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STUDY ON SEISMIC PERFORMANCE OF REACTOR FOR HIGH VOLTAGE SUBSTATION BASED ON SHAKING TABLE TEST

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ABSTRACT

Power substation transforms voltage from high to low, or the reverse, is an important part of lifeline engineering system, which is directly related to the urban disaster prevention and the earthquake loss reduction of a city. As an essential component of the power substation facilities, the reactor which limits short circuit current, restrains harmonic and stabilizes voltage, plays a key role in the overall seismic performance of a power substation. In this paper, a full scaled 220kV oil-immersed type reactor was tested dynamically by using the shaking table facility in Chongqing University. The dynamic properties of the reactor were measured. The maximum strain and acceleration responses under different seismic inputs were compared. The results indicate that reactor structure is able to withstand an earthquake at the PGA of 0.4g without any obvious damages. However, there exists a significant dynamic amplification effect at the top of high voltage bushing and the top of the hoist seat during the shaking table tests, and an unsafe seismic design of the bushing could result according to the dynamic amplification factor method. In addition, the peak relative displacement at the top of the high voltage bushing is larger than other parts during the test at the PGA of 0.4g, which may affecting the electrical performance of the reactor too.

Keywords: High voltage power system; Reactor; Shaking table test; Seismic response

1. INTRODUCTION

The earthquake may cause serious damage to the substations in the power transmission system, which resulted in widespread blackouts, as reported in the Loma Prieta earthquake in San Francisco in 1989 (Shinozuka et al. 1998), and the Northridge earthquake in Los Angeles in 1994 (Schiff and Anshel 1995). In 1995, six 275kV substations, two 154kV substations and 42 77kV substations were damaged in the earthquake (Linxu 2000) in Hanshin region of Japan. In 1999, the 380/154kV substation in the Turkish Kocaeli earthquake (Robert et al. 2000) was destroyed, caused widespread blackouts too. In

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2004 Japan Niigata earthquake, 11 substations were damaged (Qiang et al. 2006). In 2008 Wenchuan earthquake in Sichuan Province of China (China Earthquake Administration 2008), 246 substations of 500kV and under the 500kV in power system were damaged. In 2011, the earthquake and its secondary disasters in East Japan caused serious damage to the power transmission and distribution facilities, resulted in a reduction of more than 20% disability in the power generation capacity of Japan after the earthquake (Fang et al. 2011). The main research methods of seismic performance of electrical equipment are numerical simulation and shaking table test. The shaking table test can directly reproduce the vibration state of electrical equipment under earthquake and truly reflect the weak parts of the equipment, which is the best way to test the seismic performance of electrical equipment (Kumosa et al. 2005, China Electric Power Research Institute 2014). Ziguo et al. (1998) conducted the prototype experiment of S7-200/10 distribution transformers, which is the first prototype test of transformer structure in China. Matt and Filiatrault (2003) carried out a shaking table full-scale test on a 525kV transformer. The experimenter made a high-voltage simulation bushing with porcelain to simulate the dynamic response of the real bushing. A total of five seismic waves of different magnitudes and intensities were input to obtain the dynamic characteristics of the key parts of the transformer. Meigen et al. (2011) designed a transformer model for shaking table test, in which 220kV and 500kV bushings were prototypical. By inputting several seismic waves into the shaking table test, the seismic response time history curves of acceleration, displacement and strain of the key parts were obtained, and the seismic response rules and seismic weak points of the transformer and bushing system were studied. Qiang et al. (2015) carried out a shaking table test on a transformer bushing system consisting of a simulation box, a hoist seat, a prototype bushing, and other components. The seismic response in the system was analyzed in both the time domain and frequency domain, which revealed the transformer seismic response mechanism.

The reactor is an important power facility of the substation, which has the functions of limiting short circuit current, restraining harmonic and stabilizing voltage. The structural composition of the reactor is similar to that of the transformer. The seismic research results of the transformer will have some reference function for the reactor, and shaking table test of the reactor will directly reflect its seismic response. This paper focuses on researching the seismic response characteristics of a 220kV oil-immersed reactor by using the shaking table test. The dynamic properties of the reactor were studied, the seismic response characteristics under different seismic inputs were compared. The weak part of the earthquake resistance was clarified, and the corresponding anti-seismic measures and seismic design proposals were put forward, which provided the foundation for the seismic design of such reactors.

2. SHAKING TABLE TEST

2.1 The reactor for testing

The test object is a prototype 220kV oil-immersed reactor (Figure 1), which consists of a tank, hoist seat, conservator and porcelain bushing. The bushing is fixed on the corresponding hoist seat and is connected with the hoist seat by a flange, and the conservator is cantilevered over the tank. The reactor is 2.55 meters long, 2.5 meters wide and 7.033 meters high, with a total weight of 8298kg.

(a)Front (b)Back (c)side

Figure 1. 220kV oil-immersed reactor for test

2.2 Equipment for testing

The test was carried out in the shaking table Laboratory of Chongqing University. The parameters of the shaking table in the test are shown as follows. The size of the table is 6.1m×6.1m, the working frequency is 0.1~50Hz, the standard load is 60t, the maximum overturning moment is 1800kN·m and the maximum eccentric moment is 600kN·m. The maximum acceleration of the table is ±1.5g (standard load) in the X direction, ±1.5g (standard load) in the Y direction, ±1.0g (standard load) in the Z direction.

2.3 Input motion for testing

The resonant frequency search test is for determining the resonant frequencies of the reactor. White noise is used for the resonant frequency search test. According to IEEE693 (2005) and GB50260 (2013), The amplitude of the white noise input is 0.075g, the test time is 180s with the frequency range 0.1Hz-50Hz.

According to IEEE693 (2005) and GB50260 (2013), The response spectrum of the input motions should envelop the required response spectrum (RRS). So, the artificial time history is used for the time history shaking table test. The required response spectrum with the damping ratio 2% determined by IEEE693 (2005) and GB50260 (2013) is illustrated in Figure 2. The horizontal and vertical seismic waves generated by the response spectrum are shown in Figure 3, and the response spectrum of the seismic wave is shown in Figure 2. The amplitude of the seismic waves is adjusted for different intensity cases in shaking table test.

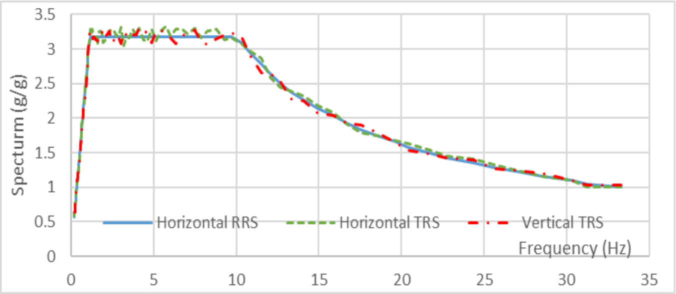


Fig 2. Required response spectrum and test response spectrum for the shaking table test

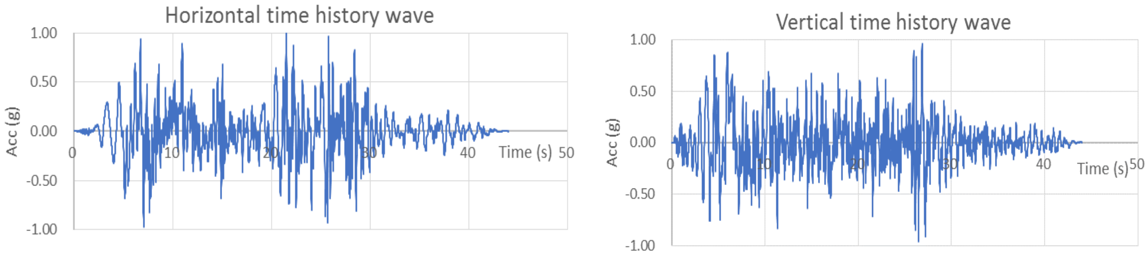


Fig 3. Acceleration time histories for the shaking table test

2.4 Arrangement of measuring points for testing

Seven acceleration measuring points (three directions in each point) and five strain measuring sections (four strain gages per section) were placed along the height of the reactor. The acceleration sensors were installed at the top of the tank, hoist seat, high voltage bushing, low voltage bushing, conservator and pressure release valve numbered from MA1 to MA7. The strain gages were glued on the root of the hoist seat, high voltage bushing, the cantilever of a conservator, column of the conservator and terminal box numbered from MS1 to MS5. Test point layout is shown in Figure 4.

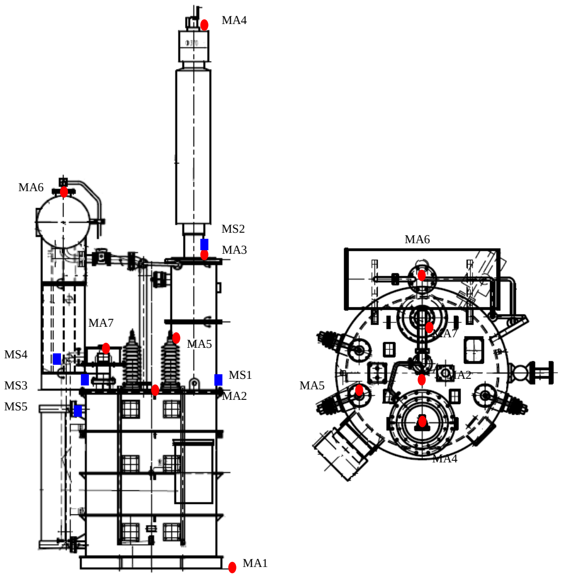


Fig 4. Measuring point layout

2.5 Cases for testing

The seismic input directions were X+Z, and Y+Z (Z-direction acceleration peak is 80% of horizontal), respectively. The seismic inputs were increased step by step according to the seismic intensity levels. The white noise was swept before and after each test. The test cases are shown in Table 1.

Table 1. Cases for testing

Case	Input wave	Direction	Peak of acceleration/ (m·s^2)
1	white noise wave	$x+y+z$	0.075 g
2	seismic wave	$x+z$	0.150 g
3	seismic wave	$y+z$	0.150 g
4	white noise wave	$x+y+z$	0.075 g
5	seismic wave	$x+z$	0.400 g
6	white noise wave	$x+y+z$	0.075 g
7	seismic wave	$y+z$	0.400 g
8	white noise wave	$x+y+z$	0.075 g

3. ANALYSIS

3.1 Resonant *frequency of the Reactor*

According to the acceleration response time history of the reactor in the shaking table test with white noise input, the frequency response function was calculated. The frequency of the reactor at the corresponding case is shown in Table 2. Figure 5 is the frequency response function curve in Case 8.

Table 2. Resonant frequencies of the Reactor Based on testing (Unit: Hz)

Case	f_x			f_y			f_z
	f_{x1}	f_{x2}	f_{x3}	f_{y1}	f_{y2}	f_{y3}	
1	5.50	13.00	23.50	5.50	8.25	19.00	28.50
4	5.25	13.00	24.25	5.50	8.25	19.25	28.50
6	5.50	12.50	23.75	5.50	8.50	19.50	28.50
8	5.50	12.25	23.50	5.50	8.25	19.25	27.75

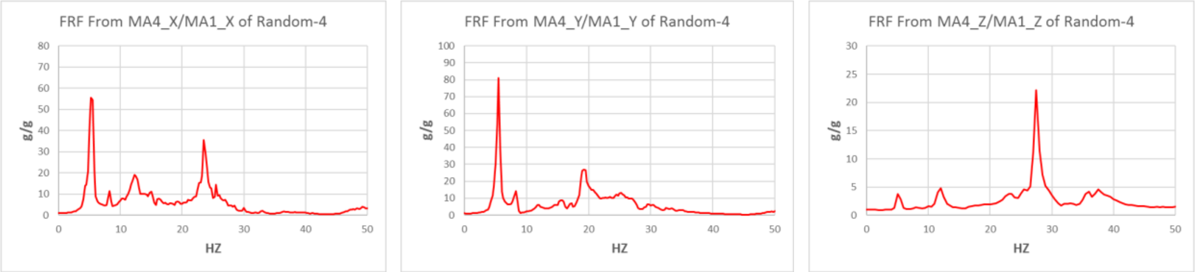
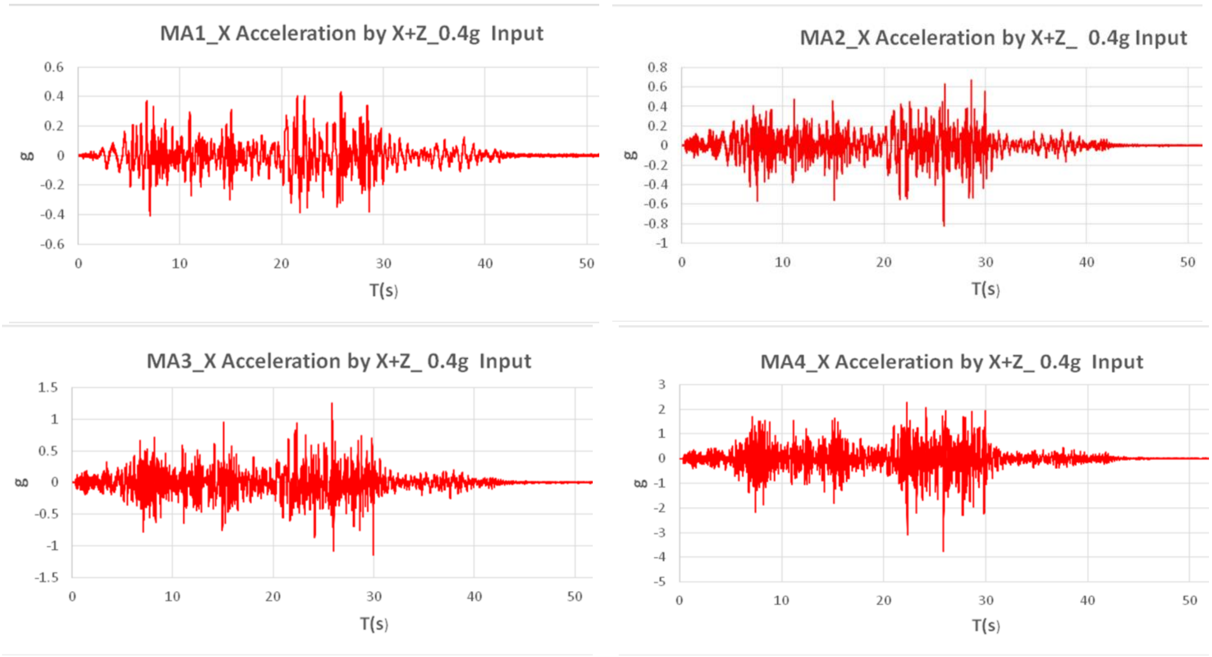


Fig 5. The frequency response function of this reactor in Case 8

Table 2 shows that the stiffness of the reactor in the X direction is similar to that in the Y direction, the frequency is 5.5Hz. After the 0.15g and 0.4g earthquake wave tests, the structural frequencies have no obvious changes. It is shown that the reactor has no obviously structural damages.

3.2 Acceleration response analysis

In Case 5, the acceleration time history of the table (MA1), at the top of the tank (MA2), hoist seat (MA3), and high voltage bushing (MA4) are shown in Figure 6.


MA1_X Acceleration by X+Z_0.4g Input

MA2_X Acceleration by X+Z_ 0.4g Input

MA3_X Acceleration by X+Z_ 0.4g Input

MA4_X Acceleration by X+Z_ 0.4g Input

Fig 6. The acceleration time history of this reactor in Case 5 shaking table test

The dynamic amplification factor is defined as the ratio of the peak acceleration of measuring point to the peak acceleration of the input values.

Table 3. Dynamic amplification factors of the measuring points

Case	Top of high voltage bushing (MA4)	Top of hoist seat (MA3)	Top of conservator (MA6)	Upper surface of tank (MA2)
2	8.18	2.94	5.99	1.46
3	8.52	3.43	5.21	1.34
5	8.74	2.91	5.81	1.91
7	3.46	2.04	3.35	1.12

Figure 6 and Table 3 show the maximum acceleration response of the reactor is at the top of the high voltage bushing, and it increased along the height of the structure. The dynamic amplification factor is close to 2 on the upper surface of the tank, close to 3.5 at the top of the hoist seat, close to 9 at the top of the high voltage bushing. Therefore, the top of the high voltage bushing in this kind of reactor has significant dynamic amplification effect. The dynamic amplification factor is close to 3 at the top of the hoist seat, and the seismic design of the bushing may be unsafe according to the dynamic amplification factor of the current code.

3.3 Displacement response analysis

The displacement response time history can be obtained by the measured acceleration response time history integration. In Case 5 and Case 7, the horizontal displacement at the top of the high voltage bushing relative to the table is shown in Figure 7. The peak displacement of the main test point relative to the table is shown in Table 4.

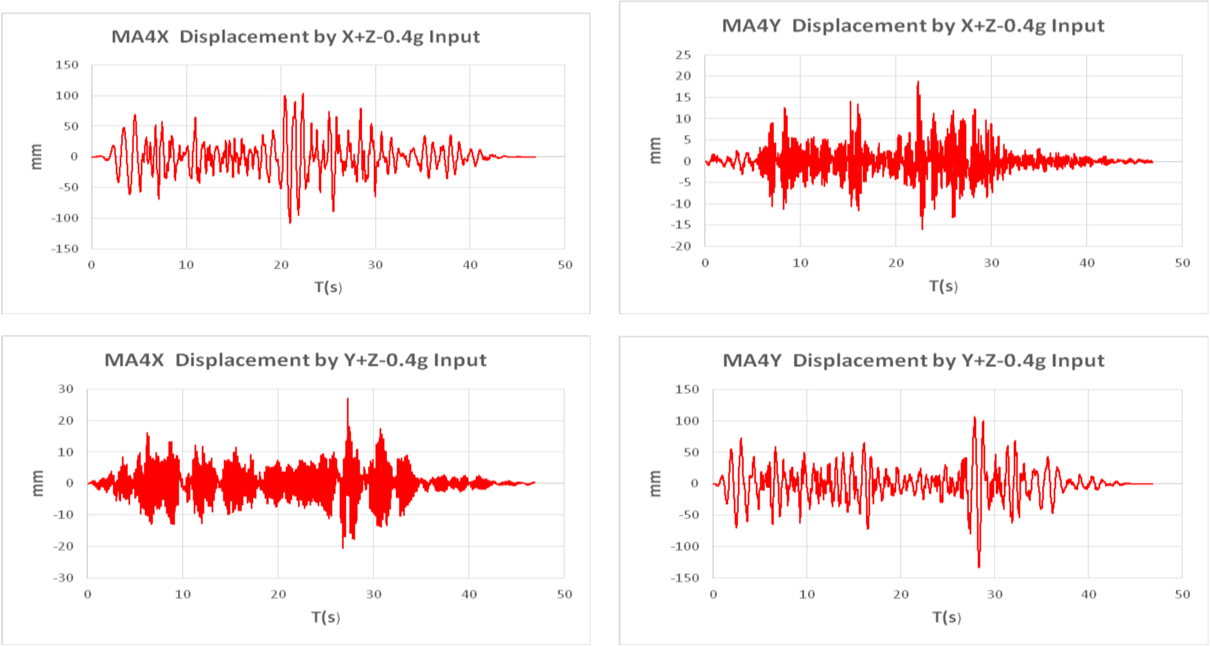


Fig 7. Horizontal relative displacement of the top of high voltage bushing in Case 5 and Case 7

Table 4. The peak displacement of the test points in Case 5 and Case 7 (Unit: mm)

Case	**Direction**	**The top of high voltage bushing (MA4)**	**The top of hoist seat (MA3)**	**The top of conservator (MA6)**
5	X	107.70	11.68	111.7
	Y	18.88	9.62	7.45
	Z	2.16	2.43	9.10
7	X	26.98	5.06	10.42
	Y	133.21	9.46	8.28
	Z	6.61	1.86	4.06

As shown in Table 4 and Figure 7, the maximum value of the peak relative displacement at the top of the high voltage bushing is 133mm in the shaking table test with the peak acceleration of 0.4g. The top of the high voltage bushing has the maximum displacement response of reactor, and the larger displacement response may affect electrical performance. In addition, the torsional effect of the reactor exists during the shaking table test.

3.4 Strain response analysis

The strain-time histories at the root of high voltage bushing in the case 5 and case 7 are shown in Figure 8. The peak strains of the test point are shown in Table 5. It is known that the maximum strain of the porcelain sleeve is located at the root of the high voltage bushing of the reactor (MS2). The maximum strain of steel structure is located at the root of conservator (MS3) and the root of the hoist seat (MS1). According to the elastic modulus of the porcelain sleeve 110GPa, the maximum stress of the porcelain sleeve is calculated to be 13.92MPa, which is less than the failure stress 50MPa of the porcelain sleeve. According to the elastic modulus of the steel 206GPa, the maximum stress of the steel is calculated to be 68.37MPa, which is less than the steel yield stress 235MPa too. The porcelain sleeve and the steel structure are safe in the shaking table test at the PGA of 0.4g. The reactor has a good seismic performance.

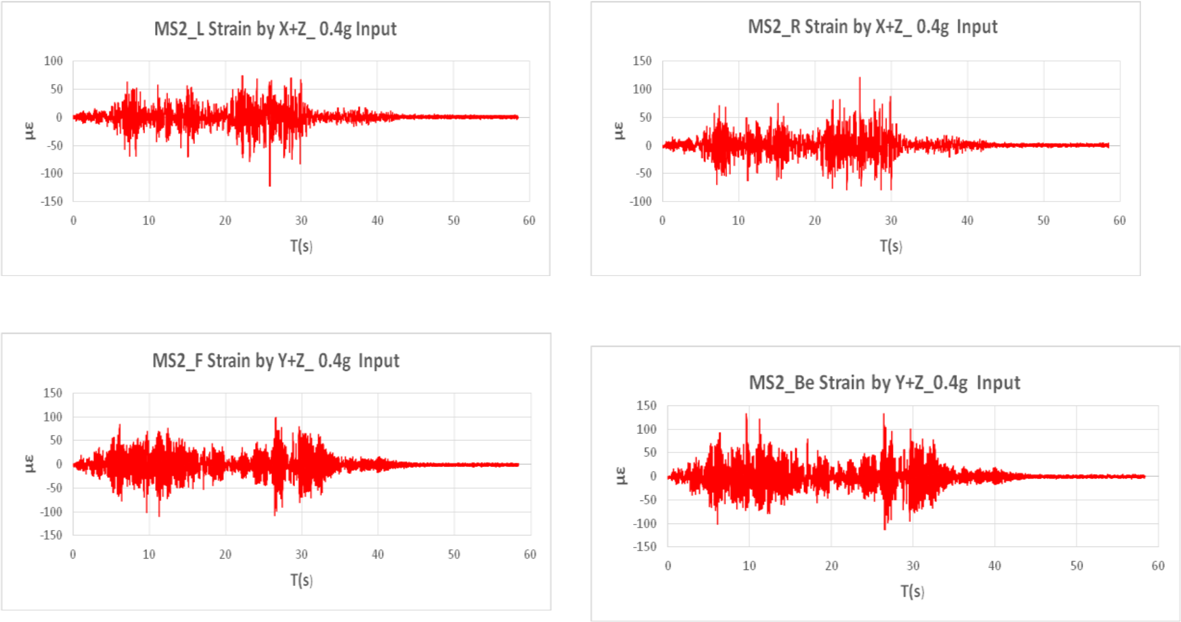


Fig 8. The strain-time history of the root of high voltage bushing in Case 5 and Case 7

Table 5. The strain peak of the strain test points (Unit: με)

Case	The root of hoist seat (steel，MS1)	The root of high voltage bushing（porcelain, MS2）	The root of the cantilever conservator (steel, MS3, MS4)
2	112	46	127
3	95	51	40
5	294	122	380
7	206	133	112

4. CONCLUSION

The test results indicate that the reactor has an excellent seismic performance at the PGA of 0.4g. No significant frequency changes in the reactor structure were observed, and all the stress values were less than the static limits of the material strength during the test.

The dynamic amplification effect is stronger at the top of high voltage bushing and at the top of the hoist seat, which is close to 3. The seismic design of the bushing could be unsafe according to the dynamic amplification factor method.

The peak relative displacement at the top of the high voltage bushing is 133mm at the PGA of 0.4g, which may affect the electrical performance of the reactor too.

5. ACKNOWLEDGMENTS

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