Study on Response Spectrum of Seismic Design of Ultra High Voltage Converter Valves in Bedrock Site

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Abstract. It is difficult to evaluate seismic performance of ultra-high voltage (UHV) converter valves reasonably because the response spectrum period used in seismic design of electrical equipment fails to cover the structural period of UHV converter valves at present. Bedrock response spectrum is the basis of seismic design response spectrum. 471 records of long period strong earthquakes in bedrock were analysed. The amplification power spectra and average spectra of all records were calculated. The seismic hazard analysis of 17 typical UHV converter stations was carried out, and the bedrock response spectra with exceedance probability of 10% and 2% in 50 years were proposed. The structural forms of the existing main response spectrum descending segments were compared and analysed. The corresponding response spectra of the long period strong earthquake records and the bedrock response spectra of the UHV converter station were fitted. The bedrock response spectrum of the UHV converter valves with the period range of 0-10s was determined, which lays a foundation for the seismic performance evaluation of the UHV converter valves.

Keywords: UHV converter valve, response spectrum, seismic performance evaluation.

1. Introduction
Located between the Pacific Ring of Fire and the Eurasian Ring of Fire, China is an earthquake-prone country. Previous earthquakes have caused serious damage to China's power facilities, impeded the power supply in disaster areas, and caused huge social and economic losses [1]. Due to the fact that most energy bases and power load areas are located in areas with high seismic intensity, a large number of converter stations are inevitably built-in areas with unfavorable earthquake resistance [2]. With the advantages of large capacity, long distance and low loss, ultra-high voltage direct current (UHVDC) transmission is an inevitable choice for energy interconnection between China's energy base and power consumption center. The seismic hazard risk of UHV converter station in high intensity area is great, and the seismic vulnerability of electrical equipment in the station is high. UHV converter valve is the key equipment of UHV converter station. It has complex structure and high operation reliability requirements whose design performance directly affects the safe and reliable operation of the whole
UHVDC transmission system. However, there are bottlenecks in the seismic evaluation and design of UHV converter valves presently. The lack of seismic design response spectrum suitable for the seismic evaluation of suspension converter valves in UHV converter stations makes it difficult to reasonably evaluate the seismic performance of UHV converter valves.

At present, in the seismic design of converter stations, the seismic performance of direct current (DC) electrical equipment is mainly evaluated according to the seismic design response spectrum in references [3,4]. However, the response spectrum period range is 0-6s [3,4]. The structural periods of ±800kV and ±1100kV converter valves are mainly distributed within the range of 6-10s as shown in Fig.1. The earthquake after the period of 6s play an important role in the seismic response of the converter valves, which cannot be ignored. Therefore, the UHV suspension converter valves can't get effective excitation under the earthquake action described in the current standard.

The seismic evaluation and design of UHV converter valves have attracted a wide spread attention recently. Zhenyu Yang established the finite element model of ±800kV valve tower-hall structure [5] and the theoretical model of multi-degree of freedom system [6]. Three earthquake records were used to analyze the influence of shock absorber parameters on the seismic responses of the converter valve, namely El-Centro wave, Landers wave and Taft wave. Lihong Zhang [7] and Yi Xing [8] selected two earthquake records, El-Centro wave and Taft wave, and one artificial seismic wave synthesized for Xinsong according to reference [4], and carried out seismic time-history analysis on the suspension converter valve in Xinsong ±800kV converter station. Two types of valve halls of hybrid structure and full-steel structure are compared and analyzed by Lihong Zhang [9]. Qian Zhang [4] carried out seismic calculation of ±1100kV converter valves using artificial seismic wave based on reference [10]. Junxin Xu selected El-Centro wave, Taft wave and artificial wave in reference [4] to analyze the seismic performance of the ±800kV converter valve tower and hall. Jun Lu used Chichi wave, El-Centro wave, Northridge wave, Panadena wave, Tianjin wave, Kobe wave and an artificial wave to analyze the seismic response of ±800kV converter valve [11]. In the above work, seismic analysis of the converter valve is accomplished by using actual seismic records or artificial waves generated according to the response spectrum provided by the standard. However, the period of response spectrum and the applicability of the converter valves structure in the current standard are ignored.

Now there is no response spectrum for seismic design of UHV converter valves, which is the key equipment in UHV converter stations, resulting the lack of reasonable seismic performance evaluation method for converter valves. It becomes a major obstacle in seismic design of UHVDC engineering. In this paper, the strong earthquake records of the bedrock site are collected and statistically analyzed. By combining with the comparative analysis of relevant standards and literatures, the suggestion of bedrock
site response spectrum for seismic design of converter valves is given, which provides a basis for the construction of response spectrum for seismic design of UHV converter valves.

2. Long-period bedrock strong earthquake record and bedrock response spectrum analysis of UHV converter station

471 bedrock sites horizontal records are collected from NGA database. The selected records have a magnitude of 5.0 ~ 8.0, epicentral distance of 0 ~ 300km, peak ground acceleration (PGA) > 30gal, shear wave velocity V30 ≥ 500m/s and filtering frequency ≤ 0.1Hz.

| Epicentral distance | Magnitude 5.0-6.5 | Magnitude 6.5-8.0 | Total |
|---------------------|-------------------|-------------------|-------|
| <50km               | 63                | 70                | 133   |
| 50-100km            | 68                | 154               | 222   |
| >100km              | 9                 | 107               | 116   |
| Total               | 140               | 331               | 471   |

Table 1. Strong earthquake records distribution of magnitude and epicentral distance.

Fig.2(a) shows magnitude-epicentral distance distribution, and Fig.2(b) shows magnitude-PGA distribution. It can be seen from the Fig.2 that the selected bedrock records are reasonable in magnitude, epicentral distance and PGA.

Fig.3 gives amplification spectra of all records. It also gives average spectrum and the average spectrum with a standard deviation. As shown in Fig.3, amplification coefficient, epicentral distance and shear wave velocity V30 have important influence on the amplification spectrum.
17 UHV converter stations in China are selected for seismic hazard analysis. The bedrock response spectra and the average value with a period ranging from 0.01s~10s for exceedance probability of 10% and 2% in 50 years are obtained. Fig.4 shows the bedrock response spectra and the average value with PGA = 0.2g for exceedance probability of 10% in 50 years.

3. Comparative analysis of the descending segment of response spectrum

The key to determining the seismic response spectrum of the converter valve lies in the construction of the response spectrum after the 6s period. The response spectrum within 0s-6s can be determined with reference to the current standard for seismic design of UHVDC equipment [3]. This paper mainly discusses the spectral value of the descending segment of the response spectrum from the characteristic period to 10s. This segment of response spectrum covers the structural period of UHV converter valve and has an important influence on its seismic performance evaluation.

3.1. The type of descending segment of response spectrum

By comparing the response spectrum shapes in different standards, it can be found that all kinds of spectrum patterns are almost identical in the ascending segment and platform segment. When \(T \geq T_p\), the response spectrum exhibits the descending segment. Especially in the long period segment of displacement control, the spectral shapes of the response spectra given by different codes are quite different in the descending segment. At present, there are three main forms.
3.1.1. The descending segment of the curve descending with $T^{-1}$ or $T^{-0.9}$. JTG/T 2231-01-2020 - Specifications for seismic design of highway bridges and IEEE 693-2018 - IEEE recommended practice for seismic design of substations show that the descending segment of the response spectrum is a curve descending with $T^{-1}$. The $T_g$~5$T_g$ segment of GB 50011-2010 - Code for seismic design of buildings shows a curve descending with $T^{-0.9}$.

3.1.2. The first segment of the curve descending with $T^{-1}$ or $T^{-0.9}$, the second segment of the curve descending with $T^{-2}$. The descending segment of the design response spectrum in American code ASCE/SEI 7-16 is divided into two segments, a descending segment descending with $T^{-1}$ is in the period of $T_s$~$T_{L}$, and a curve descending with $T^{-2}$ is in the period of $T_{L}$~$T_{L}$. Similar codes are European code Eurocode8 and Guangdong provincial standard DBJ/T 15-151-2019 - Specification for performance-based seismic design of reinforced concrete building structure.

3.1.3. Curve and linear descending segment. GB 50011-2010 divides the descending segment into speed control segment ($T_g$~5$T_g$) and displacement control segment ($T_{L}$~5$T_g$). The speed control segment is a segment descending with $T^{-0.9}$, while the displacement control segment is a linear descending segment. A similar code is GB/T 50761-2018 - Standard for seismic design of petrochemical steel equipments.

3.2. Analysis of the descending segment of Bedrock Response Spectrum of UHV Converter Valve

3.2.1. Analysis of strong earthquake records. According to the average spectrum of amplification coefficients of all records shown in Fig. 3, the segment during 0.4s~10s is fitted by $T^{-\varepsilon}$ descending mode, and the result is shown in Fig. 5. The descending rate coefficient $\varepsilon = 1.147$ is obtained by fitting. The average spectrum of records is always below the $T^{-1}$ curve, indicating that for the bedrock site, the descending segment of $T^{-1}$ is relatively conservative.

![Figure 5. The fitting result of descending segment of average spectrum for strong earthquake records.](image)

3.2.2. UHV converter station bedrock spectrum for exceedance probability of 2% in 50 years. The average value of the UHV converter station bedrock response spectrum for exceedance probability of 2% in 50 years is obtained by seismic hazard analysis. The segment during 0.3s~10s is fitted by the $T^{-\varepsilon}$ descending mode. The descending rate coefficient $\varepsilon$ is 1.115 (sites of PGA=0.05g), 1.015 (sites of PGA=0.1g), 1.05 (sites of PGA=0.2g) and 0.9755 (sites of PGA=0.3g), respectively. The descending segment is very close to the 1.0 adopted in the code for seismic design of highway bridges. Except that
the $\varepsilon$ of 0.3g site is less than 1.0, the other sites are all greater than 1.0, indicating that it is relatively conservative to use $T^{-1}$ or $T^{-0.9}$ in the descending segment, as shown in Fig. 6.

![Graph showing the descending segment of fitted average spectrum of UHV converter station.](image)

**Figure 6.** The descending segment of fitted average spectrum of UHV converter station.

### 3.2.3. The influence of descending rate coefficient

The descending rate coefficient adopted in JTG/T 2231-01-2020 is 1.0, which is 0.9 in GB/T 50761-2018. When damping ratio is 5%, the influence of descending rate coefficient on the spectral value during different period is shown in Fig. 7. It can be seen with the increase of characteristic period, the spectral value decreases. When the period is 7.0s, the specific value is between 1.2 to 1.4. It shows that if the descending rate coefficient is determined as 0.9, the long period spectral value is conservative.

![Graph showing the influence of descending rate coefficient on spectral values for different periods.](image)

**Figure 7.** The influence of descending rate coefficient on spectral values for different periods.

### 4. The bedrock response spectrum of UHV converter valve

Considering the consistency of seismic design of UHVDC equipment, it puts forward suggestion of the horizontal seismic influence coefficient curve based on GB/T 50761-2018 and GB 50011-2010, as shown in Fig.8. The shape parameter can be determined as follows:

1) Linear ascending segment, the natural period < 0.1s;
2) Horizontal segment, period from 0.1s to characteristic period $T_g$;
3) Nonlinear descending segment, period from characteristic period $T_g$ to $5T_g$;
4) Linear descending segment, period from $5T_g$ to 10s.
According to the analysis results, there are two descending segments, namely speed control segment and displacement control segment. The segment during \( T_g \sim 5T_g \) is determined by the maximum speed of ground motion, and the descending law is \( \eta_2 \alpha_{max}(T_g/T) \). The recommended value of \( \gamma \) is 0.9. \( \eta_2 \) is damping adjustment coefficient, which can be taken as 1.0 normally. \( \alpha_{max} \) is maximum earthquake influence coefficient. The segment from 5\( T_g \) to 10s is determined by maximum displacement of ground motion, and the descending law is \( \eta_1 \)\( 0.2^{\gamma} \eta_1 (T-5T_g) \alpha_{max} \). \( \eta_1 \) is slope adjustment coefficient, which can be determined as \( \eta_1=(\eta_20.2^{\gamma}-0.03)/14 \). While the calculated value of the horizontal seismic influence coefficient is less than \( 0.05 \alpha_{max} \), take it as \( 0.05 \alpha_{max} \).

5. Conclusion
In order to propose the bedrock response spectrum which is suitable for UHV converter valve, 471 long period rock strong earthquake records are analyzed, and the seismic hazard analysis of 17 UHV converter stations is carried out. The descending segments of the main response spectra are compared and analyzed. The main conclusions are as follows:

1) The segment during 0.4s~10s of long-period strong earthquake records is fitted by \( T^\epsilon \) descending method. The descending rate coefficient \( \epsilon=1.147 \) is obtained. The recorded average spectrum is below the \( T^1 \) curve.

2) The average spectral value of bedrock response spectrum during 0.3s~10s with exceedance probability of 2\% in 50 years for 17 UHV converter stations is fitted by \( T^\epsilon \) descending mode. The descending rate coefficient \( \epsilon \) is 1.115 (sites of PGA=0.05g), 1.015 (sites of PGA=0.1g), 1.05 (sites of PGA=0.2g) and 0.9755 (sites of PGA=0.3g), respectively.

3) The bedrock response spectrum of UHV converter valve is proposed, and two descending segments is adopted.

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