№ 1 (132) / 2026
ISSN: 2520-6168
Vol. 132, № 1 / 2026

Техніка, енергетика, транспорт АПК

Technology, energy, agriculture transport AIC

UDC681.5:621.31:631.3.
DOI: 10.37128/2520-6168-2026-1-10

INFORMATION-CONTROLLED MECHATRONIC SYSTEMS OF POWER SUPPLY AND AUTOMATION OF TECHNOLOGICAL PROCESSES IN THE AGRO-INDUSTRIAL COMPLEX

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The paper examines modern approaches to the development, research, and implementation of mechatronic systems for adaptive control of technological processes in the agro-industrial complex. Particular attention is paid to the integration of electrical, information, sensor, and control subsystems into a unified intelligent structure capable of self-adjustment, environmental analysis, and energy optimization. It is shown that under conditions of rapid digitalization, climate change, and the need for rational use of resources, such systems ensure flexibility, stability, and efficiency of production processes.

The study determines that effective mechatronic systems should be based on a modular structure including sensor, executive, analytical, and communication levels. The sensor level collects process data, the executive level performs control actions, the analytical level applies adaptive and optimization algorithms, and the communication level ensures integration through industrial digital networks.

It is established that adaptive mechatronic systems increase energy efficiency, reduce raw material losses, improve product quality, and maintain stable operating parameters under unstable external conditions. Special attention is given to mathematical modeling, simulation, and the use of frequency-controlled electric drives with digital control systems, which improve positioning accuracy, speed regulation, and overall energy performance.

The paper identifies key directions for further development, including autonomous robotic systems, wireless sensor networks, digital twins, intelligent energy management, and adaptive control under changing climatic conditions. The obtained results are of scientific and practical significance for precision agriculture, livestock production, smart greenhouses, and automated processing systems.

Keywords*: mechatronic systems, adaptive control, technological processes, agro-industrial complex, automation, electrical systems, intelligent control systems, energy efficiency, robotics.*

Eq. 6. Fig. 2. Table. 2. Ref. 14.

1. Problem formulation

Meeting the ever-increasing requirements for the parameters of machines in the agro-industrial complex (AIC), both mobile technological objects (MTO) and stationary technological objects (STO), cannot be ensured without significantly increasing their complexity compared to previous generations of machines. This primarily concerns the use of new types of electric drives, systems for optimizing operating modes, automatic control and technical diagnostics, as well as adaptation to environmental conditions. The implementation of intensive technological processes and the pursuit of higher product quality are already limited by the physiological capabilities of the human operator.

Machines of a new technical level are characterized by a high degree of “intelligence.” They are no longer simply “gear–motor” systems but consist, in almost equal proportions, of closely interconnected mechanical, hydraulic, electronic, electrical, and informational components. The design, manufacturing, and operation of such machines can no longer be carried out according to traditional principles.

Article received 12.01.2026. Article accepted 12.02.2026. Article published 17.04.2026.

Today, in many fields of science and technology, the mechatronic approach is being applied to ensure all stages of the life cycle of various machines. In [1], mechatronics is defined as a field of science and technology based on the synergistic integration of precision mechanical components with electronic, electrical, and computer elements, enabling the design and production of fundamentally new modules, systems, and machines with intelligent control of their functional movements.

However, the presence – and even the integration – of mechanical, electronic, and informational components within a single device can only be a necessary but not sufficient condition for the mechatronic nature of an object. In [2], the authors provide the following definitions:

- Synergistic integration – the integration of mechanical (M-components), electrical and hydraulic (collectively – power or S-components), electronic (E-components), and informational (I-components) elements to achieve a common goal, whereby the resulting system acquires qualitatively new properties unattainable by individual components and interacts adaptively with its environment.
- Necessary condition for mechatronicity –the combination of M-, S-, E-, and I-components into a system that interacts unambiguously with the environment (mechatronized objects).
- Sufficient condition for mechatronicity – the integration of M-, S-, E-, and I-components into a system that interacts adaptively with the environment, that is, synergistic integration.

As seen from the above, the key concept in defining both mechatronics itself and the necessary and sufficient conditions for the mechatronic nature of an object is synergistic integration.

2. Analysis of recent research and publications

Recent studies show that the development of mechatronic systems in the agro-industrial complex is closely connected with the integration of mechanics, electronics, electrical engineering, automation, and intelligent control methods [8–10]. A number of publications emphasize the importance of adaptive control, modular architecture, frequency-controlled electric drives, and digital monitoring systems for improving the efficiency and reliability of technological processes [1, 2, 8, 10–12]. Modern research also confirms the growing role of information technologies and intelligent systems in the automation of agricultural production, particularly in increasing reliability, improving energy efficiency, and expanding the functional capabilities of electromechanical systems [1, 2, 11, 12]. At the same time, the analysis of scientific sources indicates that further development of mechatronic systems requires an interdisciplinary approach, improved mathematical models, and the design of adaptive control systems capable of self-adjustment under variable environmental conditions [8–10, 12].

3. The purpose of the article

The purpose of the article is to analyze modern approaches to the creation and implementation of information-controlled mechatronic systems for power supply and automation of technological processes in the agro-industrial complex, as well as to substantiate the principles of building adaptive control systems capable of self-adjustment, forecasting, and energy optimization under changing operating conditions [1, 2, 8–12].

4. Results and discussion

The emergence of mechatronics within the framework of classical mechanics, as well as synergetics in general, is due to the appearance of a new class of systems – mechatronic objects – whose description and design are impossible using traditional approaches. This is primarily related to the growing requirements for the performance quality of technical systems (devices), which implies their increasingly deep interaction with the external environment and the human operator. In addition, modern technical systems are multicomponent; they contain subsystems (components) of different physical nature, including informational components that provide the capability for autonomous information processing and self-regulation, i.e., self-organization [3].

After reaching a certain level of functional and parametric characteristics, further improvement of performance becomes possible only through changes in the design of the device, which is usually accompanied by its complication and an increase in the number of functions, since improving operation requires accounting for a greater number of environmental factors.

To implement new functions, additional modules or units must be used – the device becomes more complex quantitatively [4].

After reaching a certain threshold of functional complexity, it becomes impossible to consider all possible states of the device in interaction with the environment, which creates the need to introduce various self-regulators capable of fully or partially ensuring system operation. That is, part or all of the information about the state of the environment and the device, which was previously processed by a human operator, must now be processed by the device itself. In the case of simple self-regulators with a small number of feedback loops and a relatively long response time, the functions of regulation and control can still be performed by the operator. In this case, the device's reaction can be predicted, and its operation is clear to the designer – the behavior of such a system is deterministic.

Further improvement in performance quality leads to the complication of regulators, an increase in the number of feedback connections, and a reduction in the device's response time to changes in the external environment. At a certain stage, the operator loses the ability to control the system in real time.

It is important to note that part or all of the information about the state of the environment and the system, which was previously processed by a human, must now be processed by the system itself, as a result of which it acquires features of adaptive behavior – that is, a certain level of self-organization.

Let us assume that each *i-th* component corresponds to a set of functional and parametric characteristics Φ. A system consisting of n components operates in an environment that has a set of characteristics Φ_C. Then, the condition for the operability of the system in this environment can be written as:

$$\sum_{i}^{n} \Phi \geq \Phi_C \tag{1}$$

If, at the design stage, a certain required set of characteristic values Φ_t is known, then, when everything about the environment is known:

$$\Phi_C = \Phi_t \tag{2}$$

For each component of a complex technical system, it is possible to specify the corresponding parameters, functional characteristics, and interaction conditions that ensure its full operability within a given range of operating modes. In this case, the system behaves as a structurally and functionally coordinated set of elements operating according to defined regularities. Such an approach assumes that the interaction of the system with the environment is unambiguous: any changes in external influences cause proportional changes in the characteristics of internal components, whose parameters are described by a known set of functional dependencies Φ_t.

Thus, each manifestation of the external environment (an event, disturbance, or signal) causes a clearly defined system response, meaning its behavior is linear and predictable. The system's response is neither stochastic nor random but depends solely on the current state of the environment and the internal parameters of its elements. This implies that the system dynamics can be described by deterministic equations, and its behavior can be predicted for any period of time, provided there are no significant changes in external conditions [5].

Such a system is characterized by determinism, meaning its properties, functional dependencies, and parameters are known at all stages of the life cycle – from the development of the technical specification and design stages to installation, commissioning, operation, and disposal.

The application of this approach to technical systems corresponds to the principles of traditional or classical design. This design method is codified in numerous regulatory documents, standards, and methodologies in mechanical engineering, energy, electromechanics, and automation. It underlies modern engineering practice, covering not only the process of creating machines and mechanisms but also aspects of production organization, implementation of preventive maintenance systems, technical service formation, and training of engineering personnel – designers, electromechanics, automation engineers, and information control systems specialists.

This concept is based on the assumption that any technical system (in particular, a machine, unit, or technological installation) can be completely described in terms of a deterministic model. In other words, at any stage of the life cycle – from problem definition to decommissioning – complete information about the system's state can and must be available. This ensures the possibility of accurate analysis, behavior prediction, and parameter optimization during operation [6].

At the same time, system functioning is considered the result of the combined action of its subsystems; that is, system functions are determined as the sum of the functions of all its constituent elements. Such decomposition allows the use of a hierarchical control principle, where each level performs its own tasks, ensuring the coherence of the entire structure.

Specialized literature [4] notes that during the design of a complex system, a set of conceptual representations is formed that reflects its essential properties with varying degrees of detail. These representations are not only descriptions of the object but also the foundation for its formalization, mathematical modeling, and optimization. Within these representations, structural levels – or design levels – can be distinguished, corresponding to specific stages of system development, from conceptual modeling to physical implementation.

Thus, the traditional paradigm of technical system design is based on the principle of determinism, which assumes the possibility of complete description, predictability, and controllability of system behavior. However, with the increasing complexity of modern technological processes and the emergence of nonlinear interrelations between components, such a model increasingly requires adaptation to stochastic conditions and environmental uncertainty. This necessitates a transition to a new generation of intelligent and adaptive control systems [7].

Design in this case (based on practical experience in machine-building production setup) can be carried out according to the traditional top-down hierarchical scheme, which includes the following stages:

1. Definition of system goals;
2. Definition of system functions and development of the technical specification (TS);
3. Identification of system levels (components), distribution of goals and functions among components, and preparation of component-level TS;
4. Component design;
5. Physical modeling of components and preliminary testing;
6. Coordination of components within the system, identification of conflicting elements;
7. Physical modeling of the system and acceptance testing;
8. Fixation of implemented functions, identification of necessary refinements, and development of technical conditions (TC);
9. Adjustment of design documentation for components;
10. Physical modeling of the refined system and testing of the initial production batch.

System-level decomposition implies structural analysis, but this stage is usually not formalized: during function distribution, heuristic rules based on expert experience are applied – often following the principle of “not what needs to be done, but what can be done.” This inevitably leads to functional redundancy of some components, their dominance, and residual design of others [8].

When components with rigidly defined functions are designed separately, simulation (including mathematical) modeling is generally not performed, since function distribution by the “what can I do” principle creates an illusion of clarity regarding component goals and tasks, reducing their design to conventional “well-developed” schemes [9].

Such separate design necessitates a stage of component coordination within the system. At this stage, conflicts between components are revealed, and constraints on their joint operation are introduced to achieve system goals – in the form of additional devices (couplings, adapters, matching elements, signal converters, etc.) or additional functions (protection against certain operating modes).

Moreover, our knowledge about the environment is often insufficient even for designing relatively simple technical systems, not to mention, for example, a grain harvester.

If not everything about the environment is known, then:

$$\Phi_t < \Phi_c = \Delta\Phi + \Phi_t \tag{3}$$

As can be seen, to ensure system operability, its characteristics must vary by the value of $\Delta\Phi$. In this case, the system must interact with the environment adaptively, include self-regulators, and its characteristics must exceed the set Φ_t; thus, the system must exhibit new properties not defined by the characteristics of individual components. It is impossible to determine the functional and parametric characteristics of the system components separately – only for the system as a whole. Therefore, component design can only be carried out jointly, as a single device in which function distribution is not always obvious, and the overall system functions are not a simple sum of component functions. It is in this case that synergistic integration of components occurs, fulfilling the sufficient condition for mechatronicity [10].

During the development of mechatronic objects, it is advisable to use concurrent design of components. This term is established in , but it is useful to refer to its original English form – *concurrent engineering methods*. The word *concurrent* means “simultaneous,” “compatible,” “acting in parallel,” or “interconnected.” Thus, the English term more accurately conveys the essence of this design method. However, for convenience, the established term *parallel design* will be used hereafter.

In works [10], [11], it is emphasized that parallel design is one of the key features of mechatronics.

The design sequence in this case is as follows:

1. Definition of system goals;
2. Definition of system functions, development of its functional model (F-model);
3. Analysis of the F-model, functional–structural integration (FS-integration);
4. Definition of system structure, development of structural model (S-model);
5. Analysis of the S-model, structural–constructive integration (SC-integration);
6. Mathematical modeling of the system, identification of conflicting components;
7. Development of the technical specification (TS);
8. System design;
9. Physical modeling of components, verification of mathematical model adequacy, preliminary testing;
10. Physical modeling of the system, acceptance testing;
11. Determination of necessary improvements, development of technical conditions (TC);
12. Documentation correction.

As can be seen, before the development of the technical specification, functional and structural analysis of the system is carried out. It is worth noting the possibility of using decentralized control systems instead of centralized ones, as well as intelligent sensors, which significantly increase system adaptability.

The goal of FS-integration is to reduce the number of structural elements by eliminating redundant transformations, matching devices, and similar components. The purpose of SC-integration is constructive unification – i.e., minimizing the design that implements the given structure. For example, combining an electric motor and a frequency converter in a single housing rather than placing them separately, as is commonly done. Analysis of the S-model is impossible without mathematical modeling.

The methods for resolving detected conflicts proposed in [12] arise from the analysis of a specific S-model but can be recommended for all mechatronic objects:

1. Change the functional and parametric characteristics of the entire system, limiting its interaction range with the environment.
2. Change the functional and parametric characteristics of conflicting components.
3. Modify the S-model by introducing additional modules or functional links to limit or eliminate the conflict – adding self-regulators, protections, matching devices; these additional modules may be of the same or different physical nature as the conflicting components.
4. Change the functional and parametric characteristics of other, non-conflicting components – resolving the conflict within components of a different physical nature.

The first method, although less attractive, can have wide practical application. In practice, it is often implemented not by designing a single universal device suitable for all environmental conditions, but by developing different variants of the device, allowing the conflict zone to be narrowed or completely eliminated for each size type.

The second method is the most productive, as it addresses the core of the problem, but it cannot always be applied due to constraints imposed by functional and parametric characteristics.

The third method is the most common and quite effective, though it is a compromise, as it introduces certain restrictions on interaction with the environment. It reduces operational quality, but not declaratively (by prohibiting operation under certain conditions) – rather, adaptively, since the system independently determines the permissible range of its operation.

The fourth method applies when resolving the conflict through components of another physical nature is more effective. This may be due to objective constraints determined by functional and parametric characteristics, or subjective reasons – such as designer capability, time, or development cost.

According to [13], over the last 30 years, the share of production machine functions performed by mechanical components has decreased from 90% to 40%, while those performed by electronic components have increased from 10% to 30%, and by informational components – from 0% to 30%.

The design of a complex mechatronic system consisting of numerous mechatronic units with intricate structures of nodes and modules. Resolving such contradictions is achieved precisely through parallel design, which is not merely about allocating physical space within a unit's structure but about forming the functional and parametric characteristics of individual components using various modeling techniques – based on F- and S-model analysis [14].

Identifying "conflict" parameters at the interfaces between components and developing solutions for resolving them allows harmonizing, aligning, and subordinating all parameters to a single goal – to achieve synergistic integration of components at the earliest design stages, thereby addressing the main task of mechatronic system development.

The design of modern machines – which are mechatronic objects – requires specialized professional training. The construction and analysis of F- and S-models are impossible without knowledge of system structure synthesis and control theory.

Further development of technical system design approaches, including mechatronic and electromechanical complexes, requires an expansion of the deterministic model. Under real agro-industrial production conditions, external factors such as temperature, humidity, mechanical loads, power supply fluctuations, and soil conditions cannot be described unambiguously.

For this purpose, in the design of mechatronic adaptive control systems, it is proposed to use a generalized environmental influence function.

$$F_C = f(x_{1,} x_{2,.........} x_{n,} t) \qquad (4)$$

where $x_{1,} x_{2,.........} x_n$ are the environmental parameters (temperature, humidity, voltage level, load, etc.); t – time; F_C – the integral influence function, which characterizes the combined effect of all external factors on the system.

$$K_a = \frac{P_{z\min}}{P_{nom}} \qquad (5)$$

where $P_{z\min}$ is the system performance under changing environmental conditions; P_{nom} – the nominal performance under stable conditions.

If $K_a \geq 1$, the system is considered adaptive; if $K_a < 1$, adjustment of control algorithms or modernization of the sensor module is required.

Table 1

Comparison of characteristics of traditional and adaptive control systems

Indicator	Traditional system	Adaptive mechatronic system
Nature of response	Linear, deterministic	Nonlinear, stochastically adaptive
Predictability	Complete under stable conditions	Partial, using predictive algorithms
Energy consumption	Constant	Optimized depending on load
Feedback	Single-channel	Multichannel, sensor-based
Flexibility	Limited	High

From the analysis of Table 1, it can be seen that the implementation of adaptive mechatronic systems significantly increases control flexibility and process energy efficiency. However, this requires the implementation of complex algorithms for state identification and adaptation to disturbances.

Based on the results of preliminary modeling, the dependence of the adaptability coefficient on the dynamics of external influences was obtained, as shown in Graph 1 (Figure 1).

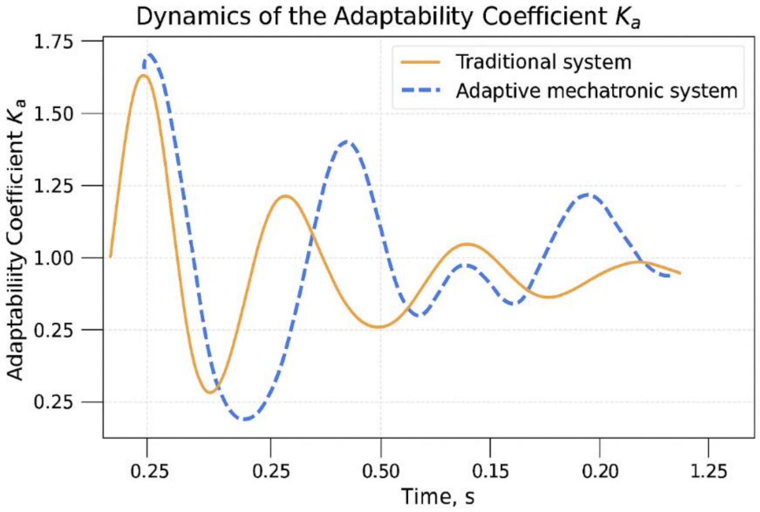

Fig. 1. Dynamics of the adaptability coefficient (Ka) under changing external conditions, showing the stability of the adaptive mechatronic system compared to the traditional one

The graph demonstrates that, under abrupt changes in external parameters, a system with a classical PID controller loses stability faster than a system equipped with an adaptive fuzzy logic controller (Fuzzy Logic Controller).

Table 2

Influence of environmental parameters on system operating stability

№	External factor	Range of variation	Impact on stability	Type of adaptation
1	Temperature	15–45 °C	Medium	Temperature compensation
2	Humidity	30–80 %	High	Coefficient correctio
3	Supply voltage	±10 %	Medium	Signal filtering
4	Mechanical load	0–100 %	High	Adaptive torque control
5	Illumination	0–12000 lm	Low	Brightness regulation

Based on experimental data, Graph 2 (Figure 2) was constructed to illustrate the dynamics of energy consumption in the adaptive system compared to the traditional one.

The graph shows that, when applying the mechatronic approach, energy consumption decreases by 12–18% due to dynamic optimization of motor operation modes and lighting systems.

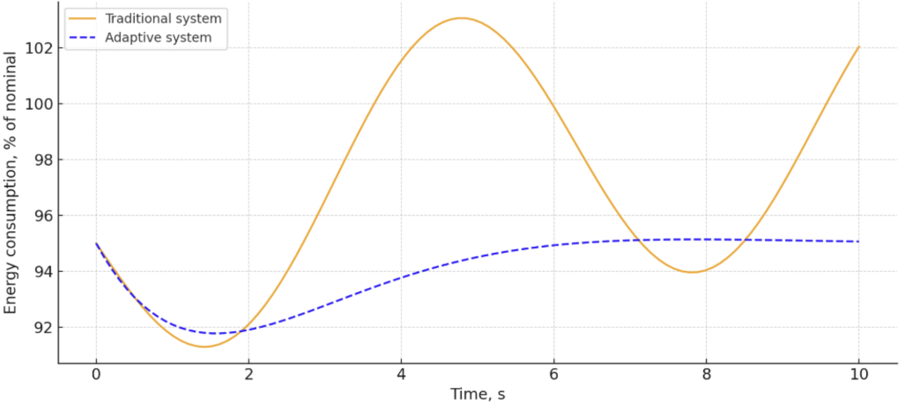

Fig. 2. Comparison of energy consumption of adaptive and traditional systems over time, demonstrating a reduction in energy costs by 10–15%

The generalized model of the system’s energy balance is described by the expression:

$$E_{total} = \sum_{i=1}^{n} (E_{i,nom} - \Delta E_{i,adapt}) \tag{6}$$

where E_{total} is the total energy consumption of the system; $E_{i,nom}$ – the nominal energy consumption of the i-th module; $\Delta E_{i,adapt}$ – the energy effect resulting from the implementation of adaptive control.

The developed methodology makes it possible not only to predict the system’s response to changes in external conditions but also to optimize its operation in real time.

The implementation of the proposed approaches in adaptive mechatronic control systems for technological processes in the agro-industrial complex ensures increased productivity, reduced energy consumption, and improved reliability indicators.

5. Conclusion

As a result of the conducted study *“Mechatronic Systems of Adaptive Control of Technological Processes in the Agro-Industrial Complex,”* it has been established that the introduction of the mechatronic approach into the automation of production processes is one of the most promising directions for the development of the modern agro-industrial complex (AIC). Mechatronics ensures comprehensive integration of mechanical, electrical, sensory, informational, and control components into a unified intelligent system capable of self-adjustment, environmental analysis, forecasting, and energy optimization.

It has been shown that adaptive control is a key component of modern mechatronic systems, as it enables rapid response to changes in both external and internal parameters of technological processes. The use of intelligent controllers, fuzzy logic algorithms, neural networks, and predictive control methods ensures the stability of technological regimes, reduces energy consumption, and improves product quality.

It has been determined that the use of frequency-controlled electric drives with digital control systems significantly improves the accuracy, dynamics, and energy efficiency of technological installations. The use of intelligent diagnostic algorithms based on the analysis of vibration and electromagnetic signals allows the prediction of failures, reducing the number of accidents and downtime.

Particular attention is paid to the role of information technologies, especially the implementation of IoT, SCADA, MES systems, cloud platforms, and digital twins, which provide remote monitoring, big data processing, and optimization of equipment operating modes. This creates prerequisites for the implementation of *Industry 4.0* in the agro-industrial sector.

The analysis shows that energy efficiency and sustainable development are key criteria for evaluating modern mechatronic systems. Optimization of energy consumption by drives, pumps, lighting, and ventilation systems allows electricity savings of 15–30%, which is especially important for agricultural enterprises with seasonal workloads.

The main directions for further development of mechatronic systems in the AIC have been identified:

- creation of mobile robotic complexes for automated harvesting and field monitoring;
- implementation of adaptive microclimate control systems in greenhouses and livestock complexes;
- application of wireless sensor networks for monitoring soil, water, and biological objects;
- development of digital twins of technological processes for predicting and optimizing equipment operating modes.

Summarizing the results, it can be concluded that adaptive mechatronic control systems form the foundation for creating the *intelligent agrotechnological complexes of the future*, combining automation, robotics, energy, and information technologies. Their implementation will increase the efficiency, reliability, and environmental sustainability of agricultural production, as well as form a new paradigm of integrated management of energy-technological processes.

The obtained results have not only scientific but also practical significance for the design, modernization, and operation of modern automated systems in agriculture, energy, mechanical engineering, and the processing industry. They can be applied in the development of smart greenhouses, energy-efficient lighting systems, irrigation installations, and robotic production lines.

Thus, the mechatronic approach forms the scientific and technical basis for the implementation of the *Smart Farming* and *Digital Agro-Industrial Complex* concepts, ensuring increased competitiveness of the sector, reduced energy losses, and the creation of sustainable, self-organizing control systems of the future.

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ІНФОРМАЦІЙНО-КЕРОВАНІ МЕХАТРОННІ СИСТЕМИ ЕНЕРГОПОСТАЧАННЯ І АВТОМАТИЗАЦІЇ ТЕХНОЛОГІЧНИХ ПРОЦЕСІВ В АПК

У роботі розглянуто сучасні підходи до створення та впровадження мехатронних систем адаптивного управління технологічними процесами агропромислового комплексу (АПК). Показано, що інтеграція електротехнічних, сенсорних, інформаційних і керуючих підсистем у єдину інтелектуальну структуру забезпечує самоналаштування, аналіз середовища й оптимізацію енергоспоживання.

Мехатронний підхід поєднує механіку, електроніку, комп'ютерні технології, автоматичне регулювання та штучний інтелект, створюючи основу для гнучких і стабільних виробничих процесів. Адаптивне управління дає змогу оперативно реагувати на зміни зовнішніх параметрів і навантажень, що особливо важливо для енергоємних та сезонних процесів у сільському господарстві.

Побудова мехатронної системи за модульним принципом включає чотири рівні: сенсорний (збір даних), виконавчий (реалізація дій), аналітичний (обчислення й оптимізація) та комунікаційний (обмін інформацією). Така структура дозволяє інтегрувати системи в цифрову інфраструктуру підприємств через промислові мережі (Ethernet/IP, Modbus, ProfiNet).

Застосування частотно-регульованих електроприводів і інтелектуальної діагностики забезпечує точність позиціонування, економію енергії до 30 % та підвищення надійності обладнання.

Використання технологій IoT, SCADA, MES та хмарних сервісів створює можливості для віддаленого моніторингу, аналізу великих даних і реалізації концепції «розумного виробництва». Це підвищує рівень автономності, скорочує людське втручання та формує основу для впровадження індустрії 4.0 в агропромисловому секторі.

Результати дослідження мають практичне значення для розроблення «розумних» теплиць, енергоефективних систем освітлення, іригаційних установок і роботизованих ліній.

Ключові слова: *мехатронні системи, адаптивне управління, технологічні процеси, агропромисловий комплекс, автоматизація, електротехнічні системи, інтелектуальні системи керування, енергоефективність, інформаційні технології, цифрова схемотехніка, сенсорні мережі, електропривод, оптимізація процесів, системи моніторингу, прогнозування, системи підтримки прийняття рішень, роботизація, інтегровані енерготехнології.*

Ф. 6. Рис. 2. Табл. 2. Літ. 14.

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