Study on Seismic Performance of UHV Transformer Based on Soil-structure Interaction

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Abstract. At present, the seismic performance of UHV transformers is mostly studied without considering the interaction between soil and superstructure. In practical engineering, the transformer is installed on the foundation slab buried in the soil. Under the action of earthquake, the interaction between the soil and the structure changes the earthquake response of the upper electrical structure. In order to study the influence of the interaction between soil and structure on the seismic performance of the transformer, the shaking table test method of simulated earthquake is used, and the shaking table test of UHV transformer with scale ratio of 1:4 is carried out in class I field conditions. The dynamic characteristics of the equipment and the seismic response of the bushing under different test conditions are obtained respectively. The test results show that when the peak acceleration is 1.2g, the acceleration response at each measuring point on the box is 1.63-1.92 times that when the peak acceleration is 0.4g. With the increase of seismic peak acceleration, the acceleration and strain increase of high voltage bushing are greater than that of medium and low voltage bushing, which has a great influence on the seismic response of high voltage bushing. The research conclusion can provide reference for substation engineering design.

Keywords. Soil-structure interaction; UHV transformer; shaking table test; seismic response.

1. Introduction
China is located in the Eurasian seismic zone, and earthquakes occur frequently. As an important part of the lifeline project, once the earthquake happens, the damaged equipment will affect the safe and stable operation of the power grid inevitably and cause economic losses extremely [1-2].

The UHV transformer is an important electrical equipment in the substation. The earthquake damage forms of the transformer are mainly as follows: the transformer body slips, falls, overturns and other phenomena; the high voltage bushing is fractured due to its material characteristics and relatively tall structure[3]. In 1994 Northbridge earthquake, transformer bushing was damaged seriously [4]. In 1995, during the Kobe earthquake in Japan, a number of 770 and 275 kV substations were damaged. Post-disaster investigation found that the power interruption was mainly caused by the damage of transformer porcelain bushings in several substations [5]. Based on the above reasons, it is necessary to conduct seismic analysis for the transformer, especially in the early stage of UHV transformer. Gilani and other researchers[6] carried out shaking table tests on two kinds of 230 kV, 3000A and U-type transformer bushings, and took improvement measures for weak seismic positions. Filiatraul[7] conducted a dynamic response analysis of bushing mounted on the bushing, which showed that the bushing response was amplified when the frequency of bushing was tuned to the frequency of bushing.
Bender and others [8] showed that the dynamic amplification factor of the bushing might be greater than 2.0. Schiff[9] proposed a new method to identify the transformer and its bushing so that it could meet the requirements of IEEE-693.

The influence of soil on the upper transformer structure was not considered in the above research. Soil-structure interaction originated from Lamb’s analysis of elastic foundation vibration in 1904 [10], and many scholars have carried out related research work on this problem from different perspectives. There are many researches on soil-structure interaction in the field of bridge and construction. But the seismic analysis of transformer has not been reported.

On the basis of the existing research, this paper uses the shaking table test method to carry out the test of UHV transformer considering soil-structure interaction. The seismic response of transformer box and bushing under different test conditions is compared and analysed to provide reference for subsequent seismic design.

2. Test Design

2.1. Prototype Size of UHV Transformer

The UHV transformer prototype used in this test is Baoding Tianwei 1000kV UHV transformer. The UHV transformer is mainly composed of a box, a body (containing iron core, winding resistance, etc.), a high voltage bushing, a medium voltage bushing, a low voltage bushing, a neutral point bushing and rising seats. Figure 1 shows the structure diagram of the UHV transformer. Among them, the size of the transformer box is (length × width × height): 10.9m×3.94m×4.84m. The thickness of the side plate of the transformer box body is 12mm, the thickness of the box cover is 30mm, and the thickness of the bottom of the box is 50mm. The total mass is about 396t. Figure 1 shows a schematic diagram of a transformer. Table 1 shows the geometric parameters of each bushing.

![Figure 1. UHV transformer schematic diagram.](image-url)
Table 1. 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 | 590                  | 710                | 10.16     | 4544        |
| Upper section of high voltage | 430                  | 500                |           |             |

2.2. Determination of Similarity

According to Buckingham’s principle, for the earthquake response of the structure, the expression within the range of linear elasticity appears as shown below:

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

In this formula, \( \sigma \) is the structural response stress, \( l \) is the size of the member, \( E \) is the elastic modulus of the member, \( \rho \) is the density of the member, \( t \) is the time, \( r \) is the displacement, \( v \) is the velocity, \( a \) is the acceleration, \( g \) is the acceleration of gravity, and \( \omega \) is the frequency.

\( S_n \) is defined as the similarity ratio between the model and the prototype. In order to enable the model test to simulate the earthquake response of the prototype structure, the similarity ratio of each variable shall meet the following requirements:

\[ \begin{align*}
S_{\sigma} &= \frac{\sigma_m}{\sigma_p}, \\
S_l &= \frac{l_m}{l_p}, \\
S_E &= \frac{E_m}{E_p}, \\
S_\rho &= \frac{\rho_m}{\rho_p}, \\
S_t &= \frac{t_m}{t_p}, \\
S_r &= \frac{r_m}{r_p}, \\
S_v &= \frac{v_m}{v_p}, \\
S_a &= \frac{a_m}{a_p}, \\
S_g &= \frac{g_m}{g_p}, \\
S_\omega &= \frac{\omega_m}{\omega_p},
\end{align*} \]

in which \( S_{\sigma} = \sigma_m/\sigma_p \), and the subscript \( m \) represents the model and \( p \) represents the prototype.

In general, the similarity constants of length, elastic modulus and acceleration can be selected as controllable similarity constants:

\[ \frac{S_l}{S_E S_\rho} = 1 \]  

Considering the performance parameters of the shaking table, the processing difficulty of the UHV transformer model and the boundary conditions of the soil-structure interaction, the geometric scale of the transformer model used in this model test is determined to be 1:4. The material of the model is the same as that of the prototype. According to expression (2), the elastic modulus is obtained, and the density similarity is 1:1. Then the acceleration ratio is 4:1. The similarity ratios of other parameters are shown in table 2:

Table 2. Similar parameters of model design.

| Physical properties | Physical parameters | Similarity constant |
|---------------------|---------------------|---------------------|
| Geometric performance | Length | 1:4 |
| Material performance | Strain    | 1:1 |
|                      | Elastic Modulus    | 1:1 |
|                      | Stress             | 1:1 |
|                      | Density            | 1:1 |
|                      | Mass               | 1:64 |
| Power performance    | Time                | 1:4 |
|                      | Frequency          | 4:1 |
|                      | Displacement       | 1:4 |
|                      | Acceleration       | 4:1 |
| Mass of model        |                     | 6.2t |
2.3. Model Size

The model size and mass of each part of the UHV transformer are determined by the design similarity constant and mass design similarity constant based on the geometric length determined by the similarity dimension relation.

The size of the transformer box is $2.7\times1.2\times1.0$ (length $\times$ width $\times$ height). The total weight of the oil tank and accessories is about 1200kg; The mass of iron core and winding resistance in the box body is 4740kg; The total bushing weight was approximately 130kg; The weight of the lift seat is about 140kg. Figure 2 is diagram of the UHV transformer model after scaling, and figure 3 is the three-dimensional model diagram.

![Figure 2. Model Size.](image)

![Figure 3. Three-dimensional model.](image)

2.4. Determination of Soil Boundary Conditions

In soil-structure dynamic interaction, the determination of soil boundary conditions is very important. In practical engineering, the soil is in a semi-infinite domain, which is subject to the test conditions during the shaking table test. Therefore, it is necessary to put the soil in a limited range to simulate the earthquake process.

According to the research in literature [11], if a rigid soil box is used in the test, the length of the box body in the direction of vibration should be greater than 4 times of its height, which will exceed the size of the shaking table. The use of flexible soil box, in which the soil can slide in one direction or both directions in the plane of the box, can greatly reduce the plane size of the box and effectively reduce the reflection of seismic waves on the boundary surface of the box. Therefore, flexible soil box is selected for the test.

The plane of the soil box is rectangular. On the basis of satisfying the bearing capacity of the shaking table of 60t, the size of the shaking table of $6\times6m$ and the size and weight of the upper transformer, the length of the model box is selected as 4.6m and the width is 2.9m. The transformer is located in the middle of the model box, with the length of 2.7m and the width of 1.0m. The lower layer of the transformer is a concrete foundation with the length of 3.3m and the width of 1.6m. The transformer is 0.95m away from the edge of the model box. In order to increase the stability of the model box, scissor cross brace is set at the bottom of the model box, and two braces are set in the transverse direction of the top of the model box, which 0.3m away from the edge of the transformer. At the same time, in order to make the laminated structure stable, brace is set around the model box, and all meet the requirements of the design specification. Figure 4 shows the plane dimensions of the soil box.
2.5. Simulation Method of Class I Site

According to the above design, the length similarity ratio of the UHV transformer is $S_l = 1:4$. In the test, the length similarity ratio is the same as that of the UHV transformer, and the length similarity ratio of soil is also $S_l = 1:4$.

$S_e = 1:1$ and $S_r = 1:1$ are used as the same cohesive soil as what geotechnical test used. The soil is the same as the UHV transformer model, and the similar model neglecting gravity is also adopted. Due to the test soil is cohesive soil and the shear wave velocity is relatively fixed, the method of controlling the thickness of soil layer is adopted to simulate different types of sites. According to the bearing capacity of the shaking table used in the test and the size of the soil box, the buried depth of the soil used in the test is 0.5m. According to the length similarity ratio of 1:4, the thickness of the prototype soil layer is respectively 2m. According to Code for Seismic Design of Buildings, when the thickness of soil layer is 0.5m during the test, the site condition can be considered as class I site.

3. Ground Motion Input and Measurement Point Layout

3.1. Test Input

In this paper, artificial synthetic ground motion and two measured ground motions—El-Centro wave and Taft wave are selected to carry out the shaking table tests of earthquake simulation. Synthetic ground vibration is generated by stipulating the response spectrum (hereinafter referred to as “the standard response spectrum”) in Technical specification for seismic design of ultra-high voltage porcelain insulating equipment and installation/maintenance to energy dissipation devices (Q/GDW 11132-2013). The characteristic period of the standard response spectrum is 0.9s, which can almost envelope Class I~III sites in China. El-Centro wave and Taft wave are typical examples of ground motion in class II or class III site soils.
3.2. Arrangement of Measuring Points

To measure the acceleration response of each bushing, an acceleration sensor (X, Y, Z direction) is arranged on the top of each bushing. The acceleration sensor is arranged at the connection between the riser seat and the box body (X, Y, Z direction) and the acceleration sensor (X, Y, Z direction) is arranged at the connection between the riser seat and the bushing. In order to obtain the seismic response of the transformer box, the acceleration sensor (X and Y direction) is arranged in two top angles of the transformer body, the centre of the top cover and the three side centre of the box body (excluding the side centre of the high voltage bushing).

The strain gauges are pasted on the bottom of the four bushing tubes (high voltage bushing, medium voltage bushing, low voltage bushing 1 and low voltage bushing 2) along the opposite side of X and opposite side of Y respectively to measure the stress.

The XY direction displacement meter is arranged at the top of the high voltage bushing and the connection between the rising seat and the bushing. XY direction displacement is arranged at the top of the medium voltage bushing, the connection between the lifting seat and the bushing, and the connection between the lifting seat and the box body. Figure 7 shows the detailed diagram of measuring points.

![Figure 7. Layout of measuring point.](image)

3.3. Table of Test Conditions

After the completion of the same seismic peak acceleration condition, the white noise test is carried out to detect whether the dynamic characteristics of the structure have changed. Transformer high voltage bushing belongs to long cantilever structure. It is necessary to carry out seismic response test in Z direction, so the seismic excitation direction is X direction and X+Z direction. The shear wave velocity of the soil was measured before and after the type I field test to ensure that the mechanical properties of the soil did not change significantly and the test conditions were consistent. Table 3 shows the table of test conditions.

| Test condition | direction |
|----------------|-----------|
| 1              | White noise |
| 2              | 0.4g artificial wave | X/XZ |
| 3              | 0.4g El-Centro wave | X/XZ |
| 4              | 0.4g Taft wave | X/XZ |
| 5              | White noise |
4. Analysis of Test Results

4.1. White Noise Result Analysis

Figure 8 shows the frequency response result obtained after the white noise sweep frequency test in test condition 1. It can be seen from the figure that the frequency in the X direction is $f_x=10.75$ Hz, and the frequency in the Y direction is $f_y=7.25$ Hz. Table 4 shows the natural frequency of the equipment under different test conditions. From Table 4, it can be seen that after the end of all test conditions, the X frequency of the equipment changes from 10.75 Hz to 10 Hz, with a decrease of 6.9%; the Y frequency changes from 7.25 Hz to 8.50 Hz, with an increase of 17.24%.

![Figure 8. Equipment frequency response.](image)

| Test condition | X direction | Y direction |
|----------------|-------------|-------------|
| 2              | 10.75       | 7.25        |
| 6              | 10.50       | 8.00        |
| 10             | 10.50       | 8.25        |
| 12             | 10.00       | 8.50        |

4.2. Analysis of Seismic Response of Transformer Box

The side wall (front) of the transformer box, the centre of the top plate of the box, the junction of the high-voltage riser-box, and the connection of the high-voltage riser-sleeve were selected as key measurement points to analyse the dynamic response change law of the transformer box. The acceleration response at the vibrating table surface propagates through the soil layer to the foundation floor, and the acceleration response is bound to change. Therefore, an accelerometer is also installed at the foundation floor to calculate the amplification effect of the soil on the acceleration. Figure 9 shows the acceleration time history under different test conditions. Table 5 shows the maximum acceleration of the box under different test conditions. It can be seen from the table that the acceleration response at each key measuring point gradually increases with the increase of seismic excitation. The acceleration response of the measuring point on the box is greater than the single X-direction input when the seismic wave is input in the X+Z direction.
For the top plate of the box, when the seismic excitation is 1.2g, the acceleration response is 1.92 times that of 0.4g. For the high voltage riser-box, when the seismic excitation is 1.2g, the acceleration response is 1.85 times that of 0.4g. For the high voltage riser-bushing, the acceleration response of 1.2g seismic excitation is 1.63 times that of 0.4g seismic excitation.

From the above analysis, it can be seen that when the seismic peak acceleration is 1.2g, the acceleration at each measuring point on the box is 1.63-1.92 times the acceleration response at 0.4g.

![Acceleration Time History](image)

(a) Foundation  (b) Sidewall  
(c) top plate  (d) high voltage riser-bushing

**Figure 9.** Acceleration time history (0.4gX direction).

**Table 5.** Maximum acceleration.

| Test condition | Foundation | Sidewall | High voltage riser-box | High-voltage riser-bushing | direction |
|----------------|------------|----------|------------------------|---------------------------|-----------|
| 3              | 0.56       | 0.6      | 0.63                   | 0.63                      | 2.37 X    |
|                | 0.54       | 0.6      | 0.68                   | 0.72                      | 3.10 X+Z  |
| 7              | 0.85       | 0.9      | 0.93                   | 0.90                      | 3.30 X    |
| 11             | 1.05       | 1.1      | 1.21                   | 1.17                      | 3.86 X    |

### 4.3. Bushing Seismic Response Analysis

In order to compare and analyze the seismic response of high, medium and low voltage bushings under different seismic excitations. Table 6 shows the strain response of the bushing under different seismic excitations. It can be seen from the table that the strain increase of the high-voltage bushing is greater than that of the medium and low-voltage bushing. When the seismic peak acceleration is 0.8g, the peak strain of the high-voltage bushing increases by 70% compared with the 0.4g test condition; the peak strain of the medium-voltage bushing and low-voltage bushing increases slightly with the increase of the peak acceleration, and when the peak acceleration is 0.8g, the peak strain of the medium and low voltage bushing increased by 6.6% and 50% respectively compared with 0.4g.
### Table 6. Maximum strain.

| Test condition | High-voltage bushing | Medium-voltage bushing | Low-voltage bushing | direction |
|----------------|----------------------|------------------------|---------------------|-----------|
| 2              | 130                  | 45                     | 38                  | X         |
| 6              | 181                  | 37.6                   | 30.28               | X         |
| 10             | 221                  | 48                     | 57.3                | X         |

#### 5. Conclusion

(1) The similarity relationship based on the soil-structure interaction shaking table test was studied, the similarity ratio of the model was determined to be 1:4, and the similarity relationship between the physical quantities was derived;

(2) The simulation method of the model foundation is determined, and the size of the soil box is determined, and the simulation method of the Class I site is determined

(3) The shaking table test based on soil-structure interaction was carried out, the X-direction frequency of the structure was $f_x = 10.75\, \text{Hz}$, and the Y-direction frequency was $f_y = 7.25\, \text{Hz}$. When the peak acceleration is 1.2g, the acceleration response at each measuring point is 1.63-1.92 times that of the response when the peak acceleration is 0.4g; with the increase of the seismic peak acceleration, the increase in acceleration and strain of the high-voltage bushing is greater than that of the medium and low-voltage bushing, which has a greater impact on the seismic response of the high-voltage bushing.

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