MODELAGEM MATEMÁTICA DE FONTES DE ENERGIA EFICIENTES DE MÓDULOS MECATRÔNICOS DE OBJETOS MÓVEIS PERSPECTIVOS

MATHEMATIC SIMULATION OF ENERGY-EFFICIENT POWER SUPPLY SOURCES FOR MECHATRONIC MODULES OF PROMISING MOBILE OBJECTS

МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ ЭНЕРГОЭФФЕКТИВНЫХ ИСТОЧНИКОВ ПИТАНИЯ МЕХАТРОННЫХ МОДУЛЕЙ ПЕРСПЕКТИВНЫХ МОБИЛЬНЫХ ОБЪЕКТОВ

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RESUMO

Com base em modelagem matemática, o problema de otimização do armazenamento de energia e parâmetros de massa-dimensão de módulos mecatrônicos de equipamentos de aviação é resolvido sintetizando a estrutura e analisando as características de várias fontes de energia; um modelo de fonte de energia generalizada desenvolvido para diferentes fontes de energia para os sistemas de acionamento de controle; uma revisão teórica das fontes químicas de energia elétrica atuais é dada; uma comparação das famílias de características externas de armazenagens capacitivas e pneumáticas com uma família de características externas de fonte química de energia elétrica é fornecida. O modelo generalizado da fonte de alimentação a bordo descrito no artigo pode ser usado no projeto de módulos mecatrônicos de alto desempenho para sistemas de controle de objetos móveis autônomos de uma nova geração.

Palavras-chave: *fonte de alimentação, método de cálculo, algoritmo de controle, absorção eletroquímica.*

ABSTRACT

On the basis of mathematic simulation, the problem of optimizing the energy storage and the mass-dimensional parameters of the mechatronic modules of aviation equipment is solved by synthesizing the structure and analyzing the characteristics of various power supplies, a generalized model of the power supply source developed for various power supply sources of the drive control systems is given, a theoretical review of the currently used chemical current sources is carried out, the comparison of sets of external characteristics of capacitive and pneumatic storage media with a set of external characteristics of the chemical current source. The generalized model of the aircraft power supply source, described in the article, can be used in the design of highly efficient mechatronic modules of control systems for autonomous mobile objects of a new generation.

Keywords: *power supply source, calculation method, control algorithm, electrochemical absorption.*

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АННОТАЦИЯ

На основе математического моделирования решается задача оптимизации энергозапаса и массогабаритных показателей мехатронных модулей авиационной техники путем синтеза структуры и анализа характеристик различных источников энергопитания, приводится разработанная для различных источников энергопитания приводных систем управления обобщенная модель источника энергопитания, производится теоретический обзор используемых в настоящее время химических источников тока, дается сравнение семейств внешних характеристик емкостных и пневматических накопителей с семейством внешних характеристик химического источника тока. Описанная в статье обобщенная модель бортового источника энергопитания может быть использована при проектирования высокоэффективных мехатронных модулей систем управления автономными мобильными объектами нового поколения.

Ключевые слова: *источник энергопитания, метод расчета, алгоритм управления, электрохимическая абсорбция.*

INTRODUCTION

The volume and weight of an autonomous power supply source is about 60% of the mass-dimensional parameters of an autonomous follower drive and significantly affect the quality of its transient process. Therefore, studies on the development of structures of these sources, optimal for energy storage and mass-dimensional parameters, are relevant. In most studies, when considering the behavior of follower drives, it is assumed that their power supply sources have an infinitely large energy reserve, and the only constraints in the drive system are the limiting dynamic capabilities (Budiman and Zuas, 2015; Belenov *et al.*, 2016). This approach to the analysis and synthesis of follower drives leads to the fact that when designing them, the real characteristics of the power supply source are not taken into account, therefore the volume and mass of the equipment of energy sources can be overestimated.

Increased requirements for drive systems of autonomous objects in terms of accuracy and stability of characteristics in combination with the requirement to reduce the mass-dimensional characteristics of the entire system require the solution of problems the principal of which are the problems of effective energy supply. Typically, chemical current sources are used to power the autonomous drive control systems (Danilin *et al.*, 2015; Danilin *et al.*, 2016; Daus *et al.*, 2018).

In most cases, the chemical current sources with "disposable charging" are used, so the characteristics depend on the discharge currents and on the operating time. This dependence is represented by discharge characteristics. In this case, as indicated in (Makarenko and Sorokin, 2017; Makarenko *et al.*, 2015; Metrikin and Peysel, 2014; Koichi *et al.*, 2011; Evers *et al.*, 2015; Makarenko *et al.*, 2014; Wei *et al.*, 2014), we can distinguish: discharge with low currents, at which the discharge characteristics are weakly dependent (practically independent) of the magnitude of the discharge current and represent a straight line; discharge with high currents, when the characteristics are a set of parallel straight lines, and with an increase in the magnitude of the discharge current, the "linear" (working) zone narrows; discharge with currents close to the limiting discharge currents; discharge characteristic is nonlinear.

THEORETICAL OVERVIEW

Typical discharge dependences of the chemical current sources, obtained on the basis of a generalization of discharge characteristics of nickel-cadmium, silver-zinc and other types of accumulators, are presented in the works (Koichi *et al.*, 2011; Makarenko *et al.*, 2014; Gerashchenko *et al.*, 2015; Sorokin *et al.*, 2017; Arakelyan *et al.*, 1977; Makarenko and Kulikov, 2015). In the ratings of such sources, due to the limitation in terms of the allocated thermal energy, the magnitude, and duration of the discharge currents are also specified.

The degree of voltage drop is different for different types of the chemical current sources: in some, it decreases insignificantly, by 5-10% of the initial value U_{nit}, for others this decrease is more significant. A fairly rapid drop is often observed at the very beginning of the discharge (especially for freshly charged batteries), and sometimes at the beginning of the discharge there is not a drop, but a short-term voltage increase, or a sharp decrease in voltage with a subsequent increase. The voltage drop at the end of the discharge can be abrupt or gradual. After reaching a certain final voltage U_{fin} the discharge must be stopped since a certain value of the residual capacity is necessary for recharging. Thus, the following representative values of the voltage can be distinguished: initial, maximum, minimum and final (Naeem *et al.*, 2014; Bugakov *et al.*, 2012; Samsonovich, 2002; Polkovnikov and Sergeev, 1988). All these values depend on the discharge current, temperature, and other parameters. As a rule, when discharging with high currents, a lower value is assumed than with a low-current discharge U_{fin}.

Discharge current I_p depends on the resistance of the external circuit. The same source of current can be discharged with small or large currents, and also at different temperatures *T* of the environment. If the current is increased, the output power increases at first and then falls, since the voltage drop predominates over the current increase.

The most important characteristic of the chemical current source is the maximum permissible discharge current with a corresponding voltage drop to a certain critical value below which the operation of the chemical current source is impossible (for example, due to vigorous heating). The maximum amount of electricity that the chemical current source gives during its full discharge is called the discharge capacity C. Accordingly, the maximum energy given up at a full discharge is called energy storage.

Nominal capacity C_0 and nominal energy storage are understood as parameters related to the nominal discharge mode and they are guaranteed by the manufacturer. As the discharge current increases, simultaneously with the voltage drop, the reagent utilization factor, and hence the actual capacity of the source, also decreases. Semi-empirical descriptions of representation of the dependence of actual capacity of the chemical current source on the discharge current are known. The most common is the dependence of the form:

$$C = k / I_p^a, \tag{1}$$

where k and $a = 0,2 \ ... \ 0,7$ – some constants.

The presented characteristics of the chemical current source indicate that the stability of the characteristics is provided only in the discharge mode (5 to 25A) with ultra-small currents in the range 0.003 ... 0.015 of the maximum discharge current (1600A). Stability is understood as a voltage change of not more than 5% over the entire range of discharge currents and a temperature change in the range of +30°C. Providing operation in the discharge mode with ultra-low currents significantly increases the mass and volume of the power supply source. In the ratings of the chemical current sources, due to the limitation in terms of the allocated thermal energy, the magnitude, and duration of the maximum discharge current are also specified.

In most cases, the reactive component of the total internal resistance of the chemical current sources is capacitive in nature. The following sources of the appearance of the capacitive component are indicated in (Makarenko *et al.*, 2015; Samsonovich, 2002; Polkovnikov and Sergeev, 1988; Krymov *et al.*, 1987; Makarenko *et al.*, 2016): capacity of a double electrical layer at the electrode-electrolyte interface C_{EL}; absorbing pseudo capacity C_D, determined by the processes of electrochemical absorption; diffusion capacity C_{UT}, associated with the uneven distribution of the electrolyte concentration in the near-electrode layer when passing current and depending on the type of electrolyte (free, liquid, matrix, etc.).

RESULTS AND DISCUSSION:

As shown in the works (Evers *et al.*, 2015; Bugakov *et al.*, 2012; Makarenko and Samokhina, 2015; Makarenko and Kulikov, 2015; Ganzburg *et al.*, 2010), the time constant in such systems is equal to the product $R_{EL}C$ (C – condenser capacity, R_{EL} – resistance of the electrolyte), and the transient process is of an aperiodic nature. Based on the analysis of theoretical and experimental studies of the chemical current source, the author of the article developed a mathematical model that takes into account its main properties:

– voltage drop on the internal ohmic (active) resistance r_{int}

$$\Delta U_{rint} = r_{int}\, I_{CCS}, \qquad (2)$$

where I_{CCS} – current of chemical current sources.

– the voltage drop at the terminals of the chemical current sources caused by an increase in the "equivalent" internal resistance proportional to the energy storage consumption:

$$\Delta U_{I_{ccs}} = k_{I_{ccs}} \int_0^{\Delta t} I_{CCS}\, dt \quad , \qquad (3)$$

where $k_{I_{XHT}}$ – coefficient of proportionality; Δt – time of consumption of energy storage from the chemical current source;

– "subsidence" and the restoration of the discharge of the chemical current source with a step-like load connection $\Delta U_{CON} = U_0 - U(t) = bU_0 e^{-\tau t}$, or $U(t) = U_0(1 - be^{-\tau t})$, where U_0 – initial voltage of the chemical current source caused by the maximum energy storage; $U(t)$ – current voltage at the chemical current source terminals with the load connected; b – rating value, which determines the degree of "subsidence" of voltage of the chemical current source when the load is step-like; $\tau = \frac{1}{\tau_{\Pi}}$ – rate of recovery of the stationary distribution of charge carrier concentration; τ_{Π} – charge recovery time constant (rating value).

Taking into account all the main macro-properties of the chemical current source, the author of the article created the structure of the chemical current source, presented in Figure 1. The presented scheme (see Figure 1) is simulated in the software environment "MATLAB-SIMULINK". The simulation results are shown in Figure 2. The results of the simulation (Figure 2) in comparison with the dependencies taken during the experimental investigation of the chemical current source testify both to qualitative and quantitative convergence. This allows us to affirm the high degree of adequacy of the model created to the "real" chemical current source. As a power supply source for the follower drive, it is proposed to use a capacitive storage.

The capacitive storage, in our case, is a supercapacitor, it has the main advantages of electric capacitors, which are determined by the high discharge rate at their own resistance and higher capacitance. Nevertheless, the specific capacity of the capacitive storage is less than that of the chemical current source, but the power parameters for the rate of energy output to the load are higher (Koichi *et al.*, 2011; Evers *et al.*, 2015; Makarenko *et al.*, 2014; Makarenko and Samokhina, 2015).

At the present time, ultrahigh-capacitance energy storage – supercapacitors (with a capacity of up to 200 Farad, with stored energy up to 30 kJ and specific energy $0,8...1,1$ J/g), having operational, cost and mass-dimensional characteristics acceptable for use on moving autonomous objects (Makarenko and Sorokin, 2017; Naeem *et al.*, 2014; Makarenko and Kulikov, 2015).

In comparison with traditional capacitors, they have insignificant inductive and active resistances; for 1 – 2 orders of magnitude higher specific energy, and in comparison with the chemical current sources – by 1 – 2 orders of magnitude higher power; 3 times longer service life; better thermal stability. The ultrahigh-capacitance energy storages can be completed in series circuits with voltage up to 150 V. The number of parallel circuits is not limited. In supercapacitors, compared with conventional capacitive storage devices, due to the very small internal resistance, the influence of thermal processes in the same discharge currents is sharply reduced, which increases the reliability and durability of capacitors. Structurally, the ultrahigh-capacitance energy storage consists of blocks of elementary storage devices, which are outwardly similar to the unit cells of the chemical current source.

Analysis of the work of the capacitive storages (supercapacitors) showed that the structure of the capacitive storages can be represented by the circuit shown in Figure 3 (by analogy with Figure 1), and, in connection with the fact that $r_{вн} \to 0$, the main factor determining the operation of the model will be an element that takes into account the energy storage consumption.

Analysis of properties and main characteristics of autonomous power sources showed that their common properties are:

– Presence of the initial (accumulated) beginning energy storage (an energy reserve);

– The possibility of consuming (discharging) the initial energy storage at a rate many times higher than the rate of accumulating (charging);

– The rate of consumption of the energy storage depends both on the value of the resistance (including the complex) of load (power and information channels of the drive) and on the individual, internal resistance of the power supply source;

– The accumulated energy initially decreases in proportion to the rate of consumption of the energy storage, i.e. the speed of energy carrier;

– If the load has purely dissipative properties, then the energy storage only decreases;

– If the load contains reactive components, it is possible to "swap" the energy storage (regenerative behavior).

The potential for energy storage U in the general case is determined by the amount of energy carrier available Q. So, for example, for power supply sources such as capacitive storage devices and chemical current sources, the level of energy storage is determined by the amount of accumulated electric charge, which is expressed both in coulombs and in ampere-hours. At the same time for battery systems, the energy reserve potential is determined in volts and depends on the number and volume of primary (electrochemical) elements. For capacitive sources, the value of the charging voltage U_c depends on the number and volume of elementary storage devices.

The rate of change (consumption) of the energy storage (the speed of the energy carrier, the consumption of energy storage) is determined by the time derivative of the energy storage $I = \partial Q / \partial t$, but, on the other hand, the rate of consumption of the energy storage can be determined from the external characteristic, as $I = \Delta U / \Delta z_{\Sigma} |_{npu\ I=I_i}$, where z_{Σ} – total impedance of the source and the consumer.

So, considering the described properties of the analyzed power supply sources and the influence of external load, it is possible to present the model of an autonomous power supply in the form of a simplified generalized structure (see Figure 4). The discharge characteristics of the generalized source are presented below (see Figure 5). The external characteristics of the generalized source are shown in Figure 6.

The characteristics of real sources differ from the characteristics of the generalized quantitatively. The discharge characteristics of capacitive storage devices and pneumatic storage devices have a greater intensity of change in potential, compared to the chemical current sources for the same relative impedance. The set of external characteristics for capacitive and pneumatic drives occupies a wider band than the set of external characteristics of the chemical current source.

CONCLUSIONS:

A review of autonomous power supply sources of drives has shown that the behavior of various energy sources can be described with the help of a limited set of qualitatively similar discharge dependencies. This allows from a unified position to present mathematical models of a system of the "source-executive mechanism" type. It is shown that the physical comparability of various sources (storage devices) manifests itself in the form of a limitation on peak power and energy reserves. The analysis of existing different schemes (structures) of autonomous drives showed that the limitation on the maximum power consumption is traditionally removed in one single way – overstating the available output power over the consumed power.

At the same time, the dimensions and mass of the power supply source also increase. Taking into account the properties of the drive, it is proposed to include in the power supply source a cyclically rechargeable drive in order to remove the peak instantaneous power without increasing the energy storage, and the structure of the primary power supply source with a capacitive energy storage device is also proposed, i.e. a unified power supply that performs the functions of a "power transformer" and significantly reduces both the power of the primary source and the mass and dimensions of the source as a whole. The developed structure with capacitive energy storage complements other known sources, including those that convert one type of energy into another. Thus, it is shown that in order to create autonomous drive control systems with high energy efficiency it is necessary to solve the following tasks:

– to analyze the existing drive structures together with the power supply source in order to develop their new structures;

– to analyze the structure of drives in terms of minimum energy costs while maintaining the output characteristics of the drives at the same level.

The generalized model of the aircraft power supply source, described in the article, can be used in the design of highly efficient mechatronic modules of control systems for autonomous mobile objects of a new generation.

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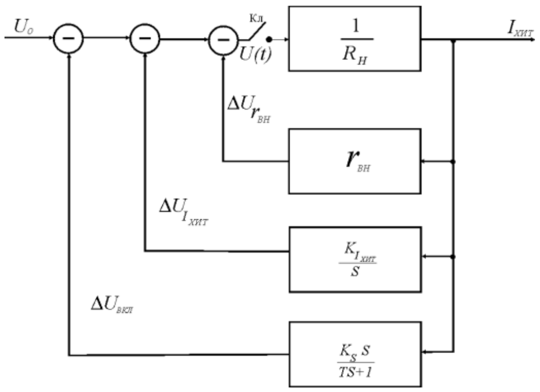
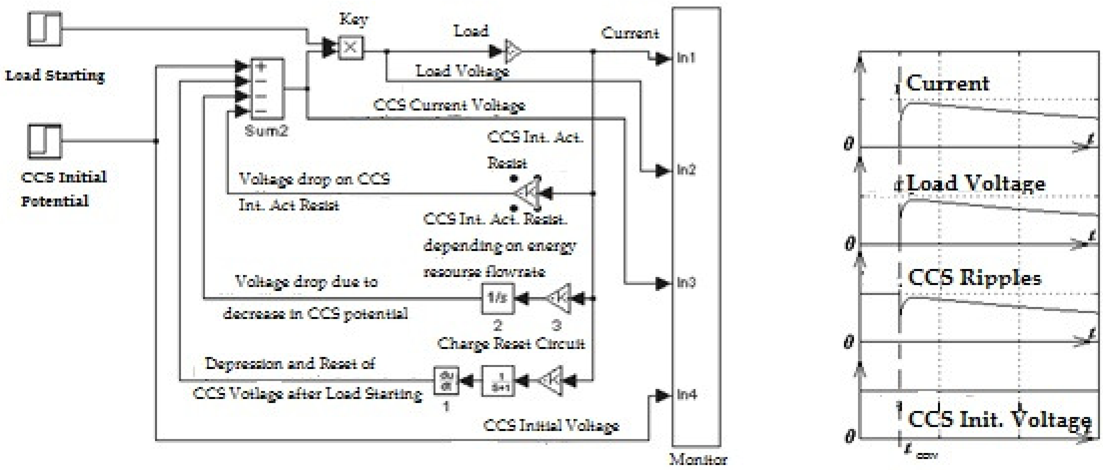


Figure 1. *Structural diagram of the generalized model of the chemical current source, where R_H – load resistance, K_S – coefficient of proportionality*



a) *b)*

Figure 2. *Simulation results: a) model of the chemical current source; b) graphs of behavior of the electrical parameters of the chemical current source*

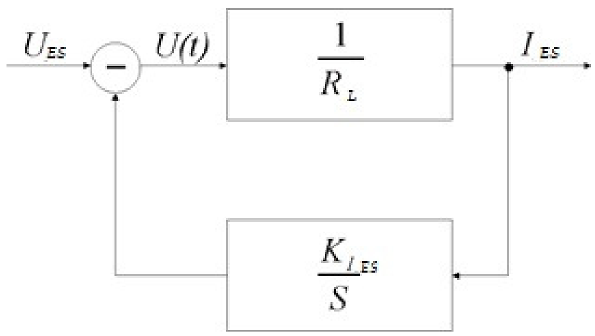


Figure 3. *Structural diagram of the capacitive storage (supercapacitor): $U_{HЭ}$ – voltage on the capacitance energy storage (initial charge); R_H – load resistance, $k_{I_{HЭ}}$ – coefficient of proportionality; $I_{HЭ}$ – the current of the capacitance energy storage, $U(t)$ – current voltage*

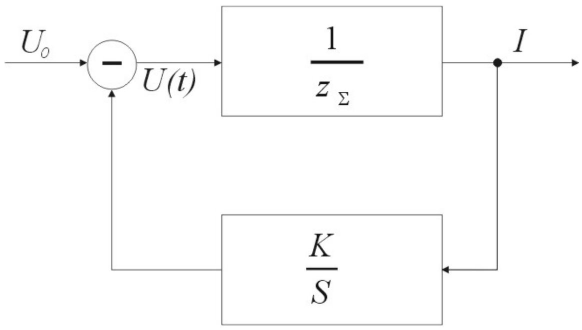


Figure 4*. Simplified generalized structure of the power supply source:* U_0 *– level of initial potential of the energy storage,* I *– rate of change of the energy storage,* K *– coefficient linking the rate of change of energy storage with the potential of the energy storage,* z_Σ *– total impedance of the source and the consumer,* $U(t)$ *– current capacity level,* $\overline{U} = \frac{U(t)}{U_0}$ *– relative level of the energy storage potential,* $\overline{I} = \frac{I(t)}{I_{\max}}$ *– relative level of change in the rate of energy storage,* $\overline{t} = \frac{t}{t_p}$ *– relative discharge time of the power supply source*

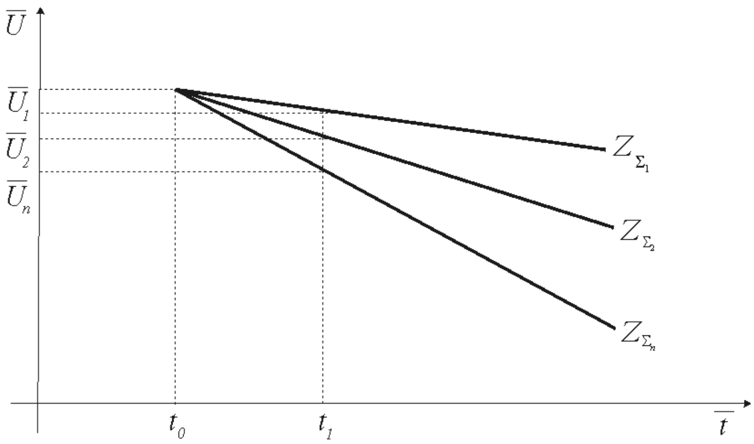


Figure 5*. Dependence* $\overline{U} = f(\overline{t})$ *at various* Z_H *:* t_0 *– moment of inclusion of the chemical current source,* t_1 *– current time,* $z_{\Sigma_1} > z_{\Sigma_2} > z_{\Sigma_3}$

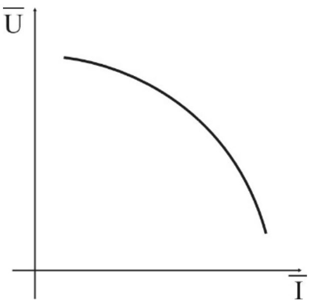


Figure 6*. Dependence* $\overline{U} = f(\overline{I})$