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Study of Earthquake Simulation Shaking Table Test on the Capacitor Bank in Untra High-Voltage Substation

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Abstract

As routine equipment in UHV substation, capacitor bank gets highly earthquake vulnerability because of its high center of gravity, big quality and low-intensity support structure. It might bring great economic loss if capacitor bank damaged in an earthquake. In this analysis, a model of 110 kV capacitor bank in UHV substation was tested by shaking table first time in China. The dynamic characteristics and seismic response regularities of the model were obtained by testing the acceleration, displacement and strain of the key parts during seismic action. The seismic behavior of 110 kV capacitor bank was verified by the test, and the seismic vulnerable site of the equipment was definite. Also the improvement measures to decrease the seismic response of capacitor bank was proposed.

Keywords: capacitor bank; shaking table test; seismic response

1. Introduction

Many seismic zone over the world was active in Recent years, which caused heavy casualties and property losses. The research on high grade earthquake shows that the damage of electrical equipment in substation is serious, which not only causes huge economic losses, but also seriously affects the development of post disaster reconstruction work[1-6].

With the popularization of UHV project, the seismic capacity of UHV substation is getting more and more attention. Compared with the conventional voltage grade substation, the capacity of UHV substation is greater which may result in more serious losses during earthquake[7].

As a conventional equipment of UHV substation, 110kV capacitor is used to compensate reactive power of power system, which makes it an important part of substation. The capacitor banks are supported by post insulator, which strength as support structure is relatively low. The equipment gets high seismic vulnerability also because its high center of gravity and large quality.

Researchers over the world have carried out a wide range of work for the seismic research of electrical equipment[8-13]. But for capacitor bank, the seismic research is lack of study, which most concentrated in the structural analysis and numerical simulation research.

Based on the summary of seismic performance study of capacitor bank, the 110kV equipment in UHV substation was tested by seismic simulation shaking table for the first time in this research. The dynamic characteristics and seismic response of capacitor bank was obtained by the determination of acceleration, displacement and strain parameters in key location. Based on the research results, the seismic vulnerable site was definited, also the improvement measures to reduce the seismic response of capacitor bank was presented.

This research makes up the blank of 110kV capacitor bank seismic test research, provides the basis for the seismic study of capacitor bank.

2. Test design

2.1 Specimen introduction

The specimen used in this test is the typical equipment in UHV substation in China. The equipment installed on the shaking table is shown in Figure 1.

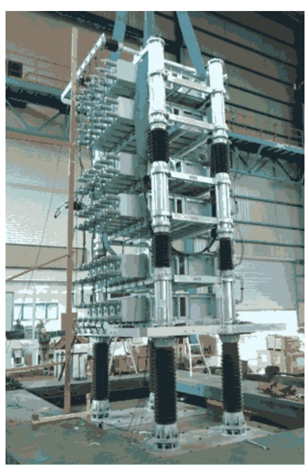

Fig.1 – 110 kV capacitor bank

The bottom size of the capacitor bank is 1300 mm * 2600 mm, and the height of the equipment is 7200 mm, the total weight is 18000 kg. The material of all insulator is porcelain and the height of the 1st layer insulator (bottom pillar insulator) is 1500 mm, and the height of the 2nd layer and 3rd layer insulator is 850 mm. The capacitor group structure is composed of 6 stainless steel layers, and the height of each single layer is 700 mm. There are 12 sets of capacitor unit for each layer, and the total number of capacitor unit is 72. The structure and direction of the specimen are shown in Figure 2.

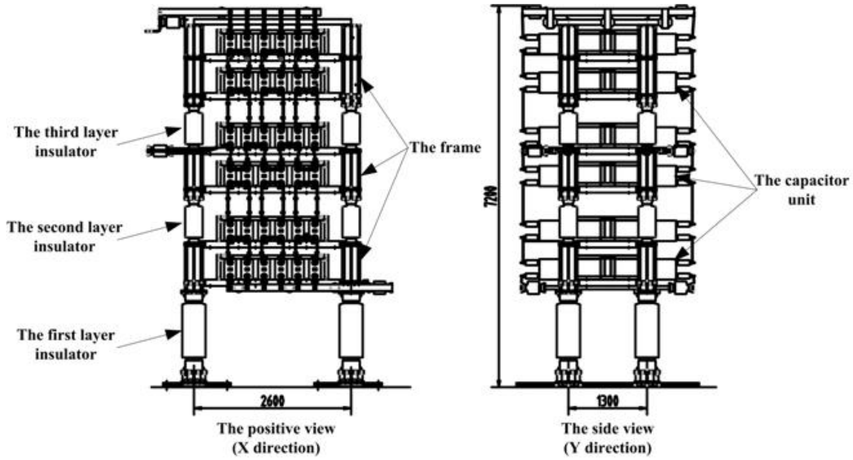

Fig.2 – Structure diagram of 110 kV capacitor bank

2.2 Test input

Researchers conducted a lot of research for the seismic design of electrical equipment[15]. According to the China national standard and China State Grid Corp enterprise standard[16, 17], white noise random waves and standard time history wave are used as the test input in this analysis. The white noise random wave is used to stimulate the specimen, and to obtain the natural frequency and damping ratio of the device. The seismic response of equipment is obtained by using the standard time history wave input. The standard time history wave adopted in this experiment is generated by the artificial standard response spectrum, which characteristic period is 0.9 s, and excellence frequency band is wide and flat. Because of this, the influence in test result by the seismic wave sensitive degree of different equipment is avoided. The maximum peak acceleration of the standard time history wave used in this test is 4 m/s2. Standard time history wave is shown in Figure 3, and the comparison of response spectrum of standard time history wave and manual standard spectrum is shown in figure 4.

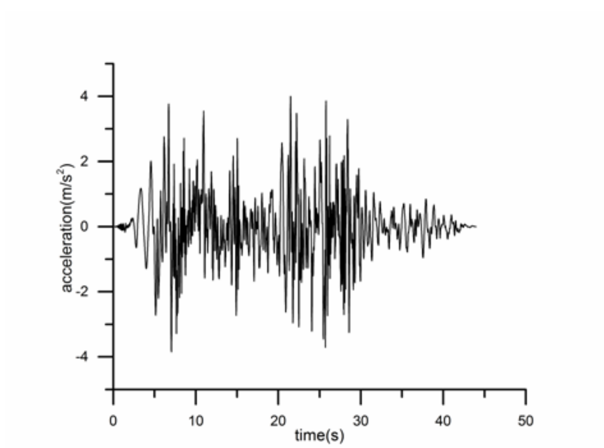

Fig.3 – 0.4g standard time history wave

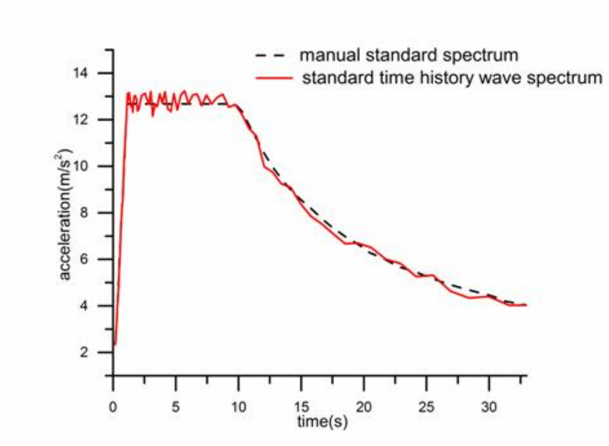

Fig.4 – Comparison of response spectrum of standard time history wave and manual standard spectrum

2.3 Arrangement of measuring points

In order to obtain the seismic response of the capacitor bank, the acceleration sensors and strain gauges are arranged in the key parts of the equipment to measure the dynamic response of the device. The arrangement of the sensor and the position of the measuring point are shown in Table 1, figure 5 and figure 6.

Table 1 – Sensors layout table

Serial number	**Sensor**	**Number**	**Position**	**Direction**
1	Acceleration sensor	A01	table	X
2	Acceleration sensor	A02	table	Y
3	Acceleration sensor	A03	1st layer	X
4	Acceleration sensor	A04	1st layer	Y
5	Acceleration sensor	A05	2nd layer	X
6	Acceleration sensor	A06	2nd layer	Y
7	Acceleration sensor	A07	3rd layer	X
8	Acceleration sensor	A08	3rd layer	Y
9	Acceleration sensor	A09	4th layer	X
10	Acceleration sensor	A10	4th layer	Y
11	Acceleration sensor	A11	5th layer	X
12	Acceleration sensor	A12	5th layer	Y
13	Acceleration sensor	A13	6th layer	X
14	Acceleration sensor	A14	6th layer	Y
15	Acceleration sensor	A15	top	X
16	Acceleration sensor	A16	top	Y

17	Strain gauge	S01	Bottom of the 2# insulator in 1st floor	X+
18	Strain gauge	S02	Bottom of the 2# insulator in 1st floor	X-
19	Strain gauge	S03	Bottom of the 2# insulator in 2nd floor	X+
20	Strain gauge	S04	Bottom of the 2# insulator in 2nd floor	X-
21	Strain gauge	S05	Bottom of the 2# insulator in 3rd floor	X+
22	Strain gauge	S06	Bottom of the 2# insulator in 3rd floor	X-

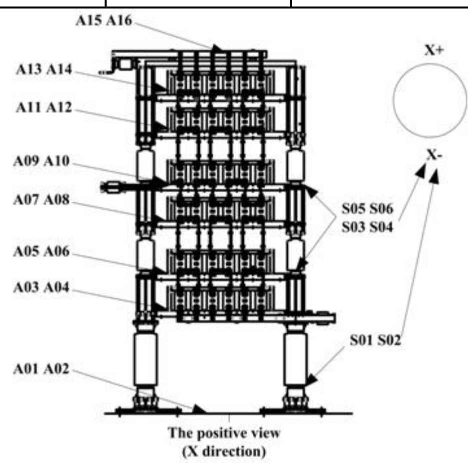

Fig.5 – Sensors layout chart

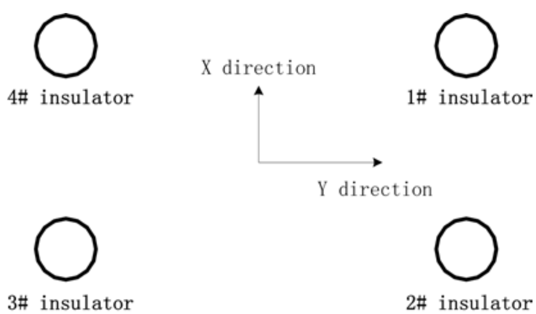

Fig.6 – Insulator numbering chart

2.4 test condition

Because of its nearly symmetrical structure, only seismic response of one single horizontal direction is determined during the test. Test conditions are shown in table 2.

Table 2 – Test conditions table

Test condition	Input	Direction	Peak acceleration(m/s^2)
1	white noise random wave	/	0.5
2	standard time history wave	X	1.0
3	white noise random wave	/	0.5
4	standard time history wave	X	4.0
5	white noise random wave	/	0.5

3. test result

3.1 test results of dynamic characteristics

The test results of the white noise random wave input are shown in table 3.

Table 3 – Result of dynamic characteristics test

Test condition	1st order frequency(Hz)	
	X direction	Y direction
1	2.27	2.31
3	2.26	2.30
5	2.11	2.26

As can be seen from table 3, the fundamental frequency of the device is not significantly changed before and after the test, it can be considered that there is no structural damage to the equipment during the test process.

3.2 test results of seismic response

Acceleration and displacement test results are shown in table 4.

Table 4 – Result of acceleration test and displacement test

Test condition	Measured peak acceleration (m/s2)							
	A01	A03	A05	A07	A09	A11	A13	A15
2	1.25	1.87	2.00	2.31	2.56	2.92	3.39	3.85
4	4.72	7.09	8.28	10.12	11.45	13.31	15.68	17.83

As can be seen from the table 4, each layer of insulator and frame structure get amplification to the seismic acceleration. The comparison of top acceleration and ground acceleration in condition 4 is shown in figure 7.

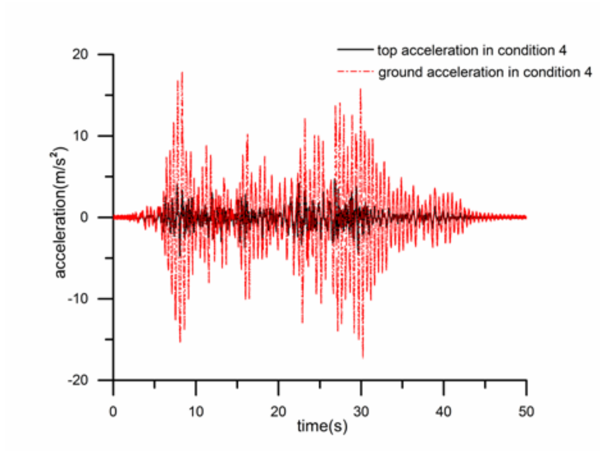

Fig.7 – Comparison of top acceleration and ground acceleration in condition 4

The test results of strain at the bottom of insulator under different work conditions are shown in table 5.

Table 5 – Result of strain test of insulators

Test condition	**Measured strain peak value (με)**		
	S01	**S03**	**S05**
2	84.67	78.77	51.95
4	407.97	366.44	224.31
The value in the table is the maximum value of the absolute value of the tension and compression strain at the measuring point			

As can be seen from the table 6, the bottom layer (1st layer) insulator strain value is the largest, which proves that the weak position of seismic performance is the bottom insulator.

4. Analysis of test results

4.1 Analysis of dynamic characteristics test results

As can be seen from the table 3, the 1st frequency at the two direction of the capacitor group is close, which means that there is no obvious weak axis. The frequency is in the ground motion excellent platform range (1Hz-10Hz), which means the equipment gets high seismic vulnerability.

4.2 Analysis of seismic response test results

The acceleration ratio of the upper and lower two layers is defined as the acceleration amplification factor, and the amplification factor of each layer insulator and frame acceleration is shown in Table 6.

Table 6 – Acceleration magnification factors statistic table

Test condition	Acceleration magnification factors						
	1st layer insulator	2nd layer frame	2nd layer insulator	3rd, 4th layer frame	3rd layer insulator	5th layer frame	6th layer frame
2	1.50	1.07	1.16	1.11	1.14	1.16	1.14
4	1.50	1.17	1.22	1.13	1.16	1.18	1.14

As can be seen from the table 5, by Contrasting the two different conditions, the acceleration amplification factor of the same position shows increasing trend with the increasement of the peak acceleration. Under the same test condition, the acceleration amplification factors of the 1st layer insulator is the biggest, which shows that the material has significant influence on the amplification factor. For the structure of same material, the acceleration amplification factor of the 5th layer and 6th layer frame is much larger than the amplification factor of lower layer frame, which showed that with the equipment height increasing, nonlinear characteristics are significant and acceleration amplification is increased.

The elastic modulus of the material of the insulator is 100GPa which is determined by mechanical test. The maximum stress of the insulator is shown in Table 7.

Table 7 Calculation result of stress at the bottom of insulator

Test condition	Maximum stress (MPa)		
	S01	S03	S05
2	8.47	7.88	5.20
4	40.80	36.64	22.43

As can be seen from the table 7, the maximum stress of the device is 40.80 MPa under input of 0.4 g standard time history wave, which is much lower than the failure stress (90 MPa) of the insulator.

5. conclusion

(1)The first order frequency of the specimen in two directions is 2.27Hz and 2.31Hz which is located at the ground motion platform and the seismic response of the equipment is obvious.

(2)Under the action of the earthquake, the structure of each layer of the capacitor group has seismic acceleration amplification effect. The effect is related to the material and the connection mode of the equipment. Compared with the steel frame, the porcelain insulator gets higher acceleration amplification effect. The acceleration amplification effect can be reduced by increasing the stiffness and connection strength of the material, by which the seismic response of the superstructure could be reduced.

(3) Under the action of earthquake, the post insulator of the equipment is the vulnerable part of the earthquake. The seismic capacity of insulator can be improved by increasing the strength and stiffness of the porcelain.

(4)The maximum stress of the device is 40.80 MPa under input of 0.4 g standard time history wave, which is far less than the material failure stress. The frequency gets no significant changes before and after the test, which shows that the equipment has the seismic capacity to resist earthquake with the basic earthquake acceleration of 0.4 g.

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