Dynamic properties and seismic vulnerability of voltage transformer in substation

Shansuo Zheng, Xingxia Wu*, Xiaohang Liu, Dianxin Chen

1 School of Civil Engineering, Xi’an University of Architecture and Technology, Xi’an 710055, China
2 Key Lab of Structural Engineering and Earthquake Resistance, Ministry of Education (XAUAT), Xi’an 710055, China
* wxx@xauat.edu.cn

Abstract. The evaluation of the seismic stability of electrical equipment is very important in substation. In this paper, the influence of support on seismic response and vulnerability of voltage transformer is studied. First, the support-voltage transformer finite element models (FEM) is established by Abaqus. Natural frequency, dynamic amplification factor of support-voltage transformer with different PGA are investigated. Afterwards, the seismic response parameters obtained by FEM simulation are applied to the vulnerability analysis of voltage transformers. Finally, the vulnerability result indicated that support height and ceramic material have significant effects on the probability of equipment failure.

1. Introduction

Substation is a key component of high voltage transmission system. Once damaged in the earthquake, it will seriously affect disaster relief and post-earthquake reconstruction. It has a huge impact on lifeline systems such as water supply, communication, transportation[1], so that water conservancy projects, civil engineering and other large construction projects unable to proceed smoothly. Voltage transformer is used as primary equipment in substation to convert voltage and current online. Its main purpose is to supply power to measuring instruments and relay protection devices, to measure the voltage, power and energy of a line, for ensuring the line safety in case of line failure[2]. Damage to voltage transformer will result in other electrical equipment in substation not working properly, so it is very important to study the seismic behavior of voltage transformer [3-6]. Cheng Yongfeng et al. [7-8] carried out seismic and damping test research on Capacitor Voltage Transformer (CVT). The test results show that the seismic performance of CVT is significantly improved after the shock absorber is installed.

In this paper, the seismic behavior of voltage transformers in 110kV outdoor substations is comprehensively studied and analyzed in combination with the Guidelines for Seismic Design of Electrical Equipment (JEAG5003-1980) [9], Code for Seismic Design of Electrical Facilities (GB50260-13) [10] and International Standards (IEEEStd693-2005) [11]. The dynamic time history analysis of 110 kV support-voltage transformers were analyzed by Abaqus. The laws of different seismic responses varying with support height and section are studied, and suggestions on equipment support factory design are given. Combining the time history analysis results with the vulnerability theory, the seismic vulnerability curve of voltage transformer is obtained. The seismic performance of voltage transformer is comprehensively analyzed, which lays a solid foundation for the seismic
reliability analysis of power system. It has certain reference value for evaluating earthquake disaster losses of substation electrical equipment and revising seismic design standards of high voltage electrical equipment in the future.

2. Model simplification and establishment of FEM
Voltage transformer is a typical high-length ceramic pillar structure, which consists of expander, pillar ceramic sleeve, oil tank and core. The pillar ceramic sleeve is connected by cast iron flange and the core is sealed inside the ceramic sleeve to meet the insulation requirements. The 110kV voltage transformer studied in this paper is a capacitive voltage transformer (TYD-110kV), as shown in Figure 1. Equipment details are provided by Xi'an Electric Power Design Institute.

Voltage transformer is usually installed on reinforced concrete support. To study the influence of different support types on equipment seismic response, finite element models (FEM) of reinforced concrete support-voltage transformer system with different support heights and section sizes are established respectively. Referring to the General design of power transmission and transformer engineering of state grid corporation (110(66)-750kV substation sub book) [9], the support height is 2000mm, 2500mm, 3000mm, 3500mm, and the section size is 300mm × 50mm, 350mm × 50mm and 400mm × 50mm, respectively. The outer diameter of the straight cylinder is used as the solid diameter of the ceramic sleeve, this is, the inner diameter of the umbrella skirt. The equivalent material parameters of the cylinder are shown in Table 1 below.

In this paper, Abaqus is used to build a simplified FEM of the support-voltage transformer equipment. Simplified geometry of insulated ceramic sleeves: The actual geometry of the ceramic sleeve is complex and serrated with different tooth lengths. In addition, the point of shape design is not based on the structure seismic performance, but increase insulating pillar outer surface length to reduce the device if discharge effect to low voltage objects. Because most of the actual seismic damage modes of voltage transformer are broken at the root of ceramic bushing. The quality is achieved by increasing the density of the ceramic sleeve and the stiffness is achieved by increasing the elastic modulus of the ceramic sleeve. Insulated ceramic sleeve simplifies the parameters of each part are shown in Table 1.

| Voltage transformer | Actual Construction (1110mm) | Simplified component |
|---------------------|-----------------------------|---------------------|
| Max outside diameter (mm) | 180 | 150 |
| Minimum Outer Diameter (mm) | 150 | 150 |
| internal diameter (mm) | 110 | 110 |
| density (kg/m3) | 0.97×104 | 1.21×104 |
| Elastic Modulus (Gpa) | 80 (70) | 96 (84) |
| quality (kg) | 110 | 109.71 |
The other components property are solid unit C3D8R, with 2019 nodes and 12544 units. The material parameters of the model are derived from Northwest Electric Power Design Institute. Table 1 shows the equipment initial data and the converted data after equivalent treatment. The rebar is divided into free grids and sweep grids. Because different material parameters are used at the joints of the parts of the equipment, it is not possible to build a whole when modeling. However, joins have the same translation and rotation, so they need to be connected by set up constraints. In this paper, the steel bar and concrete are coupled by Embedded region, and the rest of the components are coupled by tie.

3. Dynamic Time-History Analysis of Voltage Transformer

Twenty-two ground motion records recommended by the ATC-63 report are selected from the PEER ground motion database[6]. Considering the large number of ground motion records selected and the workload is enormous. To avoid redundant amplitude modulation, the unequal length method can reduce the workload while ensuring the accuracy and efficiency of the calculation, that is, PGA is taken every 0.2g in the range of 0-1g.

The main characteristics of earthquake damage to electrical equipment are tilting, dropping and breaking at the bottom of insulated ceramic bottles[6]. Therefore, the stress at the bottom of the ceramic sleeve is the focus of research.

When evaluating the seismic performance of high-voltage ceramic pillar electrical equipment, the accuracy and rationality of the support dynamic amplification factor is directly related to the equipment seismic performance evaluation results. For high-voltage ceramic pillar electrical equipment, the different parameters influence rule on support dynamic amplification factor is analyzed when they change in a certain range.

The acceleration values at the top of support under different support types and different ceramic materials are obtained by finite element calculation and analysis. Combined with equation (11), the dynamic amplification factor of different systems are obtained, as shown in Figure 2 - Figure 3.

![Figure 2 Dynamic amplification factor of voltage transformer system](a) 300×50mm (b) 350×50mm (c) 400×50mm

![Figure 3 Dynamic amplification factor of voltage transformer system](a) 300×50mm (b) 350×50mm (c) 400×50mm
Figure 2 shows the dynamic amplification factor of the high silicon ceramic support-voltage transformer. Figure 3 is the dynamic amplification factor of the ordinary ceramic material support-voltage transformer. As can be seen from Figure 2 - Figure 3, the dynamic amplification factor of each support-voltage transformer is greater than 1.2, so the support has a certain dynamic amplification effect on the equipment, which varies with the support types. As shown in Figure 2, when the height of support is 3500 mm, the dynamic amplification factor of section size 300×50mm, 350×50mm, and 400×50mm are 1.488, 1.441 and 1.420 respectively, so the mean value of dynamic amplification factor decreases with the increase of the support section size; It can be seen from Figure 2 (a), the dynamic amplification factor of the support-voltage transformer system with 300×50mm high silicon ceramic cross-section and 2000 mm, 2500mm, 3000mm and 3500mm support-voltage transformer system are 1.224, 1.327, 1.425 and 1.488 respectively. Here, it is concluded that the mean dynamic amplification factor increases significantly with the height of the support.

For Figure 2 - Figure 3, when the cross-section size is 350×50mm and the height is 2000 mm, the dynamic amplification factor of ordinary ceramic voltage transformer is 1.239 which is larger than that of high silicon ceramic 1.224. Similarly, ordinary and high-silicon ceramic voltage transformers of other cross-section sizes and heights have the same conclusion. It can be concluded that the dynamic amplification factor of the ordinary ceramic of the support-voltage transformer with the same height and cross-section size is larger than that of the high-silicon ceramic voltage transformer. Dynamic amplification effect is independent of peak acceleration of seismic waves. Acceleration amplification coefficient under 22 seismic waves is about 0.953-1.848, the mean value is about 1.203-1.546. Acceleration amplification factor under most seismic waves is greater than the minimum value 1.2 defined by the code.

4. Vulnerability Analysis of Voltage Transformer

Due to the high content of AL2O3, the destructive strength of high-silicon ceramics is much higher than that of ordinary ceramics, which makes them more widely used in substation projects in recent years. However, due to the long usage time of electrical equipment, there are still a large number of ordinary ceramic bushing in substations built in earlier years. In view of this, this paper also studies and analyses the electrical equipment made of ordinary and high silicon ceramics. Based on the binary damage index of intact/invalid, the ultimate failure strength of high-silicon and ordinary ceramics is the average destructive strength of high-silicon ceramics is 40 MPa with a standard deviation of 5.4Mpa, approximating 40Mpa. The average destructive strength of ordinary ceramics is 20MPa with a standard deviation of 2.5 Mpa, approximating 20MPa.

Logarithm of ground motion intensity index PGA is taken as transverse coordinate and maximum equivalent stress $\sigma_{\text{max}}$ of equipment is fitted as logarithm of structure seismic response index as longitudinal coordinate respectively.

A probabilistic seismic demand model for equipment using PGA as seismic ground motion intensity index is obtained. The demand model is the basis of probabilistic seismic vulnerability analysis. Consider the influence of support height (2000mm, 2500mm, 3000mm, 3500mm), support cross-section size (300×50mm, 350×50mm, 400×50mm) and ceramic material (high silicon ceramic, common ceramic) on electrical equipment. IDA analysis is carried out on electrical equipment under different support heights, support cross-section sizes and ceramics materials, and logarithmic linear regression results of probabilistic seismic demand model with PGA as seismic intensity index are obtained.
Comparing the vulnerability results in Figure 4, it can be found that the support height and ceramic material have significant effects on the probability of equipment failure under the same seismic intensity. The probability of equipment damage increases significantly with the height of the support, and the probability of damage to ordinary porcelain is higher than that of high silicon ceramic. The section size of support has little influence on the failure probability of equipment. The failure probability of equipment decreases slightly with the increase of section size of support.

Through the above steps, the exceeding probability of the variable parameter support-voltage transformer is obtained, and the corresponding seismic vulnerability curve is drawn, as shown in Figure 4.

5. Conclusions
This paper studies the variation rules of frequency, dynamic amplification factor and vulnerability of different types of support-voltage transformer systems, and proposes:

(1) Natural frequency and dynamic amplification factor of equipment system are related to support height and section size respectively. The lower the support height, the larger the section size, this is, the higher stiffness of the support, the higher natural frequency of the equipment system and the smaller the dynamic amplification factor.

(2) The study shows that the support dynamic amplification factor to its upper electrical equipment fluctuates widely and is often much larger than 1.2. In the current national standards, the value is too small. It is recommended to calculate the support and electrical equipment in detail or to increase the power amplification factor.

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