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Study on ground motion input used in seismic test of high voltage pillar type electrical equipments

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Abstract

With the continuous improvement of voltage levels, the high voltage pillar type electrical equipments are characterized in high, soft, heavy, and so on, also the equipments nonlinear characteristic of seismic action are obvious. Resonance wave and seismic wave are commonly used in the seismic test of high voltage electrical equipments. But for equipments which have nonlinear characteristics significantly, the equipments fundamental frequency are decreasing under earthquake, the equipment fundamental frequency and resonance wave frequency can not resonant during the seismic test, it is very necessary to study the applicability and limiting condition of resonance wave used in high voltage electrical equipments seismic test. In addition, the same equipment has different response under different seismic wave, in some cases, even has a big difference. Therefore, the reasonable seismic input selection determines the reasonableness of electrical equipments seismic characteristic evaluation results. By theoretical analysis and shaking table test of earthquake simulation, this paper studied the applicable condition of the resonance wave used in seismic test of high voltage electrical equipments, combined with the characteristics of high voltage electrical equipments, earthquake acceleration response spectrum which suitable for high voltage electrical equipments was proposed, and the shaking table test of earthquake simulation experimental verification was carried out, all these research provide the basis for the seismic test and seismic evaluation of high voltage pillar type electrical equipments.

Keywords: high voltage electrical equipments, seismic test, ground motion input

1. Introduction

With the development of social modernization, power system plays an increasingly important role in the national economy[1]. The destruction of power system will significantly impact our life and production. Previous destroy data of electrical equipments indicate that earthquake is one of the most important factors that affect the safety of electrical equipments[2]. With the development of power grid, power transmission and transformation projects, especially ultra-high voltage projects, inevitably located in high intensity regions. Thus, the seismic vulnerability of electrical equipments in power transmission and transformation projects is very high, especially the pillar type electrical equipments in transformer or convertor stations whose fundamental frequency are 1 Hz - 10 Hz， which is very close to the predominant period of the seismic wave. Moreover, most of those equipments are made of brittle ceramic materials, whose vulnerability is very high in earthquakes[3~4]. In order to keep the safety and stability of power grid, taking into account the required strong, smart, and intercommunication features of power grid, it requires high seismic behavior of the electrical equipments. Seismic test is still one of the most important methods to evaluate the seismic behaviors of electrical equipments.

Shaking table test is the most intuitive, accurate and straight forward method to evaluate the seismic performance of equipments[5]. Seismic test of architectures has been developed to a high level, but seismic test of electrical equipments is still having some problems to be solved. On the one hand, with the increase of voltage level, high voltage pillar type electrical equipments present“high”, “soft”, and “heavy” characcteristics. The nonlinear characteristics of equipments under seismic excitations are obvious. In many countris, their codes for seismic design of electrical installations stipulate that resonance wave is effective in seismic test of electrical equipments. However, because of the nonlinear characteristics, the fundamental frequencies of high voltage electrical equipments will decrease during tests. Thus, whether the equipments can resonant or not under resonance wave excitations during the seismic test needs further studying. On the other hand, different ground motion inputs have different frequency spectrum characteristics, thus under different seismic wave excitations, the same equipment may have very different responses. The rationality of ground motion inputs directly determines the rationality and accuracy of evaluating the seismic performance of electrical equipments. In this paper, by computational simulations and shaking table tests, the applicability of using resonance wave excitations as the input in seismic tests of high voltage electrical equipments are investigated. Combined with the characteristics of high voltage electrical equipments, the earthquake acceleration response spectrum for use in seismic test of high voltage electrical equipments is also studied, and the shaking table test experimental verification was carried out. This work may provide the basis for the seismic test and seismic evaluation of high voltage pillar type electrical equipments.

2. Dynamic properties of the high voltage pillar type electrical equipments

Dynamic properties of the high voltage pillar type electrical equipments is one of the main factors that determine their seismic performance[6~7]. The relationship between natural frequencies and periods of pillar type electrical equipments and voltage levels are illustrated in Figure 1 and Figure 2. Figure 3 shows the damping ratios of 500 kV electrical equipments, the natural periods and damping ratios are displayed in Table 1.

As shown in Table 1, for electrical equipments with the voltage level lower than 220 kV, 330-750 kV and higher than 750 kV, the average natural periods are 0.32 s, 0.48 s and 0.78 s, and while the average value plus one standard deviation are 0.52 s, 0.69 s, and 1.08 s. The average value of natural frequencies are 3.13 Hz, 2.08 Hz, and 1.28 Hz. Moreover, their damping ratios are relatively small, for electrical equipments with the voltage level lower than 220 kV, 330-750 kV and higher than 750 kV, the damping ratios are 2.35%, 3.18%, and 2.89%, respectively.

The natural period of high voltage pillar type electrical equipment increases with the increase of voltage level, and while the natural frequency decreases with the increase of voltage level. The natural frequencies of all electrical equipments are generally within the range of 1 Hz ~3 Hz, with the damping ratios of 1%~3%. For 500 kV level electrical equipments, about 70% equipments’ damping ratios are located within the same range. Thus, low natural frequencies and small damping ratios are the remarkable dynamic properties of the high voltage pillar type electrical equipments. The investigation of their seismic performance must be based on their dynamic properties.

Table 1 – Statistic of natural vibration period

Voltage level(kV)		**⩽220**	**330～750**	**>750**	**Total**
Number of samples		22	70	28	120
Natural vibration period(s)	Maximum value	0.85	1.16	1.33	1.33
	Mimimum value	0.13	0.17	0.18	0.13
	Average value	0.32	0.48	0.78	0.52
	Average value+σ(1 times standard deviation)	0.52	0.69	1.08	0.80
Damping ratio	Average value（%）	2.35	3.18	2.89	2.81

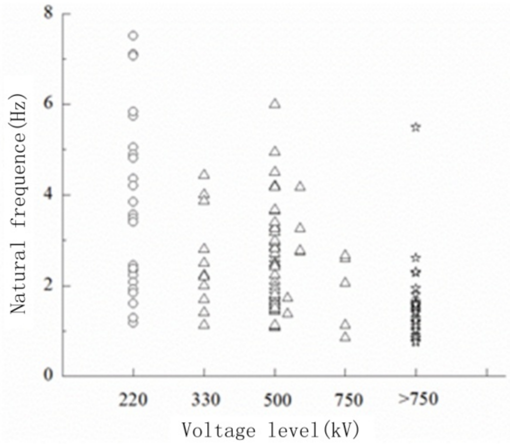

Fig. 1 – Relationship between natural frequency of electrical equipments and the voltage level

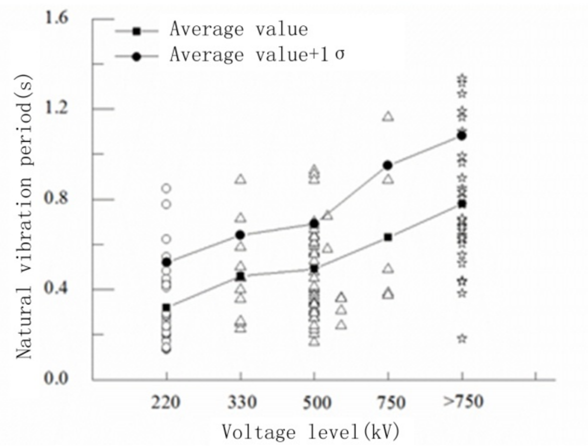

Fig. 2 – Relationship between natural vibration period of electrical equipments and the voltage level

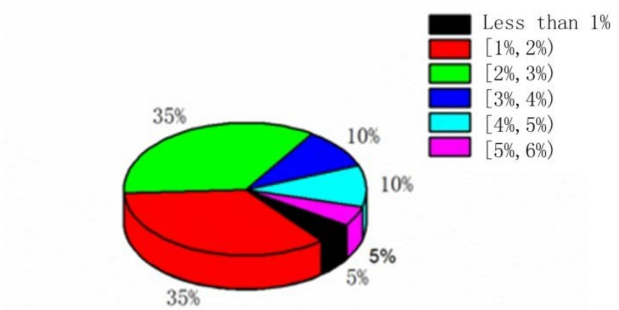

Fig. 3 – Damping ratio statistics of 500kV voltage level electrical equipments

3. Effectiveness of using resonance waves to high voltage pillar type electrical equipments

3.1 Introduction of resonance wave test

According to the"Code for seismic design of electrical installations" of China (GB 50260-2013), the beat wave that consists of 5 sine resonance wave (as shown in Figure 4) is proposed in the seismic design and seismic analysis of the parts of electrical equipments.The acceleration time history of each beat can be determined as follows:

Define $0 \leqslant t \leqslant 5T$ is a resonance wave bunch, a is calculated as:

$$a = a_s \sin \omega t \cdot \sin \frac{\omega t}{10} \qquad (1)$$

and

$$a_s = 0.75 a_0 \qquad (2)$$

where a (g) is the horizontal acceleration of each time history, t (s) is time, T (s) is the system or structure natural period of the testing direction, a_s (g) is the maximum horizontal acceleration of the ground motion, a_0 (g) is the designed fundamental acceleration of the ground motion, and ω (Hz) is the system or structure natural frequency of the testing direction.

The time step between each beat T_p can be calculated as:

$$T_p \geq (1/f)(1/\xi) \qquad (3)$$

Where f(Hz) is the fundamental frequency of the testing direction. Based on the above equations, the total time of the generated beat wave is $5 \times 5T + 4 \times T_p$。

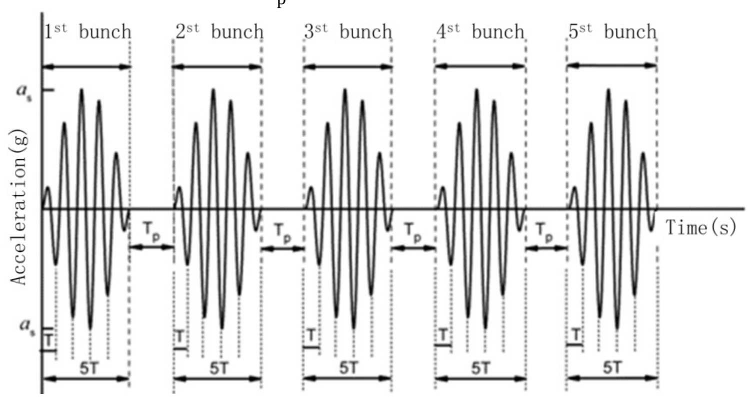

Fig. 4 – Sine beat wave

3.2 Test programs and test case

(1) Test programs

The shaking table tests of five different types of equipments under different ground motion excitations are carried out. The equipments names and numbers are displayed in Table 2. All testing equipments are axis-symmetry structures, thus only the horizontal direction (x direction) is tested. Strain gauges are pasted at the bottom of each bushing along the x direction. The acceleration sensors are located on the table tops、 the base and tops of each bushing. The laser displacement sensors are located on the top of the equipment. Figure 5 shows the schematic of the testing point distribution of equipment 1, where S is the strain gauge, A is the acceleration sensor, and D is the laser displacement sensor.

Table 2 – Test equipments name and related parameters

Number of equipments	Name of equipments	Voltage level
1	Arrester of Jinguan	750kV
2	Current transformer of Xirong	500kV
3	Arrester of Dongzhi	500kV
4	Insulator of Fuci	750kV
5	Insulator of Fuci	500kV

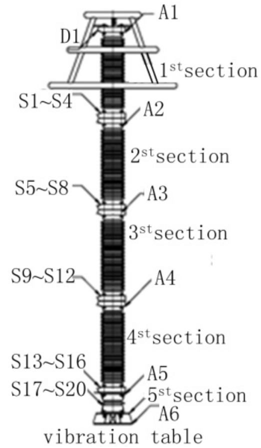

Fig. 5 – The schematic of the testing point distribution of equipment 1

(2) Test case

The seismic responses of the above mentioned equipments under ground motion excitation with the peak acceleration of 0.1g are tested. The seismic waves used in the tests include two earthquake records (the El-Centro and Landers waves), the resonance beat waves (including 0.8f, 1.0f, and 1.2f, where f is the fundamental frequency of the testing equipment), and the artificial earthquake wave. The characteristic period of the artificial earthquake wave is 0.8 s, and is generated following the response spectrum based on the "Code for seismic design of electrical installations" of China (GB 50260-2013). The input direction is the x direction. The white noise excitation tests are conducted before and after seismic tests to evaluate the frequency and damping characteristics of the testing sample. No supports are used in all tests. According to the "Code for seismic design of electrical installations" of China (GB 50260-2013),the peak acceleration of input ground motion should multiply 1.2 times of the seismic dynamic magnfication factor of the support, thus, the actual input peak acceleration of the shaking table is 0.12g.

3.3 Results and discussions

(1) White noise excitations

The evaluated equipments' fundamental frequenciy and damping ratio ζ before and after seismic tests under white noise excitations are displayed in Table 3. As shown in Table 3, as the peak acceleration of the input seismic wave is 0.12g, the reduction of equipment's frequency and the increment of its damping ratio are relatively samll. Basically, most of the equipments behave nonlinear characteristics after subjecting to a number of earthquake excitations, e.g. the frequency decreases and the damping ratio increases. The fundamental frequencies of the equipments are 1.5 Hz -7.5 Hz, which is within the range of the predominant frequencies of artificial earthquake waves. Thus, this is the first proof that the selected artificial earthquake waves are effective in evaluating the seismic behavior of equipments. Further analysis and verification will be carried out combined with shaking table tests and computational simulations.

Table 3 – Fundamental frequency and damping ratio of each equipments

Number of equipments		**1**	**2**	**3**	**4**	**5**
Fundamental frequency (Hz)	Before test	2.64	2.99	3.14	7.13	1.79
	After test	2.35	2.87	3.33	6.99	1.63
damping ratio ζ(%)	Before test	3.73	0.32	6.44	1.98	1.56
	After test	1.32	3.39	0.91	1.94	2.18

(2) Seismic wave excitations

Figure 6 shows the peak displacement responses of the topsof equipments under different seismic excitations. The peak displacement responses under artificial earthquake wave excitation is larger than their counter parts under El-Centro wave, Landers wave, and 1.2*f* resonance beat wave. Moreover, the displacement responses under artificial earthquake wave excitations are more stable, the displacement variation among different equipments is small with the amplitude of about 12 mm.

Although the displacement responses of the 750 kV arrester's top under resonance wave and 0.8*f* resonance beat wave excitations are larger than other excitation conditions, the displacement responses of the 500 kV Insulator of Fuci is smaller than other excitation conditions. Moreover, the equipment displacement responses under 0.8*f* resonance beat wave excitation are larger than that under 1.2*f* resonance beat wave excitation, which reveals the nonlinear characteristics of the equipments. Thus the equipments cannot resonate under resonance wave excitations, and resonance wave is not suitable in the seismic test of high voltage electrical equipments.

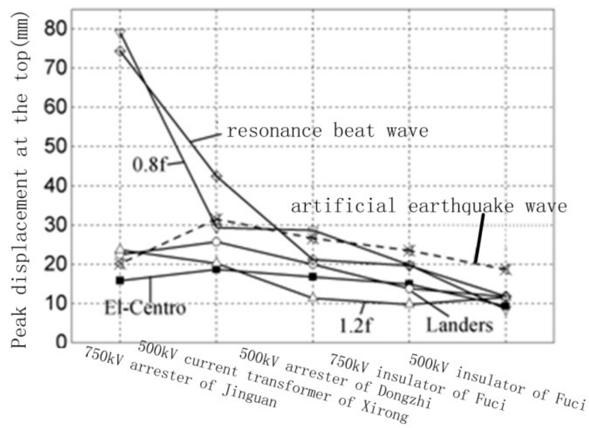

Fig. 6 – Peak displacement at the top of each equipment under different seismic excitations

Figure 7 shows the peak strains (x direction) of the equipment bottoms under different excitations. As shown in Figure 7, the strains under artificial earthquake wave excitations are larger than their counterparts under El-Centro wave, Landers wave, and 1.2*f* since beat wave, but lower than their counterparts under since beat wave and 0.8f since beat wave. However, the strain fluctuation under artificial earthquake wave excitation is smaller than that under since beat wave and 0.8*f* since beat wave.

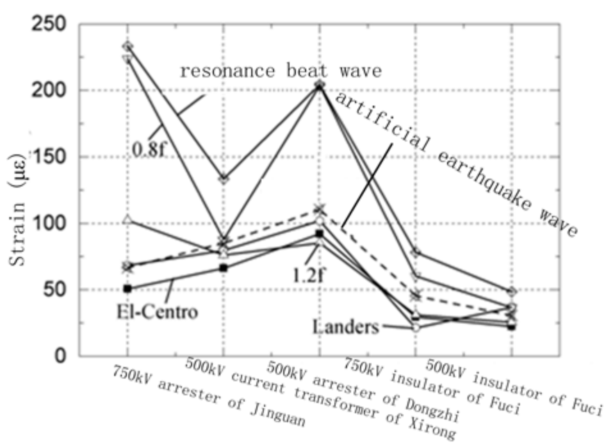

Fig. 7 – Peak strains (x direction) of the equipment bottoms under different seismic excitations

4. The proper ground motion input of high voltage pillar type electrical equipment

Figure 8 and Figure 9 show the response spectrums of output waves of the 500 kV arrester of Dongzhi and the 750 kV insulator of Fuci, respectively. As shown in Figure 8-9, the test response spectrum(TRS)of artificial earthquake waves almost envelops the request response spectrum (RRS), thus the effective frequency band of artificial earthquake waves covers the frequencies of 1.25 Hz -10 Hz. The first-order natural frequencies of high voltage electrical equipments are in the same range, thus, the artificial earthquake waves with the characteristic period of 0.8s used in this paper have a good excitation effect. However, the response spectrums of real earthquake recoards, e.g. the El-Centro wave and the Landers wave, cannot cover low frequencies, thus, for high voltage electrical equipments with first-order frequencies of 1 Hz -4 Hz, their responses under earthquake excitations are relatively small, and the seismic performance of high voltage electrical equipments can not be revealed under these excitations (especially the El-Centro wave, whose dynamic response is smaller than other excitations).Although the acceleration response spectrums reach maximum at the natural frequency or corresponding multiples of the natural frequency of the equipment under resonance waves and frequency-chane resonancewaves, its accessories' acceleration response spectrums are significantly reduced. Moreover, because of the nonlinear characteristics of the high voltage (higher than 500 kV) electrical equipments, testing equipments cannot resonate under these excitations.

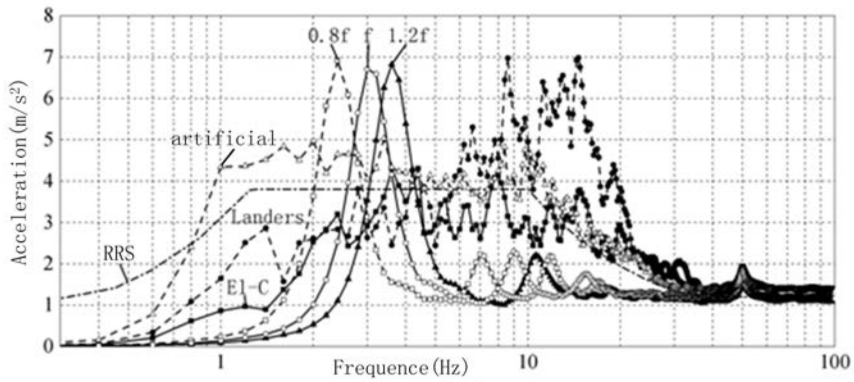

Fig. 8 –The response spectrums of output waves of the 500 kV arrester of Dongzhi

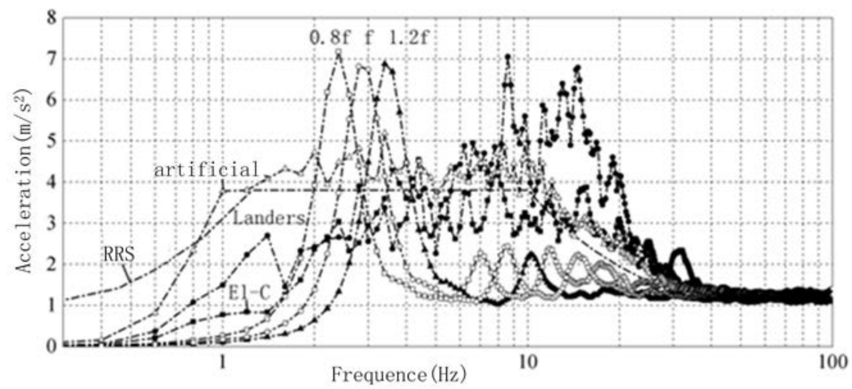

Fig. 9 –The response spectrums of output waves of the 750 kV insulator of Fuci

5. Conclusions

In this paper, the responses of high-voltage electrical equipment under different ground motion inputs are investigated by using shaking table test of earthquake simulation. Our results reveal that:

(1) In the shaking table test, the electrical equipment with strong nonlinear charcteristic cannot resonate by using resonance beat wave inputs.

(2) The artificial earthquake wave with the characteristic period of 0.8 s can almost cover the fundamentalfrequencies of electrical equipments, cover the characteristic periodsof three types ground soils, the dynamic response of equipment is strong and stable, is suitable to all kinds of electrical equipments with the voltage level of above 500 kV. Thus, we recommend using the response spectrum with the characteristic period of 0.8 s as the standard seismic response spectrum of electrical equipments.

(3) For electrical equipments with low voltage level and weak nonlinear characteristic, the resonance wave test is helpful if a high seismic performance is required. However, the nonliearity increases with the increase of voltage level, the the standard seismic response spectrumof the artificial earthquake wave that has the characteristic period of 0.8 s is proposed to be used in the shaking table test of electrical equipments with 750 kV or above voltage level.

6. Acknowledgements

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