Experimental Study on Seismic Performance of UHV Transformers

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Abstract. In order to study the seismic response characteristics of UHV transformers under different earthquakes, a shaking table experiment study of UHV transformers was carried out. The results show that with the increase of seismic excitation, the acceleration of the side wall and the top plate of the box basically shows a linear increase; when the seismic wave is input in the Y direction, the acceleration response is larger and the increase amplitude of acceleration is also larger. The acceleration response of high, medium and low voltage bushings shows similar characteristic: the response when inputting the Y direction seismic wave is greater than that when inputting the X direction; the acceleration value is the largest when inputting X+Y direction seismic wave; the response when inputting the Y+Z direction seismic wave is greater than that when inputting the X+Z direction. As the seismic peak acceleration increases, bushing acceleration and strain gradually increase, the acceleration and strain when seismic waves are input in the Y direction are greater than those input in the X direction. When the seismic excitation increases increase from 0.8 g to 1.2 g, the acceleration and strain response increase amplitude less than those the seismic excitation increases from 0.4 g to 0.8 g.

Keywords. UHV transformers, shaking table, acceleration, stress.

1. Introduction

The substation is an important part of the power facilities in the lifeline project. The seismic performance of the UHV transformer is directly related to the normal operation of the substation during an earthquake [1-2]. In recent years, with the rapid development of our country’s economy, the demand for electricity in various industries has increased. The number of voltage levels of new transmission lines has also become higher, reaching above 800kV, and corresponding electrical equipment has gradually develop in the direction of high, big and heavy. On the other hand, China is a country prone to earthquakes, with a wide distribution of earthquake zones [3-4]. Some power plants, transmission lines, and substations will inevitably be built in areas of medium and high seismic intensity. They are easily damaged in earthquakes, which has a serious impact on local production and life and subsequent earthquake relief work. Therefore, studying the seismic performance of electrical equipment in substations under strong earthquakes is of great significance to ensure the stable operation of substations and transmission lines.

In order to evaluate the seismic performance of a certain type of 1100 kV ultra-high voltage (UHV) transformer porcelain bushing and the possible weak locations of seismic resistance, Xie Q [5-6] et al. conducted an earthquake simulation shaking table experiment on the bushing and obtained the dynamic characteristics of the bushing and the seismic response under different ground motion input
conditions. The experiment results show that the UHV bushing has a low natural frequency and a small damping ratio, and it has a greater amplification effect on ground motion. Chen X D [7] et al. analysed the seismic performance of transformer bushings under different conditions. The results show that there is a strong interaction between the transformer body and the riser and the transformer bushing. The elevated seat can significantly amplify the seismic response of the bushing. Existing experiment methods have certain limitations because they neglect the dynamic coupling effect of the transformer bushing, the riser and the wall of the container. Zhu G N [8] conducted seismic design and vibration isolation research on the transformer based on the quasi-zero stiffness theory. Filiatrault [9-10] et al. numerically studied the dynamic response of the porcelain bushing installed on the transformer tank. Numerical results show that when the fundamental frequency of the porcelain bushing is closer to the fundamental frequency of the transformer box, a greater amplification effect will occur.

In this paper, shaking table experiment is carried out on the UHV transformer model, and the seismic response characteristic of the UHV transformer box and outlet bushing is obtained.

2. Determination of Similarity Relationship in Shaking Table Model Experiment

2.1. UHV Transformer Prototype Size

The prototype of the UHV transformer used in this experiment is the Baoding Tianwei 1000kV UHV transformer model. The UHV transformer is mainly composed of box, body (including iron core, winding, etc.), high-voltage bushing, medium-voltage bushing, low-voltage bushing, neutral bushing, and riser. Figure 1 shows the schematic diagram of the UHV transformer. The size of the transformer box is (length×width×height): 10.9 m×3.94 m×4.84 m. The thickness of the side panel of the transformer box is 12 mm, the thickness of the box cover is 30 mm, and the thickness of the box bottom is 50 mm. The total mass is 396 t. The mass of each part is shown in table 1. Table 2 shows the geometric parameters of each bushing.

![Figure 1. UHV transformer schematic diagram.](image_url)
Table 1. Quality of transformer parts.

| Part            | Body | High voltage bushing | Medium voltage bushing | Low voltage bushing | Neutral point bushing | Fuel tank and accessories | Riser | Total |
|-----------------|------|-----------------------|------------------------|---------------------|-----------------------|---------------------------|-------|-------|
| Mass(t)         | 303.4| 4.55                  | 1.53                   | 1.2                 | 0.25                  | 76.8                      | 8.84  | 396   |

Table 2. Transformer bushing parameters.

| Part                          | Inside diameter (mm) | Outer diameter (mm) | Height (m) | Weight (kg) |
|-------------------------------|----------------------|---------------------|------------|-------------|
| Low voltage bushing           | 220                  | 275                 | 2.12       | 602         |
| Neutral point bushing         | 160                  | 210                 | 1.2        | 256         |
| Medium voltage bushing        | 220                  | 300                 | 4.4        | 1536        |
| Lower section of high voltage bushing | 590           | 710                 | 10.16      | 4544        |
| Upper section of high voltage bushing | 430            | 500                 |            |             |

2.2. Determination of Similarity

According to Buckingham's principle, for the seismic response of structures, the expression in the linear elastic range is as follows:

\[ \sigma = f(l, E, \rho, t, r, v, a, g, \omega) \]  

where \( \sigma \) is the structural reaction stress, \( l \) is the component size, \( E \) is the elastic modulus of the component, \( \rho \) is the density of the component, \( t \) is the time, \( r \) is the displacement, \( v \) is the velocity, \( a \) is the acceleration, \( g \) is the acceleration due to gravity, and \( \omega \) is the frequency. Choose \( l, E, \) and \( \rho \) as the basic quantities, then the remaining quantities can be expressed as the power monomials of the three, and then the dimensionless product can be obtained:

\[
\prod_0 = \frac{\sigma}{E} \\
\prod_4 = \frac{t}{(lE^{0.5}\rho^{0.5})} \\
\prod_5 = \frac{r}{l} \\
\prod_6 = \frac{v}{(E^{0.5}\rho^{0.5})} \\
\prod_7 = \frac{a}{(l^{-1}E\rho^{-1})} \\
\prod_8 = \frac{g}{(l^{-1}E\rho^{-1})} \\
\prod_9 = \frac{\omega}{(l^{-1}E^{0.5}\rho^{-0.5})}
\]  

Define \( S_\sigma \) as the similarity ratio between the model and the prototype. For the model experiment to simulate the seismic response of the prototype structure, the similarity ratio of each quantity needs to meet:

\[
S_{\sigma} = S_E, \quad S_t = S_L\sqrt{S_\rho/S_E}, \quad S_r = S_l, \quad S_v = \sqrt{S_E/S_\rho}, \quad S_a = S_E/S_\rho, \quad S_g = \sqrt{S_E/S_\rho} \\
S_\omega = S_E/S_\rho
\]

among them, \( S_\sigma = \sigma_m/\sigma_p \), the subscript \( m \) represents the model, and \( p \) represents the prototype.
The shaking table experiment is planned to be completed on a 6m×6m three-dimensional earthquake simulation shaking table in the Laboratory of Civil Engineering College of Chongqing University. The standard load of the vibration table is 60t-80t, and the working frequency range is 0.1Hz to 50Hz. When fully loaded, the maximum acceleration allowed in the three directions of X, Y, and Z are 1.5 g, 1.5 g, and 1.0 g respectively; the maximum allowable displacement is 250 mm, 250 mm, and 150 mm respectively. Considering the above performance parameters of the shaking table and the difficulty of UHV transformer model processing, it is preliminarily determined that the geometric scale of the transformer model used in this model experiment is 1:4 and ignore the influence of Gravity. Table 3 shows similar parameters of model design.

2.3. Model Size
The model size and quality of each part of the UHV transformer are determined by the geometric length design similarity constant and the quality design similarity constant. The size of the transformer model box is 2738 mm×986 mm×1205 mm (length×width×height), and the length of the high-voltage bushing is 2.5 m (figure 2). The total weight of the fuel tank and accessories is about 1200 kg; the iron core in the box has a winding mass of 4740 kg; the total weight of the bushing is about 130 kg; the weight of the elevated seat is about 140 kg; the total weight of the UHV transformer scale model is about 6.2 t.

| Physical properties          | Physical parameters | Similarity constant |
|-----------------------------|---------------------|---------------------|
| Geometric performance       | Length              | 1:4                 |
|                             | Strain              | 1:1                 |
|                             | Elastic Modulus     | 1:1                 |
| Material performance        | Stress              | 1:1                 |
|                             | Density             | 1:1                 |
|                             | Mass                | 1:64                |
| Power performance           | Time                | 1:4                 |
| Mass of model               | Acceleration        | 4:1                 |

2.3. Model Size

![Figure 2. Model Size.](image-url)
3. Experimental Design

3.1. Experiment Assembly
Before the experiment, the bushing on the transformer box was installed. The high-voltage bushing is installed on the vertical high-voltage riser protruding from the side wall of the box, the medium-voltage bushing is installed on the vertical raised seat on the side of the top cover of the box. Two low voltage bushings are installed on the low voltage raised seat opposite to the medium voltage bushing. The long side of the transformer is defined as the X direction, and the short side of the transformer is defined as the Y direction. Then the whole is hoisted on the vibrating table and connected to the vibrating table. Figure 3 shows the diagram of the transformer model placed on the vibrating table.

![Figure 3. Diagram of UHV transformer.](image)

3.2. Measuring Point Layout
(1) The number and location of acceleration measuring points should be sufficient to reflect the dynamic characteristics of the UHV transformer model. In order to measure the acceleration response of each bushing, an acceleration sensor (X, Y, Z direction) is arranged on the top of each bushing; an acceleration sensor (X, Y, Z direction) is arranged at the junction of the raised seat and the box; Acceleration sensors (X, Y, Z directions) are arranged at the junction with the bushing; in order to obtain the seismic response of the transformer box, acceleration sensors are arranged at the two top corners of the transformer body, the centre of the top cover, and the centre of the three sides of the box (excluding the centre of the side of the high-voltage bushing).

(2) According to previous actual engineering experience, the maximum stress of the bushing appears at the root of the bushing. Pasting strain gauges on the bottom of the four bushings (high-voltage bushing, medium-voltage bushing, low-voltage bushing 1, and low-voltage bushing 2) along the opposite side of the X direction and the opposite side of the Y direction to measure the stress.

Figure 4 shows the detailed diagram of measuring points.
3.3. Experiment Conditions

The ground motion input of UHV transformer model experiment should mainly consider the following two aspects:

1) Two horizontal seismic experiments should be considered. For long cantilever or large-span electrical equipment, vertical seismic experiments should also be considered;

2) The experiment response spectrum (TRS) generated by the shaking table should envelope the required standard response spectrum (RRS), and the difference between the two spectrum values should be between 0-50%. It is also acceptable if a small part of the single point of the TRS is outside the tolerance band and is offset from the resonance frequency of the experiment equipment; in addition, considering that the maximum displacement of some vibration tables is limited, and the lower frequency part has little effect on the equipment, the tolerance of the spectrum value below 0.7 times the natural frequency of the equipment is not control.

According to the 1:4 similarity ratio of acceleration between the prototype and the model, the input values of the model acceleration in this study are 0.4 g, 0.8 g, 1.2 g (corresponding to the basic acceleration input values of the prototype are 0.1 g, 0.2 g, 0.3 g). The input waveform of the prototype device is a standard time history wave, and the characteristic period of the standard response spectrum is 0.9s, which can cover almost all common types of sites. Figure 5 shows the input waveform of the standard time-history wave. Table 4 shows the experiment condition of this experiment.

Figure 4. Layout of measuring point.

Figure 5. Artificial wave acceleration-time history.
Table 4. Experiment conditions.

| Experiment conditions | Seismic excitation direction |
|-----------------------|-----------------------------|
| White noise           | X/Y/XY/XZ/YZ                |
| 0.4 g artificial wave | X/Y/XY/XZ/YZ                |
| White noise           | X/Y                        |
| 0.8 g artificial wave | X/Y                        |
| White noise           | X/Y                        |
| 1.2 g artificial wave | X/Y                        |

4. Experiment Results and Analysis

4.1. Analysis of Dynamic Characteristics of Equipment

Under the action of white noise, the frequency of the high-voltage bushing in different directions can be obtained by using the transfer function. Figure 6 shows the transfer function curve of the high-voltage bushing. It can be seen that the first-order frequency in the X and Y directions are \( f_x = 11.0 \) Hz; \( f_y = 11.4 \) Hz. According to the same method, the first-order frequency can be obtained after 0.4 g artificial wave experiment conditions, 0.8 g artificial wave experiment conditions and 1.2 g artificial wave experiment conditions are completed. The results are shown in table 5. It can be seen from the table that during the experiment, the dynamic characteristics of the equipment did not change much.

![X direction transfer function](image1)

![Y direction transfer function](image2)

(a) X direction

(b) Y direction

Figure 6. Diagram of Transfer function.
Table 5. High voltage bushing first-order frequency Unit: Hz.

| Experiment condition         | X direction | Y     |
|------------------------------|-------------|-------|
| Before the experiment        | 11.0        | 11.4  |
| 0.4g experiment condition    | 11.2        | 11.0  |
| 0.8g experiment condition    | 11.0        | 11.0  |
| 1.2g experiment condition    | 10.7        | 11.1  |

4.2. Analysis of Seismic Performance of UHV Transformer Body

The UHV transformer body will have an amplifying effect on the bushing in the shaking table experiment. In order to study the dynamic response of the UHV transformer body under the action of the earthquake, the side wall of the transformer, the centre of the top plate of the box and the top angle of the top plate is chosen as three key measuring points to analyse the dynamic response change characteristic of the transformer box.

When the 0.4 g artificial wave is input in the X direction, the acceleration change curve of the side wall, the acceleration change curve of the centre of the top plate and the acceleration change curve of the top angle of the top plate are shown in figure 7. It can be seen that when 0.4 g artificial wave is input, the maximum acceleration of the side wall, the centre of the top plate, and the top angle of the top are 0.42 g and 0.44 g, 0.47 g, respectively.

![Figure 7. Acceleration-time history.](image)

(a) Side wall  (b) Top plate of the box  (c) Top angle of the box

Measuring the maximum acceleration of the side wall, maximum acceleration of top plate of the box when inputting the 0.4 g artificial wave in Y direction, 0.8 g artificial wave in X/Y direction, 1.2 g artificial wave in X/Y direction respectively, then figure 8 can be obtained. It can be seen from the figure 8 that with the increase of seismic excitation, the acceleration of the side wall and the top plate of the box basically shows a linear increase trend. For the side wall of the box, when the seismic wave is input in the X direction with the seismic peak acceleration increases from 0.4 g to 1.2 g, the acceleration response increases from 0.42 g to 1.43 g; when the seismic wave is input in the Y direction, with seismic peak acceleration increases from 0.4 g to 1.2 g, the acceleration response is increased from 1.34 g to 5.6 g. When seismic waves are input in the Y direction, the acceleration response is larger and the increase amplitude is also larger. The main reason is that the rigidity of the transformer box in the Y direction is small. So the seismic response is large.

The acceleration change characteristic of the top plate of the box is consistent with the side wall. When the seismic wave is input in the X direction, when the seismic peak acceleration increases from 0.4 g to 1.2 g, the acceleration response increases from 0.44 g to 1.37 g; when the seismic wave is input in the Y direction, when the seismic peak acceleration increases from 0.4 g to 1.2 g, the
The acceleration response increases from 0.83 g increased to 3.25 g. When the Y direction seismic wave is input, the acceleration response increases greatly.

![Graph](image)

\[\text{(a)} \text{Side wall} \quad \text{(b) Top plate of the box}\]

**Figure 8.** Acceleration response of box under different seismic excitations.

### 4.3. Analysis of Seismic Performance of Outlet Bushing

The maximum acceleration of top of high voltage bushing, medium voltage bushing, and low voltage bushing are measured when the seismic peak acceleration is 0.4 g and the seismic wave input directions are X, Y, X+Z, X+Y, Y+Z, respectively. The comparison curve is shown in figure 9. The acceleration response of high, medium, and low-voltage bushings shows similar changes: the response when inputting the Y direction seismic wave is greater than that when inputting the X direction; the acceleration value is the largest when inputting X+Y direction seismic wave; the acceleration response is the smallest when inputting X-direction; the response when inputting the Y+Z direction seismic wave is greater than that when inputting the X+Z direction.

![Graph](image)

**Figure 9.** Acceleration comparison of different seismic wave input directions.

In order to compare and analyse the seismic response of bushing under different seismic excitations, the acceleration and strain of the high-voltage bushing are measured when inputting the 0.4 g artificial wave in X/Y direction, 0.8 g artificial wave in X/Y direction, 1.2 g artificial wave in X/Y direction. Figure 10 and figure 11 show the acceleration and strain change characteristic of high voltage bushing.
It can be seen from the figure that acceleration and strain show similar changes. As the seismic peak acceleration increases, the acceleration and strain gradually increase. The acceleration and strain are greater when the seismic wave is input in the Y direction than those input in the X direction; when the seismic excitation increases from 0.8 g to 1.2 g, the acceleration and strain response increase amplitude less than those the seismic excitation increases from 0.4 g to 0.8 g.

For high-voltage bushing, as the peak seismic acceleration increases, the difference in acceleration seismic response between X-direction input and Y-direction input gradually decreases. When the seismic peak acceleration is 0.4 g, the difference is 72%; when the seismic peak acceleration is 1.2 g, the difference is 1%.

For strain of bushing, as the acceleration increases, the difference between the strain value in Y direction and the strain value in X direction increases gradually. When the seismic peak acceleration is 0.4 g, the difference between the two is 10%; when the seismic peak acceleration is 1.2 g, the difference is 41%.

5. Conclusion
(1) The first-order frequency of UHV transformer decreased by 2.7% and 2.6% after the experiment when X-direction seismic wave is input and Y-direction seismic wave is input respectively.

(2) With the increase of seismic excitation, the acceleration on the side wall and the top of the box basically shows a linear increase; when the seismic wave is input in the Y direction, the acceleration response is larger and the increase amplitude is also larger.

(3) The acceleration response of high, medium and low voltage bushings shows similar changes: the response when inputting the Y direction seismic wave is greater than that when inputting the X direction; the acceleration value is the largest when inputting X+Y direction seismic wave; the response when inputting the Y+Z direction seismic wave is greater than that when inputting the X+Z direction.

(4) With the increase of seismic peak acceleration, acceleration and strain of bushing gradually increase. The acceleration and strain are greater when the seismic wave is input in the Y direction than those input in the X direction. When the seismic excitation increases from 0.8 g to 1.2 g, the acceleration and strain response increase amplitude less than those the seismic excitation increases from 0.4 g to 0.8 g. As the seismic excitation increases, the difference between the acceleration response of the high-voltage bushing when the seismic wave is input in the Y direction and the acceleration response when the input in the X direction is gradually reduced, and the strain difference gradually increases.
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