, one of which obtained by connection the final points of odd paths of two extreme phases, and the final points of even Paths of the middle phase, and the other – by connection of final points of all remaining parallel paths.

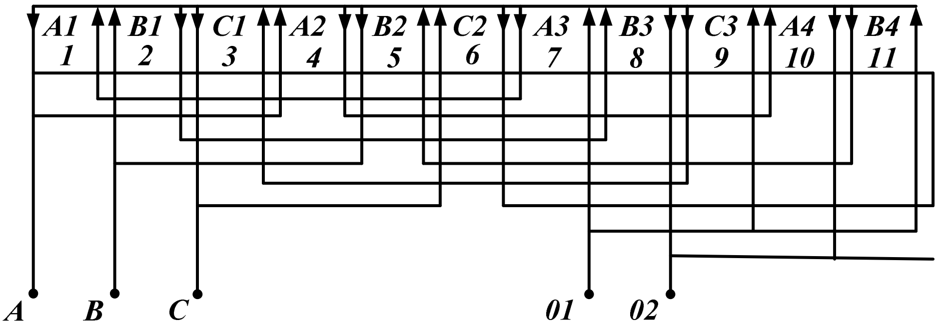


Fig. 6.17 Combined stator three-single-phase winding

If phases have two parallel paths, the odd parallel path includes the odd coils n and $n+6$, and the even path – the coils $n+3$ and $n+9$, where n is number of the coil with which the phase begins. At input of the field current to the zero points as it is indicated by arrows in Fig 6.16, the stationary exciting magnetic field with $2p_2=12$ poles is produced.

In Fig. 6.18, a there is the rotor winding with $2p_1=8$ poles. Figure 6.18, b gives the rotor excitation field distribution with $2p_1$ and exciter field with $2p_2$. The rotor winding consists of separate pole coils. Each of them is placed at its pole and is closed through a diode which connects the coil start and finish leads being connected in conducting or inverse direction depending on the magnetic pole polarity.

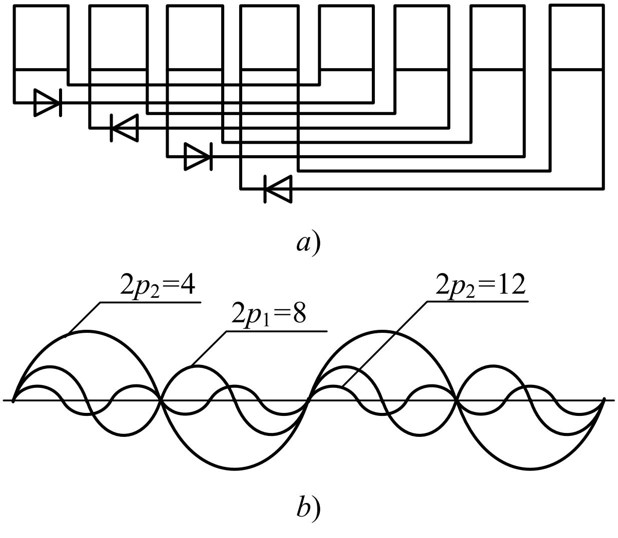


Fig. 6.18 Eight-pole rotor winding

In separately taken winding the voltage is induced by $2p_2$-pole exciting magnetic field. In Fig. 6.18, b two $2p_2$-pole fields produced by exciter field windings located at the stator for $2p_2 = 4$ and $2p_2 = 12$. The number of rotor poles equals the rotor teeth number. As at $2p_1$-pole rotor winding, each n^{th} and $(n+4)^{th}$ winding coils produce poles of the same polarity, and voltages induced in them by the exciter field with $2p = 4$ or $2p = 12$ poles are in phase, these windings may be united mutually to reduce number of diodes.

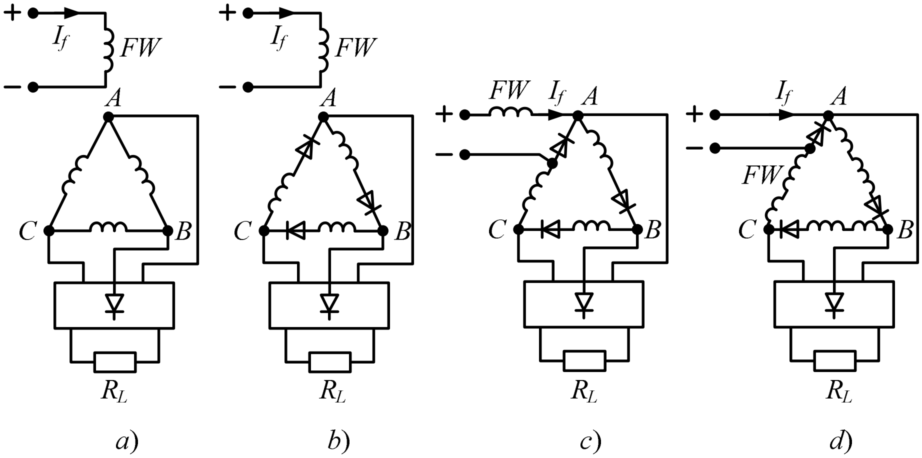


Fig. 6.19 Connections of armature and field windings of the inductor brushless synchronous generator

Different connections armature phases and field winding are given in Fig. 6.19. In Fig. 6.19, a the armature winding is connected by delta and supplies the load R_l through a full-wave rectifier. The same generator with diodes connected in series to each armature winding phase (Fig. 6.19, b) provides flowing through the armature winding at load not alternating but half-wave rectified current and its *mmf* to be directed in accordance with the field winding *mmf*. In the next circuit (Fig. 6,19, c) the field winding is connected in series with the armature winding. The field current flows as through the field as the armature winding. In Fig. 6.19,d represents circuit of heteropolar inductor generator with combined winding Each the field coil is connected in series and in accordance with the armature coil placed at the same tooth.

Test questions

1. Explain the brushless excitation system of a common-type synchronous generator.
2. Explain the principle of inductor-type generator.
3. What is construction of homopolar inductor synchronous generator?
4. What is construction of heteropolar inductor synchronous generator?
5. Explain characteristics of inductor generators.
6. What is synchronous generator with claw-shaped poles?
7. What types of claw-shaped poles generators construction do exist?
8. Explain construction of the disc-type brushless synchronous generator.
9. Explain the principle of brushless generator with combined winding.

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