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ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

DEVELOPMENT OF ALGORITHMS AND SYSTEMS FOR FAULT DIAGNOSTICS IN DEEP PUMP OIL UNITS USING RNMT

Speciality: 3338.01 – System analysis, control and processing of information (by fields)

Field of science: Technical Sciences

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GENERAL DESCRIPTION OF THE WORK

Relevance of the topic. It is well known that oil extraction from wells by mechanized methods is mainly carried out using sucker-rod pumping units (SRPU), electric submersible pumps (ESP), progressive cavity pumps (PCP), and other types of pumps. Due to its simplicity, reliability, and wide application potential, the SRPU is very popular. Although other types of pumps have been developed, more than two-thirds of the existing well stock is still equipped with SRPUs, and their number is continuously increasing. This method of oil production is expected to remain the most widespread for a long time.

At the same time, in oilfields at the final stage of operation, reservoir pressure decreases due to the reduction of oil reserves. To counter this process, water is injected into the reservoir using centrifugal pumps. If the condition of water injection and production well equipment is not diagnosed in time, emergency downtime of the equipment occurs, drastically reducing the profitability of oil production. Therefore, it is crucial to develop measures aimed at increasing the profitability of oil production in oilfields at the final stage of operation.

The results of the conducted analysis show that one of the reasons for low profitability is the insufficient capability for early diagnostics of all equipment in the control, measurement, diagnostics, and management tools used in mines at the final stage of operation. Specifically, early diagnostic functions were generally not considered in all old systems, and only partially taken into account in new systems. Therefore, failure conditions in most facilities are recorded only after they have fully manifested. This delay leads to costly breakdowns, ultimately reducing the overall efficiency of oil extraction.

Research conducted at the Institute of Control Systems of the Azerbaijan National Academy of Sciences (AMEA) under the leadership of academician T.A. Aliyev has shown that the initial period of defects causing failures is accompanied in the signals received from these objects by low-amplitude, high-frequency noise, and there is a definite correlation between this noise and the useful signal. These noises serve as carriers of information indicating the very first moment when the object transitions into a failure state. At the same time, there is sufficient time between the initial occurrence of the defect and the moment the failure happens to take measures to prevent the failure. However, in most existing control and management systems, this noise — the only source of information — is filtered out and discarded. As a result, the condition of the equipment cannot be adequately identified.

Although the theoretical foundations of diagnosing failure states of objects have been well studied in the works of scientists such as T.A. Aliyev, N.F. Musayeva, Q.A. Quluyev, F.H. Pashayev, and As.H. Rzayev, and have been partially applied in several objects, it can be concluded that the determination of the initial period of transition to failure states of pump units in oil production processes at the final stage of operation, as well as the problems of their identification, have not been fully studied.

The analysis of scientific publications on the study of pump units in oil production processes at the final stage of operation shows that fundamental work has been carried out in all directions. The work done creates a basis for the relevance of developing new robust noise monitoring, diagnostics, control systems, and algorithms based on modern information measurement tools and telecommunication technologies. Therefore, the topic set forth in this dissertation "Development of algorithms and systems for fault diagnosis in deep pump oil units using RNMT" is highly relevant.

The object of the research is the organization of early fault diagnosis in the technical condition of mechanical equipment operated at the final stage of oil field development. **The subject of the research** is the development of methods, algorithms, and a system aimed at increasing the efficiency of early diagnostics.

The aim of the dissertation is to develop a method, algorithm, and system for the early diagnosis of potential faults in the technical condition of mechanical equipment operated at the final stage of oil field development, in order to enhance the efficiency of this stage.

In order to achieve the aim of the dissertation, the following **issues** have been addressed:

1. Development of algorithms to improve the measurement

accuracy and sampling frequency of dynamogram signals from SRPU;

2. Development of a computational algorithm for the plunger dynamogram of SRPU based on surface measurements;
3. Combined computational algorithm for determining the force acting on the polished rod of the SRPU.
4. Calculation technology and algorithm of positional-binary indicators for early diagnostics of the SRPU;
5. Processing of noisy force signals by positional-binary technology for recognizing the technical condition of the SRPU;
6. Algorithm of positional-binary technology for monitoring the onset and development dynamics of the SRPU faults;
7. Structure of the early diagnostics and control system for pump equipment in the late stage of oil extraction operations;
8. Development of an early diagnostics station based on vibration parameters of sucker rod pump units;
9. Development of an early diagnostics station for pump units in oil extraction;
10. Development of an operational control system for the operation of mechanical equipment in oil extraction.

Research Methods. The work was carried out based on the following research methods:

1. Methods for creating information-measurement, communication, control, diagnostics, and management systems.
2. Practical methods and technologies of Signal Processing;
3. Algorithms and programming theory;
4. Applied methods of mathematical analysis;
5. System analysis, electrical, and pulse technology theory.

Main statements put forward for defense:

1. Algorithms for improving the measurement accuracy and sampling frequency of dynamogram signals of the SRPU.
2. Calculation algorithm of the plunger dynamogram of the SRPU based on surface measurements;
3. Combined calculation algorithm of the force acting on the suspension of the SRPU;
4. Processing algorithm of noisy force signals using

positional-binary technology for recognizing the technical condition of the SRPU;

5. Algorithm of positional-binary technology for monitoring the onset and development dynamics of faults in the SRPU pump units;
6. Structure of the early diagnostics and control system for pump equipment in the late stage of oil extraction operations;
7. Development of an early diagnostics station based on vibration parameters of sucker rod pump units;
8. Generalized early diagnostics station for pump units in oil extraction;
9. Operational control system and algorithms for the operation of mechanical equipment in oil extraction.

Scientific Novelty. The following scientific novelty were achieved in the dissertation work:

1. Development of algorithms for increasing the measurement accuracy and sampling frequency of dynamogram signals to enable more accurate detection of noise correlated with the useful signal.
2. Development of new calculation methods for the plunger dynamogram and algorithm that account for the actual weight of the rod string in each well.
3. Development of a processing algorithm using positional-binary technology for noisy force signals to recognize the technical condition of the SRPU.
4. Development of a positional-binary technology algorithm for monitoring the onset and development dynamics of faults in pump units.
5. Development of algorithms for early diagnostics and control systems of pump equipment in oil extraction processes at the late stage of operation.
6. Development of algorithmic support for the monitoring system of mechanical equipment operation in oil extraction.

Practical significance of the dissertation. The aim is to prevent a decline in the profitability of oil extraction at the late stage of reservoir development by enabling early diagnostics of potential faults in mechanical equipment (SRPU, ESP, and water injection pumps) using RNMT technologies. This early detection helps prevent possible accidents and downtime, thereby improving overall operational efficiency.

Application and Implementation of the Research Results. The results of the dissertation, including the developed algorithms for improving the quality of SRPU dynamograms and the RNMT-based positional-binary algorithms and software for early fault diagnostics of pump equipment in oil extraction processes, were developed at the Institute of Control Systems of MSERA and form the basis of the measurement, monitoring, diagnostics, and control complex (SCADA system) created in its Special Design Bureau (SDB).

This complex, developed with the direct participation of the author, has been implemented and is currently in operation at the following oilfields:

- SOCAR’s Bibiheybatneft, Absheronneft, and Amirovneft fields;
- Salyan OIL and Shirvan OC.

Validation of the research. The main statements and results of the dissertation were presented and discussed at a number of international and national scientific conferences, as listed below:

1. The 4th International Conference “Problems of Cybernetics,” Baku, 2012.
2. "Electromechanics, Electro technologies and Electrical Equipment," 2nd International Scientific-Technical Conference, Ufa (Russia), Ufa State Petroleum Technological University (USPTU), 2015.
3. "Electromechanics, Electro technologies and Electrical Equipment," 3rd International Scientific-Technical Conference, Ufa (Russia), USPTU, 2017.
4. "Measurement and Quality: Problems and Perspectives," International Scientific-Technical Conference, Baku, ATU, 2018.
5. "Electromechanics, Electro technologies and Electrical Equipment," 5th International Scientific-Technical Conference, Ufa (Russia), USPTU, 2020.
6. "Problems of Acquisition, Processing, and Transmission of Measurement Information," International Scientific-Technical Conference, Ufa (Russia), RIC UGATU, 2020.

7. Republican Scientific-Technical Conference dedicated to the 70th anniversary of Azerbaijan Technical University on the topic: "Technological Perspectives of the Fourth Industrial Revolution: Industrial Internet, Cyber-Physical Systems, and Intelligent Technologies," Baku, ATU, 2020.
8. "Information, Control and Communication Technologies (ICCT)," 8th International Conference, Vladikavkaz (Russia), 2024.

Name of the institution where the dissertation was carried out: Institute of Control Systems, Ministry of Science and Education of the Republic of Azerbaijan.

Scientific publications: In total, 47 articles have been published, including 25 in scientific journals and 22 in the proceedings of international and national conferences. Of these, 4 articles were published in *Web of Science*-indexed journals, and 3 in a *Scopus*-indexed journal.

Based on the results of the dissertation: 12 articles were published in scientific journals and 10 in the materials of international and national conferences.

Structure and Volume of the Dissertation: The dissertation consists of an introduction, 4 chapters, a conclusion, a list of 109 references, and 4 appendices. The total volume of the work is 155 pages. The main text is presented on 135 pages. The work includes 9 tables and 55 figures.

CONTENT OF THE DISSERTATION

In the **introduction**, the relevance of the research is substantiated, the level of study of the problem is described, and the object and subject of the research are identified. The research methods are presented, along with the aim of the study and the main statements submitted for defense. Furthermore, the scientific innovations achieved in the dissertation, its practical significance, application, and approval are also outlined.

In **Chapter I**, the current state of the problem of early diagnostics of faults in pump equipment used in oil extraction processes at the late stage of operation is analyzed. A systematic analysis is provided of the main pump equipment used in oil extraction, their existing diagnostic methods, current control stations, and SCADA systems.

Due to prolonged industrial exploitation, oil fields in CIS countries have generally entered the final stage of development. This stage is characterized by difficult extraction of residual reserves, low oil recovery of the reservoirs, significant water content in well production, and a rapid decline in oil production profitability. At this stage, oil is extracted from wells mainly through mechanical methods. The main methods of mechanical production include SRPU (Sucker Rod Pump Units), ESP (Electric Submersible Pumps), and water injection pumps. The first section of Chapter I analyzes the diagnostic challenges related to these pump units.

Modern SRPU systems generally consist of two main parts:
surface equipment (pumpjack, wellhead equipment), **subsurface equipment** (Pump Compressor Pipes, sucker rods, SRP, and various protective devices).

Diagnostics of the technical condition of the SRPU involves:

1. Diagnostics using dynamograms;
2. Diagnostics using wattmetergrams.

All diagnostic methods for SRPU equipment ultimately
lead to the problem of **fault recognition**. Two main recognition methods are considered:

- Recognition by comparing the current dynamogram’s shape with reference signal patterns;
- Diagnostics of SRPU faults using **positional-binary technologies**.

ESP units and their existing diagnostic methods.

All major components of ESP units are located inside the well. On the surface, measuring instruments and remote-control devices are installed to monitor the operation of the submersible pump.

During ESP operation, downhole parameters are monitored.

For this purpose, a submersible telemetry unit is lowered into the well to measure parameters such as, pressure and temperature of the fluid at the pump intake, temperature of the stator winding of the submersible motor, vibration level and the voltage at the motor terminals.

Diagnostics of ESP systems involve surface testing, downhole testing in experimental wells and monitoring of parameters based on measurements of current and voltage consumed by the motor.

Water injection pump units and their diagnostic methods. During oil extraction, low reservoir pressure often leads to a decrease in the oil recovery factor, leaving a significant portion of reserves trapped in the formation. To enhance oil recovery, **reservoir pressure maintenance (RPM)** methods are widely used in global practice.

This method involves injecting water into the productive formations at high pressure through specially located injection wells in the oil field. The injected water displaces the extracted oil, restoring reservoir pressure.

One of the key performance indicators of any RPM system is the reliability and energy efficiency of the technological equipment used in water injection.

From this perspective, monitoring and early diagnostics of the technical condition of water injection pump units is a critical issue. Diagnostic methods include vibration diagnostics, acoustic diagnostics and electrical diagnostics.

In **the second paragraph of chapter I**, a systematic analysis is conducted of the existing control stations and SCADA systems used for pump equipment in oil fields at the late stage of operation. Control controllers, stations, and systems developed both abroad and in our country that have found wide application are reviewed.

In the CIS region, enterprises engaged in the development of well control stations are mainly located in **Azerbaijan** and the **Russian Federation**. In Azerbaijan, the creation of control devices is carried out by the *"Neftgazavtomat" Scientific Research Enterprise* (developer of the NUR telecontrol complex) and the *"Cybernetics" Special Design Bureau (SDB)* (developer of the AYNA telecontrol complex).

The wellhead control device developed at the *"Cybernetics"* SDB is intended to monitor the operation of deep well pump equipment in oil wells. This device measures SRPU dynamograms and processes them using positional-binary diagnostic technology algorithms. Through the use of intelligent technologies for analyzing the obtained results, an improvement in monitoring and diagnostic quality is achieved compared to existing systems.

Another development by the *"Cybernetics" XKB* is the Robust Control Station for SRPU (SRPU-RCS). It is designed to measure technological parameters, including dynamograms and wattmeterograms, monitor the development of the most characteristic faults in both downhole and surface equipment of oil wells, enable robust adjustment of the operating mode of the pumping station, provide protection functions for the electric motor. The SRPU-RCS incorporates hybrid signal analysis technology, diagnostic technologies, positional-binary technology, correlation and spectral analysis of noisy periodic signals. As a result, the intellectualization of analysis outcomes ensures an improvement in the quality of monitoring and diagnostics, which in turn significantly extends the maintenance intervals of wells and enables savings in electric energy.

The most advanced tool for monitoring the operation of ESP (Electric Submersible Pump) wells is the submersible telemetry device. These devices are installed beneath the ESP and transmit the necessary data to the surface. The transmitted data include pressure and temperature of the fluid at the pump intake, temperature of the motor, motor vibration, insulation resistance, fluid flow rate.

To implement these capabilities, the smooth control station for SRPU (SRPU-SCS) has been integrated into the "Ayna" complex. This system combines a remote-control center and a local control station.

There is a growing need for the development of integrated systems capable of monitoring the flawless operation of technological processes and equipment in oil production enterprises and increasing their profitability through parameter control. To this end, the hardware, algorithmic, and software requirements of systems that can keep up with the modern era of information technologies and communication tools are classified as follows:

- General structure of the system and the requirements imposed on it;
- Requirements for the software and technical infrastructure of the complex;
- General requirements for data storage;
- Requirements for monitoring systems of electric motors;
- Requirements for monitoring systems of the condition of downhole equipment in oil wells.

Chapter II of the dissertation addresses the following topics improving the measurement accuracy and sampling frequency of dynamogram signals from SRPU systems in oil fields under long-term operation, developing a new methodology for determining the key parameter values required to construct the plunger dynamogram based on surface measurements, approximate calculation of the maximum and minimum values of the force acting on the polished rod depending on the operation cycle of each well pump.

In the **first paragraph of Chapter II**, the issue of reliable monitoring of the technical condition of SRP (sucker rod pump) equipment in oil fields and adequate diagnostics of malfunctions is considered through the efficient use of useful noises in the output signals of force and displacement sensors of dynamograms. The current measurement method shows the malfunctions in the signals of the force and displacement sensors, whose output signal is industrial-frequency alternating voltage. To eliminate these malfunctions and to avoid losing the noises contained in the signal, a measurement and discretization method using oversampling technologies is proposed. At the same time, to implement this method, algorithms for determining the discretization step, measuring the output signals of the sensors, and collecting dynamogramm data have been developed.

In Azerbaijan’s oil fields, mainly DUI (IQV – intensity force sensor) and DUP (ADS – angular displacement sensor), developed and produced by the “Neftgazavtomat” SIE and installed on the balancer with analog output signals, are used, along with a small number of frequency-output sensors such as DChLP (LDFS – linear displacement frequency sensor) and DChUP (ADFS – angular displacement frequency sensor). The operating principle of such a force sensor is based on determining the value of the displacement of a rod installed on the balancer relative to the sensor, caused by the deformation of the balancer under the weight of the rod string.

As can be seen, this is an indirect measurement method and is quite inaccurate. The reason for the widespread use of these sensors in SRPs is the simplicity of their operation. Despite operational difficulties, the most accurate method for determining the absolute value of the suspended load in SRPs is the use of sensors installed between traverses. However, in fields consisting of low-production wells, replacing existing sensors with new ones is not economically feasible. Therefore, the solution to the problem is to increase efficiency through low-cost measures. One such measure is to improve the measurement accuracy and discretization frequency in order to capture the noises in the output signals of the DUI and DUP sensors used in the fields.

Here, the issue of improving accuracy and discretization frequency by measuring the output signals of DUI and DUP sensors, which have industrial-frequency alternating voltage outputs, using oversampling technologies in order not to lose the noises, is considered. The essence of the oversampling technology is as follows:

1) During the observation T period, the ultra-frequency initial analog signal of $g(\Delta t)$ is converted into a digital code using an analog-to-digital converter (ADC), and a data file consisting of the measurement results is generated.

2) Taking into account adjacent repetitions at the lowest level of the obtained file, N_{q_0} the number of measurements is determined and

$f_{q_0} = \frac{N_{q_0}}{N} f_\nu$ fixed;

3) The discretization step $\Delta t_\varepsilon \leq \frac{1}{(2 \div 5) f_{q_0}}$ is determined so as not to lose the noise components.

Using this technology, during the analog-to-digital conversion (ADC) of any analog signal, it is possible to determine such a discretization step Δt_ε that the noise components within the signal are not filtered out. These noise components can then be utilized for early diagnostics of the equipment's technical condition. To implement the ultra-frequency technology, the following algorithm is proposed (see Fig. 1).

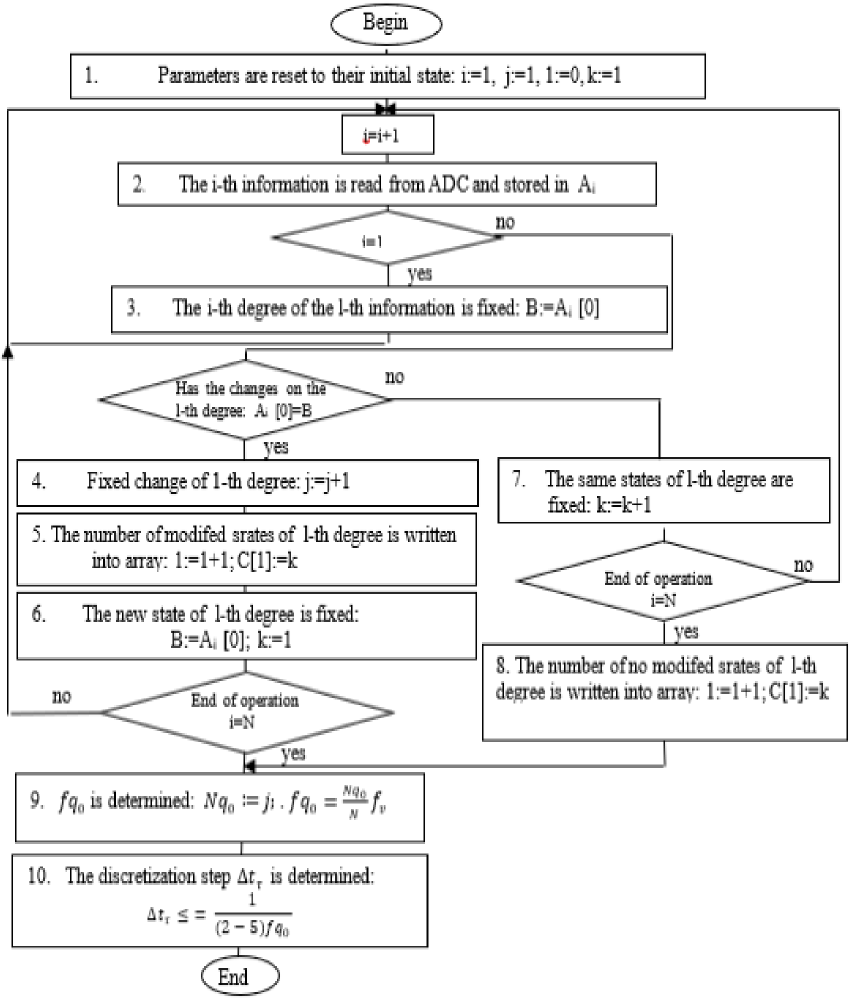

Fig. 1. Discretization step determination algorithm

The paragraph also proposes a technology for measuring the output signals of the DUI and DUP transmitters and collecting dynamogram data (Fig. 2).

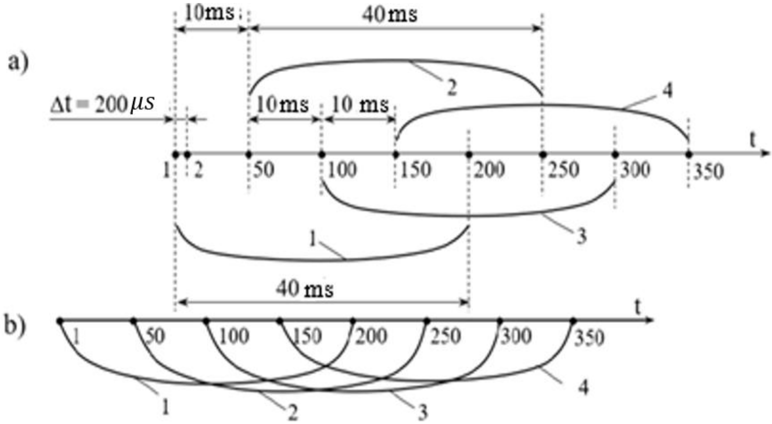

Fig. 2. Output signal measurement technology

To implement the proposed measurement technology, an algorithm was developed for measuring the output signals of the transmitters and summarization of dynamogram data. This technology, along with its algorithm and software, was tested under laboratory conditions and yielded the expected results. The algorithms were implemented as part of the software of the oil well monitoring, diagnostics, and control complex at SOCAR's "Bibiheybat" Oil and Gas Production Department.

In the second **paragraph of Chapter II**, a new methodology is proposed for determining the key parameter values for constructing the plunger dynamogram based on surface measurements. A new approach has been developed for solving the differential equation of the longitudinal waves of the sucker-rod pump (SRP) using the Laplace integral transform.

It is necessary to find the solution of the equation at

$a^2 \frac{\partial^2 u(x,t)}{\partial x^2} = \frac{\partial^2 u(x,t)}{\partial t^2} - b\frac{\partial u(x,t)}{\partial t}$ under the following initial

$u(x,0) = 0, \frac{\partial u(x,t)}{\partial t}(t=0) = 0$ boundary conditions:

$u(0,t) = u_0(t), \; \frac{\partial u(x,t)}{\partial x}(x=0) = \frac{P_0(t)}{Ef}$.

This equation has been solved under the given boundary conditions, and a corresponding algorithm has been developed. As an example, the plunger dynamogram of well No. 720 at oilfield No. 1 of 'Shirvan Oil Company' can be presented (Fig. 3).

The given example demonstrates that the plunger dynamogram significantly improves the diagnostics of the condition of underground equipment.

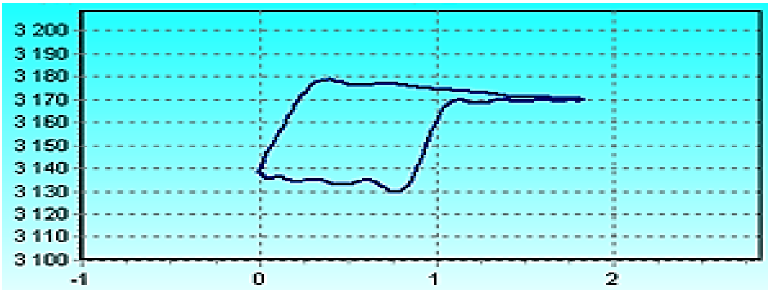

Fig. 3. Plunger dynamogram

In the third paragraph of Chapter II, it is noted that the DUİ (IFS) and DÇLP (LDFS) sensors used in the oil fields of the Republic of Azerbaijan do not allow for the accurate estimation of the absolute value of the force acting on the polished rod of the sucker rod pump (SRP). To address this limitation, an algorithm is proposed for the approximate calculation of the maximum and minimum values of the force acting on the polished rod, depending on the operation cycle of each well pump, and for scaling the output parameters of the sensors based on these calculations.

To compute the extreme (maximum and minimum) forces, formulas developed by A.S. Visnovsky are used. These formulas have been tested under all operational conditions of conventional pumping units at the Azerbaijan State Scientific Research Institute of Oil and have proven to meet all practical accuracy requirements:

$$P_{max} = P'_m + P'_{şt} + \frac{1}{3}\alpha_1 \frac{D}{d}\sqrt{\frac{\omega^2 S_0}{g}}\sqrt{a_1\psi - \frac{\lambda}{S_0}} \cdot (P_{şt} + 0{,}3kP_m) +$$

$$+\frac{1}{2}\alpha_1 \frac{\omega^2 S_0}{g}\left(a_1 - \frac{2\lambda}{\psi S_0}\right)\left(1 - \frac{\psi}{2}\right)P_{şt}$$

$$P_{min} = P'_{şt} - \frac{1}{3}a_2 \frac{D}{d}\sqrt{\frac{\omega^2 S_0}{g}}\sqrt{a_2\psi - \frac{\lambda}{S_0}}P_{şt} - \frac{1}{2}a_2^2 \frac{\omega^2 S_0}{g}\left(a_2 - \frac{2\lambda^{\varphi}}{\psi S_0}\right)\left(1 - \frac{\psi}{2}\right)$$

By calculating the values of P_{max}, P_{min} using A.S. Virnovski's formulas, and by assuming $S_{max} = S_o$, $S_{min} = 0$, the parameters P(t) and S(t) should be scaled using the following formula:

$$y_i = y_{min} + (x_i - x_{min})\frac{y_{max}-y_{min}}{x_{max}-x_{min}};$$

Where x_i , y_i are the values of the parameters at the i -th point before and after scaling, respectively; and $x_{max}, y_{max}, x_{min}, y_{min}$ are the maximum and minimum values of the parameters before and after scaling, respectively.

In the 1st oilfield of "ShirvanOil" Operating Company, the extreme forces acting on the polished rod were calculated using the corresponding data, and the dynamogram was plotted with the physical unit of force in kilograms (kg) and displacement in meters (m).

In Chapter III of the dissertation, a computation technology for position-binary indicators and a method for processing force signals using position-binary technologies are proposed for the early diagnosis of the technical condition of the equipment of the pumpjack. Additionally, the issue of identifying the onset of malfunctions and their development dynamics in response to changes in the technical condition of the SRPU is considered.

In the first paragraph of Chapter III, the issue of developing the computation technology and algorithms for position-binary indicators to perform early diagnostics of the beam pumping unit (MD) equipment is addressed.

Research conducted at the Institute of Control Systems of ANAS has shown that the initial stage of malfunctions leading to accidents is accompanied by low-power and high-frequency noises. These noises serve as carriers of information that indicate the very first moment of an object's transition to an emergency state. At the same time, there is sufficient time between the initial onset of a malfunction and the moment the accident occurs to take preventive measures. However, in existing monitoring and control systems, this noise—the only available source of information—is filtered out and discarded. As a result, the condition of the equipment cannot be adequately identified.

Therefore, in this paragraph, a technology is presented for calculating early diagnostic indicators based on the oversampled and discretized values of the acting load suspended on the rod string of SRP for the early diagnostics of the technical condition of SRP. These indicators are based on the analysis of the signal using positional-binary technologies and the integration of empirical knowledge obtained from existing diagnostic methods. For example, the rocking cycle of the pumping unit is divided into several parts (rod tension, plunger ascent, load lifting, plunger descent), and indicators are defined separately for each of these parts. Thus, for the normal operating mode of the pumping unit, the values of these indicators are determined and recorded in a memory device, and then, for each current cycle of the unit, these indicators are calculated and compared, thereby registering changes in the technical condition.

The positional-binary indicators are generally presented as follows:

$$K_{q_0}=\frac{N_{q_0}}{N}; \quad K_{q_1}=\frac{N_{q_1}}{N}; \quad \ldots\ldots K_{q_{n-1}}=\frac{N_{q_{n-1}}}{N} .$$

Here, q_0 , q_1 , ... q_{n-1} are the corresponding levels of the analog signal obtained from the sensor after it has been converted into digital form; N - the number of discretization's of the signal during one oscillation cycle of the pumpjack; $N_{q_0}, N_{q_1}, \ldots N_{q_{n-1}}$ - are the numbers of “1→0” or “0→1” transitions (positions) at the respective levels q_0 , q_1 , ... q_{n-1} after discretization during the oscillation cycle of the pumpjack.

At the same time, an algorithm for calculating the position-binary indicators for the early diagnosis of the technical condition of the beam pumping unit (MD) has been provided (Fig. 4). The corresponding software for the developed algorithm was created and tested using real dynamogram data obtained from well No. 964 of the "Bibiheybat" OGPD. The results are presented below:
Kqi(11)=0; Kqi(10)=0,01; Kqi(9)=0,01; Kqi(8)=0,02; Kqi(7)=0,03; Kqi(6)=0,07;
Kqi(5)=0,13; Kqi(4)=0,26; Kqi(3)=0,25; Kqi(2)=0,26; Kqi(1)=0,26; Kqi(0)=0,19;

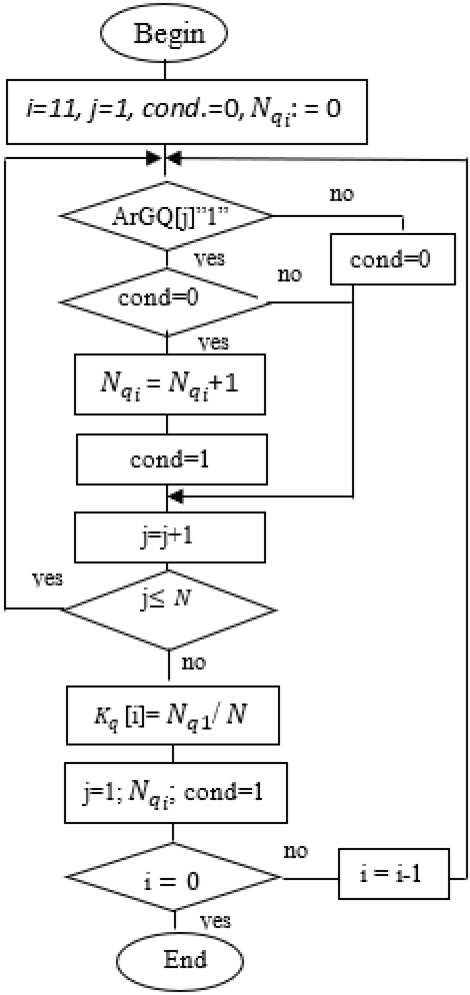

Fig. 4. The calculation algorithm of positional-binary indicators

In the second paragraph of Chapter III, a method is proposed for identifying the technical condition of the SRPU, based for early diagnosis of the technical condition of the pumpjack on the positional-binary processing of the suspended load force signal data from the rod column. This method can be applied for identifying the technical condition of deep-well pump units (SRPU). An algorithm has been developed for identifying the technical condition of the equipment.

The implementation of this algorithm on a real object through a remote monitoring system confirms the increased reliability of automatic diagnostics.

The effective use of pump equipment installed in oil fields is not possible without applying new management methods and forecasting the technical condition of the mechanisms. The development of modern diagnostic methods allows solving problems related to increasing the productivity of the equipment, reducing the commissioning time of the unit, and lowering operational costs.

The essence of the proposed method consists of the following:

1. The analyzed analog signals are divided into positional-binary patterns after being read from the data acquisition system. The length at positions q_1...n of these patterns varies depending on the shape of the initial signals;
2. The length measurements of the PBP are used as informative features;
3. After the segmentation is completed, the signals are compared, and then the similarity between the compared signals is evaluated based on the number of “1” s.

To implement the positional-binary method for two numerical signals of size N, the algorithm shown in Fig. 5 is proposed.

In the third paragraph of Chapter III, the problem of determining the onset of failures and their development dynamics during changes in the technical condition of the sucker rod pump unit (SRPU) in mechanized oil production methods is addressed. Real dynamograms obtained from the SRPU are taken as signals.

The analysis technologies of noise-contaminated signals, developed and qualitatively new at the Institute of Control Systems of the Azerbaijan National Academy of Sciences (ANAS), when applied to the force signal at the suspension point of the sucker rod, can enable the determination of the onset and development dynamics of failures in the sucker rod pumping unit (SRPU).

To identify the beginning of the hidden period of change in the technical condition of the object, it is sufficient in the initial approach to consider the following parameters over a certain time interval:

- f_{qj} — the average frequency of pulses at the j-th position;

- k_{qj} — the ratio coefficient of the average pulse length estimations to the average estimation of the pause period at the j-th position;

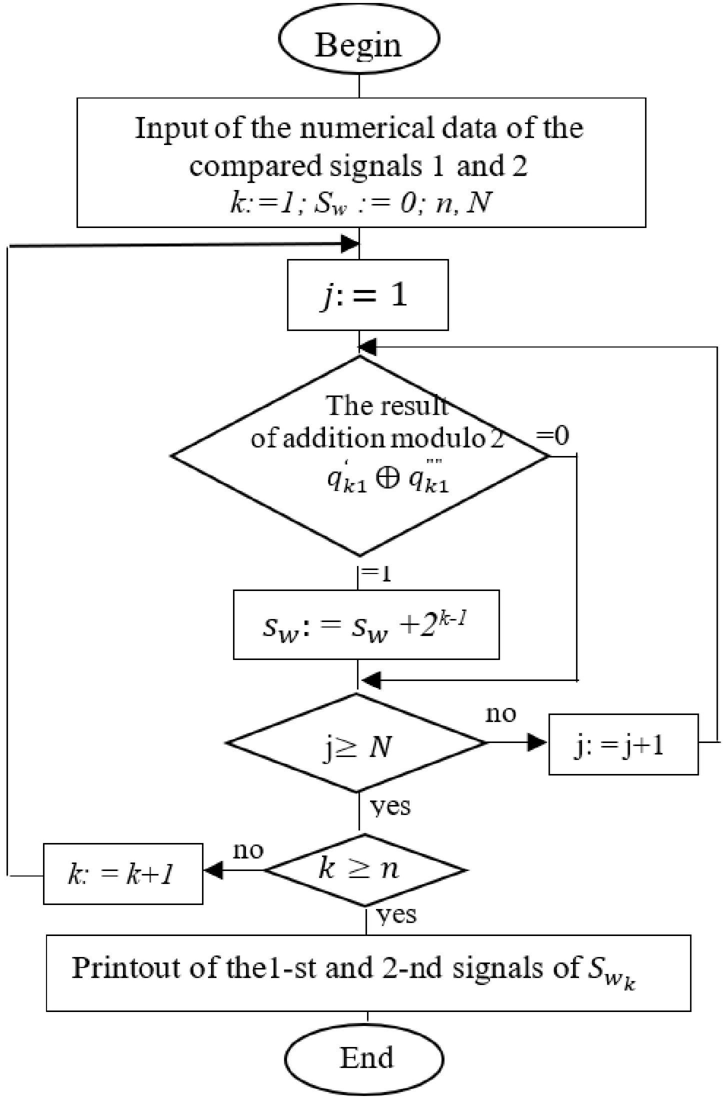

Fig. 5. Block diagram of the comparison of two numerical signals using the positional-binary method

- K_{dqj}— the filling coefficient of pulses at the j-th position.

In the first paragraph of Chapter IV of the dissertation, the technical and software requirements imposed on the structure, components, and functions of the early diagnosis and control system to be developed for oil production enterprises in the final stage of operation have been formulated. It is emphasized that the structure of the early diagnosis and control system for pump equipment in oil production processes at the final operational stage must be hierarchical from bottom to top (see Fig. 6) and comply with other key modern requirements.

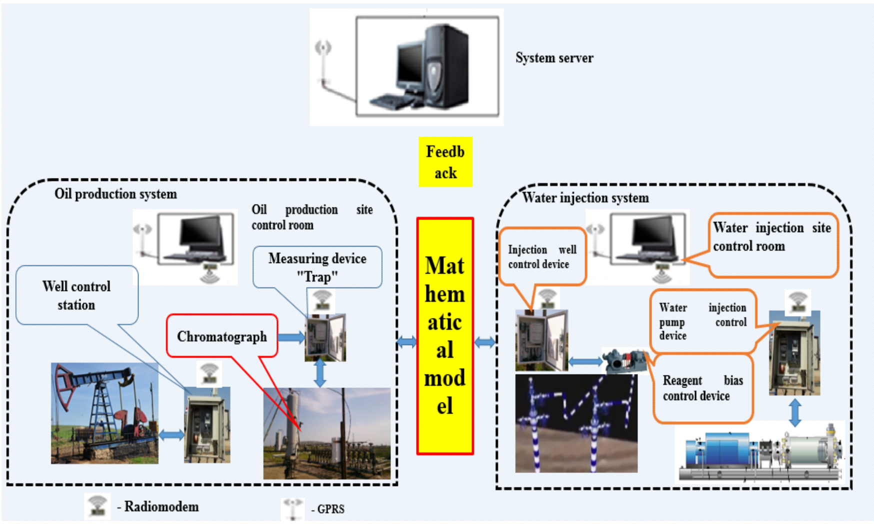

Fig. 6. Structural diagram of the early diagnosis and control system for pump equipment in oil production processes at the final stage of operation

In the second paragraph of the chapter IV, a structural diagram of the “ROBUST NOISE” measurement, monitoring, and control station for the swash plate pump unit, designed to maintain stable formation pressure, is proposed (Fig. 7). The station measures the output signals of vibration sensors at four points near the rolling bearings of the pump and motor rotors at ultra-high frequencies,

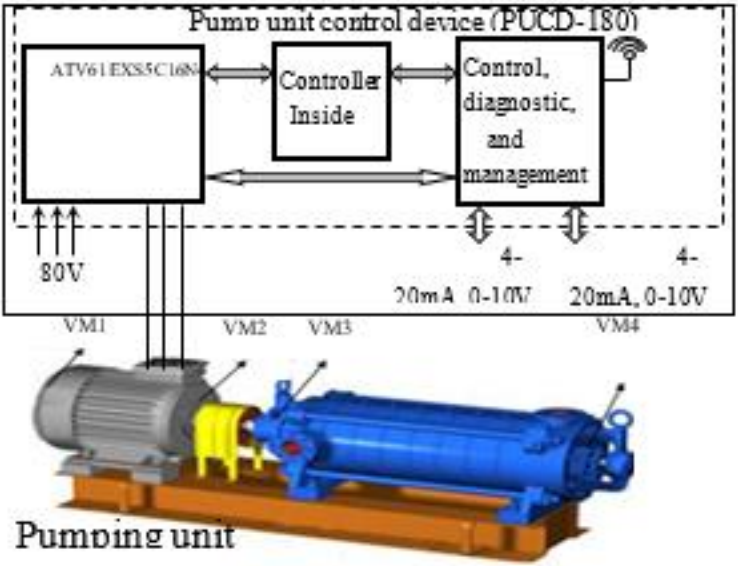

Fig.7. Structural diagram of the RN CM system of PU

performs the calculation algorithm of positional-binary indicators for early diagnosis of the pump unit's technical condition, and transmits the obtained data via radio communication to the responsible authorities for decision-making.

In the third paragraph of the chapter IV, a generalized early diagnostic station for pump units in oil production is proposed (Fig. 8).

The current problems of early diagnostics of pump units are analyzed. As a component of the noise-contaminated signals obtained from the object, a technology is proposed for analyzing the force signals at the suspension point of the sucker rod using the positional-binary method to detect failures in the underground equipment of the sucker rod pumping units (SRPUs), and for analyzing phase currents of motors to determine the onset and development dynamics of failures in the surface equipment of SRPUs and electric submersible pump (ESP) equipment.

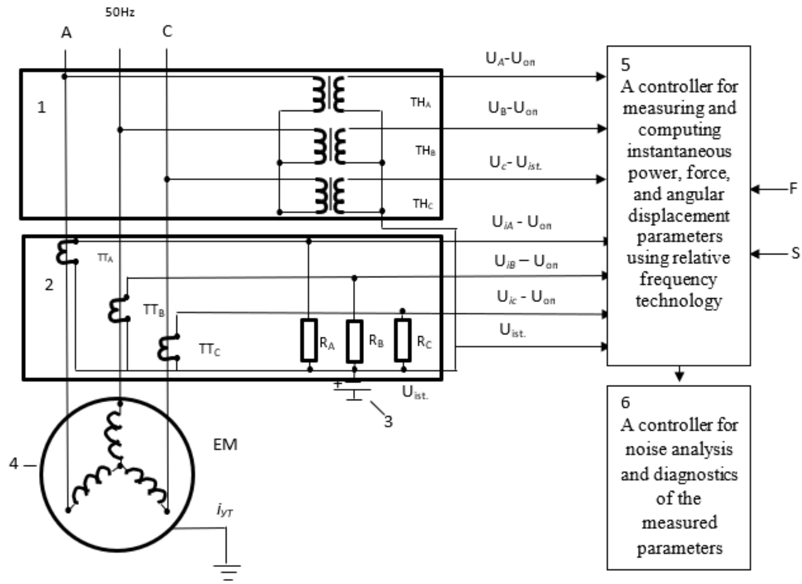

Fig. 8. Structural diagram of the generalized early diagnostic station for pump units in oil production

In the fourth paragraph of the chapter IV, the potential for energy savings is investigated by efficiently utilizing the capabilities of frequency converters that control electric motors in smooth control stations of pump units.

Asynchronous motors (AM) are widely used in all sectors of industry (compressor and pumping stations, ventilation systems, conveyors, elevators, cranes, submersible pumps, etc.). The main advantages of AM are their simple design, high reliability, low cost, and so on. Currently, a large number of frequency converters have been developed that allow wide-range regulation of the AM's rotational speed. Based on these developments, energy-saving control stations for ESPs (electric submersible pumps) have recently been created. These control stations have a significant advantage compared to conventional control stations. The implementation of these newly developed control stations at the "Bibiheybət" Oil Production Department has clearly demonstrated their effectiveness.

Based on real data from SRPU operated at the "Bibiheybat" OGPD of the SOCAR Republic of Azerbaijan, the amount of electricity savings is calculated. A general algorithm is proposed for estimating the energy savings: the output current I_2 of the frequency converter, i.e., the current consumed by the motor, is measured; the motor load is then determined as the ratio of the output current I_2 to the nominal current I_{NOM}. The motor load value given in the table on the next slide determines the value of the power factor $\cos\varphi_2$. Using the formula $\Delta I = I_2(1 - \frac{F_2 \cdot \cos\varphi_2}{F_1 \cdot 0.89})$ the current difference ΔI between input and output currents is calculated. Then, using the formula $EEQ_N = 1.5394 \cdot N \cdot U_1 \cdot \Delta I \cdot 10^{-3}$ and the input voltage U_1, the hourly value of energy savings EES is calculated.

In the fifth paragraph of the chapter IV, the development of software and the issues of its technical implementation are addressed in order to provide real-time monitoring and control of all mechanical equipment connected to the SCADA system at the oil production site.

It is necessary to automate the process of monitoring the status of wells (operating, not operating). The operating and downtime of each well must be recorded, and a database reflecting the work chronology of the wells should be created. When solving this issue, the presence of various software and technical complexes within the mine (“Gilavar,” “NUR,” “Ayna”) must be taken into account.

For the technical solution of the issue, it is planned to generate a signal at stations monitoring wells with ESPs (electric submersible pumps) that indicates the operation of the equipment. This signal makes it possible to determine and record the well’s operating status in real time. The control point’s software includes a program that queries status signals from all controllers. This query process should occur between the two queries of the well’s dynamograms. In this case, the duration of the dynamogram query cycle equally increases the query period for all wells.

An experimental version of this solution was implemented in the “Ayna” monitoring, diagnostics, and control complex at the III mining area of “Shirvan Oil” company. Later, this technology was also used in other mines where the “Ayna” complex was deployed.

To determine the status of the wells, the controller program collects data from sensors at a high frequency, while the dispatcher software queries the status signals every 3–5 minutes and saves the results in a separate file.

As a result, an operational monitoring screen of the mechanical stock has been created in the software (Fig. 9).

Fig. 9. Real-time monitoring screen of the mechanical equipment at the oilfield

On this screen operating wells are shown in green, stopped wells are shown in red. If no response is received from the object's controller during the remote signal query due to various reasons, the well is marked in yellow. Reasons may include power supply interruption, communication loss, line interference, or other malfunctions. Wells excluded from the remote signal query are marked in white on the mechanical stock panel.

By selecting any well from the table, additional information about the well can be obtained current dynamogram of the well, number of cycles, work schedule over a certain period, etc.

As mentioned above, the results of the remote signal query are stored in a separate file. This file contains information about the wells' operation over the last 15 days. This period is conditional and can be changed. One of the most important and useful pieces of information for field personnel and researchers is the ability to monitor well behavior over the specified period (15 days).

MAIN RESULTS OF THE DISSERTATION

1. A systematic analysis of existing diagnostic methods for key pumping equipment used in oil production shows that none of them are capable of performing early diagnostics. The only approach that enables early diagnostics is the analysis of correlated measurable parameters using noise analysis technologies, which can adequately characterize the condition of the equipment [1, 2, 4, 5, 7, 18, 20].
2. To increase the reliability of monitoring the technical condition of sucker rod pumping units (SRPU) and enable early and adequate fault detection through noise technologies, a new signal measurement technology and data acquisition algorithm for DUI and DUP dynamogram transmitters were developed [13, 16].
3. An algorithm for solving the inverse problem using Laplace Transforms were developed to determine the plunger dynamogram of SRPUs based on surface dynamogram data. The reliability and effectiveness of the developed algorithm were verified through practical examples [9].
4. The estimation of the load on the polished rod according to each well's design parameters and the comparison of the current dynamogram with these parameters provide operating personnel with more reliable and visual information about possible malfunctions in the well [6].
5. For early diagnostics of the technical condition of SRPU, a new technology was developed for calculating position-binary indicators from the output signal of force transducers using measurement and oversampling (high-frequency discretization)

technologies. The algorithms and software were tested on actual dynamogram data [14, 17, 19].

6. Based on the regular analysis of the SRPU's periodic force signals using position-binary technologies, identification algorithms and diagnostic methods for assessing technical condition were developed. Compared to conventional spectral analysis methods, the proposed method is simpler to implement [7, 11, 12].

7. A generalized structure of the early diagnostics and control system for pump units in oil production was developed. The components, functions, and position-binary algorithms of the system were formulated within the study [1, 18, 22].

8. With the application of RNMT, a generalized early diagnostic station for pump systems in oil production was developed. A guideline for calculating economic efficiency and a real-time operational monitoring system for equipment were also designed [3, 8, 10, 15, 20, 21].

Note: As a result of this work, the author obtained a Certificate (No. 13833) from the Intellectual Property Agency of the Republic of Azerbaijan for the official registration of the software created based on the developed algorithms.

The Author's Contribution to Co-Authored Publications

1 - Formulation of requirements for the software system of the complex and the storage of information.
2 - Analysis of data exchange protocols and development of a corresponding algorithm.
3 - Development of an operational monitoring algorithm for the mechanical stock of the oil field, implementation of a dedicated subprogram based on this algorithm, and creation of a real-time monitoring interface.
4 - Identification and structuring of additional functions in the “Ayna” software complex that distinguish it from other existing systems.
5 - Analysis of the features of software systems used in current control stations and complexes.

6 - Development of an algorithm for calculating the extreme values of force applied to the polished rod of sucker rod pumping units (SRPU), and validation of the algorithm using real well parameters.
7 - Development of a noise-analysis-based processing algorithm for the control station.
9 - Development of a new method and algorithm for constructing plunger dynamograms, and provision of examples confirming the quality of this algorithm.
10 - Development of a calculation algorithm for energy saving through the use of variable frequency drives (VFDs).
11 - Development of an algorithm for calculating informative features to simplify dynamogram recognition.
12, 13- Development of an algorithm for comparing dynamograms using position-binary technologies to assess the technical condition of SRPU, and implementation of this algorithm in software.
14, 16 - Development of a high-frequency signal acquisition algorithm for measuring the output signals of Force Intensity (DUİ) and Displacement-Speed (DUP) sensors and collecting dynamogram data.
15, 20 - Development of an algorithm for calculating energy savings through the use of VFDs in control and monitoring systems.
17, 18 - Development of a position-binary indicator calculation algorithm for early diagnosis of the technical condition of SRPU, and implementation of the corresponding software.
19 - Development of position-binary indicator calculation and simulation algorithms for monitoring the onset and evolution of malfunctions in SRPU.
22 - Development of control and monitoring system algorithms for the rational management of oil production processes.

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