Research on Monitoring Method of Impulse Vibration in Large Transformer Transportation

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Abstract. The safety of long-distance transportation of large power transformers has become an important constraint factor for the EHV projects. In view of the problems existing in the Three-dimensional impact recorders and condition monitoring system of the long-distance transportation of large power transformers, this paper analyzes the amplitude frequency characteristics and influencing factors of the impact vibration during the transportation of transformer, adopts the fast Fourier transform to deal with the interference in the vibration signal, designs a monitoring terminal of the impact vibration based on the Internet of things which can accurately measure the vibration impact of the transformer, and develops a remote real-time online monitoring system to monitor the displacement and impact of transformers at anytime and anywhere. The monitoring terminal and monitoring system are applied in the actual transportation of converter transformer in an UHVDC project. Three monitoring terminals are installed in different positions of the transformer to monitor the transformer status and send the monitored information to the monitoring system. The reliability of the terminal and the superiority of the monitoring system are verified.

Keywords. Transformer; long-distance transportation; impact vibration; fast Fourier transform; internet of things.

1. Introduction
The long-distance transportation safety of large power transformer has become an important restriction factor that affects the scheduled operation of the project with the steady development of UHV power grid construction and the stage layout of global energy interconnection.

There are strict requirements for traveling speed, impact vibration, etc. in the transportation process of large power transformer. Relevant standards and specifications put forward the requirements for safety parameters of transportation, such as impact acceleration, pressure (nitrogen filled transportation), tilt, weather, etc. [1-3].

The way of installing three-dimensional impact recorder on the transformer body to monitor its transportation process has been widely used in practical projects. Relevant scholars have also carried out a lot of research on the safety monitoring of transformer transportation, and achieved some results [4-9]. However, there are still some problems to be solved in the practical application of impact recorder as follows:

(1) Three dimensional impact recorder may give false alarm due to its own fault or abnormal interference in transit. Some manufacturers will install multiple impact recorders at different positions of the transformer body to prevent false alarm, but the impact data recorded by the recorders installed
at different positions will be different.

(2) At present, only when the transformer arrives at the destination, can it read and analyze the data in the transportation process. It is impossible to monitor and trace the abnormal conditions such as bumps and overspeed in the long-distance transportation of the transformer in real time.

Based on many years of experience in using impact recorder, this paper analyzes the amplitude frequency characteristics and influencing factors of transformer impact in long-distance transportation, designs an intelligent terminal for transformer impact monitoring based on the Internet of things, and develops a monitoring system.

2. Impact Source and Damage Analysis

2.1. Transformer Transportation Condition
The transportation distance of large transformer is long and the road condition is complex. There are highways, railways and waterways for transportation. In addition, it is often need to transfer and hang the transformer in transit. Therefore, the impact is easy to exceed the standard in the process of transportation. The impact conditions and impact characteristics of transformers in the transportation process are shown in table 1.

| Impact condition                  | Causes of impact                                                                 | Impact characteristics                        |
|-----------------------------------|-----------------------------------------------------------------------------------|-----------------------------------------------|
| Significant impact during loading and unloading | Lifting equipment failure during loading, unloading and hanging; Longitudinal impact during brake operation, Vertical and lateral impacts due to poor road conditions. | frequency range (2-20 Hz) acceleration (2.5-10 g) |
| Impact on board trailer          | Rolling, bumping and deviation caused by onboard ship transportation             | frequency range (3-350 Hz) acceleration (0.5-1.0 g) |
| Impact on board ship             | Longitudinal impact during track change, vertical vibration impact at rail joint | frequency range (2-30 Hz) acceleration (0.3-0.8 g) |
| Impact on board railway          |                                                                                  | frequency range (2-500 Hz) acceleration (0.5-4.0 g) |

2.2. Damage to Transformer Caused by Impact
It is very likely to cause the following damage to the transformer if the impact vibration during transformation exceeds the specified value:

(1) The windings or core of transformer may be deformed or twisted.
(2) The insulation materials between the corners will be scratched and worn due to the movement of some parts, resulting in short circuit and other hazards during the operation of the transformer.
(3) The clamping pressure of transformer winding is loose, which may cause winding damage due to impact during operation.
(4) The safe clearance between the transformer body and the movable part may be reduced.

3. Impact and Stress of Transformer in Transit

3.1. Characteristics of Impact Waveform
The impact of transformer during transportation is measured by the maximum value and duration of acceleration in case of acceleration or deceleration. The schematic relationship between acceleration and time during impact is shown in figure 1.

Under the same impact energy, a rigid body with a smaller mass will produce an acceleration with a larger amplitude and a shorter time period or a higher frequency, as shown in the green curve in figure 1.
Figure 1. Relation curve between acceleration and time in impact.

The vibration of the transformer will last a relatively longer time because it is an elastic object, as shown in the red curve in figure 1. This means that the vibration harmful to the transformer in transit is in a relatively low frequency band (generally 2-20 Hz).

The actual impact vibration of transformer in transit is no single frequency. Complex transportation environments often produce complex frequencies composed of single frequencies with different amplitudes. The frequency is 3-350 Hz in highway and only 2-33 Hz in ship. When this kind of large amplitude vibration frequency is consistent with the natural vibration frequency of the transformer body, it is likely to cause resonance of the transformer body, or even resonance disaster.

3.2. Impact Energy Analysis
The impact wave of transformer in transit is sine wave, and its damage degree to transformer depends on the impact energy. The energy of impact can be calculated by kinetic energy law, namely:

$$E = \frac{1}{2} m (a \cdot \Delta t)^2 = \frac{1}{2} m \cdot (\Delta v)^2$$

Equation (1)

$m$ is the mass of the object, $a$ is the acceleration, $v$ is the velocity.

3.3. Transformer Body Force Analysis
In transit of the transformer, the force in the forward direction is mainly the friction between the transformer body and the oil tank. When the force such as acceleration exceeds the static friction, the shear stress of the bolt blocks the movement of the body relative to the tank. At this time, the acceleration will produce additional shear stress on the fastener between the fastener body and the fuel tank.

Figure 2 shows the force on transformer body during transportation. In the figure, $M$ represent the mass of the transformer, $a$ represents the acceleration in the transportation direction of the transformer, $G$ represents the acceleration of gravity, and $L_1$ and $L_2$ represent the moments in the horizontal and vertical directions respectively.

When $M \cdot a \cdot L_2 > M \cdot g \cdot L_1$, shear stress and tensile stress will be generated on the fastener at the other end at the same time. The acceleration acting on the wide direction (i.e. vertical transportation direction) is more harmful to the transformer body than the acceleration acting on the long direction (i.e. transportation direction). In the vertical direction, due to its own gravity, the insulation support at the bottom will bear more pressure.
4. Impact Signal Acquisition and Analysis

4.1. Impact Signal Acquisition
The impact of transformer in transit is vector, and there are acceleration components in x, y and z directions, as shown in figure 3. It is necessary to accurately collect the vibration acceleration in these three directions to comprehensively analyze the impact signal.

![Figure 3. Measurement model of transformer impulse acceleration.](image)

It is assumed that the angles between the x, y, z axes of the impact recorder and the vibration direction are α, β, γ respectively. Then the components of the vibration in these directions are:

\[
\begin{align*}
A_x &= A \cdot \cos \alpha \\
A_y &= A \cdot \cos \beta \\
A_z &= A \cdot \cos \gamma
\end{align*}
\] (2)

Therefore, the accurate monitoring of the impact acceleration in three directions is the prerequisite and a high-precision and reliable acceleration sensor is needed.

4.2. Filtering Algorithm of Impact Signal
The impact signals collected by the acceleration sensor not only contain the harmful impact signal of the transformer, but also contain the components of the high frequency noise interference and the gravity acceleration in x, y and z directions caused by the inclination of the transformer during transportation. Transformer impulse acceleration monitoring is very vulnerable to external interference, so it is insufficient to use only acceleration amplitude to measure it.

The existing impact recorder cannot distinguish the transport impact of transformer body from the mixed signal with noise. When the data recorded by the recorder is used for analysis, it may lead to wrong estimation of potential damage. Therefore, it is necessary to use the intelligent method to analyze the waveform recorded by the impact recorder in the time and frequency domain, so as to realize the acquisition of effective impact signal.

Fast Fourier Transform (FFT) can map the original waveform data from the time-domain space to the frequency-domain space, and then distinguish the impulse which causes damage to the transformer from the mixed signal [10-11].

Figure 4 shows the acceleration signal monitored by impact recorder before and after FFT processing. It can be seen from the figure that the original impact signal is doped with high frequency signal, and the maximum amplitude reaches 5 g, while the filtered impact acceleration is only 1 g. The vibration of the transformer is still in the normal range after filtering out the high-frequency interference, which reduces the unnecessary maintenance work of the transformer.
4.3. Arrangement of Impact Recorders

The signals collected by the impact recorder installed in different positions of the transformer body are not consistent, because of the attenuation of the impact signal transmission on the transformer body. At present, impact recorders are arranged in different positions of the transformer, but it is impossible to analyze the actual impact, because there is no data synchronization between different impact recorders.

In this paper, a distributed deployment scheme of transformer impact recorders is proposed, three impact recorders are installed in different positions of converter transformer (line side, valve side, cooler side), and signal synchronization is adopted between impact recorders. The background system analyzes the impact data of three recorders at the same time, determines the location of the vibration source, and carries out the later big data analysis.

5. Impact Monitoring Terminal and System

5.1. Overall Design of Monitoring Terminal

The monitoring terminal monitors the impact acceleration during the transportation of the transformer, as well as the tilt angle, speed, nitrogen pressure and other state quantities. The monitoring terminal is used outdoors, so it meets certain IP protection level. The monitoring terminal needs to send the monitored status in real time through the wireless transmission module to meet the requirements of real-time monitoring. In addition, the monitoring terminal is powered by lithium battery and meets the endurance requirements of the whole long-distance transportation. The principle of the monitoring terminal designed is shown in figure 5.

![Figure 5. Principle block diagram of monitoring terminal.](image)

The monitoring terminal includes the main control unit, key input, display, acceleration module, nbiot module, temperature and humidity module, memory unit, power circuit and other modules.
5.2. Detailed Design of Impact Function
The function of impact signal acquisition of monitoring terminal includes hardware acquisition and software analysis of impact acceleration. In the hardware part, according to the characteristics of harmful signals of transformer vibration (2-20 Hz) and the requirements of FFT analysis and calculation, the sampling rate of impact acceleration is required to reach 50 points in each impact cycle, and the sampling frequency is more than 1 kHz. In the software part, each module shall be coordinated to complete data collection and processing, communication with the background cloud server, local setting and viewing, and the process is shown in figure 6.

![Flow chart of software.](image)

5.3. Development of Monitoring System
In order to monitor the status of transformer, a real-time remote monitoring system platform for transformer transportation is developed, which can receive monitoring terminal information in real time and display and alarm. At the same time, a mobile app for transportation monitoring has been developed, which is convenient for users to grasp the transportation situation more timely and conveniently.

6. Application of Monitoring Terminal and System in Engineering
The transportation monitoring terminal and system have been applied in the transportation of converter transformer in ± 800 kV UHVDC project, realizing the real-time online monitoring of the whole process of transformer transportation.

The actual installation of the transport monitoring terminal on the transformer is shown in figure 7. The three impact recorders are installed at different positions of the transformer (cooler side X axis, valve side Y axis, net side Z axis). Signal synchronization is adopted between the impact recorders. The background system analyzes and compares the impact data of three recorders at the same time, which greatly reduces the false alarm events.

![Terminal installation diagram.](image)
The whole transportation process lasted for more than 100 days, with a transportation mileage of more than 2000 kilometers. The transportation process covers maritime transportation, highway and railway, and 300000 pieces of monitoring data were obtained. Transformer transportation track and monitoring waveform of the transportation monitoring terminal are shown in figures 8 and 9 respectively.

Figure 8. Trajectory diagram of transportation.

Figure 9. Monitoring data curve of the whole process.

Figure 9 shows the real-time monitoring data displayed by the background monitoring system obtained through the Internet of things. From the shock vibration curve of the whole process in the figure, the shock amplitudes of x-axis and y-axis are basically in the range of 0-0.1 g, and the maximum amplitude is only 0.2 g. Most of the shock amplitudes in Z direction are in the range of 0-0.2g, and the maximum amplitude is 0.3 g. Although the amplitude of Z axis is larger than X axis and Y axis, it is still in an acceptable range.

7. Conclusion
 Based on the analysis of amplitude and frequency characteristics of transport shock signal of large transformer, this paper puts forward the method of transport shock vibration monitoring, and designs the transport monitoring terminal and system of large transformer based on the Internet of things. The monitoring terminal and system are applied in the UHVDC project, which verifies the effectiveness and superiority of the terminal.

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