*Наведено аналітичні вирази та методика розрахунку, які дозволяють встановлювати енергетично ефективні режими роботи маршового трифазного асинхронного електродвигуна автономного плавального апарата. Завдання вирішується за рахунок оцінок поточних втрат потужності і необхідної напруги живлення при різних статичних навантаженнях. Встановлення аналітично визначених режимів роботи маршового електродвигуна дозволяє у системі електроруху мінімізувати струм або потужність і збільшити час автономної роботи плавального апарата*

*Ключові слова: автономний плавальний апарат, алгоритми управління, втрати потужності, баророзвантажений маршевий асинхронний електродвигун*

*Приведены аналитические выражения и методика расчета, позволяющие устанавливать энергетически эффективные режимы работы маршевого трехфазного асинхронного электродвигателя автономного плавательного аппарата. Задача решается за счет оценок текущих потерь мощности и необходимого напряжения питания при различных статических нагрузках. Установление аналитически определенных режимов работы маршевого электродвигателя позволяет в системе электродвижения минимизировать потребляемый ток или мощность и увеличить время автономной работы плавательного аппарата*

*Ключевые слова: автономный плавательный аппарат, алгоритмы управления, потери мощности, баторазгруженный маршевый асинхронный электродвигатель*

UDC 62-83:629.584
DOI: 10.15587/1729-4061.2017.118984

# DETERMINING ENERGY-EFFICIENT OPERATION MODES OF THE PROPULSION ELECTRICAL MOTOR OF AN AUTONOMOUS SWIMMING APPARATUS

**Ya. Volyanskaya**
PhD, Associate Professor*
E-mail: yanavolaynskaya@gmail.com
**S. Volyanskiy**
PhD*
E-mail: ffogres@yandex.ru
**A. Volkov**
PhD
Department of technical operation of the fleet**
E-mail: olegoni@mail.ru
**O. Onishchenko**
Doctor of Technical Sciences
Department of navigation**
E-mail: volkov55@bigmir.net
*Department of electrical equipment of courts and informative safety
Admiral Makarov National University of Shipbuilding
Heroiv Ukrainy ave., 9, Mykolayiv, Ukraine, 54025
**National University «Odessa Maritime Academy»
Didrihsona str., 8, Odessa, Ukraine, 65029

## 1. Introduction

Under current economic and political conditions in Ukraine, the state that has to maintain defensive functions of its maritime boundaries faces a difficult task to maximally quickly create autonomous swimming apparatuses (ASA) for special purposes (marine unmanned vehicles). Such ASA and their electrical equipment have been already designed, created at the shipyards and plants in the cities of Mykolaiv and Odessa. One particular task is to create, based on electromotive motion, a series of ASA, which would perform specialized technological operations similar to those described, for example, in [1].

We should take into consideration that it is required when creating such a new Ukrainian and highly technological device as an unmanned swimming apparatus:

a) to enable control over rotation frequency of propulsion [2] complex of the apparatus in a relatively small range at minimal capital costs, short time of pre-design and structural-technological preparation for production;

b) to ensure work of propulsion electric motor with a relatively low capacity (up to 500 Watts) under a baro-unloaded mode [3];

c) to be able to accomplish a number of additional tasks and meet requirements to design, overall architecture and operation of an unmanned vehicle, including power source, control, navigation, positioning, communication, work of additional devices, mechanisms, etc.;

d) to resolve a challenging task on designing a special-purpose vessel [4, 5] – to minimize the cost of the apparatus, to ensure minimum weight and size indicators at the maximum-possible special payload, to minimize duration of design and construction. Such a complicated and relevant problem is solved only based on a systems approach [4–7].

We emphasize that for small unmanned swimming devices the main is the cruising speed mode. This is the speed of motion at which a maximum of relation $\frac{\text{Distance traveled}}{\text{Fuel costs(energy)}}$ is achieved, that is, an apparatus without charging (recharging) can travel the longest possible distance.

For any unmanned swimming apparatus, the period of its autonomous work is a very important characteristic, which determines many of its technological features and capabilities. That is why the development of energy efficient (energy-saving) [8] systems for electromotive motion of unmanned APA [1] is an important and relevant scientific and technical task.

## 2. Literature review and problem statement

Concise analysis of electromotive systems and their development trends are outlined in [9, 10]. These papers show that at present there is no a unified opinion and no general principles for selecting the types of electric motors and their control systems. Modern electromotive systems of small unmanned swimming apparatuses are based on the baro-unloaded [3] asynchronous three-phase electric motors (AM) with electronic control system [10]. However, the patterns of power saving modes are paid very little attention to. Many studies have shown that the propeller screw [5, 7] renders main load to the engine of propulsion [2, 8] complex with rarely taking into consideration the fact that the load moment $M_c$ is close to the "fan" type [11, 12]. In the first approximation, a given moment is proportional to the second degree of propeller screw rotation frequency ω:

$$M_c=k_1(\omega+k_2)^2,$$

where $k_1$ and $k_2$ are coefficients that depend on the parameters of propeller (pitch, diameter, etc.), on the features of design of the propulsion [2, 12] complex, navigation mode, level of immersion of the propeller.

An analysis of known solutions [13–17] reveals that a rather effective tool is the application of frequency control techniques. For example, papers [14–17] describe many advantages of frequency vector and scalar control methods. However, the cost of such systems for ASA that would perform tasks [1, 18] turns out to be unacceptably high.

Even a small decrease in the motion speed of ASA significantly reduces static moment of resistance and propulsion AM operates under a partial load. In addition, the propeller, depending on the condition of ASA motion, can be immersed in water not completely. All this leads to complex changes in the nature of load on the apparatus propulsion AM. The specified peculiarities in the functioning of a propulsion complex make it possible in the electromotive system of ASA motion to employ known algorithms for controlling propulsion AM by modifying power at constant frequency. For small ASA that performs tasks [1, 8] with propulsion AM and a voltage converter, it is extremely important to note the following.

Firstly, the maintenance of energy efficient (energy-saving) [19] operation modes; second, their automatic setting. When determining duration of autonomous work of the device, the specified factors are decisive.

An analysis of the scientific literature that we conducted reveals that energy-saving modes and operation algorithms for low-powered electromotive systems of ASA have not been sufficiently studied up to now. Known publications did not specify if the total losses for propulsion AM of low power (to 250 W) could be reduced. There are no estimates of conditions for achieving a minimum of power losses. It was not shown whether it is possible to attain stabilization of minimum values of current, of maximum performance efficiency, and of power factor. There are no clear-cut functional dependences of the effect of current slip, the type of steel used in AM, cooling technique, bearings condition and so on the total losses of the baro-unloaded AM. These are the problems and unresolved tasks that require detailed study.

## 3. The aim and objectives of the study

The aim of present study is to determine energy-efficient modes of operation of the propulsion baro-unloaded three-phase asynchronous electrical motor of the propulsion complex of ASA for the assigned energy parameter, based on estimates of total losses under preset conditions and assumptions.

To achieve the set aim, the following tasks have been solved:

– to estimate possibilities for reducing power losses during work of the electromotive system of ASA and to determine the values of magnetic flux at which, for the steady operation mode and incomplete load, the summary losses would be minimal;

– to analyze dependences of performance efficiency and current of the stator for AM of low power at a voltage change and under different static loads;

– to establish basic features and requirements to the control system over propulsion AM of ASA.

## 4. Material and methods of research

When propulsion AM operate in the zone of partial loads, which is typical for ASA electromotive systems, their resultant energy efficiency reduces [8, 10].

We shall illustrate it using a baro-unloaded [3] propulsion AM of power 180 W as an example. The rated AM parameters are: voltage $U_{1nom}$=220 V, $Н_{nom}$=0.66, $\cos\vartheta_{nom}$=0.76, $P_{nom}$ =180 W, $\Omega_{nom}$=288.9 rad/s, $I_{1nom}$=0.54 A. Parameters of a three-phase AM equivalent circuit were set separately. For this motor, using a laboratory bench [20], we experimentally obtained loading characteristics (Fig. 1) that explicitly express their non-linear descending character.

Characteristics are reduced to functions of relative static moment $M_c^*=M_c/M_{cnom}$, where $M_{cnom}$ denotes a nominal static moment.

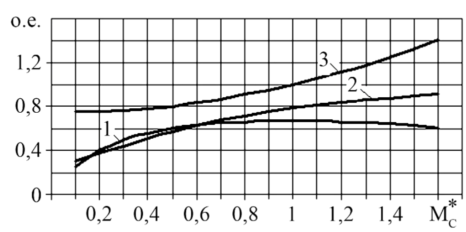


Fig. 1. Characteristics of baro-unloaded AM in a load function 1 – performance efficiency; 2 – cos ϑ; 3 – $I_1/I_{1nom}$

The above analysis of the scientific literature and characteristics of the baro-unloaded AM allows us to assume that at a decrease in load $M_c$ there is such a magnetic flux of propulsion AM when the total power losses are reduced.

We shall estimate possibilities for reducing power losses for ASA electromotive system.

In a given system, we applied a three-phase baro-unloaded AM with a squirrel-cage rotor. The analysis is performed at mean static loads from a propulsion screw, which are lower than the rated value (to 0.1 $M_{c\text{nom}}$).

Total $\Delta P_\Sigma$ power of energy losses in such AM is determined from the sum of constant $\Delta P_{=}$ and variable $\Delta P_{\sim}$ power losses:

$$P_\Sigma=\Delta P_{=}+\Delta P_{\sim}. \quad (1)$$

Constant power losses $\Delta P_{=}$ consist of losses in the steel of stator $\Delta P_{\text{st}}$ and rotor, mechanical losses $\Delta P_{\text{mech}}$ and losses to excite $\Delta P_{\text{ex}}$:

$$P_{=}=\Delta P_{\text{st}}+\Delta P_{\text{mech}}+\Delta P_{\text{ex}}. \quad (2)$$

Losses in steel from vortex currents and hysteresis depend on frequency $f$ of the power source, second degree of induction amplitude $B$, and function $f_1(s, k)$ of slip $s$:

$$\Delta P_{st}=\Delta P_{st_{nom}}\cdot\left(\frac{f}{f_{nom}}\right)^k\cdot\left(\frac{B}{B_{nom}}\right)^2\cdot f_1(s,k), \quad (3)$$

where $f_1(s, k)=(1+s^k)$, $k$ is the exponent that depends on the brand of electrical steel applied. With respect to $(B/B_{\text{nom}})^2\approx$ $\approx(\Psi/\Psi_{\text{nom}})^2$, we can write

$$\Delta P_{\text{st}}=\Delta P_{\text{st}_{\text{nom}}}\cdot\left(\frac{f}{f_{\text{nom}}}\right)^k\cdot\left(\frac{\Psi}{\Psi_{\text{nom}}}\right)^2\cdot f_1(s,k), \quad (4)$$

where $\Psi$ is the main current linkage.

We shall assign to baro-unloaded AM of small ASA maximum permissible ranges of change in relative slip $s$ and possible values of change in coefficient $k$: $s\in(0.005...0.1)$ and $k\in(1.2...1.7)$.

Mechanical losses are determined from the sliding of the rotor:

$$\Delta P_{\text{mech}}=\Delta P_{\text{mech}_{\text{nom}}}\cdot f_2(s,m), \quad (5)$$

where $\Delta P_{\text{mech nom}}\approx(0.01...0.15)\cdot P_{2\text{nom}}$ are the nominal mechanical losses; $f_2(s, m)=(1-s)^m$; $m$ is the exponent that depends on the condition of bearing units, cooling technique, and other features of mechanical part of AM.

Here we shall also set maximum permissible ranges of change in relative slip $s$ and possible values of change in coefficient $m$ for a baro-unloaded AM. We accept $s\in(0.005...0.1)$ and $m\in(1.1...1.5)$.

It should be noted that for any AM, first, coefficient $k$=const, while $m$ changes only during long enough operational period; second, when sliding decreases the function $f_1(s, k)$ decreases, while $f_2(s, m)$ – increases. Thus, it should be considered that the total change in power losses from these components is almost constant. Under the specified assumptions, it is possible to accept the following mean values of functions:

$$f_1(s,k)=k_{\text{st}}=1{,}03; \quad f_2(s,m)=k_{\text{mech}}=0{,}92.$$

From now on, these functions are accepted to be constant magnitudes at changes in slipping from the nominal value to zero value.

Losses in the stator winding copper to excite AM depend on magnetization current, which is created by the reactive component $I_m$ of the stator current:

$$\Delta P_{\text{в}}=3I_m^2R_1, \quad (6)$$

Variable losses $\Delta P_{\sim}$ consist of losses in the stator and rotor windings, excluding losses for excitation, and they are proportional to the second degree of load current. When working at small slip, variable losses will be determined from expression:

$$\Delta P_{\sim}=3I_2'^2\cdot(R_1+R_2'). \quad (7)$$

Thus, given expressions (1) to (7) are not only the main reference material of research, but also a methodological basis for solving the set tasks.

## 5. Main results of the study

**5. 1. Estimation of the possibility of reducing power losses during work of a three-phase propulsion AM in the ASA electromotive system**

We shall introduce relative units for the basic parameters of AM. Then, for the respective components, relative power losses are:

$$\Delta p_{\sim}=\frac{\Delta P_{\sim}}{\Delta P_{\Sigma_{mech}}};\ \Delta p_{=}=\frac{\Delta P_{=}}{\Delta P_{\Sigma_{mech}}};\ \Delta p_{st}=\frac{\Delta P_{st}}{\Delta P_{\Sigma_{mech}}};$$

$$\Delta p_{mech}=\frac{\Delta P_{mech}}{\Delta P_{\Sigma_{nom}}};\ \Delta p_{ex}=\frac{\Delta P_{ex}}{\Delta P_{\Sigma_{nom}}};\ \Delta p_{\Sigma_{nom}}=\frac{\Delta P_{\Sigma_{nom}}}{\Delta P_{\Sigma_{nom}}}=1, \quad (8)$$

$i_1^*=I_1/I_{1\text{nom}}$; $i_2^*=I_2/I_{2\text{nom}}$; $i_в^*=I_m/I_{m\text{ nom}}$ – for currents; $f^*=f/f_{\text{nom}}$ – for the frequency of power source; $\Phi^*=\text{F}/\text{F}_{\text{nom}}$ – for magnetic flux ($\Psi^*\equiv\Psi^*=\Psi/\Psi_{\text{nom}}$); $\omega^*=\omega/\omega_0$ – for angular velocity of the rotor; $M^*=M/M_{\text{nom}}$ – for momenta.

The relation between current of the rotor and electromagnetic moment is proportional to the product of magnetic flux by the active component of current of the rotor: $M=c\cdot\Phi\cdot I_2'\cdot\cos\vartheta_2$, where $c$ is the design factor of motor; $\vartheta_2$ is the shift angle between vectors of the rotor current $I_2'$ and EMF. When operating under a mode of small slip, we can accept $\cos\vartheta_2\approx1$.

Taking into consideration the introduced relative units, mutual relation between electromagnetic moment, current of the rotor and flow in the air clearance of AM:

$$M^*=i_2^*\cdot F^*. \quad (9)$$

In order to preliminary estimate possible reduction in power losses when operating at AM magnetic flux weakening, we shall assume that the working point shifts to the coordinate origin along a straight line. In other words, we consider the excitation current to be $i_{ex}^*=\text{F}^*$. Thus, when ASA operates at different propulsion speeds, and with a reduced static load, it is possible to write:

$$\Delta p_\Sigma=\Delta p_{\sim}+\Delta p_{=}=\Delta p_{\sim_{nom}}\cdot i_2^{*2}+$$
$$+\Delta p_{\text{st}_{\text{nom}}}\cdot f^{*k}F^{*2}\cdot k_{\text{st}}+\Delta p_{\text{mech}_{\text{nom}}}\cdot \text{k}_{\text{mech}}+\Delta p_{\text{ex}_{\text{nom}}}\cdot i_{\text{ex}}^{*2}. \quad (10)$$

At constant frequency($f^*$=1) of the power source:

$$\Delta p_\Sigma=\Delta p_{\sim}+\Delta p_{=}=\Delta p_{\sim_{\text{nom}}}\cdot\left(M^*/F^*\right)^2+$$
$$+\Delta p_{\text{st}_{\text{nom}}}\cdot k_{\text{st}}\cdot F^{*2}+\Delta p_{\text{mech}_{\text{nom}}}\cdot \text{k}_{\text{mech}}+\Delta p_{\text{ex}_{\text{nom}}}\cdot F^{*2} \quad (11)$$

and for nominal AM operating conditions $\Delta p_\Sigma$=1.

Let us determine an extremum of function (11) relative F, derived from condition $\partial(\Delta p_{\Sigma})/\partial F^{*}=0$. Extremum defined the value of the magnetic flux at which under the steady mode of work and load, less then the nominal, total power losses will be minimal:

$$F^{*}_{\mathrm{opt}} = k_{\mathrm{n}} \cdot \sqrt{M^{*}}, \qquad (12)$$

where $k_n$, coefficient of nominal power losses, is accepted equal to

$$k_{\mathrm{H}} = [\Delta p_{\mathrm{nom}} / (k_{\mathrm{st}} \cdot \Delta p_{\mathrm{st}_{\mathrm{nom}}} + \Delta p_{\mathrm{ex}_{\mathrm{nom}}})]^{0.25}, \qquad (13)$$

Taking into consideration the above assumptions, we believe that for a steady operational mode a relative value of magnetic flux at which total power losses of AM are minimal is directly proportional to the product of the coefficient of nominal power losses by the square root of the relative static moment. The difference between values of power losses at full magnetic flux with a partial load on AM and at optimal magnetic flux under the same load produces a value for the magnitude of possible saved power

$$\Delta p_{s} = \Delta p_{\Sigma}\big|_{F^{*}=1, M^{*}<1} - \Delta p_{\Sigma}\big|_{F^{*}=F^{*}_{\mathrm{opt}}, M^{*}<1},$$

hence, we obtain

$$\Delta p_{\mathrm{s}} = \Delta p_{\sim_{\mathrm{nom}}} \cdot M^{*2} + \Delta p_{\mathrm{st}_{\mathrm{nom}}} \cdot k_{\mathrm{st}} + \Delta p_{\mathrm{ex}_{\mathrm{nom}}} - 2M^{*} \cdot k_{\mathrm{n}}^{2}, \qquad (14)$$

at $u^{*}_{\mathrm{opt}} = k_{\mathrm{n}} \cdot \sqrt{M^{*}}$.

Analytical calculation of instantaneous power losses in the non-linear electromotive system of ASA with AM is complicated because expressions for the amplitude and voltage frequency include vector magnitudes and complex resistances dependent on the slip, current linkage, and other variables. To overcome these difficulties, we applied a mathematical model [21] of a baro-unloaded AM of ASA propeller screw in the $x$–$y$–0 coordinate system. We introduced to the model (into functions of voltage and frequency) nonlinear dependences of magnetic flux, the losses in steel, static fan load, and we calculate energy consumption values (instantaneous and mean), performance efficiency, cosϑ, active, reactive and mechanical power, stator and rotor current values, EMF, current linkages for coordinates.

Fig. 2 shows estimated dependences of performance efficiency and current of the stator for a baro-unloaded AM based on the engine of type 4A56A2. The dependences are constructed at a change in voltage and for different relative $M_c^{*}=M_c/M_{\mathrm{nom}}$ static loads, taking into consideration the nonlinearity of the magnetic system. Fig. 2 shows that there are clearly expressed extrema of performance efficiency and current of the stator.

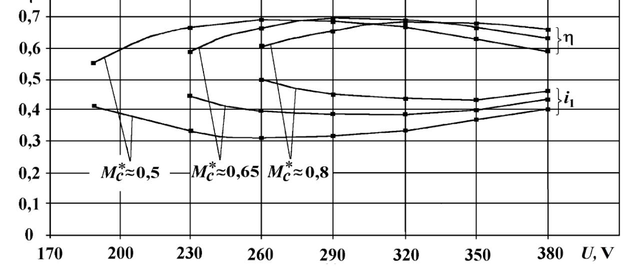


Fig. 2. Dependences of performance efficiency and current of the stator for different static loads to a baro-unloaded AM of type 4A56A2 in a function of voltage

Thus, at a static load equal to 0.65 $M_{c\mathrm{nom}}$, a minimum of current corresponds to a voltage of 300 V and almost coincides with the maximum of performance efficiency; power consumption is less than the rated by 8 %, performance efficiency improved by almost 5 %.

**5. 2. Special features in the construction of control system over propulsion AM of ASA electromotive system**

As shown above, at a certain lower, less than the nominal, value of resistance moment $M_c$, there is such a value of power voltage at which the energy-efficient mode of operation of the ASA propulsion complex is ensured – with minimal power losses of a baro-unloaded AM. Examining typical operation modes of ASA reveals that a decrease in the average value of load on the part of the propulsion propeller visibly changes only the basic resultant energy characteristics of AM – performance efficiency and cos ϑ; at the same time, ASA speed changes insignificantly.

A technique for controlling magnetic flux at a decrease in static load is implemented by a smooth change in voltage [12], in this case, control processes are easily automated. It is obvious [13] that the entire system of voltage control over electromotive ASA might be organized at small capital expenditure based on the power transistor voltage inverter, where the signals from a stator current sensor are used as controlling influence.

When employing control algorithms that stabilize any energy parameter (performance efficiency, used current, power factor, etc.) and establish energy-efficient mode of operation of propulsion AM, it is assumed that the voltage controller has an unambiguous, non-linear, U-shaped nature.

Control algorithms that establish energy-saving modes and enable reduction of power losses of propulsion AM, are implemented in different ways. They including the search procedures that automatically reduce and stabilize voltage at a decrease in static load so that an extremum of one of the functions is ensured, for example, minimum current consumption.

A typical algorithm also implies operation under the rated magnetic flow, because working with optimal, in terms of energy saving, flow is associated with a decrease in the overload capability of AM. It is also clear that magnetic flux should be automatically recovered at an increase in static load.

Energy-optimal control mode over ASA is possible through the minimization of power consumption by a baro-unloaded AM: $P_1=3u_1 \times i_1 \times \cos\varphi_1 \rightarrow \min$, where the control system automatically adjusts voltage level in order to find the point of minimum power consumption [4, 10]. It should be noted that it is not always [7] that a minimum of the stator current corresponds to the minimum in power consumption, though, for the case of electromotive systems of low-power ASA, this circumstance can be neglected.

The main advantage of the stator current minimization algorithm is its simpler, and thus inexpensive, technical implementation when compared with frequency control techniques.

It is important to note that the rotation speed of AM, and, therefore, the propulsion speed of ASA, can slightly vary for several reasons:

– the speed of ideal idling is invariable as the frequency of the power source is almost constant;

– rigidity of the working region of mechanical characteristics of AM is large enough (4...9 %);

– and finally, it is most important that a change in voltage will occur only when the static load over a long period is less than the nominal, that is, when it is necessary to ensure the cruising speed of ASA.

In addition, one of the means to increase range of operation and time of autonomous navigation of ASA is the application of search regimes for a change in the voltage on stator when controlling a propulsion propeller of the baro-unloaded AM.

## 6. Discussion of results of the study to ensure energy-efficient modes of operation of autonomous swimming apparatus

One of the major shortcoming revealed in a thorough analysis of the main results of present study is the increase in the total power losses at deep ASA speed regulation. In addition, a traditional, and largely subjective, approach to creating electromotive systems implies mandatory application of industrial frequency converters (FC).

It should be noted that industrial FC of low capacity have, first, a relatively high selling price, unacceptable for solving the tasks similar to those described in [1]. Second, such FC have redundant functionality (built-in diagnostic system, systems of protection, display, identification of AM parameters, i/o ports, etc.). Third, they are not designed to work under conditions of significant changes in the voltage of power source, they are typically not intended for work at sea, and they are not industrially produced in Ukraine.

This is why we should consider the possibility of employing various kinds of low-cost AM voltage control systems in ASA, similar to those described in [11], which make it possible to minimize the total power losses when controlling the speed of ASA. However, there are still a number of unresolved issues related to the technical support for the required control algorithms.

## 7. Conclusions

We established by calculation that for a baro-unloaded AM of type 4A56A2, installed in the ASA electromotive system, a minimum of the consumed current corresponds to voltage, which is approximately 80 % of the rated value, and almost coincides with the maximum performance efficiency. It remains valid (taking into consideration the non-linearity of magnetic system) with a decrease in voltage and at various static loads smaller than the nominal value. In the considered example, consumed current of AM becomes less than the nominal by 8 %, with the resulting value of the system's performance efficiency increased by 5 %.

The obtained expressions (13) and (14) allowed us to find values for a coefficient of nominal power losses and the magnitude of possible saved power (14) when controlling a change in voltage.

An analysis of estimated dependences of performance efficiency and current of the stator (Fig. 2) for a baro-unloaded AM of low power at a voltage change and for different relative static loads made it possible to form and establish special features and requirements to the control system of electromotive ASA. The application of specialized devices to control voltage that establish energy-efficient modes and reduce power losses of a baro-unloaded AM allows algorithmizing of the tasks to reduce total consumption of active power. This ensures work of AM with a maximum performance efficiency or minimum current consumption.

References


1. Podvodnye ubiytsy avianostsev: glubinnye bespilotniki protiv VMS SShA [Electronic resource]. – Available at: https://tvzvezda.ru/news/forces/content/201504271716-4r23.htm
2. Budashko, V. V. Design of the three-level multicriterial strategy of hybrid marine power plant control for a combined propulsion complex [Text] / V. V. Budashko // Electrical Engineering & Electromechanics. – 2017. – Issue 2. – P. 62–72. doi: 10.20998/2074-272x.2017.2.10
3. Volyanskaya, Ya. B. Razrabotka asinhronnogo dvigatelya dlya dvizhitel'no-rulevogo kompleksa podvodnogo apparata [Text] / Ya. B. Volyanskaya, S. M. Volyanskiy // Problemy avtomatiki i elektrooborudovaniya transportnyh sredstv «PAETS-2012»: Mater. Vseukr. nauch. tekhn. konf. – Nikolaev: NUK, 2012. – P. 129–131.
4. Ogay, S. A. Ponyatiya mnogotselevogo sudna ledovogo plavaniya i osobennosti primeneniya sistemnogo podhoda pri opredelenii harakteristik na nachal'nom etape proektirovaniya sudna etogo tipa [Text] / S. A. Ogay // Morskie intellektual'nye tekhnologii. – 2015. – Vol. 1, Issue 3 (29). – P. 45–54.
5. Lepistö, V. Dynamic process simulation promotes energy efficient ship design [Text] / V. Lepistö, J. Lappalainen, K. Sillanpää, P. Ahtila // Ocean Engineering. – 2016. – Vol. 111. – P. 43–55. doi: 10.1016/j.oceaneng.2015.10.043
6. Buhanovskiy, A. V. Metaontologiya issledovatel'skogo proektirovaniya morskih dinamicheskih ob'ektov [Text] / A. V. Buhanovskiy, Yu. I. Nechaev // Ontologiya proektirovaniya. – 2012. – Issue 1. – P. 53–64.
7. Heinen, S. Analyzing Energy Use with Decomposition Methods [Text] / S. Heinen // IEA Energy Training Week. – 2012. – P. 769–778.
8. Braslavskiy, I. Ya. Energosberegayushchiy asinhronnyy elektroprivod [Text] / I. Ya. Braslavskiy, Z. Sh. Ishmatov, V. N. Polyakov. – Moscow: Izd. tsentr «Akademiya», 2004. – 256 p.
9. Chan, C. C. The state of the art of electric and hybrid vehicles [Text] / C. C. Chan // Proceedings of the IEEE. – 2002. – Vol. 90, Issue 2. – P. 247–275. doi: 10.1109/5.989873
10. Emadi, A. Power Electronics and Motor Drives in Electric, Hybrid Electric, and Plug-In Hybrid Electric Vehicles [Text] / A. Emadi, Y. J. Lee, K. Rajashekara // IEEE Transactions on Industrial Electronics. – 2008. – Vol. 55, Issue 6. – P. 2237–2245. doi: 10.1109/tie.2008.922768

11. Onishchenko, O. A. Elektroprivod sistem kondensatsii holodil'nyh ustanovok [Text] / O. A. Onishchenko // Elektromashinostroenie i elektrooborudovanie. – 2006. – Issue 66. – P. 190–192.
12. Zeraoulia, M. Electric Motor Drive Selection Issues for HEV Propulsion Systems: A Comparative Study [Text] / M. Zeraoulia, M. E. H. Benbouzid, D. Diallo // IEEE Transactions on Vehicular Technology. – 2006. – Vol. 55, Issue 6. – P. 1756–1764. doi: 10.1109/tvt.2006.878719
13. Lian, J. Design for Motor Controller in Hybrid Electric Vehicle Based on Vector Frequency Conversion Technology [Text] / J. Lian, Y. Zhou, T. Ma, W. Wang // Mathematical Problems in Engineering. – 2010. – Vol. 2010. – P. 1–21. doi: 10.1155/2010/627836
14. Dong, G. Efficiency Optimizing Control of Induction Motor Using Natural Variables [Text] / G. Dong, O. Ojo // IEEE Transactions on Industrial Electronics. – 2006. – Vol. 53, Issue 6. – P. 1791–1798. doi: 10.1109/tie.2006.885117
15. Volyanskaya, Ya. B. Formirovanie vyhodnogo napryazheniya TPN, invariantnogo faze toka nagruzki [Text] / Ya. B. Volyanskaya, O. A. Andryushchenko, A. A. Boyko // Elektromashynobuduvannia ta elektroobladnannia. – 2006. – Issue 66. – P. 33–35.
16. Vittek, J. Decomposed Sliding Mode Control of the Drive with Interior Permanent Magnet Synchronous Motor and Flexible Coupling [Text] / J. Vittek, S. Ryvkin // Mathematical Problems in Engineering. – 2013. – Vol. 2013. – P. 1–17. doi: 10.1155/2013/680376
17. Gomáriz, S. An autonomous vehicle development for submarine observation [Text] / S. Gomáriz, J. Prat, J. Sole, P. Gayà // Journal of Marine Research. – 2009. – Issue 2. – P. 23–35.
18. Ghozzi, S. Energy optimization of induction motor drives [Text] / S. Ghozzi, K. Jelassi, X. Roboam // 2004 IEEE International Conference on Industrial Technology, 2004. IEEE ICIT '04. – 2004. doi: 10.1109/icit.2004.1490143
19. Raj, C. T. Energy Efficient Control of Three-Phase Induction Motor – A Review [Text] / C. T. Raj, S. P. Srivastava, P. Agarwal // International Journal of Computer and Electrical Engineering. – 2009. – P. 61–70. doi: 10.7763/ijcee.2009.v1.10
20. Marchenko, A. A. Eksperimental'nye issledovaniya protsessa iskusstvennogo nagruzheniya sudovyh asinhronnyh elektrodvigateley [Text] / A. A. Marchenko, S. Yu. Trudnev // Vestnik Kamchatskogo GTU. – 2016. – Issue 38. – P. 16–22.
21. Marchenko, A. A. Issledovanie modeli asinhronnogo elektrodvigatelya na vozmozhnost' nagruzheniya pri pomoshchi ponizheniya chastoty pitayushchego napryazheniya [Text] / A. A. Marchenko, O. A. Onishchenko, S. Yu. Trudnev // Vestnik Kamchatskogo GTU. – 2014. – Issue 29. – P. 17–24.