Research status of fault diagnosis of large and medium-sized vertical water pump units

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Abstract

This paper analyzes the development process and status quo of the fault diagnosis technology of vertical water pump units. Several common fault detection methods of vertical water pump units are introduced in detail from the analytical model-based processing method, signal-based processing method, and knowledge-based processing method. The advantages and disadvantages are analyzed and summarized, providing theoretical methods for fault diagnosis of large and medium-sized vertical water pump units.

Keywords: Vertical water pump, Fault diagnosis, Vibration detection method.

1. Introduction

Troubleshooting of large and medium-sized vertical pump units is an indispensable part of ensuring the safe operation of pumping stations. Vertical water pump is a common type of water pump. If there is no regular troubleshooting, maintenance will cost more time, and money once the vertical pump fails and may cause serious safety incidents. Vertical pump unit faults mainly include abnormal vibration faults, bearing wear, cavitation, and so on. Vibration is the most common form of vertical pump unit faults. In order to ensure the working efficiency and reliability of vertical pump unit, vibration monitoring should be carried out regularly to infer whether the vertical pump unit failed. However, the vibration situation caused by different faults is also different, so it is very necessary to process and analyze the detection signal, judge the cause of the fault and put forward corresponding improvement measures. Therefore, it is one of the effective methods to ensure the safe and stable operation of the pump station to monitor and analyze the vibration signal and infer whether the running condition of the vertical pump unit is good or not.

2. The development process and present situation of fault diagnosis technology

The development of vibration fault treatment of vertical water pump units in China can be divided into three stages:

The first stage is the post-processing stage. At that time, due to people's weak awareness of equipment maintenance and overhaul and relatively simple tools, abnormal conditions of the equipment could not be found in time and could only be repaired after the failure. Moreover, the maintenance of equipment failure depended on personal maintenance experience, which may cause a slow repair speed and long cycle, the type of failure could not be accurately judged. Delayed maintenance can easily cause a significant economic loss for a large vertical pump station.

The second stage is the preventive test stage. According to the fixed plan, the pumping station will be regularly shut down for tested and maintenance. But for the vertical pump station unit, the preventive test is essentially an off-line
detection method, which can be carried out only when the pump station stops operation. The disassembly, assembly, and detection of components require a long period and cost a lot of workforces and material resources. It may be accompanied by problems such as inflexible operation and deviation in fault judgment, which is challenging to meet the operation requirements of the pump station.

Due to the rapid development of the Internet and artificial intelligence technology, fault diagnosis technology is rapidly derived. We can now install sensors to collect the vibration signal of the vertical pump unit and process and analyze it. With a series of methods such as machine learning and big data analysis, it is possible to evaluate the operating condition without stopping the vertical pump unit. It can predict and judge the possible failure of vertical pump unit, which significantly saves workforce and material resources and time, and more effectively enhances the guarantee of the safe operation of vertical pump station and avoids sudden failure. [1]

3. Vibration fault diagnosis method of vertical water pump Unit based on analytic model

In order to describe the fault of the vertical pump system in practical engineering better, we need to analyze the signal detected by the sensor or estimate the physical parameters required to build the system. By combining the changes of physical parameters and the actual occurrence of the fault phenomenon, we can establish the vertical pump failure mathematical model. In this way, the fault can be analyzed, predicted, and located. The analytical model-based fault diagnosis methods of vertical pump units can be roughly divided into three kinds: state estimation method, equivalent space method, and parameter estimation method.

3.1 State estimation method

State estimation is a method to estimate the internal state change of a dynamic system based on the detection data. To build an accurate mathematical model of vertical water pump, and through the sensor to measure the specific data of the equipment, automatically eliminate the system due to noise or other effects of the interference information. By comparing the two data, the difference can be used to judge the fault of the equipment. Through the state estimation method, the data can be detected and identified to predict the future working state of the vertical water pump.

However, the premise of using the state estimation method is to build an accurate mathematical model, but it is difficult to achieve at present. Therefore, the current research focuses on enhancing the anti-jamming ability of the model against a series of errors such as interference and noise caused by the installation of the detection system. [2]

3.2 Equivalent space method

Equivalent space method is a method that directly compares the measured values of input and output of the vertical pump system model to form residuals. Due to the limitation of static equivalent space method, the current equivalent space method based on dynamic equivalent model is more common.

After the residual is formed from the measured values of the input and output of the system, the residual data measured can be compared with the residual data of the optimal operation of the system to evaluate the fault of the vertical pump system. When the residual is zero, the corresponding vertical pump unit is consistent with the constructed model data, and the pump unit runs normally, otherwise, there is a fault. However, the residual error of the actual vertical pump unit is not zero in the normal operation range, because of the existence of errors caused by noise and other external interference. Therefore, the choice of residual threshold is very important for fault diagnosis of vertical pump station using equivalent space method. If the residual threshold value is too high, when the initial failure of the vertical pump station occurs, the residual deviation value is small, and there will be no alarm or missed alarm. If the residual threshold is too low, a slight increase in the residual will cause an alarm, but in this case the pump unit may be intact. To sum up, it is necessary to pay attention to the choice of residual threshold when using equivalent spatial generator for fault diagnosis of vertical pump system. [3]

3.3 Parameter estimation method

When the vertical pump system fails, the system parameters of the failure part will change, resulting in changes in the parameters of the mathematical model of the pump. And different parameter changes indicate that the failure of the vertical pump system is not the same. In other words, when describing the failure of the vertical pump
system, it can be expressed by varying degrees of parameter variation of the model. We can establish the parameter model of the system and find its equivalence relation with component parameters:

$$\theta = f(p)$$  \hspace{1cm} (1)

$\theta$ is the system model parameter established, and $P$ is the physical component parameter of the system model established.

The actual unit parameter $\theta'$ is obtained through sensor measurement. Substitute $\theta'$ into the formula, the actual physical element parameter $P'$ can be obtained. By comparing the nominal value of $P'$ and $P$, the actual running status of vertical pump unit can be obtained. $P'$ can also be used to estimate the damage of the physical components of the vertical pump unit. Therefore, the principle of parameter estimation method is to speculate the running state of the vertical pump unit through the variation of the parameters of the vertical pump model. It can also compare parameters to find the fault source. However, similar to the state estimation method, it is difficult to obtain an accurate mathematical model in practical engineering. In addition, there are a series of defects in the establishment of equivalence relation, such as lack of parameters and inaccurate parameter estimation.

4. **Vibration fault diagnosis method of vertical water pump Unit based on signal processing**

When the mathematical model of the system is difficult to establish, it can reflect the advantage of signal-based processing method. This method can detect and separate faults directly by using signal model or feature extraction method without establishing a complicated vertical pump system model, which has strong applicability. Most of the original fault diagnosis methods based on signal processing are proposed for linear systems. But because it can extract signals for processing, it is easy to transform into nonlinear systems. There are three common methods, which are spectrum analysis, principal component analysis and wavelet analysis.

4.1 **Spectral analysis**

Spectrum analysis is one of the most common fault detection methods of vertical water pump units. Vibration data of vertical pump unit collected by sensor can be decomposed into vibration signal spectrum diagram by spectral analysis. Spectrum diagram can be very intuitive to see the operation of the vertical pump unit, the most prominent part of the amplitude in the figure can be fully associated with the fault, and provide diagnostic information.

Spectral analysis generally relies on the Fourier transform:

$$X(f) = F[x(t)] = \int_{-\infty}^{+\infty} x(t)e^{-2\pi ft}dt$$  \hspace{1cm} (2)

In general, $X(f)$ is a complex function, we have

$$X(f) = U(f) + V(f) = |X(f)|e^{\phi(f)}$$  \hspace{1cm} (3)

In the formula, $X(f)$ represents the amplitude distribution of the frequency curve decomposed by the signal, $\phi(f)$ is called the phase spectrum, which can represent the phase distribution of the frequency curve.\(^4\)

4.2 **Principal component analysis**

The main principle of principal component analysis method is to reduce the high-dimensional information into a new low-dimensional variable by linear transformation, and the new low-dimensional variable is a linear combination of the original high-dimensional variables. By analyzing the information generated by the low-dimensional variable, we can deduce the change information contained in the original high-dimensional variable data, and the variance of the change value of these data is compared to determine the principal component model. Once the measured signal of the sensor is inconsistent with the signal of the principal component model, the failure of the vertical pump unit can be judged. And it is very convenient to process data and fault separation.\(^6\)

Using principal component analysis method for fault diagnosis of vertical pump unit requires us to pay attention to two variables. Generally, Hotelling T2 statistics are established in the principal subspace for statistical testing, and Squared Prediction Error (SPE) statistics are established in the residual subspace for statistical testing. The main steps are shown in Figure 1.

Using principal component analysis method for fault detection makes complex problems simple and intuitive, and provides most of the original indicator information, making the data set easier to use. However, this method also has some limitations: if there is noise polluted data, the impact of noise will be more significant after standardization; The number of potential hidden variables resulting from...
4.3 Wavelet analysis

Although spectrum analysis is a convenient and practical fault detection method, for large and medium-sized vertical pump units, the Fourier transform of spectrum analysis may not help. In order to express the local characteristics of the signal in detail, the wavelet analysis method is used to detect the faults, which makes up for the shortcomings of Fourier transform in the fault detection of vertical water pumps. Wavelet transform is based on short-time Fourier transform, which has great advantages in the case of unstable signal acquisition of vertical pump units, and has good time-frequency characteristics. From a system point of view, the wavelet analysis of signal processing method is equivalent to adding a band-pass filter to collect signal, based on the analysis of operation condition of the vertical pump unit, the sensor acquisition of vibration signal. Wavelet transform can effectively distinguish between mutations in the signal and noise, have very strong antinoise ability and real-time performance, high detection efficiency, and is convenient for multi-component signal analysis.[8]

The working flow chart of detecting faults of vertical pump unit by wavelet analysis is shown in Figure 2:

Fig. 2. Flow chart of application of wavelet analysis in fault diagnosis of vertical pump station

Literature [9] gives the following fault diagnosis methods using wavelet analysis, which can provide a good idea for the fault monitoring and diagnosis of vertical water pumps:

(a) Using wavelet signal analysis to detect the singularity of signal mutation directly, so as to realize the fault monitoring of vertical water pump.

(b) Using wavelet analysis to observe the change of signal frequency structure can effectively realize the fault monitoring of vertical water pump.

(c) The failure of vertical pump unit can be judged by the change of impulse function and the change of wavelet transform coefficient.

Wavelet analysis method is applied to fault detection of vertical pump station. It is a very practical detection method to decompose the fault signals collected conveniently and obtain different signal characteristics, so as to distinguish the fault degree of each part.

5. Vibration fault diagnosis method of vertical water pump unit based on knowledge

The knowledge-based fault diagnosis method is similar to the signal processing-based fault diagnosis method, which does not require establishing an accurate vertical pump
model. This fault diagnosis method continuously accumulates people's fault diagnosis experience, makes full use of statistical knowledge, and compares the stored information with the diagnosis object to accurately determine whether the equipment fails and the type of the fault. The main methods include expert system method, artificial neural network method, fuzzy fault diagnosis method, etc.

5.1 Expert system method

Expert system method is to store a large number of existing fault information, after collecting the detection signal of the vertical pump system, through comprehensive comparison, rapid analysis and processing. The possible fault location and its specific cause can be located through a series of calculation and reasoning. The repository of expert system stores a large number of data such as fault cause, symptom, manifestation, suggestion. Therefore, it only needs to compare the measured signal with the known data to calculate the most similar optimal solution. Schematic diagram of expert system method is shown in Figure 3.

Expert system method has been widely used in the fault diagnosis of vertical water pump, but this method has some limitations because the content of knowledge base is limited, therefore, it cannot deduce the fault data that has not appeared.\(^\text{[10]}\)

5.2 Artificial neural network method

In recent years, artificial neural network has been widely used in the fault diagnosis of vertical water pumps. It is a kind of nonlinear dynamic system with self-learning ability, self-organization and self-adaptation, which can process complex information autonomously based on artificial neural network. Compared with the expert system method, the advantage of artificial neural network is greatly reflected in its learning ability. Its reasoning is a numerical calculation process with analytical processing ability and strong recognition, memory and association functions. It can continuously acquire new knowledge and apply it to solve the problems that the expert system cannot deal with.

The database of artificial neural network has strong generality and fault tolerance, and can process and analyze complex non-new systems. Through continuous learning of new knowledge and application and promotion, artificial neural network can build a database with strong adaptability and high fault tolerance, analyze and identify fault types and give fault handling suggestions, which has a wide range of applications. However, there are also some defects in practical application: similar to expert system method, artificial neural network also needs a large number of basic numerical support, so the learning process cannot be observed, which may affect the reliability of results, and there are certain requirements for sample selection.\(^\text{[11]}\)

5.3 Fuzzy fault diagnosis method

The fuzzy fault diagnosis method is simply to establish a fuzzy matrix based on the failure symptom of vertical pump unit and the failure itself, and convert it into a fuzzy equation, and get the relationship between the failure symptom and the fuzzy transformation. It has the advantages of convenient application and intuitive conclusion. Based on this method, combined with the reality that the mathematical model of...
vertical pump is difficult to establish accurately, we can use the fuzzy equation to express the vibration of vertical pump unit, so as to judge the fault cause of vertical pump. However, fuzzy fault diagnosis does not have self-learning ability, and it is difficult to master the balance between symptoms and faults, and there are deviations in the selection of membership functions and characteristic elements. Generally, fuzzy fault diagnosis can be combined with neural network, wavelet analysis and other methods.[12]

6. Conclusion

At present, the vertical pump is more and more widely used in China's water conservancy system, such as water supply, industrial pressurization, liquid transportation, irrigation and so on. Therefore, the research on the fault diagnosis of the vertical pump unit is not only limited to this, and its fault monitoring and diagnosis technology should also become a research focus. Based on analytic model, signal and knowledge processing methods, this paper summarizes a variety of common fault detection methods for vertical pump units, and analyzes and compares their advantages and disadvantages.

The analytical model-based processing method needs to build a vertical water pump model. This method can intuitively judge whether a failure occurs through data comparison. But it isn't easy to establish an accurate vertical pump model. The signal-based processing method does not need to build the pump model. This method can directly analyze and process the collected data, strongly applicable. The knowledge-based processing methods rely on establishing databases and need a long accumulation time to make a more accurate judgment. Knowledge base method can directly judge the fault location, fault cause and give maintenance suggestions, which will provide an excellent convenience for the maintenance of the vertical pump unit.

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