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Correlational Extremal System for Controlling the Beginning of Faults in Oil Field Equipment by Analyzing their Wattmeter and Dynamometer Charts

Abstract

The creation of technology for the analysis of wattmeter charts to control the main equipment of oil fields has always been of both theoretical and great practical interest. Numerous experiments have shown that the wattmeter chart of their electric motor is a highly noisy signal, and a significant part of the diagnostic information is contained in the estimates of the noise variance and the cross-correlation function between the noise and the useful signal. The lack of technologies for their analysis made it difficult and still makes it difficult to use the wattmeter chart to control the indicated equipment. The paper proposes a technology for controlling the onset of malfunctions and early diagnostics of the technical condition of sucker rod pumping units (SRPU), electric submersible pumps (ESPs), modular cluster pump stations (MCPS) of oil fields. It is shown that during operation, the wattmeter chart of the electric motors of these objects reflects information about the beginning of the latent period of change in their technical condition, which can be used as informative attributes in their diagnosis. A technology is proposed for determining the estimate of the cross-correlation function $R_{X\varepsilon}(\mu)$ between the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$ of the wattmeter chart and the technology for generating a set of reference wattmeter charts, in which the obtained informative attributes coincide with the informative attributes of the wattmeter charts of typical malfunctions. It is proposed to solve the problem of identifying faults in the equipment under consideration by the informative attributes of current and reference wattmeter charts of electric motors using correlation extremal systems. It is shown that using the proposed technology it is also possible to control the onset of similar malfunctions of SRPU by analyzing the dynamometer chart. The results of experiments showing the effectiveness and expediency of creating these control systems based on CES are presented.

Keywords: *electric motor, wattmeter chart, dynamometer chart, control, correlation extremal system, malfunction*

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Корреляционная экстремальная система контроля начала неисправностей оборудования нефтяных промыслов путем анализа их ваттметрограммы и динамограммы

Создание технологии анализа ваттметрограммы для контроля основного оборудования нефтяных промыслов всегда представлял как теоретический, так и большой практический интерес. Многочисленные эксперименты показывали, что ваттметрограмма электродвигателя представляет собой сильно зашумленный сигнал, и значительная часть *диагностической информации содержится в оценках дисперсии помехи и взаимно корреляционной функции между помехой и полезным сигналом. Отсутствие технологий их анализа затрудняло и затрудняет использование ваттметрограммы для контроля указанного оборудования.*

В статье предлагается технология контроля начала неисправностей и ранней диагностики технического состояния штанговых глубинно-насосных установок (ШГНУ), установок электроцентробежных насосов (УЭЦН), блочных кустовых насосных станций (БКНС) нефтяных промыслов. Показано, что в процессе эксплуатации на ваттметрограмме электродвигателей этих объектов отражается информация о начале скрытого периода изменения их технического состояния, которую можно использовать как информативные признаки при их диагностике. Предлагается технология определения оценки взаимно корреляционной функции $R_{X\varepsilon}(\mu)$ между полезным сигналом $X(i\Delta t)$ и помехой $\varepsilon(i\Delta t)$ ваттметрограммы и технология формирования множества эталонных ваттметрограмм, у которых полученные информативные признаки совпадают с информативными признаками ваттметрограмм характерных неисправностей. Предлагается по информативным признакам текущих и эталонных ваттметрограмм электродвигателей с помощью корреляционных экстремальных систем решить задачу идентификации неисправностей рассматриваемого оборудования. Показано, что, используя предложенную технологию также возможно осуществить контроль начала аналогичных неисправностей ШГНУ путем анализа динамограммы. Приведены результаты экспериментов, показывающих эффективность и целесообразность создания этих систем контроля на основе КЭС.

Ключевые слова: *электродвигатель, ваттметрограмма, динамограмма, контроль, объект, идентификация, корреляционная экстремальная система, оценка, помеха, авария, техническое состояние, неисправность, информативный признак*

Introduction

It is known that the process of extracting oil and gas from oil fields covers four stages [1—6]. At the first stage oil production is carried out by the free-flow production method. Then the gas lift method of production is used, followed by mechanized mining. Finally, the longest period of the oil production process in the late stage of field development begins. Naturally, over time, the late stage of operation begins for all oil fields. The need for their further development is due to the fact that, according to many leading oil specialists, in some fields the amount of remaining oil reserves turns out to be greater than the oil extracted by all methods. However, over time, ensuring the profitability of their operation becomes more difficult and requires minimization of all costs necessary for their operation. At the same time, the profitability of their operation is accompanied by numerous problems [1—6]. Among these problems, the most important is the need to minimize the cost of an energy-intensive process associated with the production of a gas-liquid mixture from a well using sucker rod pumping units (SRPU) and electric centrifugal pump units (ESP). The next problem is also related to an energy-intensive process in modular cluster pump stations (MCPS), which, using multi-stage injection pumps, pump water into the reservoir through injection wells. To reduce the costs of both these processes, it is first of all necessary to ensure the fault-free operation of these energy-intensive processes [4, 6—8].

Problem statement

Let us consider the well-known [1-4] typical flow chart of the oil production process in the late stage of oil field development (Fig. 1).

The gas-liquid mixture 1 from the well 2 with the help of production pumps 3 of sucker rod wells (SRPU) and electric submersible pumps (ESP) rises to the surface and is directed through flow lines 4 in a closed system under the pressure of the production pumps into automatic pad metering station 5 to determine the amount of yield for each well. After the metering, the well yield is transported through gathering mains 6 to the separator 7. Primary gas separation 8 takes place in the separator. Partially

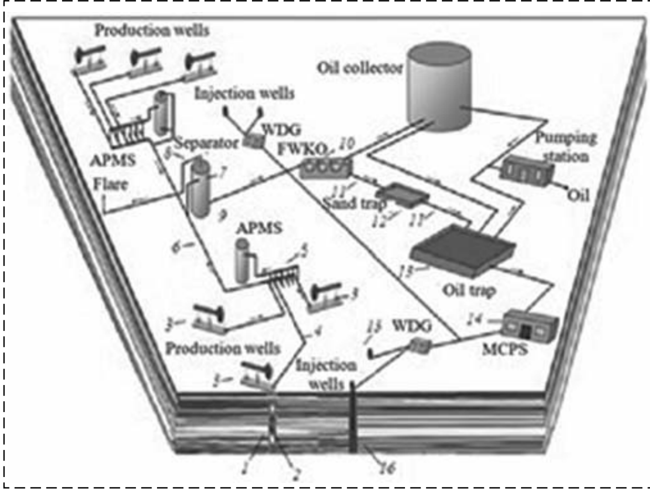


Fig. 1. Typical flow chart for oil production process in the late stage of field development

degassed fluid 9 from the separator enters the free water knock out unit 10 for the discharge of produced water from the formation fluid.

Formation water separated in the apparatus of the free water knock out unit FWKO 10 through water conducts 11 through sand traps 12 and oil traps 13 enters modular cluster pump stations (MCPS) 14, where with the help of multistage injection pumps through injection wells 15 are injected into the formation 16. Under the pressure of water in the production horizons, the gas-liquid mixture is displaced from the reservoir into the production well, and so the closed cyclic process of oil production continues in the late stage of field development by mechanized methods. Thus, the late stage of oil field development mainly includes two energy-intensive processes that require large expenses for the operation of the main equipment: these are modular cluster pump stations (MCPS) for pumping water into the reservoir to maintain reservoir pressure and equipment for artificial lift of oil (SRPU and ESP) from wells [1—4].

A study of the mechanism of operation of the SRPU, ESP and MCPS shows that information about the technical condition of these objects is reflected in the power consumed by the electric motor, namely, currents and voltages. For instance, a change in the load of the SRPU pump is reflected on the dynamometer chart, i.e., in the readings of the load cell $U_p(t)$, and also on the wattmeter chart of the electric motor $U_V(t)$, with which the SRPU operates. The same takes place in ESP and MCPS. Therefore, it is possible to control the technical condition of SRPU, ESP and MCPS [1—7] indirectly, since their malfunctions are reflected in the parameters of the power consumption of electric motors, namely, currents and voltages. The main advantage of the wattmeter chart is that it allows one to exclude primary converters of mechanical quantities into electrical ones in control and diagnostic systems, which are unreliable elements in the dynamometer chart-based diagnostic system. Such an option for solving the problem under consideration is important, since the technology for analyzing wattmeter charts of electric motors, in addition to the above equipment, can also be used in systems for controlling the onset of the latent form of emergencies at compressor stations, pumping stations, drilling rigs, etc.

Therefore, in the proposed study, the objective is to create new technologies and tools for early diagnosis of the technical condition of this equipment by using both dynamometer and wattmeter charts of their electric motors as diagnostic information carriers.

Analysis of the state of the art in existing systems for controlling the technical condition of SRPU, ESP and MCPS

Ensuring fault-free operation of energy-intensive equipment in oil fields is an important problem. In this regard, we will first consider the shortcomings of the existing technologies for controlling the technical condition of this equipment.

At present, to control the technical condition of the operation of sucker rod pumping units (SRPU), the method of analyzing the dynamometer chart obtained from the load cell is used [1—7]. One of the main disadvantages of this method is that in this case, to form a dynamometer chart, it is necessary to use an expensive load cell, which often changes its metrological characteristics in difficult climatic field conditions. Because of this, constant control and adjustment of the operation of the sensor by highly qualified service personnel is required. In addition, there is no possibility to carry out automatic identification of dynamometer charts in real time. For this reason, in most real-life cases, the identification of a dynamometer chart is carried out by an oil technologist interpreting it in a semi-automated mode. In this case, the result of diagnostics depends on the qualifications of the technologist and the diagnostic process, i.e., identification of the technical condition of wells takes quite a long time. At the same time, even a highly qualified specialist sometimes finds it difficult to accurately determine the technical condition of a submersible pump visually from dynamometer charts, especially for deep wells. As a result, due to the difficulties of control and timely elimination of equipment malfunctions, the profitability of oil production at SRPU decreases significantly [1—7].

The ESP parameter control system consists of a submersible telemetry system and a ground control and diagnostics system. Such systems are necessary in almost all cases of ESP use. However, from the point of view of modern diagnostics, vibration parameters are one of the main criteria for assessing the quality and reliability of ESP. Unfortunately, the measurement of the vibration level during the operation of ESP is complicated by its operating conditions, since there is no access to it [1—4].

In this regard, unfortunately, at present there is no single concept for diagnosing ESPs, but separate methods exist and are successfully applied. Essentially, they are carried out on the basis of an analysis of the readings of control and measuring instruments during regular checks and on the basis of test results during scheduled and unscheduled repairs of the ESP.

An analysis of reservoir pressure maintenance technologies shows [1-4] that both single-stage and multi-stage MCPS are most widely used as pumps for pumping water into reservoirs. As part of these pumping units, as a rule, a three-phase asynchronous motor with a squirrel-cage rotor is used.

Taking into account the design features and the principle of operation of these pumps, the following diagnostic methods are used:

- vibration diagnostic methods based on the analysis of vibration parameters of these objects;
- acoustic diagnostic methods based on the analysis of the parameters of sound waves generated by these objects and their components;
- electrodiagnostic control of the pump motor.

All these diagnostic methods make it possible to identify individual faults when they have a pronounced form, which often turns out to be belated and their repair leads to high economic costs [6—10].

Technology for measuring the wattmeter chart of electric motors of SRPU, ESP and MCPS

In such equipment as SRPU, ESP and MCPS, during the operation, the initiation and development of a defect until it takes on a pronounced form have significant distinctive features. They are related to the specific features of the deposit, their functions and technical conditions, modes of their operation, etc. For these and many other reasons, in this equipment, the process of the initiation of a defect before it takes on a pronounced form proceeds differently. In some objects, this occurs quickly [9, 13]. For others, this process takes many times longer. Despite all this difference, the common thing here is that during this period the information reflected in the wattmeter chart from the emergence of a defect is constantly changing and the existing control devices cannot respond to these changes. As a result, serious accidents occur at these facilities. The conducted studies have shown that the initial phase of the emergence of defects is accompanied by low-power noise in the wattmeter chart. They carry information about the initial period of change in the state of the object, which ultimately leads to an accident. At the same time, between the initial period of the change and the moment of the accident, as a rule, enough time passes for taking measures to prevent the accident. But in existing monitoring and control systems, noise, which is the only source of information, is lost as a result of signal filtering. As a result, the condition of the equipment cannot be timely and adequately identified [5—7].

Below, for a 3-wire circuit of SRPU, ESP and MCPS, through which the **electric motor** is powered, a power measurement circuit is proposed (Fig. 2), which differs by measuring the voltages and currents of all phases relative to artificial zero.

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

Experimental studies [3, 4] have shown that the occurrence of faults in controlled equipment, i.e., in SRPU, ESP and in MCPS it is reflected in the form of noise $\varepsilon(t)$ both on i_A, i_B, i_C and on u_A, u_B, u_C. Consequently, both of them contain an informative attribute about the beginning of the onset of a malfunction. However, given the measurement and analysis of signals in the form of voltage, it is more convenient to further consider the option of analyzing variables in time $u_A(t)$, $u_B(t)$, $u_C(t)$. To facilitate further presentation and generalizing these quantities, we call them wattmeters of electric motors and denote them by $u(t)$ — in continuous form and by $u(i\Delta t)$ — in discrete form.

Note that these parameters also carry additional information for diagnosing the state of the equipment. So, for instance, the difference in the sum of the instantaneous values of the phase currents means an insulation defect, that is, a current leakage to the motor housing. Measurement according to the proposed scheme allows one to separately determine the instantaneous values of the power consumption of each stator coil, determine their average values for a certain period and compare them with each other and the corresponding previous values to draw a conclusion about changes in the coils (turn-to-turn short circuits).

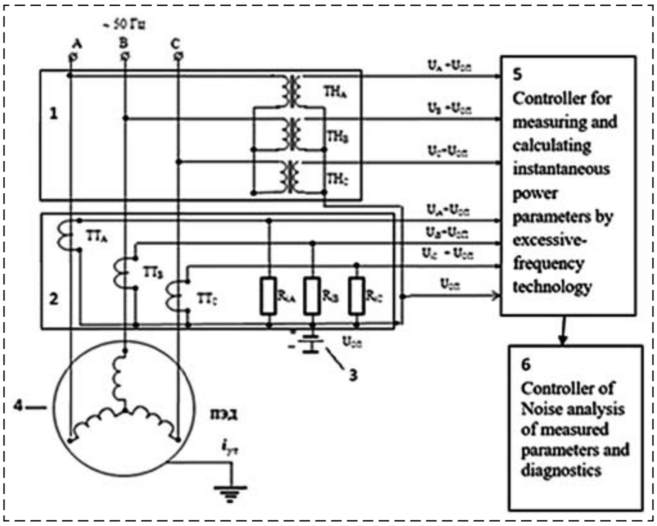


Fig. 2. Schematic diagram of the measurement of the electric motor power consumption parameters

As mentioned above, wattmeter charts of electric motors are highly noisy parameters. Experimental studies have shown that at the beginning of malfunctions during the operation of SRPU, ESP and MCPS, tangible noise $\varepsilon(i\Delta t)$ occurs in the wattmeter chart of their electric motors. Let us assume that during the oil production of the operation of the electric motor, we get a noisy discretized wattmeter chart $g(i\Delta t) = U(i\Delta t)$, which consists of the useful vibration signal $X(i\Delta t)$ and the total vibration signal noise $\varepsilon(i\Delta t)$, i.e.,

$$U(t) = g(i\Delta t) = X(i\Delta t) + \varepsilon(i\Delta t).$$

In this case, it can be assumed that low-frequency components X $X(i\Delta t)$ arise from the influence of the pump operation. At the same time, from the influence of other factors related to the technical condition of the object, high-frequency components are mainly formed, i.e., the noise $\varepsilon(i\Delta t)$. Therefore, we can assume that in the total noisy wattmeter chart $U(t)$, the useful signal consisting of low-frequency components $X(i\Delta t)$, the noise $\varepsilon(i\Delta t)$ and the coefficient of the relationship between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$ reflect information about the technical condition of the pump. Therefore, by analyzing the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$ of the wattmeter chart and the relationship $R_{X\varepsilon}(\mu)$ between them, it is possible to control the process of oil well operation.

The analysis carried out and the results of experimental studies show that the onset of faults is reflected in the wattmeter chart $U(i\Delta t)$ of electric motors driving SRPU, ESP and MCPS. They operate in the field and from external factors (strong temperature and humidity changes, winds, etc.), noise $\varepsilon(t)$ occurs and in the process of their operation, noise $\varepsilon_2(t)$ is also generated from the occurrence of various malfunctions, which has a correlation with the useful signal $X(t)$ of the dynamometer chart $U(t)$ [10]. Therefore, the noise $\varepsilon_1(t)$ accompanying the useful force signal $X(t)$ of the dynamometer chart $U(t)$, is formed under the influence of two factors:

$$\varepsilon(t) = \varepsilon_1(t) + \varepsilon_2(t), \tag{1}$$

where $\varepsilon_2(t)$ is formed from the influence of environmental changes (temperature changes, humidity, etc.);

(1) is formed during the operation of the object from the occurrence of various defects in the mechanical units of the pump (wear, bending, crack, fatigue, etc.).

The speed (sampling interval) of the analog-to-digital conversion when measuring the wattmeter chart must be selected so as not to lose diagnostic information about the onset of faults in the controlled equipment [6—10].

Difficulties in the control of the onset of faults by the estimates of the correlation characteristics of electric motor wattmeter charts

As was indicated above, it is typical for the objects under consideration during operation to go into a latent period of the initiation of various defects [10—15]. Usually all of them are reflected in the signals, i.e., on wattmeter charts in the form of noise, which, when a fault occurs, correlate with useful signals $X(i\Delta t)$. Therefore, 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 $\varepsilon_2(i\Delta t)$, which occurs as a result of the initiation of various faults. In this case, the variance of the wattmeter chart has the form:

$$\begin{aligned} D_g &\approx R_{gg}(0) \approx \frac{1}{N}\sum_{i=1}^{N} g^2(i\Delta t) \approx \frac{1}{N}\sum_{i=1}^{N} X^2(i\Delta t) + \\ &+ 2\frac{1}{N}\sum_{i=1}^{N} X(i\Delta t)\varepsilon(i\Delta t) + \frac{1}{N}\sum_{i=1}^{N}\varepsilon^2(i\Delta t) \approx \\ &\approx R_{XX}(0) + 2R_{X\varepsilon}(0) + R_{\varepsilon\varepsilon}(0), \end{aligned} \tag{2}$$

where the total noise $\varepsilon(i\Delta t)$ has a correlation with the useful signal $X(i\Delta t)$, and its variance D_ε is determined from the expression:

$$D_\varepsilon = 2R_{X\varepsilon}(0) + R_{\varepsilon\varepsilon}(0),$$

where $R_{X\varepsilon}(\mu)$ is the cross-correlation function between the useful signal and the noise $\varepsilon(i\Delta t)$.

It is also known [10—15] that the formula for determining the estimate of $R_{gg}(\mu)$ can be represented as:

$$\begin{aligned} R_{gg}(\mu) &\approx \frac{1}{N}\sum_{i=1}^{N} g(i\Delta t) g((i+\mu)\Delta t) \approx \\ &\approx \frac{1}{N}\sum_{i=1}^{N} (X(i\Delta t) + \varepsilon(i\Delta t))(X((i+\mu)\Delta t) + \\ &+ \varepsilon((i+\mu)\Delta t)) \approx \frac{1}{N}\sum [X(i\Delta t)X((i+\mu)\Delta t) + \\ &+ \varepsilon(i\Delta t)X((i+\mu)\Delta t) + X(i\Delta t)\varepsilon((i+\mu)\Delta t) + \\ &+ \varepsilon(i\Delta t)\varepsilon((i+\mu)\Delta t) \approx \\ &\approx R_{XX}(\mu) + R_{\varepsilon X}(\mu) + R_{X\varepsilon}(\mu) + R_{\varepsilon\varepsilon}(\mu) \approx \\ &\approx \begin{cases} R_{XX}(0) + 2R_{X\varepsilon}(0) + R_{\varepsilon\varepsilon}(0) \text{ when } \mu = 0 \\ R_{XX}(\mu) + 2R_{X\varepsilon}(\mu) \text{ when } \mu \neq 0. \end{cases} \end{aligned} \tag{3}$$

Experimental studies have shown [3, 4, 9] that during the operation of the wattmeter charts of electric motors of SRPU, ESP and MCPS, the estimates of $R_{X\varepsilon}(\mu)$, $R_{\varepsilon\varepsilon}(\mu)$ are tangible values, i.e., an inequality takes place:

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

and therefore there $R_{gg}(\mu)$ is a significant error in the estimate of $R_{gg}(\mu)$.

Because of this, it becomes difficult to ensure the adequacy of the results of controlling the operation of equipment by wattmeter charts. This is one of the factors hindering the use of wattmeter charts to control the indicated oilfield equipment. In this regard, it is necessary to create effective technologies for the analysis of wattmeter charts, allowing the extraction of available useful information from it by reducing errors from the influence of the noise $\varepsilon_1(i\Delta t)$, to improve the adequacy of the results obtained.

From expressions (2) and (3) it is obvious that in the presence of a correlation between the useful signal and the noise, the estimate of the correlation function $R_{XX}(\mu)$ of the useful signal of the wattmeter $X(i\Delta t)$ can be determined from the expression:

$$R_{XX}(\mu) = \begin{cases} R_{gg}(0) - 2R_{X\varepsilon}(0) - 2R_{\varepsilon\varepsilon}(0) \text{ when } \mu = 0; \\ R_{gg}(\mu) - 2R_{X\varepsilon}(\mu) \text{ when } \mu \neq 0. \end{cases} \quad (4)$$

In [7, 9] it was shown that the estimates of the variance D_ε of the noise $\varepsilon(i\Delta t)$can be determined from the expression:

$$D_\varepsilon \approx \frac{1}{N}\sum_{i=1}^{N}[g^2(i\Delta t) + g(i\Delta t)g((i+2)\Delta t) - 2g(i\Delta t)g((i+1)\Delta t)]. \quad (5)$$

However, it is obvious from expression (4) that with the estimate of D_ε available, to calculate the estimate $R_{XX}(\mu)$, it is also necessary to determine the estimate of the cross-correlation function $R_{X\varepsilon}(\mu)$ between the useful signal and the noise of the wattmeter chart.

Technology for determining the estimate of the cross-correlation function between the useful signal and the noise of the wattmeter chart

The conducted studies have shown [6, 9] that the nature of the relationship between the noise and the useful signal is clearly reflected in the estimate of the cross-correlation function $R_{gg'}(\mu)$ between the centered $g(i\Delta t)$ and the non-centered $g'(i\Delta t)$ noisy signals, which can be determined from the expression:

$$R_{gg'}(\mu) = \frac{1}{N}\sum_{i=1}^{N} g(i\Delta t)g'((i+\mu)\Delta t); \quad (6)$$

$$\begin{cases} g(i\Delta t) = X(i\Delta t) + \varepsilon(i\Delta t); \\ g'(i\Delta t) = X'(i\Delta t) + \varepsilon'(i\Delta t), \end{cases} \quad (7)$$

where $g(i\Delta t)$, $g'(i\Delta t)$, $X(i\Delta t)$, $X'(i\Delta t)$, $\varepsilon(i\Delta t)$, $\varepsilon'(i\Delta t)$ are centered and non-centered samples of the noisy signal $g(i\Delta t)$, the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$, respectively.

The analysis of equality (6), (7) showed that using the formula for determining the estimate of the cross-correlation function between centered and non-centered noisy signals, it is possible to determine the estimate of the cross-correlation function $R_{X\varepsilon}(\mu)$ between the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$. In this regard, we will consider one of the possible options for solving the problem of analyzing the relationship between the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$. To do this, let us first show the possibility of determining the estimate $R_{X\varepsilon}(\mu)$, which opens the possibility of determining the estimate $R_{XX}(\mu)$, i.e., the estimate of the correlation function of the useful signal of the wattmeter chart. It is known from the literature [4—9], [15, 16] that when the conditions of stationarity, normality of the distribution law and the absence of correlation between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$ are fulfilled, the equalities take place

$$\frac{1}{N}\sum_{i=1}^{N} X(i\Delta t)\varepsilon(i\Delta t) = 0; \quad (8)$$

$$\frac{1}{N}\sum_{i=1}^{N} X'(i\Delta t)\varepsilon'(i\Delta t) = 0, \quad (9)$$

and when calculating the estimate of $R_{gg'}(\mu)$ from formula (6), the following equalities take place between the number of N^{++} positive products of samples, $g^+(i\Delta t)$, $g'(i\Delta t)$ and the number of N^{-+}negative products of samples $g^-(i\Delta t)$, $g'(i\Delta t)$

$$\begin{cases} N^{++} = N^{-+}, \\ N^{++} + N^{-+} = N. \end{cases} \quad (10)$$

At the same time, at the beginning, with a time shift $\mu = 0\Delta t$, $1\Delta t$, $2\Delta t$, $3\Delta t$, ... the following inequality takes place between the absolute values of the readings $g(i\Delta t)$, $g'(i\Delta t)$ and between the sums of positive and negative products

$$R_{g^+g'}(\mu) = \frac{1}{N}\sum_{i=1}^{N^{++}} g^+(i\Delta t)g'((i+\mu)\Delta t) > \frac{1}{N}\sum_{i=1}^{N^{-+}} g^-(i\Delta t)g'((i+\mu)\Delta t) = R_{g^-g'}(\mu).$$

The computational experiments performed and the analysis of expressions (6), (7) show that when multiplying the samples of the non-centered signal $g'(i\Delta t)$ by its centered samples $g(i\Delta t)$, despite the fulfillment of equality (8), (9), (10) at, the inequality takes place

$$\frac{1}{N}\sum_{i=1}^{N^{++}} \left|g^+(i\Delta t)g'((i+\mu)\Delta t)\right| \neq \frac{1}{N}\sum_{i=1}^{N^{-+}} \left|g^-(i\Delta t)g'((i+\mu)\Delta t)\right|.$$

In this case, in formula (6), the difference between the sum of positive and negative products at $\mu = 0$ turned out to be significantly greater than zero, i.e.,

$$\sum_{i=1}^{N^{++}} g^{+}(i\Delta t)g'((i+\mu)\Delta t) - \sum_{i=1}^{N^{-+}} g^{-}(i\Delta t)g'((i+\mu)\Delta t) \gg 0. \quad (11)$$

Which shows that the correlation between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$ is clearly reflected in the estimate of $R_{g^+g'}(0)$, since the following inequality always holds for $\mu = 0$:

$$\frac{1}{N}\sum_{i=1}^{N^{++}} g^{+}(i\Delta t)g'((i+\mu)\Delta t) \gg \gg \frac{1}{N}\sum_{i=1}^{N^{-+}} g^{-}(i\Delta t)g'((i+\mu)\Delta t). \quad (12)$$

However, in most real-life cases, the value

$$R_{g^+g'}(0) = \frac{1}{N}\sum_{i=1}^{N^{++}} g^{+}(i\Delta t)g'(i\Delta t)$$

practically represents a rough estimate of $R_{gg'}(\mu)$ for $\mu = 0$, i.e.,

$$R_{gg'}(0) \approx R_{g^+g'}(0).$$

Due to this, in these cases, the estimate of the coefficient correlations $R_{X\varepsilon}$ between the useful signal and the noise can be determined by the magnitude of the difference between $R_{g^+g'}(0)$ and $R_{gg}(0)$ according to the formula

$$K_{X\varepsilon}(0) \approx R_{g^+g'}(0) - R_{gg}(0) = = \frac{1}{N}\sum_{i=1}^{N^{++}} g^{+}(i\Delta t)g'(i\Delta t) - \frac{1}{N}\sum_{i=1}^{N} g(i\Delta t)g(i\Delta t).$$

Naturally, in this case, the error in the estimate of the cross-correlation function depends on the difference $R_{g^+g'}(0) - R_{g^-g'}(0)$. But condition (12) is almost always satisfied, and the difference from the obtained difference can be taken as information about the presence of a correlation between the useful signal and the noise, i.e.

$$R_{X\varepsilon}(0) \approx R_{g^+g'}(0) - R_{gg}(0).$$

At the same time, taking into account expression (11), a rough, i.e., approximate, estimate of $R_{X\varepsilon}(0)$ can be determined from the formula

$$R_{X\varepsilon}(0) = [R_{g^+g'}(0) - R_{g^-g'}(0)] - R_{gg}(0) = = \left[\frac{1}{N}\sum_{i=1}^{N^{++}} g^{+}(i\Delta t)g'(i\Delta t) - \frac{1}{N}\sum_{i=1}^{N^{\mp}} g^{-}(i\Delta t)g'(i\Delta t)\right] - -\frac{1}{N}\sum_{i=1}^{N} g(i\Delta t)g(i\Delta t). \quad (13)$$

An example of the practical application of intelligent correlation extremal systems (CES) to control the onset of malfunctions using SRPU dynamometer charts

An analysis of the results of the experiments performed showed that in order to control the onset of a SRPU malfunction by an informative attribute obtained by analyzing the dynamometer chart, it is also advisable to use the correlation extremal systems shown in Fig. 3. It was experimentally found that both the dynamometer chart and on the wattmeter chart in the same degrees reflect the beginning of all typical faults of the SRPU. Taking into account that the technical personnel had experience with dynamometer charts and had a large number of real dynamometer charts, the initial experiments on the use of CES to identify a SRPU malfunction in real-life production conditions were carried out by us based on the use of a dynamometer chart. Consideration of this option of the use of CES is of independent practical interest, since at present, SRPU is widely used in oil production. Therefore, the problem of eliminating the difficulty of identifying a dynamometer chart remains valid and the pract0ical application of CES for identifying a dynamometer chart can be considered a priority. Fig. 3 shows a block diagram of the proposed version of the CES, which operates with the help of six modules:

1) module for analog-to-digital conversion of dynamometer and wattmeter charts into digital code;

2) module storing reference dynamometer and wattmeter charts of typical faults of SRPU;

3) module for monitoring the beginning of a fault using the estimates of $R_{X\varepsilon}(\mu)$ and D_ε;

4) module for alternately determining the correlation coefficient between the current values of the dynamometer chart $g_j(i\Delta t)$ and the reference dynamometer charts $g_e(i\Delta t)$, which are previously formed experimentally with the corresponding typical faults and stored in the memory of module 2;

5) module for determining the number of the reference dynamometer chart $g_e(i\Delta t)$ at which the

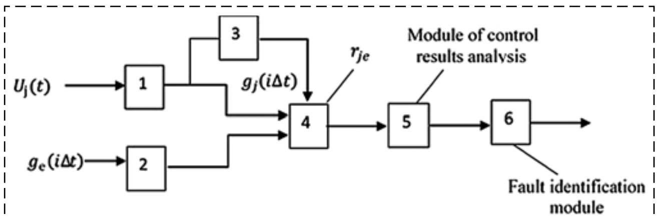


Fig. 3. An intelligent correlation extremal system for controlling and identifying the beginning of faults using a dynamometer chart

estimate of the correlation coefficient r_{je} takes the maximum value;

6) module for SRPU fault identification by the number of the found reference dynamometer chart

In the process of the operation of the correlation extremal system, the current dynamometer chart $U_j(t)$ from the load cell is received at the input of module 1, i.e., the input of the analog-to-digital converter, where it is converted into digital code $U_j(i\Delta t)$, which is fed to the inputs of modules 3 and 4, using module 3, the estimates of the variance D_ε of the noise and the cross-correlation function $R_{X\varepsilon}(0)$ between the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$ are determined according to formulas (5), (13). If they exceed the experimentally established threshold value, i.e., at $D_\varepsilon \geqslant D_\varepsilon^p$, $R_{X\varepsilon}(0) \geqslant R_{X\varepsilon}^p(0)$, then module 4 is triggered by a signal from module 3. In this case, between the current and reference dynamometer charts, alternately according to the formula

$$r_{je} = \frac{\frac{1}{N}\sum_{j=1}^{n} g_j(i\Delta t) g_e(i\Delta t)}{\frac{1}{N}\sum_{i=1}^{n} g_j^2(i\Delta t)}$$

an estimate of the correlation coefficient is determined, where j is the number of current typical faults, e is the number of the reference of typical faults, r_{je} is the estimate of the normalized cross-correlation function between $g_j(i\Delta t)$ and $g_e(i\Delta t)$.

By successively comparing the obtained estimates of the correlation coefficients between the current and reference dynamometer charts in module 5, the number of the fault is determined, at which the obtained estimates r_{je} has the maximum value. Thus, the presence of reference signals of typical faults through the use of CES allows one to register the technical state of the SRPU at the current time. Due to this, during the operation of the SRPU, the obtained results of the CES allow

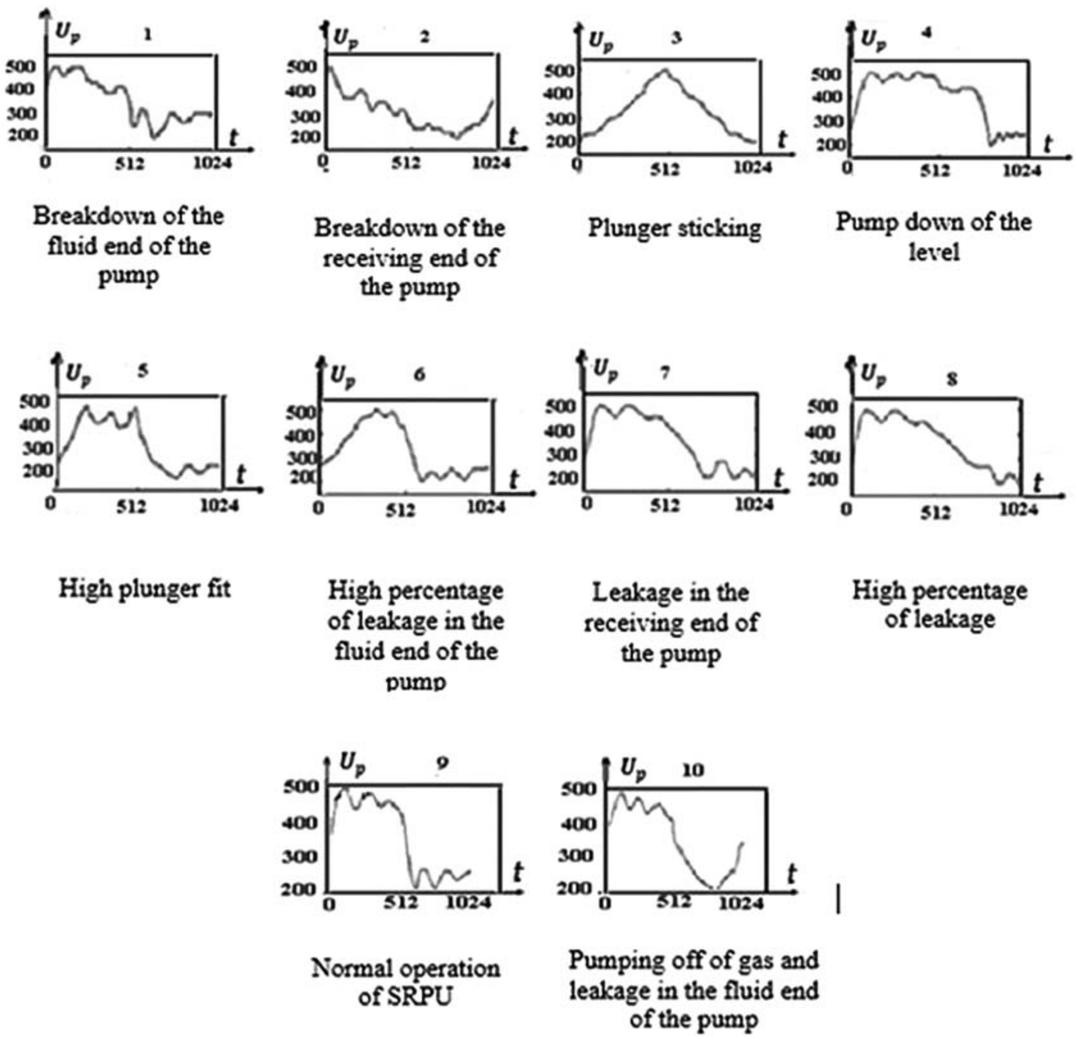


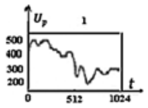
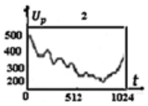
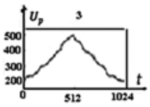
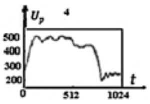
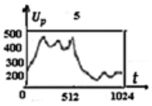
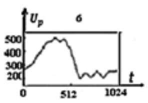
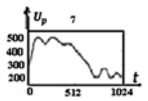
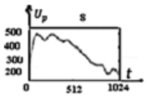
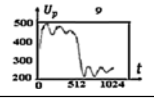
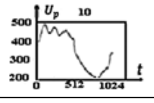
Fig. 4. Force curves of reference dynamometer charts

real-time identification of a malfunction and the formation of information about it.

In the experiments, the force curves of the reference dynamometer charts were selected for 10 typical faults of the SRPU, which are shown in Fig. 4. They were used to identify the technical condition of several facilities at the oil and gas production department of Bibi-Heybat Oil [1, 14]. The nature of the problems being solved made it possible to implement the proposed technology with the help of inexpensive modern industrial controllers (in our case, the LPC 2148 FBD64 controller was used). In this case, first of all, based on the duration of the swing period T_{ST}, the sampling interval of the dynamometer chart was determined. For the majority of oil wells in this field, the duration of time T_{ST} varies in the range of 5 to 20 seconds. It was experimentally established that in order to obtain the desired estimates with the required accuracy, it is advisable to sample dynamometer charts with frequency f = 50—100 Hz. It was also found that during the swing period, any slight change in the technical condition of the SRPU is reflected both in the dynamometer chart and in the wattmeter chart $g(i\Delta t)$. Thanks to this, during the operation of the SRPU, it is easy to form and memorize the corresponding force curves of the reference dynamometer and wattmeter charts for various typical faults. Numerous experiments have confirmed that the use of CES allows for reliable detection of the onset of failures of SRPU in real time by using the estimates of $R_{X\varepsilon}(0)$ and D_ε at which their value exceeds the threshold values. After that, according to the signal from module 3, the identification of a SRPU malfunction using the CES practically comes down to determining the number of the force curve of

Table 1

Estimates of the coefficients of correlation $r_{j_1e_1}, r_{j_1e_2}, \ldots, r_{j_1e_{10}}$; $r_{j_2e_1}, r_{j_2e_2}, \ldots, r_{j_2e_{10}}$; ...; $r_{j_{10}e_1}, r_{j_{10}e_2}, \ldots, r_{j_{10}e_{10}}$ between the curves of reference and current dynamometer charts of typical malfunctionss

1		$r_{j_1e_1}$ 0,8012	$r_{j_1e_2}$ 0,6001	$r_{j_1e_3}$ 0,4101	$r_{j_1e_4}$ 0,3005	$r_{j_1e_5}$ 0,6143	$r_{j_1e_6}$ 0,5921	$r_{j_1e_7}$ 0,5162	$r_{j_1e_8}$ 0,5301	$r_{j_1e_9}$ 0,4972	$r_{j_1e_{10}}$ 0,4151
2		$r_{j_2e_1}$ 0,6001	$r_{j_2e_2}$ 0,8101	$r_{j_2e_3}$ 0,3904	$r_{j_2e_4}$ 0,0321	$r_{j_2e_5}$ 0,1421	$r_{j_2e_6}$ 0,1605	$r_{j_2e_7}$ 0,1931	$r_{j_2e_8}$ 0,1622	$r_{j_2e_9}$ 0,0988	$r_{j_2e_{10}}$ 0,0961
3		$r_{j_3e_1}$ 0,1470	$r_{j_3e_2}$ 0,0901	$r_{j_3e_3}$ 0,8023	$r_{j_3e_4}$ 0,0499	$r_{j_3e_5}$ 0,0324	$r_{j_3e_6}$ 0,1082	$r_{j_3e_7}$ 0,0893	$r_{j_3e_8}$ 0,0668	$r_{j_3e_9}$ 0,0453	$r_{j_3e_{10}}$ 0,0384
4		$r_{j_4e_1}$ 0,3008	$r_{j_4e_2}$ 0,2915	$r_{j_4e_3}$ 0,0934	$r_{j_4e_4}$ 0,9346	$r_{j_4e_5}$ 0,6135	$r_{j_4e_6}$ 0,2106	$r_{j_4e_7}$ 0,5427	$r_{j_4e_8}$ 0,5119	$r_{j_4e_9}$ 0,6881	$r_{j_4e_{10}}$ 0,6499
5		$r_{j_5e_1}$ 0,5961	$r_{j_5e_2}$ 0,4783	$r_{j_5e_3}$ 0,0783	$r_{j_5e_4}$ 0,5022	$r_{j_5e_5}$ 0,8637	$r_{j_5e_6}$ 0,7681	$r_{j_5e_7}$ 0,7811	$r_{j_5e_8}$ 0,4633	$r_{j_5e_9}$ 0,5003	$r_{j_5e_{10}}$ 0,6021
6		$r_{j_6e_1}$ 0,6339	$r_{j_6e_2}$ 0,2901	$r_{j_6e_3}$ 0,0422	$r_{j_6e_4}$ 0,4113	$r_{j_6e_5}$ 0,5114	$r_{j_6e_6}$ 0,8706	$r_{j_6e_7}$ 0,6811	$r_{j_6e_8}$ 0,5801	$r_{j_6e_9}$ 0,6113	$r_{j_6e_{10}}$ 0,6009
7		$r_{j_7e_1}$ 0,6360	$r_{j_7e_2}$ 0,2963	$r_{j_7e_3}$ 0,0972	$r_{j_7e_4}$ 0,4662	$r_{j_7e_5}$ 0,5891	$r_{j_7e_6}$ 0,5463	$r_{j_7e_7}$ 0,8946	$r_{j_7e_8}$ 0,6561	$r_{j_7e_9}$ 0,6224	$r_{j_7e_{10}}$ 0,5937
8		$r_{j_8e_1}$ 0,4113	$r_{j_8e_2}$ 0,2131	$r_{j_8e_3}$ 0,0622	$r_{j_8e_4}$ 0,4511	$r_{j_8e_5}$ 0,2314	$r_{j_8e_6}$ 0,4241	$r_{j_8e_7}$ 0,7263	$r_{j_8e_8}$ 0,8321	$r_{j_8e_9}$ 0,8011	$r_{j_8e_{10}}$ 0,5625
9		$r_{j_9e_1}$ 0,6411	$r_{j_9e_2}$ 0,4033	$r_{j_9e_3}$ 0,0811	$r_{j_9e_4}$ 0,5910	$r_{j_9e_5}$ 0,6192	$r_{j_9e_6}$ 0,4902	$r_{j_9e_7}$ 0,4524	$r_{j_9e_8}$ 0,4101	$r_{j_9e_9}$ 0,9211	$r_{j_9e_{10}}$ 0,6012
10		$r_{j_{10}e_1}$ 0,6322	$r_{j_{10}e_2}$ 0,3951	$r_{j_{10}e_3}$ 0,0196	$r_{j_{10}e_4}$ 0,4771	$r_{j_{10}e_5}$ 0,5981	$r_{j_{10}e_6}$ 0,5503	$r_{j_{10}e_7}$ 0,4803	$r_{j_{10}e_8}$ 0,4162	$r_{j_{10}e_9}$ 0,5844	$r_{j_{10}e_{10}}$ 0,9241

the reference dynamometer chart (wattmeter chart) $g_e(i\Delta t)$, at which the desired estimate of the cross-correlation function r_{je} takes on the maximum value compared to all other reference signals. Due to this, there is no need for visual interpretation of the dynamometer chart to determine the current technical condition of the SRPU. To illustrate the possibility of the identification option under consideration in real field practice, Fig. 4 shows curves of reference dynamometer charts for the 10 most common typical faults. Table 1 shows a combination of the corresponding estimates of the normalized correlation coefficients, r_{je}.

Thus, it has been experimentally confirmed that using the number of the force curve of the reference dynamometer chart $g_e(i\Delta t)$, at which the estimate of the normalized cross-correlation functions with the curve of the current dynamometer chart $g_j(i\Delta t)$ takes the maximum value, it is possible to unambiguously determine the number of the typical SRPU fault. The advantage of using CES to identify a dynamometer chart is that it does not require the involvement of a technologist. They are easily implemented on modern inexpensive controllers (e.g., LPC 2148 FBD64). This makes it possible to control and diagnose SRPU in real time. The ease of implementation of these technologies allows one to create a simple, reliable and inexpensive control system for SRPU. Experiments on various wells of the Bibi-Heybat field in Baku and on wells of other fields showed the feasibility of the practical application of these systems. Since, at the same time, due to early diagnostics and control of SRPU, current malfunctions are easily eliminated in a timely manner and operation of the well is ensured in a profitable mode, and due to saving electric energy and shortening the overhaul period, their profitability is significantly increased.

It should be noted that based on the experience of operating the above systems, it was found that by determining the combinations of the force curves of the reference dynamometer charts with the corresponding characteristic faults for one well, they can be used in SRPU control systems of other wells of the same depths. Considering that in most cases each old field is characterized by approximately the same pump descent depths, it becomes obvious that the formation of one reference dynamometer curves for all SRPU will be sufficient. Note that at different well depths, experimental formation of various different reference curves corresponding to the dynamometer chart is required. Fig. 4 shows the force curves of the reference dynamometer charts for ten typical faults.

As can be seen from Table 1, the curves of the reference dynamometer charts of all ten typical faults were used in the experiments. First, the estimate of the correlation coefficient r_1e_1 between the curve of the first reference dynamometer chart with the first current curve r_{1e_1} is determined, then the estimate $r_{j_2e_1}$ between the first reference curve and the second current curve $j = 2$ is determined, then r_{j,e_1} between the third and the first, and so on. Finally, between tenth and first, $r_{j_{10}e_1}$. After that, this process is repeated for the curve of the second reference dynamometer chart. To do this, we first determine the estimate $r_{j_1e_2}$, then $r_{j_2e_2}$, then $r_{j_3e_2}, \ldots, r_{j_{10}e_2}$. This process is repeated for all curves of the reference dynamometer charts, and finally, for the curve of the tenth reference dynamometer chart, $r_{j_{10}e_1}, r_{j_{10}e_2}, r_{j_{10}e_3}, \ldots, r_{j_{10}e_{10}}$ are determined. This process is completed by analyzing the comparison of the results of all possible combinations between the reference and current dynamometer chart curves. As can be seen from the table, only one estimate $r_{d_je_i}$ in each control cycle takes the maximum value and by its number, i.e., according to the number of the curve of the reference dynamometer chart, at which the estimate r_{je} takes on the maximum values. As can be seen from Table 1, in each row only in one column the estimate r_{je} takes the maximum value, e,g,, in the 5th row the estimate $r_{j_5e_5}$ in comparison with other estimates of this column, has a maximum value, which corresponds to the 5th typical fault. The number of the current fault is identified.

Conclusion

Noisy signal analysis technologies used in control systems do not provide fault-free operation the main equipment of oil fields. They do not allow using diagnostic information from wattmeter charts of their motors. In addition, the diagnostic information contained in the noise of noisy signals as a result of filtering loses information about the beginning of the latent period of defect initiation in the equipment of these objects. For this reason, there is often a delay in the time of detection of the onset of malfunctions, which leads to inevitable accidents with catastrophic consequences. Therefore, to ensure fault-free operation and organization of timely maintenance of these facilities, it is necessary to create new, more efficient technologies for analyzing noisy signals. Taking into account the extreme importance of this issue, the paper proposes using noise as a carrier of diagnostic information by determining the estimates of the cross-correlation functions between the useful signal and the noise. To analyze wattmeter charts of electric motors and identify malfunctions of the equipment under consideration, the principle of constructing intelligent correlation extremal systems is proposed.

The above-mentioned studies have shown that with the use of the proposed algorithms and technologies for analyzing dynamometer and wattmeter charts, it is possible to significantly increase the efficiency and reliability of ensuring fault-free operation of similar equipment in the offshore oil and gas complex, petrochemical complexes, energy facilities, etc. Many other examples can be given where the use of the proposed wattmeter chart analysis technologies is also effective. For instance, using this technology, it is possible to solve the problem of control and diagnostics on drilling rigs, where at the beginning of the latent period of an accident, information about this is reflected in the wattmeter chart of the electric motor that rotates the drill string. By sending an early warning to the driller, many costly catastrophic accidents can be avoided.

Finally, in many industries, for instance, in pumping stations, irrigation systems, in compressor stations of main oil and gas pipelines, etc., it is also expedient to form and use reference and current informative attributes of wattmeter charts of relevant electric motors to ensure control of the onset and early diagnosis of malfunctions. Therefore, the algorithms and technologies for analyzing wattmeter and dynamometer charts proposed in this paper, in combination with an intelligent correlation extremal system, can be widely used in many industries.

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