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Cognitive Electric Drive Regulation Systems for Heavy Metal Fabrication Machinery

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ABSTRACT

The research sought to empirically evaluate the functionality of an advanced electric drive control system in high-capacity metalworking machinery. The approach involved substituting the relay control circuit of a vertical milling machine with a multi-tiered digital system featuring a frequency converter and a programmable logic controller. Ongoing surveillance of parameters and dynamic regulation were executed utilising encoders, strain gauge sensors, and an artificial neural network that adjusted the coefficients of the proportional-integral-derivative controller. The findings demonstrated a notable superiority of the intelligent system compared to conventional and static digital controllers across all operational modes. Specifically, the variation in rotation speed remained within 0.43-0.52 radians per second under fluctuating load, whereas the fixed controller exhibited values of 1.29-1.77 radians per second, and the relay system surpassed 2.8 radians per second. The duration of transition was minimised to 0.41-0.79 seconds, which is superior to the 1.01-1.39 seconds for a fixed regulator and 2.30-2.48 seconds for relay control. The mean current ranged from 7.44 to 8.42 amperes, with peak values not surpassing 10.94 amperes, signifying a 35-40% decrease in load relative to relay control. The Pearson correlation coefficient of 0.995 between current variability and response time shows a strong association between energy stability and the system's dynamic sensitivity. The system's predictive and adaptive characteristics facilitated accurate control without requiring manual recalibration. The acquired data substantiates that intelligent control frameworks offer enhanced speed stability, energy efficiency, and responsiveness to variations, establishing a foundation for their application in a high-performance industrial setting. The findings can assist design engineers, automation system creators, and technical supervisors in updating metal-cutting machinery and minimising energy usage while maintaining precision.

Keywords: Intelligent electric drive control system, frequency converter, artificial neural network, PID controller, metal-cutting equipment

Mathematics Subject Classification: 93C40, 93C83

Journal of Economic Literature (JEL) Classification : O33, L64

1. INTRODUCTION

In modern industrial production, improving the efficiency, reliability and accuracy of heavy metalworking equipment is critical to the competitiveness of enterprises. Improvement of electric drive control systems is relevant, as they directly affect the quality of processing, energy consumption and resource conservation. In this context, there is growing interest in the use of intelligent control systems capable of self-organisation and adaptation to changes in load and external conditions, which reduces operating costs and increases productivity. The use of artificial neural networks, strain gauges, encoders and digital programmable logic controllers makes it possible to achieve a qualitatively new level of automation of heavy metalworking equipment, focused on the needs of Industry 4.0.

The instability of heavy equipment operating modes under variable technological loads remains a problem for manufacturing enterprises. Such conditions cause uneven loads on electric drives, which leads to excess electricity consumption and reduced machining accuracy. The study by Krol and Sokolov (2023) examined the issue of stabilising the spindle speed of a milling machine using adaptive control. A proportional-integral-derivative (PID) controller with dynamic coefficient adjustment was proposed, but the system proved to be insufficiently sensitive to rapid load changes. This limits its effectiveness in intensive cutting modes, where a quick response from control algorithms is required.

When operating equipment with high inertia, the problem of control system response delay to input signal changes is critical. As noted by Trushkina and Dzwigol (2024), this problem is particularly relevant for lathes with hydraulic feed systems. The study proposed the use of high-speed electronic control modules, but these solutions required complex technical adaptation and did not incorporate the variable characteristics of the material being processed. As a result, the achieved control accuracy did not meet the specified technological parameters in real production conditions.

A significant challenge for engineers is the problem of electric drive overload during peak operation. This causes increased thermal load, which reduces the service life of the equipment. According to the results of a study by Yakovenko et al. (2023), the load dynamics during the processing of superhard materials require accurate prediction of current characteristics. As a result, a model for predicting current loads was created, but the lack of feedback from force sensors led to the accumulation of errors and insufficient adaptability of the algorithm in conditions of sudden fluctuations in resistance torque. Energy consumption control as a key factor in the energy efficiency of heavy equipment also remains an understudied aspect in the context of real production. According to Anh-My (2021), energy losses in frequency-controlled systems are highly dependent on load dynamics. The proposed model envisaged the limited application of static optimisation strategies, which proved ineffective when working with variable workpieces of large mass and complex geometry.

Insufficient sensitivity to changes in the mass of the workpiece and its position relative to the tool creates risks of deviations in the machining process. In a study by Hua et al. (2020), the use of visual position sensors and computer vision systems to monitor the condition of the workpiece was proposed, although noting that the processing algorithms were too slow to be integrated into real-time mode. This limited the scope of such solutions to preliminary control only, rather than direct control of the electric drive during processing. The instability of the drive's temperature regime under prolonged load causes deviations in the dynamics of the tool's movement, which makes it difficult to ensure consistent processing quality (Korzhyk et al., 2020). As shown by the results of Chai et al. (2023), the motor temperature has a significant impact on machining accuracy. The study proposed a liquid-cooled thermostabilisation system that reduced temperature fluctuations but did not solve the problem of integrating thermal parameters into the overall control model, which limited its impact on the dynamic characteristics of the process.

Another significant problem is the complexity of tuning PID controllers in multi-mode systems, where parameters often need to be changed depending on the type of operation (Voloshina et al., 2021). The publication by Hoai et al. (2020) considered the automated optimisation of PID coefficients using genetic algorithms. Despite improving accuracy in stable conditions, the algorithm proved ineffective in dynamically changing modes, where adaptability and rapid real-time control system reconfiguration are relevant. The difficulty of integrating multiple sensor types into a single control system also hinders the implementation of high-precision automation systems. As demonstrated by Wang (2024), the use of encoders, strain gauges, and gyroscopes requires an effective data fusion algorithm. Since such a solution was not implemented in the study, it led to signal conflicts and loss of accuracy in complex equipment operating modes.

In view of the above, there is a need to create a comprehensive intelligent control system that not only responds to load changes in real time but also provides parameter prediction, adaptation to complex processing conditions, and integration of multiple sensor channels into a single control structure. The study aimed to verify an innovative drive control system in heavy metalworking equipment, capable of adaptive parameter adjustment in real time, incorporating external and internal factors. The research tasks included the implementation of a digital multi-level control architecture, the introduction of neural network correction of PID controllers, the integration of encoders and strain gauges, as well as experimental verification of the effectiveness of the proposed system in production conditions.

2. MATERIALS AND METHODS

The scientific research was conducted during January-May 2025 at the Department of Electromechanical Systems of the National Technical University “Kharkiv Polytechnic Institute” (Ukraine) (n.d.). The aim was to develop and experimentally test an intelligent electric drive control system designed to modernise heavy metalworking equipment in industrial production. A 6P13 vertical milling machine with a 7.5 kW asynchronous AC motor was used as the research object. The basic relay-contact type system was replaced with a digital control system using an Altivar 71 frequency converter (Schneider Electric, n.d.) and an S7-1200 programmable logic controller (Siemens, Germany), which interacted via an Ethernet/IP network interface.

The intelligent control system was implemented as a three-layer hierarchy. Continuous monitoring of technological parameters was conducted at the lower level. For this purpose, E50S8-1000-3-T-24 incremental encoders (Autonics, South Korea), Kistler 9341B strain gauge sensors (Switzerland), and IFM Efector IG5904 inductive position sensors (Germany) were used. The signals obtained were processed by NI 9215 and NI 9401 modules connected to the CompactDAQ 9178 platform (National Instruments, n.d.). Initial filtering and pre-processing were performed in the LabVIEW 2023 Q1 environment (National Instruments, n.d.) where the input data for the adaptive controller was generated.

The middle level performed the functions of adapting control parameters in real time. The main element of the adaptive block was a PID-controller with dynamically changing coefficients, which were adjusted by an artificial neural network. The neural network was implemented as a multilayer perceptron with a ReLU activation function and a backpropagation algorithm. Training was performed offline using accumulated experimental data on changes in load, current, temperature, and vibrations. The model was trained in the MATLAB/Simulink R2022b environment (MathWorks, n.d.) and, after verification, was implemented in the controller via an OPC server. The upper level of the system provided predictive planning of equipment operating modes based on the analysis of operational load trends and the detection of deviations that could indicate a decrease in drive efficiency or mechanical wear.

The experimental tests included three types of operating modes: no load, steady load (70% of nominal) and variable load within 30-100% with a cycle frequency of 0.2 Hz. For each mode, three system options were compared: a traditional relay system, a PID-system with fixed coefficients, and an intelligent system. Data was collected at a sampling rate of 1 kHz for 60 seconds per run, with 10 repetitions per mode. The root mean square deviation of speed, transition time, load dynamics, current consumption level and the presence of overloads were recorded.

Statistical data processing to identify dependencies between indicators was performed in IBM SPSS Statistics v29 (IBM, n.d.). Correlation analysis was performed using Pearson's coefficient. In particular, a significant relationship between the system response speed and current stability under variable load was verified. The results were visualised as histograms, scatter plots, and response surfaces in OriginPro 2023b (OriginLab, n.d.).

3. RESULTS

Analysis of the root mean square deviations in the rotational speed of the electric drive shaft revealed significant differences between the three types of control systems considered. The relay system demonstrated the highest speed instability in all operating modes studied: no load, steady load, and variable load. The system with fixed PID controller coefficients showed a noticeable improvement, ensuring more uniform operation of the electric drive. The highest level of stability was achieved in the intelligent control system, which maintained speed stability even under variable load conditions. This demonstrates the effectiveness of adaptive neural network correction of controller parameters, capable of responding in a timely manner to changes in system dynamics. The generalised comparison results are presented in Table 1.

Table 1: Root mean square deviation of the electric drive shaft rotation speed in different modes.

Mode	System type	RMSC velocity deviation (rad/s)
No load	Relay system	2.87
	Fixed PID	1.77
	Intelligent system	0.52
Stable load	Relay system	3.10
	Fixed PID	1.29
	Intelligent system	0.43
Variable load	Relay system	3.38
	Fixed PID	1.66
	Intelligent system	0.45

Source: *compiled by the authors*.

An in-depth quantitative analysis of the root mean square deviations in the speed of the electric drive shaft confirmed a significant difference in control quality between the three types of control systems. At all stages of testing, the relay system consistently demonstrated the worst results. This is due to the lack of real-time control mechanisms, which prevent effective compensation for internal and external disturbances. In all modes, its root mean square values exceeded 2.8 rad/s, and under variable load conditions, they reached 3.38 rad/s. This level of instability is critical for heavy metalworking equipment, where shaft rotation accuracy directly affects the geometric quality of machining and tool life. High-speed fluctuations lead to uneven material removal, mechanical overload and premature wear (Babachenko et al., 2024).

The system with fixed parameters of the PID controller significantly reduced the amplitude of speed fluctuations. Its root mean square deviations were within the range of 1.29–1.77 rad/s. This indicates a basic ability to dampen disturbances and maintain the set speed, but its effectiveness was significantly reduced in dynamic modes. When switching between load states, the system responded with a delay, retaining residual oscillations that were not compensated for by the fixed controller coefficients. Such static settings made it impossible to ensure stable operation of the equipment under unpredictable load conditions typical for industrial environments.

The best results were observed when using an intelligent control system. Its adaptive structure with a multilayer neural network that dynamically changed the PID coefficients achieved the lowest deviation values within 0.43-0.52 rad/s. Under variable load conditions that simulated real production processes, this system ensured rotation speed stability with an accuracy of ±0.01 rad/s, which is a remarkably high indicator for electric drives without direct torque feedback systems. The high level of stability was due not only to the effective response to external influences, but also to the predictive nature of the control, where control was performed based on a pre-trained model of load, temperature, current, and vibrations. The pre-trained neural network was able to generate predictive signals, minimising the delay between the disturbance and the system response.

Thus, the results obtained indicate a significant advantage of an intelligent approach to electric drive control. Rotational speed stability is a crucial parameter for ensuring the quality of metalworking, and intelligent algorithms can achieve high accuracy without the need for constant manual adjustment or system reconfiguration (Merkulov et al., 2024). This creates the basis for the widespread introduction of adaptive control systems in modern high-performance machining complexes.

A comparative analysis of the transition process time made it possible to evaluate the response speed of electric drive systems to load changes. The results showed significant differences between the types of control studied. The relay system was characterised by the greatest inertia, which led to slow stabilisation after disturbances. In turn, the system with fixed PID controller parameters ensured faster achievement of a stable mode, demonstrating a better dynamic response to load changes. The highest efficiency in this aspect was demonstrated by the intelligent control system, which was characterised by a rapid transition to a stable state even under variable load conditions. This demonstrates the advantages of the neural network approach, which is capable of quickly adapting the controller parameters to current conditions. The generalised comparison results are presented in Table 2.

Table 2: Average time of the transition process of the electric drive.

Mode	System type	Transition process time (s)
No load	Relay system	2.30
	Fixed PID	1.01
	Intelligent system	0.79
Stable load	Relay system	2.38
	Fixed PID	1.11
	Intelligent system	0.62
Variable load	Relay system	2.48
	Fixed PID	1.39
	Intelligent system	0.41

Source: compiled by the authors.

The transition process time parameter, which reflects the duration of the electric drive system's transition to the set mode after a change in the input signal or load, is critical for assessing the dynamic performance of technological equipment. In the case of heavy metalworking equipment, this indicator determines not only the efficiency, but also the accuracy of tool positioning, the cyclical nature of processing, and the level of mechanical wear. Analysis of experimental data showed a clear ranking of the studied systems in terms of stabilisation speed.

The worst results were demonstrated by the relay control system, in which the transition process time in all modes exceeded 2.3 seconds. In variable load mode, this figure reached 2.48 seconds. This is a consequence of the limited capabilities of the circuit, the absence of proportional or integral correction, and time delays caused by the physical properties of relays and contactors. In particular, after an increase in load, the system responded with a delay, which led to overshooting of the rotation speed, the appearance of short-term torque reversals, or a decrease in the rotation amplitude. In a rapidly changing technological process, this can cause unstable processing quality, gearbox overload or premature motor failure (Rabinovich et al., 2018).

The system with fixed PID controller parameters provided a noticeable improvement in dynamics. Thanks to the presence of feedback, it reduced the stabilisation time to 1.01-1.39 s depending on the mode. The best performance was observed under stable load conditions, where the load signal was predictable and did not require significant adaptation. However, under variable load conditions, when the applied force changed every 5 seconds (0.2 Hz), the system lost accuracy. Due to the constancy of the PID coefficients, which did not incorporate the amplitude and frequency of disturbances, there was a lag in the formation of the control signal, which increased the stabilisation time to 1.39 seconds. In multi-operation systems, this means not only a decrease in overall productivity, but also an increased risk of fluctuations in the working area, especially during transitions between processing phases.

The intelligent system demonstrated the highest efficiency. Thanks to the implementation of an artificial neural network trained on a set of previous observations, it adapted the controller parameters in real time. As a result, the transition time was reduced to 0.41-0.79 s even in variable load mode. Therefore, the system not only recorded parameter changes but also formed a predictive model for rapid response. In modes where traditional PID systems lagged in compensation, the intelligent structure acted proactively. In practical terms, this means that the system's response speed was sufficient to stabilise within 1-2 load cycles without accumulating errors. In addition, such a system proved to be less sensitive to disturbances from vibrations or local temperature fluctuations, which further increased the stability of the dynamics.

Thus, analytical comparison confirmed that the transition time is one of the main criteria in choosing a control system. Relay systems are inferior even to the simplest digital algorithms(Panchenko et al., 2022). Systems with fixed parameters are only effective under stable conditions. In contrast, intelligent structures demonstrate the highest flexibility, self-tuning capability and ensure minimal delays, which is relevant in modern automated production (Brescia et al., 2023).

A comparison of electrical loads generated by different control systems revealed significant differences in current consumption. In particular, the systems differed in terms of both average and peak current loads in dynamic operating modes. The relay system proved to be the most energy-intensive, which is explained by the absence of mechanisms to compensate for variable loads. The system with fixed PID controller parameters demonstrated moderate performance, keeping consumption within more stable limits. The most efficient in terms of energy consumption was the intelligent approach, which ensured a better match between the output control parameters and the actual load conditions. This indicates the ability of the adaptive algorithm not only to maintain stable operation of the electric drive, but also to reduce the overall energy consumption of the system. The summarised data on current characteristics are presented in Table 3.

Table 3: Average and peak current values in different load modes.

Mode	System type	Average current (A)	Peak current (A)
No load	Relay system	12.15	16.58
No load	Fixed PID	9.92	12.56
No load	Intelligent system	7.44	9.30
Stable load	Relay system	12.18	17.36
Stable load	Fixed PID	9.30	12.31
Stable load	Intelligent system	8.42	10.08
Variable load	Relay system	13.00	18.36
Variable load	Fixed PID	10.12	13.32
Variable load	Intelligent system	8.03	10.94

Source: compiled by the authors.

The assessment of energy consumption by different types of control systems is a key aspect of analysing their efficiency in industrial operation. High-precision drives operating with variable loads typically function in a mode of frequent starts, decelerations and changes in inertia. Under such conditions, the control system must not only ensure stable speed and dynamics, but also minimise power consumption (Brescia et al., 2020; Cupertino et al., 2018b). This task is most difficult to achieve in traditional relay circuits, which do not have active power control mechanisms.

The experimental data obtained demonstrate that the relay system had the highest average current in all three operating modes, especially under variable load conditions, where consumption reached 13.00 A. Peak current values exceeded 18.0 A, indicating a pronounced reactivity of the system to variable dynamic loads. At the moment of load change (0.2 Hz), when the drive changes the torque, the relay circuit does not have time to compensate for the redistribution of energy, which leads to impulse current overloads. This not only reduces energy efficiency but also increases the thermal load on the motor windings, contributing to insulation degradation, accelerated ageing of materials and the risk of power circuit failures.

The fixed PID controller demonstrated more moderate energy consumption. The average current did not exceed 10.12 A, and the peak values remained within 13.32 A. This indicates a basic ability to suppress fluctuations and reduce energy losses, but the efficiency of such a system depended significantly on the stability of the load conditions. In dynamic modes, the system is often “over-regulated”, causing short-term but repetitive current surges (Cupertino et al., 2018a). Although these fluctuations were smaller than those of the relay, they indicated the limited adaptability of the fixed PID, especially when operating with variable inertia mechanisms characteristic of heavy metalworking equipment.

The intelligent system proved to be the most balanced in terms of energy consumption. In all modes, its average current did not exceed 8.42 A, and peak values remained within 10.94 A. The uniqueness of this system resides in the dynamic recalculation of PID coefficients, which is performed using a pre-trained artificial neural network. Thanks to this, the system is capable of generating smoothed control signals that do not cause impulse overloads. Adaptation does not occur post-factum, as in classical algorithms, but proactively through the analysis of load change trends. This not only reduces power losses but also ensures a uniform thermal load on the motor windings, which is critical for long-term operation (Ali et al., 2022; Marignetti et al., 2020).

The quantitative advantage of the intelligent system in energy consumption is estimated at a 35-40% reduction in load compared to the relay circuit. This is a significant argument in favour of its implementation, especially in the context of modern environmental standards, energy efficiency goals and the pursuit of carbon-free production. The rational use of energy without losing dynamic accuracy indicates the achievement of a new level of efficiency that cannot be achieved by traditional automation means (Gritsuk et al., 2017; Uspensky et al., 2019).

To identify the relationship between energy stability and dynamic characteristics of the control system, the correlation between the root mean square deviation of current and the response time of the system under variable load conditions was analysed (Table 4).

Table 4: Correlation between current stability and reaction speed.

System type	RMSC current (A)	System reaction time (s)
Relay system	1.92	2.48
Fixed PID	1.26	1.39
Intelligent system	0.84	0.41

Note: Pearson's correlation coefficient (r)=0.995.
Source: compiled by the authors.

Statistical analysis revealed a close relationship between the stability of the electric drive system's current consumption and its ability to respond quickly to dynamic load changes. In particular, the Pearson correlation coefficient calculated between the root mean square (RMSC) current deviation and the system response time was 0.995. This is almost a perfect linear relationship, indicating that the higher the current fluctuations, the slower the system stabilises the speed after a disturbance. Such a correlation is not only of theoretical but also of practical importance, as it can be used to use current characteristics as indicators of control quality without the need for additional measurement of kinematic parameters.

A relay system without any feedback mechanism became an example of this dependence. The peak current was 1.92 A, and the response time to load changes was 2.48 s. This means that the system generated large fluctuations in power consumption, which were reflected in delays in speed stabilisation. Each pulse load or motor start caused a significant amplitude of the current pulse, which not only overloaded the network but was also accompanied by mechanical stress in the system components (Kiurchev et al., 2021 ; Migal et al., 2021). The lack of a compensation algorithm caused a cascade of errors, which was incompatible with the accuracy requirements for modern heavy equipment.

A system with a fixed PID controller demonstrated improved performance. The level of current fluctuations decreased to 1.26 A, and the stabilisation time to 1.39 s. However, even with feedback, the system remained vulnerable to variable modes, as fixed PID coefficients did not provide flexibility in response to different load scenarios. As a result, the stabilisation delay was localised and remained strongly correlated with current changes. This indicates the limited self-optimisation capability of such a system: it responds only after the fact and does not anticipate disturbance dynamics.

The intelligent system demonstrated fundamentally different behaviour. Thanks to neural network adaptation of PID parameters, it maintained the current at 0.84 A, with a response time of only 0.41 s. Notably, such a system not only recorded the load change but also predicted its nature, forming a compensatory response even before the disturbance manifested itself in the current signal. This proactive control created conditions for an almost instantaneous transition to the set mode without impulse overloads, which significantly improved the reliability of the electric drive.

Thus, the strong positive correlation between the current SKV and the reaction time confirmed the close relationship between energy and dynamic characteristics. Therefore, it is possible to recommend the inclusion of current indicators in control quality algorithms. In the future, this could serve as a basis for the development of self-diagnostic systems that do not require the installation of additional speed or torque sensors. In modern production, which is focused on automation and minimisation of maintenance, this creates new approaches to digital control of technological equipment.

4. DISCUSSION AND CONCLUSION

In the presented study, the analysis of root mean square deviations (RMSC) of the electric drive shaft speed revealed a clear hierarchy of stability in the three control systems. The study found that the intelligent system is significantly more effective than traditional methods. Compared to the results of Zheng et al. (2023), which demonstrated increased stability of variable PID coefficients in laboratory conditions, this study showed even higher accuracy under more complex loads. Analysis of the fixed PID system confirms the general trends, but the intelligent structure demonstrates an advantage in terms of flexibility. Thus, this comparative assessment demonstrates the optimal performance of the adaptive approach.

Analysis of the transition process time in the study revealed the maximum efficiency of the intelligent system. In this study, the stabilisation time is significantly lower in all load modes, ranging from 0.41 to 0.79 seconds, which indicates a high level of dynamic sensitivity. This confirms the conclusions of Liu et al. (2021), who described the high speed of neural network adaptive algorithms in rotary drives, where load torque changes are frequent. Chunyi (2023) questioned the advantages of such algorithms, highlighting the complexity of their configurability and the risk of unstable behaviour under retraining conditions. However, in the study, the use of pre-trained models focused on multi-factor scenarios demonstrated that these challenges can be successfully overcome through a structured training process and by limiting the depth of adaptation. Notably, the system is capable of responding quickly even to high-frequency load variations (0.2 Hz), which is typical for complex manufacturing processes with short cycles. Thus, the results provide additional substantiated support for the implementation of intelligent systems in industrial environments where response speed and stabilisation requirements are critical to ensuring product quality.

The difference in the current characteristics of the control systems made accurate energy analysis possible. In the presented study, the average and peak current consumption for the intelligent system are significantly lower, which coincides with the conclusions of Singh et al. (2025), who noted the economic potential of adaptive PID controllers. In turn, Sarathkumar et al. (2025) expressed scepticism about energy savings with complex adaptation algorithms, arguing that this would result in additional computational costs. However, this study found that savings of up to 40% compared to relay circuits offset the processing costs. Therefore, intelligent systems are both energy efficient and dynamically flexible.

Correlation analysis between the peak current and response time showed an exceptional direct dependence (r=0.995). This value is consistent with the indicators given by Rif'an et al. (2021) in a study of similar drives, although they suggested the possibility of statistical artefacts due to small samples. The present study used a larger data set with three load modes, which gives the resulting values greater reliability. Thus, the established practical relationship can serve as a basis for developing diagnostic algorithms for control quality without additional sensors.

Intelligent systems provide predictive control thanks to a pre-trained load model. This confirms the conclusions of Jiang et al. (2020) noting the advantages of predictive architectures. At the same time, Subtil et al. (2023), analysing the control of electric drives in aggressive conditions, noted the vulnerability of neural networks to unpredictable external influences. The presented study ensures stability even under variable loads, which confirms the validity of using adaptive algorithms in real production. Thus, the advantage of the intelligent approach is justified by practical results.

Under stable load conditions, the system with fixed PID proved to be quite effective, although it did not reach the level of an intelligent algorithm. Within this load mode, its parameters remained close to the set values, which maintained the drive operation without significant fluctuations. These results are consistent with the conclusions of Khaleghi et al. (2022) and Li (2022), highlighting the optimality of classical PIDs under conditions of minimal dynamics, when external disturbances do not have a significant impact on system stability. However, in real production processes, the load changes irregularly: there are impulse effects, variations in the mass of workpieces, changes in the moment of inertia, and temperature fluctuations (Karnaukh et al., 2020; Korzhyk et al., 2021; Sydorets et al., 2017). Under such conditions, fixed controller coefficients are ineffective because they are unable to adapt to changes in the environment. This leads to slow responses, residual oscillations, and an increased likelihood of deviation from technological parameters. Intelligent systems, on the other hand, are capable of quickly adjusting parameters in response to new conditions (Kaukarov et al., 2020; Panchenko et al., 2021; 2023). Thus, this study highlights both the functional limitations of traditional PID control and the advisability of modernising it by introducing adaptive neural network logic.

Symmetrically, the results of the relay system confirm the theoretical conclusions of Qi (2025) and Hu et al. (2024), describing the high inertia and low accuracy of such circuits. At the same time, X. Han

(2024) challenged the significance of changes in the context of modern equipment, arguing that the inertia of relay systems is acceptable for heavy equipment. However, this study found that the SKV exceeds 3 rad/s, which selectively leads to uncontrolled instrument vibrations. This supports the view that it is not advisable to retain relay circuits in modern production.

The detected stabilisation time range, lower than 0.5 s for an intelligent system, exceeds the values provided by Wang (2024), who claimed the high speed of such algorithms. At the same time, Wang and Li (2019) noted that adaptive models can accumulate errors during prolonged use without regular retraining. The presented study indicates that the algorithm uses a pre-trained model and reacts proactively, which reduces the risk of error accumulation. Therefore, the applied solution demonstrates a competitive advantage over other options.

The spiral nature of the relationship between energy efficiency and dynamic characteristics confirms the concept of Wang et al. (2021), noting that the main limitation in flexible systems is the balance between response speed and current stability. This study established a clear pattern: the lower the current amplitude, the faster the stabilisation. Chen et al. (2023), on the contrary, believed that there is a trade-off when too smooth energy consumption reduces reactivity. The study showed that intelligent systems can provide both energy savings and high performance. Thus, the possibility of overcoming the compromise is confirmed.

The study found that adaptive formation of PID coefficients minimises impulse current overloads. Liu et al. (2014) noted that high-frequency loads can cause harmonics and reduce efficiency. The study showed that the intelligent system reduces peak current values to ~11 A, which is significantly less than the 18 A in the relay system. This suggests that modern methods can effectively counteract high-frequency disturbances (Abdullayev and Karimzada, 2013; Karimzada and Adullayev, 2020).

Notably, the analysis was performed without additional speed or torque sensors. This partially confirms the initial results of Q. Dong et al. [34], who believe that the current could be used as a proxy indicator for diagnostic dynamics. In the study, current characteristics were successfully used for evaluation, paving the way for simplifying the hardware base and reducing the cost of systems. Ma (2025) expressed reservations about the dependence of such methods on the accuracy of measuring equipment. However, the study showed that even with errors of ±0.1 A, the analysis remains reliable.

Thus, the results emphasise the practical significance of integrating energy and dynamic diagnostics. According to the position of L. Wang et al. [36], who concluded that such integration requires standards and certification, the study does not directly agree. At the same time, the presence of a stable correlation can be used to develop technical standards without undue complexity. Dindorf et al. (2020), in turn, noted that the testing of such systems requires lengthy trials in real conditions. Given the results presented, such trials may be the next logical step.

In general, the analysis of control systems demonstrates the significant advantage of an intelligent approach in terms of speed, stability, response speed, energy efficiency, and diagnostic capability without the need for additional sensors. A comparison of the three systems confirmed that adaptive neural network correction of PID parameters is the most optimal solution for modern automated and energy-efficient production processes. These results provide a solid foundation for the further development of standards and the implementation of intelligent systems in industrial practice.

The study conducted a comprehensive comparative analysis of the efficiency of three types of electric drive control systems: relay, fixed PID parameters, and intelligent. The analysis showed that the relay system has the lowest dynamic and energy characteristics; in particular, the root mean square speed deviation exceeds 3.3 rad/s, the stabilisation time reaches 2.48 s, and the peak power consumption exceeds 18 A. This indicates its limited ability to dampen disturbances and low adaptability to load changes. The system with fixed PID coefficients provided a noticeable improvement in stability and dynamics: the root mean square speed deviation was reduced to 1.29-1.77 rad/s, the response time was reduced to 1.01–1.39 s, and the average current was reduced to 9.0-10.5 A. However, its effectiveness is limited under variable load conditions due to the immutability of parameters that do not address the frequency and amplitude of external disturbances. Its response to load changes was slower, accompanied by residual rotation speed fluctuations and increased stabilisation time. In addition, such systems are not flexible enough in cases of fast-moving technological processes, where a response in a fraction of a second is required.

The best results were achieved by an intelligent control system, which, thanks to neural network adaptation of PID coefficients, ensured speed stability within ±0.01 rad/s, reduced response time to 0.41 s, and significantly reduced average energy consumption to 8.03 A. An additional advantage was the reduction of peak current fluctuations to a level not exceeding 10.94 A, which significantly reduces the thermal load on the electric motor and increases its service life. The strong correlation ($r=0.995$) between current consumption stability and response speed highlights the interdependence of the energy and dynamic characteristics of systems, opening up the possibility of using current signals as a diagnostic criterion for control quality. Combined with high accuracy in predicting load changes, this makes the intelligent system a promising solution for integration into automated production lines.

The limitations of the study are related to the use of a fixed neural network topology, the limited size of the training set, and the lack of experimental testing in an industrial environment with a wide range of external influences (temperature, vibration, wear). The issue of the system's resistance to external electromagnetic interference and the influence of voltage fluctuations in the power supply network also requires further analysis. Further research should address expanding the training data set, applying deeper neural networks, introducing online learning methods, and assessing the long-term stability of the adaptive system under variable loads. The development of universal software capable of integrating with various types of industrial controllers and ensuring scalability for the needs of a specific production facility is noteworthy.

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