Seismic Optimization Study of Substation Bus-Bar Connecting Circuit

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Abstract. Bus-bar is an important power transmission channel in substation. To improve the safety performance of bus under the action of earthquake, the finite element simulation calculation is carried out for the bus-bar circuit in UHV substation. And this study analyzes the influence of structural design parameters such as tube bus layout and bracket span on earthquake response of pillar insulator in the circuit. The results show that the seismic performance of the bus-bar connecting circuit can be optimized by using independent tubular bus layout for each span, increasing insulator support and reducing the span of single tubular bus.

Keyword. Bus-bar connecting circuit, seismic, substation, stress.

1. Introduction

As an important part of the lifeline project, once the power system is damaged, it will cause serious disasters and immeasurable economic losses [1-3]. Power interruption not only affects normal production and living and earthquake relief work seriously, but may also lead to fire and other secondary disasters, and it will even seriously threaten people's lives and property safety [4-5]. The seismic data at home and abroad show that the vulnerability of electrical facilities in substations are extremely high. Since the mid-1960s, seismic disasters in power systems have been reported in almost every strong earthquake disaster. Typical are the 1964 Niigata earthquake in Japan, the 1968 Tokachi-Oki earthquake in Japan, the 1976 Tangshan earthquake in China, the 1985 Mexico earthquake, the 1989 Loma Prieta earthquake in the U.S., the 1995 Hanshin earthquake in Japan, the 1999 Jiji earthquake in Taiwan, China, and on May 12, 2008, the devastating earthquake of magnitude 8 occurred in Wenchuan County, Sichuan Province, China and etc, all of these earthquakes have caused huge casualties and property damage [6-9].

In the electric power system, the bus-bar connects the current-carrying branch circuits in the power distribution device. It plays the role of collecting, distributing and transmitting electrical energy. The bus-bar is also a total conductor used for power transmission in the substation, which has an extremely important role. In this paper, by using the multi-scheme comparison analysis of the layout form of tube bus-bar and the layout change of bracket span, the seismic analysis of the bus-bar bridge circuit in the UHV substation is carried out. And this paper proposes an optimized scheme with better seismic performance, which provides technical support for the seismic design of the substation.

2. Electrical Equipment Structure

The electrical equipment with insulation support in the bus-bar connecting circuit are all 110 kV post insulators. The equipment is a section solid ceramic column structure, the outer diameter of the ceramic column is 165 mm, the total height is 1.5 m, and the total weight of the equipment is 218 kg.
Table 1 lists the structural parameters of the equipment, and figure 1 shows the equipment outline. According to the structural parameters of the equipment, a finite element model of the equipment is established in ANSYS finite element software (as shown in figure 2), and table 2 shows the frequency calculation results of the first 6 orders of the equipment structure.

### Table 1. Structural parameters of the equipment.

| Modulus of elasticity/ Pa | Poisson’s ratio | Breakdown stress/ MPa | Outside diameter/ mm | Weight/ kg | Total height/ m |
|--------------------------|----------------|-----------------------|---------------------|-----------|----------------|
| 1.1×10¹¹                  | 0.17           | 60                    | 165                 | 218       | 1.50           |

### Table 2. Calculation results for the first 6 frequencies of the device.

| Order of precedence | 1     | 2     | 3     | 4     | 5     | 6     |
|---------------------|-------|-------|-------|-------|-------|-------|
| Frequency/Hz        | 33.23 | 219.56| 401.27| 610.5 | 643.84| 1150.60|

3. Seismic Calculations for Monomer Equipment Members

According to The Code for Seismic Design of Electric Power Facilities (GB50260-2013) [10], the following equation is used for the combination of earthquake action and other loads.

\[ Z = Z_{Ge} + Z_{Eh} + 0.25Z_{Wk} + Z_{Pk} \]  \( (1) \)

In this equation: \( Z \) — the combination of seismic action and other loads, \( N; \) \( Z_{Ge} \) — the standard equipment deadweight, \( N; \) \( Z_{Eh} \) — the standard seismic action, \( N; \) \( Z_{Wk} \) — the standard wind load, based on the once-in-a-century local wind speed in the area where the equipment is applied, \( N; \) \( Z_{Pk} \) — Other loads such as standard pressure inside the equipment, actual wire tension, etc., \( N. \) The Code for Seismic Design of Electric Power Facilities (GB50260-2013) recommends the response spectrum of electrical equipment for seismic analysis, and the response spectrum curve is shown in figure 3.

With the seismic response spectrum of Acceleration is 0.4 g, when the Peak Ground Acceleration (PGA) is input to the pillar insulator equipment, the maximum stress value and displacement value of the equipment are calculated by simulation as 2.22 MPa and 0.3 mm, respectively. The calculated stress nephogram is shown in figure 4.
$Z_{Gz} = 0.09 \text{ MPa}$ is calculated by the finite element model; As the wind speed is 29 m/s and the corresponding basic wind pressure is 0.53 kN/m$^2$, $Z_{Wk} = 0.64 \text{ MPa}$; According to the use of the 110KV insulator, the horizontal and vertical wire loads are 1000N, 500N respectively, and the vertical load is 500 N, $Z_{Wk} = 3.26 \text{ MPa}$ is calculated. On the basis of the equation (1), the combined stress is 5.73 MPa and the top displacement of the equipment is 0.7 mm.

![Figure 3. Artificial wave response spectrum.](image)

![Figure 4. Stress nephogram of 110 KV column insulator equipment.](image)

4. **Bus-bar Connecting Circuit Analysis**

According to the design requirements of the substation circuit, the 110KV bus-bar connecting pillar insulator equipment is connected in the form of П-type bracket structure. It uses 4 insulators arranged in the form of A-phase, B-phase, C-phase and Zero-phase electrical function lines, and brackets as shown in figure 5. We set the direction along the tube bus-bar as X direction, the direction of parallel arrangement of equipment as Y direction, and the vertical direction of equipment as Z direction. The bus-bar is an aluminium alloy hard tubular bus, the elastic modulus of the material is 70 GPa, the yield strength is 260 MPa, the outside diameter of the tube base section is 170 mm, and the wall thickness is 7 mm.
There are three layout forms of the circuit along the direction of the hard tube bus. The total length of the circuit is 54 m. The upper support of the insulators in the same phase in layout 1 has two tube stems, one of which is arranged within the range of two-span supports (12 m+10.5 m), and the other is arranged within the range of three-span supports (11 m+11 m+9.5 m). The armour clamp is connected with the upper end of insulator and the bus-bar, which is a bracket form. Two bus-bars are respectively fixed at both ends of the bracket on the upper end of the common insulator fittings, in which the armour clamp is connected by a flexible wire to two tubular buses; In layout 2 and layout 3, the same phase insulator on the upper support of the tubular buses for each span are independent of the tubular buses, in which the spacing of each span is 12 m+10.5 m+11 m+11 m+9.5 m in layout 2 and 11 m+11 m+11 m+9.5 m in layout 3. The finite element model is shown in figure 6, and the first 6 orders of frequencies of the overall structure of each layout are shown in table 3. The fundamental frequency range is 1.19~1.52 Hz, which is within the resonant frequency range of ground shaking. It belongs to the sensitive structure system of seismic action.

| Layout type | Frequency/Hz |
|-------------|--------------|
|              | 1<sup>st</sup> order | 2<sup>nd</sup> order | 3<sup>rd</sup> order | 4<sup>th</sup> order | 5<sup>th</sup> order | 6<sup>th</sup> order |
| Layout 1    | 1.19          | 1.25          | 1.98          | 2.07          | 2.15          | 2.18          |
| Layout 2    | 1.43          | 1.52          | 1.65          | 1.75          | 1.80          | 2.09          |
| Layout 3    | 1.52          | 1.65          | 1.68          | 1.79          | 1.82          | 1.90          |

Figure 5. Π-type bus-bar connecting support.

Figure 6. Finite element model of the overall structure of Loop.

Table 3. Frequency of the first 6 orders of the overall structure of the bus-bar connecting circuit.
4.1. Calculation of Earthquake Effects

In the finite element model, the X direction and Y direction seismic response are respectively calculated, and the stress and displacement results of the equipment on the overall structure under the action of PGA=0.4 g are shown in table 4. The stress nephogram of the equipment in the circuit is shown in figure 7.

Table 4. Seismic calculation of the overall structure of the bus-bar connecting circuit.

| Disposition structure | Seismic directions | Maximum displacement on top of equipment/mm | Tubular bus max stress/MPa | Maximum equipment stress/MPa |
|-----------------------|--------------------|--------------------------------------------|---------------------------|----------------------------|
| Layout 1              | X                  | 44.6                                      | 22.21                     | 21.64                      |
|                       | Y                  | 245.9                                     | 112.32                    | 31.04                      |
| Layout 2              | X                  | 44.8                                      | 18.81                     | 21.51                      |
|                       | Y                  | 177.6                                     | 60.71                     | 28.91                      |
| Layout 3              | X                  | 40.3                                      | 15.94                     | 21.03                      |
|                       | Y                  | 140.7                                     | 60.21                     | 27.43                      |

As table 4 shows, the maximum stress of aluminium tubular bus is 112.32 MPa under different conditions. It much less than the yield strength of aluminium alloy, which will not lead to material strength failure; Under the earthquake load of X direction, the maximum stress of layout 1, layout 2 and layout 3 structure increases 8.75 times, 8.69 times and 8.47 times, respectively, higher than the maximum stress of the monomer equipment; Under the seismic load of Y direction, the maximum stresses of layout 1, layout 2, and layout 3 structures are 12.98, 12.02, and 11.36 times higher than the maximum stresses of the monomer equipment, respectively.

(a) X direction of earthquake. (b) Y direction of earthquake.

Figure 7. The stress nephogram of overall structural equipment in the bus-bar connecting circuit (Layout 1)

4.2. Earthquake Portfolio Effects

The load combination is carried out according to equation (1), and the calculation results are shown in table 5. The calculation results show that the seismic action in Y direction is greater than that in X direction in each circuit layout. Under the combined load in X direction, the maximum stress of layout 1, layout 2 and layout 3 structures are 3.40 times, 3.38 times and 3 times higher than those of monomer equipment respectively. Under the action of Y direction combined load, the maximum stress of layout 1 structure, layout 2 structure and layout 3 structure are 5.04 times, 4.67 times and 4.41 times higher than those of monomer equipment.
Table 5. Statistics of circuit seismic calculation

| Disposition structure | Seismic directions | The max displacement of tubular bus /mm | Combined stress/MPa |
|-----------------------|-------------------|----------------------------------------|--------------------|
| Layout 1              | X                 | 64.3                                   | 25.22              |
|                       | Y                 | 252.1                                  | 34.62              |
| Layout 2              | X                 | 56.5                                   | 25.09              |
|                       | Y                 | 193.4                                  | 32.49              |
| Layout 3              | X                 | 43.7                                   | 24.61              |
|                       | Y                 | 142.1                                  | 31.01              |

(a) Maximum combined stress. (b) Maximum displacement on top of insulator.

Figure 8. Bus-bar connecting circuit overall structural equipment.

Figure 8 shows the comparison of stress and displacement responses of three circuit layouts. It can be seen that layout 1 is the largest in two earthquake response indexes and layout 3 is the smallest in two earthquake response indexes. Compared with layout 1, the stress and displacement of layout 2 are reduced by 23.28% and 6.15%. For the common and independent bus arrangement, the maximum stress of the equipment appears on the insulators at different positions, and the seismic performance of each span is better by using the layout of independent tubular bus. Layout 3 compared with layout 2 in the stress and displacement reduced by 26.53% and 4.56%. After increasing insulator support, and reducing the span of single tubular bus, the layout 3 structure has better seismic performance than before. The ratio of Y direction combined stresses to X direction combined stresses ranges from 1.26 to 1.37.

5. Conclusion

Based on the finite element seismic analysis of 110 kV pillar insulator equipment and its bus circuit, the following conclusions are drawn:

(1) In terms of dynamic characteristics, the fundamental frequency of the monomer 110 kV pillar insulator is 33.23 Hz. While the fundamental frequency range of the three layout structure loops is 1.19~1.52 Hz, which is within the resonant frequency range of ground shaking. It belongs to the earthquake sensitive structure system.

(2) Due to the influence of brackets and tubular bus, the earthquake response of the pillar insulator in the circuit is significantly greater than the earthquake response of the equipment monomer. And the stress increases to a range of 3.29~5.04 times. The bus-bar connecting circuit has the largest response under Y direction seismic action.
(3) The seismic optimization method of bus-bar connecting circuit can adopt the methods of using independent tubular bus arrangement for each span, increasing insulator support and reducing the span of single tubular bus.

The seismic performance of the bus-bar connecting circuit can be optimized by using independent tubular bus layout for each span, increasing insulator support and reducing the span of single tubular bus.

Acknowledgments
This research is supported by Innovation Fund Project of China Electric Power Research Institute (5242001900F0).

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