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MECHATRONIC SYSTEMS AND FREQUENCY-CONTROLLED ELECTRIC DRIVES OF ELECTRICAL MACHINES IN ELECTROTECHNOLOGIES OF BIOENERGY PLANTS WITH OPTIMIZATION AND RELIABILITY DIAGNOSTICS

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Mechatronic systems and frequency-controlled electric drives of electrical machines in the electrotechnologies of bioenergy plants, with optimization and reliability diagnostics, represent a key area in the development of modern agricultural machinery engineering. The use of such systems ensures a high level of functional integration of mechanical, electrical, electronic, and informational components, allowing the creation of equipment with high productivity, energy efficiency, and reliability. The mechatronic approach promotes the synchronization of electric drives, sensors, and controllers, providing adaptive control under variable loads and unpredictable environments characteristic of agricultural and bioenergy processes.

The implementation of frequency-controlled electric drives enables flexible control of motor speed and torque, optimizes energy consumption, increases the accuracy of technological operations, and reduces wear on mechanical components. The use of adaptive control algorithms and regenerative systems contributes to energy savings and improves the operational efficiency of equipment across various modes of operation.

The reliability of such systems is ensured through comprehensive diagnostics and failure prediction, including the integration of sensor networks, IoT technologies, big data analysis, and predictive maintenance algorithms. It reduces the risk of failures, extends machine longevity, and optimizes maintenance planning.

Special attention is given to the systematization of agricultural machines as mechatronic objects, defining the levels of integration of modules, units, and assemblies, and describing the interaction of components with the environment. The concepts of mechatronic modules, units, assemblies, and systems are considered, along with the principles of synergistic integration that enable the combination of mechanical, electrical, electronic, and informational components into a single, adaptive system.

The research results demonstrate the effectiveness of applying mechatronic systems with frequency-controlled electric drives in bioenergy plants in the agro-industrial sector, thereby increasing productivity, energy efficiency, reliability, and the safety of technological processes. The proposed approaches align with modern Industry 4.0 standards, opening new opportunities to create modular, scalable, and highly functional solutions for contemporary agricultural production.

Keywords: *mechatronic systems, frequency-controlled electric drives, electrical machines, electrotechnologies, bioenergy plants, optimization, reliability, diagnostics, energy efficiency, system integration.*

Eq. 15. Fig. 1. Tabl. 1. Ref. 17.

1. Problem formulation

Mechatronic systems and frequency-controlled electric drives for electric machines in electrical technologies for bioenergy plants, with optimization and reliability diagnostics, are a key factor in the development of modern agricultural equipment. The creation of machines with high functional and parametric characteristics that meet modern market requirements and operating conditions is impossible without a

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comprehensive integration of interconnected components of different physical nature, i.e., mechanical, hydraulic, electronic, electrical, and information (computer) ones. Such integration requires forming a single heterogeneous system in which elements with fundamentally different operating laws interact effectively.

Components of modern mechatronic systems often have conflicting requirements: mechanical units require high rigidity and strength, electronic systems need fast signal processing and adaptability, and electric drives require stability and control accuracy. However, to achieve the general goal of increasing productivity, reliability, and energy efficiency, these heterogeneous elements must work in synchrony. Ignoring integration specifics leads to system errors, including imbalances of characteristics, mechanical component overloads, premature failures, increased maintenance costs, and a loss of the potential of individual components. For example, unsynchronized operation of electronic control systems can cause mechanical components to overload, thereby reducing the equipment's durability and reliability.

Modern conditions for the development of the agro-industrial complex (AIC), including bioenergy processes and production automation, create additional challenges for traditional machine designs. To overcome these challenges, a mechatronic approach is increasingly being used, which integrates elements of electrical technologies, sensor systems, frequency-controlled electric drives, and software based on artificial intelligence. Mechatronics enables the modeling, simulation, and optimization of complex hybrid systems in which mechanical components are closely integrated with electronic controllers, sensors, and actuators.

The use of frequency-controlled electric drives in such systems provides flexible control of electric motor speed and torque, enabling increased operational accuracy, reduced energy consumption, and extended service life for mechanical components. The use of regenerative systems and adaptive control algorithms not only saves energy but also increases the efficiency of machines across different operating modes. This is especially important for equipment operating in conditions of intensive agricultural production and bioenergy processes.

A comprehensive approach to diagnostics and failure prediction ensures the reliability of mechatronic systems. Modern solutions include integrating sensor networks, IoT technologies, big data analysis, and predictive maintenance algorithms to identify potential problems at early stages of operation. This reduces the risk of accidents, increases equipment durability, and optimizes repair planning.

In bioenergy installations of the agricultural complex, mechatronics with electrical technologies becomes the basis for creating reliable, modular, and scalable solutions that meet Industry 4.0 standards. Such systems ensure the effective integration of electric drives with biomass processing, biogas plant automation, and energy flow management. The mechatronic approach transforms potential conflicts between components into synergy, ensuring high efficiency, reliability, and competitiveness of modern agricultural machinery in the global market.

Thus, the introduction of mechatronic systems with frequency-controlled electric drives, highly developed sensor and information systems, and effective reliability diagnostics is a key factor in the development of modern agricultural machinery and bioenergy plants. This ensures increased productivity and energy efficiency, as well as the development of a new level of adaptability, scalability, and safety for technological processes in the agro-industrial sector.

2. Analysis of recent research and publications

The principles of mechatronics were initially actively applied in industries such as robotics and machine tool engineering, where the most complex control algorithms were combined with a high density of structural and intellectual components. Electronic, information, and computer components were widely used in these areas, enabling the implementation of high-tech systems with intelligent control. At the initial stages of mechatronics development, it was observed that integrating heterogeneous components requires coordinated design approaches and the prediction of potential conflicts between mechanical and electronic systems.

The term “mechatronics” was first proposed [1], and an analysis of individual components and the principles of their integration into a single system that interacts with the environment in the context of robotics was conducted. Antoshchenkov R.V. focused on the classification of mechatronic modules and on their design and reliability, particularly in machine tool construction [2]. In the research by Vozniak O.M. et al. [3], the terminology and hierarchy of mechatronic objects (MO) were proposed, and a comparative analysis of the approaches of different authors was conducted. Still, the primary focus remained on robotics, instrument making, and machine tool building. Coal engineering and the use of mechatronics principles in it were also considered [4], indicating the gradual spread of these approaches in various industries. Antoshchenkov R.V. defined mechatronics as "a field of science and technology based on the synergistic combination of precision mechanics units with electronic, electrical, and computer components that ensure the design and production of qualitatively new modules, systems, machines, and systems with intelligent control of their functional motion” [2]. In this case, the field of mechatronics is described by a pyramidal model, where the basic axes are formed by mechanics, electronics, and computer science, and the volume of the pyramid is formed by the intersection of electromechanics, computer-aided design systems, and computer control systems, known as the “mechatronics pyramid”.

Mechatronic objects consist of several main components, among which various types of relationships are possible. It allows them to be formalized as structural formulas. The mechanical component (M) provides multiple types of motion of the object or its parts, including gearboxes, various motion converters (rack-and-pinion, crank-and-rod mechanisms), and transmission links (couplings, etc.).

The electrical-and-technical component (Ce) is responsible for converting electrical energy and includes electric motors, electromagnetic couplings and brakes, electromagnets, and related components. The hydraulic component (Ch) converts hydro- or pneumatic energy and includes hydraulic cylinders, hydraulic motors, hydraulic pumps, and hydraulic distributors. Due to their similar energy nature, electrical and hydraulic components are often combined under the term “power component” (Cp).

The electronic component (E) provides the formation, transmission, and processing of electrical signals, including microprocessors, frequency converters, and other electronic devices. The information component (I) is responsible for collecting, processing, storing, and transmitting data and includes sensors, software, and monitoring systems.

There can be various types of connections between components. Coordination (-) implies that each element has its own parameters and constraints, selected to achieve a common goal, e.g., as in standard drives with a separate motor and gearbox. Connection (+) imposes typical constraints on the components, forming a new structural unit with its own functions, which is typical for most agricultural machinery drives. Connection (·) implies an inextricable connection of components into a single device, e.g., a geared motor.

3. The purpose of the article

The research aims to comprehensively improve and systematize the application of mechatronics principles in modern bioenergy production, while accounting for the specific features of agricultural engineering. The primary focus is on integrating electronic, electrical, and mechanical components into single hybrid systems, which increases the efficiency, reliability, and energy efficiency of machines. The work also aims to demonstrate the practical application of these principles through a specific example: two electric motor drives for agricultural machines, enabling the solution of real technical problems, the optimization of work processes, and increased equipment productivity. Special attention is paid to adaptive control algorithms, synchronization of mechanical and electronic components, and the implementation of diagnostic systems to predict failures and ensure the uninterrupted operation of equipment.

The research aim is to develop an integrated approach to the design and operation of agricultural machines and bioenergy plants using modern mechatronics methods that meet the current requirements of the agro-industrial complex and applicable standards.

4. Results and discussion

The need for synergistic integration of components arises as requirements for the functional and parametric characteristics of systems, and for the quality of their operation, increase. Modern agricultural machines and bioenergy plants must provide a high level of accuracy, reliability, and energy efficiency, which complicates the separate regulation of each component's characteristics. The growth in complexity and integration of systems necessitates combining heterogeneous elements into a single, synergistic structure.

According to Antoshchenkov R.V. [2], synergistic integration can be implemented in two main ways. The first method is functional-structural integration (FS-integration), which involves minimizing the number of structural blocks required to perform functions and reducing the number of coordinating devices. The second method is structural-constructive integration (SC-integration), which aims to optimize design solutions for implementing a given system structure, ensuring compactness, reliability, and component interchangeability.

FS-integration leads to the transition from the “coordination” link (-) to the “connection” link (+). In contrast, SC-integration replaces the "connection" link (+) with the “combination” or “co-location” link (·). The “-” link reflects the absence of integration; therefore, further on, only links (+) and (·) are considered integrative. It is important to note that the term 'combination of components' refers to the presence of a connection between them, whereas 'integration' involves creating an interconnected, functional, or constructive whole.

When a certain level of functional and parametric requirements is reached, further improvement in the system's characteristics cannot be ensured solely by changing the parameters of individual components. Improvement of system operation is possible only through changes in the system as a whole, which, as a rule, is accompanied by increased structural complexity and a growth in the number of functions. This is due to the need to consider a larger number of environmental features and process parameters. To implement new functions, additional modules or units are typically employed, and under design constraints, there arises a need either to integrate them or transfer functions between components.

Thus, FS and SC integrations are a consequence of the system's functional and parametric complexity: under the same constraints, they enable the implementation of more functions. Improving the quality of operations is accompanied by an increase in the number of feedback, a reduction in reaction time to changes in the external environment, and an increase in control complexity. At a particular stage, the operator loses the ability to control the system in real time, and part or all of the system's state information, previously processed by a human, is processed by automated algorithms.

The use of artificial intelligence methods in such systems enables adaptive behaviour, including self-organization, forecasting, and real-time optimization of actions. As a result, the systems can respond autonomously to changes in external conditions, increasing efficiency, reliability, and operational durability, which is critically important for modern agricultural machinery and bioenergy plants. The integration of FS and SC approaches opens new opportunities to create modular, scalable, and highly functional mechatronic systems that meet the standards of modern industrial production and the principles of Industry 4.0.

Assume that each *i*-th component corresponds to a set of functional-parametric characteristics *F*. A system consisting of *n* components operates in an environment with a set of characteristics *Fc*. Then the condition for the system’s operability in this environment can be expressed as:

$$\sum_{i}^{n} F \geq F_c \tag{1}$$

In designing, a specific set of required characteristics$_{,\ Fm,}$ is known. If everything is known about the environment, then.

$$F_m = F_c \tag{2}$$

$$\sum F = F_m \tag{3}$$

For each component, specific characteristics can be set, ensuring the system’s operability. In this case, the system interacts with the environment; i.e., a change in the environment's characteristics corresponds to a change in the components' characteristics, as determined by the known set F_m.

If not everything is known about the environment, then:

$$F_m < F_c = \Delta F + F_m \tag{4}$$

$$\sum F = \Delta F + F_m \tag{5}$$

To ensure system operability, its characteristics must change by the value *ΔF*. In this case, the system must interact with the environment adaptively, have autoregulators, and exhibit characteristics that exceed the set F_m; therefore, it must exhibit new properties. Based on the general definition of synergetics and the above definitions, the following formulation can be proposed.

Synergistic integration is the integration of M, C, E, and I components to achieve a single goal, in which the newly created system acquires qualitatively new properties that are unattainable by individual components and adaptively interacts with the environment.

A necessary condition for mechatronics is the integration of M, C, E, and I-components into a system that uniquely interacts with the environment (according to [1], [3], [4] – mechatronized objects);

A sufficient condition for mechatronics is the integration of M, C, E, and I components into a system that adaptively interacts with the environment, i.e., synergistic integration.

Thus, the mechatronic nature of an object is determined by the functional and parametric requirements for it (the set *Fm*), the level of which determines the composition of the components, the nature of integration, the type of interaction with the environment, as well as its structure:

- if there is no component in the structural equation, then the object is not

+mechatronic and not mechatronized;

- if there are all components in the structural equation, but at least one of them has a (-) link, then this object is mechatronized;
- if all the links in the structural equation are integrated, then this is a mechatronic object.

The design of any object, including a mechatronic one, always begins with defining its functions and forming a set of functions FtF_tFt, which specify the system's main tasks. According to Antoshchenkov R.V. [2], this stage is identified as the construction of an F-model, which formalizes the object's functional capabilities and enables planning the further integration of components. The synthesis and analysis of the constructive links of agricultural machines, which limit the possible types of mutual motion of their elements, are presented quite fully in research by Yehorov O.D. and Poduraiev Yu.V. [5, 17], but they mainly cover mechanical interaction and do not take into account the complex integration with electronic, electrical, and information systems.

It is a complex and highly specialized task to determine the required functions of the Ft system to achieve the goal under conditions of interaction with the environment Fc, which is characterized by numerous parameters. In this work, a detailed description of this process is not considered, but it is essential to highlight the main functions of the dual-motor electric drive of an agricultural machine. These include simultaneous start-up of both electric drives, ensuring coordination of transient processes, the ability of one drive to operate when the power is lost in the other, and compensation for uneven load distribution.

The environment for agricultural machinery includes weather and soil conditions, as well as the geometric relationships among the positions of machines and their components relative to the ground and each other. Additionally, the environment includes aerological parameters, namely air speed and temperature, moisture concentration, and the condition and operating conditions of the equipment. This environment is characterized by high spatial and temporal disorder, which complicates the unambiguous prediction of the system behavior.

Kondrakhin V.P. et al. [6, 16] proposed to use the required and sufficient number of features for control as an indicator of the degree of environmental disorder. All possible features form a set of situations, each with a corresponding control action. If the system lacks defined responses for some of these situations, the environment is considered statically open. When the number of environmental features exceeds seven, it becomes impossible to analyze all possible situations, and a control effect is formed based on rules or algorithms that provide approximate solutions for each specific case.

Therefore, the environment for modern agricultural machines should always be considered partially uncertain, and the system's interaction with it should be adaptive. Even for the simplest machines, such as feed conveyors, it is necessary to consider at least 12 environmental factors to ensure reliable operation [6]. For more complex systems with several machines, the number of situations increases exponentially; e.g., for three machines with 7 environmental features, it is necessary to consider 2,097,152 situations [6, 15], which makes the direct programming of all scenarios impossible.

This conflict can be resolved through a hierarchical system structure, where each machine adaptively interacts with a specific part of the environment and coordinates its work with other machines. This approach allows us to consider agricultural machines as autonomous mechatronic objects that function independently and effectively interact within a complex. Implementing such adaptive strategies is key to increasing the reliability, productivity, and energy efficiency of modern mechatronic agricultural systems.

It should be noted that the components of agricultural machinery have features that significantly affect the principles of their design and, most often, make it impossible to use solutions from other branches of agricultural engineering.

The main features of mechanical components:

- stochastic nature of loads at high levels of the coefficient of variation in established operating modes;
- high emergency loads in transient modes;
- strict limitations on the overall dimensions of the equipment;
- use of materials that are at the limits of their strength characteristics (possibility of further improvement is practically exhausted).

The main features of electrical components:

- dust- and moisture-proof design with strict dimensional constraints;
- wide use of asynchronous squirrel-cage motors, which is determined by relative simplicity and reliability;

- extensive use of multi-motor drives, including those operating on a single shaft, which is determined by dimensional restrictions;
- severe operating conditions characterized by a high duty cycle with a large number of starts and reversals, under stochastic load conditions.

Features of electronic components include moisture- and dust-proof design.

The operating conditions of all components of agricultural machines are characterized by increased pollution, the chemical aggressiveness of the environment, and the complexity of preventive maintenance and repair work.

These features significantly limit the range of permissible solutions in the design of agricultural machines.

For further discussion, it is necessary to define several terms using the hierarchy of MOs proposed in [4], regarding agricultural machinery as a mechatronic system with elements of electrical technologies.

The communication module (hereinafter, COM) is intended for information exchange among various objects and for interface conversion. COM can be implemented as software (as part of the software that provides data exchange), software-hardware (for example, in the form of a device that converts interfaces via a controller), or hardware (for example, devices that encode data using analog technology).

The control module (hereinafter CM) generates, converts, and transmits information signals necessary for the full or partial functioning of a mechatronic object.

Neither COM nor CM, as a rule, is a mechatronic object and often has no structural, functional, or constructive localization. These terms are introduced to simplify the construction of structural diagrams, as objects for converting interfaces and interactions, or for forming a control signal.

Mechatronic drive module (hereinafter MDM) is a unified mechatronic object of the first level of integration, designed, as a rule, to perform one function of implementing movement along one coordinate. *A mechatronic unit* (hereinafter, MU) is a non-unified mechatronic module. An example of MDM in relation to agricultural machinery is a scraper conveyor drive, which consists of an electric motor, a transmission, temperature and speed sensors, and one or more COM or CM.

An example of MU is a feed drive for agricultural machinery, consisting of an electric motor, transmission, speed and direction sensors, temperature sensors, pressure sensors, a braking device, and one or more COMs. The difference between MDM and MU in this case is determined by the fact that the MDM of the scraper conveyor drive can be used independently of other objects of the treatment complex. The MU of the feed drive of agricultural machinery is constructively, structurally, and functionally connected with other objects; that is, for different complexes, this MU will be different, therefore it is not unified.

Mechatronic assembly (hereinafter MA) is a mechatronic object of the second level of integration, consisting of several MDMs or MUs, its own COM and CM, non-mechatronic objects, for example, its own sensors, designed to perform various functions in interaction with the external environment, and the implementation of various prescribed laws of motion. In this sense, MA will be a section of a mechanized attachment with electro-hydraulic control, consisting of hydraulic cylinders, an electro-hydraulic unit, CMs, sensors, and COMs. MAs are also cleaning agricultural machines and scraper conveyors.

Horbatov P.A., Kosariev V.V., Stadnik N.I. [4] proposed to identify the term “machine” and the term “unit”. Since the term “machine” is well established in agricultural engineering, it is proposed to use it without including it in the MO hierarchy, but to define it in mechatronic terms. A machine is an object designed to perform a particular technological process, and it may be MDM, MU, or MA. Hence, an agricultural machine is a machine designed for digging, moving, and loading agrarian products, and consisting of one or more feed drive units, one or more conveyor drives, and one or more COMs and CMs.

A mechatronic system (MS) is a mechatronic object at the third level of integration, consisting of individual MDM, MU, and MA components, non-mechatronic objects, and its own COM and CM, with ordered connections. It dynamically functions in time and space while interacting with the environment as a single whole.

In mechatronics, an *interface* should be understood more broadly than its traditional interpretation, as a system of connections with unified signals for information exchange between devices. We will consider the interface as the interaction between MOs and the environment. In this sense, interfaces can take different physical forms. Possible types of interactions (taking into account the principles proposed in research [8]) are given in Table 1.

Table 1.

Possible types of interfaces

Interaction	Symbol	Variables	
		Flow type	Potential type
Transmission mechanical	μ	Force, N	Velocity, v
Rotational mechanical	ω	Torque, M	Angular speed, n
Electrical	ε	Current, I	Voltage, U
Hydraulic (pneumatic)	γ	Flow rate, Q	Pressure, P
Thermal	τ	Thermal flow, F	Temperature, T
Informational	ι	Code (signal flow)	Signal, k

The *converter* changes or transforms the interaction and interfaces. The converter can change the magnitude of the interaction of the same physical nature, for example, a gearbox or reducer – a mechanical motion type converter (hereinafter MMC), or change the nature of the interaction, for example, an asynchronous motor – a converter of electrical energy into rotational motion (hereinafter EMC, i.e. eletromechanical converter), a rack-and-pinion mechanism – a converter of rotational motion into transmission motion.

According to Antoshchenkov R. V. [2], any MO in general can be considered as an information-mechanical converter. This object converts information about the environment into the motion of the object.

Using the accepted definitions, it is possible to compile structural formulas for agricultural machines. In agricultural engineering, particularly when designing agricultural machines, SC integration was practically implemented. The need for this was caused by strict requirements for the dimensions and layout of farming machines, with a sufficiently high power, which made it impossible to use an approach in which a gearbox and a motor were designed separately, then using various components (frame, couplings, etc.), they were combined into a drive. For example, a first-generation agricultural machine could have an electromechanical drive for the cutting body, a hydrovolumetric feed drive, and manual control. The structural formula of a machine of this generation can be represented as follows (6):

$$C_e + M + 3_{\text{г}} \tag{6}$$

If this machine is equipped with electronic components, such as load and speed controllers, it ensures maximum machine performance at a given load. The structural formula in this case will be as follows (7):

$$C_e + M + C_{\text{г}} - E \tag{7}$$

When further developing agricultural machines to improve functional and parametric characteristics, it was necessary to add a cutting drive, two feed drives with electromagnetic clutches, and equip the machine with manual control. The structural formula of such a machine may be represented as follows (8):

$$(\,C_e + M + C_{\text{г}}\,) + 2\,(C_e + M)) + E \tag{8}$$

With further development of agricultural machinery, their design may incorporate electric drives with high torque and a wide speed range, as well as frequency-controlled two-motor feed drives, drives with integrated hydraulic pumps, and remote and automated control systems. The structural formula of such a machine has the following form:

$$(2(C_e + M) + C_{\text{г}}) + I \cdot E) + 2(\,C_e + M \cdot C_{\text{г}}) + (C_e \cdot C_{\text{г}}) + I \cdot E \tag{9}$$

The first term of the equation describes the motion drive, the second term describes the working drive, the third term describes the hydraulic system, and the fourth term describes the control system.

Analysis of the structural equations shows that the agricultural machines listed above meet both the necessary and sufficient conditions for mechatronics, so they can be considered mechatronic objects (MOs).

During this analysis, formalized structural equations are used to describe the interactions among mechanical, electrical, electronic, and information components within a single system. This allows us to determine to what extent the machine meets the criteria of mechatronics and provides integrated operation and adaptive control.

A necessary condition for mechatronics is the integration of heterogeneous components. In particular, the machine must include a mechanical part for performing technological operations, an electrical component with electric motors, drives, and power cells, and an electronic and information part that implements sensor systems, controllers, and control algorithms. If all these components are present and interact with each other, the necessary condition can be considered fulfilled.

The sufficient condition for mechatronics is that component functions integrate synergistically. This means that the system can adapt to changing operating conditions, such as different soil moisture levels, field irregularities, or changes in the load on machine components. In addition, sensor data must interact with actuators through control algorithms, thereby optimizing operating modes to increase energy efficiency, productivity, and reliability.

The analysis of structural equations indicates that the listed agricultural machines have sufficient integration and adaptability. This allows them to be formally classified as mechatronic objects (MO) and apply modern methods of automated control, diagnostics, optimization, and reliability prediction.

This enables the integration of heterogeneous components – mechanical, electrical, electronic, and information – into a single functional system capable of adaptively responding to changes in the environment and technological processes.

Let us consider the practical application of the principles of mechatronics and electrical technologies using the example of a frequency-controlled electric drive in modern agricultural machinery. This type of electric drive is currently one of the most versatile and widespread solutions in electrified machines of the agro-industrial complex. Its application includes grain and forage harvesters, precision seeders, self-propelled sprayers, grain ventilation and drying systems, transport conveyors, biogas plants, and other machine modules.

A frequency-controlled electric drive provides smooth, precise speed regulation of working elements over a wide range, significantly reducing starting currents and mechanical loads on transmission elements. It enables the implementation of adaptive operating modes that depend on the current technological load, as well as energy-saving modes that improve the machine's overall efficiency.

Integration of the frequency-controlled electric drive into the automated machine control system significantly increases the reliability and resource of the equipment. Reducing dynamic shocks, vibrations, and overheating makes technical systems more stable and safer to operate. In addition, such a drive facilitates diagnostics of electrical machine components and the prediction of failures, contributing to timely maintenance and increased operational availability of equipment.

Due to the relatively simple structure of the mathematical description, a frequency-controlled asynchronous or synchronous electric drive with vector or scalar control allows obtaining unified models. These models, with sufficient accuracy for engineering calculations, reflect the dynamics of most electric drives of agricultural machines and bioenergy equipment. They account for the main physical processes while simplifying some nonlinearities, making the modeling and forecasting of system operation more accessible and accurate.

The structural model (S-model) of a variable frequency drive, built taking into account the adopted simplifications – such as linearization of static characteristics, ignoring the saturation of the magnetic core and higher harmonics of the current –allows for the analysis of the drive dynamics and the assessment of the impact of different operating modes on efficiency and reliability. It serves as a basis for designing adaptive control algorithms that optimize energy consumption and synchronize the operation of several drives in a complex agricultural machine.

Thus, a variable-frequency drive, combined with principles of mechatronics and electrical technologies, creates a reliable, adaptive, and energy-efficient control system. It both increases the productivity and durability of machines and contributes to their integration into modern concepts of “smart” agriculture and bioenergy technologies.

Figure 1. Simplified structural model of a variable frequency drive for agricultural machinery. The electric drive of an agricultural machine, for example, may include:

- two identical mechatronic transmission units (MTU_1 and MTU_2), consisting of an electromechanical converter (EMC) – asynchronous electric motor), a mechanical motion converter (MMC) or reducer, a mechanical transmission converter (MTC) – kinematic transmission: sprocket-pin rack;
- an electrical power converter (EPC) – frequency converter based on a circuit with an autonomous inverter;
- a control module (CM);

- communication modules (COM_1 and COM_2).

The input function for the feed drive is an electrical signal described by the function ε_{in}. The output is mechanical movement characterized by the function μ_{out}. Thus, the feed drive converts electrical energy into a specific mechanical force under the control of the signal U_{set}.

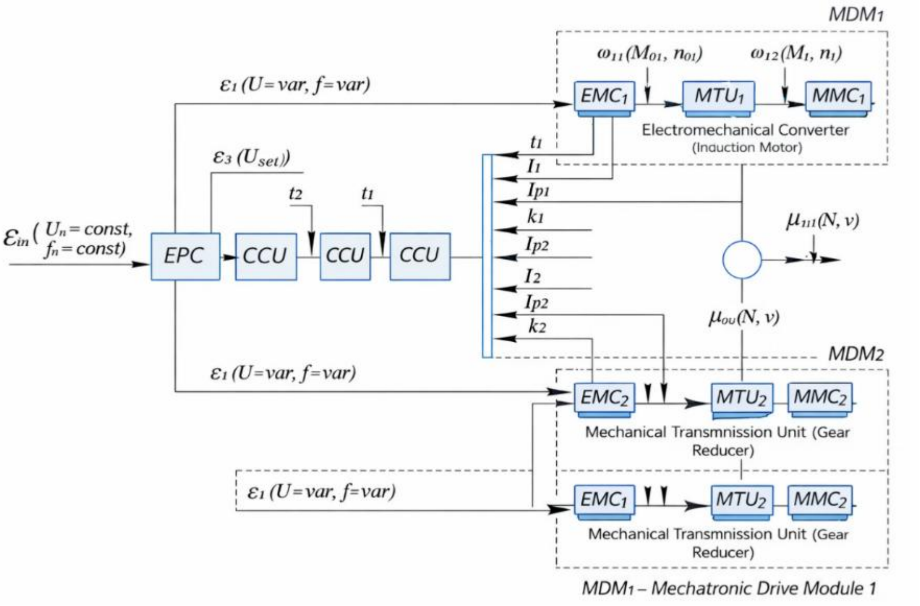

Fig. 1. S-model of mechatronic electric drive

The information component in this S-model is represented by the modules CM, COM_1, and COM_2. The COM_2 module converts the signals indicating the drives' state into a serial code i_1 (data bus). This code is transmitted to the COM_1 module, which converts the code i_1 into the service code i_2 of the CM module.

The CM module converts the code i_2 into a sinusoidal signal of the output voltage setting U_{set}, which is described by the following system of equations:

$$\begin{cases} U_{set} = \phi_1(k_0, I_1, I_2, I_{p1}, I_{p2}) \\ U_{set} = 0, (k_1 \neq k_2) \\ U_{set} = 0, (t_1, t_2 > t_0) \end{cases} \tag{12}$$

where: U_{set} is the set voltage value formed by the control module and used as a reference signal in the electric drive control system; k_0 – signal of the feed speed set by the operator; I_1 , I – load signals of the feed motors; I_{c1} , I_{2c} – load signals of the cutting motors; k_1 and k_2 – rotational speed signals; t_1 and t_2 – heating signals of the stator windings of the feed motors; t_0 – permissible temperature limit.

Thus, in this case, CM performs the functions of an automatic speed regulator with two control loops – one for the load of the motion motors and one for the load of the working-element motors – with constraints on the maximum permissible heating of the stator windings of the motion motors.

The EPC module represents the electronic component. The input function ε_n (where ε_n – voltage regulation error defined as the difference between the set (reference) voltage value and the actual (measured) voltage value, and used to generate the control action) has the value of voltage U_c and frequency f_c of the supply network and is converted by the EPC into an electrical signal ε_1 with variable values *U and f*, which are formed by comparing the sinusoidal signal of variable frequency U_{set} with the sawtooth signal of constant (carrier) frequency U_{car}. The output signals of the converter U and f are related to the signals at its input by the following dependencies:

$$\begin{cases} U = \phi_2(U_c, U_{car}, U_{set}) \\ f = \phi_3(U_c, f_c, U) \end{cases} \tag{13}$$

where U_{car} –the carrier voltage (reference or modulation voltage) used in the pulse-width modulation (PWM) of the frequency converter to form control pulses for the autonomous inverter; U_{set} – the set voltage value formed by the control module and used as reference signal in the electric drive control system;

The electrotechnical component is represented by the EMC$_i$ modules. Electrical energy ε_1 with values U and f is converted into mechanical rotational motion – interface ω_{i1} characterized by torque M_{di} and angular speed n_{di}. The relationship between the output parameters of the EMC modules and the input ones is described by a system of equations:

$$\begin{cases} M_{di} = \varphi_4(n_{\partial i}, U, f) \\ n_{di} \equiv f \end{cases} \quad i = 1,2 \tag{14}$$

The MMC$_i$ and MTC$_i$ modules represent the mechanical component. The MMC$_i$ modules convert interface i$_1$ into interface i$_2$ – rotational motion into rotational motion with the different parameters. The MTC$_i$ modules convert mechanical rotational motion into mechanical transmission motion — function μ_i. The tractive force is realized by summing the forces generated by the MTUs. The following equations can represent the mathematical description of the mechanical component:

$$\begin{cases} N_i = \dfrac{M_{di}}{r_{ci}} u \\ n_{di} = u \dfrac{v}{r_{ki}} \\ N = \sum\limits_i N_i \end{cases} \quad i = 1,2 \tag{15}$$

where: u – gearbox transmission ratio; v – feed speed; r_{ci}, r_{ki} – reduced force and kinematic meshing radii [10]; N_i – tractive force of each MTU; N – total tractive force.

Thus, the S-model of the MO feed drive is described by equation 12.

The control signal specified by the human operator during autonomous operation of the MAOK, or by the MSOK control module during the combine harvester operation within the system, is the set speed signal k_0. Environmental influences are accounted for by the parameters I_{p1} and N. The feed drive has fixed constraints: U_c, U_{car}, f_c, t_0, u . These quantities are the initial data for solving the system of equations, as a result of which the main parameters M_{di}, n_{di}, N_i, ni , U, U_{set}, f, v , as well as the associated feedback signals k_i, I_i, t_i are determined.

Analysis of the S-model and its mathematical description enables the determination of methods to resolve the conflict that has arisen.

1. Change the functional-parametric characteristics of the system as a whole by limiting the area of interaction between the system and the environment, that is, reducing the quality of functioning.

For example, this means changing the technical specification for the drive by limiting the application area of the agricultural machine to those design modifications that ensure the required operating parameters.

2. Change functional-parametric characteristics of the conflicting components. It is necessary to select the parameters of the two-motor mechanism so that the uneven load is absent.

3. Change the S-model of the system by introducing additional modules and/or functional connections to limit or eliminate the conflict, by introducing additional autoregulators, protection, and matching devices; while the additional modules can be of the exact physical nature as the conflicting components, or of a different one.

In the analyzed S-model, introduce protection that turns off the engines when they are overloaded (according to the I_i signals), ensuring the machine operates within optimal and permissible values.

To resolve potential conflicts within the mechanical component, differential gearboxes with a kinematic ring-gear connection can be used instead of planetary gearboxes. It will allow compensating for the difference in the reduced meshing radii Δr at any of its values, due to the corresponding change in the gear ratios of the modules, and hence in the torques of both engines. In this case, the S-model is supplemented by a functional connection between the modules MMC$_1$ and MMC$_2$, characterized by the rotational speed of the ring gear, n_{rg}. The system of equations (15) must be supplemented by two equations: the first connects the values of n_{gr} (according to the Willis formula), and the second connects the values of n_{rg}.

Uniform load sharing between the two drives for any value of r can also be achieved by introducing an additional module of a different physical nature – the second frequency converter EPC$_2$. This allows equalizing motor rotation frequencies by adjusting the voltage and supply frequency of each motor separately. In this case, the S-model is supplemented with a structural block EPC$_2$, with input function ε_{inp} and output ε_2, characterized by the parameters U_2 and f_2. The system of equations (12) will be solved for two values, U_{set1} *and*

U_{set2}, and is supplemented by an equation that relates them. The system of equations (13) will be solved for four parameters, U and f, for which it will be supplemented with the necessary equations.

The first variant complicates the structure to a lesser extent and therefore should be considered preferable. However, implementing this variant requires significant modifications to the main elements of the combine harvester. In this case, it is appropriate to consider changing the combine harvester's layout scheme to eliminate the conflict in another way.

4. Change the functional and parametric characteristics of other components that do not conflict with each other, i.e., resolve the conflict within components of a different physical nature.

The methods of conflict resolution discussed above are applicable to mechatronic objects of any degree of complexity, ranging from simple mechanisms with a small number of sensors and actuators to complex systems integrating numerous electrical, electronic, and information modules. Each of the proposed methods has its own advantages and disadvantages, which determine its appropriateness for specific operating and design conditions. It is essential to consider not only technical aspects but also economic, time, and organizational constraints, since the choice of a conflict-resolution method directly affects the system's efficiency, reliability, and adaptability to a changing environment.

Although the first method of conflict resolution is the least attractive from a modern technological perspective, it still finds application. Its essence is to design the system or its components in a way that helps avoid conflicts arising from limitations in the device's structure. The technical task is often formulated at the conceptual design stage to anticipate potential conflicts between system components or between the system and the environment. In practice, this method is implemented not by creating a single universal device for all possible operating conditions, but by developing a series of device modifications or standard sizes. This approach promotes the localization of the conflict area, reduces the risk of negative impact on the system's functioning, and even eliminates it for a specific type of machine or equipment. The main disadvantages of this method include reduced system flexibility and the high costs of producing and supporting multiple modifications of a single device.

The second method of resolving conflicts is considered the most productive in terms of design, as it directly eliminates the problem's source at the development stage. Here, the designer seeks to resolve the essence of the conflict by integrating it into the system's structure and altering component interactions at the functional or parametric level. This approach ensures maximum system adaptability and high operational efficiency under changing conditions. However, its practical implementation is not always possible due to the limitations imposed by the system's functional and parametric characteristics. For example, the physical properties of materials, the design features of electric motors, or the capabilities of sensors can limit the range of solutions available to the designer, requiring compromises in choosing the optimal parameters.

The third method is the most common in modern mechatronic design. It combines efficiency and relative simplicity of implementation, but it is a compromise in nature. Its feature lies in the adaptive approach to resolving conflicts: the system independently determines the permissible limits of component interaction and responds to changes in operating conditions. Unlike the first method, which imposes constraints declaratively, the third method provides more flexible control while maintaining sufficient operational quality. The disadvantage of this approach is the possible limitation of the system's interaction with the environment, which can reduce performance in some modes. However, its main advantage lies in the system's ability to adapt to unforeseen situations, making it especially valuable for complex agro-energy or industrial processes, where load and external factor variability is constant.

The fourth method is used when resolving a conflict through components of a single physical nature is less effective or impossible. In such cases, the designer can use elements of a different physical nature, which allows resolving the conflict more effectively from the point of view of functional or economic feasibility. The reasons for using this method can be both objective and subjective. Objective reasons include functional and parametric limitations of the components, such as maximum loads, speeds, or permissible temperature conditions. Subjective reasons can be limitations related to the designer's capabilities, development time, or budget for creating a prototype. Using components of a different physical nature not only effectively resolves the conflict but also increases the system's reliability and stability in real operation. Thus, each of the considered methods has its own specifics and scope, and the choice of a specific process for resolving the conflict depends on the complexity of the mechatronic object, its operating conditions, technical limitations, and resources available for design and implementation. In practice, a combined approach is often used, combining different methods to achieve optimal performance, adaptability, and system reliability. This approach both localizes conflict areas and ensures effective interaction of all system components in dynamic conditions.

The use of these methods in modern mechanical engineering, especially in agro-industrial and bioenergy plants, enables the creation of systems that meet Industry 4.0 standards, providing high levels of automation, adaptability, and component integration into a single mechatronic structure. This is a crucial condition for enhancing the efficiency of production processes, reducing energy consumption, and improving the reliability of equipment operation.

5. Conclusion

Research and design of modern agricultural machinery and bioenergy plants require integrating principles of mechatronics and electrotechnology to ensure the effective operation of electromechanical systems. The study aimed to determine the optimal structure of a frequency-controlled electric drive that can adapt to changing environmental conditions, providing high reliability and energy efficiency.

Analysis of scientific sources indicates that the mechatronic approach enables the integration of mechanical, electrical, electronic, and information components into a single system. This creates a synergistic effect in which disparate elements interact in a coordinated manner, ensuring increased productivity, stability, and adaptability of the system. Within the framework of the project, a detailed analysis of components of the electric drive and their interaction was carried out: electric motors, gearboxes, power and sensor elements, controllers, and software.

The functional goals of the system were determined, including the simultaneous start of two electric drives, coordinated speed control of the working elements, overload compensation in case of the loss of power by one of the drives, and uniform load distribution. To implement these functions, a mathematical model of the system's dynamic characteristics was developed, enabling the optimization of electric motor and gearbox parameters to increase energy efficiency and operational reliability.

The design utilized a frequency-controlled electric drive with vector control. Such a structure enables the smooth adjustment of the working elements' rotation speed over a wide range, reduces starting currents and mechanical shocks, thereby significantly extending the equipment's lifespan. In addition, variable-frequency electric drives are easily integrated into automated machine control systems, ensuring process synchronization and increasing overall system reliability.

A crucial stage of design is to ensure the diagnostics and self-monitoring of components. Each element of the electric drive is equipped with temperature, current, voltage, and vibration sensors, enabling the detection of deviations from regular operation and the prediction of potential failures. Algorithms for processing sensor data allow adaptive responses to changing operating conditions, thereby increasing system safety.

The project also involves integrating electric drives into bioenergy plants, where they control pumps, conveyors, mixers, and other technological units. The use of adaptive control algorithms ensures real-time optimization of energy consumption and stability of technological processes.

The results of research and design demonstrate that applying mechatronics principles in combination with frequency-controlled electric drives enables the creation of systems with high reliability, energy efficiency, and adaptability, which can be scaled and integrated into various types of agricultural machinery and bioenergy plants. This creates the basis for the development of “smart” mechanical engineering and enhances the competitiveness of equipment in the agro-industrial sector.

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МЕХАТРОННІ СИСТЕМИ ТА ЧАСТОТНО-РЕГУЛЬОВАНІ ЕЛЕКТРОПРИВОДИ ЕЛЕКТРИЧНИХ МАШИН У ЕЛЕКТРОТЕХНОЛОГІЯХ БІОЕНЕРГЕТИЧНИХ УСТАНОВОК З ОПТИМІЗАЦІЄЮ ТА ДІАГНОСТИКОЮ НАДІЙНОСТІ

Мехатронні системи та частотно-регульовані електроприводи електричних машин у електротехнологіях біоенергетичних установок із оптимізацією та діагностикою надійності є ключовим напрямом розвитку сучасного агропромислового машинобудування. Використання таких систем забезпечує високий рівень функціональної інтеграції механічних, електротехнічних, електронних та інформаційних *компонентів, що дозволяє створювати обладнання з високою продуктивністю, енергоефективністю та надійністю. Мехатронний підхід сприяє синхронізації роботи електроприводів, сенсорів та контролерів, забезпечуючи адаптивне управління в умовах змінних навантажень і непередбачуваного середовища, характерного для сільськогосподарських та біоенергетичних процесів.*

Впровадження частотно-регульованих електроприводів дозволяє реалізувати гнучке управління швидкістю та моментом електродвигунів, оптимізувати споживання електроенергії, підвищити точність виконання технологічних операцій і зменшити знос механічних компонентів. Використання адаптивних алгоритмів керування, а також регенеративних систем сприяє економії енергії та підвищенню ефективності роботи обладнання в різних режимах експлуатації.

Надійність таких систем забезпечується комплексною діагностикою та прогнозуванням відмов, включаючи інтеграцію сенсорних мереж, IoT-технологій, аналіз великих даних і алгоритми прогнозного обслуговування. Це дозволяє знизити ризик аварій, підвищити довговічність машин і оптимізувати планування ремонтних робіт.

Особливу увагу в роботі приділено систематизації сільськогосподарських машин як мехатронних об'єктів, визначенню рівнів інтеграції модулів, вузлів та агрегатів, а також опису взаємодії компонентів із навколишнім середовищем. Розглянуто поняття мехатронного модуля, вузла, агрегату та системи, а також принципи синергетичної інтеграції, що дозволяють об'єднувати механічні, електротехнічні, електронні та інформаційні компоненти у єдину адаптивну систему.

Результати дослідження демонструють ефективність застосування мехатронних систем із частотно-регульованими електроприводами у біоенергетичних установках АПК, забезпечуючи підвищення продуктивності, енергоефективності, надійності та безпеки технологічних процесів. Запропоновані підходи відповідають сучасним стандартам Industry 4.0 і відкривають нові можливості для створення модульних, масштабованих та висофункціональних рішень у сучасному агропромисловому виробництві.

Ключові слова: *мехатронні системи, частотно-регульовані електроприводи, електричні машини, електротехнології, біоенергетичні установки, оптимізація, надійність, діагностика, енергетична ефективність, інтеграція систем.*

Ф. 15. Рис. 1. Табл. 1. Літ. 17.

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