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L. Mazurenko,
orcid.org/0000-0002-7059-249X,
V. Grebenikov,
orcid.org/0000-0002-1114-1218,
O. Dzhura*,
orcid.org/0000-0002-0224-3351

Institute of Electrodynamics of the National Academy of Sciences of Ukraine, Kyiv, Ukraine
* Corresponding author e-mail: suoma1715@gmail.com

ELEMENTS OVERVIEW AND A COMMERCIAL UAV ELECTRIC DRIVE MODEL

In recent years, there has been an accelerated development of technologies and an expansion of the application area of unmanned aerial vehicles. Accordingly, scientists need to consider current trends in development of unmanned aerial vehicles and the current state of research.

Purpose. Review of the main elements of unmanned aerial vehicle drives. Development of a simplified mathematical model of a helicopter-type unmanned aerial vehicle electric drive for assessing the energy consumption and capacity of the unmanned aerial vehicle battery.

Methodology. The proposed model is based on the rotor motion equations of the motors and the fan load equations. It was assumed that all electric drives operate under a cyclic load repeated periodically and defined by the time relations of motor torque reference during the operating cycle.

Findings. Based on the motion equations, torque (frequency) controller equations, and load equations, a simplified mathematical model of a multi-rotor unmanned aerial vehicle drive was synthesized. The developed mathematical model of the unmanned aerial vehicle electric drive was verified using the created simulation model. Transients for torque and speed were obtained and compared for two torque control algorithms.

Originality. The developed “inertial” mathematical model of the electric drive of a multi-rotor unmanned aerial vehicle, compared to the known models, operates with fewer parameters and variables, which speeds up calculations. The developed model takes into account the equations of torque (frequency) controllers of electric drives. Accordingly, this allows computing long-term processes using different control algorithms.

Practical value. The review materials presented in this article may be useful for technical specialists who are starting to work in the field of unmanned aerial vehicle design and development. The developed mathematical model allows evaluating the approximate capacity of the battery for arbitrary motor reference torque schedules, arbitrary battery voltage reference, and the required maximum flight duration.

Keywords: *electric drive, unmanned aerial vehicle, mathematical model, motion equation*

Introduction. The *21st* century has seen accelerated development of unmanned aerial vehicles. In [1] an unmanned aerial vehicle (UAV) is defined as “a remotely piloted or self-piloted aircraft...”. It is believed that the history of UAVs began in the *19th* century when attempts were made to use self-piloted balloons. At the beginning of the *20th* century, the first radio-controlled UAVs appeared, which are now widely used.

There are many classification characteristics used to classify UAVs: weight, wing type, flight altitude, application, etc. In particular, UAVs are classified according to their destination as commercial, civil, and military, and according to their type of propulsion as internal combustion engine, electric, and combined (hybrid) [2].

The following main types of UAVs are distinguished by type (design): single-rotor, multi-rotor UAVs, aircraft-type UAVs (with fixed wings), hybrid helicopter-aircraft with vertical take-off, and aerostats [3]. Quite often, single-rotor and multi-rotor UAVs are classified in the same category, calling them multi-rotor UAVs or helicopter-type UAVs. Depending on the tasks performed, technical characteristics, and installed equipment, known helicopter-type UAVs are equipped with one (monocopter) to ten (decacopter) propellers [4].

One of the world-famous applications of UAVs is the use of the Ingenuity Mars Helicopter UAV to study the surface of Mars [5]. This helicopter-type rotorcraft is specially designed to fly in the thin atmosphere of Mars. It can be classified as hybrid in terms of its primary energy source, as in addition to a rechargeable battery, it also has a solar panel for recharging. It is equipped with an electric drive based on direct current (DC) motors, whose rotors are mechanically connected to two propellers that rotate in opposite directions.

Brushless DC motors (BLDC motors) have been broadly used since 1970s thanks to the advancements in permanent magnets characteristics and have been gaining popularity in applications that require low-maintenance operations [6]. These motors are mostly used for dynamic applications such as the automotive industry, pump manufacturing, rolling mill production, electric vehicles, unmanned aerial vehicles, the manufacture of various drives, water supply, and consumer electronics [7].

The market for electric motors for drones was valued at US$5,182.84 million in 2024 and is forecast to reach US$9,700.87 million by 2032, growing at a compound annual growth rate of 9.37 % from 2026 to 2032 [8]. The basic segments of the electric motor market for drones are the segment of multi-rotor drones, the segment for fixed-wing drones, and the segment for FPV drones.

Most of the electric motors for drones manufactured are designed for commercial use. The scope of commercial drone use is constantly expanding. Noteworthy new areas of application for commercial UAVs include rapid sowing and monitoring of large areas of crops in agricultural regions, remote sensing, search and rescue, fire

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prevention on the upper floors of skyscrapers in everyday life, and the distribution of food and cargo [9, 10]. They can also be used for geological exploration and inspection of mines.

Expanding the scope of UAVs use requires the development of technical solutions and mathematical and computer models that provide improvement of UAV performance, diversify development and production, and accelerate preliminary design and analysis using simulation studies.

Purpose. The purpose of this article is to review the main elements and approaches to modeling, as well as to develop a simplified mathematical model of a helicopter-type UAV electric drive. The use of such a model will allow for preliminary determination of the capacity of the UAV battery at the design stage. Using this model, assessment of energy consumption from the battery at different fan-type mechanical load torque references to helicopter-type UAV drives (single and multi-rotor), can be achieved as well.

To achieve the specified purpose, the authors analyzed the literature and reviewed structural elements of UAV electric drives. Besides this, a simplified mathematical model and an "inertial" model of an electric drive for a multi-rotor UAV with a battery power source will be developed to verify it.

Literature review. ***Main elements of UAV drives.*** The main part of energy consumption in a UAV falls on its drive. For this reason, motors with a high power-to-weight ratio are used. The most common types of electric motors with a high power-to-weight ratio are BLDC motors and synchronous motors with permanent magnets (PMSM). BLDC motors and PMSMs are manufactured by a number of well-known manufacturers. KO Technologies, Constar Micromotor Co., KDE Direct; Ltd., Faulhaber Micromo, LLC, Hacker Motor USA, Nidec Corporation, SunnySky USA, MGM COMPRO, FUKUTA, Mechtex, and others are among them.

Both above-mentioned motor types, PMSM and BLDC, use permanent magnets on the rotor and are quite similar in design. The main difference between them concerns the shape of the counter-EMF, which is sinusoidal in PMSM and trapezoidal in BLDC. This is a consequence of the different distribution of the stator winding in the stator slots.

Typically, drones use motors with radial magnetic flux and an external rotor [11].

BLDC motors with an external rotor (Outrunner) have a rotor located outside the stator, which provides more space for magnets than in BLDC motors with an internal rotor [12, 13]. Outrunner BLDC motors are widely used in commercial UAVs just due to their design. In these electric motors the stator with three-phase windings is located inside, and the rotor with permanent magnets is located outside, forming a rotating shell. This design provides high torque at low rotational speeds due to the increased rotor diameter. Due to this, the need for gearboxes is eliminated and allowing large propellers to be driven directly, increasing aerodynamic efficiency and reducing losses.

An additional advantage is effective cooling: the rotation of the housing creates an air flow that promotes heat dissipation from the windings and magnetic circuits increasing reliability under prolonged loads. The simplicity of the design without gearboxes reduces the weight and number of failure-prone components, facilitating maintenance.

Among the limitations are a lower maximum angular velocity due to rotor inertia and magnet mounting restrictions, which is not critical for UAVs, where torque is more important than speed. A more serious drawback is the vulnerability of the open rotor to dust, moisture, and mechanical damage, which can cause vibration and reduce efficiency.

Axial flux permanent magnet (AFPM) motors are becoming an alternative solution in a number of applications [14]. In these motors, the magnetic flux is closed along the axis of rotation. The interaction of the rotor and stator magnetic fields occurs on the end surfaces rather than on the cylindrical surfaces, as in traditional radial machines. This topology provides a significant increase in torque with comparable dimensions due to the increased area of interaction between the magnetic fields.

The advantages of AFPM motors include high power and torque with minimal axial length. Due to their compactness and low moment of inertia, they can provide fast acceleration and deceleration dynamics, which is especially important for maneuverable UAVs. In addition, the axial layout facilitates integration into flat structures and allows the design of highly modular motors, for example, in the form of multi-disc systems. In such systems several rotor-stator pairs operate in parallel, increasing power without a significant increase in weight.

However, such motors also have a number of disadvantages. Heat dissipation in axial machines is less efficient compared to outrunner designs, as the active windings are often located between the disc rotors and have limited access to airflow. This creates a risk of local overheating at high currents. In addition, the production of AFPM motors is technologically more complex: high precision manufacturing and assembly are required, especially in terms of ensuring a uniform gap between the end surfaces.

Comparing both types of machines, we can note that outrunner motors are simpler, more reliable, and more efficient for tasks that require high torque at low speeds with relatively low requirements for compactness and technological precision. At the same time, AFPM motors have better power-to-weight and power-to-volume ratio, as well as higher dynamics, but have increased requirements for cooling and protection.

Thus, the choice between radial and axial flow motors is determined not only by the required electromechanical characteristics, but also by the operating conditions. For mass commercial UAVs, it is more rational to use outrunner machines due to their simplicity and reliability, while AFPM motors find applications in cases where compactness, high specific torque, and fast system response are important.

Although a BLDC motor is called a direct current motor, its winding is powered by a bipolar voltage source of variable frequency. Such a source is based on an inverter and a battery or DC voltage source. Inverters are important electronic devices that convert direct current energy into alternating current. This key component consists of several components: rectifiers, filters, inverter circuits, control circuits, output filters, and protection circuits [15]. At low voltages, the simplest two-level inverters are usually used. If it is necessary to reduce the total harmonic distortion of the inverter output voltage, three-level inverters can be used. In [16], the authors evaluated the reliability of multilevel inverters for use in hybrid drones. According to the method proposed by these authors, it was concluded that a cascade H-bridge inverter is the best choice in terms of reliability for systems with hybrid power sources. The use of a GaNFET inverter controlled by a high-frequency sinusoidal PWM algorithm is more effective than a traditional MOSFET inverter. When operating as part of a UAV instead of a traditional MOSFET inverter with low-frequency trapezoidal PWM, a GaNFET inverter can reduce power consumption by several hundred watts per motor. Due to this, an increase in flight time by several minutes will be achieved [17].

Accurate detection or estimation of the BLDC shaft position is important in multi-rotor UAVs to maintain high efficiency and low power losses in the system [18]. Optical encoders and Hall sensors are used to determine the BLDC shaft position. To improve electric drive reliability, sensorless BLDC control methods have been developed.

When high accuracy is not required, the scalar control method is a good choice for BLDC and PMSM drives due to its simplicity of implementation. The scalar control method is often used in combination with the so-called six-step commutation algorithm. The six-step commutation technique can use 120-degree and 180-degree conduction modes. When the 120-degree conduction mode is used to control three-phase BLDC motors, the commutation technique involves powering only two phases at a time. When the 180-degree conduction mode is used, currents flow in all three phases simultaneously. In three-phase BLDC motors, three Hall sensors are typically mounted on the motor stator core between the stator phases. As the rotor rotates, the Hall sensors generate logical “1/0” signals with equal low and high time intervals at each rotation period. Although scalar control combined with a six-step commutation algorithm is still used in low-power BLDC drives, vector control, direct torque control, and mathematical model-based prediction algorithms are more preferable. These improved control technics result in a smaller torque ripple and improved transient control in dynamic modes under various operating conditions with increased loads [19]. The advantages and disadvantages of the main known algorithms for controlling electronic frequency regulators of UAVs are discussed in [20].

Scalar and vector control algorithms, as noted, can be implemented without the use of encoders and Hall position sensors to increase the reliability of the electric drive. With such algorithms, the problem of determining the rotor position is solved mathematically using instantaneous values of currents and voltages. In particular, with scalar six-stage control, the back-EMF of the phase that is not currently powered is measured. Often, scalar control is combined with a pulse-width modulation algorithm. Typically, with scalar control, a given ratio between the frequency and the RMS voltage of the first harmonic of the voltage generated by the inverter is maintained. This occurs due to a change in the PWM signal duty ratio. The sensorless vector control algorithm is much more complex. With vector control, there are two control loops: a torque control loop and a flux linkage control loop, which should not affect each other’s operation. The parameters of the regulators of both loops depend on the parameters of the electric machine. The Clark 3/2 and Park 2/3 coordinate transformations are used. The counter-EMF observer is digitally implemented based on the mathematical model of the machine. The PLL (phase locked loop) structure can be used to estimate the angular speed. Furthermore, the problem of digital signal filtering is additionally solved. Hence, it is obvious that sensorless vector control of BLDC and PMSM motors is much more complicated than scalar control. However, significant advantages are obtained with vector control. The main ones are better quality of torque control in dynamic modes and small torque ripples. Accordingly, more accurate processing of the UAV movement coordinates is ensured, and the noise level is reduced.

Vector control systems are implemented on the basis of high-performance 16- or 32-bit microcontrollers, while even the computing capabilities of 8-bit microcontrollers may be sufficient to implement scalar control.

The next important element of an electric-powered UAV is the rechargeable battery. The most common batteries for electric-powered drones are Li-Po and Li-Ion batteries. Li-SOCl2 batteries have twice the energy density per kg compared to the above, and lithium-air (oxygen) batteries can have up to seven times higher energy density. But unfortunately, they are not as widely available and are much more expensive than Li-Po and Li-ion [21, 22].

Mathematical modeling of UAV drives. Mathematical models of varying levels of complexity and detail are developed and used for research on BLDC, PMSM, and electric drives based on them. A model based on a space vector, a d-q model, a model based on a single-phase equivalent circuit, a model of concentrated parameters, finite element analysis (FEA) models are known. Linear and nonlinear state space models, rotor dynamics model, coupled electromechanical model, lumped thermal model, and finite element method-based thermal model are used as well [23, 24]. The calculation of characteristics and design of BLDC and PMSM is performed using the finite element method and specialized multiphysics modeling software packages [25, 26]. In highly detailed models, inverters are modeled by systems of algebraic-differential equations that take into account the current state of semiconductor elements (conductive/non-conductive) [27]. Most of the noted models are characterized by a large number of parameters and require specialists with extensive experience in using highly specialized software packages. For simulation of electric drives with power AC/DC and DC/AC converters in the MATLAB/SIMULINK package, it is convenient to use the Universal Bridge block. This block allows modeling semiconductor switches as ideal switches or parallel-connected transistors and reverse diodes, taking into account their internal resistances.

Each of the above-mentioned models and approaches to modeling has its advantages and disadvantages, as well as a range of tasks that it is designed to solve.

Methodology and findings. ***Simplified dynamic” inertial” mathematical model of an UAV electric drive.*** Simplified mathematical models of electric drives based on the equation of motion are characterized by simplicity and a small number of variables. They can be used for mathematical modeling and in the development of algorithms for controlling electric drives [28, 29].

In this article a simplified mathematical model of a multi-rotor electric drive for unmanned aerial vehicles was developed using the theory of electromechanical systems and the theory of automatic control. The proposed model is based on the rotor motion equations, equations of the torque (frequency) controllers of the motors and the fan load equations.

A UAV (quadcopter) equipped with four identical permanent magnet motors is shown in Fig. 1. Suppose that the time dependencies of the electromagnetic torque values of the motors are known for the time interval of the operating cycle. Then, for scalar (frequency) control of the motors, the angular speed reference of the i^{th} motor can be calculated from the following equation

$$\omega^*_{ip.u.} = \left(\omega_{ip.u.} + \delta_{Np.u.} k_i \frac{M^*_{ip.u.} - M_{ip.u.}}{s}\right)\frac{1}{T_c s + 1}, \qquad (1)$$

where $\omega_{ip.u.}$ is angular speed of the i^{th} motor related to the nominal speed ω_N; $\delta_{Np.u.} k_i \frac{M^*_{ip.u.} - M_{ip.u.}}{s} = \Delta\omega^*_{ip.u.}$ is speed increase reference of the i^{th} motor; $\delta_{Np.u.}$ is the nominal motor load angle, p.u.; $k_i = \text{const}$; $M^*_{ip.u.}$ $M_{ip.u.}$ are the electromagnetic torque reference and electromagnetic torque of the i^{th} motor related to the nominal torque M_N; T_c is the time constant of the torque controller; $i = \overline{1 \ldots 4}$; $s = d/dt$.

Let us assume that the electromagnetic torque is proportional to the motor load angle, and the load angle is proportional to the difference between the reference and instantaneous angular speed. Then the equation for electromagnetic torques of the UAV motors will be as follows

$$M_i = \frac{\omega^*_{ip.u.} - \omega_{ip.u.}}{\omega^*_{ip.u.}\delta_{Np.u.}} \frac{M_N}{T_e s + 1}, \quad i = \overline{1 \ldots 4}, \qquad (2)$$

where $\frac{\omega^*_{ip.u.} - \omega_{ip.u.}}{\omega^*_{ip.u.}\delta_{Np.u.}} = \delta^*_{ip.u.}$ is load angle reference of the i^{th} motor, p.u.; T_e is equivalent time constant of the motor electrical circuits [30].

The rotation speed of motors is obtained using the equation of motion

$$\omega_{ip.u.} = \frac{1}{J\omega_N}\int\left(M_i - M_{Li} - M_{Fi}\right)dt, \quad i = \overline{1 \ldots 4}, \qquad (3)$$

where J is the total moment of inertia of the motor rotor and blades; M_{Li}, M_{Fi} are the load torque and friction loss torque of the i^{th} motor; $M_{Fi} = k_F\omega_i$; $w_i = w_{ip.u.} w_N$; $\omega_N = \pi n_N/30$; n_N is the nominal rotational speed, rpm.

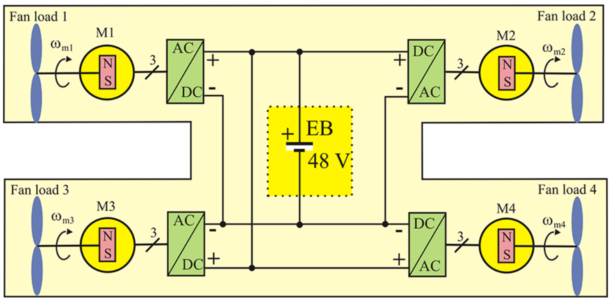

Fig. 1. Schematic diagram of the UAV drive system

The total energy value (kW·h) consumed from the electric battery (EB) or direct current source during the time T_{cy} is defined as follows

$$E_{cy} = \frac{1}{Eff}\frac{0.001}{3600}\int_0^{T_{cy}}\left(\sum_{i=1}^{4} M_i\omega_i\right)dt, \qquad (4)$$

where Eff is the overall efficiency of the controller (inverter) and motor (for simplicity, we assume it to be the same for all motors).

The load torque of each motor is fan-like, and therefore, its value can be calculated using the following equation

$$M_{Li} = k_{Bl}\omega_i^{\alpha}, \quad i = \overline{1 \ldots 4}, \quad i \in N, \qquad (5)$$

where k_{Bl} = const is the proportionality coefficient; the α value of the fan load is usually taken to be within the range of [1.5; 2.5], $\alpha \in \mathbf{R}$.

The k_{Bl} value is defined in such a way that at the rated rotational speed, the load torque of the fan is equal to T_N

$$k_{Bl} = \frac{M_N}{\omega_N^{\alpha}}. \qquad (6)$$

To estimate the required EB capacity, at first the maximum flight time T_{fl} is set. Next, assuming an operation cycle occurring at $[0 \ldots T_{cy}]$ interval will occur again cyclically during the flight time, the consumed energy (kW · h) will be equal to

$$E_{fl} = E_{cy}\frac{T_{fl}}{T_{cy}}. \qquad (7)$$

Since $E_{fl} = U_{Bat}I_{Bat}T_{fl} = U_{Bat}Q_{Bat}$, where U_{Bat} and I_{Bat} are the voltage and average discharge current of the EB, the estimated value of the EB capacity (A · h) will be equal to

$$Q_{Bat} = \frac{E_{fl}}{U_{Bat}}1{,}000. \qquad (8)$$

The electromagnetic torque of the motor for the sensorless vector control algorithm can be defined in a simplified way from the following equation

$$M_i^{vc} = \frac{M^*_{ip.u.}}{T_M s + 1}M_N, \quad i = \overline{1 \ldots 4}, \qquad (9)$$

where T_M is uncompensated time constant due to delays in speed and torque controllers.

Equations (3) and (5) are equations of the mechanical part of the motor model. They describe the dynamics of the rotor, taking into account the inertia of rotating masses and load. Since equations (3) and (5) are the basis of model (1–9), the developed model can be called an “inertial” model.

The proposed model (1–9) was verified in the MATLAB/Simulink software packages. The results of modeling the system (Fig. 1) are shown in Fig. 2, Fig. 3 and Fig. 4.

The numerical experiment was carried out using the following parameters and settings.

M1, M2, M3, M4 motors. Rated rotational speed is 4800 rpm; total moment of inertia of the rotor and blades: $J = 5.7 \cdot 10^{-3}$ kg · m²; the number of pole pairs is 1; friction loss coefficient: $k_F = 3.78 \cdot 10^{-5}$ N · m · s/rad;

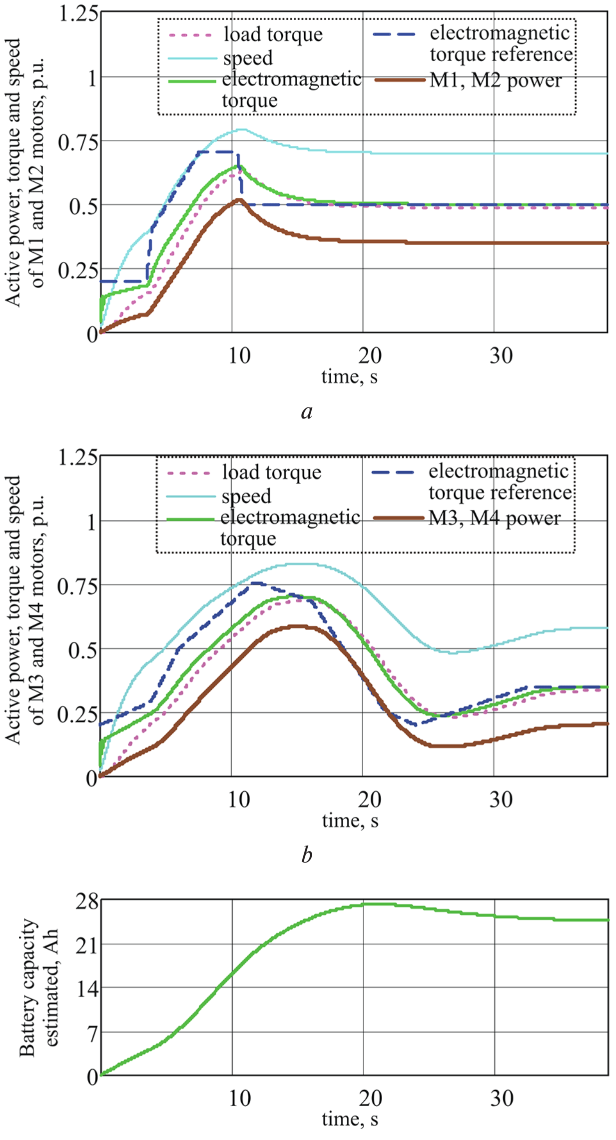

Fig. 2. Electromechanical processes in the system for scalar control with $k_i = 0.5$:

a – M1, M2 time dependencies of active power, torque and speed; b – M3, M4 time dependencies of active power, torque and speed; c – evaluation of EB capacity

equivalent time constant of the motor electrical circuits: $T_e = 0.0035$ s; rated load angle: $\delta_{Np.u.} = 0.01$ p.u.; rated torque: $T_N = 3.8$ N · m.

Load and control system. $\alpha = 2$; $k_{Bl} = 1.504 \cdot 10^{-5}$ N · m · s/rad; torque controller time constant is $T_c = 0.00025$ s; $T_M = T_e$; simulations were performed with $k_i = 0.5$ and $k_i = 7$.

Other parameters and characteristics. EB voltage is $U_{Bat} = 48$ V; total efficiency of the motor and power controller (inverter) in equation (4) is $Eff = 0.807$; maximum flight time is $T_{fl} = 25$ min.

Basic values of power, torque, and frequency for time dependencies in Figs. 2–4. 1,910 W = 1 p.u. of power; 3.8 N · m = 1 unit of torque; 4,800 rpm = 1 unit of speed.

Figs. 2 and 3 show the operation of the system under scalar (frequency) control with $k_i = 0.5$ and $k_i = 7$. Fig. 4 relates to vector control.

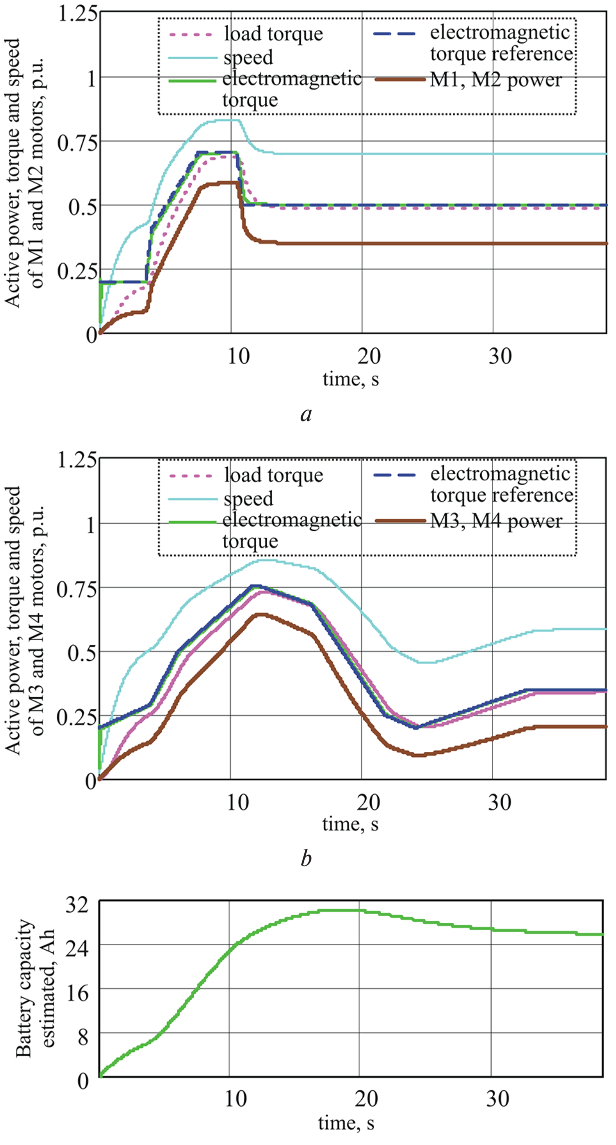

Fig. 3. Electromechanical processes in the system for scalar control with $k_i = 7$:

a – M1, M2 time dependencies of active power, torque and speed; b – M3, M4 time dependencies of active power, torque and speed; c – evaluation of EB capacity

In simulation, the torque references of motors M1, M2 (Figs. 2, *a*; 3, *a*; 4, *a*) and M3, M4 (Figs. 2, *b*; 3, *b*; 4, *b*) were assumed to be identical.

As can be seen from the comparison of Fig. 2, *a* and Fig. 3, *a* with Fig. 2, *b* and Fig. 3, *b*, increasing the gain coefficient k_i increased the accuracy of torque control. It is seen that the maximum error, excluding the initial acceleration interval, decreased from 0.14 p.u. to 0.055 p.u. The transient time caused by a rapid decrease in the torque reference was reduced by 7–8 times, from 6 s to 0.75–0.8 s. With vector control, the torque and torque reference time dependencies did not differ significantly due to the small time delay in torque response (Figs. 4, *a* and 4, *b*).

The estimated value of the battery capacity at the end of the simulation interval did not differ significantly for scalar and vector control. It amounted to (24.6–25.7) A · h, as can be seen in Figs. 2, *c*; 3, *c*; 4, *c*. This is due to non-accounting of electromagnetic pro-

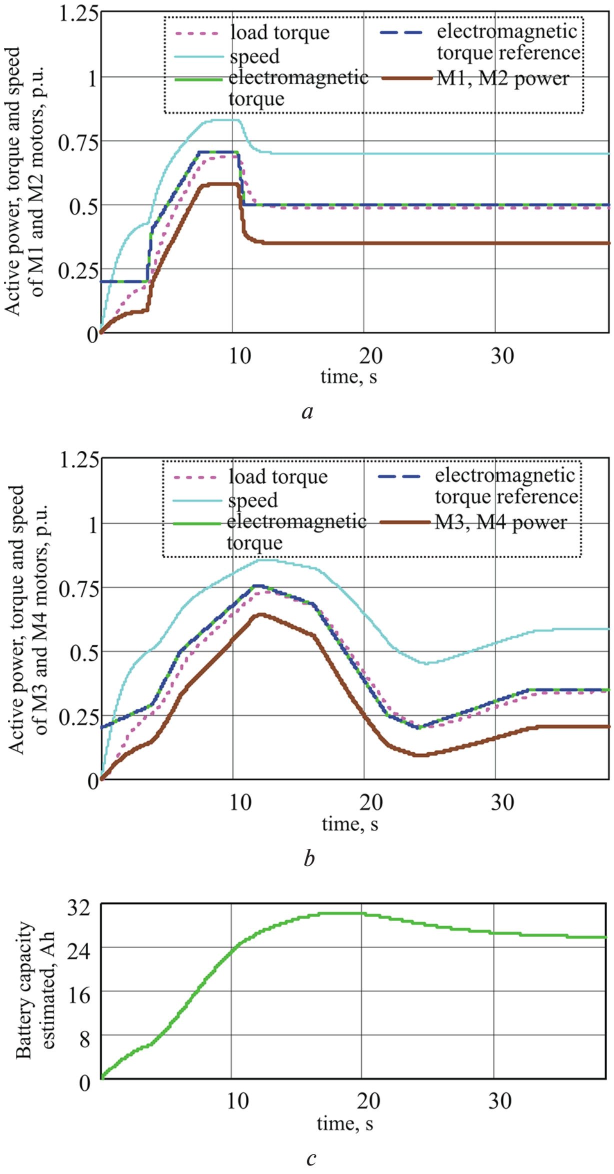

Fig. 4. Electromechanical processes in the system for vector control

a – M1, M2 time dependencies of active power, torque and speed; b – M3, M4 time dependencies of active power, torque and speed; c – evaluation of EB capacity

cesses in the developed model (core and winding losses are not taken into account).

Conclusions and direction of further research. The literature review showed a steady growth of the UAV market and significant interest of scientists and technical specialists in the development and improvement of UAV electric drives. The projected growth of the market for electric motors for UAVs is 9–10 % per year until 2032.

Video surveillance, cargo delivery, video recording of territories, treatment of agricultural crops, robotaxis is only an incomplete list of known applications of unmanned aerial vehicles.

The most common UAV electric drives are based on so-called BLDC motors due to their high Power-to-Weight Ratio (W/kg). The typical power-to-weight ratio value of a BLDC itself designed for UAVs can be 3 g/W or even less. For comparison, the power-to-weight ratio an asynchronous motor of the same power is at least three times worse. Synchronous motors with permanent magnets are less involved. It is obvious that this trend will continue in the future.

For mass commercial UAVs, it is rational to use BLDC motors with an external rotor (Outrunner) due to their simplicity and reliability.

The simulation of the UAV electric drive was carried out using a developed mathematical model and created on its basis "inertial" simulation model of the UAV electric drive. The developed model is distinguished by its simplicity and accessibility of parameters. The simulation results do not contradict with the theory of electromechanical systems. This allows recommending the developed "inertial" model in investigations at the preliminary design stage of the UAV electromechanical system. In particular, it can be useful for EB capacity estimation and for estimating energy consumption at different torque or speed time schedules of the electric motors of the electric drive. A comparison of simulation results obtained using a detailed model and the considered model is also planned.

In the future, it is planned to use a more detailed dynamic mathematical model of the UAV electric drive by taking into account electromagnetic processes in electric drive motors. This will provide an opportunity for comparing different inverter control algorithms in terms of their impact on the energy performance of UAV drives.

Another promising area of research is the advancements in the control theory of hybrid UAV electric drives.

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Огляд елементів і модель електроприводу комерційних БПЛА

Л. І. Мазуренко, В. В. Гребеніков, О. В. Джура[*]

Інститут електродинаміки Національної академії наук України, м. Київ, Україна

[*] Автор-кореспондент e-mail: suoma1715@gmail.com

В останні роки спостерігається прискорений розвиток технологій і розширення сфери застосування безпілотних літальних апаратів. Відповідно, науковцям необхідно враховувати поточні тенденції розвитку безпілотних літальних апаратів і поточний стан досліджень.

Мета. Огляд основних елементів приводів безпілотних літальних апаратів і розробка спрощеної математичної моделі електроприводу для оцінки енергоспоживання й ємності акумуляторної батареї безпілотних літальних апаратів вертолітного типу.

Методика. Запропонована модель базується на рівняннях руху ротора двигунів і рівняннях навантаження вентиляторного характеру. При розробці моделі були зроблені припущення, що всі електроприводи працюють за циклічного навантаження, яке повторюється із заданою періодичністю та визначається часовими залежностями зміни заданих моментів електричних двигунів на робочому циклі.

Результати. На основі механічних рівнянь двигунів, рівнянь регуляторів моменту (частоти) і рівнянь навантаження синтезована спрощена математична модель багатороторного приводу безпілотного літального апарату. Розроблена математична модель електроприводу безпілотного літального апарату верифікована із використанням створеної імітаційної моделі. Отримані й співставлені перехідні процеси по моменту і частоті за двох алгоритмів регулювання моменту.

Наукова новизна. Розроблена «інерційна» математична модель електропривода багатороторного безпілотного літального апарату у порівнянні з відомими оперує з меншою кількістю параметрів і змінних, що прискорює розрахунки. У розробленій моделі враховане рівняння регуляторів моменту (частоти) електроприводів. Відповідно, це дозволяє розраховувати довготривалі процеси за різних алгоритмів керування.

Практична значимість. Представлені в роботі оглядові матеріали можуть бути корисними для технічних фахівців, які розпочинають працювати в області проєктування й розробки безпілотних літальних апаратів. Розроблена математична модель дозволяє розраховувати орієнтовну ємність акумуляторної батареї за довільних графіків зміни заданих моментів двигунів, заданої величини напруги акумуляторної батареї та заданої максимальної тривалості польоту.

Ключові слова: *електропривод, безпілотний літальний апарат, математична модель, рівняння руху*

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