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Development of double-layer rotors for asynchronous drives of mining and transport machines

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Abstract

Due to the simplicity of the design and high energy indicators, asynchronous electric motors (AM) are the main consumers in the power supply systems of mining enterprises. Large starting currents of motors lead to heating and damage to the insulation of the stator windings. An urgent problem to improve the reliability of mining and transport machines is the development of AM, providing smooth transients with increased starting torque and reduced starting current.

In an AM with a closed-loop rotor, a magnetic conductor is performed by a charged cylinder on the rotor shaft, which is made of electrotechnical steel with high magnetic permeability. The electrical conductor is often a squirrel cage-type short-circuited rotor made of a material with high specific conductivity. A technology has been developed for producing ferro-copper alloys for the active outer cylinder of a double-layer rotor, replacing a "squirrel cage". These alloys combine the properties of an electric current conductor and a magnetic flux. This allows us to obtain the effect of displacement and reduction of current in the rotor, which is accompanied by an increase in the effective resistance of the rotor and the electromagnetic torque during the start-up process.

Full-scale experiments have been carried out with asynchronous motors with various rotors having a displacement effect. Motors having double-cage or deep-groove rotors develop an increased starting torque at a relatively lower starting current. The starting quality of these motors is, on average, 1,5 times higher than that of a motor without current displacement. Replacing a double-cage rotor with a double-layer rotor leads to a decrease in the starting current by 25% and an increase in the starting torque by an average of 2,5 times. The quality factor of starting an asynchronous motor with a double-layer rotor is 3-4 times higher than the quality factor of starting similar motors with a conventional rotor cage without current displacement, 2-2,5 times compared with a double cage or a deep groove and 1,3-1,5 times compared with a rotor with a high electrical resistivity.

The use of double-layer rotors limits voltage fluctuations in the network, ensures a reliable, smooth start, eliminates vibration and extends the service life of all equipment.

Keywords

Asynchronous motor; double-layer rotor; displacement effect; iron-copper alloy; electromagnetic properties, performance characteristics.

Introduction

AM are widely used in most underground mining and transport machines electric drives - tunnelling and cleaning combines, conveyors, loading machines, and mine lifting mechanisms (Kovanič et al., 2020; Kovanič et al., 2021; Lyakhomsky et al., 2007; Tulin, 2017; Stepanov, 2017; Kovanič et al., 2023).

The operating modes of mining actuators are characterized by dynamic load and frequent and severe start-up and braking conditions. Transient currents that occur during engine start-up are the main cause of accelerated wear and damage to the insulation of the stator winding of electric motors due to significant electrodynamic and electromechanical forces, as well as intensive thermal ageing (Yamansarin et al., 2011; Katsman, 2011; Vazhnov, 1980).

The drives of long-term operation modes use the well-known AM with a short-circuited rotor (AMCR), made in the form of a cast winding of a squirrel cage-type rotor made of ordinary aluminium alloy (Fig.1). Short-circuited rotors of dynamic, short-term and repeated-short-term motors, in order to obtain large starting moments and reduce starting currents, contain an aluminium alloy winding with increased resistance, or are made of copper rods with welded short-circuited brass rings (Voldek, 1978; Schoenfer, 1939; Kopylova et al., 1980).

The energy performance, efficiency and power factor of engines with increased rotor resistance are lower than those of conventional short-circuited engines of long-term operation, but they have improved starting properties (increased starting torque and reduced starting current).

Increased requirements for the performance characteristics of asynchronous drives of dynamic operating modes led to the creation of AM with special parameters with current displacement in the rotor. Such engines include two-cell and deep-groove engines, as well as AM with a massive and double-layer rotor (AMDR).

The massive rotor is a solid cylinder made of a special alloy with an optimal value of electrical conductivity and magnetic permeability. It performs the functions of current and magnetic field conductors. Motors with such a rotor have improved starting properties compared to short-circuited motors due to the strongly pronounced effect of current displacement in the rotor. However, the energy performance of these engines is much lower than that of engines with increased rotor resistance, which did not allow these engines to find wide application and led to the creation of engines with double-layer rotors (Danilevich, 2007; Danilevich, 2010; Kruchinina, 2011).

The double-layer rotor (Fig.1) is a hollow ferromagnetic cylinder made of a special alloy with optimal electrical conductivity and magnetic permeability values mounted on a charged cylinder made of sheets of electrical steel. The magnetic permeability of the charged cylinder is significantly greater than the magnetic permeability of the outer hollow cylinder. The material of the active layer of a double-layer rotor combines the functions of conductors of both current and magnetic field, while in a conventional short-circuited rotor, these functions are performed separately. The efficiency and power factor in the nominal mode of the AMDR is almost the same as that of engines with increased rotor resistance and much higher than that of an engine with a massive rotor, but still less than that of a conventional short-circuited engine. However, a motor with a double-layer rotor, like a motor with a massive rotor, has good starting properties due to the strongly pronounced effect of current displacement in ferromagnetic bodies (Mogilnikov et al., 1983; Annenkov et al., 2009; Annenkov et al., 2009).

In well-known deep groove and double squirrel cage motors, the phenomenon of current displacement in the rotor is also used, but the effect of current displacement in a double-layer rotor is more pronounced. If the ratio of the active resistance of the rotor at start-up and in nominal mode for an engine with a double-layer rotor is 4-5, then modern engines with a deep groove of the rotor have only 2-3. As a result, the starting properties of engines with a double-layer rotor are better than the starting properties of engines with a deep groove and with a double squirrel cage (Oleynikov et al., 2008).

The use of AMDR is recommended in drives of repeated short-term modes, in drives with frequent starts, if necessary, a large starting torque and parking under current, as well as in long-term modes with severe start-up conditions. The advantages of motors with a double-layer rotor compared to a short-circuited one at increased rotational speeds and voltage regulation, as well as in terms of vibroacoustic characteristics and rotor reliability, are noted. This type of motor is most suitable for dynamic mode drives instead of AMCR.

Material and Methods

Application of electric motors in the mining industry

Almost all types of AC and DC electric motors are used in the mining industry. High-voltage asynchronous motors with a squirrel-cage rotor are used to drive pumps, crushers, conveyors, fans and excavators with capacities from 200 kW to 1200 kW. Asynchronous motors with severe starting conditions, phase rotor motors, and adjustable asynchronous motors are used for mining combines, tunnelling shields and lifting equipment. Low-voltage asynchronous motors are used to drive local ventilation fans, pumping stations, conveyor units, winches, vibrating feeders, and crushers.

Asynchronous motors with a squirrel-cage rotor currently make up the bulk of all industrial electric drives. The main disadvantage of asynchronous motors with a squirrel-cage rotor is a large starting current, which can exceed the motor's rated current by 5-7 times (Kozyrev et al., 2021).

Electric drives of belt conveyors with asynchronous motors, when starting at the rated voltage of industrial frequency, have high starting currents in the stator and rotor windings, low energy indicators and develop a small starting torque value. An increase in the starting current in the electric drive of an asynchronous motor above the rated value leads to the occurrence of large electrical losses in its stator and rotor windings, overheating and delamination of the winding insulation and premature failure of the latter (Polovinka et al., 2023).

At present, mine self-propelled cars are widely used for delivering rock mass in non-ferrous metallurgy mines, potash and coal industries. A multi-speed asynchronous motor with a squirrel-cage rotor is used as an electromechanical converter. A common disadvantage of a two-speed asynchronous motor with a squirrel-cage rotor is an additional impact moment, which creates high mechanical stresses and impacts in gears when starting and switching from one rotation frequency to another (Toshov et al., 2022).

High-voltage electric motors are used in oil and gas production and transportation. However, the direct start of high-voltage motors causes mechanical and electrical shock loads on the motors themselves, connected process mechanisms and the electrical network. The motor winding can heat up to critical temperatures during one start, which causes insulation ageing and makes it impossible to restart for several hours. Therefore, the introduction of soft start devices for high-voltage motors allows not only to reduce mechanical and electrical loads but also to extend the service life of motors and equipment (Gilmanov et al., 2023).

In electromechanical systems of self-propelled mining machines, low-frequency hidden oscillations can almost always be observed during start-up (Yeshin, 2023). The problem of forming a smooth speed diagram of a mine hoisting machine is transformed into the problem of controlling the electromagnetic moment of an induction motor to calm oscillatory movements (Yeshin., 2021).

Requirements for increased efficiency and reduced cost of drives are driving a worldwide trend to replace high-voltage motors with low-voltage motors, DC motors and wound-rotor induction motors with variable-speed induction motors and motors with improved starting characteristics.

Features of the design and physical processes in the AMDR

AMDR can be obtained from AMCR by replacing a conventional short-circuited rotor with a double-layer rotor. At the same time, no structural changes are made to the body and stator of the base machine. The only exceptions are those cases when further improvement of energy characteristics for long-term operation is carried out by installing magnetic wedges in the stator slots or by capacitive encapsulation of the frontal parts of the windings. To reduce the additional losses from the higher harmonic fields of the stator, the air gap in a machine with a double-layer rotor is increased by one and a half to two times. Defective short-circuited rotors with broken rods in which the tooth layer is cut off are used as a massive charged cylinder on which a ferromagnetic sleeve is installed. The thickness of the sleeve of a ferromagnetic cylinder is approximately equal to or slightly less than the height of the tooth of a conventional short-circuited rotor.

The ferromagnetic sleeve is mounted on a massive cylinder with a hot fit. To reduce the transverse edge effect, short-circuited rings made of high-quality copper are welded to the ends of the sleeve, and the sleeve's reach is increased by up to 20%. To improve energy characteristics by reducing additional losses, in some cases, coatings made of materials with an increased value of magnetic permeability are applied to the rotor, annular corrugation is performed on the surface of the rotor, magnetic wedges are installed in the slots of the stator. Axial slots are sometimes made on the surface of the ferromagnetic rotor sleeve to obtain anisotropic properties (Oleynikov, 1980).

Experiments have established that iron and copper alloys are the most suitable electromagnetic characteristics for manufacturing a ferromagnetic sleeve of a double-layer rotor. They allow for the possibility of changing magnetic permeability and electrical conductivity within specified limits, and their Curie Point mainly meets the requirements. These alloys are inexpensive, well-processed, easy to weld and solder, and are currently used to manufacture double-layer rotors. The smelting of ferrous alloys is carried out in induction furnaces with the addition of alloying elements: manganese, silicon, phosphorus, and aluminium. Conventionally, these alloys are designated by the CM index. The figure after the index indicates the percentage of copper. The alloy structure is heterogeneous. The alloy has a granular structure and consists of two solid solutions - an iron solution in copper with an iron content of less than 0,2% and a copper solution in iron with a copper content of about 0,15%. Combining these solutions in certain proportions makes obtaining alloys with optimal electromagnetic properties possible.

The casting of blanks is carried out in moulds for the sleeve of a double-layer rotor using conventional technology. To stabilize the electromagnetic characteristics, the workpieces are annealed in furnaces heated to 800°C and kept at this temperature for 6 hours, followed by slow cooling. After heat treatment, the casting of the massive sleeve is drilled with a landing tolerance and mounted on a stacked massive cylinder located on the rotor shaft. Short-circuited copper rings with heat-removing blades are welded to the ends of the cylinder. After that, the double-layer rotor is placed in the stator of the base engine, bearings and bearing shields are installed.

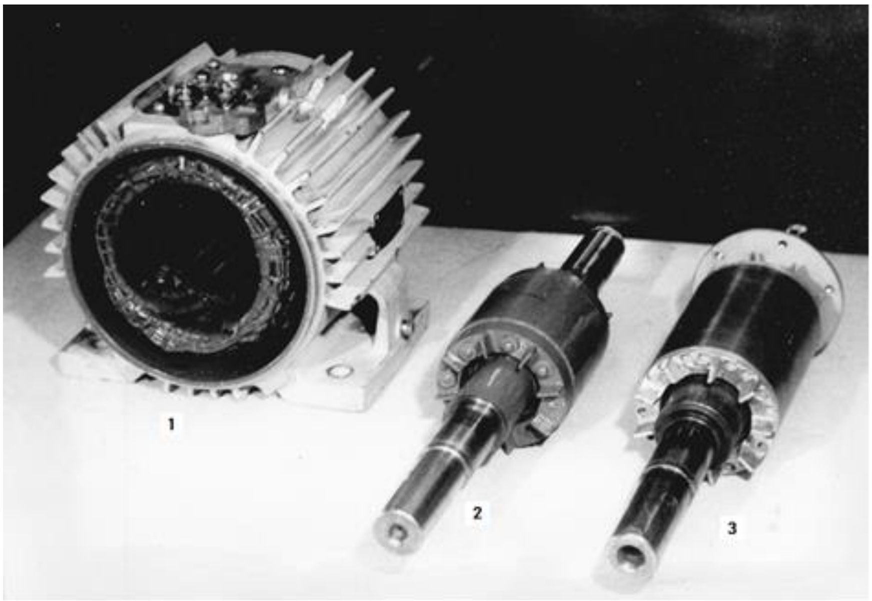


Fig. 1. Asynchronous motor with different rotors
1 – asynchronous motor stator; 2 – short-circuited rotor; 3 - double-layer rotor

When launching the AMDR in the area of large slides, the depth of penetration of the electromagnetic wave into the rotor body is less than the thickness of the massive sleeve. In this case, the magnetic field does not penetrate the charged massive cylinder or affect the engine's operation. In a massive sleeve, only the tangential component of magnetic induction takes place, and its normal component is missing. Therefore, the AMDR will have a large initial starting torque with a small initial starting current, as well as small energy losses during start-up.

As the engine accelerates, in the area of small slides, the depth of penetration of the electromagnetic wave into the rotor body will be greater than the thickness of the massive sleeve. In this case, the main magnetic field will be shifted to the charged part of the massive cylinder since its magnetic resistance is much less than the magnetic resistance of the massive sleeve. As a result, the normal component increases in the massive sleeve, and the tangential component of magnetic induction decreases. An increase in the normal component of magnetic induction will increase the EMF in the massive sleeve and, consequently, the rotating electromagnetic torque, all other things being equal. A qualitative examination of the physical processes in a double-layer rotor shows that, compared with a massive rotor, the presence of a charged cylinder with small slides creates conditions for increasing the efficiency and cost of the engine.

Alloy smelting technology for double-layer rotors

For asynchronous motors of low and medium power with massive or double-layer rotors, the performance characteristics are the best if the relative magnetic permeability of the material of the active part of the rotor is $\mu_r = 40–60$. If we take into account that in the nominal operating mode, the magnitude of magnetic induction in the gap and in the rotor body is, on average $B_\delta = 0.7–0.8$ T, and the magnetic field strength in the rotor is approximately equal to $H = (10–14) \times 10^3$ A/m, then the magnetic permeability of the rotor material should be within the range of $\mu_r = 40–50$. At start-up, the magnetic permeability is determined by the degree of saturation of the rotor and will be within $\mu_{rs} = 15–25$.

It is known that the magnetic properties of ferromagnetic materials change with temperature changes. The greatest change in magnetic permeability occurs at a certain critical temperature, called the Curie point temperature (Fig. 2). It is clear that the rotor must have stable magnetic characteristics; otherwise, when the rotor is heated, the operating characteristics of the motor will change. Considering the necessary overheating margin for the material of the massive rotor, the Curie point temperature should be at least $\theta_k = 300–350$°C.

As for the electrical resistivity, this value depends both on the power of the designed engine and on its operating mode. For low– and medium-power motors designed for continuous operation, the electrical resistivity of the rotor material should be within $\rho = (0{,}75–1{,}2)\cdot10^{-7}$ Ω·m. For high–power engines (hundreds of kilowatts) and for dynamic mode engines, it can increase to a value of $\rho = (2{,}0–2{,}5)\cdot10^{-7}$ Ω·m.

There are no ready-made materials with an optimal value of magnetic permeability in nature. Of the pure ferromagnetic materials, only nickel has suitable electromagnetic characteristics and can be used for low-power engine rotors. However, its application possibilities are limited by high cost and poor machinability. Electrical steel and its alloys have increased values of magnetic permeability. A common magnetic grey cast iron occupies an intermediate position but is poorly processed and has a low Curie point equal to $\theta_k = 240$°C.

The properties of magnetic materials depend on the chemical composition, the method of their preparation, and heat treatment. The presence of impurities or alloying elements significantly affects these properties. To create materials with specified values of magnetic permeability and electrical resistivity, fusion of various metals with the addition of alloying elements and subsequent heat treatment was used. A.N. Strelnikov investigated the possibility of obtaining electromagnetic properties of alloys based on iron-aluminium, nickel-copper, iron-nickel, and iron-copper (Strelnikov, 1981).

The fusion of iron and aluminium gives a material with a low magnetic permeability value. Iron-nickel alloys, with the addition of copper, give increased magnetic permeability and electrical resistivity values.

Nickel-copper alloys may have satisfactory electromagnetic characteristics, but their magnetic permeability varies significantly with temperature changes. In addition, they have a low saturation induction $B_S = 0{,}2\text{–}0{,}35$ T. For the first time, prototypes of massive and double-layer rotors were made from this alloy (75% nickel, 20% copper and 5% iron), which experimentally demonstrated the possibility of improving the characteristics of AM.

The best electromagnetic characteristics were obtained on iron and copper alloys, which allow for the possibility of changing the magnetic permeability and electrical resistivity within the required limits while maintaining the high temperature of the Curie point (Pruss et al., 1985; Shurygin et al., 1963).

With regard to the smelting of iron-copper alloys, work was carried out to clarify the optimal ratios of basic and alloying materials, melting and heat treatment modes, which helped eliminate defects and ensure more accurate compliance of electrical and magnetic properties with the specified ones (Oleynikov et al., 2018; Oleynikov et al., 2015).

Iron-copper alloys with a reduced magnetic permeability value belong to the group of high–alloy steels containing large amounts of copper with the addition of certain alloying elements - manganese, silicon, phosphorus, and aluminum. Conventionally, these alloys are designated by the CM index. The alloy number is determined by the percentage of copper; thus, the CM19 alloy contains 19% copper, the CM25 alloy contains 25% copper, etc.

The alloy structure is heterogeneous (Fig. 3); the alloy has a granular structure and consists of two solid solutions: an iron solution in copper and a copper solution in iron. The combination of these two solutions in certain proportions makes it possible to obtain alloys with the necessary (optimal) electromagnetic properties.

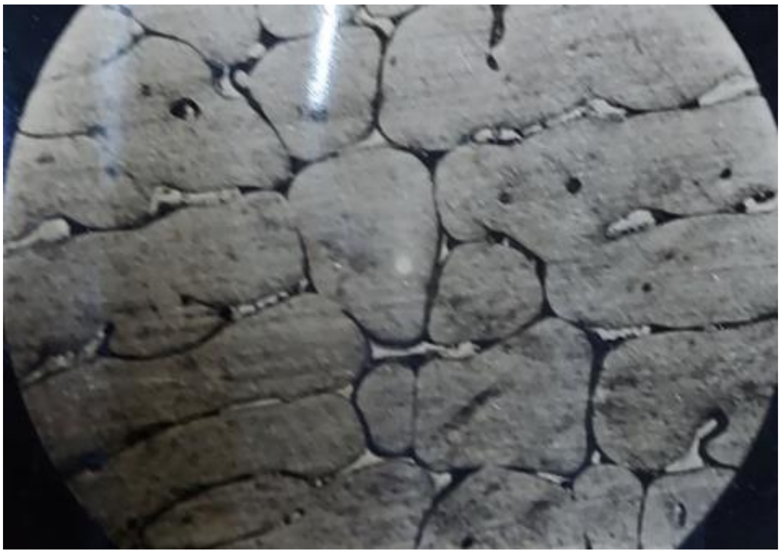


Fig.3. Microstructure of the ferro-copper alloy CM19

CM alloys are smelted in induction furnaces using standard materials - copper, scrap steel or low-carbon steel and the above alloying elements. The individual components of the alloy affect its mechanical characteristics and electromagnetic properties as follows.

Copper - reduces the specific magnetic permeability μ_r, the specific electrical resistance ρ and the saturation induction B_S. The coercive force increases with an increase in the copper content, and the strength of the alloy decreases.

Manganese - gives a maximum magnetic permeability of μ_r at a content approximately equal to 0,8%. When this content changes up or down, the specific magnetic permeability of the μ_r decreases.

With increased manganese content, the electrical resistivity increases continuously, and the coercive force and hysteresis losses increase.

Silicon is a deoxidizer that contributes to the production of high-quality castings. Increases the specific magnetic permeability μ_r and the specific electrical resistance ρ, reduces eddy current losses and hysteresis.

Aluminum is a strong deoxidizer. With an increase in the aluminium content, the electrical resistivity increases while the specific magnetic permeability changes slightly.

The percentage of manganese, silicon and aluminium can regulate the magnetic and electrical properties of the alloys.

Phosphorus is a deoxidizer, which is a useful impurity that increases the corrosion resistance of ferrous alloys.

Carbon – lowers the magnetic permeability and increases the electrical resistivity. The carbon content of the alloy should be minimal.

The furnace load is determined by the required amount of alloy (Table 1 shows a variant of CM20 alloy smelting).

Tab. 1. Loading the furnace for alloy CM-20

Alloying elements	Content, %
Iron (scrap steel)	78,6 -78,7
Copper	19,9 - 20,1
Manganese	0,76 - 0,79
Silicon	0,22 - 0,24
Aluminum	0,09 - 0,1
Phosphorus	0,015 - 0,020
Nickel	0,05 - 0,07
Chromium	0,05 - 0,07
Carbon	0,025 - 0,045
Sulfur	0,2

Iron and copper are the main components;
Manganese, silicon, aluminium, and phosphorus are alloying elements;
Nickel, chromium, carbon, and sulfur are impurities.

The lining of the furnace can be basic or acidic. Using a basic lining based on chromomagnesite with the addition of 2% boric acid is preferable.

The melting process is carried out under approximately the same conditions as in the smelting of steel and begins with loading all steel scrap. The use of scrap steel is economical but introduces a certain uncertainty into the melting process since uncontrolled impurities may appear in the alloy.

The alloy's composition may also change due to its interaction with the surrounding atmosphere, slag and furnace lining. Therefore, it is necessary to select steel scrap carefully. The best results are obtained by using Armco-iron or structural steel Ст.3. Since steel Ст.3 has an increased carbon content (C = 0,17–0,25%), it is advisable to decarbonize it in an arc furnace. The boiling of steel at a temperature of 1680–1700°C continues until the carbon content is below 0,05%.

When melting in an acid-lined furnace, after melting the steel, if necessary, an ОСЦ-45 welding flux or glass is introduced into the furnace, which protects the liquid metal from oxidation and saturation with gases. Then, for preliminary deoxidation, a part of ferromanganese is added (at the rate of 40-50% of the total ferromanganese).

After 3-5 minutes, copper is introduced into the furnace in small portions so as to prevent cooling of the metal in the upper part of the melting bath.

At the end of the melting of all copper, a phosphorous component is introduced for the final deoxidation of the alloy; then, the remaining manganese is deposited.

Aluminum is introduced into the furnace in a very limited amount (0,1–0,15)% of the weight of the entire charge immediately before the end of melting and transferring the metal to the ladle, preheating it to a temperature of approximately 400°C.

Before casting the alloy into moulds, magnesium or cadmium is introduced into the bottom of the bucket on the rod in a small amount, approximately 0,02% of the melting weight. Rapid mixing occurs, and the alloy turns out to be homogeneous without stratifications. The magnesium in the alloy burns up. The temperature at the beginning of casting should be slightly higher than the melting point and be 1500-1550°C. The workpieces must be filled into sandy, dry moulds. The production of moulds in flasks is carried out using conventional technology.

Heat treatment of workpieces is an integral part of the technological process of production of ferrous alloys. It is produced to stabilize the electromagnetic characteristics and form the specified mechanical properties of alloys (Table 2).

Tab. 2. Results of heat treatment of the alloy

Type of heat treatment	θ,°C	28	60	100	140	180	200	250
Without heat treatment	$\rho \cdot 10^{-7}$ Ом·м	1,2	1,27	1,38	1,5	1,66	1,72	1,97
Normalization	$\rho \cdot 10^{-7}$ Ом·м	1,42	1,52	1,68	1,85	2,03	2,15	2,37

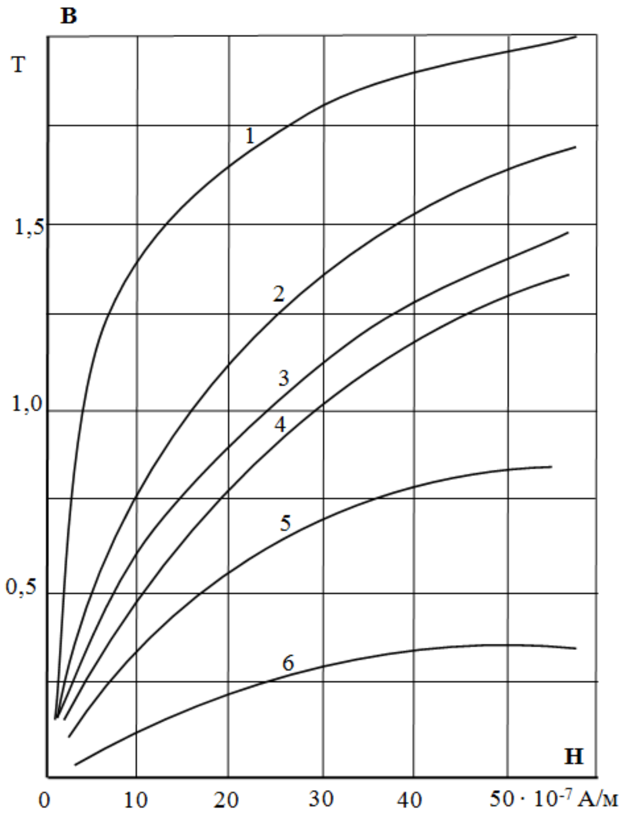


Fig.4. Electromagnetic properties of alloys CM

1. CM15 ρ = 2,16 10^{-7} Ω·m; 2. CM19 ρ = 1,6 10^{-7} Ω·m; 3. CM25 ρ = 1,37 10^{-7} Ω·m;
4. CM30 ρ = 0,645 10^{-7} Ω·m; 5. CM40 ρ = 1,14 $\cdot 10^{-7}$ Ω·m; 6. CM63,8 ρ = 0,6 10^{-7} Ω·m

The following heat treatment mode is installed in furnaces with gas, fuel oil or electric heating: heating to a temperature of 750-800°C and exposure at this temperature for 6 hours; cooling - slow with the oven. Overheating above 800°C is not recommended, as the alloy is prone to severe scale formation. As a result of heat treatment, the alloy structure is fine-grained, and internal stresses are removed. Figure 4 shows the magnetization curves B = f (H) of the obtained CM alloys with different copper content and electrical resistivity ρ.

The working conditions and features of the manufacturing technology of massive and double-layer rotors determine several special requirements for the mechanical characteristics of ferrous alloys. In particular, alloys must have good casting properties and be easily amenable to welding and soldering, as well as mechanical processing. Since the rotor is subjected to significant dynamic loads during engine operation, the strength of the alloy should not be lower than the strength of structural steel.

In the course of experimental studies, it was found that iron-copper alloys mainly meet the requirements (Table 3).

Tab. 3. Mechanical properties of the alloy

Tensile strength, $\sigma_в \cdot 10^7$ Pa	Yield strength, $\sigma_т \cdot 10^7$ Pa	Brinell hardness, HRB·10^7 Pa	Elongation, %	Temperature coefficient of linear expansion, α, $°C^{-1}$	Temperature coefficient of resistance, α, K^{-1}
30÷34	21÷21,6	61÷67	5÷7	(13,5÷15,5) ·10-6	0,00245

The alloys have good casting properties, making it possible to obtain thin-walled castings. Alloys are not amenable to forging and rolling. This is due to the fact that at temperatures above 300°C, alloys are prone to cracking, and at lower temperatures, they have a sufficiently high hardness. Hollow cylindrical castings are well-processed on lathes to fit the outer diameter of the AM stator and the inner diameter of the charged rotor package to obtain a two-layer structure.

Results and Discussions

The starting properties of the engine are determined by the dependence of the torque and current on the rotational speed. These characteristics determine the start-up duration, energy loss in the windings and their heating. They tend to increase the starting torque and reduce the starting current to reduce the start-up time and energy losses in the motor windings and their heating. The starting properties of the motors are characterized by the multiplicity of the starting torque to the nominal torque $k_{m,s} = M_s/M_n$ and the starting current to the nominal current $k_{i,s} = I_s / I_n$, as well as the starting quality equal to the ratio $D_s = k_{m,s} / k_{i,s}$.

AM with different rotors was studied on the stand (Fig. 5). The experimental installation contains a three-phase asynchronous motor and electronic equipment for measuring voltages, currents, power, shaft torque, temperature and rotational speed (Gervais et al., 1984; Shaitor, 2024).

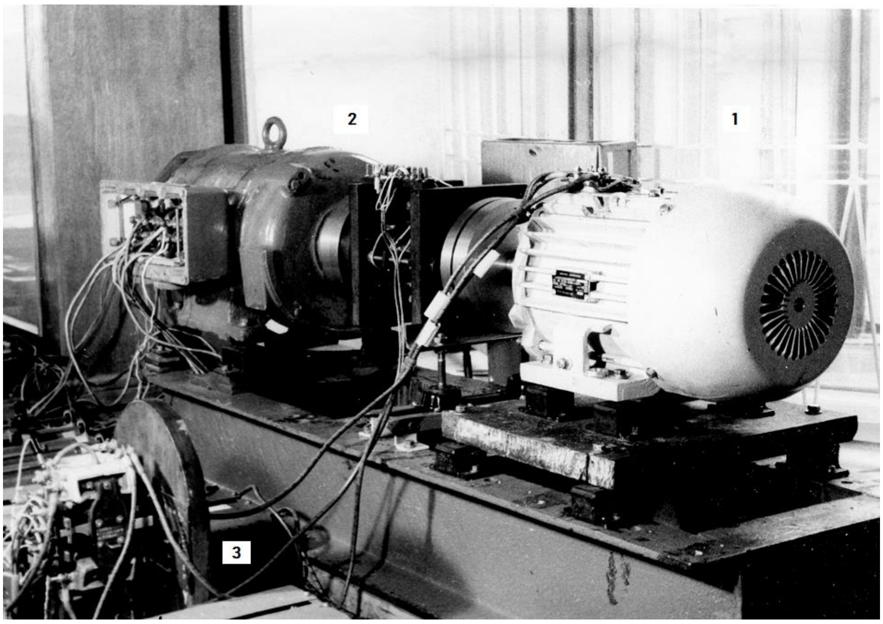


Figure 5 – A stand for the study of AM with various rotors:
1 – asynchronous motor; 2 – load generator; 3 – automatic mode

Table 4 shows the comparative characteristics of low-power asynchronous motors with different rotors (Shaitor et al., 2021; Shaitor et al., 2020). Along with the undeniable advantages of starting properties, engines with a double-layer rotor have reduced energy performance in long-term operation modes compared to general-purpose short-circuited engines with a conventional rotor.

A double-layer rotor motor, like other short-circuited current displacement motors, belongs to high-slip motors, so the rotor efficiency of these motors is lower, and the rotor losses are greater than those of general-purpose short-circuited motors.

The magnetic permeability of the double-layer rotor sleeve is less than the permeability of the massive stacked cylinder of the short-circuited rotor, and the air gap of the motor with a double-layered rotor is greater than that of the short-circuited one. These factors lead to an increase in the magnetizing current and the idling current of the motor, which decreases the power factor and efficiency of the stator.

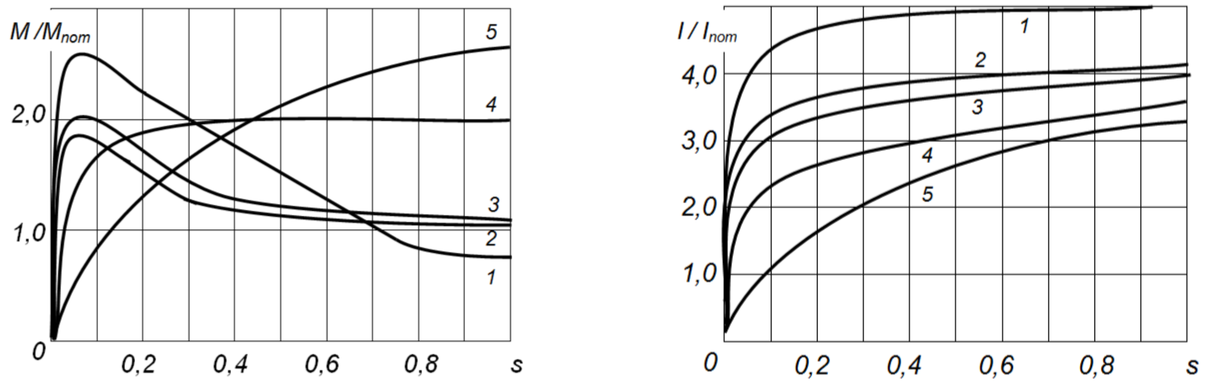
In addition, higher harmonic magnetic fields caused by stator serration cause increased additional losses in the double-layer rotor. Thus, a double-layer rotor engine's power factor and efficiency are slightly lower than that of a short-circuited engine. In order to maintain the temperature regime due to the insulation class, in long-term operation, the motor with a double-layer rotor must operate at the same thermal losses as the base engine, i.e. the power of the motor with a double-layer rotor must be reduced.

Tab. 4. Characteristics of asynchronous motors with different rotors

Type of AM	Rotor (material)	P_2, кW	η	$cos\ \varphi_1$	S	$\frac{I_{п}}{I_{н}}$	$\frac{M_{п}}{M_{н}}$	$\frac{P_2}{P_{2н}}$	$\frac{I_1}{I_{1н}}$
A41-2	The usual short-circuited	2,8	0,82	0,87	0,043	6,3	1,65	1,0	1,0
A41-2	Massive (CM25)	2,38	0,60	0,65	0,19	3,3	2,34	0,85	1,52
A41-2	Double-layered (CM25)	2,60	0,75	0,87	0,06	4,6	3,6	0,93	1,0
AO 2-31-2	The usual short-circuited	3,0	0,84	0,89	0,045	6,1	1,0	1,0	1,0
AO 2-31-2	Double-layered (CM20)	2,7	0,78	0,79	0,075	3,5	3, 2	0,85	1,15
МАП111-4	With increased resistance	2,4	0,8	0,82	0,05	5,9	2,0	1	1

The starting characteristics of the engines are closely related to the design of the rotor. Short-circuited windings of general-purpose asynchronous motors without current displacement cannot always provide the required starting characteristics, especially under severe or frequent starting conditions.

The most favourable starting conditions are for motors with a phase rotor and contact rings when the starting rheostat is inserted into the rotor circuit. However, these motors are much more difficult to manufacture and operate, less reliable and more expensive than short-circuited ones. In order to improve the starting properties, short-circuited rotors with high electrical resistivity, a double cage, and a deep groove are used. Motors with different rotors have different mechanical (Fig. 6, *a*) and electromechanical (Fig. 6, *b*) characteristics (s-sliding).



a *b*

Figure 6. Characteristics of asynchronous motors with different rotors:
1 - AMCR without current displacement; 2 - AMCR with a double cage; 3 - AMCR with a deep groove;
4 - AMCR with high electrical resistivity; 5 - AMDR

Motors having double-cage or deep-groove rotors develop an increased starting torque at a relatively lower starting current. The starting quality of these motors is, on average, 1,5 times higher than that of a motor without current displacement. Replacing a double-cage rotor with a double-layer one leads to a decrease in the starting current by 25% and an increase in the starting torque by an average of 2,5 times. The quality factor of starting an asynchronous motor with a double-layer rotor is 3-4 times higher than the quality factor of starting similar motors with a conventional rotor cage without current displacement, 2-2.5 times compared with a double cage or a deep groove and 1,3-1,5 times compared with a rotor with a high electrical resistivity.

In addition, in many electric drives with frequent starts or severe start-up conditions, there is a massive failure of the short-circuited windings due to softening and breakage of aluminium rods. Engines with a double-layer rotor do not have this disadvantage. It should be noted that by appropriate selection of the electrical resistivity and magnetic permeability of the double-layer rotor material, the starting properties of asynchronous motors can be widely changed.

Conclusion

The limited reliability of mining and transport machines with asynchronous electric drive is caused by significant dynamic loads, as a result of which large inrush currents lead to increased heating of the motors, accelerated wear of electrical insulation and breakage of aluminium rods of short-circuited rotors. It is proposed that the problem of increasing the reliability of mining equipment with asynchronous electric motors be solved by replacing short-circuited rotors with double-layer rotors made on the basis of an iron-copper alloy. A technology for manufacturing double-layer rotors has been developed, containing the smelting of ferrous alloys with specified electromagnetic properties. Studies of asynchronous motors with various rotors have shown the undeniable advantages of double-layer rotors, which significantly reduce starting currents and generate heat in dynamic modes with increased starting torques.

Reduction of starting currents limits voltage dips in the power grid, eliminating the negative impact of voltage surges on the power receivers of the entire mining complex. High starting torque with increased engine slip ensures reliable start-up and smooth acceleration of the electric drive, eliminating hidden low-frequency oscillations and actuator vibration. The heating of the stator and rotor of the electric motor does not reach critical temperatures, which allows multiple starts of drives, prevents the ageing of insulation and extends the service life of all equipment.

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