Research and application of digital virtual maintenance system for steam turbine

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Abstract: After a 430MW machine unit was started with C repair finished, the shafting vibration of it increase rapidly at the phase of on-load. Using the on-line vibration monitoring and fault diagnosis system (TDM system) matched with the unit to check the vibration historical data, and according to the vibration characteristics, oil film vortex fault is diagnosed. In view of this, the vacuum test was carried out on the lubricating oil temperature of the main transformer engine and the condenser of the unit. The results show that the low frequency variable oil temperature and the condenser can be restrained in a large certain load range. The distribution measures of bearing load are adjusted by unit's adjustment to increase the load of No.3 bearing, so as to eliminate the unit's low-frequency vibration fault and ensure the normal operation of the unit.

1. Introduction
The digital virtual maintenance system is the product of the integration of equipment maintenance technology and virtual reality technology. The system provides the guidance of equipment fault online diagnosis and processing scheme comprehensively. The equipment fault identification criteria mainly adopts the signal analysis methods of time and frequency domain to calculate the characteristic value of instantaneous value and rate of range of sampled signal, and determine the fault type and reliability CF (Certainty-Factor). Reliability calculation is mainly divided into two methods of the instantaneous value type and the rate of change type, fault reasoning is sorted from high to low in terms of reliability. By using grey relational analysis method, the grey relational degree of the operation data, maintenance data and vibration data input by the system is calculated. The large correlation degree is diagnosed as the operation factor causing the fault, and the corresponding operation guidance suggestions are pushed.

The oil whirl fault of f-stage gas turbine unit introduced in this paper is technical research and application practice of digital virtual maintenance technology for steam turbine.

2. Unit overview
Two F-class (2×430MW) gas steam combined cycle cogeneration units in a certain plant are equipped with a heating network. The generator set adopts multi axis layout, the fuel adopts the mixed natural gas of Shanghai urban pipe network, and the power outlets is connected to Shanghai power grid through 220kV booster station. Model of steam turbine islzcl40-13.0/1.2/555/550, double cylinder (high and medium pressure cylinder and low pressure cylinder), three pressure reheat, one driven one equipped with f-stage gas turbine, adjustable extraction and condensate extraction turbine. The model of steam turbine generator is QF-150-2, turbine-generator shaft system of which is shown in Figure 1.
On February 5, 2018, the unit was started after C repair, and in the process of first full load, each vibration of bearing liner was within the alarm value. In the process of unit load down, the vibration of bearing 3 and 4 appears "sudden increase" and "rapid decrease", the vibration change time is within 30s, the vibration of bearing 3 and bearing 4 fluctuates from about 30μm to about 120μm and 70μm respectively, and the maximum fluctuation is about 200μm and 110μm.

3. Online fault diagnosis of digital virtual maintenance system
The fault feature analysis module is the foundation of vibration fault diagnosis in digital virtual maintenance system. The first part is whether the phase modifier goes wrong, and the second part is to determine the location and cause of the fault if the fault has been confirmed. This module is in line with the operation data, maintenance data and change features of shaft vibration as input, forms fault characteristic through mathematical calculation and transformation and compares with expert system data for evaluation to do qualitative and quantitative analysis. From the point of view of fault diagnosis, symptoms are helpful to judge all kinds of fault phenomena, including some normal phenomena, such as vibration stability. Using normal phenomena, some faults can be eliminated.

3.1. Reliability of calculation of instantaneous value condition
Instantaneous value condition is determined by the data of a certain time. For example, when the symptom are "the speed is more than twice of the first critical speed", "the amplitude of the first octave frequency in the vibration spectrum is large", "the unit operates with load", the reliability is 0 or 1, or the value between [0,1].

For example, when calculating the reliability of the symptom "amplitude of a certain frequency component in the vibration spectrum is large", we can adopt the methods of comparing the amplitude of this frequency component with that of other frequency components, and it is shown in the following formula:

$$CF(1X) = \frac{A(X)}{(a1 \times A(TX) + a2 \times A(LX) + a3 \times A(HX))}$$

In the formula, $A(X)$, $A(TX)$, $A(LX)$ and $A(HX)$ and are the amplitudes of the frequency, pass frequency and high frequency, and $a1$, $a2$, $a3$ are proportionality coefficient less than 1. Depending on the nature of the fault, for the same description of conditions, the calculation methods are different in different faults. $a1$, $a2$, $a3$ are mainly determined based on experience, and the numerical value reflects the influence degree of different frequency components on it.

3.2. Calculation of change rate conditional credibility
The condition of change rate type is determined by the data at different times. When the rate of change type is used to calculated the reliability of large amplitude fluctuation with the constant speed, the change of two groups of data can be compared with the set threshold value when the speed change is less than 10 rpm, as shown in the following formula:

$$CF(X) = \frac{(A1 - A0)}{A0}$$

In the formula, $A0$ and $A1$ are the amplitude of two sets of data successively, and $A_b$ is the threshold value of amplitude.
According to the symptom reliability, we can further deduce the fault reliability. Take a diagnosis rule of "quality imbalance" fault as an example:

If the frequency doubled in the vibration spectrum is large
And the amplitude is basically the same when the rotating speed is constant
And the phase of the first octave is basically the same when the rotating speed is constant
Then the mass is unbalanced

The credibility of the rule itself is given by domain experts, and the credibility of the conclusion is calculated. The credibility of quality imbalance rules is $CF_r = 0.95$, the relationship between symptoms of each diagnosis rule is generally "and". The fault credibility $CF$ is the product of the minimum value in the symptom credibility and the rule credibility:

$$CF = CF_r \times \min(CF_s)$$

In order to diagnose the fault, it is need to introduce the impact factor $IF$, which is using for represents the influence degree of the fault on the vibration of phase modifier. For example, for the falling off vibration fault of rotating part, when the unit is at 3000 rpm, the vibration amplitude is 60μm, and after 2 seconds, the vibration amplitude is 120μm. The main impact factors of falling off fault of rotating parts are time, speed, and load. Based on 3000 rpm, it can be calculated that:

After 2 seconds, at 3000 rpm, the influence factor is: $IF = 120/60 = 2$

The fault severity is represented by $SF$, which is the product of the reliability of vibration fault and the fault influence factor, that is $SF = CF \times IF$.

The criteria of $SF$ are as follows:
If $0 \leq SF < 0.3$, it is normal, and the units operates normally.
If $0.3 \leq SF < 0.5$, it is slight, and does not affect the normal operation of the unit;
If $0.5 \leq SF < 0.8$, it is a warning, and the unit can operate foe a short time;
If $SF \geq 0.8$, it is dangerous, and should be shut down as soon as possible.

When the $SF$ value reaches the warning value, the diagnosis system outputs the fault name (sort by credibility) and the explanation of the diagnosis conclusion. As shown in Table 1:

| No. | Fault name                  | Reliability |
|-----|-----------------------------|-------------|
| 1   | Rotating parts fall off      | 1.00        |
| 2   | Mass unbalance              | 0.60        |
| 3   | Thermal bending of rotor    | 0.46        |

In order to further confirm the specific fault factors, the diagnosis system will analyze and process the input operation parameters and vibration data, and calculate the correlation between each operation parameter (such as lubricating oil temperature, unit deviating from the rated cycle operation, load and etc.) and vibration data. The grey relation analysis method is applied to calculate the grey relation degree of the operation data, maintenance data and vibration data input by the expert system. The large relation degree is diagnosed as the operation factor causing the fault, and the operation guidance suggestions will be given.

3.3. Forward and backward reasoning fault diagnosis

Reasoning backward is also called objective direct reasoning, and it refers to reversely deduces vibration fault according to vibration characteristics. The premise of forward reasoning is that the scope of vibration fault must be clear. Adopting the one-by-one elimination method through search, comparison and analysis with the general catalog of unit fault, the remaining faults that cannot be eliminated are the diagnosis result.
Table 2: Parametric statistics after sudden increase of vibration during unit operation with load

| Channel name | Peak value | 1X amplitude | 1X phase | 2X amplitude | 2X phase | 0.5X amplitude | Gap voltage |
|--------------|------------|--------------|----------|--------------|----------|----------------|-------------|
| 1#X          | 72μm       | 29           | 112      | 4            | 127      | 40             | -10.247V    |
| 1#Y          | 130μm      | 35           | 226      | 3            | 320      | 74             | -8.828 V    |
| 2#X          | 75μm       | 43           | 110      | 9            | 176      | 20             | -9.575 V    |
| 2#Y          | 63μm       | 34           | 195      | 9            | 317      | 13             | -8.954 V    |
| 3#X          | 58μm       | 22           | 19       | 5            | 110      | 16             | -7.995 V    |
| 3#Y          | 205μm      | 24           | 150      | 10           | 252      | 148            | -8.718 V    |
| 4#X          | 113μm      | 40           | 201      | 11           | 138      | 41             | -9.520 V    |
| 4#Y          | 96μm       | 11           | 313      | 10           | 266      | 67             | -9.191 V    |
| 5#X          | 75μm       | 44           | 66       | 18           | 128      | 12             | -11.370 V   |
| 5#Y          | 67μm       | 44           | 157      | 11           | 242      | 7              | -10.540 V   |

Keyphasor speed: 3001RPM

Data time: 2018-02-06 23:57:52

Temperature of each bearing in the loaded operation stage of the unit is shown in Table 3.

Table 3: Temperature of each bearing in the loaded operation stage of the unit ℃

| Lubricating oil temperature | 1W | 2W | 3W | 4W |
|-----------------------------|----|----|----|----|
|                             | 43 | 74.6 | 94.7 | 55 | 83.8 |

The system obtains the vibration symptom data of speed, vibration waveform, frequency spectrum, octave amplitude and phase from the vibration on-line system. The main features extracted are as follow:

1) During the loaded operation of unit 3, the shafting vibration increased abruptly, and the variation was mainly composed of low frequency (25Hz).

2) The fault originates from the low pressure rotor.

3) After the sudden increase of vibration, the low frequency component of 3Y measuring point is the largest, the power frequency component is only more than 20 microns, and the amplitude of low frequency component is more than 140μm, which is far greater than the power.

4) Under the load operation condition of the unit, when the temperature of 3 bearing is 59 ℃, the temperature of 2 bearing is 94 ℃, the temperature of 4 bearing is 83 ℃, and the temperature of 3 bearing is much lower than that of 2 and 4 bearing; At the same time, when the unit runs from zero speed to on load, the gap voltage of vibration measuring points of axis 3X and 3Y changes from -12V and -12V to -7.85V and -7.498V, which is larger than that of vibration gap voltage of other bearing shafts. And from the gap voltage of difference, it can be seen that the diameter of 3 watts rises the most in the bearing. Combining the characteristics of tile temperature and gap voltage, it can be concluded that no.3 bearing has a lighter load and a thicker oil film than other tiles.

5) Before and after the sudden change of vibration, the power frequency amplitude and phase of 3 and 4 bearing shaft vibration are basically stable.

Through the collection and processing of real-time digital information, combined with the protection fixed value, experience as a troubleshooting expert and algorithm model system of the unit design, the digital virtual maintenance system automatically carries out fault forward and reverse reasoning. Figure 2 is the schematic diagram of the system's fault reverse reasoning, Figure 3 is the schematic diagram of the system's fault forward reasoning (fp is equipment rotation frequency).
Starting or operating speed running (speed $> 60 \text{R} / \text{min}$) 
Shaft vibration $a \geq 80 \text{um}$, 
Bearing vibration $a \geq 35 \text{um}$, initiating the diagnostic system

Location and cause of fault:
Half speed whirl occurs in the bearing with the largest low frequency vibration component.

Suggestions for operation guidance:
There are two reasons of oil whirl fault, one is the excessive vibration of shaft diameter, the other is the poor stability of bearing bush. It is known from the vibration conditions of the unit that the power frequency amplitude of the vibration of 3 and 4 bearing shells is usually lower than 30μm, which indicates that the vibration of the shaft diameter is not large. To deal with the oil film whirl fault of the unit, the main task is to improve the stability of the bearing bush.

There are many factors affecting the stability of the bearing bush, including the design, manufacture, maintenance and operation of the bearing bush. The main measures to improve the stability of bearing bush on site are as follow:

1. Reduce the bearing bush top clearance;
2. Change the form of bearing bush;
3. Use the lubricating oil with small viscosity coefficient;
4. Increase the specific pressure of bearing;
5. Reduce the width diameter ratio of bearing;
6. Bearing pedestal elevation changes.

There are several ways to eliminate the whirling fault of bearing oil film. According to the maintenance plan of the unit, the operation parameters should be optimized first (increasing the oil inlet temperature of bearing bush and properly reducing the vacuum of the unit). Use the maintenance opportunity to reduce the elevation of No. 2 bearing by 80-100μm and raise the elevation of No. 3 bearing by about 80μm.

First, increase the oil inlet temperature of bearing bush $(\text{max} = 44 \degree \text{C})$.
According to the forward and backward reasoning of the digital virtual maintenance system, the vibration fault of the unit is diagnosed as the oil whirl fault, which is mainly caused by the oil whirl fault, and it causes the low-frequency vibration component of the adjacent bearing synchronously.

**Figure 4:** Vibration monitoring diagram of unit under load after maintenance

**4. Conclusion**

The digital virtual maintenance system of steam turbine, based on the real data of the unit, simulates the real working environment and equipment, and has the real-time simulation function of data monitoring, fault diagnosis and operation and maintenance processing.
Online monitoring and fault diagnosis system of vibration is an important foundation to realize steam turbine virtual overhaul simulation. For example, under the specific fault conditions, through comprehensive diagnosis of vibration data and operation inspection data of the unit, the system will automatically push the fault nature and operation and maintenance guidance of the unit, provide key drill points for the operators, guarantee the training effect of the maintenance personnel, and improve the maintenance and repair quality, which is of great significance to turbine maintenance.

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