Seismic Vulnerability Analysis of the High-end Suspended Converter Valve Hall Circuit in the ±800kV Converter Station

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Abstract. Suspended converter valve hall circuit is a crucial subsystem within the UHV converter station. It is characterized by electrical equipment possessing attributes of "high, large, heavy, and flexible," making them prone to seismic-induced damage. In order to evaluate the seismic performance and vulnerability of the equipment within this circuit environment, this study establishes a refined finite element model for the high-end valve hall circuit of a specific 800kV converter station. Through time-history response analysis, the seismic response characteristics and potential failure modes under seismic action are investigated. Utilizing Multiple stripe analysis method, seismic vulnerability curves for each failure mode as well as the overall circuit are obtained. A comparative analysis is conducted between the overall circuit vulnerability curve and the circuit vulnerability curve considering each equipment failure as an independent event. This study serves as a reference for seismic reinforcement of critical equipment in existing converter stations at the circuit level, establishing the groundwork for evaluating the seismic resilience of converter stations. The results indicate that the base frequency of the converter valve tower in the valve hall is relatively low, leading to excessive bottom displacement response under seismic action. Moreover, significant stress responses are observed in the electrical component support structures, post insulators, and 800kV wall bushings within the valve tower layers under seismic action. Failure modes of the high-end valve hall circuit include relative displacement of adjacent converter valve tower bases, exceeding stress limits in electrical component support structures within the layers, as well as exceeding stress limits at the bottom of post insulators and 800kV wall bushings. Furthermore, the failures of each equipment are correlated, and treating equipment failures as independent events would greatly overestimate the vulnerability of the circuit.

Keywords: High-end suspended converter valve hall circuit; Suspended converter valve; Finite element; Seismic vulnerability; Multiple stripe analysis

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1 INTRODUCTION

Converter stations are a unique type of substation in DC power transmission engineering, where the converter valve tower serves as a crucial and expensive equipment enabling the conversion between AC and DC currents.

Protecting the converter valve and the entire converter valve hall circuit from damage during earthquakes and maintaining their electrical performance effectively ensures the safety of the power system, which has significant economic value. Currently, in UHV converter stations, slender tension insulators are commonly used to hang from the roof of the converter valve hall to reduce their seismic impact.

Due to the limited number of HVDC transmission projects worldwide, there have been few cases of converter stations being damaged by strong earthquakes. In 1994, the Sylmar converter station was struck by an earthquake, resulting in the failure of a large number of electrical equipment. Millions of dollars' worth of electrical equipment were damaged, including suspended converter valves, resulting in the largest single economic loss[1].

In recent years, many scholars have conducted research on the seismic performance of converter valves, focusing primarily on their dynamic characteristics and weak points. In 2011, Wu Xiaofeng[2] conducted a modal analysis of the converter valve and found that it mainly exhibits horizontal and torsional vibration modes. Additionally, both the insulator axial force and the interlayer bolts were found to meet seismic requirements. In 2016, research by Yang Zhenyu[3] also found that under seismic action, the horizontal displacement at the bottom of the valve tower is significant, with responses exceeding 1 meter. Additionally, the nonlinear characteristics of insulators result in severe vertical acceleration responses of the valve tower, causing the valve layers to exhibit "bouncing" phenomena. The study suggests that the valve tower faces issues of excessive displacement and significant vertical acceleration responses, which need to be taken into consideration. In 2018, Jinxiao[4] compared and analyzed the seismic response of the converter valve excited by three different periodic characteristics. It is found that under the action of the long-period seismic wave synthesized in this paper, the swing and stress of the suspended converter valve are larger. Furthermore, in 2020, Xu Junxin[5] et al found through analysis of the seismic performance of the converter valve hall circuit that the horizontal acceleration response of the valve tower in the overall model has decreased, but the horizontal displacement response remains significant.

As a suspended structure, the converter valve may experience significant horizontal displacement during seismic events. Insufficient redundancy in the wiring connections between the converter valve and other equipment could result in damage to the other devices. In previous earthquakes, damage caused by pulling between devices has been observed multiple times. This includes instances such as breakers being pulled apart by adjacent current transformers during the 2003 Bam earthquake in Iran[6] and damage caused by insufficient wiring redundancy during the Wenchuan earthquake[7]. Consequently, under the coupling of various equipment in the valve chamber, there may be significant differences in seismic response compared to individual devices.

Previous research has shown significant seismic responses of converter valves in both horizontal and vertical directions under seismic loading. Circuit coupling has a notable impact on the acceleration response of converter valve towers, which could potentially result in the tensile failure of electrical equipment. However, the converter valve apparatus, characterized by a multi-layer suspended configuration, presents a complex internal structure. Further investigation into the failure modes of valve towers under seismic conditions is necessary. Additionally, the complex interconnections among equipment in the converter valve hall circuit, combined with the numerous devices involved, have led to a lack of studies focusing on the seismic resilience of individual devices while considering their interactions within the converter valve hall circuit. Moreover, there is a significant gap in the seismic vulnerability analysis of individual devices within the converter valve hall circuit, both domestically and internationally.

To address these deficiencies and gaps, this study utilizes a case study of a ±800kV ultra-high voltage converter station's high-end valve hall circuit. A detailed finite element model of the entire circuit is developed using ABAQUS software. The seismic performance of each device is assessed using the seismic response time-history method to identify vulnerable locations and potential failure modes within the high-end valve hall circuit. Leveraging Baker's[8] multiple stripe vulnerability analysis method, this study conducts seismic vulnerability analyses of individual devices within the high-end valve hall circuit. It also compares the overall seismic vulnerability of the circuit using the exceedance probability calculation method and a defined calculation method. The aim is to provide insights to enhance the seismic resilience of power systems and facilitate seismic risk assessment efforts.

2 SEISMIC RESPONSE ANALYSIS OF ±800KV HIGH-END CONVERTER VALVE HALL

2.1 Introduction to the Structure of ±800kv High-end Converter Valve Hall

This section focuses on the high-end valve hall circuit of a certain ±800kV converter station, as shown in Figure 1. And the actual converter valve is shown in Figure 2. The main equipment includes: 800kV converter valves, 600kV converter valves, surge arresters, 800kV independent wall bushings, 400kV independent wall bushings, and post insulators inside the valve hall. The valve hall is composed of steel roof trusses and steel rack columns. There are three sets of 800kV converter valves and three sets of 600kV converter valves, with a total of six sets of valve towers and surge arresters suspended on steel frames attached to the valve hall roof trusses using suspension insulators. They are interconnected with wall bushings, converter transformers, other equipment, post insulators inside the valve hall, and flexible conductors to form a coupled circuit.

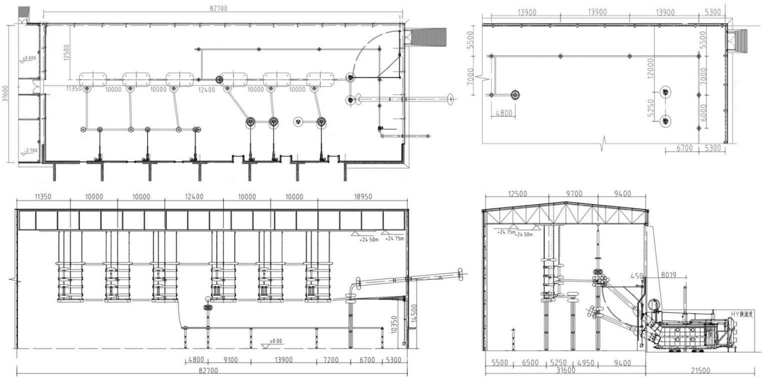

Fig. 1. High-end converter valve hall circuit overall layout and cross-sectional diagram.

Fig. 2. 800kV UHV converter valve

2.2 Finite Element Model and Dynamic Characteristics Analysis

In this paper, the finite element model of the high-end valve hall circuit is established using ABAQUS finite element software. In the model, the shielding cover of the valve layer in the converter valve tower is modeled using S4R shell elements, electrical components inside the valve layer are modeled using C3D8R solid elements, electrical component support structures, connections between valve layers, and top connection insulators are modeled using B31 beam elements, while the valve hall and other equipment inside the valve hall are modeled using B31 beam elements.

The damping ratio of the finite element model for the high-end valve hall circuit is set to 2%. The finite element model and equipment numbering of the high-end valve hall circuit are shown in Figure 3. Modal analysis is conducted, and Table 1 lists the main modes and frequencies of the high-end valve hall circuit model.

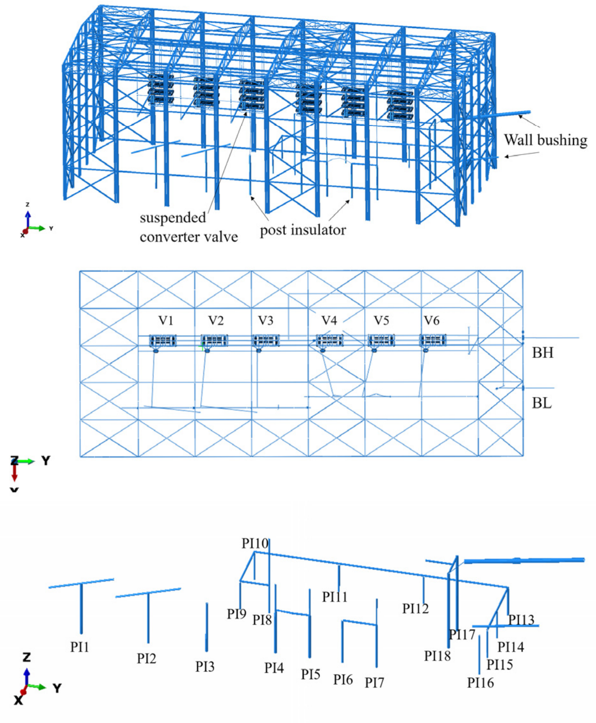

Fig. 3. FE model of high voltage sidevalve hall circuit

The modal analysis results of the finite element model of this converter valve hall circuit indicate that the frequency range of the first to seventh mode shapes of the overall model is 0.146-0.173Hz, which may result in significant displacement response during earthquakes. The large displacement response of the valve tower may lead to insufficient air clearance between the valve tower and the sidewall of the valve hall, causing air breakdown, as well as excessive relative displacement between adjacent valve towers, leading to connector damage and excessive tension damage to other connected equipment such as post insulators. The frequency range of the 155th to 261st mode shapes is 2.320-3.402Hz, which falls within the platform segment of the specification demand spectrum (2.22-10Hz). Therefore, it is prone to cause resonance under seismic action, resulting in excessive response or even damage to 800kV wall bushings and electrical component support structures within the valve layer.

Table 1. Major mode shapes and frequencies of high voltage side valve hall circuit

Modal order	Frequency/Hz	Modal Shape
1	0.146	Valve X-axis Translation
2-6	0.147-0.161	Valve X-axis Translation
7	0.173	Valve Y-axis Translation

8	0.184	Busbar Vibration
9-14	0.186-0.223	Valve Tower Torsion
15	0.280	Valve Y-axis Translation and Torsion
16-86	0.322-1.296	Valve and Busbar Vibration
87	1.302	Insulator Support and Busbar Translation
115	1.623	Valve Hall X-axis Translation, Valve Tower Vibration
155-162	2.320-2.561	Vertical Vibration of Electrical Components in Valve Layer
165	2.600	Vibration of 800kV Wall Bushing
233-261	3.353-3.402	Vertical Vibration of Electrical Components in the Valve Layer

3 ANALYSIS OF SEISMIC RESPONSE IN THE ±800KV HIGH-END CONVERTER VALVE HALL CIRCUIT

3.1 Selection of Seismic Waves

In this paper, the site category of the converter valve hall is Class II site, the design seismic grouping is the third group, the characteristic period is 0.45 seconds, and the location is in an area with an 8-degree fortification. According to the Chinese national standard 'Code for Seismic Design of Electrical Installations,'[9] electrical facilities in important power facilities can increase the fortification intensity by 1 degree. Therefore, the basic seismic design acceleration is considered to be 0.4g.

To investigate the seismic response of the converter valve hall circuit while meeting current code requirements and considering site factors to adequately cover the demand spectrum platform, this section calculates the use of a set of artificial waves that can effectively cover the site demand spectrum. Figure 4 provides the acceleration response spectra of the site demand spectrum and artificial waves (with a damping ratio of 2%). It can be observed that the acceleration response spectrum values of the artificial waves effectively envelop the demand response spectrum. The ratio of peak ground accelerations in three directions is X:Y:Z = 1:0.85:0.65, with a peak ground acceleration of 0.4g in the X direction.

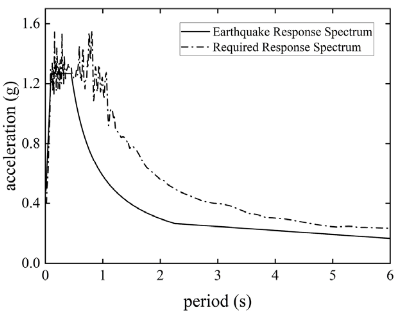

Fig. 4. Response Spectrum of Demand and Artificial Wave Acceleration Response Spectrum

3.2 Seismic Response Analysis

Under the excitation of this artificial seismic wave, the maximum values of stress response in the support components inside the valve layer, stress response at the bottom of insulator supports and bushings, axial force response at the suspension point of insulators at the top of the valve tower, relative displacement response in the X-direction between the bottom of the valve tower and the sidewall of the valve hall, and relative displacement response at the bottom of adjacent valve towers are listed in Tables 2, 3, and 4, respectively.

Table 2 presents the peak stress responses of the electrical component support structures, insulator supports, and bushings for six converter valves. The results indicate that the stress responses of the support structures inside the valve layers of all six converter valves are relatively high. Converter valve V2 has the smallest stress safety factor of 1.67, while the stress safety factors of the other converter valves are close to the specified value of 1.67. The stress responses of the electrical component support structures in the valve layers of all six converter valves are considered one of the failure modes of the circuit. The stress responses of insulator supports PI11, PI12, and PI17 inside the valve hall are 39.24 MPa, 42.20 MPa, and 43.48 MPa, respectively, significantly higher than those of the other insulator supports. Their safety factors of 1.91, 1.78, and 1.72, respectively, are close to the specified value of 1.67, suggesting that the failure of insulator supports PI11, PI12, and PI17 could be one of the failure modes of the circuit.

Table 2. Peak seismic stress responses at critical locations in the high-end valve hall circuit

Position		Stress /MPa	Ultimate Strength /MPa	Stress Safety Factor
Support Components for Electrical Equipment	V1	79.79	160	2.01
	V2	95.99		1.67
	V3	77.93		2.05
	V4	90.74		1.76
	V5	80.10		2.00
	V6	87.00		1.84
Insulator Supports	PI1	16.61	75	4.52
	PI2	16.61		4.52
	PI3	8.28		9.06
	PI4	15.84		4.73
	PI5	24.45		3.07
	PI6	9.52		7.88
	PI7	21.01		3.57
	PI8	27.62		2.72
	PI9	23.51		3.19
	PI10	27.74		2.70
	PI11	39.24		1.91
	PI12	42.20		1.78
	PI13	27.71		2.71
	PI14	20.09		3.73
	PI15	16.38		4.58
	PI16	9.38		8.00
	PI17	43.48		1.72

PI18	30.82		2.43
400kV wall bushing	13.64	71	5.21
800kV wall bushing	42.42		1.67

Table 3 provides the peak axial force responses of the suspension insulators for the six converter valves. The results show that the maximum axial force for all suspension insulators of the converter valves is 45.45kN, significantly lower than their ultimate axial force of 120kN. The safety factor for axial force is 2.64, indicating that the axial forces on the suspension insulators of all converter valves are much lower than their ultimate axial forces. Therefore, it is considered unlikely for them to fail under seismic loading and thus not considered as a failure mode of the circuit.

Table 4 provides the peak relative displacement responses in the X-direction between the bottom level of the converter valve and the sidewall of the valve hall, as well as the peak relative displacement responses between adjacent converter valves. Based on the air clearance requirements provided by the manufacturer and the distance between the sidewall of the valve hall and the converter valve, the calculated limiting relative displacement in the X-direction between the bottom level of the converter valve and the sidewall of the valve hall is 5.1m. The maximum displacement response at the bottom level of the converter valve is 2.335m, which is only 46% of the limit value, indicating that the failure mode of air clearance between the bottom level of the converter valve and the sidewall of the valve hall is unlikely to occur.

The distance between converter valve V4 and V5 is 0.291m, and the distance between converter valve V5 and V6 is 0.616m, both exceeding 0.2m. At this point, the connecting fittings are damaged, and the failure of the connecting fittings is considered one of the failure modes.

Table 3. Peak seismic axial force responses at critical locations of the high-end valve hall circuit

Position		Axial Force /kN	Ultimate Axial Force /kN	Axial Force Safety Factor
Converter Valve Suspension Insulator	V1	39.33	120	3.05
	V2	33.58		3.57
	V3	37.37		3.21
	V4	45.45		2.64
	V5	40.02		3.00
	V6	35.13		3.42

Table 4. Peak seismic displacement responses at critical locations of high-end valve hall circuit

Position		Displacement /m	Displacement Limit /m
Relative displacement in	V1	2.335	5.12
	V2	2.329	

the X-direction at the bottom level of the converter valve	V3	2.310	
	V4	1.040	
	V5	1.832	
	V6	1.328	
Relative displacement between adjacent converter valves	V1_V2	0.096	0.2
	V2_V3	0.154	
	V4_V5	0.291	
	V5_V6	0.616	

3.3 Determination of Potential Failure Modes

In the seismic response analysis of the ±800kV high-end valve hall circuit, potential failure modes were identified. These include damage to the converter valves caused by stress exceeding the limit in the support components of the valve layer's electrical elements, potential failure of insulator supports PI11, PI12, PI17 due to stress exceeding the limit at the bottom, potential failure of the 800kV bushing through wall due to stress exceeding the limit at the bottom, and potential failure of connecting fittings between the busbars of the converter valves and adjacent converter valves due to relative displacement exceeding the limit.

4 SEISMIC VULNERABILITY ANALYSIS OF ±800KV HIGH-END CONVERTER VALVE HALL CIRCUIT

4.1 Multiple Stripe Analysis

The seismic vulnerability curve describes the failure probability of a structure under seismic action as a function of PGA. Studies[8] have shown that the PGA at the occurrence of electrical equipment failure can be treated as a random variable, which approximately follows a lognormal distribution. Therefore, the failure probability can be expressed as:

$$P(IM = x) = \Phi\left(\frac{\ln x - \theta}{\beta}\right) \tag{1}$$

P(IM = x) represents the failure probability of the structure under seismic action with PGA as x, where θ is the mean and β is the standard deviation. The key issue in vulnerability analysis is to obtain the values of θ and β. In this study, a Multiple Stripe Analysis method[8] is employed. Different PGA groups are set, and a set of seismic waves is selected. The seismic waves are modulated according to the PGA of different groups, and the failure probability of the structure under each group of seismic waves is calculated, which forms the sample points. The parameters of the vulnerability curve are obtained through moment estimation methods[10], and further fitting is performed using nonlinear least squares method to obtain the values of θ and β.

4.2 Selection of Seismic Waves

This paper selects shear wave velocity to comply with Site Class II from the Pacific Earthquake Engineering Research Center (PEER) and includes a total of 32 ground motion records in three directions as ground motion inputs. These records are modulated to peak ground accelerations (PGA) of 0.2g, 0.4g, 0.6g, and 0.8g, forming four sets of ground motion records. The ratio of peak ground accelerations in the three directions is X:Y:Z = 1:0.85:0.65. Figure 5 shows the 32 ground motion acceleration response spectra and the site-specific demand response spectrum.

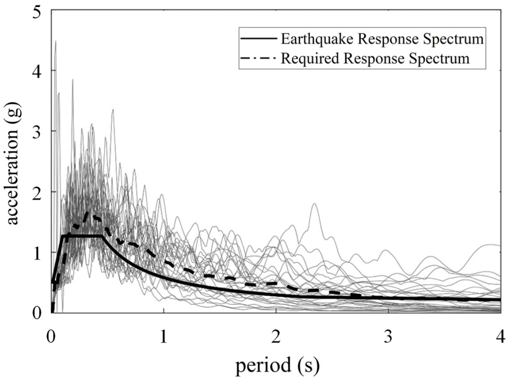

Fig. 5. Response spectra of 32 earthquake ground motions and required response spectrum

4.3 Vulnerability Analysis of High-End Valve Hall Circuit

According to the conclusion in Section 3.3, potential failure modes of the converter valve hall under seismic conditions may include: stress exceeding the limit in the support components of electrical elements inside the valve layer, stress exceeding the limit at the bottom of insulator supports, stress exceeding the limit at the bottom of the bushing through wall, and relative displacement exceeding the limit between adjacent converter valves.

Considering the safety factor in seismic design, according to the Chinese " Code for Seismic Design of Electrical Installations" (GB50260-2013)[9], the safety factor for equipment experiencing strength failure is 1.67. Therefore, the peak stress response of the support components inside the valve layer should not exceed 95.8 MPa, the stress at the bottom of insulator supports should not exceed 45 MPa, and the stress at the bottom of the bushing through wall should not exceed 42 MPa.

The busbars between adjacent converter valve bottoms are connected to the converter valve via connecting fittings. Therefore, when the relative displacement between adjacent converter valve bottoms exceeds a certain limit, it may lead to tensile failure of the connecting fittings. According to the data provided by the manufacturer, the relative displacement between adjacent converter valve bottoms should not exceed 200mm.

Using nonlinear least squares method for parameter estimation, the estimated values of θ and β for each mode type are obtained, as shown in Table 5.

Table 5. Fitted parameters of vulnerability curves

Failure Modes		Parameters	
		θ	β
Stress in Support Components	V1	-0.5778	0.2391
	V2	-0.5834	0.2657
	V3	-0.5437	0.2610
	V4	-0.7440	0.2953
	V5	-0.5570	0.2637
	V6	-0.6516	0.3050
Stress at the Bottom of Insulator Supports	PI1	-0.0736	0.4797
	PI2	-0.7109	0.4147
	PI3	-0.7266	0.4329
Relative Displacement between Adjacent Converter Valve Bottoms (Connecting Fittings)	V1_2	-0.2023	0.2677
	V2_3	-0.1686	0.4972
	V4_5	0.3068	1.1504
	V5_6	0.1783	1.0523
Stress at the Bottom of 800kV Wall Bushing		-0.7532	0.3821

Based on the parameter estimation results, the seismic vulnerability curves for the four failure modes corresponding to the two types of damage can be plotted, as shown in Figures 6 to 9. The symbols such as "Δ" in Figure 6 represent the discrete failure probabilities obtained by statistically analyzing the selected sets of seismic records.

Analyzing the overall trend of vulnerability, the bushing through wall exhibits the highest vulnerability, followed by the insulator supports, and then the connecting fittings. Figure 6 indicates that converter valve V4 has the highest vulnerability, followed by converter valve V6, while the remaining converter valves have lower vulnerability. The failure probabilities of converter valve V4 and converter valve V6 at PGA=0.4g are 28.13% and 18.75%, respectively.

Measures such as adding dampers to the suspended insulators on top of the converter valves can be implemented to reduce the vertical seismic response of the valve layer, thereby lowering the response of the support components. According to Figure 8, at PGA<0.6g, the highest vulnerability is observed in the connecting fittings V4_5 and V5_6, followed by V1_2, and V2_3 has the lowest vulnerability. The failure probabilities of fittings V1_2, V3_4, V4_5, and V5_6 at PGA=0.4g are 0.38%, 6.63%, 14.39%, and 14.91%, respectively.

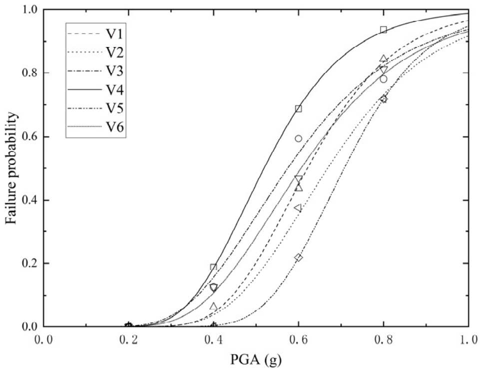

Fig. 6. vulnerability curve for the converter valves

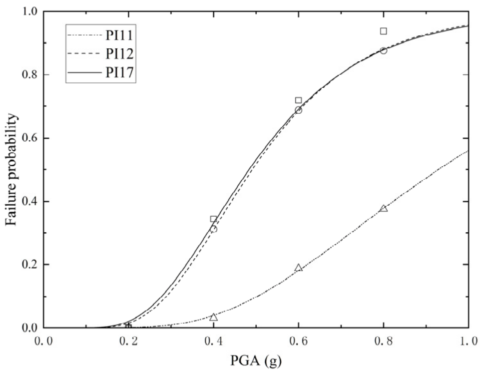

Fig. 7. vulnerability curve for the post insulator

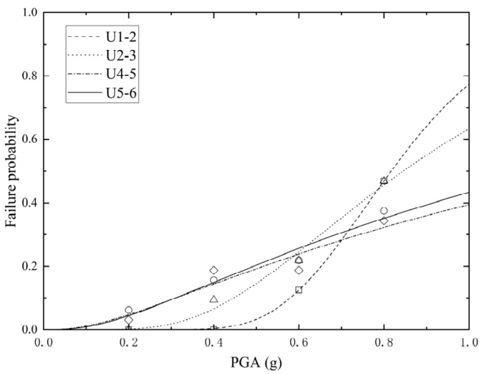

Fig. 8. vulnerability curve for the connecting fittings

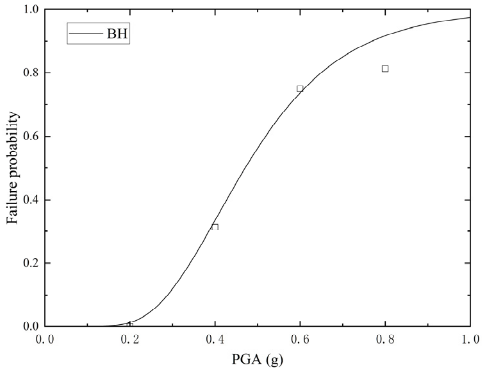

Fig. 9. Vulnerability curve for the 800kV through-wall bushing

4.4 The Vulnerability Analysis of High-End Converter Valve Hall Circuit

For the vulnerability analysis of the high-end valve hall circuit system, this paper presents two methods:

Probability Calculation Method: By calculating the vulnerability of each failure mode, the failure events at each vulnerable position are assumed to be independent of each other. It is considered that failure at any one or more vulnerable positions leads to the failure of the circuit system. The failure probability can be expressed as:

$$P(IM = x) = 1 - \prod(1 - P_i) \quad (2)$$

P_i represents the failure probability at PGA for the ith failure mode.

Definition calculation method: The high-end valve hall circuit studied in this paper considers that if any one of the failure modes reaches the failure criterion under the same seismic wave, the high-end valve hall is judged to have failed. According to this criterion, the discrete failure probabilities are calculated based on the seismic responses of each PGA grouping. Nonlinear least squares method is used for parameter estimation to obtain the seismic vulnerability curve of the high-end valve hall circuit.

Based on the parameter estimation results, the seismic vulnerability curves corresponding to the two methods for the high-end valve hall circuit can be plotted as shown in Figure 10.

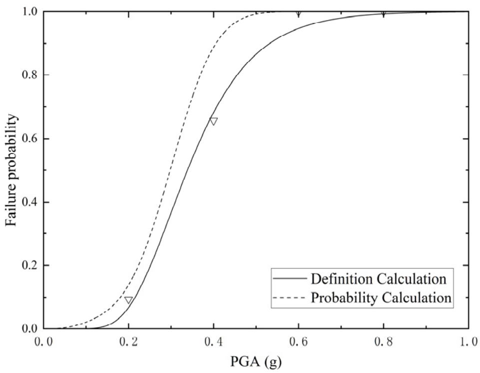

Fig. 10. High-end Valve Hall Circuit Vulnerability Curve

The probability calculation method assumes that the failure events of each failure mode are independent of each other. The fitting results show that the failures of various equipment in the same valve hall are correlated. The probability calculation method overestimates the failure probability of the circuit system. When PGA is 0.3g, the failure probability corresponding to the probability calculation method is 60.4%, and the failure probability corresponding to the definition calculation method is 36.6%. When PGA is 0.4g, the failure probability corresponding to the probability calculation method is 91.9%, and the failure probability corresponding to the definition calculation method is 68.2%. The results indicate that assuming the failure events of each failure mode are independent will significantly overestimate the vulnerability of the circuit system.

5 CONCLUSION

This paper establishes a sophisticated finite element model of the 800kV high-end converter valve hall circuit. The study examines the seismic response characteristics and potential failure modes through dynamic characteristic analysis and time-history response calculations. Vulnerability analyses were conducted on individual components, such as the converter valves in the circuit-coupled environment, as well as on the overall circuit of the converter valve hall. The conclusions obtained are as follows:

The fundamental frequency of the converter valve is less than 1 Hz, resulting in a significant bottom displacement response during seismic activity. However, it is unlikely to cause air breakdown damage between the converter valve and the valve hall wall, but it may lead to excessive relative displacement between converter valves, resulting in connector failure. The fundamental frequency of the through-wall sleeve is 2.60 Hz, which falls within the demand response spectrum platform segment of the current specifications. Under the action of a 0.4g artificial wave, the safety factor of the base stress is 1.67, precisely meeting the specified value of 1.67 in the specifications, indicating a vulnerable position. The safety factors of the support insulators PI11, PI12, and PI18 are 1.91, 1.78, and 1.72, respectively, all close to the specified value of 1.67. Therefore, they are considered weak positions.

The vulnerable equipment in the high-end converter valve hall circuit includes six converter valves, support insulators, and 800 kV through-wall sleeves. Potential failure modes include excessive relative displacement between adjacent converter valves, stress exceeding the limit in the electrical component support structures of the converter valve layer, stress exceeding the limit at the base of support insulators, and stress exceeding the limit at the base of 800kV through-wall sleeves. The vulnerability analysis of 32 sets of seismic records indicates that the vulnerability of converter valves, support insulators, and 800kV through-wall sleeves in the valve hall is relatively high, highlighting the necessity of adopting isolation measures to decrease the overall vulnerability of the circuit.

The vulnerability of the converter valve hall under coupling obtained from the overall calculation is significantly lower than the vulnerability obtained assuming independent equipment failures. This indicates that equipment failures have a certain degree of correlation. When calculating the seismic vulnerability of sub-circuits and even the entire converter station, individual equipment failures cannot be simply considered as independent events. Otherwise, the vulnerability of the system will be severely overestimated.

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REFERENCES

1. Litzenberger, W. (2008). Advances in HVDC technology as applied to the pacific HVDC intertie. 2008 IEEE/PES Transmission and Distribution Conference & Exposition, 1044–1047.
2. Sun, Q., Wu, X., Di, J., Zhou, Y. (2012). Seismic Analysis for the Suspended Converter Valve Tower of the UHV. Applied Mechanics and Materials, 187, 196–201. https://doi.org/10.4028/www.scientific.net/AMM.187.196
3. Yang, Z., Xie, Q., He, C., Ma, G. (2016). Seismic response analysis of ±800 kv UHVDC converter valves. Zhongguo Dianji Gongcheng Xuebao/Proceedings of the Chinese Society of Electrical Engineering, 36(7), 1836–1841. https://doi.org/10.13334/j.0258-8013.pcsee.2016.07.009
4. Xiao J., Huang M., Sun Q. (2019). An Artificial Seismic Wave Suitable for Suspended Converter Valve in the UHVDC Transmission Project. E3S Web of Conferences, 118, 02039 (4 pp.). https://doi.org/10.1051/e3sconf/201911802039
5. Xu J., Xie Q., Yang Z., Zhuo R., Hu R., Sun B. (2020). Seismic Performance Analysis of ±800 kV UHVDC Converter Valve-hall System. High Voltage Apparatus, 56(1), 96–103. https://doi.org/10.13296/j.1001-1609.hva.2020.01.015

6. Khalvati, A.H., Hosseini, M. (2009). Seismic performance of electrical substations' equipments in bam earthquake (Iran 2003). TCLEE 2009: Lifeline Earthquake Engineering in a Multihazard Environment, 357, 23. https://doi.org/10.1061/41050(357)23
7. Yu W., Zhou Y., Zhu L., Ge X. (2014). Research on seismic disaster and prevention countermeasures of electric power system. Advanced Materials Research, 838–841, 1538–1542. https://doi.org/10.4028/www.scientific.net/AMR.838-841.1538
8. Baker, J.W. (2015). Efficient Analytical Fragility Function Fitting Using Dynamic Structural Analysis. Earthquake Spectra, 31(1), 579–599. https://doi.org/10.1193/021113EQS025M
9. Code for seismic design of electrical installations: GB 50260—2013
10. Wang H., Li J., Chen Q., Ni D. (2011). Logistic modeling of the equilibrium speed-density relationship. Transportation Research, Part A (Policy and Practice), 45(6), 554–566. https://doi.org/10.1016/j.tra.2011.03.010