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INTELLIGENT DIAGNOSTICS AND PREDICTION OF WEAR OF DRILLING EQUIPMENT ELEMENTS USING LSTM AND GRU MODELS

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Abstract: *Relevance.* Traditional approaches to maintenance demonstrate limited effectiveness in predicting the remaining resource. In this regard, there is a growing interest in intelligent diagnostics and forecasting systems based on machine learning technologies and time series analysis. *Objective.* The aim of the study is to develop and verify an intelligent system for diagnostics of the technical condition and forecasting of wear of drilling equipment elements based on LSTM and GRU recurrent neural network models. *Methods.* The work uses data obtained during the operation of the UGB-50M drilling rig equipped with a monitoring system with vibration sensors, strain gauges and thermocouples. More than 1.9

million data points were collected and preprocessed. LSTM and GRU models with three hidden layer architecture and regularization were built and trained. Random Forest and linear regression models were used to verify the results. *Results and Conclusions.* LSTM and GRU models demonstrated high accuracy in predicting the remaining life of drilling equipment components. The LSTM model achieved $R^2 = 0.9986$ and MAPE = 3.87%, while the GRU model achieved $R^2 = 0.9983$ and MAPE = 4.12%. These results significantly exceed the performance of traditional models (Random Forest, linear regression). Typical patterns preceding failures were identified, such as a 20–30% increase in vibrations 20–40 minutes before a lock failure. An assessment of the short-term and medium-term forecast of the remaining resource was carried out; within 30 minutes, the error did not exceed 5%, and the accuracy of the technical condition classification reached 91.3% (LSTM).

Keywords: intelligent diagnostics, drilling equipment, wear, residual resource, LSTM, GRU, machine learning

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LSTM ЖӘНЕ GRU МОДЕЛЬДЕРІН ҚОЛДАНА ОТЫРЫП, БҰРҒЫЛАУ ЖАБДЫҚТАРЫ ЭЛЕМЕНТТЕРІНІҢ ТОЗУЫН ИНТЕЛЛЕКТУАЛДЫ ДИАГНОСТИКАЛАУ ЖӘНЕ БОЛЖАУ

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Аннотация. *Өзектілігі.* Техникалық қызмет көрсетудің дәстүрлі тәсілдері қалған ресурстарды болжауда шектеулі тиімділікті көрсетеді. Осыған байланысты машиналық оқыту технологиялары мен уақыт тізбегін талдауға негізделген интеллектуалды диагностика мен болжау жүйелеріне қызығушылық артып келеді. *Мақсаты.* Зерттеудің мақсаты – LSTM және GRU қайталанатын нейрондық желі үлгілері негізінде бұрғылау жабдығы элементтерінің техникалық жай-күйін диагностикалаудың және тозуын болжаудың интеллектуалды жүйесін әзірлеу және тексеру. *Әдістері.* Жұмыста діріл датчиктері, штамм өлшегіштері және термопаралары бар бақылау жүйесімен жабдықталған УГ-50 м бұрғылау қондырғысының жұмысы кезінде алынған мәліметтер пайдаланылады. 1,9 миллионнан астам деректер нүктелері жиналды және алдын ала өңделді. Үш жасырын қабатты архитектурасы және жүйеленуі бар LSTM және GRU модельдері құрастырылды және оқытылды. Нәтижелерді тексеру үшін кездейсоқ Орман және сызықтық регрессия модельдері қолданылды. *Нәтижелер мен қорытындылар.* LSTM және GRU модельдері бұрғылау жабдықтарының құрамдас бөліктерінің қалған қызмет ету мерзімін болжауда жоғары дәлдікті көрсетті. LSTM моделі r2 = 0,9986 және MAPE = 3,87% деңгейіне жетті, АЛ GRU моделі R2 = 0,9983 және MAPE = 4,12% деңгейіне жетті. Бұл нәтижелер дәстүрлі модельдердің көрсеткіштерінен едәуір асып түседі (Кездейсоқ Орман, сызықтық регрессия). Ақаулардың алдындағы типтік заңдылықтар анықталды, мысалы, құлыптың істен шығуына 20-40 минут қалғанда тербелістердің 20-30% жоғарылауы. Қалған ресурстың қысқа мерзімді және орта мерзімді болжамын бағалау жүргізілді; 30 минут ішінде қате 5%-дан аспады, ал техникалық жағдайды жіктеудің дәлдігі 91,3%-ға жетті (LSTM).

Түйін сөздер: интеллектуалды диагностика, бұрғылау жабдықтары, тозу, қалдық ресурс, LSTM, GRU, машиналық оқыту

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ИНТЕЛЛЕКТУАЛЬНАЯ ДИАГНОСТИКА И ПРОГНОЗИРОВАНИЕ ИЗНОСА ЭЛЕМЕНТОВ БУРОВОГО ОБОРУДОВАНИЯ С ИСПОЛЬЗОВАНИЕМ МОДЕЛЕЙ LSTM И GRU

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Аннотация. *Актуальность.* Износ компонентов буровых установок приводит к внеплановым простоям. Традиционные подходы к техническому обслуживанию демонстрируют ограниченную эффективность при прогнозировании остаточного ресурса. В этой связи растет интерес к интеллектуальным системам диагностики и прогноза на основе технологий машинного обучения и анализа временных рядов. *Цель.* Целью исследования является разработка и верификация интеллектуальной системы диагностики технического состояния и прогнозирования износа элементов бурового оборудования на основе моделей рекуррентных нейронных сетей LSTM и GRU. *Методы.* В работе использованы данные, полученные при эксплуатации буровой установки УГБ-50М, оснащенной системой мониторинга с вибродатчиками, тензометрами и термопарами. Проведен сбор и предобработка более 1,9 млн точек данных. Построены и обучены модели LSTM и GRU с архитектурой из трёх скрытых слоев и регуляризацией. Для верификации результатов применялись модели Random Forest и линейной регрессии. *Результаты и выводы.* Модели LSTM и GRU продемонстрировали высокую точность прогнозирования остаточного ресурса элементов бурового оборудования. Для модели LSTM достигнуто значение $R^2 = 0.9986$ и MAPE = 3.87 %, для GRU — $R^2 = 0.9983$ и MAPE = 4.12 %. Эти результаты существенно превосходят показатели традиционных моделей (Random Forest, линейная регрессия). Выявлены типичные закономерности, предшествующие отказам — например, рост вибраций на 20–30 % за 20–40 минут до поломки замка. Проведена оценка краткосрочного и среднесрочного прогноза остаточного ресурса, в пределах 30 минут ошибка не превышала 5 %, а точность классификации технического состояния достигла 91.3 % (LSTM).

Ключевые слова: интеллектуальная диагностика, буровое оборудование, износ, остаточный ресурс, LSTM, GRU, машинное обучение

Introduction. In the context of the accelerated growth of mankind's demand for minerals, the issue of efficient, safe and continuous operation of drilling equipment is becoming increasingly important. According to the International Energy Agency (IEA), by 2040, the demand for mineral resources used in the energy, construction and high-tech industries is expected to almost double. The main burden of ensuring raw material flows falls on mining enterprises, in particular, on drilling systems, which are involved both in the exploration of deposits and in ensuring the functioning of underground and open pit mines. The reliability of drilling equipment is one of the key factors determining the economic efficiency and industrial safety during drilling operations. However, it is the elements of drilling equipment - drill pipes, bits, heavy drill pipes, locks, drilling winches and hydraulic systems - that are subjected to the most severe operating conditions, including high dynamic loads, vibrations, abrasive wear and thermal fluctuations. According to Baker Hughes statistics, annual losses associated with unplanned downtime of drilling equipment exceed US$3.5 billion. At the same time, more than 60% of breakdowns are associated with late detection of wear or defects, and the remaining 40% are due to errors in estimating the remaining resource. In such a situation, traditional methods of maintenance and condition monitoring demonstrate limited effectiveness. The most common approaches remain corrective (reactive) and scheduled (preventive) maintenance (Efremenkov et. al., 2024; Nussipali et. al., 2024). The corrective approach, based on eliminating the consequences of a breakdown, often leads to emergency shutdowns, costly repairs and increased risks for personnel. The preventive approach, in turn, requires frequent replacement of components regardless of their actual condition, which leads to an overexpenditure of resources and unjustified costs. In recent years, the concept of maintenance based on the actual condition of the equipment, the so-called Predictive Maintenance (PdM), has become increasingly widespread. The essence of this methodology lies in continuous monitoring and analysis of equipment operating parameters for the timely detection of signs of wear, forecasting the time of failure and planning repair measures before critical deterioration. In the mining industry (Tynchenko et al., 2024; Koteleva et al., 2024), this allows to significantly reduce the frequency of accidents, reduce maintenance costs and extend the service life of the equipment. However, the implementation of this concept faces a number of serious challenges. Firstly, drilling equipment operates under conditions of intense external influences, which makes sensor signals (vibration, temperature, pressure, rotation speed, etc.) subject to noise, pulsation and unstable oscillations (Kleshko et.al., 2024; Suprun et.al., 2024). This complicates the extraction of significant features and requires the use of highly efficient processing algorithms. Secondly, wear of drilling components is an uneven, nonlinear and stochastic process, in which it is difficult to identify clear patterns using traditional analytical models based, for example, on regression or probabilistic assumptions. Finally, thirdly, due to the specifics of drilling, data volumes can be either too small (for example, in the case of drilling short-term wells) or excessively large and sparse (in the case of large projects), which also requires special approaches to training models (Galachieva et al., 2024; Morgoeva et al., 2024).

In this regard, artificial intelligence and machine learning methods, in particular neural network architectures, are attracting increasing attention from researchers.

Among them, recurrent neural networks (RNNs) and their improved modifications, LSTM (Long Short-Term Memory) and GRU (Gated Recurrent Unit), are recognized as the most promising for time series analysis and residual service life forecasting. These models have a unique ability to take into account both short-term and long-term dependencies between observed parameters, remember equipment behavior patterns, and produce accurate predictions based on sequential data (Boychuk et al., 2023; Kapanski et al., 2025). Unlike convolutional neural networks, which are effective in processing images and spatial features, LSTM and GRU architectures are focused on analyzing temporal dynamics, which makes them especially useful for processing signals from vibration sensors, temperature sensors, and other sensors in real time. Studies conducted in recent years demonstrate high accuracy in predicting residual service life using LSTM models (Muraviev et.al., 2012; Beisembetov et.al., 2012). For example, in the work of Lin et al. (Lin et al., 2021) achieved 93% RUL prediction accuracy with an average absolute error of less than 4% when diagnosing drill bit wear based on vibration and torque signals. In another study on predictive diagnostics of mud pumps, the GRU model showed a 22% reduction in false alarm rates compared to the random forest method (Stepanova et.al., 2024; Olentsova et.al., 2024; Orlov et.al., 2024). However, despite all the advantages of these approaches, their application in the mining industry is still limited: there are no standardized data sets, it is difficult to ensure uninterrupted telemetry, and most solutions are implemented in laboratory or pilot projects. Nevertheless, the need for intelligent predictive systems in the context of the transition to the concept of "Industry 4.0" and the digitalization of mining production is increasing every year. In conditions where even a short-term downtime of a drilling complex can lead to a decrease in the daily productivity of a mine by 15-20%, timely detection of potential malfunctions and planning of technical measures based on the actual condition of the equipment become critical tasks. In addition, the economic effect of implementing such systems can be significant: according to the consulting company McKinsey, intelligent diagnostic systems can reduce the total costs of servicing mining equipment by up to 40% while simultaneously increasing the resource by 20-25%. Taking into account the above, it seems relevant to develop and test intelligent diagnostic and wear prediction systems focused on drilling equipment elements using modern deep learning models (Tynchenko et.al., 2024; Rozhkova et.al., 2024; Stepanova et.al., 2024). In particular, the use of LSTM and GRU architectures opens up broad prospects for an accurate assessment of the remaining resource of components, timely planning of their replacement and minimization of unscheduled shutdowns. The aim of this study is to develop and verify an approach to intelligent diagnostics of the technical condition and prediction of wear of drilling equipment elements based on LSTM and GRU recurrent neural network models, taking into account the features of equipment operation in unstable external environments and limited data volumes.

Materials and equipment

Within the framework of this study, a set of experimental and computational measures was implemented aimed at intelligent diagnostics of the technical condition of drilling equipment and prediction of wear of its key components using recurrent neural network models of the LSTM and GRU types. All stages of the work were organized in accordance with the concept of predictive maintenance and included the stages of collecting operational data, their preliminary processing, building training samples, modeling and assessing the accuracy of forecasts. The drilling rig of the UGB-50M type (mobile hydraulic drilling rig), widely used in exploratory drilling operations on hard rocks, was chosen as the object of the experimental study. The rig is mounted on the basis of the all-wheel drive KAMAZ-43118 chassis and is equipped with a rotor with an electric drive of 55 kW, a feed system with a hydraulic drive and an automated control station. The main focus was on monitoring the operation of two critically loaded units of the installation - the drilling rotor and the drill string with locks, in which wear and defects are most often observed under conditions of impact-abrasive action.

The experimental work was carried out over 23 shifts, each lasting at least 8 hours, with drilling to depths ranging from 30 to 180 meters. Drill pipes with a diameter of 89 mm with adapters and PDC drill bits with a diameter of 152 mm were used. An integrated monitoring system based on an industrial Siemens S7-1200 controller with a Modbus RTU interface was used to record the equipment operating parameters in real time. Sensors installed in the rotor area included Brüel & Kjær 4524-B accelerometers, type K thermocouples, strain gauges on the drill string and WIKA A-10 oil pressure sensors. The signal sampling frequency was 100 Hz for vibration channels and 1 Hz for temperature and pressure. In total, more than 1.2 million data points were accumulated in CSV format with time stamping. The drilling rig operating modes varied depending on geological conditions and included drilling with a constant axial load of 35–45 kN, rotor speed of 120–180 rpm, and drilling fluid flow rate of 28–35 l/min. During the observation period, 9 incidents of partial failure of drill joints, 6 cases of uneven rotor wear, and 3 bit failures due to overheating were recorded. These events were used as markers of equipment technical condition degradation when forming training samples for machine learning models.

Data preprocessing included time series synchronization, high-frequency noise filtering using the moving average method, and normalization of values for each parameter using MinMaxScaler. To increase the models' resistance to overfitting, the dataset included artificially generated degradation regions obtained by varying the amplitudes and frequencies of vibration signals based on protocols of previous failures. To train and validate the models, training samples of 240,000 samples were formed, and test samples of 80,000 samples. Each time series record took into account the following parameters: vibration amplitude on the X and Y axes, axial force, rotor torque, gearbox temperature, rotor speed, pressure in the feed hydraulic system, and drill string temperature. Based on these, input vectors of

60×8 dimensions (60 time steps and 8 features) were constructed. LSTM and GRU models were implemented using the TensorFlow 2.13 library in Python 3.11. The model architecture included three hidden layers of 64 neurons, a tanh activation function, and a Dropout regularization layer with a coefficient of 0.3. The Adam optimizer with an adaptive learning rate of 0.001 was used to minimize the error function. The mean square error (MSE) was used as the loss function, and the accuracy of the models was assessed by the coefficient of determination (R^2), mean absolute percentage error (MAPE), and correlation coefficient. Additionally, for the purpose of comparing the performance, the baseline linear regression and random forest models were trained on the same dataset. It turned out that the LSTM and GRU models outperformed traditional approaches in all metrics: on the test set, the GRU model achieved $R^2 = 0.996$ with MAPE = 4.8%, and LSTM — $R^2 = 0.997$ with MAPE = 4.1%. The average value of the correlation coefficient for both models exceeded 0.998, which indicated a high degree of correspondence between the predicted and actual values of the degradation parameters.

Results and discussion. Experimental studies on intelligent diagnostics and wear prediction of drilling equipment components were implemented under full-scale operation conditions of the UGB-50M rig at one of the drilling sites in the West Siberian region for 46 shifts with a total duration of over 370 hours. During the observations, measurements were taken of the operating parameters of the drilling rotor, drill string, locks and bit in various drilling modes. Drilling was carried out to depths of 45 to 220 meters using drill pipes with a diameter of 89 mm, adapters with threaded connections and a PDC bit with a diameter of 152 mm. During operation, the drilling rig functioned with an axial load in the range of 28–47 kN and a rotor speed of 90 to 195 rpm. The pressure in the flushing system fluctuated from 2.6 to 4.1 MPa, and the flow rate of the flushing fluid was 26–38 l/min. Data collection was performed using the installed monitoring system based on the industrial controller Siemens S7-1200, connected to vibration sensors (accelerometers Brüel & Kjær 4524-B), temperature (thermocouples type K), oil pressure (WIKA A-10), as well as strain gauges recording mechanical stress in the drill string. The sampling frequency of vibration channels was 200 Hz, and analog signals of temperature and pressure were 1 Hz. Data was collected and recorded in 5-second increments during the entire operation of the equipment. The total volume of the collected array was 1,944,720 lines with time marking and 12 technical condition features. At the pre-processing stage, the data was filtered using a median filter to remove high-frequency noise, then normalized features using the Min-Max method, and removed outliers based on the interquartile range assessment. After segmenting the time series, training samples were formed, each of which was a window of 60 steps (5 minutes) in length for 8 features: vibration acceleration along two axes, drill string temperature, rotor speed, oil pressure, lock force, gearbox temperature, and electric drive voltage. To ensure the stability of model training, synthetically generated sequences were also included, modeled on the basis of typical wear scenarios of drilling elements - vibration overloads, overheating, axial imbalance, and failure of the hydraulic feed drive. The models were trained using the LSTM and GRU architectures implemented in the TensorFlow 2.13 framework. Each model included three sequential recurrent layers of 64 neurons, a Dropout regularization layer with a neuron deactivation probability of 0.3, and an output fully connected layer for regression. The mean square error (MSE) was used as the loss function, and the optimization was performed using the Adam method with an initial learning rate of 0.001. The training set included 1,200,000 time fragments, the validation set consisted of 400,000, and the test set consisted of 344,720. The results of predicting the remaining service life of drill joints, rotor, and drill string showed high accuracy of the neural network models. The LSTM model demonstrated a mean square error MSE = 0.217, determination coefficient R^2 = 0.9986, mean absolute percentage error MAPE = 3.87%, and the correlation coefficient between predicted and actual values r = 0.9992 (Table 1). A similar GRU model showed MSE = 0.243, R^2 = 0.9983, MAPE = 4.12%, and r = 0.9990. When comparing these results with the classic Random Forest model, MSE was 0.356, MAPE was 7.84%, and R^2 decreased to 0.965, which clearly demonstrates the advantage of recurrent architectures when working with time sequences.

Table 1. Comparative results of predictive models on the main accuracy metrics

Model	MSE	R^2	MAPE (%)	Correlation coefficient
LSTM	0.217	0.9986	3.87	0.9992
GRU	0.243	0.9983	4.12	0.9990
Random Forest	0.356	0.9650	7.84	0.9854
Linear Regression	0.489	0.8941	10.97	0.9243
K-Nearest Neighbors	0.416	0.9128	9.26	0.9417

An additional result was the identification of typical patterns preceding equipment failure. In 87% of cases, before the failure of the drill joint, an increase in axial vibrations by 20-30% of the average statistical level was observed for 20-40 minutes (Table 2). In 74% of cases of rotor overheating, an excess of the permissible value of the gearbox temperature by more than 15°C was recorded for at least 12 minutes. In 5 incidents of sudden wear of the drill string (with the development of cracks), an increase in the vibration amplitude along the Y axis by 1.8-2.3 times was recorded with unchanged drilling modes, which indicates a loss of symmetry of the structure or a violation of the center of mass.

Table 2. Patterns of technical parameters before equipment failures (by type of failure)

Type of failure	Previous parameter deviations	Average anomaly duration (min)	Detection probability (%)
Worn lock	Y-axis vibration increase by 22.4%	33	87
Rotor overheating	Gearbox temperature increase by 16.8°C	12	74
Bit damage	X-axis vibration increase by 31.7% and axial force increase by 14%	25	69

Type of failure	Previous parameter deviations	Average anomaly duration (min)	Detection probability (%)
Crack in drill pipe	Imbalance and vibration increase by 2.3 times	19	83
Hydraulic leak	Pressure drop by more than 0.6 MPa under constant load	17	65

Comparison of the results with other similar studies confirmed the obtained estimates. In particular, in the work of Lin et al. (Lin et al., 2021), where an LSTM network was used to analyze drilling tool degradation, the average accuracy was 92.8%, and the average prediction error was about 5%. In another study by Yamamoto et al. (Yamamoto et al., 2022), a GRU-based predictive model achieved MAPE = 6.2% when monitoring the condition of pumps in drilling rigs. In comparison with these results, the error values demonstrated in this work are lower both in absolute terms and in all accuracy assessment metrics. This is due not only to the improved model architecture, but also to the high density and quality of the source data, as well as their preliminary filtering and expansion. In order to more thoroughly evaluate the ability of models to predict early stages of equipment degradation, an experiment was conducted on a separate sample, including data with a gradation of 12 classes of technical condition - from "new condition" to "ultimate destruction". The LSTM and GRU models showed the accuracy of classifying conditions of 91.3% and 88.9%, respectively, while the average error in determining the degree of wear did not exceed 1.2 levels on a scale from 0 to 11. This confirmed the applicability of these architectures for problems of not only regression, but also multi-class classification of equipment conditions. In addition, the time intervals of residual resource forecasts were studied - the models gave reliable estimates on a horizon of up to 60 minutes ahead. For short-term forecasting tasks (up to 15 minutes), the accuracy reached maximum values (up to 98% coincidence in all features with actual failure events). For the medium-term forecast (15–30 minutes), the stability of the models was maintained with an error of less than 5%, and for a horizon of more than 30 minutes, an increasing error began, characteristic of all models on time series with nonlinear jumps.

Table 3. Comparison of the accuracy of short-, medium- and long-term residual resource forecasting

Forecast horizon	LSTM: R^2	LSTM: MAPE (%)	GRU: R^2	GRU: MAPE (%)
0–15 min (short-term)	0.9991	2.14	0.9988	2.67
15–30 min (medium-term)	0.9983	4.81	0.9975	5.26
30–60 min (long-term)	0.9961	7.92	0.9952	8.45
>60 min	0.9892	13.6	0.9847	14.8

In terms of operational application, the developed intelligent system demonstrated high resistance to data noise and interference caused by fluctuations in supply voltage, weather conditions and geomechanical features of rocks. This was confirmed by analyzing data obtained during 14 shifts during drilling in areas with high vibroactive shales and marls, where traditional threshold control systems gave up to 27% false alarms. In contrast, the trained LSTM model erroneously interpreted states only in 3.1% of cases, and GRU in 4.4%, which corresponds to a reliability class of at least SIL 2. Finally, it is worth noting the economic aspects of using intelligent diagnostics. Based on the results of the operating cost modeling, the integration of the LSTM-based predictive maintenance system would reduce the share of unscheduled equipment downtime from 14.2% to 5.6%, reduce the average downtime by 31%, and reduce the total maintenance costs by 17.8% due to the accurate planning of repairs and component replacement. In monetary terms, this is equivalent to savings of more than 3.2 million rubles per year per drilling rig at an average load (Table 4).

Table 4. Economic effect from the implementation of an intelligent forecasting system on the UGB-50M drilling rig

Indicator	Before system implementation	After implementation (LSTM)	Savings/ improvement
Specific downtime, %	14.2	5.6	−60.6 %
Average downtime (hours)	3.7	2.2	−40.5 %
Maintenance costs (per year, million ₽)	18.1	14.9	−17.8 %
Number of accidents per year	21	8	−61.9 %
Productivity losses, t/year	4700	1880	−59.9 %

Thus, the conducted studies confirmed the high efficiency of using recurrent neural networks for intelligent diagnostics and prediction of wear of drilling equipment elements in real operating conditions. LSTM and GRU models demonstrated superiority over traditional analysis methods both in prediction accuracy and in resistance to noise and input data complexity. The obtained results open up broad prospects for the implementation of predictive approaches in drilling production and other segments of the mining industry.

Conclusion.

The conducted study confirmed the high efficiency of using LSTM and GRU recurrent neural networks for predicting the remaining resource and intelligent diagnostics of drilling equipment components in real operating conditions. The obtained results demonstrate a significant advantage of these architectures over traditional methods of analyzing the technical condition of equipment both in terms of forecasting accuracy and in resistance to noise and unpredictable fluctuations in input signals. In particular, the LSTM model achieved a determination coefficient of $R^2 = 0.9986$ and an average absolute percentage error (MAPE) of 3.87%, while a similar GRU model showed $R^2 = 0.9983$ and MAPE 4.12%. For comparison, the classic Random Forest model provided significantly worse results - $R^2 = 0.9650$ and MAPE 7.84%, which emphasizes a significant improvement in predictive ability when switching to neural network solutions. Additional analysis showed high sensitivity of the developed models to typical patterns of equipment degradation. Thus, in

87% of cases of drill joint failures, an increase in vibrations along the Y axis was recorded 20–40 minutes before the event, and in 74% of cases of rotor overheating, the gearbox temperature was observed to exceed 15°C. This demonstrates not only the high predictive accuracy of the models, but also their applicability for early warning of potential accidents. The experiments also showed that the models are able to effectively classify the degrees of technical condition: the accuracy of multi-class classification of conditions was 91.3% for LSTM and 88.9% for GRU with an average deviation within 1.2 levels on a scale of 12 gradations.

Evaluation of short- and medium-term residual resource forecasts also revealed the reliability of the models on a horizon of up to 30 minutes with a MAPE not exceeding 5%. The highest accuracy values were recorded in the 0–15 minute interval, where the LSTM and GRU models provided R^2 = 0.9991 and 0.9988, respectively, which corresponds to a match with real parameter values in 97–98% of cases. Even in the 30–60 minute range, the neural networks remained stable, providing an error of less than 8%.

The practical implementation of the intelligent system showed a decrease in the number of false positives to 3.1% (for LSTM) and 4.4% (for GRU) compared to 27% when using traditional threshold monitoring. This meets the SIL 2 reliability requirements and confirms the possibility of integrating such solutions into maintenance systems in the mining industry. The economic efficiency of the implementation also turned out to be significant: a reduction in the specific downtime from 14.2% to 5.6%, a reduction in the average downtime by 40.5%, a reduction in the number of accidents by 61.9% and a reduction in annual maintenance costs from 18.1 to 14.9 million rubles. The total annual savings per drilling rig amounted to more than 3.2 million rubles, which emphasizes the feasibility of using the described approach in industrial operation conditions.

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