Parametric Modelling and Seismic Analysis of 220kV Power Distribution Equipment in Electrical Substation

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Abstract. Power grid is an important part of the earthquake lifeline project. As electrical substation is the node of the power grid, and the safety evaluation of the substation under earthquakes is essential. There are a wide variety of electrical equipment in substations, and multi pieces of equipment are interconnected to form the complex circuits. Seismic modelling of substation equipment requires engineering researchers to have an accurate understanding of the structure of electrical equipment, as well as to collect complete electrical equipment structural parameters. This process takes a lot of time and effort. This paper proposed a parametric modelling method for substation equipment, which can achieve effectiveness in seismic modelling. Parametric modelling and seismic analysis of high-voltage equipment of a 220 kV substation in Xinjiang is carried out, which verified the validity and applicability of the method.

1. Introduction
The Xinjiang region of China, located in the south-central part of the Eurasian plate, has a complex tectonic structure. Strong tectonic activity and frequent earthquakes make it a strongly active continental seismic zone. According to statistics, in the Xinjiang region of China, 86 earthquakes with a magnitude of 5 or greater and 12 earthquakes with a magnitude of 6 or greater have occurred in the past decade. See Table 1 for details.

Table 1. Earthquake in recent years in Xinjiang Province in China

| Year       | Ms 5~6 | Ms >6 |
|------------|--------|-------|
| 2019       | 3      | 0     |
| 2018       | 4      | 0     |
| 2017       | 3      | 1     |
| 2016       | 6      | 2     |
| 2015       | 4      | 1     |
| 2009–2014  | 49     | 7     |

Frequent earthquakes in Xinjiang pose a serious threat to the safety of power grid facilities, especially substations, which are the nodes of the power grid. Electrical equipment in substation is
vulnerable to earthquakes [1]. Electrical transformers, cylindrical equipment such as disconnect switches, transformers, capacitors and surge arrester are all susceptible to damage by seismic action [2]. Figure 1 shows the collapsed electrical equipment in the Wenchuan earthquake [3][4]. The structural forms of the transformers, capacitors and lightning arresters in different substations are similar. The horizontal seismic force acts on the insulator forming bending moment at bottom, which will lead to the brittle fracture of the insulator when the limit value is exceeded [5]. Cylindrical electrical equipment is connected by bus-bar or flexural conductor, which are coupled in seismic response [6][7]. It makes the seismic design and evaluation of substation equipment difficult.

Figure 1. Seismic failure of electrical equipment in Wenchuan Earthquake [3]

Hence, earthquake disasters pose a major threat to the safety of the power grid, causing huge economic losses after the disaster. Seismic modelling of substation equipment requires engineering researchers to have an accurate understanding of the structure of electrical equipment, and collect complete structural parameters [8]. This process takes a lot of time and effort. This paper proposes a parametric modelling method for substation equipment, and demonstrates by python programming language. Seismic analysis of high-voltage substation distribution equipment in a 220 kV substation in Xinjiang is taken as an example, verifying the validity and applicability of the method. It provides a new method for seismic evaluation of substation equipment.

2. Structural feature of power distribution equipment in substation

High-voltage distribution equipment in substation is mostly pillar-type cylindrical equipment [9]. Steel supporting structure are installed at the bottom of the equipment. Bus bars or flexural conductor are installed at the top of equipment, connecting the nearby equipment. So the seismic response between the nearby equipment will be transmitted through each other. As shown in Figure 2, the disconnect switches, surge arrester, and capacitor voltage transformer in a substation forms a typical connection circuit in substation.

Figure 2. Typical structure of cylindrical equipment in electrical substation
Porcelain insulators are an important part of the structure of cylindrical electrical equipment, which consists of porcelain parts, upper flange and lower flanges. Figure 3 shows the connection structure between the flange and the porcelain component, which can be simplified in seismic modelling. As shown in the figure on the right, the porcelain insulator is divided into three sections of varying stiffness.

![Figure 3. Seismic modelling of cylindrical electrical equipment [8]](image)

### 3. Parametric modelling method for electrical equipment

In order to improve the efficiency of the seismic analysis, parametric modelling of the structure has received attention. Parametric modelling identifies the main parameters of the structure and imports them into the program to build the model, eliminating the need for complex modelling operations, which can effectively reduce the time investment by the researcher. The common modelling process generally requires basic information about the form of the structure, material properties, cross-section dimensions, constraints, etc., and then following step-by-step operations to build models in FEM software. Parametric modelling is achieved by extracting the standard parameters of the structure, creating a standardized parameter table, reading and compiling it using a program, and implementing the program for modelling.

Different types of power equipment have their corresponding parameter tables, but same type of equipment from different manufacturers can adopt a same parameter table. This enables standardization for each type of equipment in seismic modelling. The Python program can quickly read the parameter table of different parameter tables, and then combine it with the general-purpose finite element program. When one of the data in the model needs to be modified, it only needs to correct the parameter values in the structural parameter table and then re-run the program again. The flowchart of parametric modelling is shown in Figure 5.

![Figure 4. Parametric modelling flow chart](image)

For conventional electrical structures, beam unit can be used in FEM modelling. The information of the node position, the unit cross-sectional sizes and the material properties of each unit can be
calculated for each component. The simulation of the porcelain casing and the flanges at both ends is the key to modelling, and the connection structure between the three is more complex, and the connection stiffness needs to be considered. The equipment models are connected to each other with bus bars, and the bus bar shape is calculated according to the suspended chain line geometry. Non-structural appurtenances can be transformed into additional mass to consider the effect on the dynamic property of the electrical equipment. The mapping between parametric dataset and the finite element model is shown in Figure 5.

4. Seismic analysis of 220kV interconnected power distribution equipment – case study
This section takes the 220 kV high-voltage distribution equipment in substation as an example. It contains four types of common electrical equipment, which are circuit breaker, capacitors voltage transformers, surge arrester and dis-connector switch, as seen in Figure 6. The seismic input is selected according to the GB50260 specification [10], as seen in Figure 7. The data set for surge arrester is shown in Table 2, and similar data sets are obtained for the other three pieces of equipment.
Figure 7. Waveform of input ground motion

Table 2. Parametric data set for surge arrester

|                         | Unit 1 | Unit 2 | Unit 3 |
|-------------------------|--------|--------|--------|
| 1 Weight of insulator (kg) | 163    | 163    | 50     |
| 2 Weight of upper flange (kg) | 14     | 14     | 9      |
| 3 Weight of lower flange (kg) | 14     | 14     | 9      |
| 4 Length of insulator (mm) | 1410   | 1410   | 300    |
| 5 Outer diameter at upper end (mm) | 184    | 184    | 184    |
| 6 Inner diameter at upper end (mm) | 124    | 124    | 124    |
| 7 Outer diameter at lower end (mm) | 184    | 184    | 184    |
| 8 Inner diameter at lower end (mm) | 124    | 124    | 124    |
| 9 Height of cement layer at upper end (mm) | 141    | 141    | 30     |
| 10 Thickness of cement layer at upper end (mm) | 10     | 10     | 10     |
| 11 Diameter at the cement layer at upper end (mm) | 184    | 184    | 184    |
| 12 Height of cement layer at lower end (mm) | 141    | 141    | 30     |
| 13 Thickness of cement layer at lower end (mm) | 10     | 10     | 10     |
| 14 Diameter at the cement layer at lower end (mm) | 184    | 184    | 184    |
| 15 Elastic modulus of porcelain (Pa) | 1E+11  | 1E+11  | 1E+11  |
| 16 Poisson ratio | 0.3    | 0.3    | 0.3    |
| 17 Added mass at upper end (kg) | 100    | 0      | 0      |
| 18 Added mass at lower end (kg) | 0      | 0      | 0      |

Parametric modelling is establish, as seen in Figure 8. Eigenvalue analysis is carried out to find the model shapes, as seen in Figure 9. The fundamental frequency for those equipment are 2.4Hz, 4.0Hz and 6.3 Hz. And in the 0.3g artificial wave which is compatible to GB 50260 wave, the maximum response values for those equipment are found, which are listed in Table 3. It was found that the circuit breaker has the largest seismic response in acceleration, displacement and bending moment. This case study demonstrates the advantage of parametric modelling for seismic evaluation of electrical equipment.

Figure 8. FEM model by parametric modelling
Figure 9. Modal shapes

Table 3. Maximum response data in 0.3 g artificial seismic wave load case

| Equipment item       | Response name | X direction | Y direction |
|----------------------|---------------|-------------|-------------|
|                      |               | Min | Max | Min | Max |
| Circuit breaker      | Acc. (m/s²)   | -7.54 | 8.29 | -7.46 | 8.15 |
|                      | Disp. (mm)    | -40.49 | 35.74 | -38.37 | 32.88 |
|                      | Bending Moment (N.m) | -16752 | 14850 | -15874 | 13681 |
| CVT                  | Acc. (m/s²)   | -7.66 | 8.12 | -7.04 | 7.70 |
|                      | Disp. (mm)    | -37.22 | 35.26 | -33.68 | 29.49 |
|                      | Bending Moment (N.m) | -12658 | 12518 | -11324 | 10347 |
| Switch disconnector, column 1 | Acc. (m/s²)   | -4.12 | 3.75 | -5.79 | 6.40 |
|                      | Disp. (mm)    | -2.80 | 2.88 | -4.04 | 3.77 |
|                      | Bending Moment (N.m) | -3254 | 3077 | -2285 | 2184 |
| Switch disconnector, column 2 | Acc. (m/s²)   | -3.71 | 5.18 | -7.45 | 8.24 |
|                      | Disp. (mm)    | -1.20 | 0.92 | -5.27 | 4.65 |
|                      | Bending Moment (N.m) | -1896 | 1415 | -2710 | 2439 |
| Switch disconnector, column 3 | Acc. (m/s²)   | -4.07 | 6.00 | -6.07 | 6.65 |
|                      | Disp. (mm)    | -3.51 | 2.79 | -4.49 | 4.27 |
|                      | Bending Moment (N.m) | -3611 | 2715 | -2881 | 2792 |
| Surge arrester       | Acc. (m/s²)   | -6.63 | 6.22 | -7.57 | 8.30 |
|                      | Disp. (mm)    | -8.24 | 8.81 | -12.83 | 11.21 |
|                      | Bending Moment (N.m) | -3255 | 3495 | -5417 | 4732 |

5. Conclusions
The following conclusions can be drawn from the parametric modelling study and case study of 220kV electrical equipment in substation.

1. Compared with traditional modelling methods, parametric modelling of common electrical equipment can significantly reduce the modelling time and improve the modelling efficiency.
(2) The simplified beam element model is suitable to simulating the response of cylindrical electrical equipment under seismic effects.

(3) The case study of 220 kV electrical equipment in substation demonstrate the effectiveness and parametric modelling method proposed in this paper.

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