VIBRATION MONITORING APPROACH IN INTEGRATED SYSTEM OF HYDROELECTRIC GENERATING SETS FOR SMART POWER STATIONS

Yuechao Wu, Zhaohui Li, Bailin Li, Fanwu Chu, and Xiaolong Cui

Abstract

Vibration monitoring is the most important module of an integrated monitoring system of hydroelectric generating sets (HGSs) due to the fact that most faults of HGSs are reflected in the form of vibration. To improve the vibration monitoring ability of the integrated monitoring system of HGSs, a novel integrated monitoring approach based on team intelligence is proposed in this paper. The monitoring functions are assigned to some team members with complementary capabilities and expertise, based on which the integrated monitoring framework of HGSs is established. The vibration state data are divided into five layers, for which selective storage strategies are proposed to improve the pertinence of the data and save storage space. In addition, real-time and time-lapse cooperative monitoring are realized with the driving of condition synchronization, event synchronization and time-lapse inspections. Meanwhile, the selective storage and associative storage of the state data are completed during the process. Besides, the temporary data continuously stored can be extracted and permanently stored by experts to prevent the omission of selective storage. Currently, the proposed approach has been successfully applied in Gezhouba Hydropower Station, which significantly improves the intelligent level of the power station.

Key Words

Smart power station, integrated monitoring, vibration, selective storage, team intelligence, cooperation

1. Introduction

On the background of planning and development of the smart grid, the construction of smart hydropower stations has been the mainstream in the hydropower industry [1], [2]. Meanwhile, the condition monitoring system of hydroelectric generating sets (HGSs) is an important part of smart hydropower stations, with the aid of which, the faults can be detected in advance and the abnormal equipment can be maintained timely, thus to avoid the extension of the accident and ensure the safety and reliability of HGSs [3].

In recent years, some specialized monitoring systems (SMSs) have been applied to HGSs, which have improved the intelligent level of hydropower stations to some extent, such as SMS for vibration [4], turbine cavitation [5], partial discharge of generator [6] and partial discharge of transformer [7]. To further improve the intelligent level of hydropower stations, the integrated monitoring systems are established to strengthen the link among SMSs and eliminate information island of a hydropower plant. Generally, the existing integrated monitoring system can be divided into two main types, i.e., simple data integrated monitoring system and integrated monitoring system based on interaction and cooperation. Although simple data integrated monitoring system gathers data from different SMSs together through a special data platform, the SMSs still operate independently. In addition, the data centre of integrated monitoring system cannot cooperate with the internal SMSs effectively, leading to the data deficiency in terms of integrality and relatedness. By comparison, the integrated monitoring system based on interaction and cooperation not only can collect data from SMSs effectively but also can cooperate with internal SMSs. For instance, Xie and Li [8] presented an integrated monitoring system based on community intelligence.

Among the existing monitoring subsystems of the integrated monitoring system of HGSs, the vibration monitoring system is the most basic part, which plays an important role in ensuring the safety of HGSs [9], [10]. Therefore, it is significant to improve the vibration monitoring ability of the integrated monitoring system of HGSs. For this purpose, a novel integrated monitoring approach based on team intelligence is proposed in this paper as well as applied to the vibration monitoring of HGSs. In this approach, the monitoring functions are abstracted as some
team members (TMs), based on which the integrated monitoring framework of HGSs is built. According to the requirements of vibration monitoring and data application demands of smart power stations, the vibration state data are divided into five layers, including raw sampled data, supervisory control state data, overview state data, hourly data and daily data. Meanwhile, selective storage strategies are proposed to improve the pertinence of the data and save storage space. Under the framework of integrated monitoring, the cooperative monitoring based on team intelligence is realized, the state data are collected with the selective storage strategies and associative storage strategies. Besides, with the help of analysis web site, the temporary data continuously stored can be extracted and permanently stored by experts to prevent the omission of selective storage.

The structure of this paper is organized as follows. The framework of integrated monitoring system is presented in Section 2. Subsequently, the data organization and intelligent storage strategies for vibration state data are proposed in Section 3. And then, cooperative monitoring based on teamwork is described in Section 4. Following this, artificial extraction and storage of data are described in Section 5. Afterwards, application cases are presented in Section 6. Finally, the conclusion of this paper is drawn in Section 7.

2. The Framework of Integrated Monitoring System of HGSs

The monitoring functions are assigned to some TMs with complementary capabilities and expertise, based on which the integrated monitoring framework of HGSs is built.

2.1 TM Model

To improve the ability of interaction and cooperation, the TM model based on message and knowledge is built, mainly including five components shown in Fig. 1.

Figure 1. TM model.

(1) The expert knowledge base consists of two parts, i.e., behaviour rule base and professional knowledge base. The behaviour rule base contains the cooperation rules among TMs in the form of “TM-message-behaviour”. The professional knowledge base provides knowledge for monitoring and analysing, such as threshold values, correlation states and characteristic frequency spectra.

(2) The information interaction module (IIM) is designed to make it easy for TMs to interact with each other, used to receive and send messages.

(3) The decision-making module (DMM) is used for assigning tasks and scheduling, acts as the brain of TM. It can not only analyse the semantics of the message transferred from the IIM by referring to the behaviour rule base but also instruct core function modules to complete the cooperation tasks and IIM to interact with other TMs.

(4) The core function modules are the symbols of the difference among TMs, complete the monitoring and analysis functions of the TM. The vibration TM mainly includes data acquisition module, peak-peak value calculation module, spectrum analysis module, spatial characteristics analysis module, threshold analysis module and data storage module.

(5) The data warehouse includes two types, i.e., MYSQL database and data file. All the databases are designed in the unified format, all the data files are in binary form, thus to private convenience for data sharing among TMs.

2.2 The Framework of Integrated Monitoring

The framework of the integrated monitoring system is shown in Fig. 2, mainly including the following three parts.

2.2.1 On-line Monitoring System

The on-line monitoring system is composed of three specialized monitoring and analysis units (MAUs) for mechanical specialty, electrical specialty, secondary specialty, the monitoring equipment for dissolved gas in oil and synthetic unit [11].

Figure 2. The framework of integrated monitoring system of HGSs.
Some real-time specialized monitoring and analysis team members (RSMATMs) are deployed in MAUs after considering their specialization division and the load balance of the integrated monitoring system, as shown in Fig. 3. The monitoring objects of RSMATMs include governor, excitation, water temperature, vibration, pressure pulsation, cavitation, partial discharge in generator and transformer, ground current in transformer and dissolved gas in transformer oil. Their functions are as follows: (1) on-line and continuously acquire the state data of HGSs through sampling or sharing; (2) conducting real-time analysis; (3) sharing state data and analysis results to other TMs; (4) selectively store state data based on analysis results and shared information and (5) cooperating with other TMs to complete the monitoring tasks.

A real-time comprehensive analysis team member (RCATM) is deployed in the synthetic unit. Its functions are as follows: (1) getting state data and analysis results from RSMATMs and local control unit of supervision control and data acquisition (SCADA) system; (2) conducting real-time comprehensive analysis; (3) sharing comprehensive analysis results to other TMs and (4) selectively store state data based on comprehensive analysis results and shared information.

### 2.2.2 Condition Monitoring Center in the Plant Level

The condition monitoring center is connected to the online monitoring system with optical fibre. It is composed of data server, web server, analysis server, communication server and switch. The data server is used to store characteristic data of all HGSs. Some time-lapse inspection team members (TITMs) are deployed in analysis server, such as vibration TITM and temperature TITM. Among them, the functions of vibration TITM are as follows: (1) carrying out inspections regularly with the data from other TMs; (2) establishing the relationships among the related states and (3) extracting the data temporarily stored by vibration RSMATM based on the inspection results. The data analysis and fault diagnosis results are provided to plant-level users through the web server.

#### 2.2.3 Decision Center in the Enterprise Level

The decision center and condition monitoring center are separated by the forward isolation device and reverse isolation device. The data analysis and fault diagnosis results used for making decision are provided to enterprise-level users through the web server.

### 3. The Data Organization and Storage Strategy

#### 3.1 Hierarchical Data Organization Strategy

According to the requirements of vibration monitoring and data application demands of smart power stations, the vibration state data are divided into the following five layers as shown in Fig. 4.

![Five layers of state data](image)

- (1) The raw sampled data are obtained by sampling vibration sensor signals in 1024S per rotating period, contain abundant information for fault diagnosis.
- (2) The supervisory control state data are the characteristic data analysed from raw sampled data according to the calculation period of SCADA system, give a general view of an operating process, including peak–peak value, spectrum analysis result (such as amplitude of rotating frequency, amplitude of two times rotating frequency).
- (3) The overview state data are the average, maximum and minimum values of the supervisory control state data in every 15 min, used to observe the variation states over a long time, such as 24 h, a week, a month or even one year [12].
- (4) The hourly data are the average, maximum, minimum values of overview state data in every hour or the values of supervisory control state data on the hour, mainly used for intelligent report forms.
- (5) The daily data are the average, maximum, minimum values of hourly data in every day, mainly used for intelligent report forms.

#### 3.2 Selective Storage Strategy

Due to the great amount of vibration state data, continuous storage not only causes a waste of storage space but also
affects the efficiency of data analysis. For this reason, selective storage strategies are applied to improve the pertinence of data and save storage space.

### 3.2.1 Selective Storage Strategy for Raw Sampled Data

The vibration raw sampled data are continuously stored in the mechanical MAU as binary files for 24 h. Meanwhile, the characteristic raw sampled data are selectively stored in the mechanical MAU or synthetic unit for three months and will be transferred to the data server when the network load is low. The selective storage strategies for raw sampled data are as follows:

1. The normal operation process of HGSs is shown in Fig. 5, including acceleration, connection to grid, load increase, loaded state, load decrease, de-excitation and deceleration. The storage conditions during these processes are shown in Table 1.

2. In general, the operators and maintainers of hydropower stations obtain the vibration performance of HGSs by artificial tests, including the rotating speed test, excitation test and load test. The storage conditions during the artificial test processes are shown in Table 2.

3. Several rotating period data during abnormal event processes (such as over-limit, tendency anomaly in time domain characteristics or significant change in frequency domain characteristics) are permanently stored for fault diagnosis.

In addition, if other TMs detect abnormal events and inform the vibration RSMATM, several rotating period data during abnormal events will be permanently stored.

### 3.2.2 Selective Storage Strategy for Supervisory Control State Data

The supervisory control state data are stored in the synthetic unit for three months and will be transferred to the data server when the network load is low. Its selective storage strategies are as follows: (1) The data during artificial tests are continuously stored into the database. (2) The data during dynamic processes (such as start-up, connection to grid, shut-down, load rejection and breaker action), alarm processes, fault processes are continuously stored into the database [12]. (3) Three minutes data are stored in every 30 min when the HGS is in steady processes, but none data are stored after the HGS is shut down.

Due to the small amount, the overview state data, hourly data and daily data are continuously stored into the database.

### 4. Cooperative Monitoring Based on Team Intelligence

#### 4.1 Real-Time Cooperative Monitoring

Real-time cooperative monitoring is realized with the driving of condition synchronization and event synchronization.

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#### Table 1

<table>
<thead>
<tr>
<th>Process</th>
<th>Storage Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration and deceleration</td>
<td>Several rotating period data when the speed near 60%, 80% and 100% rated speed</td>
</tr>
<tr>
<td>Connection to grid and de-exciton</td>
<td>Several rotating period data at rated speed without excitation and with 100% excitation</td>
</tr>
<tr>
<td>Load increase and load decrease</td>
<td>Several rotating period data when the load stability time $T &gt; T_H$, $T_H$ is the threshold of stable time</td>
</tr>
<tr>
<td>Steady operation of loaded condition</td>
<td>Several rotating period data when new water head or load appears</td>
</tr>
</tbody>
</table>

#### Table 2

<table>
<thead>
<tr>
<th>Test name</th>
<th>Storage conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotating speed test</td>
<td>Several rotating period under each speed</td>
</tr>
<tr>
<td>Excitation test</td>
<td>Several rotating period data under each field current</td>
</tr>
<tr>
<td>Load test</td>
<td>Several rotating period data under each load</td>
</tr>
</tbody>
</table>
4.1.1 The Cooperative Monitoring Driven by Condition Synchronization

The vibration of HGSs is closely related to the operating condition (such as start-up, connection to grid, steady operation without load, steady operation with different water heads and different loads, load increase and decrease operation, shut-down, de-excitation, load rejection). With the driving of condition synchronization, the vibration state data and other state data are synchronously stored, the performance indices during the operating condition are calculated, the relationships among operating conditions, state data and performance indices are established, thus to provide good support for operating condition association analysis and condition assessment. Its basic process is shown in Fig. 6.

Figure 6. The cooperation driven by condition synchronization.

Step 1. The governor and excitation RSMATM identify the operating condition based on the Petri Net module and state data (such as water head, active power, guide vane opening, frequency, field current) in real time [13].

Step 2. The governor or excitation RSMATM broadcasts the operating condition to other TMs every 50 ms, including start time, end time, operating condition number, serial number and parameters.

Step 3. The IIM of RCATM receives the operating condition message, after which the DMM instructs the storage model to store the operating condition into the record table and adjust the storage strategies of the supervisory control state data by referring to Section 3.

Step 4. The IIM of vibration RSMATM receives the operating condition message, after which the DMM instructs the storage module to store the characteristic raw sampled data into the database based on the operating condition message and the roles in the behaviour rule base as well as establish the relationships between the raw sampled data and operating condition events through the serial number, and then instructs the analysis module to calculate the performance indices (such as spatial characteristics) under the operating condition. Subsequently, the IIM send data upload request message to RCATM.

Step 5. The DMM of RCATM instructs the IIM to send data request message to vibration RSMATM after receiving the data upload request message.

4.1.2 The Cooperative Monitoring Driven by Event Synchronization

The abnormal events are captured by RSMATMs and RCATM in real time. With the driving of event synchronization, the data before and after the abnormal events from different TMs are synchronously stored, the performance indices during the abnormal event process are calculated. Meanwhile, the relationships among abnormal events, state data and performance indices are established, thus to provide good support for event analysis and fault diagnosis. As the cooperative monitoring driven by event synchronization is similar to condition synchronization, the process is not described in this paper.

4.2 Time-Lapse Cooperative Monitoring

The inspections are carried out regularly through dynamic threshold analysis and trend analysis of related impact factors (water head and active power) by the vibration TITM. With the driving of inspections, the temporary raw sampled data continuously stored as the binary file by vibration RSMATM are extracted and permanently stored, the performance indices are calculated, the inspection results, state data and performance indices are associated regularly, thus to provide good support for operation analysis and fault diagnosis. Its basic process is shown in Fig. 7.

Figure 7. The cooperation driven by time-lapse inspections.

Step 1. The vibration TITM carries out inspections regularly and captures alarm events regularly with the data from RCATM and vibration RSMATM. Meanwhile, the relationships among the related states and alarm events are established by referring to the professional knowledge base.

Step 2. The DMM of vibration TITM instructs the IIM to send raw sampled data extraction message to vibration RSMATM, including start time, end time and serial number.

Step 3. The IIM of vibration RSMATM receives the data extraction message, after which the DMM instructs the data extraction module to extract raw sampled data from the binary data files and store them into database as
well as establish the relationships between the raw sampled data and alarm events through the serial number, and then instructs the IIM to send the extraction success message to vibration TITM.

**Step 4.** The IIM of vibration TITM receives the extraction success message, after which TITM instructs IIM to get raw sampled data from the database of vibration RSMATM and instructs the spectrum analysis module and spatial characteristics analysis module to calculate the performance spectra and spatial characteristics and stored them into the database.

5. Artificial Extraction and Storage of Data

Considering that the selective storage may not be able to meet the requirements of experts, artificial extraction of raw sampled data is developed. With the help of the web site, the raw sampled data continuously stored as binary files can be extracted and permanently stored by experts within 24 h. The extraction process is shown in Fig. 8.

![Diagram of artificial extraction process](image)

**Figure 8.** The process of artificial extraction.

**Step 1.** The web server dynamically generates the web page of artificial extraction when experts visit the web site.

**Step 2.** Experts send extraction command to vibration RSMATM through the web server after setting start time, time length and unit number.

**Step 3.** Vibration RSMATM receives the raw sampled data extraction message, after which the DMM instructs the data extraction module to extract raw sampled data from the binary data files and store them into the database, and then instructs the IIM to send the extraction success message to the web server.

**Step 4.** The web server reads raw sampled data from database and sends them to the page after receiving the extraction success message.

After the above steps, the time domain curve is displayed in the web page.

6. Application Notes

Currently, the approach proposed in this paper has been successfully applied to Optimal Maintenance Information System for Hydropower stations (HOMIS) [14]. In this section, the application cases are presented to illustrate the effectiveness of the approach.

6.1 Excitation Test Case

Generally, the experts evaluate the electromagnetic unbalance of HGSs by an artificial excitation test. With the help of HOMIS, the excitation test can be automatically completed based on the operating conditions. In this section, the excitation test of an HGS in Gezhouba Hydropower Station is taken as an example to explain the implementation process.

6.1.1 Automatic Identification of Excitation Test Based on Operating Conditions

Excitation RSMATM identifies the excitation test under the following operating condition: the active power is zero, the speed is rated speed and the field current is varying along with time.

6.1.2 Automatic Storage of Test Data

Excitation RSMATM sends excitation test message to other TMs. The vibration RSMATM and RCATM record the excitation test process data (raw sampled data and supervisory control state data) by referring to the selective storage strategies in Section 3. Figure 9(a) and (b) shows the shaft orbit with none excitation and 100% excitation based on the raw sampled data. Table 3 shows the peak-to-peak values of vibration with none excitation and 100% excitation based on supervisory control state data.

6.1.3 Automatic Calculation of Performance Indices

The performance indices of the excitation test are automatically calculated based on the state data and their definitions and algorithms are obtained by referring to the standards or operation rules. For example, the performance indices for the effect of unbalanced magnetic pull on the operating centre of the main shaft are offset value A, and offset angle θ, as shown in Table 4, their algorithms are as follows:

\[
A = \sqrt{(\bar{x}_1 - \bar{x}_2)^2 + (\bar{y}_1 - \bar{y}_2)^2} \tag{1}
\]

\[
\theta = \arctan \frac{\bar{y}_1 - \bar{y}_2}{\bar{x}_1 - \bar{x}_2} \tag{2}
\]

where \(\bar{x}_1\) and \(\bar{x}_2\) are the averages of raw sampled data in the X direction of guide bearing with none excitation and 100% excitation, respectively. \(\bar{y}_1\) and \(\bar{y}_2\) are the average of raw sampled data in the Y direction of guide bearing with none excitation and 100% excitation, respectively.

6.1.4 Electromagnetic Unbalance Evaluation

According to the state data and performance indices, the electromagnetic unbalance of HGSs can be evaluated. It can be clearly observed from Table 3 that the vibration of
Table 3
The Relationships between Vibration and Excitation

<table>
<thead>
<tr>
<th>Vibration Position</th>
<th>None Excitation</th>
<th>100% Excitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper guide bearing X (μm)</td>
<td>277.3</td>
<td>353.4</td>
</tr>
<tr>
<td>Upper guide bearing Y (μm)</td>
<td>286.0</td>
<td>394.4</td>
</tr>
<tr>
<td>Turbine guide bearing X (μm)</td>
<td>404.1</td>
<td>414.1</td>
</tr>
<tr>
<td>Turbine guide bearing Y (μm)</td>
<td>424.1</td>
<td>415.0</td>
</tr>
</tbody>
</table>

upper guide bearing $X, Y$ under 100% excitation is greater than none excitation, which indicates that there is unbalanced magnetic pull in this HGS. Contrasting Fig. 9(a) and (b), it can be seen that the shaft orbit of the upper guide under 100% excitation is significantly greater than none excitation and the unbalanced magnetic pull leads to an offset (the offset value is $87.9 \mu m$ and offset angle is $262.2^\circ$, as shown in Table 4) in the operating centre of the main shaft, from which it can be concluded that the air gap between the stator and rotor of the generator is not uniform and the air gap in the $-Y$ direction is smaller than others.

6.2 Fault Diagnosis Case

According to the data storage strategies and cooperative monitoring process, the data during the abnormal event are synchronously stored. In addition, the raw sampled data continuously stored as binary files can be extracted and permanently stored by experts to prevent the omission of selective storage. These strategies provide a good support for fault diagnosis.

An abnormal vibration occurred in an HGS of Gezhouba Hydropower Station in July 2010 [15], as shown in Fig. 10, the peak-to-peak values of turbine guide bearing $X, Y$ (Fig. 10(a) and (b)) and support cover vertical $X, Y$ (Fig. 10(c) and (d)) suddenly increased from July 31, 2010.

The raw sampled data during the abnormal event process are automatically stored during the cooperative monitoring process driven by event synchronization, so that it is easy to diagnose the fault cause based on the frequency spectrum. Figure 11 shows the spectrum analysis result, from which it can be seen that the amplitude of four times rotating frequency is very obvious. As the number of the hydroturbine blade is four, it can be concluded that the vibration is caused by uneven flow of runner blade based on spectrum matching rules shown in Table 5. The parameters
Table 5
Characteristic Spectrums and Corresponding Faults

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>Corresponding Fault</th>
</tr>
</thead>
<tbody>
<tr>
<td>((1/6-1/2)f)</td>
<td>Vortex in the draft tube</td>
</tr>
<tr>
<td>(0.5f)</td>
<td>Oil whirl</td>
</tr>
<tr>
<td>(f)</td>
<td>Mass imbalance of the rotor</td>
</tr>
<tr>
<td>(2f)</td>
<td>Rotor misalignment</td>
</tr>
<tr>
<td>(Mf)</td>
<td>Uneven flow of guide vane</td>
</tr>
<tr>
<td>(Nf)</td>
<td>Uneven flow of runner blade</td>
</tr>
<tr>
<td>50/100 Hz</td>
<td>Vibration mode of stator core</td>
</tr>
<tr>
<td>300–500 Hz</td>
<td>Cavitation</td>
</tr>
</tbody>
</table>

*M, N and *f* shown in Table 5 are the number of guide, hydroturbine blade and rotating frequency, respectively. A lot of debris was observed in guide vane after a close examination, as shown in Fig. 12.

7. Conclusion

To improve the vibration monitoring ability of the integrated monitoring system of HGSs, a novel integrated monitoring approach based on team intelligence is proposed in this paper. The framework of the integrated monitoring system of HGSs is first established, which eliminates information island of the hydropower plant effectively and provides a prerequisite for interaction and cooperation. Then, the hierarchical data organization strategies and selective storage strategies are proposed to improve the pertinence of vibration state data and save storage space. Subsequently, real-time and time-lapse cooperative monitoring are realized with the driving of condition synchronization, event synchronization and time-lapse inspections. Meanwhile, the selective storage and associative storage of the state data are completed during the process. Besides, the temporary data continuously stored can be extracted and permanently stored by experts to prevent the omission of selective storage. Finally, the effectiveness of the proposed approach is verified by two cases of Gezhouba Hydropower Station.
References


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