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INCREASING RELIABILITY AND ENERGY EFFICIENCY OF ELECTRICALLY DRIVEN DRILLING UNITS

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ПІДВИЩЕННЯ НАДІЙНОСТІ ТА ЕНЕРГОЕФЕКТИВНОСТІ ЕЛЕКТРОПРИВОДНИХ БУРИЛЬНИХ УСТАНОВОК

Purpose. The creation of scientific and methodological basis for increasing a reliability and energy efficiency of power supply systems and electrical equipment of oil and gas industry drilling units.

Methodology. The mathematical models of an electrotechnical complex functioning of a drilling unit are synthesized with taking into account technological factors of influence on reliability and energy efficiency during drilling of wells by an electric rotation downhole motor. It allows working out measures to increase the reliability and energy efficiency indicators of electrically driven drilling units.

Findings. Mathematical models of reliability and energy efficiency of power supply systems and electrical equipment of a drilling unit in programming medium of virtual LabVIEW devices have been constructed. The power parameters of electrically driven drilling units have been experimentally obtained by using information-measuring control system of power parameters. The influence of technological and power parameters on reliability and energy efficiency of the electrical drilling equipment has been defined. The requirement of working out the organizational and technical actions directed at the improvement of the electrical drilling equipment functioning has been substantiated.

Originality. The influence of drilling mud temperature in a well on resistance of the electric rotation downhole motor of the electric power supply system has been considered. It has been established that the current spectrum of the submersible electric motor of the electric rotation downhole motor does not contain an inadmissible level of higher harmonics, but asymmetry of currents and voltage decreasing at the electric rotation downhole motor terminals in operation modes occur.

Practical value. The created mathematical models allow predicting the value of the basic indicators of energy efficiency and serviceability of electrotechnical complexes of drilling units on the basis of technological and power parameters for the purpose of an optimal operation mode choice.

Keywords: *reliability, energy efficiency, electric equipment, measurement, virtual devices, electrotechnical complex*

Introduction. The analysis of the current state of the issue of increasing reliability and energy efficiency shows that most enterprises, institutions and organizations are equipped with worn out and out-dated technological equipment, which operates inefficiently, with a low efficiency factor. Power supply systems of electrotechnical complexes of the oil and gas industry do not correspond to the value of installed capacity of consumers and are not adjusted according to the electromagnetic regime compatibility that causes increase in energy losses and deterioration of its quality. Lack of technical electricity metering systems and monitoring of its quality indicators often makes it impossible to analyse power consumption by enterprises divisions. Increase of the voltage level in electricity networks over the acceptable value and the wrong choice of electrical equipment reduce the resource of consumers and increase their power consumption greatly. Drilling units are equipped with regu-

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lated electric drive which is equipped with thyristor converters that distort the current curve shape in phase of electricity network conductors. This fact increases the losses of active electric power. The electrical power supply system of electric rotation downhole motor (EM) “two wires-pipe” causes asymmetry of electric current and voltage of the electric motor, which increases power consumption and decreases the reliability of the whole system.

Analysis of research and publications. The issues concerning research of reliability and energy efficiency of power supply systems and electrical equipment have been considered in works by J. Endreny, I. I. Sud, S. G. Blanter, B. G. Menshov, Ya. V. I. Kostyrko, S. P. Shevchuk, O. S. Beshta and P. V. Vasiuchenko [1, 2]. The solution of the problem was originated in the works of the authors and the research results are presented in their publications [3].

As a result of statistical data analysis obtained at Carpathian drilling enterprises, it was found that the failure mechanisms of the main electrical equipment are described by Weibull-Gnedenko law, which indicates the occurrence of both instant and gradual failures. During its mathematical processing, the statistical information was tested for anomaly by the Smirnov Criterion, then it was tested for uniformity of samples using Fisher’s and Student’s criteria; as for the distribution law hypothesis, it was tested using the criteria of Kolmogorov and Pearson. The density of distribution is determined by the formula

$$f_i\left(t\right)=\left(\frac{t}{a}\right)\left(\frac{b}{a}\right)^{b-1}\cdot e^{-\left(\frac{t}{a}\right)^{b}},$$

where a is the parameter of distribution form for the i-node of electric rotation downhole motor; b is the parameter of distribution scale for the i-node of the electric rotation downhole motor [3].

The parameters of distribution for individual elements are given in Table 1.

The most damaged dipping elements of the electric drilling equipment (EDE) are cable sections, insulation control device, telemetry system, electric motor of electric rotation downhole motor. This is caused by extremely difficult conditions of work in the aggressive environment of drilling mud, namely, by high temperature and pressure (up to 150 °C and 100 MPa respectively), significant vibration (amplitude up to 5 mm), and the presence of small abrasive. The cyclic operating mode of EDE while drilling wells also reduces the resource of dipping elements.

Table 1

The parameters of distribution of Weibull-Gnedenko

Name of the element	Parameter ***a***	Parameter ***b***
Transformer	19729	1.33
Control station	1039	1.17
Current collector	263.5	1.05
Insulation control device	168.7	1.35
Telemetry system	115	1.25
Electric rotation downhole motor	132	1.55
Cable sections	151.8	1.72

The quantitative indicators of reliability of power supply system of the electric rotation downhole motor are given in Table 2.

Unsolved aspects of the problem. To achieve the goal it is necessary to solve the following problems: to develop a mathematical model of reliability and energy efficiency of drilling units in the LABview medium; to investigate the impact of technological and energy parameters on energy efficiency and reliability of electrical equipment; to carry out the experimental energy study of the electric part of drilling units.

Presentation of the main research. To carry out research on an electrotechnical complex for the electrical drilling in the medium of LabVIEW virtual programming of National Instruments Company, a model of power supply system of EM was created.

Although LabVIEW software is designed mainly for automation of the metrological part of active experiments and control tasks, it includes subroutine libraries of standard algorithms of data processing and mathematical functions. The advantage of the mathematical modeling in LabVIEW is the possibility of combining computer programs of the mathematical models and measurements as well as registration of data during experimental research of electrotechnical complexes functioning on a real time basis.

The initial data for calculation are the parameters of drilling transformer (DT) and electric motor EM: nominal secondary voltage of DT windings; nominal secondary current; short-circuit voltage and power losses of short-circuit. The above parameters are obtained from catalog data of drilling electrical equipment.

Table 2

The quantitative indicators of reliability of the power supply system electric of the rotation downhole motor

Name of the element	Mean time between failure, hour	Failure flow parameter, $\times 10^{-4}$	The average repair time, hour
Current collector	186	1.4	23.6
Telemetry system	244.7	1.2	20.4
Insulation control device	106.2	1.6	13.9
Cable section	149.9	1.3	18.8
Electric rotation downhole motor control station	988.4	0.96	16.4
Overhead power transmission line 6 kV	16 723.2	0.46	20.3
Drilling transformer	17 914.1	0.5	70.2

For EM, we enter: the nominal voltage value of the electric motor; nominal current of stator phase; active and inductive resistances of stator and rotor phase; active and inductive resistance of magnetizing circuit; synchronous and nominal rotation speeds. The value of active and inductive resistances of EM electric motor used in the equivalent circuit, are obtained by recalculating nameplate data.

The mathematical model allows exploring the functioning of the EM.

The complex resistance of electric motor phase

$$Z(s) = Z_1 + \frac{Z_m \cdot Z_2(s)}{Z_m + Z_2(s)},$$

where Z_1 is complex resistance of the stator phase; Z_m is complex resistance of magnetizing branch; $Z_2(s)$ is resistance of the rotor phase that depends on the slipping.

Taking into account the temperature of drilling mud, the specific active resistance of the pipe and cable cores of current lead of the “two wires–pipe” system is

$$R_t = r_{t20}(1 + 0.006T_{br});$$

$$R_g = r_{g20}(1 + 0.004T_{br}),$$

where t_{r20}, r_{g20} are the specific active resistances of the pipe and cable core at a temperature of 20 °C; T_{br} is the temperature of drilling mud.

The complex resistance of drill pipe and cable core takes into account components of inductive resistances which are obtained by approximation of their tabular values given in the instructions for electric drilling

$$Z_t(s) = R_t(s) + X_t(s) \cdot i;$$

$$Z_g(s) = R_g(s) + X_g \cdot i,$$

where X_t is inductive resistance of the pipe; X_g is inductive resistance of the cable core which is determined by the calculation-experimental method taking into account the capacitive component.

The complex resistances of **a, b, c** phases of power supply system of electric motor depend on the slipping

$$Z_a(s) = Z(s) + Z_t(s) + Z_{tr};$$

$$Z_b(s) = Z_c(s) = Z(s) + Z_g(s) + Z_{tr},$$

where Z_{tr} is complex resistance of the drilling transformer, which is calculated taking into account the actual voltage of secondary winding, which varies depending on the depth of drilling; $Z_t(s)$, $Z_g(s)$ are complex resistances of the drill pipe and cable cores taking into account inductive resistances which are obtained by approximation of their tabular values.

The calculation of currents in phases of the current lead, the voltage at the clamps of electric rotation downhole motor and torque on its shaft is carried out according to the known formulas.

The active power that is consumed at the beginning of the current lead is

$$P(s) = P_a(s) + P_b(s) + P_c(s).$$

The power losses in the current lead are

$$\Delta P(s) = I_a^2(s)R_t(s) + I_b^2(s)R_g(s) + I_c^2(s)R_g(s).$$

The active power that is consumed by electric rotation downhole motor is

$$P_{elb}(s) = P(s) - \Delta P(s).$$

The dependence of the mechanical power on the motor shaft on the slipping is

$$P_{mech}(s) = \omega \cdot M(s),$$

where ω is angular shaft rotation velocity, $с^{-1}$; $M(s)$ is torque on the motor shaft, Н · m.

The modeling results in active power of consumption of EM power supply system, active power on the shaft EM and power losses. Energy efficiency coefficient of conversion of electric power at the current lead beginning into the mechanical power of chisels is determined according to their values

$$K_{enef}(s) = \frac{P_{mech}(s)}{P(s)}.$$

As a result of calculations we obtain the dependence of energy parameters of the electric motor of the electric rotation downhole motor on load; Fig. 1 illustrates the parameters.

Particularly, dependences of the currents in the cable cores and drilling pipe, phase voltages at the clamps of the electric motor, torque on its shaft, active power at the beginning of the current lead and mechanical power on the shaft of the electric motor EM are shown.

The above energy parameters are obtained for the electric rotation downhole motor of E240-8M brand in the course of directional drilling of gas operational wells at a depth of 2 km.

When drilling rocks that are deposited at a depth within 2 km from the surface and range of EM load changes from a non-working stroke to the critical slip, the energy efficiency coefficient K_enef of drilling a well depending on the drilling depth L and slipping s is shown in Fig. 2.

Thus, the maximum efficiency of drilling lower intervals of wells may be provided at load of electric motor slightly less than nominal.

The developed model is a precondition to the creation of an information-measuring complex for studying the energy indicators of electrical equipment and indicators of electrical power quality.

The complex is a universal information-measuring computer portable system that is designed for carrying out experimental scientific research on electrotechnical complex functioning.

The work is developed on the technology of virtual devices that is based on the methods of digital signal processing and graphical programming of algorithms of application programs.

The information-measuring complex includes multi range flexible coils for measuring current of Rogowski type Fluke i3000 Flex; voltage converters of compensat-

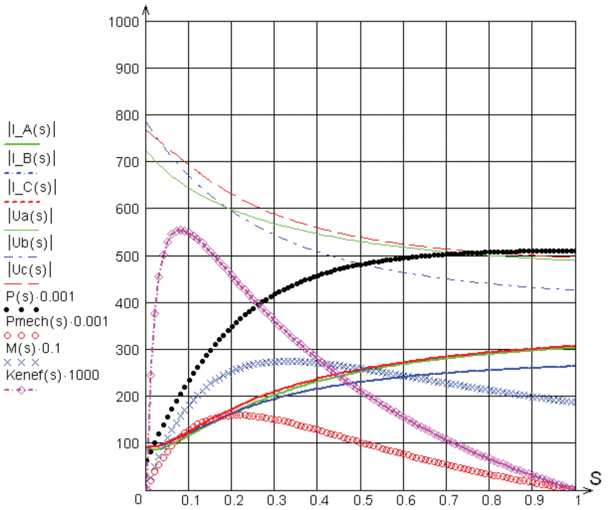

Fig. 1. Energy parameters of E240-8M electric rotation downhole motor in the course of well drilling at a depth of 2 km

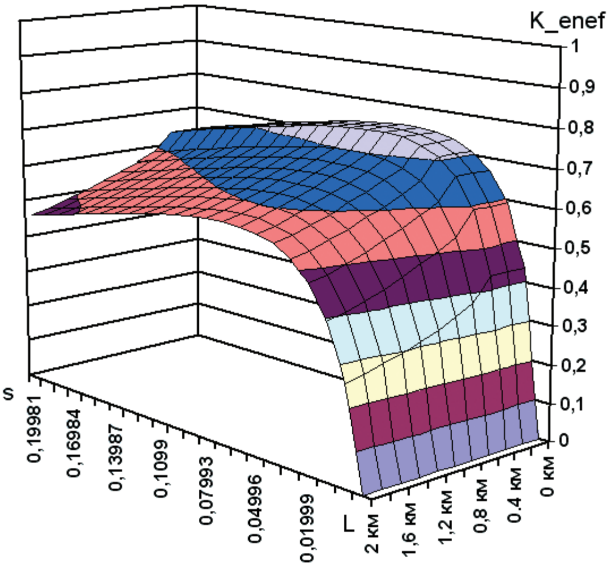

Fig. 2. Changes of the energy efficiency coefficient of well drilling at different depths and loads

ing type of CV3-1000 brand; a 4-channel 16-bit analog-to-digital converter (ADC) with USB-interface NI-6210 and a laptop with developed software.

Rogowski coils are mounted around a conductor with current or tire without breaking the electrical circuit, structurally composed of measuring winding, placed inside a flexible electrical insulating frame that closes into the ring with a special lock and an electronic amplifier-normalizer of a signal with a coaxial clamp for connection to the oscilloscopes or ADC. The upper limit of the measuring range of the alternating current is 30 A, 300 A and 3000 A in the frequency range from 20 to 10,000 Hz. The accuracy class of voltage measurement makes 0.5, that of current measurement is 2, and of power measurement is 2.5.

First, the recording of initial measured instantaneous values of voltages and currents in the file is carried out, and then the program of their mathematical processing is launched.

Efficient voltage values of phase voltages and currents at the beginning of the current lead are determined by a method of integrating the squares of instantaneous values

$$U=\sqrt{\frac{1}{T}\int_0^T u(t)dt};$$

$$I=\sqrt{\frac{1}{T}\int_0^T i(t)dt},$$

where $u(t)$, $i(t)$ are instantaneous values of voltage and current; T is an integration period.

The active power at the beginning of the current lead is calculated by averaging for the period value of the instantaneous power

$$P=\frac{1}{T}\int_0^T p(t)dt.$$

Using the control system also makes it possible to define unreliable elements by fixing the rejection of their technological parameters behind permissible limits.

The collection of experimental data at “Sybivka” No. 111 wellsite of Carpathian Drilling Office in Yasenovets village, Rozhniativ district, Ivano-Frankivsk region was conducted by means of the measuring complex.

The next data are acquired during the experiment: active motor power P_zed, current asymmetry coefficient εі, torque on drill bit M_dol, phase currents IA, IB, IC and voltages Ua, Ub, Uc at a depth of 2300 m (Fig. 3).

The spectral analysis of voltage and current curves was conducted in the course of further processing of experimental data in order to determine the coefficient of harmonics, which is shown in Fig. 4.

The conducted experimental research on the existing drilling units and mathematical modeling results show that the value of the efficiency coefficient of well drilling by the electric rotation downhole motor ranges from 40 to 60 %, the coefficient of harmonic distortions of current of the electric rotation downhole motor does not exceed 3 %, and the coefficient of current asymmetry ranges from 3 to 7 %. The low energy efficiency is caused by significant losses of active power in the current lead of the “two wires – pipe” system. Quantitative indicators of the reliability of submersible equipment are low.

It should be noted that the existing electric drilling equipment is outmoded and obsolete, has a low indicators of energy efficiency and reliability, which causes the necessity of improvement of energy efficiency of functioning as well as modernization and reconstruction.

Conclusions. The monitoring of energy parameters of the system of electric drive of a drill chisel, which has showed significant load imbalance of electric drill in the process of active drilling, current unsymmetry and the absence of higher harmonics was conducted by means of developed information-measuring system.

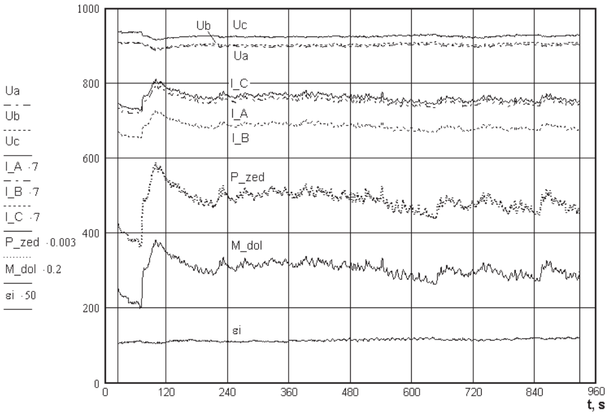

Fig. 3. Dynamics of change of phase voltages, currents, powers and asymmetry coefficient of currents of EM in the process of well drilling

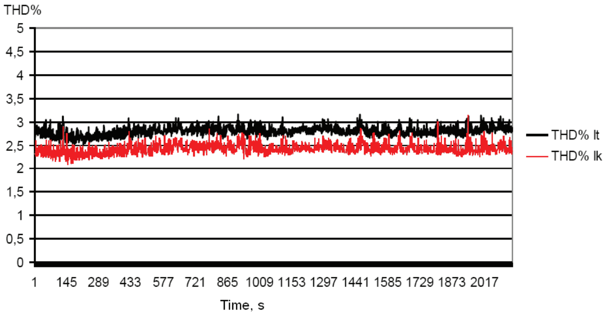

Fig. 4. Dependence of the current harmonics coefficient of the cable core and pipe in time

The energy indicators of functioning have been defined and their lack of efficiency has been marked by calculation-experimental method using a mathematical model of power supply system of electric drill.

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Мета. Створення науково-методологічної бази для підвищення надійності та енергоефективності систем електропостачання та електрообладнання бурильних установок нафтогазової промисловості.

Методика. Математичні моделі функціонування електротехнічного комплексу бурильної установки синтезуються з урахуванням технологічних факторів впливу на надійність та енергоефективність у процесі буріння свердловин електробуром. Це дозволяє розробити заходи з підвищення показників надійності та енергоефективності електроприводних бурильних установок.

Результати. Побудовані математичні моделі надійності та енергоефективності систем електропостачання та електрообладнання бурильної установки в середовищі програмування віртуальних приладів LabVIEW. За допомогою інформаційно-вимірювальної системи контролю енергетичних параметрів експериментально отримані енергетичні параметри електроприводних бурильних установок, визначений їх вплив на надійність і енергоефективність обладнання. Обґрунтована необхідність розробки організаційних і технічних заходів, спрямованих на покращення функціонування електробурильного обладнання.

Наукова новизна. Враховано вплив температури бурильного розчину у свердловині на опори струмовідводу електробура. Встановлено, що спектр струму занурювального електродвигуна електробура не містить недопустимого рівня вищих гармонік, однак наявні несиметрія струмів і зниження напруги на затискачах електробура в робочих режимах буріння.

Практична значимість. Створені математичні моделі дозволяють прогнозувати значення основних показників енергоефективності та експлуатаційної надійності електротехнічних комплексів бурильних установок на базі технологічних і енергетичних параметрів з метою вибору оптимального режиму роботи.

Ключові слова: *надійність, енергоефективність, електрообладнання, вимірювання, віртуальні прилади, електротехнічний комплекс*

Цель. Создание научно-методологической базы повышения надежности и энергоэффективности систем электроснабжения и электрооборудования буровых установок нефтегазовой промышленности.

Методика. Математические модели функционирования электротехнического комплекса буровой установки синтезируются з учётом технологических факторов влияния на надёжность и энергоэффективность в процессе бурения скважин электробуром. Это позволяет разработать мероприятия по повышению показателей надёжности и энергоэффективности электроприводных буровых установок.

Результаты. Построены математические модели надежности и энергоэффективности системы электроснабжения и электрооборудования буровой установки в среде программирования виртуальных приборов LabVIEW. С помощью информационно-измерительной системы контроля энергетических параметров экспериментально получены энергетические параметры электроприводных буровых установок, определено их влияние на надежность и энергоэффективность оборудования. Обоснована необходимость разработки организационных и технических мероприятий, направленных на улучшение функционирования электробурового оборудования.

Научная новизна. Учтено влияние температуры бурового раствора в скважине на сопротивления токоподвода электробура. Установлено, что спектр тока погружного электродвигателя электробура не имеет недопустимого уровня высших гармоник, но присутствуют несимметрия токов и снижение напряжения на зажимах электробура в рабочих режимах бурения.

Практическая значимость. Созданные математические модели позволяют прогнозировать значение основных показателей энергоэффективности и эксплуатационной надежности электротехнических комплексов буровых установок на базе технологических и энергетических параметров с целью выбора оптимального режима работы.

Ключевые слова: *надежность, энергоэффективность, электрооборудование, измерения, виртуальные приборы, электротехнический комплекс*

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