Rational design of rotor of the asynchronous motor fan for cooling units of diesel locomotives

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Summary. A comparative analysis of the design and performance of asynchronous motor fans (AMF) on the results of experimental studies of samples on the test bench. Determined rational variant for new locomotives, the frequency of which is regulated by varying the voltage on the stator winding. Identified strengths and weaknesses of rational option.

Keywords: asynchronous motor fans, percentage slip, rotor design, speed control.

INTRODUCTION

Energy properties of diesel may be improved by reducing the unused directly to the traction energy consumption in auxiliary units of the locomotive. This task is important because of the relative increase in energy costs with an increase in these sectional power locomotives. For modern high-power locomotives amount of costs to drive auxiliary devices reaches 12% efficient diesel power, and the locomotive cooling devices consume up to 75% of the power consumed by the drive auxiliary devices.

One of the actual tasks in locomotive engineering is to create a system of continuous fan speed control for diesel engines, which reduces energy costs for cooling the diesel locomotive, improves thermal regulation of diesel [9, 11, 15, 16], therefore, increases the reliability of the locomotive in operation. Therefore the search for the best option for cost-effectiveness of the system of continuous thermal regulation of locomotive diesel engine [2, 10, 18, 13, 26] and the rational design of controlled asynchronous motor-fan (AMF) is very important.

The use of diesel locomotives inverted asynchronous squirrel-cage motors built into the axial fan – fan motor has reduced the weight of the fan drive for 1000 ... 2000 kg. [7] The advantage of the drive is reliability, long life, easy maintenance.

Electric fan drive on alternating current is widely used in foreign locomotives type FP-9, SD-35, SD-38, SD-45, DD-40A, DD-35, GT-16, GT-26CW (diesel power from 1470 to 4850 kW) produced by General Motors (USA) on diesel locomotives type "Kestrel" company Brush (UK) in locomotives CC2400, SS2700 firm Alstom (France) in locomotives Swedish firm Nokhab [4, 19].

A characteristic feature of the motor-fan is their low efficiency in the regulation of the relay. AMF used to power the auxiliary alternators power the locomotive. In locomotives with electric transmission AC-DC power supply for use as the main AMF traction synchronous generators [10], which provides a significant reduction in weight of the drive. In locomotives equipped with systems of electric heating of passenger cars, to power the AMF using synchronous generators heating train (locomotive TEP150).

Locomotives type 2TE116 are exploited in Ukraine and other post-Soviet Unions countries with the group asynchronous electric fan relay. Currently, it is the main diesel locomotive in Ukraine and other post-Soviet Unions countries.

Fan drive cooling device for diesel locomotive 2TE116 by four AMF rated at 24 kW (with a diameter of blades of 1100 mm, with a speed of 1960 rev / min), which are powered by the traction of the synchronous generator.

Apply the dual-circuit cooling diesel engine (cooling water and oil cooling). Each circuit is cooled by two motor-fan relay staggered way (mode short S3-S4).

A characteristic feature of the fans is the increased power consumption, their low efficiency with periodic on-off switch.. It is advisable to apply the regulation of the air flow continuous variation of speed fan motor (operating mode S6). From the graph in Fig. 1 that the total energy consumption when using the continuous fan control (curve 1) is lower than in the ladder step. Figures do not take into account losses in the drive.

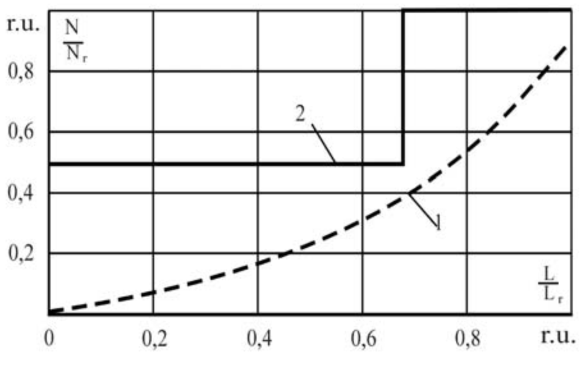

Fig. 1. Changing the shaft power of fans with continuous air flow (1) and two-stage (2) regulation ($L_n = 45.6\, m/c$, $N_n = 112\ kW$)

Fig. 2 shows the modes AMF temperature heat transfer fluids and diesel locomotives 2TE116 depending on the outside temperature with the real hysteresis temperature sensors T35. In zones 1 and 1′ MF2 (water) and MF4 (oil) work in relay mode, MF1 and MF3 disabled. In zones 2 and 2′ MF2 and MF4 operated permanently. In zones 3 and 3′ are connected MF1 and MF3 running in the relay mode. In zones 4 and 4′ MF operated permanently. The dashed lines show the range of the temperature of the coolant-static error of automatic temperature control system (ATCS) taking into account the thermal inertia of the cooling unit and the diesel. Consequently, the total static uneven ATCS a change of more than 10°C.

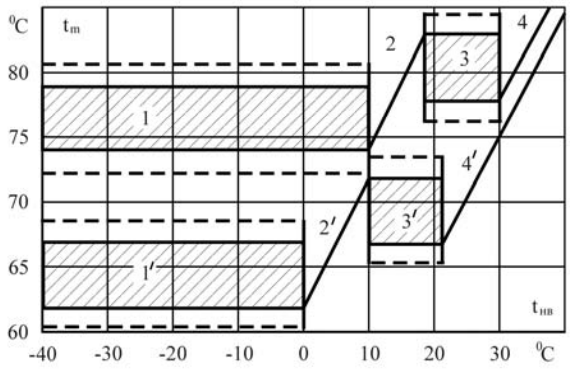

Fig. 2. Modes of motor fans on the locomotive 2TE116

Fig. 3 shows the experimental graphs of temperature of the cooling water outlet (1) and the inlet (2) diesel locomotive 2TE116 for continuous ATCS. Curve 3 is speed AMF. Tests were conducted on the rheostat in $t = +4...7\,°\mathrm{C}$, the regulation is carried out automatically by one AMF.

From Fig. 3 it follows that when the relay ATCS diesel have been major fluctuations in water temperature, which reduces the efficiency and reliability of diesel due to thermal fluctuations, relay mode is accompanied by heavy starting AMF with frequent switch on-of (curve 3, Fig. 3), which reduces the reliability and efficiency of the drive. Smooth regulation of fan speed to cool the diesel engine is the most preferred.

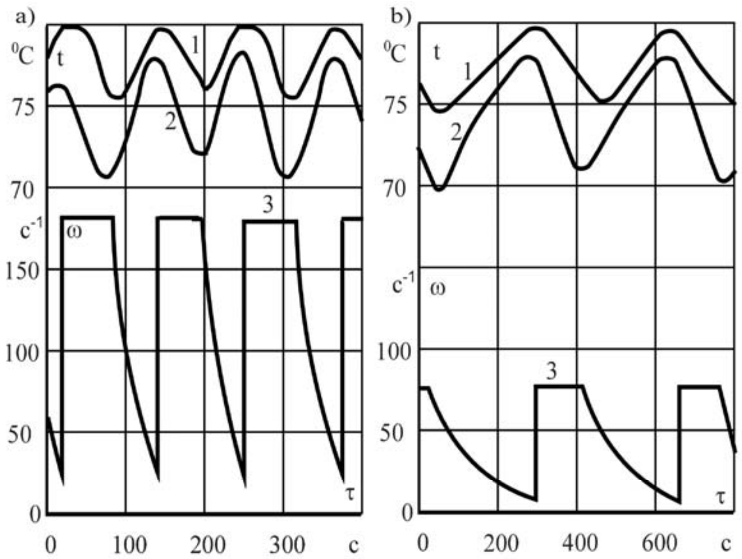

Fig. 3. Stationary processes as standard relay ATCS diesel locomotive 2TE116 at 100% (a) and 10% (b) loads

According to the PAO "LuganskTeplovoz" the results of performance tests 2TE116 locomotive number 521 in truck traffic in areas Ilovaiskaya-Volnovaha-Kamush-Zariy-Bologi Donetsk railway for 68 hours of recording to identify any significant changes in the intensity of the modes as diesel and motor-fan operating in relay mode. Over 68 hours of registration of the locomotive to operate the average number of starts per hour AMF was: № 1 - 38, № 2 - 11, № 3 - 8, № 4 - 13.

Continuous speed control of induction motor fan by varying the voltage on the stator winding can be done by using phase control thyristor voltage converter [8, 21]. The converter has six power thyristors included pairwise opposite in every phase asynchronous motor fan. By changing the angle of thyristors regulate the voltage on the stator winding, hence the speed of AMF.

Speed control by varying slip when slip power is released in form of heat in the circuit of rotor windings, accompanied by a significant decrease in efficiency At sufficiently large losses in the rotor slides predominate over other losses in the motor and efficiency determined by:

$$\eta = \frac{P_{mec}}{P_1} \approx \frac{P_{em} - s \cdot P_{ем}}{P_{em}} = 1 - s, \qquad (1)$$

where: P_{mec}, $P_{ем}$, P_1 - mechanical, electromagnetic and power consumption of induction motor, respectively.

Mechanical characteristics of the induction motor when the voltage change as shown in Fig. 4 (curves 1, 2, 3). If you change the maximum torque is proportional to the square of the voltage and the critical speed remains the same (the line in Fig. 2). With decreasing point changes stable operation of the "induction motor-fan" and changes the frequency of rotation (see Fig. 4 points a, b).

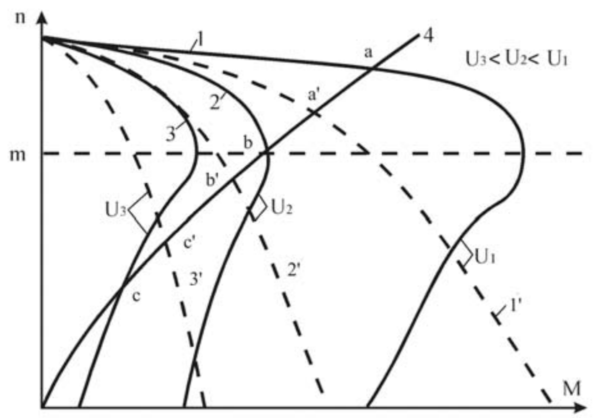

Fig. 4. The mechanical characteristics of the asynchronous motor-fan: 1-3 – serial AMF with the rotor winding alloy AK12M4, -1'-3' – regulated AMF with increased resistance of the rotor winding, 4 – fan characteristic

To expand the limits of regulation - the ratio of maximum to minimum speed n_{max} / n_{min} you have a soft mechanical characteristics of the motor. At the same time expanding the limits of regulation (see Fig. 4, points a', b', c').

The fan load torque is proportional to the frequency of rotation of the second degree. The condition of equilibrium points for AMF:

$$M_{em} = M_n \left(\frac{n}{n_n} \right)^2 + M_o, \tag{2}$$

where: M_{em} – the electromagnetic torque of induction motor,

M_n – AMF shaft torque at nominal frequency,

n, n_n – the current and the rated speed value,

M_0 – the initial point of friction in the bearings of AMF.

The value of slip is determined by:

$$s = \frac{n_1 - n}{n_1} = \frac{\omega_1 - \omega}{\omega_1}, \tag{3}$$

where: ω_1 - the synchronous speed, rad/s, $\omega = 2\pi \cdot n$ - rotational speed of the rotor.

Shaft power of AMF

$$P_2 = M_{em} \cdot \omega. \tag{4}$$

Electromagnetic power transmitted from the stator to the rotor

$$P_{em} = M_{em} \cdot \omega_1. \tag{5}$$

The difference of power $p_p = P_{em} - P_2$ is released as heat in the circuit of rotor windings. Consequently, losses in the rotor can be:

$$p_p = M_{em}(\omega_1 - \omega) = M_{em} \cdot s \cdot \omega_1 = P_{em} \cdot s. \tag{6}$$

Part of the electromagnetic power $P_2 = P_{em}(1 - s)$ is transmitted to the rotor shaft. From the expressions (5) and (6) that the rotor losses increase is proportional to the slip, which is not economical in constant torque load and requires operating at low speeds using motors with high power reserve.

When the fan load, the expression (6), taking into account the equations (2) and (3) becomes:

$$p_p = \left[M_n \left(\frac{1-s}{1-s_n} \right)^2 + M_o \right] \cdot s \cdot \omega_1, \tag{7}$$

where: s_n – the nominal slip,

M_0 – initially torque at $s = 1$.

From (7) it follows that when the fan load compared to the load with constant torque at equal values of slip losses in the rotor is much less. Electromagnetic torque is determined by:

$$M_{em} = \frac{p \cdot m_1}{\omega_1} (I_2')^2 \cdot \frac{r_2'}{s}, \tag{8}$$

where: p – number of pole pairs,

m_1 – the number of phases of the stator winding,

I_2' – reduced secondary current (rotor current),

r_2' – the reduced resistance of the rotor to the stator winding.

According to equation (8):

$$M_{em} \equiv (I_2')^2 \cdot \frac{r_2'}{s}. \tag{9}$$

At steady state $M_{em} = M_c$. For the fan load, ignoring the point of friction and additional losses $M_c \equiv \omega^2$, accept it. From (9) with (3), neglecting the magnetizing current, we get:

$$I_1 \equiv I_2' \equiv (1 - s)\sqrt{s / r_2'}. \tag{10}$$

From the expression (10) that the stator winding current I_1 is inversely proportional to $\sqrt{r_2'}$. After differentiating expression (10) and equating it to zero, we obtain that the current has a maximum value when sliding $s = 0.33$.

Thus, for obtaining satisfactory operation modes of induction motor with a fan torque load applied to the shaft motors with increased rotor resistance, moreover, to inflate induction motor power to provide normal heating mode by sliding the rotor $s = 0.33$.

On diesel locomotives, which are produced in Ukraine for cooling heat-transfer agent uses asynchronous motor fans (AMF) inverted design with a short-circuited rotor winding "squirrel cage" [3] (Fig. 5).

AMF consists of a stator 1, which is rigidly connected to the base via the sleeve 2, which carries the support bearings 3, the shaft 4 connected to the rotor through the shield 5. The rotor consists of a fan wheel with blades 6 and 7, laminated package 8, which is filled with "squirrel cage" (rotor winding) 9 with aluminum alloy AK12M4. Rated power AMF – 24 kW, the frequency of the network, which feeds the AMF in the locomotive of 100 Hz, the phase voltage– 230V. Synchronous speed 2000 r/min. In the cooler diesel locomotive has four AMF – two: into the cooling water and oil cooling circuit. Each of AMF operates in intermittent mode, the number of starts is up to 38 per hour. This mode of operation AMF does not provide sufficient reliability of the drive fans to use and the quality of temperature control heat transfer fluids (water and oil) diesel locomotive, as well as the increased cost of power required to drive the fans.

There are three ways a more cost-effective continuous control of temperature change of locomotive diesel engine air flow through the radiator cooling device:

1) the regulation of the angle of the blades AMF [22],

2) speed control AMF frequency change of voltage on the stator winding [1, 20],

3) speed control AMF change of the supply voltage to the stator windings [5, 24, 25].

In the newly developed shunting and freight locomotives AMF supplied with an auxiliary synchronous generator, the power of which is commensurate with the power of asynchronous drive fans (150-200 kW).

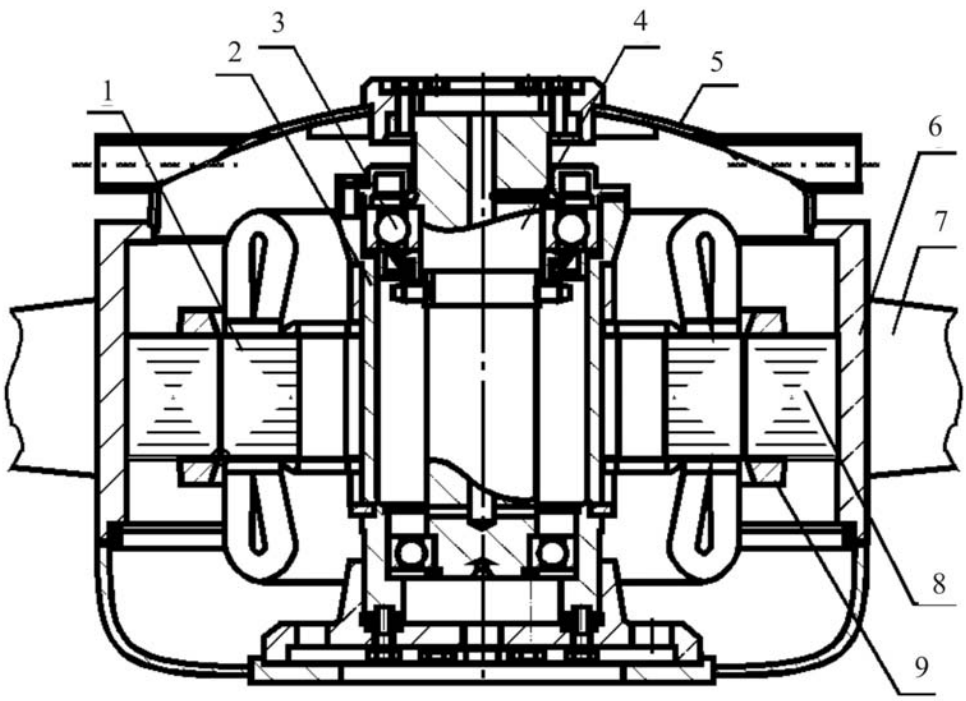

Fig. 5. The design of the serial asynchronous motor-fan for relay and frequency control

Comparative analysis of the average operating cost ways to regulate temperature diesel determined that continuous processes in 3.7-5.8 times more economical then relay method. The difference in annual fuel savings of the locomotive for continuous processes does not exceed 0.6% of the average working hours of the locomotive, so the type of drive is infinitely variable is determined largely by cost and design factors than the economy of operation that justifies the advantage of the method of regulation by varying the voltage on the stator winding AMF (change of the output voltage of the synchronous generator by changing the excitation current of the thermostat) as the most simple, cheap and reliable.

OBJECT OF RESEARCH

Object of research is asynchronous motor-fan installed on cooling units of diesel locomotives which is regulated by varying the voltage on the stator winding.

PURPOSE OF RESEARCH

The purpose of research was to determine rational variant for new locomotives. Identified strengths and weaknesses of rational option.

RESULTS OF RESEARCH

Rational embodiment of the motor-fan speed control by varying the voltage on the stator winding determined experimentally on the bench. Short-changed the design of the rotor winding 9. A laminated package of the rotor 8 by slidably inserted into fan wheel 6, which are welded to the blade 7. The tests were conducted at the same temperature in the test bench, where AMF installed to preserve the identity of the aerodynamic characteristics of the fan. Thus, the net power an asynchronous motor in bench testing of various designs of rotors was the same.

The stator of the motor-fan has the following structural data: the phase winding resistance is 0.069 ohms at t=115 ^{0}C, the number of turns of the winding phases is 60, random-wound coil of soft sections, the active length – 0.12 m, pole pitch – 0.18 m, outer diameter – 0.344 m, internal diameter – 0.164 m, the number of pole pairs – 3, backrest height of the yoke – 0.046 m, tooth height – 0.045 m, the number of slots – 72, the groove half-closed, tooth width – 0.00845 m, electrical steel – 2411. The length of the stator pack – 0.12 m outside diameter of the rotor package 0.46 m, internal – 0.346 m. Number of rotor slots – 56. The air gap between stator and rotor – 1 mm.

We investigated the following options for the design of the rotor.

Variant 1. The rotor is wound with aluminum alloy AK12M4 with an electrical resistivity of $\rho = 0.0952 \cdot 10^{-6}$ ohm·m at 115ºC. The cross section of the rotor slots to fill rod coil is shown in Fig. 6. The number of slots in the rotor – 56. Cross-section of a shorting ring coil is shown in Fig. 7.

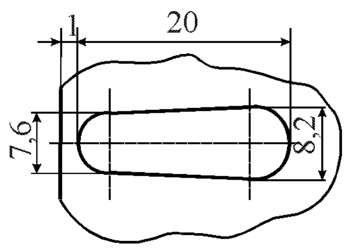

Fig. 6. AMF rotor slot

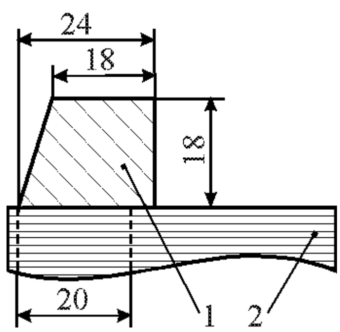

Fig. 7. Cross-section of a shorting ring rotor windings for series AMF: 1 – short-circuiting ring, 2 – package a laminated rotor

Variant 2. Rotor winding containing copper rods (copper M1 $\rho = 0.025 \cdot 10^{-6}$

Ohm·m at a temperature of 115ºC) and ferromagnetic short-circuiting ring of steel St. 3 ($\rho = 0.172 \cdot 10^{-6}$ Ohm·m at 115ºC). Scheme for construction of the rotor winding rods and ferromagnetic rings of steel shown in Fig. 8 (coil rolled on the plane).

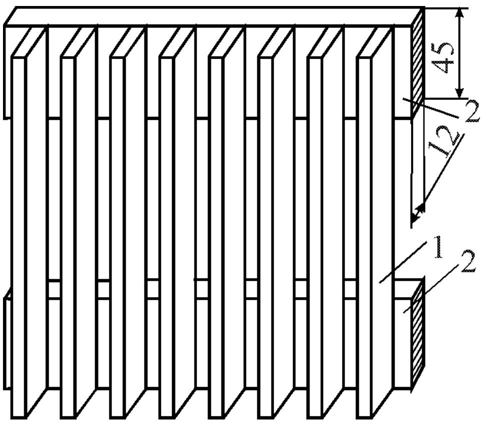

Fig. 8. Construction rotor winding deployed on plane 1 – copper rods 2 – short-circuiting ring of steel St. 3

Shape and dimensions of the rotor slot shown in Fig. 9. The package was made of the rotor pilot series of slots by melting the aluminum alloy in an electric furnace. Then slots serial AMF (Fig. 9) inserted rods 1 made of copper sheet mark M1, 4 mm thick (two in slot) to which are soldered brass ring of ferromagnetic steel St. 3 0.012×0.045 m section as the flux applied bit. In the manufacture of the rotor winding slots were involved in 28 (z_2 = 28) of the 56 series (through the slot rods were absent).

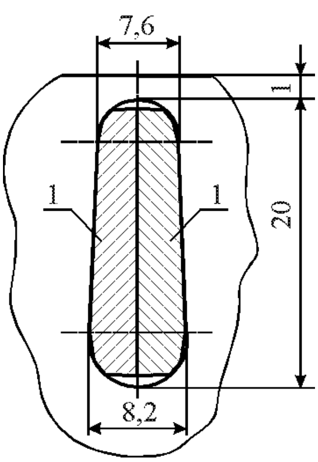

Fig. 9. The cross section slot of the rotor with copper rods: 1 – copper rods

Variant 3. Rotor winding containing brass rods (manganese brass L96 $\rho = 0.118 \cdot 10^{-6}$ Ohm·m at 115ºC, number of rods z_2=42) and ferromagnetic short-circuiting ring of steel St. 3.

Variant 4. The two-layer rotor (Fig. 10), which is a winding plug 1 of the special ferromagnetic alloy thickness b=10 mm, compacted in a laminated rotor 2 package of electrical steel 2411. Bush has one frontal outreach 3 length of 50 mm of the same alloy to reduce the equivalent resistance of the rotor winding. The alloy contains in % copper Cu – 18.7, carbon C – 0.06, manganese Mn – 0.91, silicon – 0.28, P – 0.054, sulfur S – 0.017, chromium Cr – 0.06, nickel Ni – 0.25, aluminum Al – 0.21, iron Fe – the rest [23].

Variant 5. The two-layer rotor [14, 12] (Fig. 10) with the sleeve 1 steel St. 3. Thickness 3 mm, b = 8. Sleeve has one frontal outreach 3 length of 50 mm.

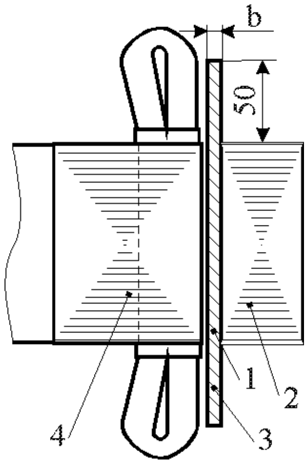

Fig. 10. Scheme for construction of a two-layer rotor AMF: 1 – ferromagnetic sleeve, 2 – package a laminated rotor, 3 – frontal outreach of sleeve material, 4 – stator

Variant 6. The two-layer rotor (Fig. 11), the coil which is one of the ferromagnetic sleeve steel St. 3, 8 mm thick, pressed in a laminated rotor package 2 of electrical steel in 2411. By the sleeve 1 soldered copper brass ring 3 to reduce the resistance of the rotor winding.

At the beginning of the test net power induction motor in the motor-fan determined to "squirrel cage" (winding rotor 9, Fig. 5) aluminum alloy AK12M4 with an electrical resistivity $\rho = 0.0952 \cdot 10^{-6}$ Ohm·m at a temperature of 115ºC. Fulfilling experience idling (no blades 7). We determined the stator iron losses and mechanical losses for rated power mode with frequency 100 Hz, and a phase voltage 230 V. Experiments were also conducted at idle power for other frequencies below 100 Hz.

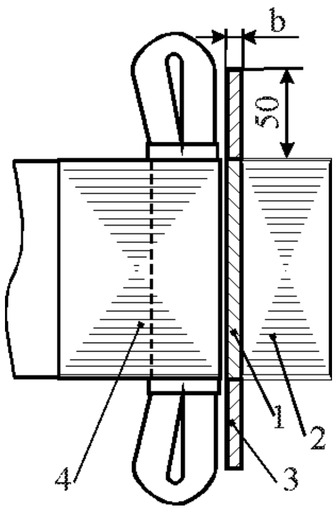

Fig. 11. Scheme for construction of a two-layer AMF rotor and copper frontal outreaches: 1 – ferromagnetic sleeve of steel St. 3, 2 – a laminated rotor package, 3 – ring of copper M1 (frontal outreach), 4 – stator

The shape of the voltage – sinusoidal. The maximum voltage for these experiments was set proportional to the square of the frequency of the current. Next to the fan wheel 6 (Fig. 5) were welded blades 7 at an angle of 18 degrees, and the stand was carried out under a load of experience at the same frequencies and the current values of the maximum stress that the experiments and idling. The method of separation of losses to determine the relation of the net power of the fan wheel speed.

Measuring instruments used in class 0.5. The maximum error in the determination of net power does not exceed 0.5% of the active power supplied to AMF, as additional losses in the AMF to be equal to 0.5% of the input power to the AMF according to GOST 183-74 "Rotating electrical machinery. General specifications" (experimentally determine them was not possible). Thus the experimental characteristics (efficiency, cosφ) motor fan with a different rotor design were determined using the same net power AMF depending on the speed.

Table shows the results of experimental studies of AMF in the nominal mode. Fig. 12 shows the results of experimental investigations of options rotors number 1 – № 3 in the regulation of sinusoidal voltage, from which it follows: AMF with squirrel-cage rotor alloy AK12M4 not controlled by varying the voltage on the stator winding (at U <100 V – "tipped") with AMF copper rods (z_2 = 28) and the steel ring is not good enough in regulating energy characteristics (maximum current value I_{max} in regulating a half times the nominal value I_n) with AMF rotor winding of a brass rod (z_2 = 42) and rings of steel St. 3 has a good leveling properties ($I_{max} = 1.25 I_{max}$).

Table. The results of experimental studies of AMF in nominal mode (supply frequency – 100 Hz, phase voltage – 230 V)

The embodiment of the rotor	Active power consumption, kW	The power factor, cosφ	Efficiency, %	Slip of the motor, %	Useful power, kW
№1	27.0	0.74	90.0	1.44	24.4
№2	26.4	0.65	88.0	3.1	23.4
№3	27.0	0.64	86.0	5.0	23.2
№4	26.6	0.73	87.6	4.6	23.3
№5	26.1	0.67	85.0	6.7	22.2
№6	26.1	0.73	88.5	3.5	23.1

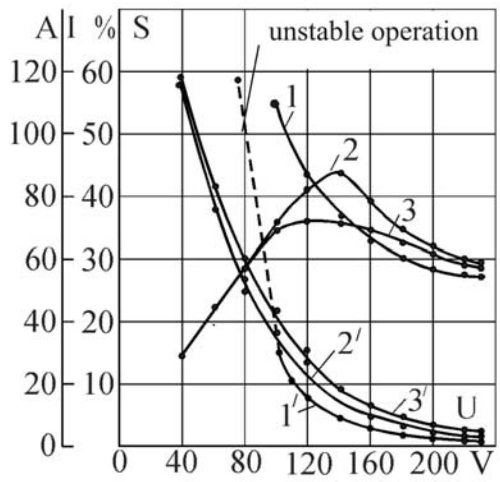

Fig. 12. Dependence consumed current I (1-3) of rotor and slip s (1'-3') AMF supply voltage at various squirrel cage construction: 1 – rotor embodiment 1, 2 – № 2, 3 – № 3

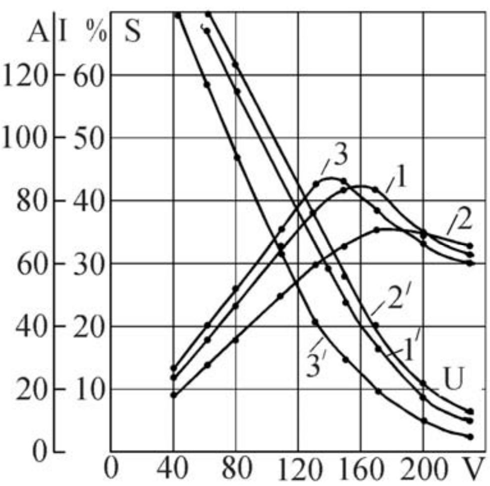

Fig. 13. Dependence consumed current I (1-3) of rotor and slip s (1'-3') AMF supply voltage for different rotor-layer ferromagnetic sleeves 1 – embodiment number of the rotor 4, 2 – № 5, 3 – № 6

CONCLUSIONS

1. From the design of the rotor compared (Table, Fig. 12-13) that the most rational choices are: squirrel cage rotor with brass rods and ferromagnetic short-circuiting rings of steel St. 3 (variant 3) and double-layer rotor-magnetic alloy (variant 4). At acceptable nominal characteristics (efficiency 86.0-87.6%, cosφ 0.64-0.73) motor fans have good regulation properties, with a maximum current of the stator in the regulation of 1.25-1.3 of the rated value.

2. However, variants number 3 and number 4 are significant shortcomings in series production. Variant number 3 requires a manual and labor-intensive technology soldered brass rods to steel rings – for AMV 24 kW with the number of poles $2p=6$, the number of solder joints is $2z_2=84$ for AMF power of 65-75 kW with the number of poles $2p=8-10$ number of solder joints is $2z_2=168-216$. For option number 4 to cast a special low-magnetic alloy. In fact - it is a solid solution [19].

3. For the manufacturing application to the series locomotives are also needed additional vibration testing of solder joints and low-magnetic alloy in order to determine the mechanical characteristics of the winding under severe operating conditions, AMF operation - by vibrations during rotation of the rotor windings in single-bearing rotor blades (see Fig. 5), which summed up with the vibration of the body of the locomotive diesel engine is running, and dynamic accelerations during the motion of the locomotive.

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РАЦИОНАЛЬНАЯ КОНСТРУКЦИЯ РОТОРА АСИНХРОННОГО РЕГУЛИРУЕМОГО МОТОР-ВЕНТИЛЯТОРА ДЛЯ ОХЛАЖДАЮЩИХ УСТРОЙСТВ ТЕПЛОВОЗОВ

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Аннотация. Приведен сравнительный анализ конструкций и характеристик асинхронных мотор-вентиляторов (АМВ) по результатам экспериментальных исследований натурных образцов на стенде. Определен рациональный вариант АМВ, частота вращения которого регулируется изменением напряжения на обмотке статора, для новых тепловозов. Определены достоинства и недостатки рационального варианта.

Ключевые слова: асинхронный мотор-вентилятор, скольжение, конструкция ротора, регулирование частоты вращения.