Diagnosis of Electric Submersible Centrifugal Pump

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Abstract. The paper deals with the development of system operational diagnostics of electrical submersible pumps (ESP). At the initial stage of studies have explored current methods of the diagnosis of ESP, examined the existing problems of their diagnosis. Resulting identified a number of main standard ESP faults, mechanical faults such as bearing wear, protective sleeves of the shaft and the hubs of guide vanes, misalignment and imbalance of the shafts, which causes the breakdown of the stator bottom or top bases. All this leads to electromagnetic faults: rotor eccentricity, weakening the pressing of steel packs, wire breakage or a short circuit in the stator winding, etc., leading to changes in the consumption current.

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.

2. The purposes of research
In this paper were set and solved the following scientific and technical objectives:
- Comparative analysis of existing methods of submersible centrifugal pumps diagnosis.
- Identified the relationship between the presence of typical harmonics and the corresponding defects of submersible centrifugal pumps through computational and physical experiments.
- On the basis of the obtained dependences developed a technique of ESP diagnostics. There are the following maintenance strategies of submersible centrifugal pumps:
  - In terms of preventive maintenance or equipment failures, which is economically unjustified and is a major cause of production downtime.
  - ‘On the state’, by applying the recognition method to the actual technical state of equipment on set of diagnostic characteristics to identify existing or developing defects and to determine the optimal timing of repair work.

3. The existing methods of submersible centrifugal pumps diagnosis
Condition monitoring and technical diagnostics of ESP includes assessment of the thermal status of equipment (thermodiagnosis), vibration measurement of equipment (vibration analysis), modeling, etc. [1].

Thermodiagnosis is based on the fact that in the place of occurrence of the defect of the electrical equipment the temperature rises and, as a consequence, increases the intensity of infrared radiation, which is recorded by thermal imaging devices. Simulation, including the stage of development of a
computer model of the electrical submersible pump connected to the engine by using sensors. Provides an opportunity to measure multiple operating signals to the pump that is used to solve equation of state in time. This method is implemented only with direct access to the motor and the pump, i.e. it does not provide remote diagnostics; has low accuracy; the complexity of the required measurements that illustrates it impossible to use for diagnostics [2].

Vibration diagnostics, during which register and analyze the signals generated by the vibration of the motor. According to the obtained data analyze the form and amplitude of the received signal and compare with threshold values, to assess the possibility of further operation of the unit. However, the need to install additional vibration sensors on the pump housing, and additional communication lines to transmit information about vibration of the pump, which reduces the reliability of the entire diagnostic system and increases its cost, thus limiting the possibility of applying this method [1].

However, such diagnostic methods are not applicable in all situations, and make it impossible to determine the exact cause of origin of a process malfunction. Diagnosis of all the above types of faults can be accurately and timely implement on the basis of spectral analysis of stator current.

Despite the fact that the proposed method of spectral diagnostics of electric parameters is widely used in many industries, in oil production, this issue has received little attention.

To identify patterns, the spectral structure of the motor current and the corresponding types of pump faults, a mathematical model of ESP was developed, including models of the frequency converter, the submersible motor, centrifugal pump and hydraulic system (load). The dynamic variables of the models of the component parts of a submersible centrifugal pump located in relationship between them and provide mutual influence on each other. In addition, ESP has developed mechanical and hydraulic subsystems, which greatly affect the dynamics of the whole complex [3].

The results of calculations of the model are indicators for which determined a critical value. When the deviation of the values for the boundaries of critical values are needed to identify the causes of deviations and develop corrective actions.

4. The influence of parameters deviations of centrifugal pumps
One of the important parameters to determine the performance of the pumping unit is the relative deviation in efficiency from the nameplate. Coefficient characterizes the degree of wear consider, and fluctuation, associated with the use of the bypass. The lowest coefficient values enable to select pumps with the highest wear and/or the greatest influence of the bypass regulation. After defining the checklist, you need to check the source data of the selected aggregates. The value of the accumulated energy and operating time can be taken in different time periods, which can lead to errors. It is necessary to verify the actual power of the unit. The power value of pumps can be obtained from the experts. The optimal solution is plotting the power of pumps, which can be used to compare values.

After checking the source data, checks the presence and the use of the unit using the bypass. The use of bypasses due to the necessity of operation of the pumps with too small volumes of liquid. Units that can be installed by-passes, have a significant mismatch between the passport and the actual performance of the pump with the real output pressure of pumps. Corrective activity may be the exception of the bypass regulation by means of choose of the optimal pump for the pumped fluid volume.

The second factor of the deviation of actual efficiency from the nameplate is wear. If it is revealed that bypasses regulation is not used or has little impact, units must be checked according to the method of the optimal time of removal the equipment for repair, then takes a decision on the necessity for an early overhaul of the pump [2].

Relative excess of pressure pumping units above the yearly maximum line pressure – the ratio of the sum of the actual pressure at pump inlet and passport for the actual volume to the maximum line pressure for the 12 months increased by 35 m (normative losses from the pump to the line). Coefficient characterizes the redundancy of the pump head in relation to the maximum for the object. The highest coefficient values enable to define the pump units with excessive pressure. These pumps should be checked for the possibility of reducing the number of working wheels.

Corrective activity can be the replacement of all or part of the pumps with the pumps with lower
nominal pressure. After replacing the operating pump, at maximum should be used the units with lower pressure. In this case, if replaced only a part of the pump during the increase of pressure in the line can be used reserve pumps, having a higher pressure.

The coefficient of irregularity of pressure – the ratio of the maximum pressure in the line to the middle. Coefficient characterizes the oscillation amplitude of the pressure in the line (elevation of the maximum line pressure on the average linear pressure during the period under review). The highest coefficient values allow to select objects with the most irregular mode of operation. As well as pumps is usually selected to work with the maximum pressure lines, as shown on the diagram, on such installations pumps main time working in a pre-loaded condition. This leads to excess of energy consumption [3].

At such installations it is necessary to develop activities for alignment of the pumping mode. This can be applied to the redistribution of flows between installations, coordinated delay of pumps start, so that they were not carried out simultaneously.

Also, such problems can be solved by running multiple pumps with different pressure or with large and constant fluctuations by installing of variable frequency drives (Figure 1).

![Figure 1. The pressure of electrical submersible pump](image)

Load factor – the ratio of the actual and the nominal capacity of the pumping pump. The coefficient indicates the deviation of the operation of the pump in the left or right area.

With the coefficient deviation it is needed to analyze redistribution of volumes between units for more efficient loading or selection of optimal combinations of equipment.

Efficiency of the pump – the ratio of hydraulic energy, transferred to the line, to energy consumption during the period under review. Coefficient characterizes the overall energy efficiency. The indicator influenced by the following critical factors [4]:
- deviation of the pump in the left/right area;
- excess pressure;
- technical condition.

The indicator allows to select the pump with the greatest power overconsumption. The first step in the analysis it is necessary to determine the reasons for low efficiency, and offer solutions for increasing it. A common solution for a pump with low efficiency is the selection of optimal equipment combinations for the parameters of the current pump. In the list you need to determine the most efficient configuration of equipment available in reserve. A similar check must be done on the parameters of the pumping unit [5].

The boundary values for the criteria are reconsidered at least 1 time per year.
5. The faults of electric motors of centrifugal pumps

Consider one of the faults of electric motors centrifugal pumps. Rotor eccentricity is quite often occurred in practice, the reason of increased vibration of electric machines arising from the wear of rolling bearings.

In the presence of rotor eccentricity in the distribution of the electromagnetic field in the gap of the engine there is a number of features. The density of the electromagnetic field around the circumference of the gap changes with rotation of the rotor, leading to uneven traction engine. When the overlap of the axis of the stator field with the area of increased gap, traction is somewhat reduced, with increasing the slip value of frequency.

![Figure 2. Spectrum of current with rotor eccentricity](image)

During the displacement of the axis fields in the lower zone of the gap, pulling force increases, the slip frequency decreases. When the number of pairs of poles of the stator is greater than one, this process is repeated ‘p’ times.

Figure 2 shows the range of current with rotor eccentricity.

In the interval of displacement of the rotor from the zone with the increased gap zone to the zone with the reduced gap, the rotor is accelerated in its speed at the small value. In the interval of transition of the rotor back to the area with an increased gap, the rotor is slowed to the same value. This is noticeable in the spectrum [6].

On current spectrum around the fundamental frequency of rotation of the rotor, appear symmetrically located side peaks (harmonics), resembling the teeth of a crown. The symmetry of the peaks relative to the fundamental frequency is a consequence of the accelerations and decelerations of the rotor speed around its mean value.

Similar to the teeth of higher intensity appear around the peak electromagnetic power at a frequency equal to the second harmonic of the mains [7].

The eccentric rotation of the rotor modulates the conductivity of the gap with twice the frequency. When the number of pairs of poles equal to one, the frequency of rotation of the field equal to 50 Hz, twice the line frequency, the frequency of the electromagnetic vibrations to 100 Hz. The eccentricity of the rotor leads to a modulation of the electromagnetic force. By reducing the number of pairs of poles of the frequency of rotation of the field in the gap is reduced to p times. Variable gap of the rotor during one circulation will modulate the electromagnetic force, 2*p times the frequency of its rotation that corresponds to the frequency of the electromagnetic force.

The eccentricity of the rotor is usually appeared both in vertical and transverse projections of the vibration. Sometimes it is possible to detect even in the axial projection. It is possible in the presence of eccentricity of the rotor along its entire length, but only in the region of one edge of the package electrical steel [8].

The eccentricity of the rotor often is transient in nature, when in the spectrum of the engine has a characteristic pattern, and the practical measurement of the gap doesn’t confirm the diagnosis. The reason is usually in thermal processes when the rotor is asymmetrically heated, bent, and gives a picture of eccentricity.

After motor shutdown, in the process of disassembly to measure the gap, the temperature quickly equalized and the diagnosis is not confirmed. Often it happens when breakages of the rods or partial
“grazing” of the rotor about the stationary elements when the rotor begins to heat up one-sided [9].

During conducting the research was diagnosed the mode of operation of pumping system with open circuit and phase stator fault. In Fig. 3.1 shows the spectrum of the motor current in normal operation and when one phase is open. In Fig. 3.2 shows the range of current when operating in normal mode and the misalignment of one of the phases.

![Figure 3.1 and 3.2](image1)

Figure 3.1 and 3.2. The spectrum of the motor current in normal operation and in failure mode

Analysis of the graphs in Fig.3.1 reveals that the open phase of AD leads to an increase of the harmonics number 3 (3 dB) No. 5 (1 dB) No. 7 (1.7 dB), as well as to the emergence of a peak at the area of 490 Hz. A comparison of the spectrograms in Fig.3.2 revealed that when imbalance is present the growth of harmonics number 3 (1.6 dB) No. 5 (1.3 dB), No. 7 (1.6 dB).

![Figure 4](image2)

Figure 4. The spectrum of the motor current in normal operation and during turn-to-turn fault

![Figure 5.1 and 5.2](image3)

Figure 5.1 and 5.2. The spectral composition of current in normal mode and during the wear of radial bearings

When turn-to-turn fault (Figure 4) harmonica No. 3 increased by more than 4 dB. Also revealed the other odd harmonics: No. 5 (1.5 dB), No. 7 (2 dB) No. 9 (10 dB). Additionally in the spectrum is
observed 8 (400 Hz) and 10 (490 Hz) harmonics.

In experimental researches were obtained spectrograms of current during normal operation (Figure 5.1), as well as during the wear of the radial bearings (Figure 5.2).

Analysis of the obtained data allowed to conclude that the wear of the radial bearings of the pump leads to the appearance of additional harmonics at the frequency of 200 Hz, which is twice the frequency of rotation of the motor shaft of the pump.

6. Conclusion
The comparative analysis of existing methods of diagnosis ESP system showed that the most reliable diagnostic method is a method based on spectral analysis of stator current [10]. Obtained the relationship between the presence of the characteristic harmonics and certain types of faults ESP. The results of the experiments for the same mode do not differ more than 5%. Analysis of the obtained spectra showed the differences between the modes of operation of motor that allows to diagnose in the initial stages the appearance of a fault in the operation of ESP.

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