PERIÓDICO TCHÊ QUÍMICA
ARTIGO ORIGINAL

MODELO MATEMÁTICO DA EFICIÊNCIA ENERGÉTICA DE MÓDULOS MECATRÔNICOS E FONTES DE ENERGIA PARA OBJETOS MÓVEIS PROSPECTIVOS

MATHEMATICAL MODEL OF ENERGY EFFICIENCY OF MECHATRONIC MODULES AND POWER SOURCES FOR PROSPECTIVE MOBILE OBJECTS

МАТЕМАТИЧЕСКАЯ МОДЕЛЬ ЭНЕРГЕТИЧЕСКОЙ ЭФФЕКТИВНОСТИ МЕХАТРОННЫХ МОДУЛЕЙ И ИСТОЧНИКОВ ПИТАНИЯ ПЕРСПЕКТИВНЫХ МОБИЛЬНЫХ ОБЪЕКТОВ

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Received 22 May 2019; received in revised form 14 June 2019; accepted 19 June 2019

RESUMO

O desenvolvimento intensivo de equipamentos contribui para um impacto significativo no alto nível de competitividade de novas amostras, melhorando as tecnologias e a promessa de ideias consagradas, bem como a intensidade dos recursos e o tempo de sua implementação. A relevância deste trabalho científico reside no fato de que, no processo de projetar sistemas de acionamento para guiar equipamentos de aviação, um dos elementos importantes é levar em consideração as limitações do armazenamento de energia da fonte de energia. O objetivo deste trabalho é desenvolver um modelo matemático de eficiência energética de módulos mecatrônicos e fontes de energia para objetos móveis prospectivos. Uma abordagem integrada é usada para estudar a influência de estruturas e elementos de dispositivos de armazenamento nas características de fontes de energia no interesse de encontrar maneiras de aumentar a eficiência energética de todo o sistema de acionamento para orientar módulos mecatrônicos de sistemas de aviação em geral. Foi determinado que, a fim de reduzir os parâmetros de tamanho de peso da fonte de alimentação, o estabilizador na seção de energia, como regra, não está definido. Descobriu-se que as seções de potência e informação dos sistemas de acionamento diferem uma da outra em termos da estabilidade das coordenadas de energia. E parâmetros estabilizados (potencia, corrente) são necessários apenas para o canal de informação. Com o auxílio de dependências analíticas, os principais parâmetros da fonte primária foram avaliados dependendo da eficiência do consumidor, eficiência do estabilizador e eficiência da fonte de energia secundária. Um método para estudar a influência de elementos do canal de energia (potência) na potência de saída da fonte de energia que os módulos mecatrônicos para objetos móveis de aviação prospectiva (*drives* de aviação autônomos, mísseis guiados, sistemas de pára-quedas guiados) está sendo desenvolvido.

Palavras-chave: *modelo matemático, fonte de energia, eficiência energética, módulo mecatrônico, canal de potência*.

ABSTRACT

Intensive development of equipment contributes to a significant impact on the high level of competitiveness of new samples, improving technologies, and promise of enshrined ideas as well as resource intensity and time of their implementation. The relevance of the scientific paper lies in the fact that in the process of designing drive systems for guiding aviation equipment, one of the important elements is taking into account the limitations on the power source energy storage. The purpose of the scientific paper is to develop a mathematical model of energy efficiency of mechatronic modules and power sources for prospective mobile objects. An integrated approach is used to study the influence of structures and elements of storage devices on

DOI: 10.52571/PTQ.v16.n32.2019.547_Periodico32_pgs_529_541.pdf

the characteristics of power sources in the interest of finding the ways to increase the energy efficiency of the entire drive system for guiding mechatronic modules of aviation systems in general. It has been determined that in order to reduce the weight-size parameters of the power supply source, the stabilizer in the power section, as a rule, is not set. It has been found out that power and information sections of drive systems differ from each other in terms of the stability of the energy coordinates. And stabilized parameters (potential, current) are necessary only for the information channel. With the help of analytical dependencies, the main parameters of the primary source were evaluated depending on the efficiency of the consumer, efficiency of the stabilizer and efficiency of the secondary power source. A method to study the influence of elements of the energy (power) channel on the output power of the power source the mechatronic modules for prospective aviation mobile objects (autonomous aviation drives, guided missiles, guided parachute systems) is being developed.

Keywords: *mathematical model, power source, energy efficiency, mechatronic module, power channel.*

АННОТАЦИЯ

Интенсивное развитие техники в мире способствует существенному влиянию на высокий уровень конкурентной способности новых образцов, усовершенствование технологий, и безусловно на перспективность заложенных идей, а также ресурсоёмкость и время их реализации. Актуальность статьи заключается еще и в том, что в процессе проектирования приводных систем управления авиационной техники, одним из важных элементов является учет ограничений по энергозапасу источника питания. Цель статьи – разработать математическую модель энергетической эффективности мехатронных модулей и источников питания для перспективных мобильных объектов. В работе, на основе комплексного подхода, проводились исследования влияния структур и элементов накопительных устройств на характеристики источников энергопитания в интересах поиска путей повышения энергетической эффективности всей приводной системы управления мехатронными модулями авиационных систем в целом. Определено, что с целью уменьшения массогабаритных показателей источника энергопитания стабилизатор в силовой части, как правило, не ставится. Установлено, что силовые и информационные части приводных систем отличаются друг от друга требованиями к стабильности энергетических координат. А стабилизированные параметры (потенциал, ток) требуются только для информационного канала. С помощью аналитических зависимостей были оценены основные параметры первичного источника в зависимости от коэффициентов полезного действия потребителя, стабилизатора и вторичного источника питания. Разработан метод исследования влияния элементов энергетического (силового) канала на выходную мощность источника питания мехатронных модулей перспективных авиационных мобильных объектов (авиационные автономные приводы, управляемые ракеты, управляемые парашютные системы).

Ключевые слова: *математическая модель, источник энергопитания, энергетическая эффективность, мехатронный модуль, силовой канал*.

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1. INTRODUCTION

A specific feature of all autonomous mobile objects is the use of stored energy in the power source to perform motion control tasks. Obviously, the amount of this energy is limited. Considering that an autonomous power supply source has certain weight and size characteristics, its energy storage capacity is also limited (Gitin and Movchan, 2003; Amirgaliyev *et al.*, 2017). The main consumer of energy is the drive control systems of flight (motion). The structure of autonomous mobile objects necessarily includes various drive systems, which are the main energy consumers. Typically, these are servo drives that are to guide moving autonomous objects. Drive systems of autonomous objects are united by a common feature; they refer to systems with limited energy resources. In most cases, when considering the behavior of servo drives (SD), it is assumed that their energy sources have an infinitely large store of energy, and the only limitation existing in the drive system is the limitation on the ultimate dynamic possibilities. This approach to the analysis and synthesis of servo 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 (Andreev and Gridina, 2017).

The overestimation of the required energy storage of the power supply sources does not guarantee that in transient (dynamic) modes when the external conditions are modified, for example, when the ambient temperature changes, etc., there will not be a limitation due to the limiting rate of change of the energy storage.

The problems of increasing energy intensity, the stability of the output parameters of the power supply source, associated with a decrease in its mass and decrease in volume, are one of the main tasks of designing prospective autonomous objects, largely determining the possibility of creating a new type of guided product (Gridina and Andreev, 2017).

In the process of designing drive systems for guiding aviation equipment, in particular with autonomous power supply (aviation autonomous drives, guided missiles, guided parachute systems, etc.), one of the important elements is the limitations on the power source energy storage to be taken into account. Physically, the limitations on the power source energy storage are manifested not only by the maximum available values of the moment-kinematic coordinates of the operating mechanism of the drives but also by their change (decrease) over time of the system operation.

In the dynamics, limited power source energy storage leads to the deterioration of the main characteristics of the drive control system: it reduces operation speed, reduces bandwidth, etc. In connection with the above, this scientific paper examines the influence of structures and elements of storage devices on the characteristics of power sources in the interest of finding ways to improve the energy efficiency of drive systems in general.

2. THEORETICAL OVERVIEW

It is known (Metrikin and Pasel, 2014; Makarenko *et al.*, 2014; Pan *et al.*, 2014; Makarenko *et al.*, 2015; Gerashchenko *et al.*, 2015; Formalev *et al.*, 2015; Kolesnik *et al.*, 2015; Formalev *et al.*, 2016; Formalev and Kolesnik, 2016; Okonechnikov *et al.*, 2016; Prokofiev *et al.*, 2016; Formalev and Kolesnik, 2017; Babaytsev *et al.*, 2017; Lurie *et al.*, 2017; Kakhramanov *et al.*, 2017; Kurbatov et al., 2018; Astapov et al., 2018; Bulychev *et al.*, 2018; Rabinskiy and Tushavina, 2018; Formalev and Kolesnik, 2018a; Formalev and Kolesnik, 2018b; Rabinskiy and Tushavina, 2018; Bulychev *et al.*, 2018; Formalev *et al.*, 2018a; Formalev *et al.*, 2018b; Formalev *et al.*, 2018c; Formalev and Kolesnik, 2019;) that the servo drive system can be represented as a set of energy converters. The first group of converters is used to extract and process input signals and to form an algorithm for controlling the servomotor – these are the so-called elements (receivers) of the information channel. The second group of energy converters is used to amplify the control signal generated by the information part, and convert it into the drive's operation – these are energy (power) channel converters. Typical functional diagrams of drive control systems are shown in Figures 1 and 2.

In order to ensure the stability of the characteristics of the power supply source (PSS), stabilizers of its output parameters are used. Independence of energy coordinates (stability of energy characteristics) in autonomous power supply sources is provided by:

- the inclusion of stabilizers of the energy coordinate between the source and the consumer;

- the use of a stabilization system based on the implementation of the principles of automatic control according to the output coordinates of the power source.

Stabilization of the energy coordinates practically eliminates the mutual influence of the power supply source and the consumer. However, since any process of energy consumption is inherently dynamic in its physical nature, the constancy of the energy coordinate is largely determined not only by the dynamic properties, but also by the inevitable excess of the energy incoming from the power source over the energy consumed, i.e. associated with additional energy costs (Makarenko *et al.*, 2014; Ono *et al.*, 2011; Korshunov et al., 2017).

And still, stabilizers have their unsatisfactory features (Metrikin and Pasel, 2014; Evers *et al.*, 2015):

- only in the case of slowly changing processes of pulsation of one energy coordinate, stabilizers can provide high-quality regulation (stabilization) of another energy coordinate;

- impact on the dynamics of the system's dynamic properties of voltage stabilizers with impulse voltage surges at the input to the stabilizer, which is observed when starting and stopping the operating mechanism of the drive, leading to the occurrence of “self-oscillations” (Metrikin and Pasel, 2014; Bugakov *et al.*, 2012).

In order to reduce the mass and dimension parameters of the power supply source, a stabilizer in the power section, as a rule, is not installed. In connection with this, during the operation of the energy channel, its interrelation with the information channel through the power supply source is observed. The mass and dimension parameters of the power supply source are determined by the power and energy consumed by the autonomous drive control system (ADCS). The entire power channel of the autonomous drive control system is analyzed in order to select its structure that is the most efficient in terms of energy costs. Let us analyze the influence of the energy channel elements on the mass and dimension parameters of the power supply source on a step-by-step basis.

3. MATERIALS AND METHODS

The analysis of the influence of the energy channel elements on the mass and dimension parameters of the power supply source is carried out using prospective plans of power supply sources, control algorithms that minimize energy consumption, which allow saving energy in drive control systems for autonomous moving objects.

The research method is complex, which is characterized by the simultaneous use of general principles of mathematical analysis, methods of the theory of ordinary differential equations, optimal control theory, point to point transformations, methods of the theory of electrical, electromechanical systems combined with computer simulation and experimental research of drive systems.

To solve this problem, the methods of the theory of automatic control, mathematical physics, methods of optimal design, and mathematical programming are also used. In constructing mathematical models, numerical methods for solving systems of algebraic and differential equations, matrix and topological algorithms for constructing mathematical models, and also the theory of signal graphs for the synthesis of the strength and deformation characteristics of the drives were used.

4. RESULTS AND DISCUSSION:

The energy channel of mechatronic modules of prospective aviation mobile objects (a functional diagram of a drive control system is shown in Figure 1) consists of a primary power supply source (PSS), static power amplifier (SPA) and operating mechanism (OM), see Figure 3.

Let us estimate the coefficient of performance of the energy channel η_{EC1} (see Figure 3) through its output and dissipation power of the elements, or through their coefficient of performance, as Equation 1. Let us define η_{OM} and η_{SPA} as Equations 2, 3, 4, 5. The distribution of the output power of the power supply source of the autonomous drive control system (see Figure 3) is represented in the form of a diagram shown in Figure 4.

If stabilization of the energy coordinates is used in the energy channel of the autonomous drive control system, the scheme will have the form shown in Figure 5. The expression of the coefficient of performance of the stabilizer η_{ST} can be written as Equation 6. Then the distribution of the output power of the power supply source to ensure the operation of the autonomous drive control system (see Figure 5) is shown in the diagram (see Figure 6).

From Equations 2, 3, 4, 5, we determine the power dissipated in the stabilizer, static power amplifier, and operating mechanism (Equations 7, 8, 9). Based on Equations 3, 4, 5, 6, we determine the total power of P_{Σ} , consumed by the energy channel of the autonomous drive control system, and equal to the power of the power supply source Equation 10. Let us estimate the coefficient of performance of the energy channel η_{EC2} of the autonomous drive control system (see Figure 5) through its output and dissipation power of the elements, or through their coefficient of performance, as Equation 11.

According to the expression, we construct the dependence $\eta_{EC2} = f(\eta_{ST})$, see Figure 7. When the autonomous drive control system is powered by the secondary power source (SPS), the functional diagram of the energy channel has the form shown in Figure 8. The expression for the coefficient of performance of the secondary power source – η_{SPS} has the following form Equation 12.

Then the distribution of the output power of the primary power supply source to ensure the operation of the autonomous drive control system (see Figure 8) is shown in the diagram (see Figure 9). From the Equations 3, 4 and Equation 8, we determine the power dissipated in the secondary power source, stabilizer, static power amplifier, and operating mechanism (Equations 13, 14, 15, 16). Based on Equations 3, 4, 8 and Equation 9, we determine the total power of $P_{\Sigma 1}$, consumed by the energy channel of the autonomous drive control system (see Figure 8), and equal to the power of the primary power supply source, as Equation 17

Let us estimate the coefficient of performance of the energy channel $\eta_{ЭК\,3}$ of the autonomous drive control system (see Figure 8) through its output and dissipation power of the elements, or through their coefficient of performance, as Equation 18. According to Equation 11, we construct the dependence $\eta_{EC3} = f(\eta_{SPS})$, see Figure 10.

5. CONCLUSIONS:

According to the dependencies that found the graphical display in Figure 7 and Figure 10, it can be concluded that when the stabilizer and the secondary power source are included in the energy channel, the power consumption increases and, as a result, the energy storage from the power supply source of the autonomous drive control system increases as well. Consequently, the mass and dimension parameters of the primary power supply source deteriorate since to compensate for losses in the stabilizer and in the secondary power source, it is required to increase the power and, therefore, the mass and dimension parameters of the primary power supply source.

The developed method of studying the influence of the energy channel elements on the output power of the power source shows that using the obtained expressions for the coefficient of performance in connection with the power and dependencies consumed by each element (see Figures 7, 10), it is possible to choose the structure of the autonomous drive control system for aviation equipment that is rational in respect of the minimum energy consumption. Furthermore, in connection with the power consumed by each element using mass dependencies of the power supply source on the power and energy consumption, it is possible to determine the mass and dimension parameters of the power supply source (m_{PSS} and V_{PSS}) of the drives of control systems for aviation mechatronic modules.

The power and information parts of the drive systems differ from one another in the requirements for the stability of the energy coordinates. Stabilized parameters (potential, current) are required only for the information channel. A characteristic feature of the information channel is that it is a load of approximately constant power consumption in relation to the power supply source.

In order to eliminate the mutual influence between the information and power parts of the autonomous drive control system channels, as well as to equalize the current surges of the consumer, it is necessary to include the energy storage between sources and channels.

In cases where the primary power supply source is a chemical current source, even ensuring the operation of the autonomous drive control system in the mode of small discharge currents is not a guarantee that in the transitional regimes the mutual influence of the energy and information channels will be excluded, especially when the ambient temperature changes. In practice, since the energy consumption of the information channel is substantially less than the energy consumption of the power channel, then a separate power supply source shall be installed in order to power the information part.

Studies of traditional power supply sources of the autonomous drive control system have shown that, from the standpoint of their own energy consumption, the main disadvantage is the presence of stabilizers, especially in the secondary power source. Firstly, it significantly reduces the total coefficient of performance of the power supply source. Secondly, due to the increase in the power and stored energy of the primary power supply source, it's mass and dimension parameters deteriorate.

The analytical dependences obtained in this scientific paper allow us to estimate the main parameters of the primary power supply source depending on the coefficient of performance of the consumer, the coefficient of performance of the stabilizer, and the coefficient of performance of the secondary power source.

6. ACKNOWLEDGMENTS:

The work has been conducted with the financial support of the grants “No 18-08-00821-a and No 17-08-01127-a” from the Russian Foundation for Basic Research.

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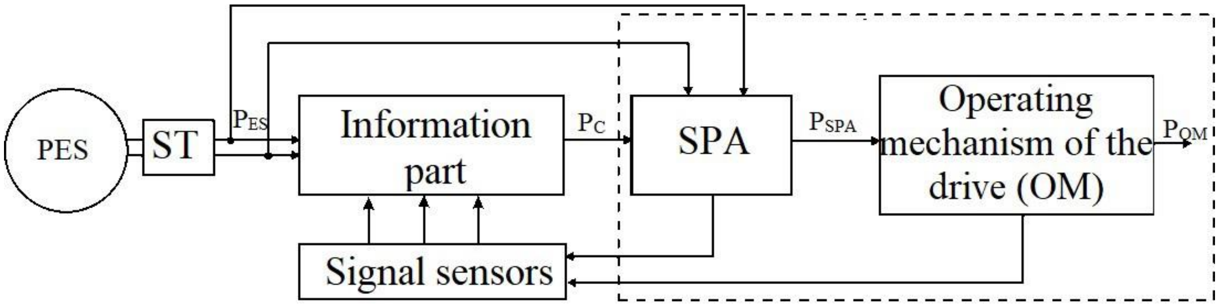

***Figure 1**. Functional diagram of the drive control system when powered by a primary power source, where PES – primary energy source, SPA – static power amplifier, P_{ES} – energy source output power, P_C – power required to control, P_{SPA} – output power of static power amplifier, P_{OM} – output power on operating mechanism takeoff shaft, ST – stabilizer of output energy coordinates of primary energy source*

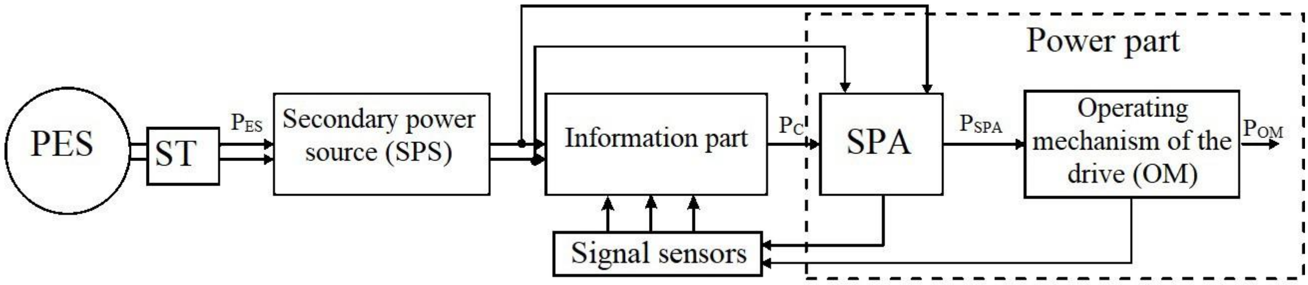

***Figure 2**. Functional diagram of the drive control system when powered by a secondary power source (SPS)*

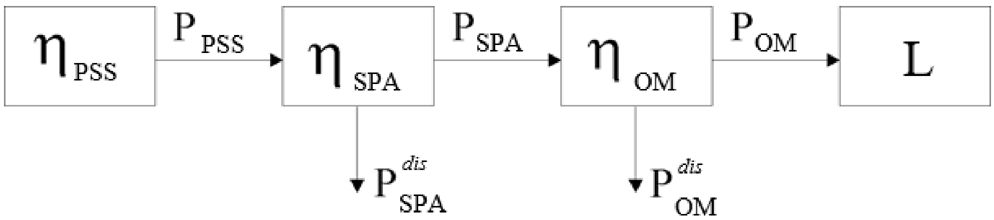

***Figure 3**. Diagram of energy conversion in the power channel of the autonomous drive control system, where η_{PSS} and P_{PSS} – coefficient of performance and output power of the power supply source, η_{SPA} and $_{SPA}$ – coefficient of performance and output power of the static power amplifier, P_{SPA}^{dis} - power dissipated in the static power amplifier, η_{OM} and P_{OM} – coefficient of performance and dissipated power of the operating mechanism, P_{OM}^{dis} - power dissipated in the operating mechanism, L – load on the output shaft of the operating mechanism*

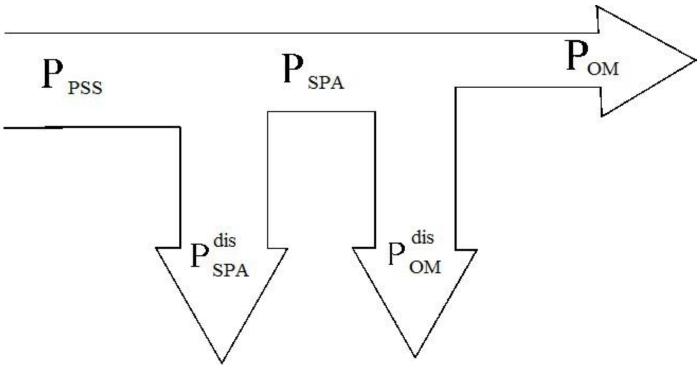

***Figure 4**. Diagram of power distribution from the power supply source using the static power amplifier – operating mechanism system*

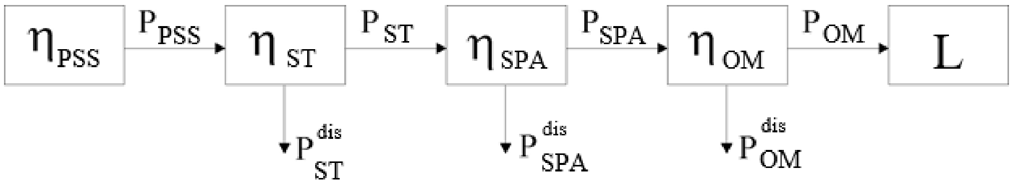

***Figure 5**. The scheme of energy conversion in the power channel of the autonomous drive control system taking into account the stabilizer (ST), where η_{PPS} and P_{PPS} – coefficient of performance and output power of the power supply source, η_{ST} and P_{ST} – coefficient of performance and output power of the stabilizer, P^{dis}_{SPA} – power dissipated in the stabilizer, η_{SPA} and P_{SPA} – coefficient of performance and output power of the static power amplifier, P^{dis}_{SPA} – power dissipated in the static power amplifier, η_{OM} and P_{OM} – coefficient of performance and dissipated power of the operating mechanism, P^{dis}_{OM} – power dissipated in the operating mechanism, L – load on the output shaft of the operating mechanism*

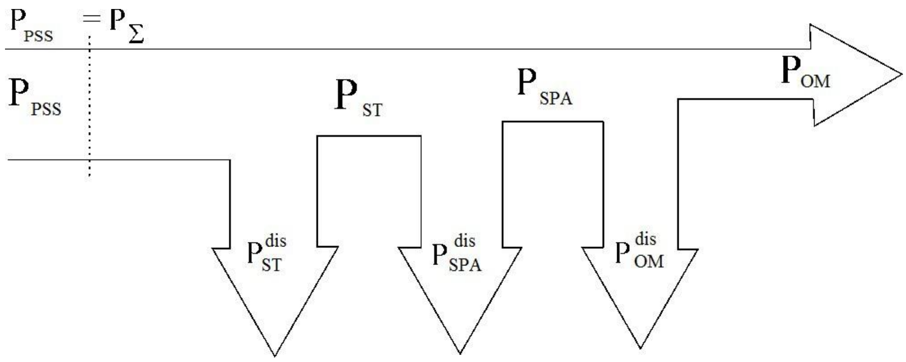

***Figure 6**. Diagram of power distribution of the power supply source in the energy channel of the autonomous drive control system of the stabilizer – static power amplifier – operating mechanism type*

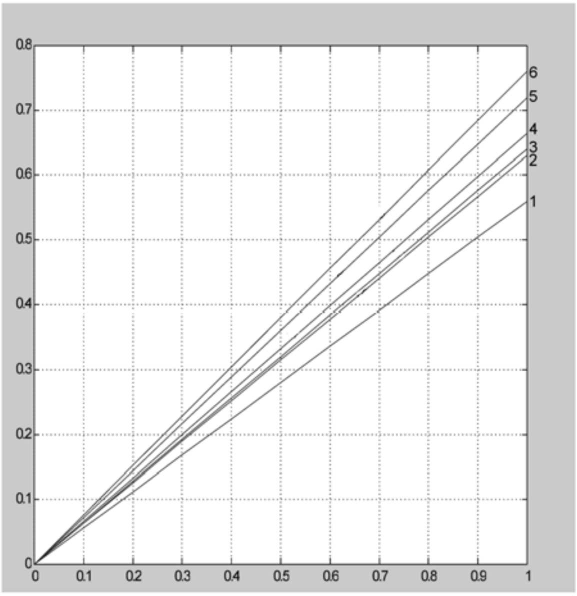

***Figure 7**. Dependence diagrams $\eta_{EC2} = f(\eta_{ST})$, where **1** – diagram $\eta 1$ while η_{SPA} = 0,8; η_{OM} = 0,7; **2** – diagram $\eta 2$ while η_{SPA} = 0,8; η_{OM} = 0,8; **3** – diagram $\eta 3$ while η_{SPA} = 0,9; η_{OM} = 0,7; **4** – diagram $\eta 4$ while η_{SPA} = 0,9; η_{OM} = 0,8; **5** – diagram $\eta 5$ while η_{SPA} = 0,95; η_{OM} = 0,7; **6** – diagram $\eta 6$ while η_{SPA} = 0,95; η_{OM} = 0,8.*

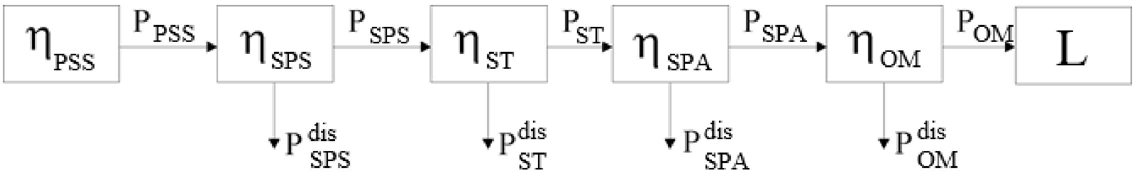

***Figure 8**. The scheme of energy conversion in the power channel of the autonomous drive control system when powered by the secondary power source with the output power – P_{SPS}, dissipated power – P_{SPS}^{dis}, coefficient of performance – η_{SPS}*

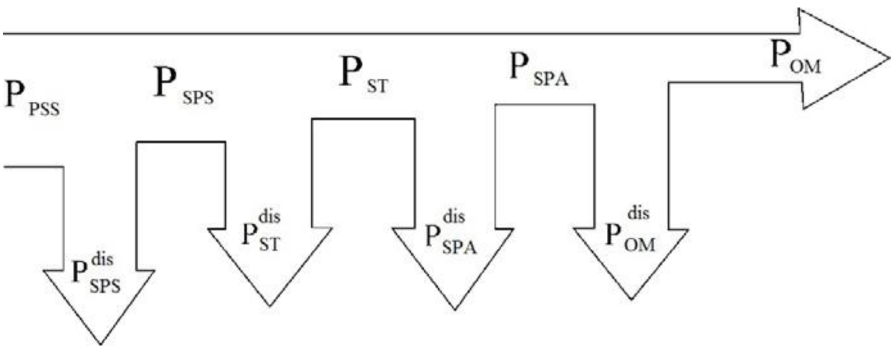

***Figure 9**. Diagram of power distribution of the primary power supply source in the energy channel of the autonomous drive control system of the secondary power source – stabilizer – static power amplifier – operating mechanism type*

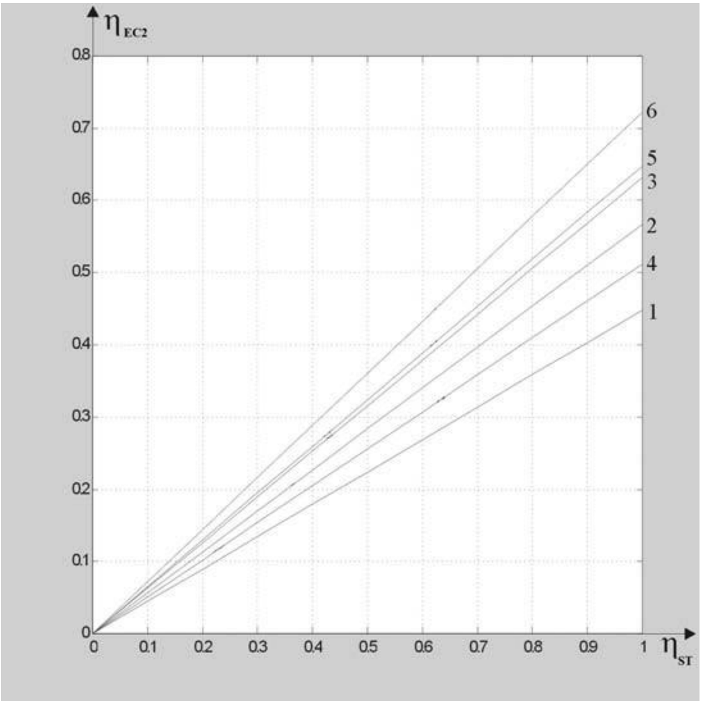

***Figure 10**. Dependence diagrams $\eta_{EC3} = f(\eta_{SPS})$, where **1** – diagram $\eta 1$ while η_{SPA} = 0,8; η_{ST} = 0,8; η_{OM} = 0,7; **2** – diagram $\eta 2$ while η_{SPA} = 0,9; η_{ST} = 0,9; η_{OM} = 0,7; **3** – diagram $\eta 3$ while η_{SPA} = 0,95; η_{ST} = 0,95; η_{OM} = 0,7; **4** – diagram $\eta 4$ while η_{SPA} = 0,8; η_{ST} = 0,8; η_{OM} = 0,8; **5** – diagram $\eta 5$ while η_{SPA} = 0,9; η_{ST} = 0,9; η_{OM} = 0,8; **6** – diagram $\eta 6$ while η_{SPA} = 0,95; η_{ST} = 0,95; η_{OM} = 0,8.*

$$\eta_{EC1} = \frac{P_{OM}}{P_{PSS}} = \eta_{OM}\eta_{SPA} \quad \text{(Eq. 1)}$$

$$\eta_{OM} = \frac{P_{OM}}{P_{SPA}} \quad \text{(Eq. 2)}$$

$$\eta_{SPA} = \frac{P_{SPA}}{P_{PSS}} \quad \text{(Eq. 3)}$$

$$P_{OM} = P_{SPA} - P_{OM}^{dis} \quad \text{(Eq. 4)}$$

$$P_{PSS} = P_{SPA} + P_{SPA}^{dis} \quad \text{(Eq. 5)}$$

$$\eta_{ST} = \frac{P_{SPA}^{dis} + P_{OM}^{dis} + P_{OM}}{P_{ST}^{dis} + P_{SPA}^{dis} + P_{OM}^{dis} + P_{OM}} \quad \text{(Eq. 6)}$$

$$P_{ST}^{dis} = P_{PSS}(1 - \eta_{ST}) \quad \text{(Eq. 7)}$$

$$P_{SPA}^{dis} = P_{ST}(1 - \eta_{OM}) \quad \text{(Eq. 8)}$$

$$P_{OM}^{dis} = P_{SPA}(1 - \eta_{OM}) \quad \text{(Eq. 9)}$$

$$P_{\Sigma} = \frac{P_{OM}}{\eta_{ST}\eta_{SPA}\eta_{OM}} \quad \text{(Eq. 10)}$$

$$\eta_{EC2} = \frac{P_{OM}}{P_{PSS}} = \frac{P_{OM}}{P_{\Sigma}} = \eta_{ST}\eta_{SPA}\eta_{OM} \quad \text{(Eq. 11)}$$

$$\eta_{SPS} = \frac{P_{ST}^{dis} + P_{SPA}^{dis} + P_{OM}^{dis} + P_{OM}}{P_{SPS}^{dis} + P_{ST}^{dis} + P_{SPA}^{dis} + P_{OM}^{dis} + P_{OM}} \quad \text{(Eq. 12)}$$

$$P_{SPS}^{dis} = P_{PSS}(1 - \eta_{SPS}); \quad \text{(Eq. 13)}$$

$$P_{ST}^{dis} = P_{SPS}(1 - \eta_{ST}); \quad \text{(Eq. 14)}$$

$$P_{SPA}^{dis} = P_{ST}(1 - \eta_{SPA}); \quad \text{(Eq. 15)}$$

$$P_{OM}^{dis} = P_{SPA}(1 - \eta_{OM}) \quad \text{(Eq. 16)}$$

$$P_{\Sigma 1} = \frac{P_{OM}}{\eta_{SPS}\ \eta_{ST}\ \eta_{SPA}\ \eta_{OM}}$$ (Eq. 17)

$$\eta_{EC3} = \frac{P_{OM}}{P_{PSS}} = \frac{P_{OM}}{P_{\Sigma 1}} = \eta_{SPS}\ \eta_{ST}\ \eta_{SPA}\ \eta_{OM}$$ (Eq. 18)