Complex mathematical modelling of mechatronic modules of promising mobile objects

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Abstract: *The characteristics of power sources affect the performance of autonomous electrically driven systems, such as unmanned aerial vehicles, aircraft missiles, guided bombs, torpedoes, space and aerospace vehicles, controlled gliding parachutes. The creation of control systems for the aircraft flight control surfaces of autonomous mobile objects is an urgent topic in modern research. This article provides how a mathematical model based on integrated approach is developed for an energy-efficient mechatronic module for control systems of promising mobile objects powered by various current sources; a comparison of the energy and dynamic characteristics of mechatronic modules of promising mobile objects for various power options is made. As a result, a new type of integrated power-supply source based on capacitive energy storage with floating charge from a primary chemical source of current has been developed. The proposed approaches, dependencies and algorithms can be used in the design of highly efficient mechatronic control algorithms for autonomous mobile objects of a new generation.*

Key Words: *chemical source of current, power efficiency, calculation method, control algorithm, autonomous mobile object*

1. INTRODUCTION

Currently, more and more attention is paid to the creation of control algorithms for the aircraft flight control surfaces of autonomous mobile objects with an actuator based on an electric motor with a power source. At the same time, the characteristics of the power supply source and its type have a significant impact on the dynamic, energy and weight-size parameters of autonomous electrically driven control algorithms for promising mobile objects, such as unmanned aerial vehicles, aircraft missiles, guided bombs, torpedoes, space and aerospace vehicles, controlled gliding parachutes.

As a power source in autonomous electrically driven control algorithms, chemical sources of current (CSC) are most often used. An analysis of the mathematical model of a servo driver with a DC motor and independent excitation [1] allows us to draw some conclusions about the disadvantages inherent in chemical sources of current: the output resistance of a chemical source is non-zero and increases with increasing discharge current. The influence of an autonomous source, taking into account the voltage slump, leads to a delay in transients, while the stabilized speed changes (decreases) and the drive's performance deteriorates. To ensure the required speed of the drive, it is necessary to raise the supply power (CSC) for transient conditions, and this, as a result, leads to an increase in the weight-size parameters of the drive.

The analysis and studies made it possible to develop a new type of integrated power-supply source (IPSS) based on a capacitive energy storage (CES) with floating charge from a primary chemical source of current. In the charging mode of a capacitive energy storage, the CSC operates in the discharge mode by low and ultra-low currents, which ensures high stability of the output voltage with the CES not only when the temperature changes, but also with a significant change in power consumption. One of the distinguishing features of CES-based current sources is the low internal resistance of the source itself [2], [3], [4], [5].

2. STRUCTURAL CONTROL ALGORITHMS FOR POWER SOURCES

A significant contribution to improving the power efficiency of the control algorithms of promising mobile objects is the development and application of the integrated power-supply source in them [6], [7], [8] [9], [10]. A functional diagram of a servo driver with an integrated power-supply source is shown in Figure 1. The structure of the studied servo driver with IPSS (Figure 2) has much in common with the structures of other electric drives and consists of an energy intensive in the information part, includes encoders for input and output shafts, amplifying converter installation, in the power part - the actuator [11], [12], [13]. In our case, the energy intensive is an electric motor (with technical characteristics $U_{en}; i_{en}; R_{en}; L_{en}$), interlocked with the load [14], [15].

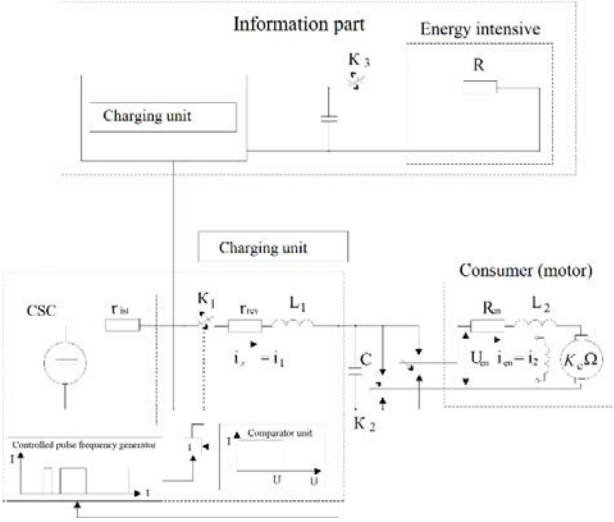

Fig. 1 – Functional diagram of a control algorithm with an integrated power-supply source

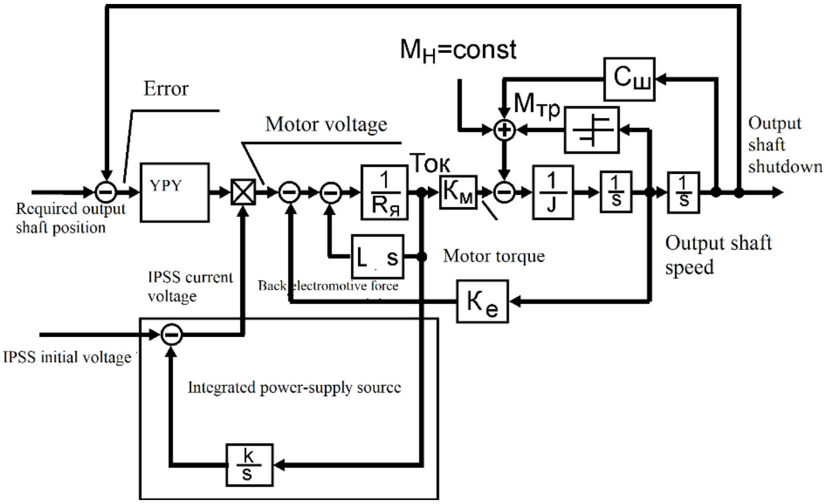

Fig. 2 – Block scheme of a servo driver with power source

A characteristic feature of the implemented scheme is that a multiturn potentiometer is used as an encoder [16], [17], [18], [19], [20]. This allows you to get a fairly linear regulating characteristics of the servo driver on the continuity section, the stability of which is ensured by introducing an error deadband.

However, such parameters are selected for which a linear regulating characteristic and a static error are obtained that satisfy the Q-factor of the driver [21], [22], [23], [24], [25], [26], [27].

The main difference from the known structures of drive systems lies in the features of the integrated power-supply source, namely, the IPSS has a parallel/series architecture – one channel feeds the information part (non-inductive load), the other feeds the power part – the “non-inductive and inductive” load (drive servo electric motor) [28]. Each drive channel included in the system must have its own energy storage.

3. INTEGRATED POWER-SUPPLY SOURCE TRANSIENTS

The current consumed by the information channel is direct, therefore, in the work, we consider transients in the actuator of a servo driver with IPSS. Behavior of a drive system with an actuator when powered by IPSS (Figure 1), where the key K_1 is open and K_2 is closed, i.e. power is supplied from a capacitive energy storage (supercondenser), can be described by the following equations:

$$\begin{cases} R_{en} i_{en}(t) + k_e \Omega_{en}(t) + L_{en} \dfrac{di_{en}(t)}{dt} = U_0 - \dfrac{1}{C} \displaystyle\int i_{en}(t)dt; \\ M_{en}(t) = k_M i_{en}(t); \\ J_{en} \dfrac{d\Omega_{en}}{dt} = M_{en}(t) + M_l \chi_l, \end{cases} \tag{1}$$

where $U_{en} = U_0 - \frac{1}{C}\int i_{en}(t)dt$; $M_l = const$; $U_{en}(t)$ and $i_{en}(t)$ are current values of voltage and current of the armature winding, accordingly; R_{en} – active resistance of the electric motor armature winding; k_e - back emf constant of the drive and output shaft; L_{en} – inductance of the motor armature circuit; $M_{en}(t)$ – the moment developed by the actuator; J_{en} - inertia of the motor, reduced to the output shaft; M_l – load torque; $\Omega_{en} = \frac{d\delta(t)}{dt}$, $\delta(t)$ - the rotation angle of the drive output shaft. In the initial period, when $t = 0$; $i_{en}(t)|_{t=0} = 0$; $\Omega_{en}(t)|_{t=0} = 0$ and the motor is in the process of “acceleration”, i.e. transient, we determine from expression (1) the laws of change of current and speed in the following form:

$$i_{en}(t) = C_1 e^{r_1 t} + C_2 e^{r_2 t} + A \tag{2}$$

where $r_{1,2} = -\frac{1}{2T_{ya}}\left(1 \pm \sqrt{1 - \frac{4\mathrm{T}_{ya}}{\mathrm{T_M}}}\right)$, moreover $4\mathrm{T}_{ya} < T_M$, where T_{ya}, T_M – electromagnetic and electromechanical time constants of the motor; $A = -\frac{M_l \chi_L T_c}{k_M T_M\left(1+\frac{T_c}{T_M}\right)}$; $T_c = R_{en}\mathrm{C}$, where C is the capacitance of the supercondenser; $\mathrm{C}_1 = -A - \frac{\dot{I}+Ar_1}{r_2-r_1}$; $\dot{I} = \frac{I_{max}}{T_я}$; $\mathrm{C}_2 = \frac{\dot{I}+Ar_1}{r_2-r_1}$.

$$\begin{aligned}\Omega_{en}(t) = \mu T_M - \frac{T_M k_M}{T_c J_\Sigma}\left[\frac{C_1}{r_1}(e^{r_1 t} - 1) + \frac{C_2}{r_2}(e^{r_2 t} - 1) + At\right] \\ - \frac{T_{ya} T_M k_M}{J_\Sigma}(C_1 r_1 e^{r_1 t} + C_2 r_2 e^{r_2 t}) - \frac{T_M k_M}{J_\Sigma}(C_1 e^{r_1 t} + C_2 e^{r_2 t} + A)\end{aligned} \tag{3}$$

Consider the behavior of the actuator described by the system of equations (1), when

$$M_l = M_{TR} + k_{VT}\Omega_{en} + k_{SH}\int_0^t \Omega_{en}(t)dt \tag{4}$$

The laws of changing current, speed and angle in the starting mode are found from (1) and we obtain in the form:

$$\begin{aligned} i_{en}(t) = \frac{J_\Sigma}{k_M T_M^2}\left(C_1 r_1\, e^{r1^t} + C_2 r_2\, e^{r2^t} + C_3 r_3\, e^{r3^t} + C_4 r_4\, e^{r4^t}\right) \\ - \frac{\chi_L M_{TR}}{k_M} - \frac{\chi_L k_{VT}}{k_M}\left(C_1 e^{r2^t} + C_2 e^{r2^t} + C_3 e^{r3^t} + C_4 e^{r4^t}\right) \\ - \frac{\chi_L k_{SH}}{k_M}\left(\frac{\mathrm{C}_1}{r_1} e^{r1^t} + \frac{\mathrm{C}_2}{r_2} e^{r2^t} + \frac{\mathrm{C}_3}{r_3} e^{r3^t} + \frac{\mathrm{C}_4}{r_4} e^{r4^t} - \frac{C_1}{r_1} - \frac{C_2}{r_2} - \frac{C_3}{r_3} - \frac{C_4}{r_4}\right)\end{aligned} \tag{5}$$

where r_1, r_2, r_3, r_4 are the roots of the characteristic equation real and different. We introduce the following notation:

$$\begin{gathered} a_0 = L_{en}\frac{J_{en}}{k_M};\ a_1 = R_{en}\frac{J_{en}}{k_M} - L_{en}\frac{\chi_L k_{VT}}{k_M};\ a_2 = k_e - R_{en}\frac{\chi_L k_{VT}}{k_M} - L_{en}\frac{\chi_L k_{SH}}{k_M} + \frac{J_{en}}{Ck_M} \\ a_3 = -R_{en}\frac{\chi_L k_{SH}}{k_M} - \frac{\chi_L k_{VT}}{Ck_M};\ a_4 = -\frac{\chi_l k_{SH}}{Ck_M}\end{gathered} \tag{6}$$

Then r_1, r_2, r_3, r_4 are found from the biquadratic equation

$$a_0 r^4 + a_1 r^3 + a_2 r^2 + a_3 r + a_4 = 0 \tag{7}$$

The constants C_1, C_2, C_3, C_4 are found from a system of linear equation

$$\begin{cases} C_1 + C_2 + C_3 + C_4 = 0 \\ C_1 r_1 + C_2 r_2 + C_3 r_3 + C_4 r_4 = b_1 \\ C_1 r_1^2 + C_2 r_2^2 + C_3 r_3^2 + C_4 r_4^2 = b_2 \\ C_1 r_1^3 + C_2 r_2^3 + C_3 r_3^3 + C_4 r_4^3 = b_3 \end{cases} \tag{8}$$

$$b_1 = \frac{M_{TR}\chi_L}{J_{en}};\ b_2 = \frac{k_M U_0}{J_{en}L_{en}} + \frac{\chi_L^2 k_{VT} M_{TR}}{J_{en}^2}$$
$$b_3 = \frac{\chi_L^2 M_{TR}}{J_{en}^2}(\chi_L k_{VT}^2 + k_M) - \frac{k_M R_{en} U_0}{J_{en} L_{en}^2} + \frac{\chi_L k_M}{J_{en}^2 L_{en}}(k_{VT} U_0 - k_e M_{TR}) \tag{9}$$

$$\Omega_{en}(t) = C_1 e^{r_1 t} + C_2 e^{r_2 t} + C_3 e^{r_3 t} + C_4 e^{r_4 t} \tag{10}$$

$$\delta_{en}(t) = \frac{C_1}{r_1}(e^{r_1 t} - 1) + \frac{C_2}{r_2}(e^{r_2 t} - 1) + \frac{C_3}{r_3}(e^{r_3 t} - 1) + \frac{C_4}{r_4}(e^{r_4 t} - 1) \tag{11}$$

Using expressions (5)-(11), we plot the graphs of laws of changes in current, speed, and angle in the starting mode at $M_L \neq const$, when the roots of the characteristic equation are real and different.

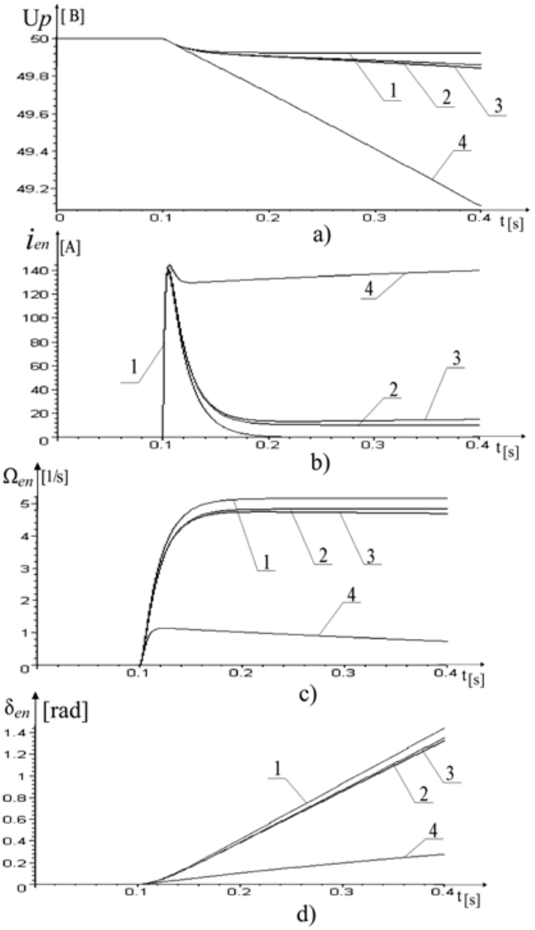

Fig. 3 – Graphs of changes: a) $U_P = f(t)$; b) $i_{en} = f(t)$; c) $\Omega_{en} = f(t)$; d) $\delta_{en} = f(t)$

Figure 3 shows the laws of change a) $U_P = f(t)$; b) $i_{en} = f(t)$; c) $\Omega_{en} = f(t)$; d) $\delta_{en} = f(t)$: 3 – at $k_{VT} = 10\text{H} \cdot m \cdot s/rad,\ k_{SH} = 20\text{H} \cdot m/rad;$ 4 – at $k_{VT} = 1000\text{H} \cdot m \cdot s/rad,$ $k_{SH} = 2000\text{H} \cdot m/rad.$

When solving system of equations (1) in the presence of a certain hinge load, it is possible that the characteristic equation has two complex roots and two real ones. The laws of changing current, speed and angle in the transient process (starting mode) are found according to the above method (Fig. 3a, 3b, 3c, and 3d). Figure 3a shows how the voltage across the super condenser changes and it can be seen that at the end of the transient process it does not recover (curve 4). As shown above, it is necessary to recharge the super condenser from a chemical source of current.

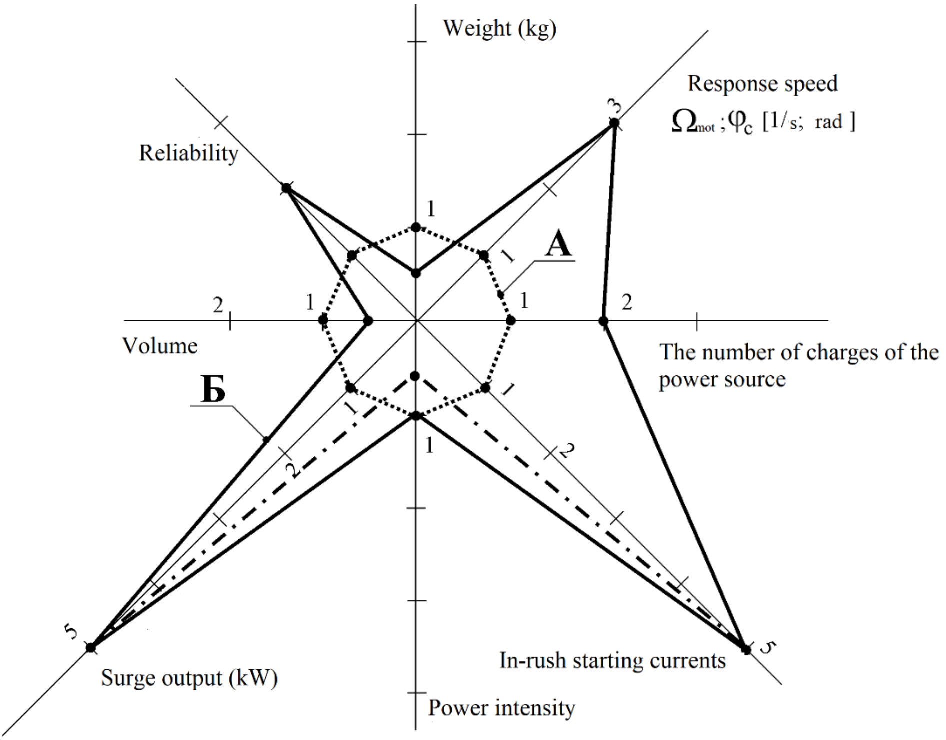

Fig. 4 – Diagrams of the main characteristics of promising mobile objects control algorithms: A – for algorithms using CSC; B - for algorithms using IPSS

With a “helping” load, energy is regenerated in IPSS, and if for a chemical source of current this charging does not give significant results due to the large internal resistance, then, as is known from [2], the voltage across a storage device in the regeneration mode is substantially restored. In [4], [29], [30], [31], a comparison was made of the processes occurring in the drive when it is powered by a chemical source of current and when powered by the “CSC – drive – integrated power-supply source” system.

Peculiarities of changing the main characteristics of the control algorithms of promising mobile objects when powered by IPSS in comparison with the characteristics of control algorithms when powered by CSC are shown in Figure 4. All characteristics of the control algorithms shown in Figure 4 were obtained by the results of experimental studies [1], [2], and are given in relative units.

4. CONCLUSIONS

The analysis of the obtained graphs and dependences shows that the static and dynamic characteristics of the motor when powered by IPSS are not only inferior to the static and dynamic characteristics of the motor when operating from CSC, but also surpass them in a number of indicators. For example, at in-rush starting currents and a higher speed value in transient conditions. Since the discharge dependences of the IPSS are practically independent of the ambient temperature and the magnitude of the discharge current, the IPSS provides greater stability of the processes occurring in the electric drive than with a CSC source. The use of the IPSS allows increasing power efficiency and reducing the weight-size parameters of the control algorithms of promising mobile objects. The proposed approaches, dependencies and algorithms can be used in the design of highly efficient mechatronic control algorithms for autonomous mobile objects of a new generation.

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