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# EFFECT OF THE MAXIMUM MAGNETIC ENERGY ON DYNAMIC PARAMETERS OF THE ELECTRIC DRIVE

**ABSTRACT** *In the paper there are questions of increase of the angular velocity of the airship rudder surfaces for the sinusoidal control input signal under conservation of the electric drive dynamic parameters by using the permanent magnets with higher maximum magnetic energy.*

**Keywords:** *brushless electric motors, improving dynamic characteristics, maximum magnetic energy*

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# 1. ELECTRIC DRIVE OF THE AIRSHIP CONTROL RUDDER SURFACES

JSC «Electroprivod» carries out development of the automated electric drive of new generation EPD-02E on the basis of the brushless DC electric motor (BDCM) with rare-earth permanent magnets and electronic device for the airship control rudder surfaces and control elements of the power-plant vector of thrust (Fig. 1).


**Fig. 1. Three-dimensional model of the airship AE-02E**

The automated electric drive of the airship aerodynamic control surface and the power-plant is a practical step in realization of the “all electric aircraft” concept. Use of last achievements in the field of high-energy rare-earth magnetic materials and new devices of power electronics and microprocessor engineering has allowed to create the modern aircraft electric drive. This electric drive excels hydraulic and pneumatic drives in the performance characteristics.

BDCM of the aircraft automated electric drive contains electromechanical and electronic parts. The electronic part represents voltage inverter controlled by IGBT. The electromechanical part consists of the brushless electric motor – the synchronous machine with permanent magnets (Fig. 2), rotor position sensor and electromagnetic brake.

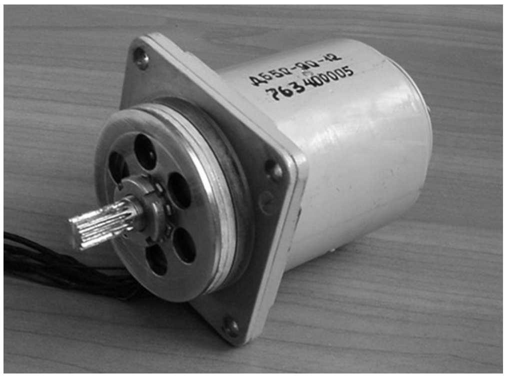

**Fig. 2. The brushless DC electric motor DB50-90-8 of the aerodynamic control surface electric drive**

For transformation of rotary movement in forward movement the ball-and-screw actuator is used. It is connected with the electric motor through summing differential and planetary reducer. The screw, making forward movement, changes position of the airship controlled elements of vector of thrust or rudder surface (depending on purpose of the electric drive) in automated operation or pilot commands at manual control.

The kinematics scheme of the electric drive for the aircraft control rudder surfaces is shown in Fig. 3.

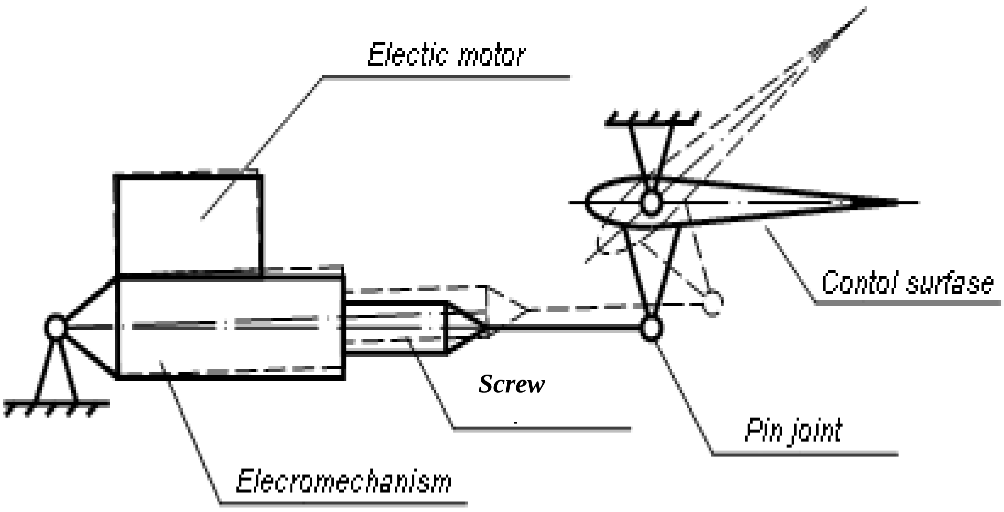


**Fig. 3. The kinematics of the airship control rudder surfaces electric drive**

The basic characteristics of the electric drive:

| | |
|---|---|
| Maximal force to output link $F_{max}$, $H$ | 1920 |
| Movement speed of the screw under $F_{max}$, $V_{\min}^{skrew}$, mm/s | 9 |
| Reduced distance from a point of application of force to an axis of surface rotation $R$, mm | 96 |
| Linear movement of a output link, $l_{screw}$, mm | 45 |
| Moment of inertia of the rudder surface load $J_l$, kg·m$^2$ | 1,176 |
| Lead of screw, $h$, mm | 4,5 |

## 2. PROBLEM DEFINITION

The electric drive should perform the sinusoidal control input signal $\varphi^{in} = \varphi_m^{in} \sin \omega t$ on a frequency of 0, 2 Hz. On the basis of this:

- frequency band $f = 0,2 Hz$ ,
- angular frequency of a harmonic signal $\omega = 2\pi f$ = 1,256 rad/s,
- control signal amplitude $\varphi_m^{in} = V_{\min}^{skrew} / \omega = 7,2 mm$ .

During the elaboration of the airship automated electric drive there was a necessity to increase movement speed of the rudder surfaces 2, 5 times at the same values of dynamic and static loads under conservation of the electric drive dynamic parameters.
In this case:

- movement speed of the screw $V_{\min}^{skrew}$=23 mm/s,
- control signal amplitude $\varphi_m^{in} = V_{\min}^{skrew} / \omega = 18{,}4 mm$.

Analysis of means of the problem solving with tolerance for the practice fallibility can be carried out on the expression of mechanical time constant of the electric drive

$$T_m = \frac{J_\Sigma \varphi_{motor}^0}{T_{start} - T_l / i} \tag{1}$$

where

$J_\Sigma$ – moment of inertia;
$\varphi_{motor}^0$ – angular velocity of the electric motor of no-load operation;
$T_{start}$ – starting torque,
$T_l$ – static load torque of the rudder surfaces,
$i$ – gear ratio from the electric motor to the rudder surfaces.

Expression of mechanical time constant $T_m$ shows that at the same power and specified dimensions increasing of the electric motor rated speed 2, 5 times reduces the starting torque 2, 5 times. As a result, with other equal conditions, $T_m$ increases 5 times. Hence, the electric motor dynamic parameters with higher rated speed have deteriorated.

This conclusion is reflected in classical works about electric machines and electric drives [1, 2] where it is told, that the high-speed electric motor is less preferable according to condition of response time reduction because its speed rises faster, than moment of inertia decreases.

This conclusion is absolutely correct for all types of electric machines, except BDCM with rare-earth permanent magnets of the inverted machine when permanent magnets are placed on rotor. Rare-earth permanent magnets characterized by higher maximum magnetic energy $(BH)_{max}$ have allowed create the same magnetic fields under appreciably smaller rotor volume and consequently moment of inertia. Rare-earth permanent magnets are capable to conserve electric motor dynamic parameters and improve mass-overall parameters of BDCM at increasing of the electric motor rated speed.

# 3. THREE METHODS OF PROBLEM SOLVING OF CONSERVATION OF DYNAMIC PARAMETERS

On the basis of expression $T_m$ (1) three methods of problem solving of conservation of dynamic parameters of the electric drive were considered:

1) Increase of the electric motor rotation speed 2, 5 times. In this case it is necessary to increase starting torque and rated power of the electric motor 5 times.

2) Decrease of reducer gear ratio 2, 5 times. In this case reduced torque of static load of the rudder surfaces $T_l/i$ will increase 2, 5 times. It requires increase of starting torque, rated power of the electric motor and inverter 2, 5 times.

3) Reduction of the electric motor moment of inertia at increase of rotation speed 2, 5 times.

The third method can be realized in BDCM with rare-earth permanent magnets using permanent magnets with higher maximum magnetic energy.

The additional data and expressions for calculations have been gathered in table 1. In the table there are four variants: base variant, where movement speed of the airship rudder surfaces at $F_{max}$ is $V_{\min}^{skrew}$ = 9 mm/s. The other variants reflect three methods of realization of the required dynamic parameters at increase of movement speed of the airship rudder surfaces ($V_{\min}^{skrew}$ = 23 mm/s).

The base electric motor has rated speed 8000 *rpm*. With gear ratio of a reducer $i$ = 108 the electric motor provides movement speed of the screw 9 mm/s. Moment of inertia of rotating parts of the electric motor is $1{,}1\cdot10^{-5}$ kg·m$^2$. Mechanical time constant of the electric motor with starting torque ratio $k_{start}$ = 3 is 0, 07 s.

**For estimation of the first method** the base electric motor had been re-computed for rated speed 16000 prm without change of its active sizes. With gear ratio of a reducer $i$ = 108 the electric motor provides movement speed of the screw 23 mm/c. Moment of inertia of rotating parts of the electric motor is $1{,}1\cdot10^{-5}$ kg·m$^2$. Mechanical time constant of the electric motor has been increased in comparison with the base variant to 0, 19 s.

**For estimation of the second method** the base variant has been chosen but the gear ratio of a reducer $i$ is decreased to 42, 8. With this gear ratio the electric motor provides movement speed of the screw 23 mm/c.

**For estimation of the third method** new variant of the electric motor with increased maximum magnetic energy $(BH)_{\max}$ = 240 kJ/m$^3$ for rated speed

16600 prm has been designed. With gear ratio of a reducer $i$ = 108 the electric motor provides movement speed of the screw 23 mm/c. Moment of inertia of rotating parts of the electric motor is 0, 27·10$^{-5}$ kg·m$^2$. Mechanical time constant of the electric motor has been decreased in comparison with the base variant to 0,037 s.

For each variant the following dynamic parameters (table 2) have been designed:

- minimal required torque of the electric motor for guarantee of prescribed values of static and dynamic loads $T_{motor}$,
- minimal power of the electric motor $P_{motor}^{\min}$,
- power rate of the electric motor $T_{start}^2 / J_{motor}$ [3],
- angular velocity of the rudder surface $\dot{\varphi}^{rud}$,
- angular acceleration of the rudder surface $\ddot{\varphi}^{rud}$,
- mechanical time constant of the electric drive $T_m$.

**TABLE 1**
The calculation data of the airship rudder surfaces electric drive

| **The calculation data of the airship rudder surfaces** | **Variants** | | | |
|---|---|---|---|---|
| | Base | 1 | 2 | 3 |
| Movement speed of the screw, mm/s | 9 | 23 | 23 | 23 |
| Amplitude of the rudder angle, $\varphi_m^{rud}$, rad | 0,0746 | 0,191 | 0,191 | 0,191 |
| Angular velocity of the rudder $\dot{\varphi}^{rud}$, rad /s | 0,0937 | 0,239 | 0,239 | 0,239 |
| Angular acceleration of the rudder surface $\ddot{\varphi}^{rud}$, rad/s$^2$ | 0,117 | 0,301 | 0,301 | 0,301 |
| Maximum load torque of the rudder surface $T_l$, Nm | 188,8 | 188,8 | 188,8 | 188,8 |
| Maximum power of the output link $P_{rud}, W$ | 55 | 142 | 142 | 142 |
| Power of the electric motor $P_{motor}, W$ | 27,7 | 71 | 71 | 71 |
| Gear ratio from the electromechanism to the electric motor, $i$ | 108 | 108 | 42,8 | 108 |
| Gear ratio from the axis of the rudder surface to the axis electric motor | 14464 | 14464 | 5732 | 14464 |
| **The calculation data of BCDM** | **Variants** | | | |
| Minimum of the electric motor required rated speed, rpm | 6480 | 16500 | 6563 | 16560 |
| Electric motor rated speed, $rpm$ | 8000 | 16000 | 8000 | 16600 |
| Moment of inertia of rotating parts of the electric motor, $J_\Sigma, kg \cdot m^2$ | 1,1·10$^{-5}$ | 1,1·10$^{-5}$ | 1,1·10$^{-5}$ | 0,27·10$^{-5}$ |
| Mechanical time constant of the electric motor $T_m$, s | 0,07 | 0,19 | 0,07 | 0,0037 |
| Maximum magnetic energy of permanent magnets $(BH)_{max}$, kJ/m$^3$ | 130 | 130 | 130 | 240 |

**TABLE 2**
Results of dynamic parameters calculation of the airship control surface electric drive

| **Variants** | Base | 1 | 2 | 3 |
|---|---|---|---|---|
| Gear ratio $i$ | 14464 | 14464 | 5732 | 14464 |
| Prescribed angular velocity of the rudder $\dot{\varphi}^{rud}$, rad/s | 0,0937 | 0,239 | 0,239 | 0,239 |
| Calculated angular velocity of the rudder $\dot{\varphi}^{rud}$, *rad /s* | 0,115 | 0,231 | 0,292 | 0,240 |
| Calculated angular acceleration of the rudder $\ddot{\varphi}^{rud} = T_{start} i\eta_{red} - T_l / J_l + i^2 J_{motor}\eta_{red}$, rad /s$^2$ | 0,112 | 0,3 | 0,292 | 0,301 |
| Prescribed angular acceleration $\ddot{\varphi}^{rud}$, rad /s$^2$ | 0,117 | 0,301 | 0,301 | 0,301 |
| Mechanical time constant of the electric drive $T_m = (J_{motor} + \frac{J_l}{i^2\eta_{red}})\dot{\varphi}^0_{motor} \Big/ T_{start} - \frac{T_l}{i\eta_{red}}$, s | 0,663 | 0,426 | 0,634 | 0,449 |
| Prescribed mechanical time constant, s | 0,8 | 0,8 | 0,8 | 0,8 |
| Power rate $T^2_{start} / J_{motor}$, W/s | 327 | 736 | 1420 | 1080 |
| Prescribed power rate $\frac{4}{\eta_{red}}\ddot{\varphi}^{rud}(J_l\ddot{\varphi}^{rud} + T_l)$,W/s | 285 | 735 | 735 | 735 |
| $T_{motor} = J_{motor}\ddot{\varphi}^{rud} i + \frac{J_l\ddot{\varphi}^{rud}}{i\eta_{red}} + \frac{T_l}{i\eta_{red}}$, Nm | 0,0186+0,00003+0,042=0,061 | 0,0478+0,00008+0,042=0,09 | 0,0189+0,00019+0,106=0,125 | 0,01175+0,00008+0,042=0,054 |
| $P^{\min}_{motor} = T_{motor} \cdot \dot{\varphi}^{\min}_{motor}$, W | 41 | 156 | 86 | 93 |

## 4. ANALYSIS OF CALCULATION RESULTS

Calculation results of the first variant show that increase of the electric motor rated speed 2,5 times leads to increase of dynamic component of the electric motor torque 2,5 times and the minimal required torque 1,5 times. Increase of the electric motor rated speed and the torque is a result of increase of electric motor power 3, 8 times (Fig. 4, point I). This variant demands to increase installed power of inverter and its dimensions.

From the second variant it is followed that reduction of gear ratio 2,5 times demands to increase a static component of the electric motor torque 2,5 times and minimal required torque and power 2 times (Fig. 4, point II). This variant demands to modify a design of reducer, and also to increase mass and dimensions of inverter of BDCM.

Calculation results of the third variant show that application of permanent magnets with higher maximum magnetic energy with increase of the electric motor rated speed 2, 5 times allows to reduce the moment of inertia of the electric motor 5 times, mass of the electric motor - 2 times, dynamic torque of the electric motor – 1, 6 times and minimal required torque - 1, 3 times (Fig. 4, point III). Power of the electric motor rises 2 times, power density – 4 times. Consumption current of the electric motor increases insignificantly due to rise of efficiency coefficient.

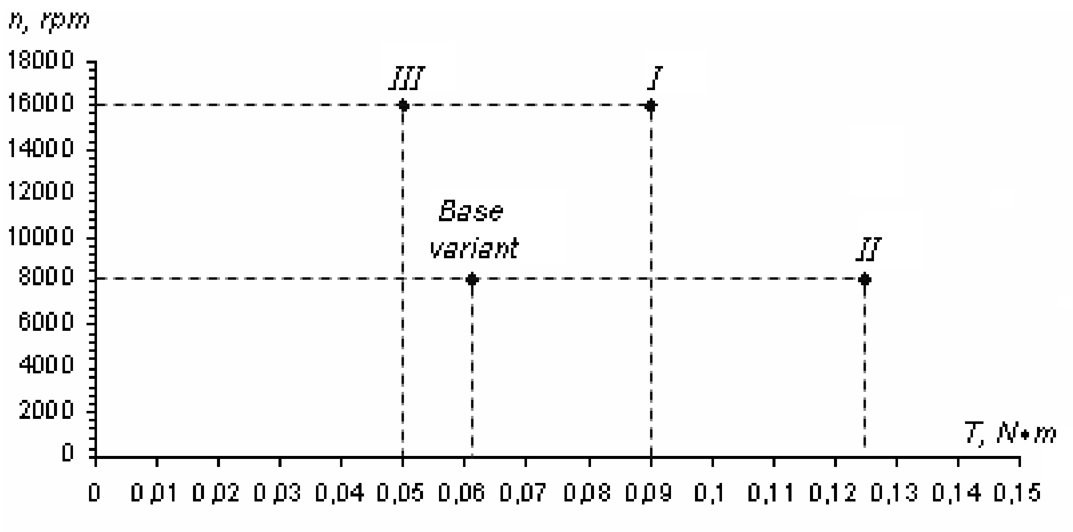


**Fig. 4. Nominal points of speed-torque characteristics of the electric motor**

## 5. CONCLUSIONS

Increase $(BH)_{max}$ of samarium-cobalt permanent magnets from 130 to 240 kJ/m$^3$ has allowed reduce the moment of inertia and conserve of the electric drive dynamics and improve mass-overall parameters BDCM with increase of the rudder surface rated speed:

1) On the basis of the calculations the practical estimation of three methods of conservation of the dynamic parameters of the airship control surface electric drive is realized.

2) Possibility of conservation of dynamic parameters of the electric drive is confirmed due to use of permanent magnets with higher maximum magnetic energy at increasing of the electric motor rated speed.

3) According to the results of the analysis the third method realized on the basis of increase of maximum magnetic energy $(BH)_{max}$ from 130 to 240 kJ/m$^3$ is the most effective:

- speed of response the electric drive is kept with increase of the electric motor rated speed,
- changes in reducer and inverter are not required,
- coefficient of efficiency of the electric motor raises,
- the mass and dimensions of the electric motor decrease,
- power density of the electric motor raises.

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### WPŁYW MAKSYMALNEJ ENERGII MAGNETYCZNEJ NA DYNAMICZNE PARAMETRY NAPĘDU ELEKTRYCZNEGO

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**STRESZCZENIE** *Artykuł omawia problemy wzrostu prędkości kątowej powierzchni sterów statków powietrznych dla sinusoidalnego wejściowego sygnału sterowania przy zachowaniu dynamicznych parametrów elektrycznego napędu przy użyciu magnesów trwałych o wyższej energii maksymalnej.*