Seismic Evaluation Method of UHV Transformers for Soil-structure Interaction

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Abstract. China is an earthquake-prone country. In recent years, Wenchuan earthquake and other earthquakes have caused serious damage to power facilities. As the most important electrical equipment in UHV substations, transformers are facing great threat of earthquake disasters. Currently, seismic evaluation of UHV transformers does not consider soil-structure interaction, which is not conducive to fine seismic design and evaluation of UHV transformers. Based on the structural features of the UHV transformer equipment, the seismic evaluation method of the UHV transformer with soil-structure interaction is proposed in this paper, which provides a basis for the seismic performance evaluation of the UHV transformer.

1. Introduction

China is an earthquake-prone country. In recent years, Wenchuan earthquake (2008), Yushu earthquake (2010) and Lushan earthquake (2013) have caused serious damage to power facilities, and caused secondary losses such as power outage, water cut, out of production, communication barriers, have difficulties in rescuing. At present, many of the proposed and under construction UHV projects in China are located in high seismic region. Therefore, the transformer, the most important electrical equipment in UHV substation, is facing the great threat of earthquake disaster. Figure 1 and figure 2 are the photos of damage of typical transformer in Wenchuan earthquake [1-2].

Figure 1. The damage of transformer bushing in Wenchuan earthquake
At present, seismic evaluation of UHV transformers in China often neglects soil-structure interaction. Actually, when the ground foundation and foundation frequency are more than 10 times of the frequency of the equipment itself, the dynamic amplification effect coefficient of the foundation and foundation frequency on the equipment can be approximately considered to be 1. Otherwise, the dynamic amplification effect should be considered [3]. In fact, in most of the UHV transformer structural systems, the ground foundations and basements and the frequency of the equipment body is between 1-10 times, and soil-structure interaction should not be neglected. It is the most effective and accurate method to evaluate the seismic capacity of UHV transformers considering soil-structure interaction in high seismic region, which can help to improve the seismic design level of UHV transformers.

2. Ground motion input
The artificial wave corresponding to the response spectrum (hereinafter referred to as the “standard response spectrum”) jointly proposed by China Electric Power Research Institute and China Earthquake Disaster Prevention Center is used as the boundary condition for the seismic assessment input of the UHV transformer. At present, this standard response spectrum has been adopted by the Technical specification for seismic design of ultra-high voltage porcelain insulating equipment and Installation/maintenance to energy dissipation devices (Q/GDW 11132-2013) and other specifications. The characteristic period of the standard response spectrum is 0.9s, which can almost envelop the I0–III field in China. The artificial waves corresponding to the standard response spectrum are shown in figure 3.
3. Simulation of soil boundary conditions in seismic evaluation

At present, there are two main seismic evaluation methods, one is seismic test, the other is numerical simulation. In the above two methods, the determination of soil boundary conditions is very important, and the accuracy of boundary conditions simulation is directly related to the seismic evaluation results of UHV transformers.

3.1. Simulation of soil boundary conditions in seismic tests

The total weight of the UHV transformer is about 400 tons. If the weight and size of the foundation soil are considered in the test, both the size and weight are beyond the test capacity of the existing earthquake simulation shaking table. Figure 4 shows a typical UHV transformer. When the test conditions of the prototype structure are not available, the earthquake simulation shaking table test of the model is a common method in scientific research and the seismic capacity evaluation of the structure. Therefore, model test can be used to evaluate the seismic performance of the UHV transformer based on soil-structure interaction.

In actual projects, the soil is in a semi-infinite domain, which is subject to the test conditions during the shaking table test. It is necessary to put the soil in a soil box with a limited range to simulate the earthquake process. Therefore, the design of soil box is directly related to the rationality of soil boundary conditions. The ideal test soil box should be able to simulate the shear deformation of soil under the boundary conditions. There are generally three forms of soil box commonly used in shaking table tests [4-5].

(1) The rigid soil box. This kind of box is generally made of steel braced frame and wooden board that combined of rigid wall to restrain the soil. The interior along the vertical direction of horizontal vibration is provided with a flexible barrier (rubber plate or polyethylene foam plastic board). It can ensure the similar shear displacement with the soil, absorb earthquake waves, and reduce the boundary effect. Due to the influence of the material properties and thickness of the inner wall of the experimental chamber, it is difficult to simulate the free site earthquake response of the soil layer accurately. Existing research results show that if a rigid soil box is used, the length of the box in the direction of vibration should be greater than 4 times of its height, which is difficult to meet for a large shaking table test. At present, this type of soil box has been rarely used.

(2) The flexible soil box. The test soil box is composed of a rubber film, and its upper and lower ends are fixed on the steel ring and the steel plate at the bottom of the chamber. The rubber film covered with fiber band or steel wire provides radial stiffness. The distance between the outer fiber bands of the flexible test soil box has a great influence on the test results. If the distance is too small, the box becomes rigid test soil box, which is difficult to provide shear deformation. If the distance is too large, the soil will expand outward, resulting in the decrease of soil restraint and the possible bending deformation of the soil layer.
(3) The layered shear deformation soil box. The layered shear-deformed soil box consists of a multi-layered rectangular plane steel frame stacked from bottom to top, with bearings placed between the layers. By sliding, the steel frame simulate the shear deformation of the soil. The layered shear test box can reproduce the original reaction well, and it has better boundary simulation property, which is obviously better than other test boxes in simulating the shear deformation of soil.

Based on the above comprehensive analysis, the layered shear deformation soil box should be selected to simulate the shear deformation of soil under earthquake more truly. It will improve the accuracy of test results when carrying out the isolation shaking table test of UHV transformer based on soil-structure interaction. Figure 5 shows the 1:4 model earthquake simulation shaking table test of UHV transformer based on layered shear deformation soil box.

![Figure 5. Shaking table test of UHV transformer for soil-structure interaction](image)

3.2. Simulation of soil boundary conditions in numerical simulation

The problem of UHV transformer dynamic response under earthquake originates from the problem of structure interact with semi-infinite space. The integral finite element method intercepts the limited foundation soil and structure for calculation and analysis. So the spread of earthquake wave in a limited area on the truncated boundary reflection, rather than like infinite area of direct transmission. Therefore, the reflected earthquake waves at the truncation boundary will affect the numerical simulation results of soil-UHV transformer dynamic interaction. Therefore, we need to deal with the boundary of foundation soil reasonably, so that the finite space of the finite element model can absorb the earthquake wave and the numerical simulation can accord with the actual situation. The elastic artificial boundary of the whole structural system can be set by installing the ground spring and the ground damper at the boundary nodes of the foundation soil, as shown in figure 6.

![Figure 6. Application of elastic boundary in soil-transformer model](image)
4. Assessment Methods

4.1. Safety factor and load combination

At present, there are mainly two methods to evaluate the mechanical properties of structures or components. One is to evaluate the bearing capacity based on the probability theory and reliability theory. Another method is to evaluate the safety factor based on the allowable stress or failure stress. In the field of building structure, considering the ductility and energy absorption performance of structural components, the first evaluation method is mainly adopted. For the safety evaluation method of seismic performance of electrical equipment, the second method is mostly used in domestic and foreign codes at present. The safety factor is the ratio of the equipment failure stress to the calculated stress value. According to the requirements of DL/T5352-2006 Code for design of high voltage electrical switchgear, it is stipulated that the safety factor corresponding to the failure stress of the equipment should not be less than 2.5 under the long-term action of loads such as strong winds. According to the requirements of GB50260-2013 Code for seismic design of electric installations and Q/GDW 11132-2013 Technical specification for seismic design of ultra-high voltage porcelain insulating equipment and installation/maintenance to energy dissipation devices, it is stipulated that the safety factor corresponding to the failure stress of the equipment should be greater than or equal to 1.67 under the short-term action of earthquake load. In addition to meeting the above mechanical performance requirements, the electrical equipment shall also ensure the functions required for its normal operation. Load combination modes and stress safety factor limits under different working conditions are shown in Table 1.

| Calculation conditions | Load combination | Safety factor |
|------------------------|------------------|--------------|
| Wind load combination  | 1.0×load combination + 1.0×wind load combination | 2.50         |
| Earthquake conditions  | 1.0×load combination + 0.25×wind load combination + 1.0×earthquake conditions + equipment operating load | 1.67         |

4.2. Displacement limit of transformer bushing

As for the displacement limit of transformer bushing under earthquake action, there are no relevant requirements for the displacement of electrical equipment under earthquake action in relevant domestic codes at present. The maximum allowable deflection limit of composite bushing or bushing under the action of IEEE Recommended practice for seismic design of substations only in the United States abroad, as follows: 138KV ~ 230KV equipment 21cm, 230KV ~ 361KV equipment 26cm, 361KV ~ 500KV equipment 31cm, 500KV ~ 800KV equipment 46cm. Considering that the ceramic material equipment is brittle material and its displacement is relatively small under the action of earthquake, there is no specific requirement for the displacement limit of ceramic material equipment. However, since the electrical equipment made of UHV composite materials is more flexible than ceramic materials, its displacement under earthquake action is increased. In order to avoid the excessive displacement of the equipment and increase the seismic coupling effect of the equipment, it is necessary to consider the displacement limit of the equipment when evaluating the mechanical properties of the electrical equipment made of composite materials.

In IEEE693 specification, it is proposed that the top displacement of composite equipment under seismic load should be considered in the design of bus redundancy setting, ensuring the interaction between electrical clearance and short circuit. The specific value is as follows: the top displacement of electrical equipment below 230kV voltage level should be controlled at 210mm; The top displacement of 230KV-361KV grade electrical equipment is controlled at 260mm; The top displacement of 361KV-500KV electrical equipment is controlled at 310mm; The top displacement of 500kV-800kV
electrical equipment is controlled at 460mm. The recommended value of this code was put forward in 2005, which does not consider the displacement requirements of composite electrical equipment in UHV AC/DC engineering.

Most of the UHV composite pillar equipment used in China were tested by China Electric Power Research Institute, and the top displacement results were converted to the value of 0.5g fortified acceleration level linearly. The research results show that the top displacement of the composite arrester is 312mm, and the two-section pillar bushing with an outer diameter of 358mm is 564mm. Five-section pillar bushing with an outer diameter of 280mm is 767mm. The top displacement of the GIS bushing is 75mm, and the top displacement of the high-resistance bushing is 340mm.

Based on the current use of UHV AC/DC composite seismic displacement response of the electrical equipment, and the setting of sliding armor clamp and soft wire, the equipment design and the manufacture of economy and the transitivity of the IEEE standard, the top displacement limit of UHV composite pillar equipment is determined by the smaller value of 600mm and 1/18 of the equipment height (when the displacement current value is 600mm, the statistical displacement angle of each equipment is below 1/18). Therefore, for the bushing with composite material used in the transformer, the bushing displacement should also be the smaller value of 600mm and 1/18 displacement angle as the limit index under earthquake action.

5. Conclusions
In this paper, based on the structural features of UHV transformers, the seismic evaluation method of UHV transformers under soil-structure interaction is proposed from the aspects of ground motion input, simulation of soil boundary conditions in seismic evaluation, and the specific evaluation methods. The basic principles that should be followed in the seismic evaluation of UHV transformers based on soil-structure interaction are defined, which provides a basis for the seismic performance evaluation and fine seismic design of UHV transformers based on soil-structure interaction.

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