Представлені можливості підвищення енергетичних показників трифазних загальнопромислових асинхронних електродвигунів (АД), що використовуються у автономних плавальних апаратах (АПА). На основі методу аналогій обґрунтовано застосування укорочених трифазних чотириполюсних АД замість двополюсних. Розраховані основні конструкційні й енергетичні характеристики модернізованих АД. Доведено, що для модернізованого чотириполюсного АД АПА суттєво знижуються масогабаритні показники при мінімальній його конструкційної модернізації

Ключові слова: автономний плавальний апарат, енергетичні показники, трифазний асинхронний електродвигун, частотний перетворювач

Представлены возможности повышения энергетических показателей трехфазных общепромышленных асинхронных электродвигателей (АД), применяемых в автономных плавательных аппаратах (АПА). На основе метода аналогий обосновывается применение укороченных трехфазных четырехполюсных АД вместо двухполюсных. Рассчитываются основные конструкционные и энергетические характеристики модернизированных АД. Доказано, что для модернизированного четырехполюсного АД АПА существенно снижаются массогабаритные показатели при минимальной его конструкционной модернизации

Ключевые слова: автономный плавательный аппарат, трехфазный асинхронный электродвигатель, частотный преобразователь, энергетические показатели

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ANALYSIS OF POSSIBILITIES FOR IMPROVING ENERGY INDICATORS OF INDUCTION ELECTRIC MOTORS FOR PROPULSION COMPLEXES OF AUTONOMOUS FLOATING VEHICLES

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1. Introduction

Modern autonomous floating vehicles (AFV) [1, 2] implement technological tasks of various type and purpose – both civilian and military applications [2–4]. Almost all propulsion [3, 4] AFV complexes are created based on electromotive systems with different types of propeller electrical motors. Duration of autonomous navigation, as well as basic economic and tactical-technical characteristics (TTC) of AVF, are largely determined by the efficiency of the propulsion complex, specifically its general weight and size indicators and its performance efficiency coefficient. Existing AFV [1], as well as newly-developed prospective samples of AFV, utilize as propulsion electric motors the induction three-phase electric motors (IM), both baro-unloaded [6] and of general industrial use.

Given the structural considerations, as well as TTC requirements to highly specialized AFV, it is necessary to regulate rotation frequency of the shaft of an electric motor in the range from 500 to 3,500 rpm. In this case, control over linear velocity of AFV movement is executed by frequency converters (FC) of various types, usually standard industrial, designed for marine application.

The main characteristic of economic feasibility of using the system of electric motion of AFV based on FC with IM is the capital costs. The electric propulsion system manufacturing costs are determined mostly by its specific materials consumption G. It should be emphasized that the materials consumption for a flexible shafting, couplings, a gearbox, and AFV propeller is an almost constant magnitude.

The cost of structural and insulation materials amounts to approximately 25 % of the total cost of materials that IM is made of. For electric motors with power up to 0.5 kW, at the same height of the rotation axis, this cost is practically constant and thus could be disregarded. The only possibility to reduce the overall material consumption is to bring down specific materials consumption for the propeller IM. However, the resulting energy efficiency of IM is highly dependent on the amount of active materials (steel, copper) used in it. For IM, specific materials consumption is an integrated indicator, which includes: the mass of copper of a winding wire *Gm,* the mass of aluminum of a shirt-circuited rotor winding *Ga*, the mass of steel of stator *Gs* and rotor *Gr*. Therefore, when performing a structural modernization (redesign), or when creating new types of IM, these indicators should be subjected to comparative analysis as they significantly affect the resulting energy efficiency of an electric motor.

2. Literature review and problem statement

Papers [7, 8] outline the main directions for improvement, principles and possibilities for enhancing the energy efficiency of controlled induction motors. These works show ways for the development and improvement of energy efficiency (improvement of insulation, winding materials, cooling, steel) of standard industrial IMs intended for mass applications. They, however, fail to consider opportunities to improve energy efficiency of high frequency low power IM (with a rated frequency exceeding 50/60 Hz).

There are well known developments of high-frequency (200 and 400 Hz) low-voltage IM for handheld electric tools [9, 10], aviation and medical equipment, powerful high-voltage IM for auxiliary cooling systems of locomotives (100 Hz), traction systems of electric transport, and others. But the low power IM are most often used at high speeds of rotation (over 3,000 rpm), which is unacceptable for the propulsion systems of AFV; the character of load in the AFV electric propulsion system and that, for example, of the traction system of electric transport, differ significantly.

Bipolar general-purpose IM (4A, AIR, 5A) with a power up to 1 kW [7, 8] are very close and almost identical in terms of energy performance indicators (performance efficiency coefficient – 0.6...0.68, cosφ – 0.7...0.77) and specific materials consumption (total weight: steel of stator and rotor – 1.35...2.1 kg, copper of windings – 0.4...0.54 kg). The efforts of engineers in the field of electromechanics are aimed at increasing the proportion of percentage for the performance efficiency coefficient and cosφ.

A promising direction to improve energy efficiency is the structural modernization (re-engineering) of IM, including for the AFV electric propulsion systems with FC. Such a possibility is discussed in [10] with its essence being the application, instead of bipolar standard industrial IM, of four-pole IM. Energy efficiency assessment and calculation of losses in the IM, similarly modernized, are also given in [10]. However, a given paper investigates the possibility of structural modernization of standard IM for work from industrial frequency converters, with no changes to the length of the machine. In addition, authors of [10] employ proprietary original software that is out of reach for a wide range of researchers. It is shown in [11, 12] that the possibilities for structural modernization of existing three-phase industrial IM, under condition of minimal costs, remain insufficiently investigated, they require justification, clarification, and further development.

The prospects for application of modernized standard IM are predetermined by the fact that, when IM is powered by voltage with the frequency increased in proportion to the number of pairs of poles, there is a reduction in the basic dimensions of the stator and rotor. In this case, it is necessary to:

a) provide IM with a rated voltage of 100 Hz [11, 13] while maintaining electromagnetic loads;

b) change main dimensions of the stator, rotor, and winding data [11, 14].

Comparative experimental research for specific types of AFV is rather difficult because there emerges a need for manufacturing separate (experimental) pieces of two-, four- and six-pole IM with the same seats. At present, such experiments are unnecessary because the modern theory of electrical machines makes it possible to accurately enough calculate the expected characteristics of an upgraded IM. During estimation calculations, it is very effective to apply the method of analogies for geometrically similar electrical machines [7]. Thus, to compare different variants, it is possible to use reference data on standard industrial IM, for example, series 4A [8].

It is obvious that there could be a noticeable saving of active materials and improvement of energy characteristics when using the system FC-IM with modernized electric motor as compared to employing bipolar IM that operate at a rated frequency of 50 Hz. A significant shortcoming because of which the system FC-IM is poorly implemented in AFV is the cost of standard FC, which makes up about 25 % of the total cost of AVF propulsion complex. It should be noted that most of serial FC are not only poorly integrated into AFV but also have such service, configuration, diagnostic and safety features that prove to be redundant for AFV but definitely add up to their price. It is clear that there is a need to create FC that would be simpler in design and circuitry, aimed specifically for use in AFV, which is the subject of a separate study.

An analysis of procedures for the recalculation of parameters of general-purpose IM based on the method of analogies of geometrically similar electric machines is the subject of this study. Such an analysis would make it possible to identify possibilities to improve energy indicators of standard industrial IM to be used in the AFV propulsion complexes.

It could be argued [7, 12–14] that structural-technological possibilities for improving energy characteristics of virtually any type of IM have been almost exhausted. Therefore, any additional opportunities to improve technical-economic indicators of IM, used in the AFV propulsion complexes, are in high demand in the practice of specialized shipbuilding.

3. The aim and objectives of the study

The aim of present study is to estimate possible energy indicators of induction three-phase electric motors of general industrial application, used in AFV, at their minimal structural reconfiguration to an increased frequency of their voltage supply.

To accomplish the aim, the following tasks have been set:

– to estimate the possibility of applying multi-pole IM at increased frequency of a power source;

– to conduct a comparison between basic technical and energy characteristics of various structural adaptations of IM at the same height of rotation.

4. Material and methods of research

4. 1. Preliminary estimation of the possible application of three-phase general-purpose IM at increased frequency of a power source

Let us analyze a decision on the possibility of applying a four-pole IM in the AFV propulsion complex. An analysis will be based on the example of comparison of designs of the most common IM with a synchronous rotational frequency of 3,000 rpm at a rated power frequency of 50 Hz. In order to validate a change in the design of a four-pole IM, we shall compare parameters of electric motors, series 4A, of general (standard industrial) purpose (Table 1–3), which are similar in:

a) the height of rotation axis (50 mm);

b) the rated power (90 W);

c) the build for a degree of protection (*IP*44);

d) climatic design (U3);

e) cooling mode (*ICA*0141).

Table 1

IM rated parameters [13, 14]

Parameter	4AA50A2U3	4AA50V4U3
ω_0, rad/s	314	157
P_n, W	90	90
s_n, %	8.6	8.6
η_n, %	60	55
$\cos\varphi_n$	0.7	0.6
M_n, N·m	0.31	0.62
ω_n, rad/s	287	143.5
$k_{\max}$	2.2	2.2
k_n	2.	2.0
k_i	5.0	5.0

Table 2

IM winding parameters [13, 14]

Parameter	4AA50A2U3	4AA50V4U3
D_{a1}, mm	81	81
D_{i1}, mm	41	46
l_1, mm	42	50
h_1, mm	9.6	11.0
z_1, pcs.	12	12
δ, mm	0.25	0.25
l_m, mm	294	246
d, mm	0.27	0.31
m, kg	0.44	0.55
R, Ohm	82.5	59.1

Table 3

IM stator electromagnetic loads [13, 14]

Parameter	4AA50A2U3	4AA50V4U3
B_δ, Tl (specification)	0.62	0.68
A_1, A/cm (specification)	105	152
J_1, A/mm^2 (specification)	4.4	4.9
B_{c1}, Tl (estimated)	1.51	1.63
B_{z1}, Tl (estimated)	1.75	1.84

The following designations are accepted in Table 2 and in Fig. 1:

D_{a1} and D_{i1} are, respectively, the external and internal diameters of the stator core;

l_1 is the length of the stator core;

h_1 and z_1 are, respectively, the height of the tooth and the number of stator slots;

δ is the one-way air gap between stator and rotor;

L_{av} is the average length of a coil winding;

d and m are, respectively, the diameter of a wire (without insulation) and its mass;

R is the resistance of phase at 20 °C;

B_δ, B_{c1} and B_{z1} is the maximum value of magnetic induction in, respectively, the gap, back, and the stator tooth layer.

Comparative analysis of data in Table 1 and Table 3 reveals:

– due to the smaller size of the front parts of the winding and greater tooth height, maximum electromagnetic loads (B_δ, A_1) and current density J_1 for a four-pole and a six-pole IM can be markedly greater than that of the bipolar IM;

– due to different designs and patterns in the formation of a rotating magnetic field by a four- and six-pole IM, a bipolar motor, all other things being equal, demonstrates larger values of performance efficiency coefficient and of power factor.

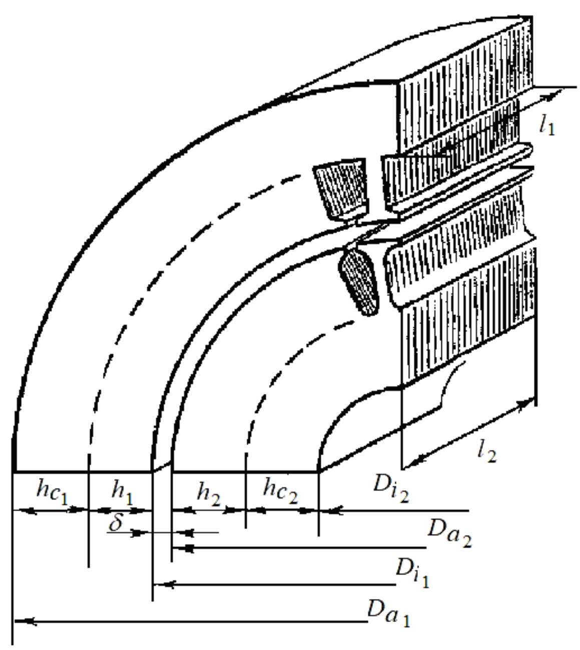

Fig. 1. Design of stator core

Basic dimensions that characterize IM mass and size and, consequently, the entire propulsion complex of AFV, are the internal diameter of stator D_{i1} and stator core length l_1. Changing the diameter of the core will lead to changes in the technological process of stamping and need to calculate the new geometry of the slots, which it is not desirable for economic reasons. Therefore, we shall consider the possibility of reducing IM mass and size indicators at the expense of changes in length of the stator core l_1. It should be noted, however, that the lids and bearing units of the motor remain unchanged, which would also have a positive impact on the resulting cost of IM.

Therefore, one should expect that increasing the frequency of supply voltage while maintaining the electromagnetic loads constant, the performance efficiency coefficient and cosφ of multi-pole IM will also grow and may even surpass analogous values of bipolar IM. At the same time, multi-pole IM will have a significant margin of power and electromagnetic moment [3, 4].

4. 2. Analytical dependences and theoretical substantiation of comparison sequence of the basic characteristics of modernized IM

We can write based on the main estimation-structural equation [14] for electric machines (the Arnold constant):

$$D_i^2 \cdot l_1 = P_n / (k_B \cdot k_{w1} \cdot a_i \cdot \omega_n \cdot B_\delta \cdot A_1), \qquad (1)$$

where, for the examined machines of the same size, the following are accepted to be constant: $k_B \approx 1.11$ is the sinusoidal field curve shape factor in the gap; $k_{w1} \approx 0.96$ is the winding coefficient for the fundamental harmonic of emf; $a_i \approx 0.64$ is the pole overlapping coefficient equal to the ratio of average value of magnetic induction in the gap $B_{\delta av}$ to its maximum value B_δ; A_1 is the linear load, derived from expression

$$A_1 = \frac{2 \cdot m_1 \cdot w_1 \cdot I_1}{\pi \cdot D_1},$$

where we denote m_1 to be the number of phases of the stator and I_1 is the stator phase current, A. It is possible to take without a large error that dependence $A_1 = f(l_1, f_1, w_1)$ is linear relative to electromagnetic load $B_\delta = f(l_1, f_1, w_1)$. Therefore, we can assume that magnitude A_1 will remain unchanged at a decrease in length of the stator l_1, at an increase in frequency f_1 and at a proportional change in the number of windings w_1.

The product $A_1 \times B_\delta$, recorded in (1), of the full current of slot layer A_1 of the stator (linear load) by the maximum value of magnetic induction in the gap B_δ for each machine is a constant magnitude. The value of magnetic induction in the machine [16] is defined by expression:

$$B_\delta = \frac{\Phi}{\alpha_i \cdot \tau \cdot l_1 \cdot 10^{-6}},$$

where Φ is the basic magnetic flux of the stator, Wb; $\tau = \pi D_1/(2p)$ is the pole division, mm. In turn, magnetic flux of the machine is determined from expression:

$$\Phi = \frac{E_1}{4 \cdot k_B \cdot f_1 \cdot w_1 \cdot k_{w1}},$$

where E_1 is the stator emf, V; w_1 is the number of sequentially-connected coils of a stator phase winding; f_1 is the voltage frequency.

Expression:

$$D_i^2 \cdot l_1 \sim P_n / \omega_n = M_n, \qquad (2)$$

explains known assertion [2, 15] on that at assigned power P_n and electromagnetic loads A_1 and B_δ the consumption of active materials for the manufacture of an electric machine will be the less the higher its rated rotation speed ω_n.

The ratio K_M of the moments of a four-pole and a bipolar IM:

$$K_M = \frac{(D_i^2 \cdot l_1)_4}{(D_i^2 \cdot l_1)_2} = \frac{(46 \cdot 10^{-3})^2 \cdot 50 \cdot 10^{-3}}{(41 \cdot 10^{-3})^2 \cdot 42 \cdot 10^{-3}} \cong 1.5,$$

was derived from the basic geometrical dimensions of machines (Table 2) at equal rotation frequencies. This ratio allows us to argue about the possibility of reducing the length of the stator core of a four-pole machine, from approximately 50 mm to 33.4 mm, while maintaining the same rated moment as a bipolar machine demonstrates. In this case, it is necessary to also ensure that the electromagnetic loads (B_δ, A_1) are unchanged.

We shall reduce, with a 10 % margin for the moment, the length of the stator pack to a value of l_1=37 mm and, determine, based on Fig. 1 and data given in Table 1–3, for subsequent comparison, a number of structural and energy parameters.

Note that the number of turns in the winding of a four-pole IM, when passing to the frequency (100 Hz) of power that is twice as large, must be two times less.

Therefore, when switching two successive branches, existing in IM, to the parallel connection, the number of turns will be twice as less. In this case, resistance is reduced four times, causing a corresponding decrease in electrical losses for excitation. The relative sliding will also drop two times (as the rigidity of the working area of mechanical characteristic remains unchanged), which will also cause a reduction, proportional to sliding, in the electrical losses in the rotor winding.

Basic magnetic losses (hysteresis and vortex currents) in IM are determined by the losses in stator steel:

$$\Delta P_{st1} = \Delta P_{c1} + \Delta P_{z1}, \qquad (3)$$

where ΔP_{c1} and ΔP_{z1} are, respectively, the losses in the back and in the stator tooth layer.

Losses in the back and in the stator tooth layer are determined from formulae [15, 16]:

$$\Delta P_{c1} = k_\tau P_{1,0/50} (f / f_n)^\beta B_c^2 m_{c1}, \qquad (4)$$

$$\Delta P_{z1} = k_\tau P_{1,0/50} (f / f_n)^\beta B_z^2 m_{z1}, \qquad (5)$$

where k_T=1.7 is the technological assembly factor; $P_{1,0/50}$ and b are, accordingly, specific magnetic losses, W/kg, and an exponent, depending on the brand of steel used (for steel of grade 2211: $P_{1.0/50}$=2.6 W/kg and β=1.5; for steel of grade 2312: $P_{1.0/50}$=1.75 W/kg and β=1.4; 1.5 Tl<B_c<1.65 Tl; 1.75 Tl<B_z<1.95 Tl); m_{c1} and m_{z1} are, respectively, the mass of the back steel and the tooth layer steel, kg, defined based on the estimated volume, which is determined from [15, 16] at a density of electrical steel of $7.8 \cdot 10^3$ kg/m^3.

Losses in the steel of rotor ΔP_{st2} are very small and can be taken equal to:

$$\Delta P_{st2} = 0{,}1 P_{st1}. \quad (6)$$

Electrical losses in the stator copper are derived from expression:

$$\Delta P_{e1} = 3 I_{1n}^2 R_{75\,^\circ\mathrm{C}} \quad (7)$$

and in the rotor winding –

$$\Delta P_{e2} = (P_{el} - \Delta P_{st1} - \Delta P_{e1}) s_n, \quad (8)$$

where $P_{el} = 3 U_n I_{1n} \cos\varphi_n$ is the electromagnetic power in air gap δ.

Mechanical losses are taken to be constant:

$$\Delta P_{mec} = 0.01 P_n. \quad (9)$$

Additional losses:

$$\Delta P_{add} = 0.005 P_{em}. \quad (10)$$

Applying the data that describe geometry of the semi-closed trapezoidal groove, we calculate masses of the active parts of the motor, included in (4) and (5), and the corresponding losses. Then we derive parameters [15] for IM phase equivalent circuit and calculate coefficients of power.

Magnetic losses in steel due to vortex currents and hysteresis depend on power source frequency f, the second degree of induction amplitude B, and a function $f_1(s, k)$ of sliding s [15, 16]:

$$\Delta P_{st} = \Delta P_{st_n} \cdot \left(\frac{f}{f_n}\right)^k \cdot \left(\frac{B}{B_n}\right)^2 \cdot f_1(s,k), \quad (11)$$

where $f_1(s,k) = \left(1 + s^k\right)$, k is the exponent that depends on the brand of electrical steel applied. At a frequency of 100 Hz these losses are higher than at a frequency of 50 Hz. However, by reducing the electrical losses and the mass of stator steel, relative cumulative losses in a shortened IM become smaller (Table 5). There is an increase in the shaft power (102 W) and in the resulting IM performance efficiency coefficient.

It should be noted that active resistance of the stator phase can be calculated from expression:

$$R_1 = \frac{\rho_m \cdot w_1 \cdot \left(l_1 + l_f\right) \cdot 2}{q_w}, \quad (12)$$

where ρ_c is the specific electric resistance of copper, l_f is the length of the frontal part of the stator winding, q_w is the cross-sectional area of the stator winding wire. It is clear that when the number of conductors in the stator groove changes, it is necessary to change the section of stator winding conductors in order to maintain the constancy of the groove copper fill factor. The new value of the wire section can be defined from formula:

$$q_w' = q_w \cdot \frac{w_1}{w_1'} = q_w / K_w \quad (13)$$

and choose the nearest standard value from a catalog. Magnitudes q'_w and w'_1 represent the new values of a wire section and the number of turns in the stator winding, respectively.

According to expressions (12) and (13), resistance R_1 is directly proportional to the second degree of the number of turns in the stator winding and the stator core length:

$$R_1 = \left(K_1 \cdot K_l + K_l\right) \cdot K_w^2 \cdot R_{1n}, \quad (14)$$

where R_{1n} is the nominal value of active resistance of the stator phase at a frequency of 50 Hz; K_1 and K_f are coefficients that depend on the ratio of lengths of the active l_1 and the frontal parts of the stator winding:

$$K_1 = \frac{l_1}{l_1 + l_l}, \quad K_l = \frac{l_l}{l_1 + l_l}. \quad (15)$$

Inductive resistances of dispersion of stator and rotor can be calculated from expressions:

$$X_1 = \frac{\pi \cdot f_1 \cdot l_1 \cdot w_1^2}{2 \cdot p \cdot q_1 \cdot 10^5} \lambda_1, \quad X_2' = \frac{7{,}9 \cdot k_{w1} \cdot f_1 \cdot l_2}{10^6} \lambda_2, \quad (16)$$

where λ_1 and λ_2 are the magnetic conductivity coefficients of dispersion of the stator and rotor, respectively, q_1 is the number of grooves per a pole and a phase, $l_2 = l_1$ is the core length of rotor, k_{w1} is the coefficient of reduction of the rotor winding resistance to the stator winding, proportional to the second degree of the number of turns in the stator winding ($k_{np1} \sim w_1^2$). Coefficients λ_1 and λ_2 are weakly non-linear dependent on the stator core lengths l_1 and this dependence can be neglected. Given the above, it can be assumed that inductive resistances of the stator and rotor scattering are determined by expressions:

$$X_1 = K_l \cdot K_f \cdot K_w^2 \cdot X_{1n}, \quad X_2' = K_l \cdot K_f \cdot K_w^2 \cdot X_{2n}', \quad (17)$$

where X_{1n} and X'_{2n} are the nominal values of inductive resistances of scattering of the stator and rotor at a frequency of 50 Hz.

In the most general case, the main inductive resistance of stator winding X_m depends on the magnitudes of l_1, w_1 and f_1 nonlinearly, mainly due to the nonlinearity of the magnetization curve of steel that the stator and rotor of the machine are made of. However, by ignoring the error that occurs, it can be argued that the magnitude of main inductive resistance X_m is directly proportional to the second degree of the number of turns in the stator winding, to the supply voltage frequency, and to the length of the stator core:

$$X_m = K_l \cdot K_f \cdot K_w^2 \cdot X_{mn}, \quad (18)$$

where X_{mn} is the rated value of the main inductive resistance of the stator winding at a frequency of 50 Hz.

5. Results of the analysis of compared induction electric motors

Applying the above-described sequence of calculations, the main results of comparison of nominal parameters of IM, identical for the height of rotation, are summarized in Table 4, 5.

Table 5 shows that, for example, mass of the active materials can be significantly reduced (from 1.52 to 1.32 kg) while ensuring a higher resultant performance efficiency coefficient (61 %).

Table 4

Basic specified and estimated rated parameters of compared IM

Rated parameters	4AA50A2U3	4AA50V4U3, standard	4AA50V4U3, shortened
Power source frequency, f_n, Hz	50	100	100
Moment, M_n, N×m	0.31	0.46	0.34
Speed, ω_n, rad/s	287	300	300
Power, P_n, W	90	138	102
Phase current, I_{1n}, A	0.32	0.50	0.37

Table 5

Structural and energy parameters of compared IM

Parameter	4AA50A2U3	4AA50V4U3, standard	4AA50V4U3, shortened
Stator winding	No changes	Branch re-commutation	Branch re-commutation
Wire diameter, d, mm	0.27	0.31	0.31
Mean length, mm:			
l_t, turn	294	246	220
l_f, frontal part	105	73	73
l_w, working part	42	50	37
Phase resistance, $R_{75\,°C}$, Ohm	98	17.5	15.7
Losses in stator copper, ΔP_{e1}, W	30.1	13.1	6.5
Losses in rotor winding, ΔP_{e2}, W	9.3	7.8	5.3
Mass/volume, kg/mm^3:			
back	0.67/85,900	0.45/58,000	0.33/42,980
teeth	0.42/53,850	0.69/88,157	0.51/65,320
stator	1.09/139,750	1.14/146,157	0.84/108,300
rotor	0.43/55,440	0.65/83,050	0.48/61,500
Mass of active part, kg	1.52	1.79	1.32
Losses in stator steel, ΔP_{st1}, W	10.1	44.1	37.2
Losses in rotor steel, ΔP_{st2}, W	1.0	4.4	3.7
Mechanical losses, ΔP_{mech}, W	9.0	14.0	11.0
Additional losses, ΔP_{add}, W	0.8	1.2	1.0
Total losses, ΔP_{S}, W	60.3	84.6	64.7
IM rated performance efficiency coefficient, η_n	0.6	0.62	0.61
Power factor, $\cos\varphi_n$	0.7	0.68 (0.98)	0.68 (0.98)
FC rated performance efficiency coefficient, η_n	–	0.95	0.95
Energy factor, k_e	0.42	0.57	0.56

Note: values in brackets denote power factor when we enable active power factor corrector from the side of a power source.

6. Discussion of results of the analysis of compared induction electric motors

Discussing the results, it should be stressed that this work was not aimed at designing an optimal new IM; instead, we demonstrated the expediency of use of available resources – to reengineer (to modernize structurally, to redesign) standard IM of low power with a view to their application in floating vehicles for special purposes. This is why the rated frequency of the power source is not optimized; it is determined only by the use of a multipole IM.

Thus, a 100 Hz frequency is chosen for illustrative purposes only, to illustrate the sequence of calculation, to estimate the resulting energy efficiency, to demonstrate the identified benefits.

The relevant task is to as quickly as possible equip AFV for special purposes with an effective and inexpensive propulsion complex; it relates to solving a particular task. This particular task comes down to creating AFV, based on the electromotive system, that would perform a specialized technological function, close to [4]. It must be taken into consideration that it is required, when creating such a device as AFV, which is new for Ukraine:

a) to enable control over rotation speed of the propulsion complex of AFV;

b) to ensure the fulfillment of certain additional tasks and requirements to the functioning of AFV, including to a power source, control, navigation, positioning, communication, additional devices, mechanisms.

Comparative analysis of winding data and geometrical dimensions of IM of low power, proposed for application in the propulsion complex of AFV, reveals that due to the smaller size of the frontal parts of the winding, larger height of the teeth and greater step of laying, the maximum electromagnetic loads of a four- and a six-pole motor are noticeably higher than those for a bipolar motor.

In general, it is necessary to solve the task on consistent design of a special-purpose vessel. It implies the minimization of AFV cost, ensuring minimum weight and size indicators at the highest possible payload, the minimization of AFV design and building time. Such a task is solved only based on the systems approach [19, 20].

Fabrication of active part of the motor using the steel of brand 2311 with a high content of silicon makes it possible to reduce absolute losses in the steel of stator and rotor and thereby increase the resulting performance efficiency coefficient of IM by a further 0.8...1.2 %. Such an increase in performance efficiency coefficient is explained by certain features of the chemical composition of modern electrotechnical steels, specifically the presence of silicon, preventing the formation of chemical compounds of iron (FeO and Fe_3C), which increase the losses for hysteresis.

Specific electrical resistance ρ of electrotechnical steel depends on the amount of silicon. The resistance is the higher the larger is the content of silicon in steel (the steels of grade E1 have resistance $\rho=0.25$ Ohm·mm^2/m, grade E4 – 0.6 Ohm·mm^2/m).

The presence of silicon in iron in quantities of 4 % or higher increases specific electrical resistance ρ compared to pure iron, resulting in markedly reduced losses for vortex currents. Saturation induction Bs of iron increases significantly with an increase in its silicon content (at 6.4 % silicon, Bs=2,800 Gs).

An increase in the silicon content leads to the enhanced resultant performance efficiency coefficient in transducers and electric motors, however, the fragility of steel increases, that is mechanical strength of the engine design is compromised. Therefore, the addition of silicon up to 4.8 % is the limit.

Note that for a four-pole IM, in contrast to a bipolar IM, it is possible to use anisotropic cold rolled steel, for example, brand 3413 with a sheet thickness of 0.35 mm ($P_{1.5/50}=1.3$ W/kg, $P_{1.7/50}=1.9$ W/kg), which would produce an additional increase in the resulting performance efficiency coefficient of not less than 0.2 %. Such an enhanced performance efficiency coefficient is explained by peculiarities of technological process in the production of modern electrotechnical steels. There are cold- and hot-rolled electrotechnical steels. Iron has a cubic crystalline structure. As regards IM and transducers, it is desirable that all iron crystals of iron in a sheet should be arranged (while rolling) in rows along the edges of the cube (anisotropy). This is achieved by the multiple rolling of sheets with strong compression and annealing in the hydrogen atmosphere. Steel is thus purified from carbon and oxygen; the crystals are enlarged and oriented along the direction of rolling. Such a technology produces textured steel (anisotropic steel). Anisotropic steel's magnetic properties along the direction of rolling are noticeably higher than those of ordinary hot-rolled steel. High-quality textured steel sheets are manufactured only by cold rolling. Therefore, the magnetic permeability of steel is much higher while the losses for hysteresis are less than those of hot-rolled sheets. In addition, for the thinner cold rolled textured steel, induction in weak magnetic fields grows stronger than that of hot-rolled steel. In other words, the magnetization curve in weak fields lies much higher than the magnetization curve of hot rolled steel (at induction 1.0 Tl in the direction of rolling magnetic permeability $\mu_m=50{,}000$).

The main advantage of the proposed modernization of IM for AFV is a relatively simple technology that enables such a structural modernization. When implementing a given technology, there is no need to produce new stamps, no need to make new lids and bearing units. It is possible to employ very simple frequency converters without excess functionality. Some of the possible simple technical solutions are given in [17, 18]. Such converters do not contain internal protection, automatic configuration, the nodes of indication and self-diagnosis, which is why they are inexpensive and extremely technological in production.

Solution to use multi-pole IM at the elevated frequency of a power source is badly needed for AFV that fulfill the tasks similar to those described in [3, 4, 9]. For such tasks, the cost of material resources is critical.

The reported results of comparative calculations (Table 4, 5) by all means require confirmation for a larger number of compared IM with the same height of rotation. It is also required to refine electromagnetic loads after modernization, to carry out experimental study of the proposed changes. These are the tasks that would be essential for the further research.

7. Conclusions

1. We have established, based on the estimation of possible application of multi-pole IM at the elevated frequency of a power source, that such an application of IM is very effective, which is justified by the analogy methods of geometrically similar electric machines and the theory of electrical machines. As a result, it was found that such a possibility emerges when transferring four- or six-pole three-phase induction electric motors to the elevated (by two or three times) rated power frequency, provided the required electromagnetic loads are ensured.

2. Comparison of the basic technical and energy characteristics for various structural adaptations of IM with the same height of rotation was performed based on the analysis of technical-economic parameters of three-phase IM for AFV. The analysis was conducted for a technically simple modification of IM, specifically shortening the length of the stator and the appropriate redesign of the windings. The procedure accounts for key estimated ratios that make it possible to give a comparative assessment of mass and size and energy parameters of electric motors.

We have established, based on the comparison of motors 4AA50A2 and 4AA50V4, that upon a minimal structural modification the power of a redesigned motor increases from 90 to 102 W. At the same time, length of the stator core decreases from 50 to 33.4 mm, weight of the active part reduces by 0.2 kg, and the energy factor increases from 0.42 to 0.56. Such characteristics emerge subject to the application of cold rolled steels, with a high content of silicon, and the use of power factor corrector.

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