

Intelligent System for Signaling the Beginning of Accidents on Drilling Rigs Based on the Wattmeter Charts

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Abstract—At present, in order to ensure accident-free operation of drilling rigs, advanced and expensive multifunctional systems of drilling monitoring and control are used. In spite of that a significant number of accidents take place and the probability of their occurrence to a certain extent depends on qualification of a driller, who, on the basis of his experience and also taking into account information from control systems, determines the current technical condition of the drilling string and beginning of possible accidents. Malfunctions are indirectly reflected in the wattmeter chart of the drill string motor. However, the information contained in the wattmeter charts, which reflects the technical condition of the drilling rigs and has a great diagnostic information potential, is not used in the control systems. Therefore, in order to exclude possible mistakes of a driller it is necessary to provide him with tools, allowing to facilitate his intuitive activity. In this regard, in order to ensure accident-free drilling process, it is proposed to create a signaling system to warn the driller about the beginning of a latent period of equipment malfunctions by analyzing the wattmeter chart with the use of possibilities of noise analysis technology and adaptive analogue-digital sampling.

Keywords—drilling rig, wattmeter chart, correlation, the noise, accident, malfunction, informative attribute, control, signaling

I. INTRODUCTION

At present, the most widespread is rotary drilling, in which the rock-cutting tool is rotated by a special mechanism - rotary spindle or rotor through the drill string. Various modern systems have been developed and are used to monitor and control the drilling process in order to minimize possible accidents. All these systems of control and management of the drilling process take readings of sensors in real time, carry out processing of measurements, and also perform continuous control and management of a full technological cycle of well construction, carry out forecasting for timely prevention of emergency situations [1-4].

The set of parameters to be controlled when drilling deep wells include: weight on the hook, pressure of flushing fluid at the well inlet, flushing fluid density at the well inlet, rotor torque, flushing fluid flow rate at the well outlet, flushing fluid flow rate at the well inlet, tripping speed, mechanical drilling speed, temperature at the well outlet, etc. [1-4].

Despite the use of the above-mentioned rig control systems (RCS), at present the process of well drilling is accompanied by an unreasonably high number of costly accidents. This is due to the fact that the occurrence of accidents while drilling wells is due to its features such as multifactorial and uncertain mechanisms of accidents, their regional specificity, rapidity, difficult accessibility for instrumental control, vagueness and ambiguity of the observed symptoms [1-4]. Of the above, the results of measurements made during drilling are affected by random factors and, therefore, many experts reasonably believe that the efficiency and safety of drilling with the use of existing systems largely depend on the qualification of the driller.

II. PROBLEM STATEMENT

As stated above, nowadays rotary drilling is common, when the rock-cutting tool receives rotation from a special mechanism - rotary spindle or rotor through the drill pipe string or from downhole motor [1, 2]. All these processes are inevitably reflected in the signals received from the sensors of such controlled drilling parameters as bit rotational speed $g_1(t)$, torque on the rotary spindle of the drilling rig $g_2(t)$, drill rotor torque $g_3(t)$, mechanical drilling speed $g_4(t)$, and axial load on the bit $g_5(t)$. They carry certain information about the technical condition of the drill rig.

Analysis of the operation of drilling rigs [1, 2] shows that its technical condition in addition to the above signals is also reflected on the wattmeter chart $g(t)$ of its electric motor. And at the beginning of the latent period of the emergency

state on the rig on the wattmeter chart $g(t)$ along with the noise $\varepsilon_1(t)$, caused by external factors, the influence of the onset of a malfunction causes the noise $\varepsilon_2(t)$ correlated with the useful signal $X(t)$, which is the carrier of information about the beginning of the latent period of an accident [1-4] $g(t) = X(t) + \varepsilon_1(t) + \varepsilon_2(t)$. This occurs much earlier than the readings of measuring instruments of the RCS change, with the help of which the operating personnel performs control and makes appropriate decisions. In this case, due to the presence of correlation between the useful signal $X(t)$ and the total noise $\varepsilon(t) = \varepsilon_1(t) + \varepsilon_2(t)$, the variance of the wattmeter chart $g(t)$ is determined from the expression:

$$D_g = M[(X(t) + \varepsilon(t))(X(t) + \varepsilon(t))] = \\ = M[X(t)X(t)] + 2M[X(t)\varepsilon(t)] + M[\varepsilon(t)\varepsilon(t)],$$

where

$$M[X(t)X(t)] = D_x, \quad M[X(t)\varepsilon(t)] = R_{x\varepsilon}(0) \neq 0, \\ M[\varepsilon(t)\varepsilon(t)] = D_{\varepsilon\varepsilon} \neq 0.$$

Consequently, the formula for determining the variance D_g of the wattmeter chart $g(i\Delta t)$ can be represented as:

$$D_g \approx D_x + 2M[X(t)\varepsilon(t)] + D_{\varepsilon\varepsilon},$$

which shows that at the beginning of the malfunction of the rig on the wattmeter chart, correlation emerges between the useful signal $X(t)$ and the total noise $\varepsilon(t)$, making it difficult to monitor the onset of a malfunction using conventional techniques. For this reason, RCS does not provide the driller with adequate information about the initial latent period of the malfunction condition.

At first glance, filtering of the noise that accompanies the useful signal $g(i\Delta t)$ can eliminate the influence of these errors on the control result. When the noise spectrum is stable, application of filtering technology usually gives satisfactory results. However, the noise spectrum changes over a wide range during drilling due to drastic changes in the factors of its formation. Because of this, the range of noise spectrum also changes over a wide range and often overlaps with the range of the spectrum of the useful signal. For these reasons, application of the wattmeter chart filtering technology does not achieve the desired result.

On the contrary, a more realistic variant of solving the problem comes down to using noise as a carrier of diagnostic information. However, in this case, in order to ensure the adequacy of the control results, it is also necessary to ensure the accuracy of selection of the sampling interval of the noise $\varepsilon(t)$ of the wattmeter chart $g(i\Delta t)$. Given this reason, when creating a system for signaling the beginning of a latent period of malfunctions of drilling rig equipment, based on the analysis of the wattmeter chart noise $g(i\Delta t)$ it is also necessary to ensure its adaptive sampling.

III. TECHNOLOGY OF MEASURING THE WATTMETER CHART OF THE ELECTRIC MOTOR ON THE DRILLING RIG.

At drilling rigs the beginning of the latent period of accidents and dynamics of its development depend on specifics of the field and technical condition of the equipment, the mode of its operation, etc. The latent period of accidents before they become explicit is always preceded by the onset of malfunction, which is reflected on the wattmeter chart. However, existing control systems do not detect this information about the beginning of the accident reflected in wattmeter charts. Because of this, the information contained in the wattmeter chart and the accompanying noise, which is an important source of information about the onset of malfunctions, is not used. At the same time, between the initial latent period and the time of the accident, there is usually enough time to take measures to prevent the accident. Due to the above, there are cases when it is not possible to prevent an accident on drilling rigs [2-4].

Below, for the 3-wire circuit of the drill string, which supplies power to its **electric motor**, we propose a circuit for measuring power (Fig. 1), with a distinguishing feature of measuring voltages and currents of all phases relative to the artificial zero.

As a result, unlike the traditional scheme in which the parameters were measured: i_A, i_B, u_{AC}, u_{BC} , the proposed scheme measures the parameters: $i_A, i_B, i_C, u_A, u_B, u_C$.

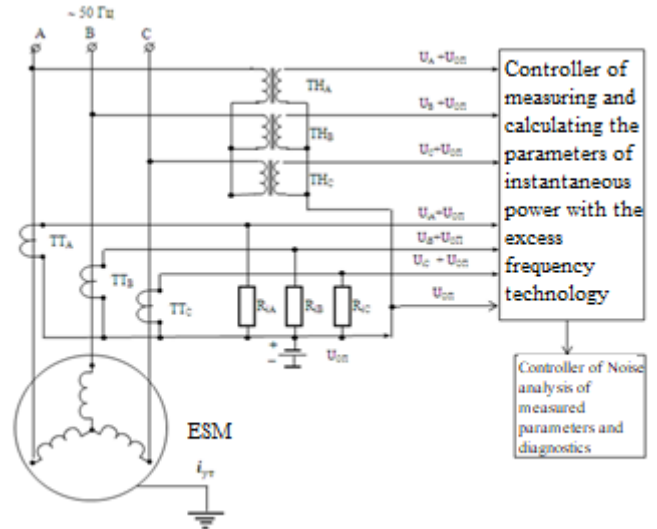


Fig. 1. Schematic of the measurement of the electric motor power consumption parameters.

Experimental studies have confirmed that when malfunctions occur on drilling rigs on the wattmeter of the electric motor, by which the drilling string is driven, from a variety of geological and technical drilling conditions, from strong variations in temperature, humidity, wind, etc. the noise $\varepsilon_1(t)$ emerges. From the occurrence of various defects in the mechanical parts of the string in the process of drilling (wear, bending, cracking, fatigue, etc.) the noise $\varepsilon_2(t)$ forms, which has a correlation with the useful signal $X(t)$ of the wattmeter

chart [10]. The total noise that accompanies the useful signal $X(t)$ wattmeter chart has the following form:

$$\varepsilon(t) = \varepsilon_1(t) + \varepsilon_2(t),$$

and it is reflected symmetrically in all three phases of the wattmeter chart $g(i\Delta t)$. Therefore, when forming informative attributes, reflecting the technical condition of the drilling rig, it is advisable to analyze one of the three phases. At the same time, to exclude additional errors arising during analog-to-digital conversion of the wattmeter chart, it is necessary to ensure adaptivity when selecting the sampling interval [6-10].

Note that the parameters of the wattmeter chart $i_A, i_B, i_C, u_A, u_B, u_C$ also contain additional information for equipment diagnostics. For example, the difference in the sum of instantaneous values of phase currents means insulation failures, i.e. current leakage to the motor housing. Measurement according to the proposed scheme allows to determine instantaneous values of power consumption of each stator winding separately, to determine their average values for a certain period, and comparing them with corresponding previous values to make a conclusion about changes in windings (turn-to-turn short circuits).

IV. CONTROL OF THE BEGINNING OF A MALFUNCTION OF RIGS BASED ON CHANGES IN THE RATIO OF ESTIMATES OF THE TOTAL SIGNAL, THE USEFUL SIGNAL AND THE NOISE OF THE NOISY VIBRATION SIGNAL

It is known that in the process of drilling from the occurrence of torsional, axial and lateral vibrations a random vibration process is formed, which is reflected on the wattmeter chart $g(i\Delta t)$. Here, the drilling string in the process of operation goes into the latent period of initiation of various defects [10-12], which are reflected on the wattmeter chart $g(i\Delta t)$ as the noise $\varepsilon_2(i\Delta t)$, which, starting from this moment has a correlation with the useful signals $X(i\Delta t)$. Because of this, the total noise is formed from the noise $\varepsilon_1(i\Delta t)$, which arises from the influence of external factors and from the noise $\varepsilon_2(i\Delta t)$ caused by various malfunctions. This affects the estimate of the correlation function $R_{gg}(\mu)$ of the wattmeter chart, which is determined from the formula:

$$\begin{aligned} R_{gg}(\mu) &\approx \frac{1}{N} \sum_{i=1}^N g(i\Delta t)g((i+\mu)\Delta t) \approx \frac{1}{N} \sum_{i=1}^N (X(i\Delta t) + \varepsilon(i\Delta t))(X((i+\mu)\Delta t) + \varepsilon((i+\mu)\Delta t)) \approx \\ &\approx \frac{1}{N} \sum_{i=1}^N X(i\Delta t)X((i+\mu)\Delta t) + \varepsilon(i\Delta t)X((i+\mu)\Delta t) + \\ &+ X(i\Delta t)\varepsilon((i+\mu)\Delta t) + \varepsilon(i\Delta t)\varepsilon((i+\mu)\Delta t) \approx \\ &\approx R_{XX}(\mu) + R_{\varepsilon X}(\mu) + R_{X\varepsilon}(\mu) + R_{\varepsilon\varepsilon}(\mu) \approx \\ &\approx \begin{cases} R_{XX}(0) + 2R_{X\varepsilon}(0) + R_{\varepsilon\varepsilon}(0) & \text{when } \mu = 0 \\ R_{XX}(\mu) + 2R_{X\varepsilon}(\mu) & \text{when } \mu \neq 0 \end{cases} \end{aligned}$$

Experimental studies have shown [3,4-9] that during the drilling the estimates of $R_{X\varepsilon}(\mu)$, $R_{\varepsilon\varepsilon}(\mu)$ of the wattmeter chart of electric motors of drilling rigs represent a tangible value, i.e. the inequality:

$$\begin{cases} R_{X\varepsilon}(\mu) \gg 0 \\ R_{\varepsilon\varepsilon}(\mu) \gg 0 \end{cases}$$

takes place, and therefore there is a considerable margin of error in the estimate of $R_{gg}(\mu)$.

Because of this there is a difficulty in ensuring the adequacy of the results of control of the performance of the equipment using the estimate of $R_{gg}(\mu)$ of the wattmeter chart. This is one of the factors hindering the use of traditional noisy signal analysis technologies for malfunction control on drilling rigs. At the same time [4-10], changes in the technical condition of the rig are primarily reflected in the estimates of the variance D_g , the wattmeter chart $g(i\Delta t)$, the variance of the useful signal D_X , and the noise variance D_ε .

The studies have shown that in this case an effective informative attribute of the beginning of accidents is the coefficients obtained from the ratios of these estimates, which are determined from the formulas:

$$K_1 = \frac{D_X}{D_g}, K_2 = \frac{D_{\varepsilon\varepsilon}}{D_g}, K_3 = \frac{D_{\varepsilon\varepsilon}}{D_X}. \quad (1)$$

where

$$D_g = \frac{1}{N} \sum_{i=1}^N g^2(i\Delta t) \quad (2)$$

$$D_X = \frac{1}{N} \sum_{i=1}^N X^2(i\Delta t), \quad (3)$$

$$D_{\varepsilon\varepsilon} = \frac{1}{N} \sum_{i=1}^N \varepsilon^2(i\Delta t). \quad (4)$$

However, the estimates of D_X and $D_{\varepsilon\varepsilon}$ cannot be practically determined from formulas (3), (4).

It has been shown in [1, 2] that the estimates of $D_{\varepsilon\varepsilon}$ of the variance of the total noise $\varepsilon(i\Delta t)$ can be determined from the expression:

$$\begin{aligned} D_{\varepsilon\varepsilon} &\approx R_{\varepsilon\varepsilon}(0) \approx \frac{1}{N} \sum_{i=1}^N [g^2(i\Delta t) + g(i\Delta t)g((i+2)\Delta t) - \\ &- 2g(i\Delta t)g((i+1)\Delta t)] \end{aligned} \quad (5)$$

Due to this the estimate of the variance of the useful signal $X(i\Delta t)$ can be determined from the formula:

$$D_X = D_g - D_{\varepsilon\varepsilon}. \quad (6)$$

Thus, after determining the estimates of D_g , D_X , $D_{\varepsilon\varepsilon}$ from formulas (2), (5), (6) it is possible to determine from formula (1) the estimates of coefficients K_1 , K_2 , K_3 which can be used as informative attributes when creating a system for signaling the beginning of malfunctions of a drilling rig.

V. EXAMPLE OF PRACTICAL APPLICATION OF THE SYSTEM FOR SIGNALING THE BEGINNING OF ACCIDENTS ON DRILLING RIGS BASED TO THE RESULTS OF THE ANALYSIS OF WATTMETER CHARTS OF THEIR ELECTRIC MOTORS

It is experimentally established, the beginning of all characteristic accidents on drilling rigs is reflected that on the wattmeter charts of electric motors, and it is possible to use this information for signaling the beginning of malfunctions. Therefore, this feature of the wattmeter chart is of the most important practical interest, because using them we can increase the degree of accident-free operation of drilling rigs. Because of this, the solution of the problem, creation and practical application of intelligent systems for signaling the beginning of the latent period of failures with the use of diagnostic information contained in the wattmeter chart, can be considered a priority.

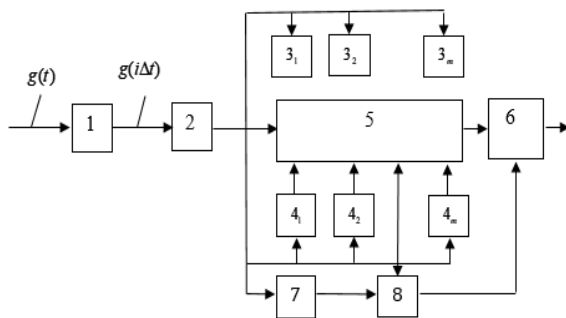


Fig. 2. Intelligent system for signaling the beginning of accidents ISSA

It is known that nowadays the driller intuitively identifies the occurred malfunction by the information provided from the existing monitoring and control systems on the basis of many years' experience, according to the situation in real conditions. However, sometimes his decision turns out to be belated, and a catastrophic accident is not prevented. To prevent it, Fig. 2 shows a block diagram of one of the possible variants of the system for signaling the beginning of accident, which consists of the following modules [1-4]:

1-wattmeter measurement module;

2-module of analog-to-digital conversion of the wattmeter chart, $g(t) = g(i\Delta t) = X(i\Delta t) + \varepsilon(i\Delta t)$;

3- 3_{1m} - modules for determining estimates of informative attributes;

4_1 - 4_{-m} modules for saving current estimates of informative attributes;

5- module for identifying the latent period of malfunctions;

6- information and signaling module;

7- module for storing reference wattmeter charts $g(i\Delta t)$ of typical malfunctions;

8- module for determining the number of reference wattmeter charts of typical malfunctions, at which the estimate of the correlation coefficient r_{je} with the current wattmeter chart takes the maximum value.

During the operation of the ISSA, the input of module 1, i.e. the input of the analog-to-digital converter, receives a wattmeter chart $g(t)$, converting it to digital code $g(i\Delta t)$. Using formula (6) in module 2 the estimates of corresponding informative attributes

$\{K_1, K_2, K_3, R_{X\varepsilon}^1, R_{X\varepsilon}^2, R_{X\varepsilon}^3, R_{X\varepsilon}^4, R_{X\varepsilon}^5, K_{f_{q_0}}, K_{f_{q_1}}, \dots, K_{f_{q_m}}, \dots, K_{q_0}, K_{q_1}, \dots, K_{q_m}\}$ are determined,

which are stored in the modules $3_1, 3_2, \dots, 3_m$. If they exceed the experimentally set threshold value, then the corresponding signals are sent to module 6. In this case, if all the current estimates are greater than the corresponding reference estimates, then module 5 generates a warning signal and also triggers an alarm about the beginning of the accident. However, in cases where some of the estimates will be greater than the reference ones, and others will be lower than their reference ones, then only a warning signal is formed. As a result, during the system's operation, the results obtained due to the use of estimates of the proposed informative attributes allow signaling the beginning of malfunctions in real time and provide information about it to the driller.

In order to increase the efficiency of the ISSA, there is also a mode of using the information contained in the wattmeter chart during the occurrence of typical, i.e. frequently recurring malfunctions. For this purpose, during the operation of the unit, when typical malfunctions occur, at the command of the driller, reference wattmeter charts are saved into the memory of module 7 $g_e(i\Delta t)$. This process continues for a sufficient period of time and results in the storage of reference wattmeter charts of all possible recurring malfunctions.

VI. CONCLUSION

1. The technological process of well drilling is characterized by the following features: a large number of random factors, changing over time and affecting the quality and technical and economic performance of works; variety of geological and technical drilling conditions; distortion of useful signals (load on the hook, torque, power consumption, mechanical drilling speed, etc.) that are used to determine the parameters of drilling mode 1,2 operates in a continuous oscillatory mode, and the largest amount of information about the beginning of a latent period of emergency state is contained in the wattmeter chart of the electric motor of the drilling rig.

3. The use of traditional algorithms and technologies of spectral and correlation analysis of noisy signals in control and diagnostics systems of the drilling rig would be effective and expedient in the absence of correlation between the useful signal and the noise of the wattmeter chart. However, in real-life conditions, there is always a correlation between the useful signal and the noise in the wattmeter chart during the rig's transition to an emergency state. Because of this the use of traditional technologies of control and diagnostics of technical condition of drilling rigs is ineffective.

4. At the beginning of the latent period of the emergency state, noises form in the wattmeter chart of the electric motor of the drilling rig, correlated with useful signals. These noises are important diagnostic information. However, in existing drilling rig control and management systems, this valuable information is lost as a result of filtering. At the same time, by using technology to form informative attributes from noise estimates, it is possible to create tools for signaling the beginning of the latent period of malfunctions. This can relieve the driller of the tedious and exhausting work that requires constant attention. This makes it possible to reduce the dependence of the degree of accident-free drilling on the health and qualifications of the master. However, it is advisable to leave the decision on measures to eliminate the causes of a suspected accident to the master.

5. The conducted research has shown that ensuring the adequacy of the control results in the proposed signaling system requires algorithms and technologies for adaptive determination of the sampling interval in real time. This is due to the fact that depending on the depth of the rock-cutting tool, on changes in geological and technical drilling conditions, etc., the spectrum of wattmeter chart changes in time over a wide range, and it depends on many factors. Therefore, taking into account the change over time of both the spectrum of useful signals $X(i\Delta t)$ as well as the noise $\varepsilon(i\Delta t)$ caused by the specified factors, to obtain the desired estimates with necessary accuracy, the sampling interval has to be determined adaptively in real time.

6. It is shown that at the redundant analog-to-digital conversion of the wattmeter chart, the frequency of changes in the state of its low-order bits corresponds to the sampling frequency obtained by traditional technologies. Therefore, it is reasonable to use this property of redundant samples to exclude the errors arising at a constant sampling interval of the wattmeter chart by ensuring the adaptivity of the analog-to-digital conversion of the wattmeter chart.

7. The above studies have shown that the use of the proposed algorithms and technologies can also significantly increase the degree of accident-free operation of similar equipment at reservoir pressure maintenance stations, at pumping stations, compressor stations of main oil and gas pipelines, etc. This is due to the fact that at the beginning of the latent period of the accident, information about the beginning of malfunctions is also clearly reflected in the wattmeter chart of their electric motors. Consequently, by timely alerting the maintenance personnel, it is possible to

avoid many costly catastrophic accidents. Obviously, the algorithms and technologies proposed in this work, combined with the intelligent system, can also find wide application in many other industries.

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