Seismic analysis and retrofitting countermeasure for 1315 kV capacitor with multi-column posts

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Abstract. A number of power substations and converter stations are inevitably built in high earthquake intensity regions. There are many types of electrical equipment with multi-column posts in power substations and converter stations. The PLC/RI capacitor with high seismic vulnerability is a typical electrical equipment with multi-column posts. A 1315 kV PLC/RI capacitor was modeled and analyzed using finite element technique. The modal analysis results show that the primary frequency of the capacitor is close to the earthquake dominant frequency. Additionally, the 2nd, 3rd and 4th order frequencies are within the range of the flat segment of the seismic response spectrum. After performing seismic analysis, the most fragile location was identified, that is the porcelain insulator at the bottom of the capacitor. The stress safety factor of the porcelain insulator is 0.71, which indicates the capacitor does not meet the seismic requirement for peak ground acceleration (PGA) = 0.3 g. To improve the seismic performance of capacitor with multi-column posts, enhancing connection stiffness of the structure is proposed. Based on this countermeasure, the thickness of the connecting plate between the upper hollow composite insulators and the porcelain insulators at the bottom of capacitor was increased from 20 mm to 50 mm. After the optimization, the 1315kV PLC/RI capacitor satisfies the seismic requirement for PGA value of 0.3 g.

1. Introduction
China is located between the Eurasian seismic belt and the circum-Pacific seismic belt. Because of the imbalance of energy distribution and load center, many areas with abundant coal and water resources, where PGA > 0.2 g, are selected as substation sites[1]. For getting close to the energy base, a large number of power substations (converter stations) are inevitably built in unfavourable areas with high seismic intensity. Inspired by lessons from earthquake damage in recent years, it is clear that the electrical equipment in the power substation (converter station) was quite vulnerable to an extremely intense earthquake (PGA > 0.2 g), which not only caused huge economic losses, but also seriously hindered the reconstruction after the disaster[2-4]. The ultra-high voltage (UHV) substation (converter station) has great capacity. Once it is damaged in the earthquake, it may cause the function loss of large-scale power grid system[5]. A big amount of equipment with multi-column posts exist in substations (converter stations), such as capacitor tower, PLC/RI capacitor, reactor. Under the action of high intensity earthquake, multi-column posts interact with each other owing to the bending and shear deformation. The dynamic effects of all multiple-columns posts cause the electrical equipment's high vulnerability.

PLC/RI capacitor is installed outside the valve hall at direct current (DC) side of converter station and connected in parallel with bus. It can prevent noise interference to the DC PLC system caused by
high harmonics generated by the converter valve, or prevent interference between PLC systems on both sides of a DC relay station[6]. Therefore, PLC/RI capacitors are essential components in many converter stations. PLC/RI capacitor is typically supported by post insulators. The strength of supporting structure is low, and the equipment center of gravity is high and the quality is large, resulting in vulnerability of the capacitor with multi-column posts subjected to earthquake.

In early years, a great deal of work was carried out to study the seismic performance of cylindrical electrical equipment in power substation and converter station[7-10]. However, very meagre efforts have been dedicated to investigating the seismic performance of capacitor with multi-column posts. Sun Yuhan studied a model of 110 kV capacitor bank in UHV substation by shaking table[11]. The 110 kV capacitor model consists of three layers of frame, which is supported by four insulators at the bottom. The equipment model has high center of gravity, large mass, low strength of supporting structure and high seismic vulnerability. The test results show that the acceleration amplification effect is nonlinear with the height under the earthquake action, and the key part of anti-seismic is the bottom post insulator. The test results show that the acceleration amplification effect is nonlinear with the height under the earthquake action. The critical location of the equipment is bottom insulator. He Chang evaluated and optimized the seismic performance of ±800 kV UHVDC filter capacitor[12]. Through the analysis on the coefficients of the pretension force and installation angles of bottom insulators, It is concluded that the seismic responses can be reduced by optimizing the pretension force in insulators and the installation angles of bottom insulators. Liao Bin calculated the seismic response of UHVDC filter capacitor bank tower by finite element method (FEM)[13]. Measures to improve the seismic performance of capacitor bank towers, such as increasing the base area at the bottom of capacitor bank towers and improving the mechanical strength of insulators, were proposed.

In this research, the dynamic characteristics and seismic responses of UHV 1315 kV PLC/RI capacitor with multiple-column posts are simulated by FEM. After inspecting the maximum stress in different parts of the model, the most vulnerable location of the electrical equipment was identified. Additionally, the retrofitting countermeasure to reduce the seismic response is proposed, which can be employed to improve seismic performance of similar electrical equipment with multi-column posts. It is helpful for the safe operation of the whole power system.

2. Numerical simulation and seismic analysis of UHV capacitor

In the design of power transmission and transformation engineering, numerical simulation technology plays an important role. When the structural model test is impracticable for various reasons, the numerical simulation becomes an indispensable technique to check the mechanical behaviour and predict the failure of the structure. Even structural model experiment can be conducted, numerical simulation is still an important tool because it can help understand structural characteristics and guide structural design.

2.1. Finite element model of UHV PLC/RI capacitor

The reasonableness of the numerical model is directly linked to the accuracy of the analysis results, especially for electrical equipment. For the sake of reflecting the mechanical behaviour of the structure truly, proper elements should be adopted to model the structure. According to the structure drawing and relevant parameters provided by the manufacturer, the finite element model of the electrical equipment can be established. In the UHV PLC/RI capacitor, hollow composite insulators, porcelain insulators and connecting flanges are modelled by beam elements. Counterweights are modelled by mass elements. The connection plate between bottom porcelain insulators and upper hollow composite insulators is modelled by shell element. When performing finite element meshing, the unit size should be uniform and moderate to ensure sufficient calculation accuracy.

As shown in figure 1 and figure 2, the height of the UHV 1315 kV PLC/RI capacitor is about 15 meters and the weight is about 9 tons. The capacitor contains three upper hollow composite post insulators and 12 bottom porcelain insulators. Each hollow composite post insulator consists of 6 composite segments connected by metallic flange.
Figure 1. Structure of 1315 kV PLC/RI capacitor.

Figure 2. PLC/RI capacitor in UHV converter station.

The main parameters of insulators are shown in table 1. The composite insulators and porcelain insulators are connected by a steel plate. In the initial design scheme of the electrical equipment manufacturer, the thickness of the steel plate is 20 mm.

Table 1. Main parameters of insulators.

| Component                | Length(m) | Weight(kg) | Mandrel diameter(mm) | Failure stress(MPa) |
|--------------------------|-----------|------------|----------------------|--------------------|
| Single segment of composite insulator | 2.14      | 331        | 300                  | 120                |
| Porcelain insulator      | 0.45      | 56.5       | 145                  | 60                 |

Because the actual damping ratio of the capacitor is unknown, the value is taken as 2% during the modelling process according to relevant standard[14]. The finite element model is developed as shown in figure 3. Define the vertical direction as Z-direction, X-direction as the direction of the line connecting centers of the two composite insulators, and Y-direction as the direction perpendicular to X-direction and Z-direction.

Figure 3. Finite element model of PLC/RI capacitor.
2.2. Earthquake action and combination of load effects

Figure 4 shows the seismic influence coefficient curve for assessing the seismic performance of UHVDC equipment defined by reference[15]. The seismic influence coefficient curve can be expressed as follows:

\[ \alpha = \begin{cases} 
0.4\alpha_{\text{max}} & 0 \leq T < 0.03 \\
0.4 + \eta_2 - 0.4 \left( \frac{T - 0.03}{0.07} \right) \alpha_{\text{max}} & 0.03 \leq T < 0.1 \\
\eta_2 \alpha_{\text{max}} & 0.1 \leq T < T_g \\
\left( \frac{T_g}{T} \right)^\gamma \eta_2 \alpha_{\text{max}} & T_g \leq T < 5T_g \\
\left[ \eta_2 0.2^\gamma - \eta_1 (T - 5T_g) \right] \alpha_{\text{max}} & 5T_g \leq T < 6.0 
\end{cases} \]  

(1)

\[ \gamma = 0.9 + \frac{0.05 - \xi}{0.3 + 6\xi} \]  

(2)

\[ \eta_1 = 0.02 + \frac{0.05 - \xi}{4 + 32\xi} \]  

(3)

\[ \eta_2 = 1 + \frac{0.05 - \xi}{0.08 + 1.6\xi} \]  

(4)

where \( \alpha \) is seismic influence coefficient. \( \alpha_{\text{max}} \) is maximum value of seismic influence coefficient. \( T \) is natural vibration period of structure. \( \gamma \) is attenuation curve of falling section. \( \eta_1 \) is adjustment coefficient of descent slope of straight-line descent section, if less than 0. \( \eta_1 \) is adjustment coefficient of descent slope of straight-line descent section, if less than 0. \( \eta_2 \) is damping adjustment coefficient, when it is less than 0.55, it should be taken as 0.55. \( \xi \) is structural damping ratio, 0.02 in calculation.

![Figure 4. Seismic influence coefficient curve.](image)

![Figure 5. Seismic acceleration response spectrum of UHVDC equipment.](image)

When the site condition is not clear, the design characteristic period of ground motion should be taken as 0.9 s[15]. The UHV capacitor is arranged on the pedestal in converter station. If the electrical equipment is supported by the pedestal, the dynamic amplification effect of support structure should be considered[15]. Because design parameters of the support structure are not available, the dynamic amplification factor of the pedestal should be taken as 1.4[15]. In addition, the input acceleration of ground motion should be multiplied by the dynamic magnification factor of the support structure. The seismic acceleration response spectrum (PGA = 0.3 g) is constructed as shown in figure 5.
Seismic calculation of electrical equipment should combine the earthquake action effect and other load effects using the expression below[15]:

\[ S = S_{Gk} + S_{Ek} + 0.25S_{Wk} + S_{Dk} + S_{pk} \]  \hspace{1cm} (5)

where \( S \) is combination of earthquake action effect and other load effects. \( S_{Gk} \) is gravity load. \( S_{Ek} \) is earthquake action effect. \( S_{Wk} \) is wind load effect. \( S_{Dk} \) is terminal force effect. If the flexible conductor with sufficient redundancy is connected to the terminal, the terminal tension is taken as 0. \( S_{pk} \) is internal pressure effect of equipment.

In this study, \( S_{Dk} \) and \( S_{pk} \) have slightly influence on the simulation result. \( S_{Gk} \), \( S_{Ek} \) and \( S_{Wk} \) are mainly focused on. Taking environmental conditions in different regions of China into account, the basic wind pressure is conservatively selected as 766 Pa in the evaluation of the equipment response caused by wind load.

2.3. Seismic evaluation criteria

The stress generated at the critical cross-section of electrical equipment obtained by seismic analysis should satisfy the formula:

\[ F_s = \frac{\sigma_s}{\sigma_{tot}} \geq \gamma \]  \hspace{1cm} (6)

where \( F_s \) is stress safety factor. \( \sigma_{tot} \) is the total stress generated by earthquake action and other loads. \( \sigma_s \) is failure stress of equipment. \( \gamma \) is minimum safety factor, which equals to 1.67.

The main failure mode of electrical equipment during earthquake is the fracture and cracking of the post segment connecting to the flange. Therefore, the load condition of insulator root should be paid attention to in seismic assessment of conjunction with flange. The failure stress of hollow composite insulator is 120 MPa, and that of porcelain insulator is 60 MPa.

3. Simulation results and discussion

3.1. Modal analysis

The modal analysis is conducted for the finite element model of the capacitor. The first four modal shapes of the equipment are shown in figure 6. The primary frequency of the capacitor is close to the earthquake dominant frequency, and the 2nd, 3rd and 4th order frequencies are within the range of the flat segment of the seismic response spectrum.

Figure 6. First four modal shapes of the 1315 kV PLC/RI capacitor.
3.2. Seismic analysis

The mode-superposition response spectrum method is adopted in the seismic analysis of finite element model. Taking the capacitor weight and wind load into account, the maximum stresses of hollow composite insulators and porcelain insulators are calculated to estimate whether the equipment meets the seismic requirement. The combined condition described in equation (5) is applied to the finite element model of capacitor, where earthquake action and wind load are calculated in in X-direction and Y-direction respectively. Stress nephograms of capacitor insulators under the combined condition in two directions are obtained, as shown in figure 7 and figure 8 respectively.

Results indicate that the maximum stress of composite insulators and that of porcelain insulators under X-direction condition are 69.5 MPa and 74.2 MPa, respectively. Therefore, the stress safety factor of composite insulator and that of porcelain insulator calculated by formula (6) are 1.73 and 0.81, respectively. The maximum stress of composite insulators and that of porcelain insulators under Y-direction condition are 67.3 MPa and 84.6 MPa, respectively. The stress safety factor of composite insulator and that of porcelain insulator are 1.78 and 0.71, respectively. It is evident that the most fragile location is the porcelain insulator connecting with the flange. The stress of bottom porcelain insulator exceeds the allowable stress under the combined condition in the preliminary design scheme provided by the capacitor manufacturer. The preliminary design of 1315 kV PLC/RI capacitor can not meet the seismic requirement for PGA = 0.3 g.

![Figure 7. Stress distribution of insulators under X-direction condition.](image)

![Figure 8. Stress distribution of insulators under Y-direction condition.](image)
4. Retrofitting countermeasure for UHV capacitor

For improving the seismic performance of the capacitor and optimizing the structure, the retrofitting countermeasure that increasing the connection stiffness between upper hollow composite insulators and bottom porcelain insulators is proposed. The analysis results show that it is helpful for reducing the seismic response of the porcelain insulator. The thickness of the connecting plate between the upper hollow composite insulators and the porcelain insulators at the bottom of capacitor was increased from 20 mm to 50 mm. After the optimization, stress nephograms of insulators under the combined condition in X-direction and Y-direction are obtained by finite element analysis, as shown in figure 9 and Figure 10 respectively.

The maximum stress of composite insulators and that of porcelain insulators under X-direction condition are 70.3 MPa and 28.9 MPa, respectively. Therefore, the stress safety factor of composite insulator and that of porcelain insulator are 1.71 and 2.08, respectively. The maximum stress of composite insulators and that of porcelain insulators under Y-direction condition are 71.8 MPa and 34.8 MPa, respectively. The stress safety factor of composite insulator and that of porcelain insulator are 1.67 and 1.72, respectively. The retrofit 1315 kV PLC/RI capacitor satisfies the seismic requirement for PGA = 0.3 g.

![Figure 9. Stress distribution of insulators under X-direction condition after retrofitting.](image)

![Figure 10. Stress distribution of insulators under Y-direction condition.](image)
5. Conclusions
In this paper, a finite element model of 1315 kV PLC/RI capacitor with multi-column posts was established. The modal analysis and seismic analysis were carried out. To solve the problem that the stress safety factor of the porcelain insulator at the bottom of the capacitor does not meet the seismic requirement in the preliminary design scheme, the retrofitting countermeasure was proposed. Following conclusions are achieved.

1) The primary frequency of the capacitor is close to the earthquake dominant frequency. Additionally, the 2nd, 3rd and 4th order frequencies are within the range of the flat segment of the seismic response spectrum.

2) The finite element simulation results show that the most fragile location is the porcelain insulator connecting with the flange at the bottom of the capacitor. Under the combined condition, the minimum stress safety factors of porcelain insulators are 0.81 and 0.71 in X-direction and Y-direction respectively, which are both less than 1.67. It indicates that the preliminary design of 1315 kV PLC/RI capacitor can not meet the seismic requirement for PGA = 0.3 g.

3) To optimize the seismic performance of the capacitor, the connection rigidity of the upper hollow composite insulator and the bottom porcelain insulator is improved by increasing the thickness of the connecting plate from 20mm to 50mm. The minimum stress safety factors of porcelain insulators are increased to 2.08 and 1.72 in X-direction and Y-direction, respectively. The retrofit 1315 kV PLC/RI capacitor satisfies the seismic requirement for PGA = 0.3 g.

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