Analysis of the reliability of the power cable of an electric-centrifugal pump unit

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Abstract. The article is devoted to assessing the reliability of the cable line installation of an electric-centrifugal pump. Based on the analysis of the time between failures, the probability of failure-free operation of the cable line of the ESP installation was calculated to determine the time of scheduled repair.

1. Introduction

When oil is recovered using medium and high-rate oil wells, electric-centrifugal pumping units, designed for normal operating conditions, are used.

ECP units (ECPU) can be considered as a system of such serially connected main elements as: pump, hydroprotection, downhole motor, cable extension (connecting cable), main cable, field control station [1].

Failures of wells equipped with ECP units occur for the following main reasons [2-5]:
- the presence of a significant amount of mechanical impurities. Flow sections are clogged and the working parts of the pump wear out, which leads to an increase in the level of vibration;
- paraffin formation;
- intense scaling. Radial wear increases in the pump working bodies (wear of the rotors, guide apparatus, shaft protective sleeves and intermediate radial bearings of the ECP), consequently, vibration increases. In some cases, the pump becomes jammed, and the ECP strum box becomes clogged;
- aging of the cable insulation (reduction of the electrical insulating properties of the cable during operation due to operation in conditions of high temperature, gas content;
- a hidden defect in the cable body (microcracks in the covering not detected during cable testing, but which manifested themselves during tripping or operation of the ECP system;
- corrosion of electrical cable;
- mechanical damage to the electric cable ECP. Most often occurs when the ECP is lowered due to exceeding the permissible speed of the ECP or the presence of foreign bodies in the well;
- elevator leakage;
- lack of inflow or incorrect selection of ECP, in which the capacity of the installation is greater than the inflow of formation fluid from the reservoir. In the low-flow mode, intense heating of the working bodies and the pump body occurs. Melting of the insulation is possible, which leads to a decrease in the resistance of the insulation layer and the failure of the submersible electric motor and the cable line;
- corrosion of pumping equipment;
- high viscosity of the production fluid;
- ingress of stratum or displacement fluid into the cavity of the engine through leakage of mechanical hydroprotective seals, seal failure of input lead;
- poor quality of ECP installation process. Violation of the installation technology leads to failure of the ECP system;
   - defective equipment;
   - equipment repair defect;
- poor quality ramp-up to the mode in which the cooling of the Electric Submersible Motor is disturbed, which leads to overheating, reduced insulation resistance and failure of the ESM and cable line;
- failures on ground electrical equipment;
- experimental work carried out to test new types of equipment, components, new technologies (ECP + packer).

2. Results and discussion
The impact on the time to failure of the ECP system of operational factors in oil wells was studied. The results showed high significance of the influence of these factors: temperature, concentration of mechanical impurities in the well fluid, corrosive activity of the well fluid, water content, scaling, paraffin formation, high viscosity of the production fluid, deepening under the dynamic level.

The most typical causes of failures of ECP units are: 1) a decrease in the insulation resistance of the cable line; 2) seizure of the pump shaft; 3) the clogging of the working bodies of the pump; 4) wear of working steps of the pump.

Failures of ECP in most cases are associated with failures of electrical insulation of cable lines and ESM. The most negative unit of the ECP installation is the cable power line. The share of ECP unit failures caused by a decrease in the insulation resistance of cables is very significant [9-11].

The experience of operating ESP units in field conditions shows that a significant proportion of “failures at units” falls on the cable, namely, on the cable section adjacent to the pump — the cable extender. ECP failures associated with a decrease in insulation resistance in cable extenders can be divided into 4 categories: 1) failures associated with the operation of equipment - insufficient cooling of ECP (no flow or improper selection of ECP), pump clogging, scaling, paraffin formation, etc., and as a result, the overheating of the cable extender (in 80% of failures), the effect of gas, the wear-out of equipment; 2) failures associated with defects in the performance of work and the organization of work - installation damage, mechanical damage to the cable; 3) failures for organizational reasons - installation of equipment at low temperatures; 4) failures associated with the factory equipment defects.

The temperature of the medium in the location zone of the cable extender often exceeds 100 °C, which leads to a melting of the electrical insulation and the displacement of the electric conductors. and Thus, “short circuit” mode occurs. A similar phenomenon is observed when using a heat-resistant cable extender, with a working temperature of 230 ° C; in case of using a heat-resistant extension cord, the overheating is transmitted to the coupling connection with the electric submersible motor, which leads to the failure of the electric motor.

The overheating of the pump is caused by the operation of an electric centrifugal pump in the modes close to “pump starvation” – that is, in the extreme left part of the pressure-flow characteristic of the ESM (minimal flow, maximal pressure).

The mechanism “Failure of the cable line” is a failure of the ECP system caused by a decrease in the insulation of the submersible cable line. This type of failure is characterized by reflow, burnout of the immersion cable and (or) cable extender as a result of resource wear of the cable line or overheating as a result of high operating temperatures in the reflow interval of the submersible electric cable.

3. Experimental
One of the indicators of the operation of the cable electric line ECP is time between failures. When analyzing the work of the ECP unit, data on operating time of the cable line before the first failure was
collected. The calculation of the reliability of the cable section was conducted. The minimum value of the operating time is 5 hours, the maximum is 1798 hours. The dispersion zone is divided into 9 intervals and is \( R = 1798 - 5 = 1793 \) hours. The interval is equal to \( \frac{\text{ч}}{K} \).

\[
\Delta t = \frac{R}{K} = \frac{1793}{9} \approx 200 \text{ (h)}.
\]

Determine the boundaries of each interval: 1 interval: 0…200 h.; 1 interval – 200…400 h.; 1 interval – 400…600 h.; 1 interval – 600…800 h.; 1 interval – 800…1000 h.; 1 interval – 1000…1200 h.; 1 interval – 1200…1400 h.; 1 interval – 1400…1600 h.; 1 interval – 1600…1800 h. The number of failures corresponding to each interval: 

\[
\begin{align*}
&n_1 = 61; \quad n_2 = 12; \quad n_3 = 9; \quad n_4 = 7; \quad n_5 = 3; \quad n_6 = 4; \quad n_7 = 3; \quad n_8 = 2; \quad n_9 = 2.
\end{align*}
\]

### Table 1. Statistical Information Series

| Number of interval, \( i \) | Time interval, \( \Delta t_i \), h. | Class mark, \( t_{\text{cpi}} \), h. | Number of failures, \( \Delta n_i \) | Frequency of failures, \( u_i = \frac{\Delta n_i}{N} \) | \( t^2_{\text{cpi}} \cdot 10^{-4} \) | \( u_i \cdot t_{\text{cpi}} \) | \( u_i \cdot t^2_{\text{cpi}} \) |
|-----------------------------|---------------------------------|---------------------------------|-----------------------------|---------------------------------|-----------------------------|-----------------------------|-----------------------------|
| 1                           | 0-200                           | 100                             | 61                          | 0.592                           | 1                           | 59.2                        | 59200                      |
| 2                           | 200-400                         | 300                             | 12                          | 0.117                           | 9                           | 35.1                        | 10530                      |
| 3                           | 400-600                         | 500                             | 9                           | 0.087                           | 25                          | 43.5                        | 21750                      |
| 4                           | 600-800                         | 700                             | 7                           | 0.068                           | 49                          | 47.6                        | 33320                      |
| 5                           | 800-1000                        | 900                             | 3                           | 0.030                           | 81                          | 27.0                        | 24300                      |
| 6                           | 1000-1200                       | 1100                            | 4                           | 0.039                           | 121                         | 42.9                        | 47190                      |
| 7                           | 1200-1400                       | 1300                            | 3                           | 0.029                           | 169                         | 37.7                        | 49010                      |
| 8                           | 1400-1600                       | 1500                            | 2                           | 0.019                           | 225                         | 28.5                        | 42750                      |
| 9                           | 1600-1800                       | 1700                            | 2                           | 0.019                           | 289                         | 32.3                        | 54910                      |
| In total                    |                                 |                                 | 103                         | 1.00                            | 353.8                       | 342960                     |

The expected value is:

\[
M(t) = 59.2 + 35.1 + 43.5 + 47.6 + 27.0 + 42.9 + 37.7 + 28.5 + 32.3 = 353.8 \approx 354 \text{ hour}
\]

Dispersion is determined by the formula:

\[
D(t) = \sum_{i=1}^{\text{9}} u_i \cdot t^2_{\text{cpi}} - M^2(t) = 59200 + 10530 + 21750 + 33320 + 24300 +
\]

\[
+ 47190 + 49010 + 42750 + 54910 - 354^2 = 217644 \text{ (h)^2}
\]

Calculating the Grubbs’ criterion:

\[
\tau_{\text{min}} = \frac{|t_{\text{min}} - M(t)|}{\sigma} = \frac{[5 - 356]}{466} = 0.753
\]

\[
\tau_{\text{max}} = \frac{|t_{\text{max}} - M(t)|}{\sigma} = \frac{|1798 - 356|}{466} = 3.094
\]

For a given level of significance \( \alpha = 0.1 \) and the number of observed objects \( N = 64 \), we determine the critical value of the Grubbs’ criterion.

\[
\tau_{\text{cr}} = 3.54 + \frac{3.72 - 3.54}{100 - 50} (64 - 50) = 3.59
\]

As \( \tau_{\text{min}} < \tau_{\text{ap}} \), \( \tau_{\text{max}} < \tau_{\text{cr}} \) then the members under consideration are not excluded from the totality under consideration.
Statistical estimation of the probability of equipment failure-free operation:

\[ P^*(t_{cpi}) = \frac{N(t_{cpi})}{N(0)}. \]

The number of non-defective items \( N(t_{cpi}) \) to the point in time \( t_{cpi} \):

\[ N(t_{cpi}) = N(0) - n(t_{cpi}), \]

The number of defective items \( n(t_{cpi}) \) to the point in time \( t_{cpi} \):

\[ n(t_{cpi}) = \Delta n_{i-3} + \Delta n_{i-2} + \Delta n_{i-1} + \frac{\Delta n_i}{2}, \]

The statistical frequency of failures is determined by the expression:

\[ f^*(t_{cpi}) = \frac{\Delta n(\Delta t_i)}{N(0) \cdot \Delta t_i}. \]

The statistical failure rate is determined by the expression:

\[ \lambda^*(t_{cpi}) = \frac{\Delta n(\Delta t_i)}{N(t_{cpi}) \cdot \Delta t_i}. \]

**Table 2. Determination of statistical indicators of reliability**

| Number of interval | Time interval, \( \Delta t_i \), h. | \( N(t_{cpi}) = N(0) - n(t_{cpi}) \) | \( P^*(t_{cpi}) \) | \( Q^*(t_{cpi}) \) | \( f^*(t_{cpi}) \) | \( \lambda^*(t_{cpi}) \) |
|-------------------|-------------------------------|-------------------------------------|-----------------|----------------|----------------|----------------|
| 1                 | 0-200                         | 72.5                                | 0.704           | 0.296         | 0.00296       | 0.00421       |
| 2                 | 200-400                       | 56                                  | 0.349           | 0.651         | 0.00038       | 0.00167       |
| 3                 | 400-600                       | 25.5                                | 0.248           | 0.752         | 0.00044       | 0.00176       |
| 4                 | 600-800                       | 17.5                                | 0.170           | 0.830         | 0.00034       | 0.00200       |
| 5                 | 800-1000                      | 12.5                                | 0.121           | 0.879         | 0.00015       | 0.00120       |
| 6                 | 1000-1200                     | 9                                   | 0.087           | 0.913         | 0.00019       | 0.00222       |
| 7                 | 1200-1400                     | 5.5                                 | 0.053           | 0.947         | 0.00015       | 0.00272       |
| 8                 | 1400-1600                     | 3.0                                 | 0.029           | 0.971         | 0.00010       | 0.00333       |
| 9                 | 1600-1800                     | 1.0                                 | 0.001           | 0.999         | 0.00010       | 0.01000       |

The dependences of the reliability indicators of the cable line \( P^*(t_{cpi}), Q^*(t_{cpi}), f^*(t_{cpi}), \lambda^*(t_{cpi}) \) are shown in Figures 1-4.
Figure 1. The statistical probability of failure-free operation of the cable line

Figure 2. The statistical probability of the cable line failure

Figure 3. The statistical frequency of the cable line failures
Confidence limits of dispersion of the average value for the exponential distribution law are determined by the formulas:

\[ t_\mu = M(t) \cdot r_1 \quad \text{and} \quad t_\nu = M(t) \cdot r_3, \]

where \( r_1 = 1.18; \quad r_3 = 0.86. \)

\[ t_\mu = M(t) \cdot r_1 = 356 \cdot 0.86 = 306.16 \text{ (h.)} \]
\[ t_\nu = M(t) \cdot r_3 = 356 \cdot 1.18 = 420.08 \text{ (h.)} \]

4. Conclusion
1. The increase in time to failure of the mechanized well stock is the main direction for improving the efficiency of the oil producing enterprise.
2. To determine the reserves for increasing the time between failures of the mechanized well stock, and in particular the ECP units, it is necessary to conduct factor analysis of information on failures of the submersible equipment, effective statistical studies and use the theory of reliability.
3. When developing measures to increase the time to failure of a mechanized well stock, special attention should be paid to modes of operation of wells with ESP, optimization of parameters of wells, the introduction of technologies and techniques to combat the complications of mechanized oil.

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