Research on On-line Dynamic Testing and Operation Time Control Method for Critical Vibration Zone of Water Turbine Generator Set

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Abstract. At present, there is no relevant definition and requirement for the critical vibration zone of hydropower units. By summarizing and analyzing the operation stability of the unit, the definition of critical vibration zone is given. An on-line dynamic testing method for vibration region based on comprehensive stability index of hydropower units is proposed. For the two methods of dynamic on-line testing and manual setting in critical vibration zone, the operating time control functions are given respectively to ensure the safe operation of the unit and to improve the operation range and adjustability of the unit.

1. Introduction

China is rich in hydropower resources. Hydroelectric energy has the advantages of low pollution, low cost and fast revenue. The development of hydropower energy has become an important strategic direction for improving energy structure[1-2], protecting natural ecological environment, accelerating the rapid economic development and achieving sustainable development, and has developed rapidly in recent years.

When the hydropower unit deviates from the design condition, it will cause the vibration of the unit, which is called the "vibration zone". Vibration of hydro-generating units will not only affect the normal operation of the turbine, increase the loss of the turbine blades, but also cause damage to the mechanical parts of the unit and the plant. Therefore, it is necessary to avoid the operation of the hydro-generating units in the vibration zone [3-4]. The critical vibration zone is the load region near the vibration zone, and there is no relevant literature to study it at present. In this paper, the critical vibration zone is studied, and the on-line test method and operation time control method are given.

2. Critical vibration zone

When the turbine deviates from the optimal operating condition, the flow pattern in the runner deteriorates, which results in a certain circulation of the runner outlet flow, and unstable eddy bands are formed in the draft tube, resulting in pressure pulsation and turbine power pulsation. Excessive pressure pulsation can cause unit vibration and endanger the safe and stable operation of unit, which is the main source of unit vibration zone [5]. Therefore, it is forbidden to operate the unit in the vibration zone, and only in the stable operation zone can the unit run for a long time.
The critical vibration zone is the load region near the vibration region, and it’s shown in Figure 1. In this load zone, the unit can operate, but it can not run for a long time. It should be controlled and restricted.

![Figure 1. critical vibration zone](image)

Vibration zone under different working head can be determined by stability test, and then set by manual input mode. However, parameters such as vibration, swing, pressure fluctuation are related to working head, and vibration zone under different working head is different. If the vibration zone can not be determined according to the working head, only one or more larger vibration zones are set artificially, which will virtually reduce the operating zone of the unit. In order to solve the above problems, the vibration and swing data of the unit can be collected by on-line monitoring device, and then the evaluation model can be established to dynamically determine the vibration zone and critical vibration zone.

3. On-line dynamic test of vibration zone based on comprehensive stability standard of generating unit

The data of unit vibration, swing, pressure fluctuation and cavitation noise intensity under different water head and loads are obtained by using unit water regimen automatic measuring and reporting system, vibration swing and on-line monitoring system. Then, the distribution zones of vibration zone, critical vibration zone and stable operation zone under each head are determined by the following algorithm. The detailed flow chart of the algorithm is shown in Figure 2. After choosing a working head, the vibration zone and critical vibration zone under the working head can be described by analyzing the characteristic parameters involved in the stability evaluation under all load conditions.

Set $V_{ij}$ ($i = 1, 2, ..., m$) as the measurement value of vibration, swing, pressure fluctuation and cavitation noise intensity of a unit, $n$ is the number of units in a power station, $m$ is the eigenvalue number of the stability evaluation parameters of unit $i$. Then, there is a formula (1):

$$L_{ij} = \begin{cases} 
0 & V_{ij} \geq V_{ij}^{\text{max}} \\
1 & V_{ij} < V_{ij}^{\text{max}} 
\end{cases}$$

(1)

In formula (1), $L_{ij}$ is the stability index of the $j$ th eigenvalue of unit $i$ in a power station. $V_{ij}^{\text{max}}$ is the maximum allowable operation value of $V_{ij}$. If $V_{ij}$ exceeds $V_{ij}^{\text{max}}$, then $L_{ij}$ is 0, otherwise $L_{ij}$ is 1.
Start
Input parameters: working head

Setting Pa is the analysis load from 0.0MW, ΔP is the load step.

Retrieving Vibration and Swing Data from Data Table.

Successful retrieval

Normalization and weighted average processing of all data to obtain analysis samples.

Normalization and weighted average processing of all data to obtain L_{ij} of analysis samples.

Vibration zone, stability zone and critical vibration area are determined according to L_i.

The stability attributes of P_a are marked.

All load conditions have been scanned.

Reset: P_a = P_a + ΔP.

All the stability attributes of P_a are marked. The vibration load area, stable operation area and critical vibration area are determined under the water head.

Return.

Figure 2. Flow chart of algorithm for on-line measurement of vibration zone

Define the following formula (2):

\[
L_i = \frac{\sum_{j=1}^{m} W_{ij} \times L_{ij}}{\sum_{j=1}^{m} W_{ij}}
\]

(2)

In formula (2), W_{ij} is the evaluation weight of the parameter of the jth evaluation characteristic index on the ith unit; L_i is the comprehensive stability index of the unit, and the operation stability is positively related to it, 0 means running in the vibration zone, 1.0 means running in the stable zone, and the intermediate value means that the unit is running in part of the vibration zone. Usually, when it is less than a certain threshold (L_i^{\text{min}}), e.g. L_i^{\text{min}} = 0.2, it is considered that it is seriously deviating from the allowable operation zone.

According to the measured V_{ij} value under different loads at a certain head, the corresponding L_i under a load can be obtained. If L_i \leq L_i^{\text{min}}, the corresponding load is the vibration load. If
$L_i^{\text{min}} < L_i < 1$, the corresponding load is the critical vibration load, and if $L_i \geq 1$, the corresponding load is the stable operation zone.

4. **Control method of continuous operation time control method in critical vibration zone.**

The maximum running time of the unit in the critical vibration zone is determined by the following methods:

4.1. **Time control method in dynamic online testing mode**

Under the mode of automatic dynamic identification of vibration zone, the control function of critical vibration zone operation time is determined by the following methods:

$$T_i = f(L_i) = \begin{cases} 0 & L_i \leq 0.2 \\ \frac{60.0}{e^{(2.75e(0.1 - L_i))} - 1.0} & 0.2 < L_i < 1.0 \\ \infty & L_i \geq 1.0 \end{cases}$$

In Formula (3), $L_i$ is the comprehensive stability index of unit $i$ of a power plant, $T_i$ is the primary running time of unit determined by the comprehensive stability index under a certain load, and the units of measurement is minute. The corresponding $T_i$ values under typical $L_i$ values are shown in Table 1 and its relation curve in Figure 3:

| Serial number | $L_i$ | $T_i$ (min) (Rounding) |
|---------------|------|------------------------|
| 1             | 0.1  | 0                      |
| 2             | 0.2  | 0                      |
| 3             | 0.3  | 10                     |
| 4             | 0.4  | 14                     |
| 5             | 0.5  | 20                     |
| 6             | 0.6  | 30                     |
| 7             | 0.7  | 47                     |
| 8             | 0.8  | 82                     |
| 9             | 0.9  | 190                    |

Figure 3. The curve of relationship between $L_i$ and $T_i$.
From Table 1 and Fig. 3, the following conclusions can be drawn: when the unit runs in the critical vibration zone, the higher the comprehensive stability index of the unit, the longer the allowable one-time continuous operation time, and the lower the comprehensive stability index, the shorter the allowable one-time continuous operation time.

4.2. Control method of continuous operation time in manual setting mode

Under the mode of setting the range of vibration zone manually, the control function of critical vibration zone operation time is determined by the following methods:

Assuming that the vibration zone is in the range \( \{P_{v,l}, P_{v,u}\} \), the zone less than \( P_{s,l} \) and greater than \( P_{s,u} \) is in the stable operation zone of the unit load, and the zone \( \{P_{s,l}, P_{s,u}\} \) and \( \{P_{v,u}, P_{v,s}\} \) are in the critical vibration operation zone, as shown in Figure 1.

For the lower critical vibration zone, the current load is set as \( P_{v,l} \), where \( P_{v,u} \) is the lower boundary of the critical vibration operation region (the load region less than \( P_{s,l} \) is the stable operation region), \( P_{v,l} \) is the lower boundary of the vibration region, and \( P \) is the critical vibration zone composed of the region between \( P_{s,l} \) and \( P_{v,l} \). Then there are:

\[
T_i = f(P) = \begin{cases} 
0 & P \geq P_{s,l} + (P_{v,l} - P_{s,l}) \times 0.8 \\
60.0 & P = P_{v,l} \\
\frac{P - P_{v,l}}{P_{v,l} - P_{s,l}} e^{2.75 \times \frac{P - P_{s,l}}{P_{v,l} - P_{s,l}} - 1} & P < P_{s,l}
\end{cases}
\] (4)

In Formula (4), \( T_i \) is the single continuous operation time determined by the critical vibration zone boundary and the vibration zone boundary of a unit under a certain load, and the units of measurement is minute.

The corresponding \( T_i \) values under typical \( P \) values are shown in Table 2 and its relation curve in Figure 4 (The lower boundary of the vibration region is \( P_{v,l} = 10 \text{MW} \), and the lower boundary of the critical vibration region is \( P_{s,l} = 8 \text{MW} \)).

| Serial number | \( P \) (MW) | \( T_i \) (min) (Rounding) |
|---------------|-------------|--------------------------|
| 1             | 8.1         | 408                      |
| 2             | 8.2         | 190                      |
| 3             | 8.4         | 82                       |
| 4             | 8.6         | 47                       |
| 5             | 8.8         | 30                       |
| 6             | 9.0         | 20                       |
| 7             | 9.2         | 14                       |
| 8             | 9.4         | 10                       |
| 9             | 9.6         | 0                        |
| 10            | 9.8         | 0                        |
| 11            | 10.0        | 0                        |
Figure 4. The curve of relationship between $P$ and $T_i$

From Table 2 and Fig. 4, the following conclusions can be drawn: The farther the operating load is from the boundary of the vibration zone, the longer the allowable time to operate in this area.

A similar method, for the upper critical vibration zone, the current load is set as $P$, $P \in \{P_{v-u}, P_{s-u}\}$, where $P_{s-u}$ is the Upper boundary of the critical vibration operation region (the load region greater than $P_{s-u}$ is the stable operation zone), $P_{v-u}$ is the upper boundary of the vibration region, and $P$ is the critical vibration zone composed of the region between $P_{v-u}$ and $P_{s-u}$. Then there are:

$$T_i = f(P) = \begin{cases} 0 & P \leq P_{v-u} + (P_{s-u} - P_{v-u}) \times 0.2 \\ \frac{60.0}{2.75-P_{v-u}} & \frac{P-P_{v-u}}{P_{s-u}-P_{v-u}} - 1 \\ \infty & P \geq P_{s-u} \end{cases}$$ (5)

The load distribution program must periodically check the units operating in the critical vibration zone. When the running time of the units operating in the critical operation zone reaches the upper limit, the load distribution program must adjust the unit from the critical vibration zone to the stable operation zone.

5. Conclusions
The concept and definition of critical vibration zone are put forward based on the analysis of operation conditions of hydropower units. It is pointed out that critical vibration zone needs controlled and restricted operation. During the operation of the unit, the vibration and swing of the unit can be monitored on-line, and the evaluation model can be established to determine the vibration zone and critical vibration zone dynamically. The control method of running time under dynamic on-line test and manual setting mode is formulated. When the time reaches the upper limit, the adjustment can ensure the safe operation of the unit and improve the operation range and load adjustability of the unit.

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