Simulation analysis of the seismic performance of electrical equipment by redundant length of flexible conductors in interconnected circuits

Zhenlin Liu*, Yuhan Sun and Po Gao
China Electric Power Research Institute, Beijing 100055, China
*Corresponding author’s e-mail: liuzhenlin@epri.sgcc.com.cn

Abstract. The interconnection circuit of composite pillar insulators with five different redundant lengths of flexible conductors is established, and the simulation analysis of seismic effects is carried out to study the effect of flexible conductors on the seismic performance of electrical equipment when they are used in the interconnection circuit of electrical equipment. Numerical simulation results are used to analyze the changes in the stress and displacement response of pillar insulators when the redundant length of flexible conductors is varied, and the seismic response law of electrical equipment in the interconnection circuit connected by flexible conductors is obtained, which provides a reference for the seismic design of electrical equipment circuit.

1. Introduction
With the continuous and rapid development of economic construction, the demand for energy is also growing. However, the characteristics of energy distribution have contributed to the significant development of grid technologies for high-voltage and long-distance transmission. Due to high voltage requirements for ground insulation spacing, substations are equipped with a large number of pillar-type electrical equipment, which are seismically sensitive electrical equipment with thin and high structure. In China’s Wenchuan and Ya’an substation earthquake damage investigation [1], the damage of pillar electrical equipment is serious, mainly due to the slim and high structure of the pillar electrical equipment. The insulating and supporting materials of traditional electrical equipment are electro-ceramic materials with low destructive strength, in addition to the unfavorable response to the pulling action of busbars in electrical equipment circuits in substations, etc. all make the pillars of electrical equipment seismic vulnerability higher [2]. With the development of new material technology, glass fiber composites with higher material strength and better insulation properties are used in various types of electrical equipment.

Foreign scholars and research institutions in various countries have conducted partial studies on the mechanical and seismic performance of composite electrical equipment and the seismic performance of the flexible wire connection circuit [3-7]. They proposed the force state and seismic test methods and requirements of composite materials, and the design guidelines of the flexible wire connection circuit. However, the research results of the flexible conductor circuit mainly focused on the seismic performance of the flexible conductor circuit of porcelain electrical equipment. Compared with porcelain electrical equipment, composite electrical equipment is more flexible in structural rigidity and more sensitive to flexible conductors. When electrical equipment is connected to the circuit system through wires or tube mothers, the electrical equipment in the interconnected loops have
coupling effects due to asynchronous displacements caused by differences in their own structural dynamic characteristics, and the overall dynamic characteristics of the loop system change under the action of earthquakes. As a result of the relative displacement of the devices in the interconnected loop system, a compressive force is generated on the connecting bus, and the bottom of the equipment is not only subjected to its own seismic load, but also to the load generated by the tensile pressure of the busbar, thus changing the structural response of the equipment under seismic action.

This paper establishes a circuit model of ultra-high voltage composite pillar insulators connected by five redundant lengths of flexible conductors, analyzes the electrical equipment in the circuit under seismic wave excitation, conducts a comparative study of frequency, stress and displacement response, and analyzes the effects of peak acceleration, ground shaking excitation direction, and redundant length of flexible conductors on the seismic performance of the interconnected circuits of composite electrical equipment.

2. Composite pillar insulator circuit with flexible conductor connection

In order to analyze the effect of flexible wires on different devices, two different sizes of device structures are used in the analysis. The structural parameters of ultra-high voltage composite pillar insulators are shown in Table 1, the structural difference between the two composite pillar insulators is obvious, for the convenience of subsequent presentation, FZSPW1-800 composite pillar insulators are abbreviated as “CI2” and FZSPW1-800 composite pillar insulators are abbreviated as “CI5”.

| Model number | Nodes | Height (m) | Inner/outer diameter (mm) | Weight (kg) | Modulus of elasticity (GPa) | Maximum mechanical load stress (MPa) |
|--------------|-------|------------|------------------------|------------|--------------------------|-------------------------------|
| FZSPW1-800   | 2     | 12.15      | 311/358               | 1234       | 30                       | 80                             |
| FZMW4-800    | 5     | 12.27      | 0/280                 | 2300       | 25                       | 120                            |

According to the arrangement of the pillar insulators in the DC filter circuit of a converter station project (shown in Figure 1), the height and span of the loop equipment are 16.1 m and 11.5 m, among which the support structure is lattice type. The bottom of the support root opening is 1.2 m × 1.2 m, the top root opening is 0.8 m × 0.8 m, the size of the main material is Ø194 mm × 12 mm, and the size of the slanting and auxiliary materials is Ø83 mm × 8 mm. The loop is connected by 6-part LGKK-600 flexible conductors, which are steel-core aluminum stranded wires, and the relevant structural parameters are shown in Table 2.

Define the X direction in the plane as the direction of the wire span, the Y direction as the vertical X direction in the plane, and the Z direction as the vertical horizontal plane. Based on the structural parameters of the devices, the ANSYS finite element model of the two devices with brackets is established. Dynamic characteristic analysis yielded a base frequency of 1.11 Hz for CI2 device monoblocks and 0.65 Hz for CI5 device monoblocks. The former is more rigid.

Five soft wire redundancy length loop models and the finite element model is shown in Figure 2, where model_1 model wire redundancy length is 0 m, model_2 model wire redundancy length is 0.2 m and the redundant length of the model_3, model_4 and model_5 wires are 0.4 m, 0.8 m and 1.1 m respectively. The total mass of the five models of flexible conductors ranged from 185.96 kg to 219.91 kg. Referring to the engineering experience, a spacer is arranged every 2m ~ 3m to ensure the parallel distribution of each conductor.
Figure 1 Circuit of composite pillar insulators with flexible conductor connection

![Figure 1](image1)

**Tab.2 Configuration parameters of bus**

| Outside diameter of the conductor (mm) | cross-sectional area (mm²) | Tensile strength (kN) | Mass (kg/km) | Modulus of elasticity (GPa) |
|----------------------------------------|---------------------------|-----------------------|--------------|-----------------------------|
|                                        | aluminum                  | steel                 |              |                             |
|                                        | 51                        | 586.69                | 49.48        | 143.67                      | 2690                        | 65.50                        |

Figure 2 Finite element model of a flexible wire connection circuit

![Figure 2](image2)

3. **Seismic response analysis**

The seismic wave input for the seismic calculation is shown in Figure 3, which has a superior frequency of 1Hz to 10Hz and can cover most of the site conditions in China, so the analysis results have good generality. The peak ground acceleration (PGA) input in the calculation is 0.1g, 0.2g, 0.3g and 0.4g. The seismic response in X direction and Y direction is calculated respectively.

![Figure 3](image3)

Figure 3 Time History Wave of Ground Motion
Seismic calculations show that the maximum stress of both devices in the circuit occurs at the root of the lowermost insulator, and the maximum stress trend of the devices obtained from five redundant lengths of flexible conductors is shown in Figures 4 and 5. As can be seen from the figure, the stress response of CI2 is greater in the X direction than in the Y direction under seismic action, and the seismic stress response in both directions decreases with increasing length of wire redundancy, where the X-direction decreasing trend gradually increases, while the Y-direction decreasing trend is not obvious; The stress response of CI5 under X-direction seismic action is smaller than that of Y-direction, where the X-direction seismic response increases with the increase of wire redundancy length, and the Y-direction stress results do not differ much under each redundancy length of the flexible wire.

Figure 4 Comparison of CI2 stress results

Figure 5 Comparison of CI2 stress results

The displacement results of the equipment obtained from the simulation analysis are shown in Figure 6 and Figure 7. It can be seen that the displacement response of CI2 under the action of the earthquake in the X direction is larger than that in the Y direction, and the seismic displacement response in both directions decreases with the increasing length of wire redundancy, where the X-directional decrease tends to increase gradually, while the Y-directional decrease tends to be insignificant; The displacement response of CI5 under X-direction seismic action is smaller than that of Y-direction, where the X-direction seismic response increases with the increase of wire redundancy length, and the Y-direction stress results do not differ much in each redundancy length of the flexible wire.
It can be seen from the results of stress and displacement that CI2 has a larger seismic response in the X-direction after the interconnection circuit is connected by soft wires, and is obviously influenced by the change of wire redundancy length; CI5 has a larger response in the Y direction, but its X-directional seismic response is significantly influenced by the change of wire redundancy length.

According to the results of the above analysis, the wire redundancy length has some influence on the seismic response of the interconnected equipment. Increasing the length of wire redundancy can help interconnect equipment seismic performance, but continue to increase the length of soft wire redundancy will not significantly improve the seismic performance, and will reduce the height of the wire to ground. The increased length of wire redundancy affects its height to ground, thus requiring an increase in the height of the equipment rack, which will also adversely affect the seismic resistance of the equipment.

4. Conclusion
In this paper, a comparative study of the seismic response of different flexible conductor redundant length connection schemes is carried out through a simulation analysis of flexible conductor connection loops for composite pillar insulators and the following main conclusions were drawn:

(1) The maximum stress of the equipment in the interconnection circuit under the action of earthquake appears at the root of the lowermost insulator, and the seismic response of the equipment basically changes linearly with the size of the earthquake.
（2）Through the results of stress and displacement, it can be seen that after the interconnection circuit is connected with soft wires, the seismic response of the equipment with large rigidity is larger in the X-direction, and is obviously influenced by the change of wire redundancy length. Seismic response decreases with increasing redundancy length; The Y-direction seismic response of equipment with small stiffness is larger, but the X-direction seismic is obviously influenced by the change of wire redundancy length, and the seismic response increases with the increase of redundancy length.

（3）The length of wire redundancy has a certain influence on the seismic response of interconnected equipment, and increasing the length of wire redundancy can help the seismic performance of interconnected equipment. However, it is necessary to pay attention to the height of the conductor to ground requirements, and select appropriate redundant length design scheme according to the requirements of comprehensive seismic and electrical functions.

Acknowledgments
Supported by National Key R&D Program of China(2018YFC0809400).

References
[1] Cheng Yongfeng, Zhu Quanjun, Lu Zhicheng. Progress and development trend on seismic measures of electric power equipments in transformer substation[J]. Power System Technology, 2008,32(22):84-89.
[2] XIE Qiang, WANG Yafei. Shake-table Test on Earthquake Simulation of Substation Equipment Interconnected by Flexible Bus[J]. Proceedings of the CSEE, 2011,31(4):112-118.
[3] Dastous J B, Filiatrault A, Pierre J R. Estimation of displacement at interconnection points of substation equipment subjected to earthquake[J]. IEEE Transactions on Power Delivery, 2004,19(2):618-628.
[4] Bhuyan G S, Zhai E, Ghalibafian H, et al. Seismic behavior of flexible conductors connecting substation equipment, part II: shake table test[J]. IEEE Transactions on Power Delivery[J]. IEEE Transactions on Power Delivery, 2004,19(4):1680-1687.
[5] Philippe Bonhote, Thomas Gmür, John Botis, Konstantin O Papailiou. Stress and damage analysis of composite–aluminium joints used in electrical insulators subject to traction and bending[J]. Composite Structures 64 (2004) 359-367.
[6] Song J, Kiure A D, Sackman J L. Seismic interaction in electrical substation equipment connected by non-linear rigid bus conductors[J]. Earthquake Engineering and Structural Dynamics,2007,36(2):167-190.
[7] Hwasung Roh, Nicholas D Oliveto, Andrei M Reinhorn. Experimental test and modeling of hollow-core composite insulators[J]. Nonlinear Dyn. 2012, 69: 1651-1663.