Ensuring the Reliable Operation of the Pumping Units by Efficient State Diagnosis

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Abstract. The paper deals with the application of mathematical models to identify the state of the induction motor through the hodograph analysis of the stator and rotor currents and stator voltage (Park method). The use of the mathematical model to identify the state of the motor will provide an opportunity to establish patterns in the results, as well as to make conclusions about the state of the motor. The model used is sufficient for the diagnosis of the motor by analyzing the picture of the hodographs of the motor main parameters. The results of the study and the comparative characteristics of the hodograph of properly functioning and faulty motor at its idle start-up are given.

1. Introduction
The installation of electrical submersible pumps (ESP) plays a significant role in the complicated and energy-intensive technical oil and gas facilities and used for extraction production oil wells. Failures in the functioning modes of ESP are the leading cause of unplanned downtime wells stock, leading to significant financial losses.

Currently, the quality and efficiency of accepted diagnostic decisions about the status of ESP, taking into account the great range of the analyzed parameters and analyze huge amounts of information about the modes of operation of submersible electric centrifugal pumps, are not large enough, which increases the probability of error evaluation of its condition and failure to take appropriate operational decisions.

In this regard, the actual task is the development of new effective methods of diagnostics of the ESP oil producing wells [1].

2. The purposes of research
In this paper were set and solved the following scientific and technical objectives:
- development of the mathematical model that allows to analyze the state of the motor on the obtained hodographs of rotor and stator currents, as well as the stator voltage;
- development of the operational diagnostics system for submersible centrifugal pumps motors.

Modern diagnostic algorithms require massive databases that form a collection of data from multiple and diverse sensor suites. Information typically is extracted, in the form of features or condition indicators, from such databases and used as the input to diagnostic routines whose goal is to declare impending failure conditions [2].

The idea of the analysis using the Park vector is to identify the connection between the end of trajectory vector (hodograph) diagnostic features and different faults.
3. Machine diagnosis and prognosis

Machine diagnosis and prognosis involves an integrated system architecture with the following main modules (fig.1) [3]:

1. A sensor suite and suitable sensing strategies to collect and process data of critical process variables and parameters.
2. A failure modes and effects criticality analysis module that determines and prioritizes according to the frequency of occurrence and their severity possible failure modes and catalogs systematically effect–root-cause relationships.
3. An operating-mode identification routine that determines the current operational status of the system and correlates fault-mode characteristics with operating conditions.
4. A feature extractor that selects and extracts from raw data features or condition indicators to be used by the diagnostic module.
5. A diagnostic module - the diagnostician - that assesses through online measurements the current state of critical machine components.
6. A prognostic module - the prognosticator - that estimates the remaining useful life of a failing component/subsystem.
7. The final module of the integrated architecture - the maintenance scheduler - whose task is to schedule maintenance operations without affecting adversely the overall system functionalities, of which the machine in question is only one of the constituent elements.

The development of methods for diagnosing the state of asynchronous motors is of great practical importance. The diagnostic results provide an opportunity to identify and predict the probability of motor failure, to improve the control system of motor and configure its protection, and to improve qualitative indicators of work of electric drives installed in executive mechanisms. Since the performance of a faulty motor is always significantly lower than that of a serviceable motor, the diagnosis and determination of the type of fault reduces the probability of an accident and increases the life cycle of the motor. The most dangerous damage for induction motors are internal breaks in the rotor winding. A break in the rotor phase leads to the impossibility of current flow, which interacts with the
electromagnetic field of the stator, which leads the motor to an inoperable state. When the rotor winding is damaged, its speed is reduced both in the nominal mode and in the idle mode. In the case of a motor with a phase rotor, its high resistance leads to an increase in sliding when operating in nominal mode. The reason for this may be a poor condition of the contacts or breakage of the rotor rod, poor-quality soldering of the rotor winding connection points with the contact rings, as well as contamination of the rotor brush apparatus contacts [4].

4. The mathematical model for identifying the state of the motor

The vast majority of the diagnostics methods of asynchronous motors involves a comprehensive examination of the motor in the repair workshop with motor disassembling. The mathematical model is created for faults identifying, that allows to determine the behavior of the motor in case of various damage of the rotor (breakage of the rods, internal cracks, caverns in the rod, defects of the closed rings) and the stator and their combinations. The parameters of the asynchronous motor can be determined with the help of observers, which are widely used in the systems of frequency-vector control of electric drives. The use of a mathematical model to diagnose the condition of the motor will allow to assess the preliminary condition of the damage and to determine its faulty parts by taking readings from the existing electric drive, without the need for disassembly and inspection of the asynchronous motor [5].

The model (fig.2) is sufficient for the diagnosis of the motor by analyzing the picture of the hodographs of the rotor and stator currents, and the stator voltage of the motor. The results of the study and the comparative hodographs of properly functioning and faulty motor at its idle start-up are given in the next section.

5. Analysis of the motor condition using the Park vector

The Park vector analysis has been successful in detecting a large number of faults in an asynchronous three-phase motor. So damage of the stator winding leads to the elliptical shape of the hodograph. The degree of ellipticity is proportional to the degree of damage, and the orientation of the axes of the ellipse
depends on the winding of which phase is damaged. Breaks in the stator grooves lead to the fact that the circular trajectory described by the end of the Park vector becomes smeared (has a certain "thickness"), which serves as a diagnostic sign of this defect. A special form of hodograph corresponds to the eccentricity of the air gap and the engine. Information about the degree of damage is obtained from the analysis of individual sections of the hodograph [6].

In case of an asynchronous drive with an inverter, the shape of the hodograph corresponding to the normal state of the motor differs from the circumference, however, in this case, significant deviations in the form can be judged on the fault line in the components of the electronic power control of the motor. For example, the orientation of the hodograph can determine the presence of a short circuit or a circuit break in the semiconductor inverter switch.

In the extended method of the Park vector perform the spectral analysis of the variable component of the module of the Park vector. The constant component, determined mainly by the component of the main frequency of the supply current is not informative in terms of identifying possible damage of the motor.

The advanced method combines the simplicity of analysis using the Park vector with the capabilities of more detailed research provided by spectral analysis. In addition, it overcomes a number of technical limitations of conventional motor current spectral analysis. It is often difficult to remove the current component of the main frequency of the power supply from the signal without distorting the components of its side bands. In the extended Park vector method, this difficulty is absent because the fundamental frequency component of the power supply is automatically eliminated when the Park is transformed. If we consider that the Park vector contains information about the currents of all three phases of the engine, the extended Park vector method provides more information for analysis than the usual method of spectral analysis of the motor current [7].

Extended Park vector technique allows to detect the presence of several faults in the motor. At the beginning, a reference spectrum corresponding to the normal technical condition of the motor is obtained, with the appearance of new components in the spectrum, the presence of a particular fault is judged. Thus, the breaks in the grooves of the rotor define with the appearance in the spectrum of the component at twice the frequency of sliding, and eccentricity of the gap or misalignment of the mechanical loads - the presence of spectral components near the frequency of rotor rotation. Stator winding faults can be detected by the presence of a component at twice the frequency of the motor power supply.

Asynchronous motors are widely used in various industries in different conditions of their application, including conditions of highly variable loads over time. In particular, slow current unsteady processes are typical for the use of compressors. Variable loads cause the appearance of additional components in the spectrum of the motor current, which can mask the signs associated with the faults of the motor itself. As a result, when analyzing the motor current spectrum, it is easy to confuse the signs associated with real malfunctions with signs of changes in the motor load [8].

Further improvement of the method involves the use of Park vector representation in a synchronized coordinate system, which will allow to identify the asymmetry of the rotor even in the conditions of changing load moment. In case of a failure of the rotor it becomes an ellipse, the major axis oriented in the direction of the second quadrant, while the load changes is the ellipse oriented in the direction of the first quadrant [9].

The results of the study and comparative hodographs of the stator and rotor currents, and also the stator voltage in the properly functioning and faulty motor at its idle start are presented (fig.3, 4, 5, 6, 7).
Figure 3. Properly functioning motor.

Figure 4. Short circuit between phases A and B in the stator winding.

Figure 5. Short circuit between phases A, B and C in the stator winding.

Figure 6. Short circuit between phases A and B in the rotor winding.
The hodograph of the currents of the rotor and the stator and the stator voltage of the serviceable engine (Fig. 3) have the form of a correct circle [10]. Whereas at the faulty engine (Fig. 4, 5, 6, 7), hodographs contain several concentric circles and are characterized by an uneven increase in magnetic flux, which is due (when considering, for example, a malfunction in the rotor) to a significant increase in the active resistance of the rotor winding, which is associated with a break in the rotor rod. Processes at start-up of the faulty engine are longer on time, there is an uneven acceleration, amplitudes of harmonics of stator currents increase, radial and axial components of vibration increase.

6. Conclusion

The use of the mathematical model to identify the state of the motor will provide an opportunity to establish patterns in the results, as well as to make conclusions about the state of the motor. Hodograph analysis of the currents of the rotor and the stator, and voltage of the stator allows to determine the type of fault in induction motor. For asymmetric phase currents, the hodograph vector is an ellipse whose axis ratio is determined by the degree of asymmetry. The limiting state of this hodograph in the absence of asymmetry will be a circle, and with the equality of the components of the direct and inverse sequence - a line segment with a length equal to the double value of their module.

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