Condition monitoring and fault diagnosis of electric submersible pump based on wellhead electrical parameters and production parameters

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ABSTRACT

Electric submersible pump (ESP) has become an important mechanical oil equipment in the digital oil field, and it is necessary to perform the condition monitoring and fault diagnosis on the ESP system. An on-line technique is proposed based on the electric parameters and production parameters. To realize the fault diagnosis of the ESP in the ground, the algorithms are designed by feature extraction, and the algorithms combine the electric parameters in the electric cabinet with the production parameters, which are separated by a newly designed gas–liquid two-phase flow meter. Meanwhile, electrical parameters are the main ones and production parameters are the auxiliary ones. The parameter features are extracted from different faults by digital signal processing, and the study accurately monitors nine typical operating conditions of the faults. Importantly, the method enormously reduces the impact on the sensors in the down hole, and the test data show that the method has the advantages of low cost and high efficiency.

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1. Introduction

With the constant development of science and technology, people pay more attention to energy shortages and environmental pollution. In particular, the exploitation of oil fields has higher requirements for oil production, development, evaluation and other technologies. The electric submersible pump (ESP) has been widely used in oil fields for its advantages of high lift, large displacement and convenient for management. Therefore, it is of great significance to carry out the research on the theory and technology for fault diagnosis of the ESP. At present, the working condition detection and fault diagnosis of the ESP in the point of signal source mainly include traditional detection methods and modern detection methods. Traditional detection methods include current card method and system control efficiency control chart. Modern detection methods mainly include vibration analysis and working condition diagnostics. There are many research studies on the methods to analyse different kinds of signals.

Yang (2004) studied the characteristics and application of the ESP in the oil recovery system. Liu, Tao, and Liu (2011) studied the data analysis and application of vibration signals based on wavelet analysis and wavelet transform in the ESP. Xi (2008) used the method of traditional mechanical fault diagnosis and wavelet analysis and realized the extraction of excessive shaft thrust and wear fault characteristics. Li (2010) extracted features for the ESP in the case of eccentric wear of the impeller, sand plug of the impeller and eccentric wear of the bearing. Liu et al. (2011), Dong (2004) and Li, Zhang, Song, Yu, and Duan (2008) got the mathematical model of the ESP pressure curve, and drew the characteristic curve of the typical pressure under different working conditions, and completed the diagnosis of different faults and effectively improved the oil production. Zhao, An, and Yang (2006), Zhang (2008), Gan, Cao, and Huang (2002) and Sakthivel, Sugumaran, and Babudevasenapati (2010) proposed a qualitative and quantitative analysis method for fault tree diagnosis of the ESP. Li (2010), Peng (2016), Wang (2007), Wang (2013) and Rajakarunakaran, Devaraj, and SuryaparakasaRao (2008) adopted artificial fuzzy mathematics and so on. Li, Yang, Li, and He (2010), Zhao (2011) analysed the vibration signal of ESP, the feature extraction and the establishment of the typical fault vibration mechanical models. Mckee et al. (2015), and Feng (2007) studied a comprehensive diagnosis method based on the system analysis. In addition, Zheng, Hao, and Huang (2012) combined the measured pressure data of the oil field to research on the verification of downhole working.
conditions. The current card is an actually used method in the spot, and it had low efficiency and multiple faults.

In this paper, the working principle of the ESP and the theory of fault diagnosis algorithm are studied. The study proposes a technique for establishing the features library of current electrical parameters and production parameters in different fault modes of the ESP. To reduce the influence of the production environment and the complex of the downhole conditions, all of the parameters are obtained in the ground which can reflect the condition of the underground. In addition, the study designs algorithms, which are based on field experience and the schematic diagrams, which indicates that the method effectively improves the oil production.

2. Pressure pulse communication system

2.1. ESP systematic component

The ground power is input into the submersible motor through the submersible pump dedicated cable under the tubing into the well. Then the motor drives the multi-stage centrifugal pump to rotate for generating centrifugal force, lifting the crude oil in the well to the ground. As shown in Figure 1, the ESP consists of a downhole part, a ground part, and an intermediate part. The ground part is made up of a transformer group, an automatic console and auxiliary equipment, and the intermediate part is composed of a cable and a tubing. The steel cable is used to hold the cable and tubing string. Lastly, the downhole part is mainly the unit of the ESP.

2.2. The source of the six sets of signal

The newly developed tubular gas–liquid two-phase flow meter has the advantage of measuring gas production and liquid production in real time. The value of gas–liquid ratio can be obtained by calculating these two sets of parameters. The single-phase current and the single-phase voltage can be obtained from the electric cabinet. The pressure of the production string of the ESP is obtained from the wellhead with the pressure sensor. The six parameters are passed to the control centre through the RTU equipment terminal by the Internet.

Compared with the advantages of signal acquisition in traditional detection methods and modern detection methods, the selected six sets of parameters are related to the parameters in the diagnosis instrument. In this paper, we have adopted the current parameters in the traditional detection method and some related parameters in the modern detection method. Besides, the winding temperature, the leakage current, and motor vibration in the modern detection method have a certain impact on the operating current and voltage of the motor. In addition, the suction inlet temperature, the outlet pressure, and the inlet pressure still have an effect, which are reflected in the production parameters. Therefore, the diagnosis instrument provides a theoretical basis for the selection of the parameters. However, these parameters of the diagnosis instrument are obtained from the downhole. The diagnosis instrument is easily affected by the downhole environment. Thus, the study adopts electric parameters and production parameters to diagnose in real-time working conditions, which can remove the disturbing factor.

2.3. The mechanism of signal measurement

Some formulas are used to deduce the relevance of the attempt and the reliability of the measurement method. The suction pressure of the pump is equal to the height of the liquid column above the suction inlet plus the sleeve pressure. The relationship can be written as

\[ P_{in} = H + \Delta P \]  

where \( P_{in} \) is the suction pressure of the pump, \( H \) is the height of the liquid column above the suction inlet, and \( \Delta P \) is the sleeve pressure. So the bottom hole flowing pressure can be expressed as

\[ P_{wf} = P + (H - L_p)\bar{\rho}g \]  

where \( P_{wf} \) is the bottom hole flowing pressure, \( H \) is the pump height, and \( \bar{\rho} \) is the average liquid density.

According to the productivity prediction model, the liquid output under pump inlet pressure can be obtained by

\[ Q = f(P_{wf}) \]  

where \( Q \) is the output, which can be expressed as

\[ Q = Q_L + Q_g \]
where $Q_l$ is the liquid production and $Q_g$ is the gas production.

$u_1, u_2, \ldots, u_8, u_9$ is the fault set, and the faults, including underload, overload, the gas effect, gas locking, insufficient liquid supply in oil wells, leakage of tool string, voltage greater than the rated value, voltage lower than the rated value, the changes in suction pressure, current, voltage, bottom hole flowing pressure and liquid output, are obvious. Therefore, these six data are used to evaluate the working conditions of ESP. This relationship can be given by

$$U = \{u_1, u_2, \ldots, u_8, u_9\} = \{P_{in}, I, V, P_{wf}, Q\} \quad (5)$$

### 3. Fault detector design

#### 3.1. Feature recognition algorithms

As shown in Table 1, the parameter features of the ESP are analysed from different conditions for different faults. Combining the major judgement with the assistant judgement is shown in Figure 2. Moreover, the major judgment adopts the pre-judgment and the fine-analysis methods. The pre-judgement method can recognize whether there is a fault in a simple judgement. The fine-analysis method can diagnose the fault models accurately.

#### 3.2. Feature extraction

Several categories of faults are described and the changing trends of parameter features are extracted. The changing trends include the expectation and variance. The parameters include the electrical parameters and production parameters. The mapping relation between faults and changing trends of parameter features is shown in Table 1.

According to the theory of probability and statistics by Zhang, Chen, and Wang (2017) in the current study, the expectation reflects the average of the random variable size. The maximum value and the minimum value reflect the deviation of the data. Actually, time domain is adopted to measure the degree between the random variable and its expectation.

### 4. Typical faults

In this section, we analyse nine typical faults encountered in the production process which are mainly represented by the electrical parameters and production parameters. Considering the field condition, nine schematic diagrams are drawn, which can reflect the changing trend of parameters. Compared with the change in actual application parameters, these charts can be used as a reference.
The initial condition of the nine schematic diagrams analyzed is normal, so changes in the normal range are shown in the first segment of parameters.

4.1. Normal

Case 1: In the normal condition, the designed power and actual power is nearly equal to the normal value. Besides, oil pressure and wellhead temperature are within the normal fluctuation range, and in Figure 3 shows that parameters are in the normal range.

4.2. Underload

Case 2: The a–b segment shown in Figure 4 indicates that the motor is working properly. During the continuous operation, the single-phase current is decreasing owing to the ESP in the underload condition, as shown in the b–g segment. When the current drops to the underload shutdown set value, the motor continues to work at the underload set value for some time. The g–h segment indicates that the current turns to be zero suddenly after working at the underload condition for a long time. Liquid productions are increasing because of the small load selection as shown under the normal condition, so the first segment of parameters are in the normal range of changes.

4.3. Overload

Case 3: Similarly, the a–b segment shown in Figure 5 indicates that the ESP is working well. During continuous operation, current is increasing owing to the overload in submersible pump, which is shown in the b–c segment. When the current rises to the overload shutdown set value, the motor continues to work at the overload set value for some time. The g–l segment indicates that the current turns to be zero suddenly. After working in the overload for a long time, liquid production is decreased.
because of the large load selection as shown in the b–c segment. After shutdown, liquid production continues to decline, as shown in the g–h segment. The e–f segment indicates that the gas–liquid ratio does not change during the entire operating conditions.

4.4. The gas effect

Case 4: Similarly, the a–b segment as shown in Figure 6 indicates that the ESP is working properly. Then, the intake pressure fluctuates frequently, so the ESP is deeply affected by gas. At the same time, the lifting capacity of the pump becomes weaker. The gas production is increasing in the b–c segment. The current curve fluctuates due to more free gas. What is more, the current is unstable and fluctuates regularly. The inlet pressure and outlet pressure drop slightly, liquid production has a slightly increase or remains unchanged in the b–c segment. Above all, gas–liquid ratio fluctuates severely and increases in the b–e segment.

4.5. Gas locking causes underload shutdown

Case 5: The a–b segment as shown in Figure 7 indicates that the motor is working properly. When the ESP is severely affected by the gas, a lot of gas enters into the pump, liquid production has a fluctuation downward trend in the b–l segment, the gas production has a fluctuation rising trend in the b–d segment and gas–liquid ratio is rising in the b–c segment. When the working fluid level is close to the pump suction entrance, the current fluctuates significantly and the declining trend is unstable. What is more, excessive gas content is locked in the pump, the current drops rapidly in the m–p segment because of underload protection. At the shutdown state, production parameters are in the downward trend.

4.6. Insufficient liquid supply in oil wells

Case 6: When the moving surface drops, then the oil pressure drops, and the ESP operates abnormally. The characteristics of the parameters are obvious on the single-current. There is also a significant fluctuation in the gas–liquid ratio .

Similarly, the a–b segment as shown in Figure 8 indicates that ESP is working properly. The current lower than below rated value in the b–c segment and its steady descent according to a certain slope. The current drops rapidly in the m–p segment because of protection underload shutdown. After the ESP shutdowns for some time, it restarts again in the b–e segment.

4.7. Leakage of tool string condition

Case 7: When the production string is outflowing, the liquid flows out of the tubing under the pressure difference
between the inside and outside of the tube. The relationship between the pressure and time of the original column is damaging and the load is decreasing.

Similarly, the a–b segment as shown in Figure 9 indicates that the motor is working properly. The liquid production lower than below rated value in the b–d segment. In the moment of working conditions in the b–e segment. Oil pressure abruptly decreases in the b–e segment. However, unidirectional current does not change throughout this condition in the a–c segment.

**4.8. Voltage greater than rated value condition**

Case 8: When the voltage of the submersible motor is higher than its rated value, ESP is not in the normal operating range and the lifting capacity pump is rising.

Similarly, the a–b segment as shown in Figure 10 indicates that the motor is working properly. The motor supply of power rises in the b–d segment. Then, single-current, liquid production and gas production are rising in the b–m segment, c–f segment and b–h segment, respectively. When the current reaches its set overload current in the b–c segment, after working for a while, the ESP has an overload protection shutdown in the m–n segment. The current, the liquid-producing capacity, the gas production and the oil pressure are falling in the f–g segment and h–l segment, d–e segment and o–p segment in the process of n–o segment, respectively. Above all, the gas–liquid ratio is always in the normal range in the a–p segment over the entire operating condition.

**4.9. Voltage below rated value**

Case 9: When the voltage of the submersible motor is lower than its rated value, the ESP is not in the normal operating range, the lifting capacity pump is declining.

Similarly, the a–b segment as shown in Figure 11 indicates that the ESP is working properly. The motor supply of power declines in the b–d segment. Then, current, liquid-producing capacity, gas production are going down in the b–d segment, b–m segment and b–h segment, respectively. But current reaches its set underload current in the d–e segment. After working for a while, the ESP has an overload protection shutdown in the e–f segment. The current, the liquid-producing capacity, the gas production,
production and the oil pressure are falling in the f–g segment, h–l segment and d–e segment in the process of the f–g segment, respectively. The gas–liquid ratio is always in the normal range in the a–p segment over the entire operating condition.

5. Recognition algorithms

5.1. Deviation degree

After a discrete sampling of the signal, the mean value of the signal in the normal working period is regarded as the standard signal.

By normalizing the signal and comparing the data obtained from each sampling, the degree deviation of the current single-current working condition and the normal condition are distinguished. The equation of the degree deviation is

\[ B = \frac{I_i}{I_s} \]  
(6)

where \( I_s \) represents the value of the standard variable and \( I_i \) represents a discrete random variable.

5.2. Statistical properties

When the ESP runs, there may be gas influence which causes unidirectional single-current fluctuations, especially in the case of the gas locking conditions, and the fluctuation characteristics of the variance are obvious.

In terms of overload, underload and leakage of the pipe string, the mean value characteristics are obvious, and they are stable in a certain range.

The current fluctuation in the normal range is \( \pm 5\% \). The single-current value is stable at 0.8 times under underload conditions, and the current value is fluctuating at 1.2 times under underload conditions. The current parameters are adjusted dynamically in the actual spot. The equations of expectation and variance of electrical parameters are

\[ E(X) = \sum_{i=1}^{n} p_i x_i \]  
(7)

\[ D(X) = \sum_{i=1}^{n} p_i (x_i - \mu)^2 \]  
(8)

where \( \mu = E(X) \), \( x_i \) is the value of the discrete random electrical variable and \( p_i \) is the probability of electrical parameter variable.

5.3. Method of threshold

In the conditions of overload and underload, electrical parameters of the ESP should be adjusted according to different well conditions and the size of the threshold.

5.4. Frequency characteristics

The single-current is frequency-converted according to the actual production conditions during operation. The current signal is mainly frequency-signal, which is controlled by power frequency.

5.5. Cross-correlation detection

Because of the complex and similar working conditions, such as gas effect and gas locking, insufficient liquid supply condition cannot be distinguished from leakage of tool string condition with its statistical characteristics and frequency characteristics using the current parameters. In the different conditions, current signal waveform has a big difference.

Due to the influence of the complex conditions, such as gas locking, the shortage of liquid supply and leakage of the tool string state cannot be identified by only using the statistical and frequency characteristics of current parameters. Besides, in the different conditions, the waveforms of current signals are quite different.

According to the prior experience of the field experience, the wave shape of the current is similar in different wells. In order to realize real-time diagnosis, the study adopts the cross-correlation detection method, which was used to calculate the similarity between the collected periodic wave signals and standard samples, the fluctuation characteristics of signals are effectively distinguished. And, the equation of similarity between the real current and standard samples current is

\[ r = \frac{\text{Cov}(X, S)}{\sqrt{D(X)D(S)}} \]  
(9)

where \( \text{Cov}(X, S) = \sum_{i=1}^{n} (x_i - E(X))(s_i - E(S)) \), \( r \) is the degree of similarity between discrete real current variable and standard sample current.

By setting an appropriate threshold, the fluctuation characteristics of current can be effectively distinguished. Moreover, the standard sample signal is changed dynamically by the actual situation. The cross-correlation detection is adopted between sample curve and actual signal curve. Lastly, it can be easily discriminated depending on the degree of the similarity.
5.6. Features match principle

If features match principle only relies on the current parameters in the electrical parameters, there is a blind spot in the pre-judgement method. Production failures are often unable to be diagnosed immediately. It is impossible to diagnose by the single-current or the single-voltage, and the single-current parameters are often more obvious than the single-voltage parameters in most of the conditions. There are many blind areas to be diagnosed only by using electrical parameters, but also need to unite the auxiliary parameters. The flowchart of features matches as shown in Figure 12. In short, the working condition diagnosis mainly includes the following four cases:

The first case: the pre-judgement combines with the assistant judgement, mainly relying on assistant parameters, such as leakage of tool string condition and gas causes underload shutdown condition. As per the flowchart, algorithms are carried out in the order of 2, 3, 5 and 8.

The second case: the pre-judgement combines with the assistant parameters, such as leakage of tool string condition and normal working condition. Similarly, as shown in the flowchart, algorithms are carried out in the order of 2, 4, 5 and 7.

The fourth case: the pre-judgement combines with assistant judgement, and mainly relies on the assistant judgement parameters, such as the voltage greater than rated value condition and normal working condition. Similarly, as shown in the flowchart, algorithms are carried out in the order of 2, 4, 5 and 7.

6. Conclusions

The working condition monitoring scheme of the ESP based on the electrical parameters and production parameters of the wellhead has been put forward. At the same time, the production status in the underground has been distinguished by the different manual input parameters in the different wells, which has improved the fault diagnosis recognition efficiency.

In accordance with the actual cases, the parameters of nine types of the ESP have been plotted. The technical personnel have accurately determined the cause of the faults with the analysis of the schematic diagrams. The algorithms designed by feature extraction have addressed the models of faults in a timely manner. Besides, more experiments have been conducted in the ESP, and the test results of the laboratory have indicated that algorithms have achieved the requirements by practical engineering applications.

Disclosure statement

No potential conflict of interest was reported by the authors.

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