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BRUSHLESS VALVE ELECTRIC DRIVE WITH MINIMUM EQUIPMENT EXCESS FOR AUTONOMOUS FLOATING VEHICLE

Purpose. Development of a brushless valve electric drive with a minimum apparatus excess for an autonomous floating vehicle. Methodology. The construction of models of an automated electric drive with a contactless DC motor and the subsequent technical implementation of such automated electric drive under various control methods are possible using coordinate transformations of differential equations describing the electric motor under the assumed assumptions. Results. The analysis of the current state of an automated electric drive with a brushless DC motor in a special technique is carried out, possible directions for the improvement of automated electric drives are determined. A simple technical solution of an automated electric drive with a brushless DC motor was proposed and its mathematical model for an electric drive of an automatic floating vehicle with improved technical and economic parameters was developed. Model of an automated electric drive with a brushless DC motor are carried out. Originality. A simple technical solution for the construction of an automated electric drive with a brushless DC motor is proposed, which excludes the use of intermediate computation of coordinates and an expensive encoder. Practical value. Model of the proposed scheme of an automated electric drive with a minimum hardware redundancy, which confirmed the operability of the proposed solution, were carried out. Analysis of the dynamic and static characteristics of the proposed scheme of an automated asynchronous electric drive with a brushless DC motor with a simplified rotor position sensor has made it possible to determine the maximum speed control range with an allowable level of its pulsations. References 20, tables 2, figures 7.
Key words: **automated electric drive, autonomous floating vehicle, DC brushless motor, Hall sensor, coordinate transformations, encoder.**

Предложено простое схемотехническое решение построения автоматизированного электропривода (АЭП) с бесконтактным двигателем постоянного тока (БДПТ), отличающееся исключением промежуточных программно-аппаратных преобразований координат, широтно-импульсного модулятора, двух регуляторов тока и высокоразрядного энкодера. Проведено компьютерное моделирование предложенной модификации АЭП с БДПТ и показана его работоспособность в заданных диапазонах регулирования скорости. На основании результатов моделирования АЭП с БДПТ обоснована возможность его применения в автономных плавательных аппаратах. Библ. 20, табл. 2, рис. 7.
Ключевые слова: **автоматизированный электропривод, автономный плавательный аппарат, бесконтактный двигатель постоянного тока, датчик Холла, координатные преобразования, энкодер.**

Introduction. Currently, in most electromechanical systems of small-sized autonomous floating vehicle (AFV) for various purposes, brush DC electric motors (DCM) are used. Such motors have a significant starting torque, excellent adjusting and dynamic characteristics [1-3], as well as well-developed control systems. Because brush DCM have irreparable defects (frequent maintenance, high mechanical wear, acoustic noise, sparking), more and more utilization in foreign samples of the AFV have contactless DC motors (BLDCM), in other words – *Brushless DC* (*BLDC*) *motors* [4-6]. Such electric motors, due to the use of high-coercivity magnets in the excitation system, have the best energy characteristics in comparison with classical DC electric motors and induction electric motors [9, 10]. The adjusting, dynamic and static characteristics of modern automated electric drives (AED) with vector control methods of BLDCM are close to properties of AED based on high-frequency pulse-width modulation (PWM) with a brush DCM of independent excitation.

AED with BLDCM foreign production (Japan, USA, Western Europe) are widely used in domestic aviation, medicine, various industries. It should be noted that the majority of mass-produced foreign AED based on BLDCM are oriented to complex applications. These are, for example, high-precision tracking devices, numerical control machines, electromechanical systems where a very high speed control range, precise positioning or tracking modes are required. That is why such AEDs have very high selling prices. Thus, the AED of the *Mitsubishi Electric* Company MR-C10A-UE, 100W, 3000 rpm with the speed control range $D = 1000$ in the middle of 2016 was released in Ukraine at a price of almost USD 600 (approximately USD 400 – a system unit, USD 200 – BLDCM with a built-in high-speed encoder). Such solutions of the leading manufacturers of electrical equipment (*Mitsubishi*, *Danfoss*, *ABB* and others) have very high functional and technological properties, developed self-diagnostics and protection systems, management capabilities over the local network and have many other additional service functions. Despite the relatively high cost of the BLDCM, such parameters as reliability, a high value of the design coefficient C_m, speed and low-speed reception allow us to consider very promising application of AED with BLDCM in special marine technology [7, 8] of domestic production, for example, in experimental samples of the AFV type «Hydrograph», Nikolaev (Table 1). If you analyze the basic requirements for AED for devices of a similar type, you can see that to provide the basic functions of the AFV, it is enough to have a range of speed control $D = 3 ... 15$ with the accuracy of maintaining it at the lower control ranges of up to 10 %. At the same time, there is no need for most internal protections, interfaces, a high-resolution encoder is not needed.

In Ukraine, automated electric drives with BLDCM are only beginning to be manufactured (LLC «Electrical Engineering – New Technologies», Odessa), and their circuitry base has not been fully worked out yet. Since specialized AFVs, as dual-purpose devices, are in high demand, and since there are no mass production of such devices in Ukraine, the creation of an AFV with simple and functional electromechanical systems based on the BLDCM based on the domestic industrial base is an important and urgent scientific and technical task.

Table 1

Some characteristics
of the experimental AFV «Hydrograph» (Nikolaev)

No.	Indicator	Value
1	Mass of the device	65 kg
2	Propulsion motors power, design	2×250 W, baro-unloaded
3	Working speed range of the device	0.25…2 m/s
4	Hydropropulsion complex	Direct transmission
5	Diameter of screws in the nozzle	250 mm
6	Performance with a step change in the set speed	3 s
7	The accuracy of maintaining the speed of horizontal rectilinear displacement on the lower characteristic of the range	0.05 m/s
8	Maximum speed overshoot	20 %

The goal of the paper is development of a contactless valve electric drive with a minimum hardware excess for an autonomous floating device.

Main material. It is generally known that the BLDCM is a synchronous AC motor whose stator windings are powered by a frequency converter that switches the phase currents as a function of the angular position of the rotor with an envelope frequency equal to the number of poles of the rotor multiplied by the angular rotational speed of the rotor. For operation of the AED based on the BLDCM in a wide range of speed control a high-quality (1000 or more pulses per revolution) rotor position sensors (RPS, encoders) are needed and therefore expensive ones are used [11, 12].

Simpler AED with BLDCM use scalar control methods and, often, experimental BLDCM samples are produced on the basis of serial induction motors, replacing the short-circuited rotor with a rotor with permanent high-coercivity magnets, using the simplest rotor position sensors – based on Hall effects, photoelectric or induction effects [13].

Traditionally, the development and research of the majority of modern AED are carried out with the help of coordinate transformations (KT). It is known that KT of variables are valid if the basic assumptions for the generalized electric machine are fulfilled: the sinusoidal distribution of the MMF of the stator winding with sinusoidal feeding of the symmetrically distributed stator and rotor windings. Therefore, to apply KT for investigations of AED with BLDCM and scalar control,

there are no formal conditions: relatively simple BLDCMs are created with lumped windings and, since the stator windings are powered from a rectangular-shaped voltage source, their MMF is close to rectangular.

In order to increase the competitiveness of the built-in electromechanical control systems of the AFV created on the domestic element base, the authors carried out investigations [14-16], which, as a result, allowed to abandon the vector control method of the BLDCM [17, 18]. Naturally, the use of RPS with a low number of pulses per revolution [13] leads to a significant reduction in the range of speed control and an increase in the pulsations of the electromagnetic torque. Taking into account the inertial nature of the load of the propulsion complex [19, 20] of the AFV and its «fan» nature, and also the not very high requirements for the range and accuracy of maintaining the speed, according to modern hardware capabilities, it can be assumed that there are reserves for simplifying the circuit design basis for constructing the AED with BLDCM for AFV.

Since in BLDCM, applied in experimental AFV samples, the windings are symmetrically located on the stator, then under the rectangular form of the supply voltage, it is possible to determine the main voltage harmonics and MMF. Since the assumptions adopted in the model of a generalized electric machine are satisfied for the first harmonics, then subsequently further coordinate transformations are also valid, and the main properties and characteristics of the BLDCM with scalar control can be identified on the basis of two-phase models.

The indicated approach is often used, for example, in the analysis of the operation of induction electric motors (IM) powered by frequency converters (FC). Note that if the symmetry conditions for an electrical machine are made constructively and its power is supplied from a non-sinusoidal source, then the application of coordinate transformations of variables will be adequate to real physical processes only for quasi-steady dynamic modes. In such modes, the speed and the electromagnetic torque oscillate about the mean values, while the amplitude, frequency, and shape of the oscillations of the variables will be different for the two- and three-phase descriptions of the AED.

Thus, the construction of models of AED with BLDCM and the subsequent technical realization of such AED under different control methods are possible using coordinate transformations of differential equations describing the electric motor under the assumed assumptions. It is clear that the technical implementation of the AED should be justified by comparing the operation modes of the BLDCM with various control methods to the characteristic reactive static load, which for the AFVPA is a fan type.

In the rotating coordinate system *d-q*, the coordinate transformations for the equivalent voltages of the symmetrical winding of the BLDCM stator are related to the phase voltages by the two systems of equations – (1) and (2). When changing from a three-phase to a two-phase coordinate system {3/2}, the following is valid:

$$u_d(\tau) = \frac{2}{3}[U_a(\tau)\cdot\sin(\omega_c\cdot\tau) + U_b(\tau)\times$$
$$\times\sin\left(\omega_c\cdot\tau - \frac{2\pi}{3}\right) + U_c(\tau)\cdot\sin\left(\omega_c\cdot\tau + \frac{2\pi}{3}\right)];$$
$$u_q(\tau) = \frac{2}{3}[U_a(\tau)\cdot\cos(\omega_c\cdot\tau) + U_b(\tau)\times$$
$$\times\cos\left(\omega_c\cdot\tau - \frac{2\pi}{3}\right) + U_c(\tau)\cdot\cos\left(\omega_c\cdot\tau + \frac{2\pi}{3}\right)]; \qquad (1)$$
$$u_0(\tau) = \frac{1}{3}[U_a(\tau) + U_b(\tau) + U_c(\tau)],$$

and when changing from a two-phase to a three-phase coordinate system {2/3}:

$$U_a(\tau) = u_d(\tau)\cdot\sin(\omega_c\cdot\tau) + u_q(\tau)\times$$
$$\times\cos(\omega_c\cdot\tau) + u_0(\tau);$$
$$U_b(\tau) = u_d(\tau)\cdot\sin\left(\omega_c\cdot\tau - \frac{2\pi}{3}\right) +$$
$$+ u_q(\tau)\cdot\cos\left(\omega_c\cdot\tau - \frac{2\pi}{3}\right) + u_0(\tau); \qquad (2)$$
$$U_c(\tau) = u_d(\tau)\cdot\sin\left(\omega_c\cdot\tau + \frac{2\pi}{3}\right) +$$
$$+ u_q(\tau)\cdot\cos\left(\omega_c\cdot\tau + \frac{2\pi}{3}\right) + u_0(\tau),$$

where $U_a(\tau)$, $U_b(\tau)$ and $U_c(\tau)$ are the phase voltages of the three-phase system; $u_d(\tau)$ and $u_q(\tau)$ are the projections of the phase voltages on the axes of the rotating with frequency ω_c coordinate system d-q; $u_0(\tau)$ is the vector of the zero sequence equal to zero at zero initial conditions and the stator winding symmetry; $\Theta = \omega_c\cdot\tau$ is the angular position of the vector in the coordinate system d-q. We emphasize that for other variables of the BLDCM (currents, MMF), the coordinate transformations {3/2} and {2/3} are valid.

In the case of vector single-zone control of the BLDCM, in the most general case, the projections of the phase voltages $u_d(\tau)$ and $u_q(\tau)$ are formed by the signals of the high-order RPS in the function of given from the external source along the corresponding coordinate axes voltages. This formation is carried out, for example, by means of a sinusoidal-cosine rotating transformer (SCRT)

having a small proper delay time τ_n, with the geometric angle of the RPS setting is oriented along the d axis. Then:

$$u'_d(\tau) = u_d(\tau)\cdot\cos(\omega_c\cdot\tau_n) - u_q(\tau)\cdot\sin(\omega_c\cdot\tau_n);$$
$$u'_q(\tau) = u_q(\tau)\cdot\cos(\omega_c\cdot\tau_n) + u_d(\tau)\cdot\sin(\omega_c\cdot\tau_n). \qquad (3)$$

We write the equations of the BLDCM in the coordinate system d-q, tied to the rotational angular frequency of the rotor.

Equations of electrical equilibrium in the operator form:

$$u_d(s) = R_s\cdot i_d(s) + L_d\cdot s\cdot i_d(s) - \omega_c(s)\times$$
$$\times L_q\cdot i_q(s);$$
$$u_q(s) = R_s\cdot i_q(s) + L_q\cdot s\cdot i_q(s) + \omega_c(s)\times \qquad (4)$$
$$\times L_d\cdot i_d(s) + \omega_c(s)\cdot\psi_e(s),$$

where R_s is the stator phase resistance; $i_d(s)$, $i_q(s)$ и L_d, L_q are the currents and inductances by coordinate axes d-q, respectively; $\psi_e(s) = \psi_e = $ const is the flux linkage determined by the coercive force of the rotor magnets.

We preliminary analyze the properties of a vector single-band AED with a BLDCM for a single-mass constant reactive load and a RPS functioning on the basis of a sinusoidal-cosine rotating transformer (SCRT), i.e. «ideal» position sensor. In this case, $L_d = L_q$, the equations of motion of the AED and the electromagnetic torque will be as follows:

$$M(s) - M_c(s) = J\cdot s\cdot\omega(s); \qquad (5)$$

$$M(s) = \frac{m\cdot p_n}{2}\cdot i_d(s)\cdot\psi_e, \qquad (6)$$

where p_n and m are the number of pole pairs and number of phases of BLDCM; $\omega(s) = \omega_c(s)\cdot p_n$ is the angular frequency of the rotation of the BLDCM rotor; J is the moment of inertia of the BLDCM rotor.

A simplified functional scheme of AED with BLDCM functioning on the basis of PWM and using high-rate RPS when powered from an industrial network is shown in Fig. 1. Note that it is on the basis of such a scheme that most foreign-made AEDs are created.

In Fig. 1 setting signals are indicated by «*», the current stabilization circuit in coordinate d and the control circuit for the clamp circuit (VT, R_T) are not shown, the angular position of the rotor is defined as $\Theta(s) = s\cdot\omega(s)$.
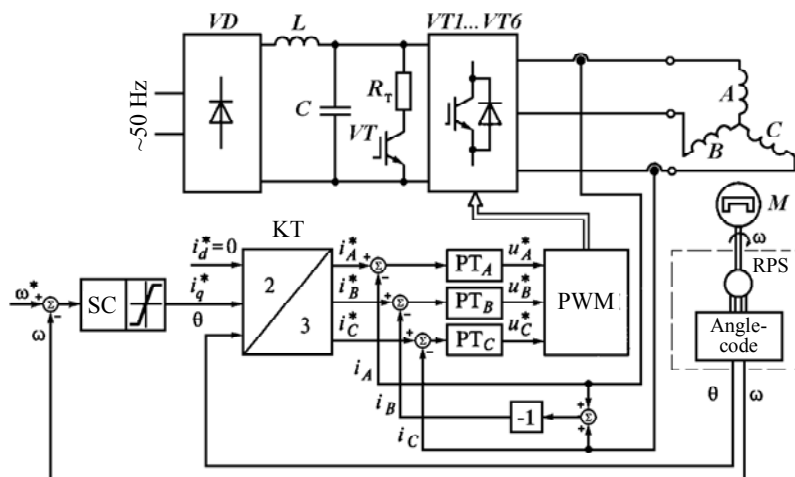

Fig. 1. Simplified functional scheme of a single-zone vector AED for AFV based on BLDCM and high-rate RPS

The authors offer a simpler technical solution, which, although it limits the functional and technological capabilities of the electric drive, but allows the implementation of its technical characteristics in accordance with Table 1. Simplification is associated with the exclusion of high-rate RPS and the installation of a simpler RPS [13], as well as the exclusion of PWM and the KT unit from the control system.

Let's consider an example of construction of a contactless valve electric drive with a minimum hardware Excess for an autonomous floating device with total weight of 20 kg. For further analysis, let us consider the operation of the system constructed on the basis of the scheme shown in Fig. 1 using the experimental sample of BLDCM with high-coercivity samarium-cobalt magnets produced by LLC «Electrical Engineering – New Technologies» (Odessa). The main technical parameters of the BLDCM are given in Table 2.

Table 2

Main parameters of the BLDCM

Number of poles	8
Number of phases	3
Rated feed voltage, V	24
Rated rotated speed, rad/s	418.9
Rated torque, N·m	0.041
Maximal torque, N·m	0.17
Rated power, W	17
Phase resistance at 60 °C, Ω	1.2
Maximal permitted current, A	6.4
Phase inductance, mH	1.0
Rotor moment of inertia, kg·m^2	$1 \cdot 10^{-4}$

In Fig. 2,*a* a diagram of the power part of the inverter is presented, and in Fig. 2,*b* – a functional PWM circuit with distributor of control pulses of inverter keys is shown. The operation of the speed controller SC and current controllers CC corresponds to known schemes. The coordinate converter KC is described by system (1), BLDCM and RPS – by equations (2)-(6).

The results of simulation of the starting process with M_r=0.04 N·m and the subsequent load shedding at time τ = 0.35 s to the value M_r=0.015 N·n for the AED corresponding to the scheme shown in Fig. 1 at generator frequency G of PWM 8 kHz and τ_n=0.25·10^{-3} s are shown in Fig. 3. The system was simulated in the *Matlab / Simulink* environment.

With the help of coordinate transformations, it is possible to simulate AED with BLDCM in natural axes (for a three-phase model) and, if necessary, take into account the features introduced by higher harmonics of MMF and voltages. In the course of the investigations, it was found that when the PWM frequency is increased by more than 20 kHz, the time τ_n reduced by an order of magnitude and reducing the hysteresis loop of the DA1-DA3 elements, a high speed control range (if necessary, 500 and more) can be obtained with practically zero torque pulsations. The application of a rather complex software and hardware base of AED with BLDCM according to the scheme shown in Fig. 1 (high-rate RPS

and microprocessor with programmable PWM, two galvanically separated current sensors, three current controllers) dramatically increases the cost of such AED with excess for AFV range of speed regulation of the motor shaft of the propulsion complex [19, 20] of AFV.
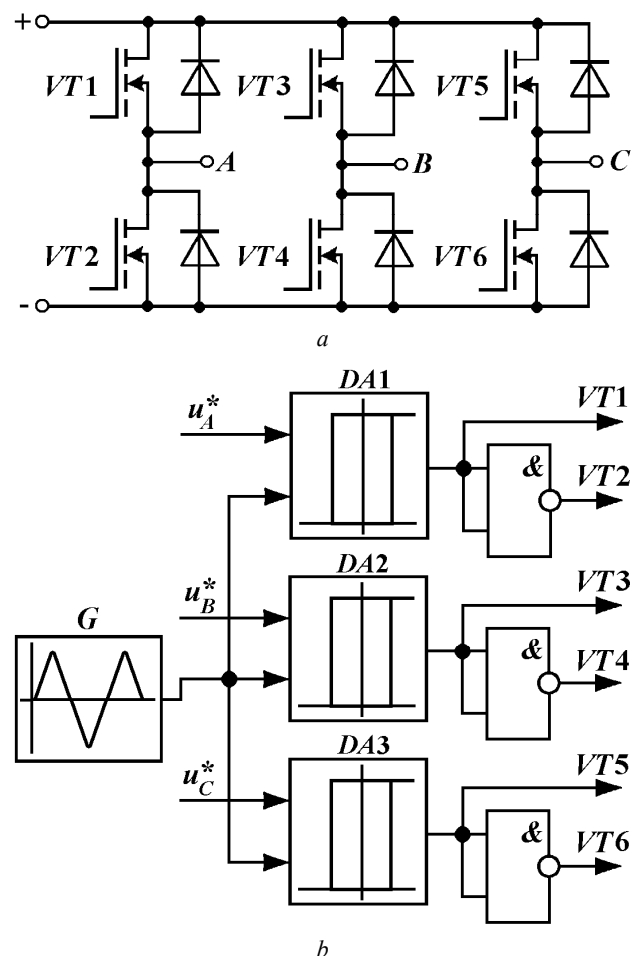

a

b

Fig. 2. The circuit of the transistor inverter (*a*) and PWM (generator *G*, comparators *DA*) with a distributor of pulses on the elements «2AND-NO» (b)

A simpler technical solution of AED with a BLDCM is proposed, which excludes the use of intermediate computation of coordinates and an expensive encoder (Fig. 4).

This AED uses as RPS three geometrically offset Hall sensors [13] and a specialized inexpensive control microcontroller *MC33035*. The main function of the microcontroller is to generate the pulse distribution (PD) signals to the *VT*1, ... , *VT*6 keys of the inverter by the RPS commands. Another feature of the proposed solution is the feature of realizing negative current feedback. This feedback is realized with the help of only one current sensor installed in the power supply circuit, which made it possible to apply the current controller common for the three phases, although slightly reducing the accuracy of its stabilization. The speed feedback signal is formed from the impulse signals of an extremely simple RPS (6 pulses per revolution of the shaft, [13]) using an active analog filter AF with dominant time constant of 0.015 s, which significantly affects the dynamics of the AED.
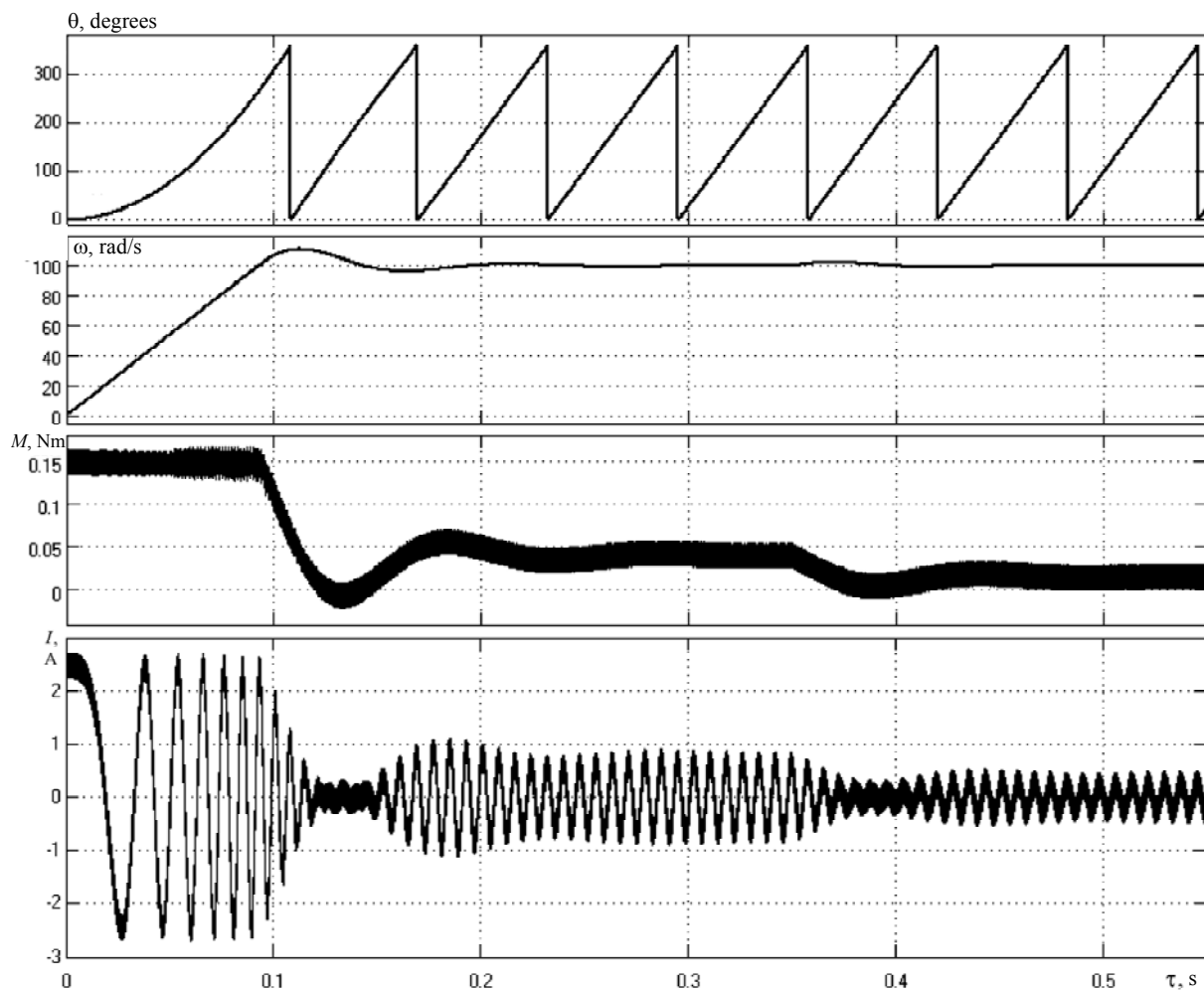
Fig. 3. Start of AED with BLDCM (according the scheme presented in Fig. 1) at rated M_r with a subsequent load shedding to 0.015 N·m
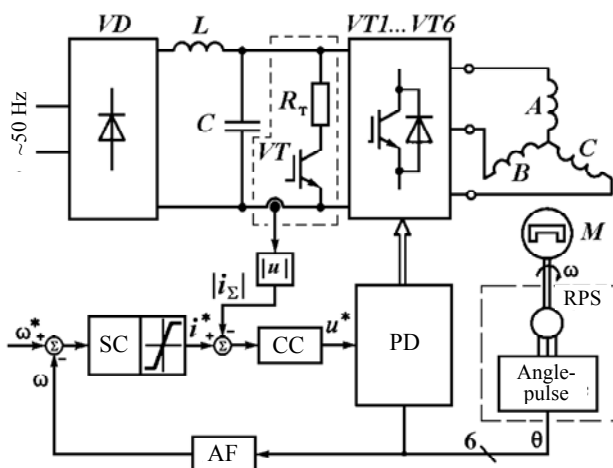

Fig. 4. Simplified functional diagram of single-zone AED for AFV based on BLDCM with Hall RPS

Let us compare the solutions represented by the schemes in Fig. 1 and Fig. 4.

1. Preliminary analysis of design solutions, based on a comparison of the hardware of the AED, constructed according to the schemes depicted in Fig. 1 and Fig. 4, points to certain advantages of AED with BLDCM, constructed according to the scheme shown in Fig. 4:

a) the expected reduction in the cost of the structure in small-scale production by 18 ... 25 %;

b) decrease in the weight and dimensions of the control board by 5 ... 7 %;

c) improving the reliability of the structure by using a smaller number of components, by 7 ... 14 %.

It is obvious that with such a technical solution, the torque pulsations on the motor shaft will increase, but the cost of the technical realization of the electric drive will be significantly less.

2. Graphs of the formation at the output of the PD of logical signals for controlling the keys of the inverter $VT1, ..., VT6$ (according to Fig. 2,a) in the function of the RPS signals V_{H1}, V_{H2} and V_{H3} in the mode of 50 % duty cycle at the steady rotor speed are shown in Fig. 5. The graphs of the change in the electric and mechanical angular position of the BLDCM eight-pole rotor are also shown here.

Fig. 6 presents the results of simulating the start-up processes of AED with BLDCM, according to the scheme shown in Fig. 4: start in the «linear» mode at speed of 20 rad/s (graphs 1) and start in the current limiting mode (graphs 2). It is determined that the maximum value of the speed control range in this case can reach $D \approx 30$, which is quite enough for performing any technological tasks of the AFV. In Fig. 7 the graphs of the currents change in the phases of the BLDCM at start-up for speed of 100 rad/s are additionally presented confirming the efficiency of the current control circuit with one common current sensor.
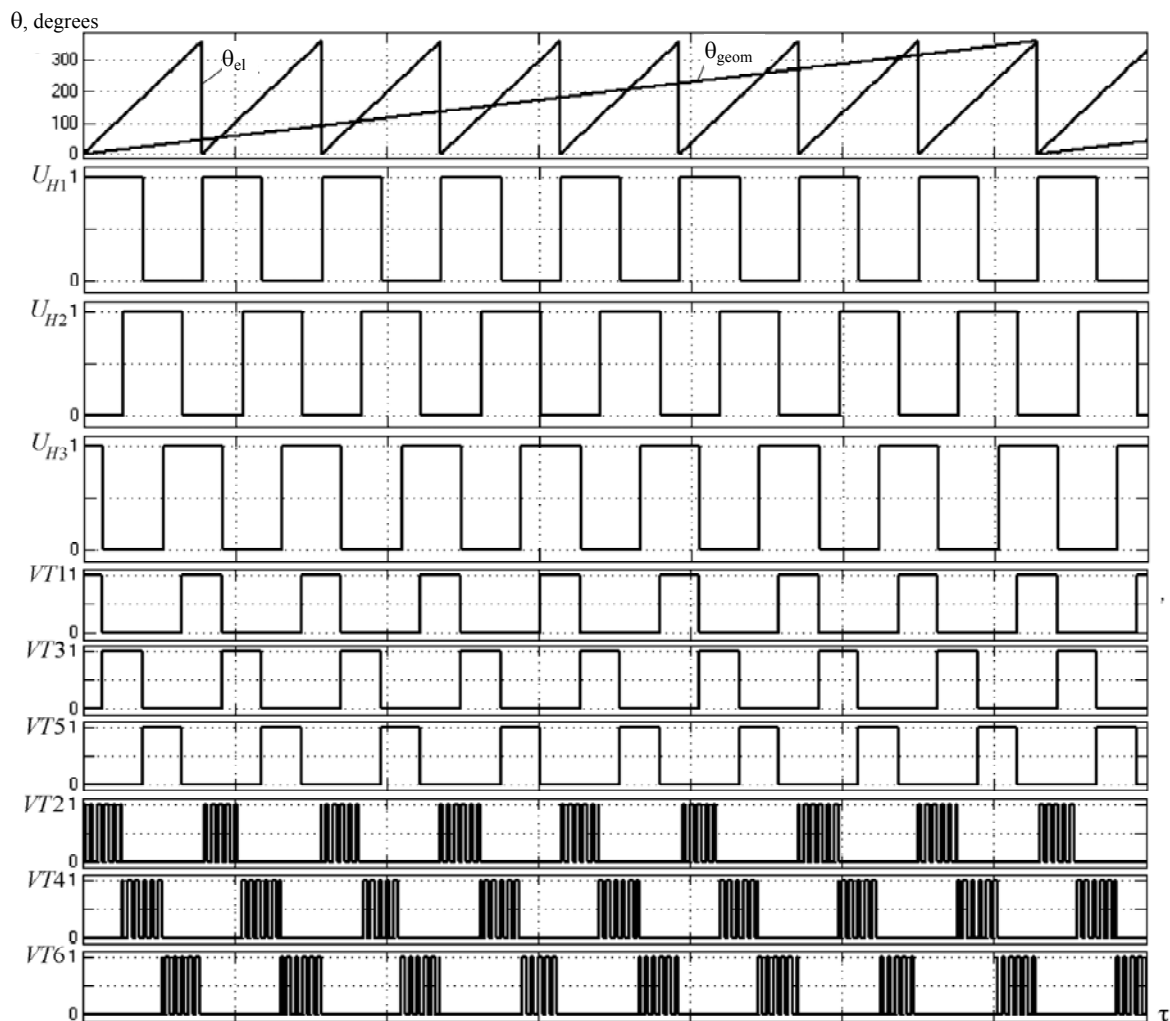
Fig. 5. Formation of key control pulses of the inverter $VT1$, …, $VT6$ at the output of the PD as a function of the RPS signals
(V_{H1}, V_{H2}, V_{H3}) and change in the angular position Θ of the BLDCM eight-pole rotor
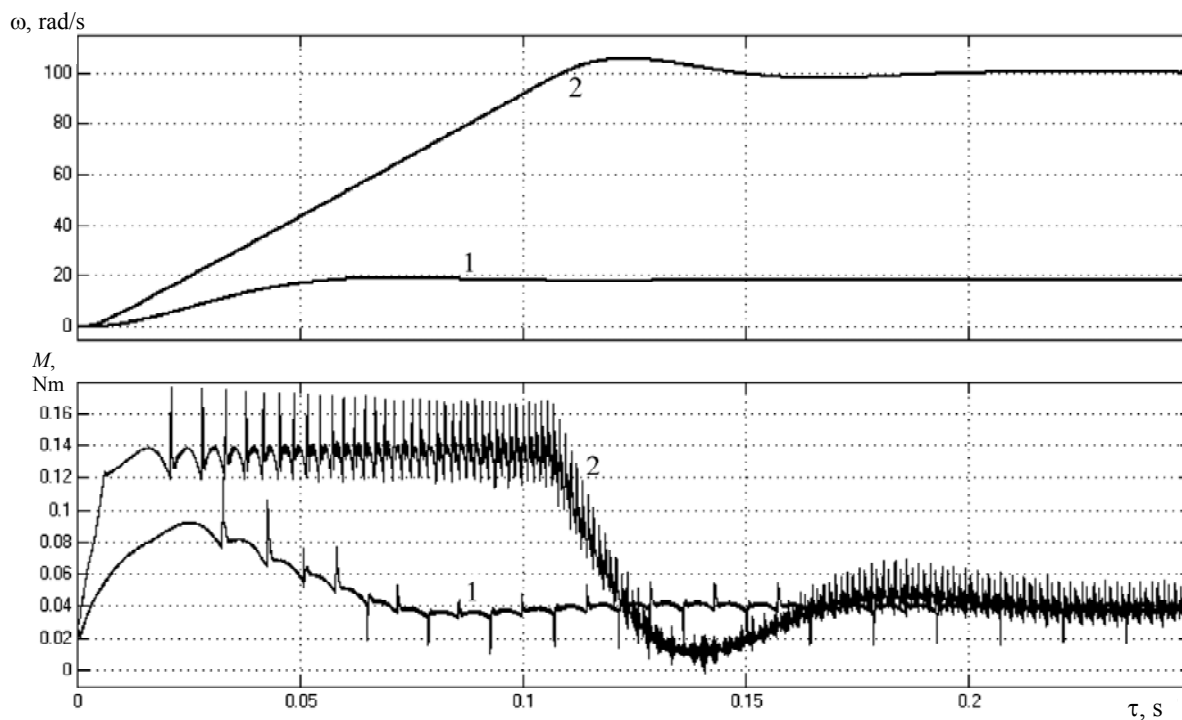

Fig. 6. Start of AED with BLDCM at M_r=0.04 N·m (according the circuit presented in Fig. 5): 1 – for small rotation speed
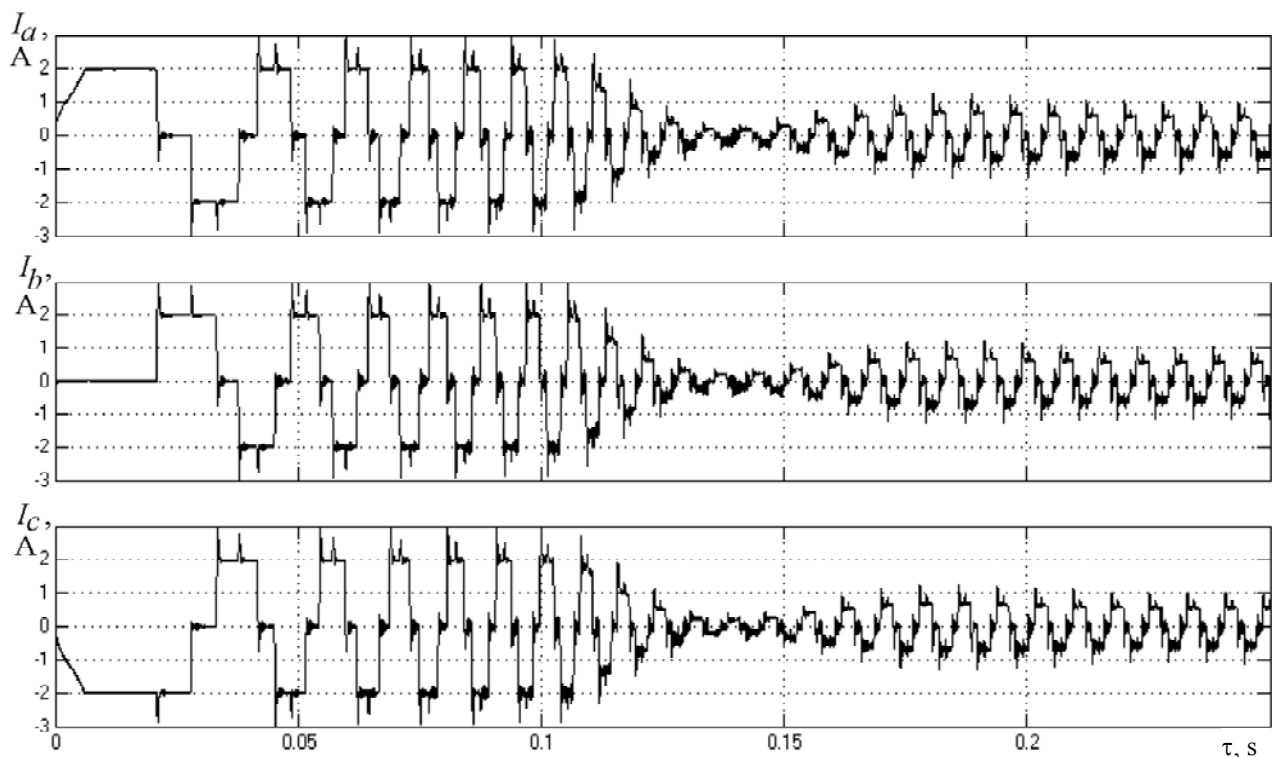(till current limiting); 2 – for high rotation speed (at current limiting)

Fig. 7. BLDCM phase currents at start in the current limiting mode

The graphs shown in Fig. 6 and Fig. 7 were obtained by installing the RPS with an «advance» angle Θ_{aa} of 45 electrical degrees, which was determined after a number of model investigations of the proposed AED with minimal hardware excess. The rate of increase in speed was limited by the active filter (AF) of the second order and the torque pulsations allowed for the BDPT.

Thus, if we compare the start-up graphs (Fig. 3 and Fig. 7) to the frequency of 100 rad/s of two AEDs functioning on the basis of the solutions shown in Fig. 1 and Fig. 4, then one can be convinced only of the insignificant differences in the processes of speed variation.

Conclusions.

1. Based on the analysis of the specified technical characteristics of the electric drive of an autonomous floating vehicle with a brushless DC motor («fan» load character, speed control range 1-10 with allowable overshoot of 20 %), the possibility of implementing an electric drive with minimum hardware excess due to justified rejection of PWM modulation and vector control with a high-resolution encoder is shown.

2. Model investigations of the proposed circuit of the electric drive in the *Matlab / Simulink* software environment have been carried out, which confirmed the operability of the proposed technical solutions and the possibility of realizing the required static and dynamic characteristics of the electric drive with maximum speed control range of 1-30 at acceptable level of its pulsations up to 10 % under inertia conditions of the load comparable with the moment of inertia of the applied motor.

3. The expected reduction in the cost of the structure of the electric drive with BLDCM performed according to the proposed circuit with minimal hardware excess, in the small-scale production will be 18 ... 25 %, while reducing the weight and size of the control card will be 5 ... 7 %.

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