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PERFORMANCE STUDY OF ULTRA-HIGH-VOLTAGE CONVERTER UNDER EARTHQUAKE

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Abstract

Aimed to the dynamic response study of large Ultra-High-Voltage (UHV) converter transformer, the 3-D FEM analysis model of a actual isolated ±800kV converter transformer was built considering oil-solid interaction. Then the natural vibration characteristics, dynamic response rules and vulnerable points of isolated ±800kV converter transformer were analyzed based on LS-DYNA software. Then the shaking table test of the experimental model which of scale is 1/4 to pure model was carried out. Simulation and testing results show that interaction of oil and wall of active part has obvious amplification effect on dynamic response of converter transformer, and the oil-solid interaction should be considered in the analysis of natural vibration characteristics and seismic response for converter transformer. The vulnerable points of sleeve are at the root and middle of sleeve and the max tensile and press stress at these points appear in turn. The sleeves of converter transformer have large displacement under earthquake, therefore, electric wire at the top of sleeve should have enough reserved length.

Keywords: converter transformer, oil-solid interaction, seismic response; dynamic analysis, ultrahigh voltage equipment

1. Introduction

The converter transformer is an important electrical equipment in converter station, which usually has two main features: large size and large mass. Under earthquake, especially under high intensity earthquake, converter transformer will have greater seismic force and displacement, as a result, the converter transformer was damaged, which will threaten the safe operation of the converter transformer and brings great economical damage. Since 1960s, earthquake happens many times in China and many converter transformers and other electrical equipments were damaged. Especially in the recent two or three decades, destruction of the power system, especially the high-voltage electrical equipment, has attract people's attention in the destructive strong earthquake occurred in the world. Because the high-voltage electrical equipment is often installed in independent outriggers that form a series system with independent outriggers. Supporter has obvious amplification effect on seismic waves. Due to the special structure form of equipment, little damping ratio of high-voltage electrical equipment, the poor plastic deformation ability of porcelain in equipment , the high-voltage electrical equipment is easy to resonate in earthquake and so on. These reasons aggravate the damage of high voltage electrical equipment. The survey on earthquake disasters at domestic and abroad shows that when the earthquake occurs, the main transformer in the substation maybe collapse, slip and fracture of the porcelain bushing and so on, Therefore, the earthquake resistance of the transformer has been one of the hot topics in civil engineering, earthquake engineering and electronic engineering.

In this paper, the 3-D FEM analysis model of a actual ±800kV converter transformer was built considering oil-solid interaction, The oil-solid interaction has influence on dynamic response of converter transformer and seismic response rules were studied.

2. THE SURVEY ON EARTHQUAKE DISASTER OF HUGE TRANSFORMER IN CHINA

2.1 Earthquake disaster of huge transformer

Strong earthquake severely threaten the safe operation of power system and it causes serious destruction of various types of electrical equipment. Now, converter transformer and its own characteristics become more and more important influence to the safety of the power system under earthquake, such as converter transformer has complex, subtle structure and the relatively weak seismic capacity, converter transformer need the relatively high value of equipment, converter transformer is difficult to maintenance after earthquake and its restore cycle is longer, etc. In recent years, because of the destruction of converter transformers caused by earthquake, large-area blackouts happens occasionally around the world, which badly affects power supply and disaster recovery. Since the 1960s, earthquake happens many times in China and many of converter transformers and other electrical equipments were damaged by larger earthquake, such as 1962 Heyuan earthquake in Guangdong Province, 1966 Xingtai earthquake, 1969 Yangjiang earthquake in Guangdong Province, 1970 Tonghai earthquake in Yunnan Province, 1975 Haicheng earthquake, 1976 Tangshan earthquake, 1996 Baotou earthquake, 1999 Chi-Chi (Taiwan) earthquake and 2008"5.12" Wenchuan earthquake. Seismic performance of the converter transformers inferred from earthquake disaster data is one of the most important analytical tools. Therefore, there are many research units in the world devoted to this research.

2.2 Survey on main earthquake disaster of transformer in Wenchuan earthquake of China

During the M8.0 Wenchuan earthquake on May 12, 2008, according to incomplete statistics, there are about 109 110kV and above main transformers damaged, including eight 500kV transformers, seven 500kV high-voltage reactors, fifty 220kV transformers, ninety-two 110kV transformers. The damage of transformer in “5.12” Wenchuan earthquake is shown in Table 1.

Table 1 – the damage of transformer in "5.12" Wenchuan earthquake

Failure Types / Voltage Grade	Main Transformer Oil Leakage	Main Transformer Action		Derailment and Displacement	Cashing
		Heavy Gas	Differential		
500kV	2	0	0	0	13
220kV	18	2	2	11	17
110kV	20	0	0	22	50
35kV	2	0	0	1	11
10kV	0	0	0	0	4

As can be seen from the table above, during “5.12” Wenchuan Earthquake, the transformer equipment is damaged more seriously, the main earthquake disasters is as follows:

(1) The transformers occur large displacement and fall off from platform, as shown in Fig.1 and Fig.2.

(2) Medium-voltage and high-voltage bushing fracture. transformers malposition and transformers oil leakage, as shown in Fig.3. Most of the oil leakage for the transformer is caused by the damage of the bushing. Therefore, it is very necessary to improve the seismic capacity of the transformer bushing.

(3)Transformer fire or malfunction. Because the transformer is filled with insulating oil under earthquake action, the seismic acceleration response on transformer is great, causing oil-solid interactive vibration for transformer, which may make insulating safety distances too near, then causing transformer and bushing fire. As shown in Fig.4 .

Fig.1 – Power Transformer falling platform

Fig.2 – Shift of power transformer

Fig.3 – Oil leakage at the bottom of casing

Fig.4 – 500kV power transformer on fire

3. THE FINITE ELEMENT MODEL OF HIGH VOLTAGE CONVERTER TRANSFORMER

A ±800kV converter transformer, located in HVDC substation of high intensity seismic area in China, is used for the analysis model, converter transformer structure as shown in Fig.5. The mass of each part is shown in Table 2. The transformer body mainly includes the iron core and the winding that usually is fixed on the base plate of converter transformer oil tank by positioning device. In order to reflect the real structure layout and consider the stability of the tank under earthquake, the inner core and the winding should be regarded as entity unit when to carry out the finite element analysis . Under normal operating conditions, the inner of oil tank and oil pillow is filled with insulating oil, and insulating oil mainly plays the role of insulation and cooling. Oil is evenly distributed into the tank and the oil pillow, and the mass is evenly distributed, Oil is regarded as flowing medium that will have oil-solid interaction with tank wall and converter transformer. Therefore, in order to get the accurate seismic response, the liquid boundary condition of the converter transformer can not be ignored.

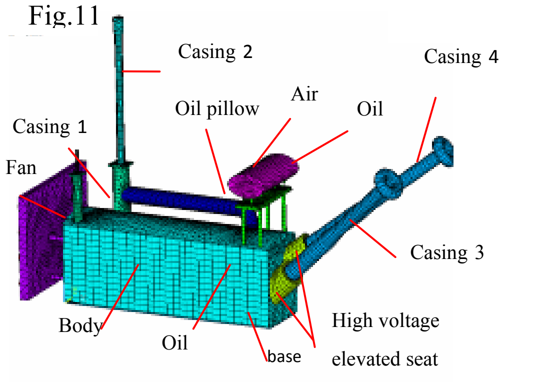


Fig.5 – Structure and FEM model of converter transformer

Table 2–Component mass of 800KV converter transformer

Structure composition	mass/t	Material properties
Transformer body	285	Q235D
High and low pressure rise seat	74.7	Q235D
Fan	8.7	Q235D
Oil pillow	4	Q235D
Oil in the Transformer	130.5	A fluid model with density of $0.85kg/m^3$
Oil in cooling device	1.7	A Solid model with density of $0.85kg/m^3$
Oil in pillow	4.35	A Solid model with density of $0.85kg/m^3$
Total	509	

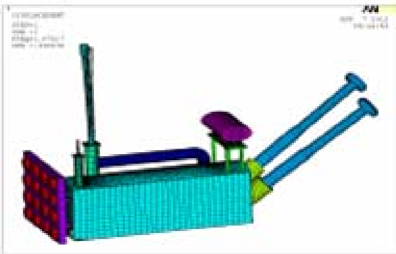
In this paper, the impact of oil in the tank on tank body is mainly considered, and the oil-solid interaction model is used to describe oil in the tank. Because the grid points in the oil are continuously updated according to the motion of the liquid free surface or the movement of contact between structure and oil. The nonlinear effect of moving boundaries should be incorporated into calculating methods. Finite-element discrete scheme is used in the spatial domain, and fractional step method is used for Navier-Stokes Equations in Time-domain, and the High-voltage bushing and body are connected by flange. An elastic connection is formed between bonding materials (cement) and the flange, and the flange connection can be regarded as flexible node, rather than rigid node. The mechanical model of high voltage bushing flange connection can be regarded as a semi-rigid joint model. According to the Chinese code for seismic design of electric power equipment, the bending stiffness calculating formula for this flange connection is

$$K_c = \beta \frac{d_c h_c^2}{t_e^2} \tag{1}$$

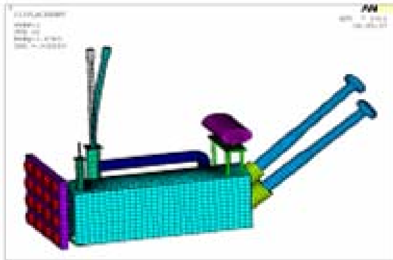
Where K_c is bending stiffness, β is calculation coefficient, which chooses 6.54×10^7 based on standard. d_c is the outer diameter of the adhesive binding part of the high-voltage bushing, and h_c is adhesive binding height between the high-voltage bushing and flange. t_e gap distance between flange and the high-voltage bushing.

3.1 The analysis of natural vibration characteristics

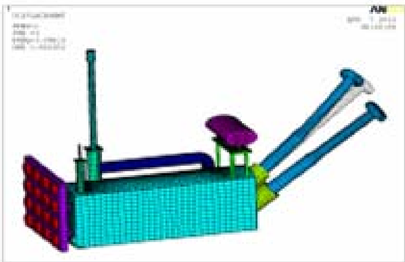
The fluid unit is used to simulate oil in the main body and oil-solid interaction between tank and oil, The first 10 vibration modal parameters for ABB converter transformer and bushing system are obtained based on subspace iteration method. The natural vibration frequency of ±800kV converter body is 15.2Hz and the first 4 vibration modal shapes are shown in Fig.6. From these we can seen, whether it is a 220kV casing or a 800kV casing, the natural frequencies are all in the period of the earthquake wave. Especially for 800kV casing, because its length is longer and its weight is heavier, it is very easy to resonate.



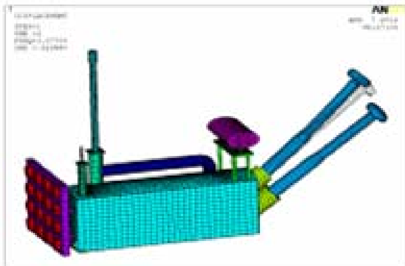
The first mode (1.675 Hz)



The second mode (1.679 Hz)



The third mode mode (3.658 Hz)



The fourth mode (3.678 Hz)

Fig.6 — Mode of converter transformer

3.2 Analysis of seismic response for converter transformer

The seismic fortification intensity is eight degree(0.30g), its site class is II site. El Centro wave, Taft wave and Kobe wave are used as the inputting seismic wave. The peak of inputting seismic waves are 0.31g and 0.51g, the finite element analysis is carried out in this seismic wave at x direction (that is the short side of the converter transformer) and y direction (that is the long side of the converter transformer) and calculate acceleration, displacement and distribution of stresses of the converter transformer.

3.2.1 Analysis of displacement response

Under the action of two-direction input El Centro wave, Taft wave and Kobe wave with the peak of 0.31g and 0.51g, the responses peaks at the top of cashing 3 and cashing 4 are shown in Table 3. Because the stiffness of converter transformer is higher than cashing, under the action of these three waves, the relative displacement of the converter transformer is relatively small and the relative displacement response peak at the top of casing is larger than converter transformer. Therefore, in order to avoid casing to be pulled by wire that caused by non-uniform phase motion between casing of converter transformer and wire, the wire at the top of the casing should set up enough distance of stretch out and draw back, or properly increasing the conductor sag.

3.2.2 Analysis of acceleration response

The acceleration at the top of converter transformer and cashing, and dynamic magnification factor are shown in Table 4. From the table we can see that the average of maximum acceleration dynamic magnification factor at the top of cashing 3 is 3.30, and the cashing 4 is 3.731, the converter transformer is 1.265. Therefore, we can conclude that the converter transformer has magnification effect on seismic wave. In dynamic analysis, converter transformer and its inner oil can not be seen as rigid body, on the other hand, because the dynamic magnification factor of the casing system is large, so that it is easy to resonate. We should take effective measures to reduce the acceleration dynamic magnification factor at the top of cashing.

Table3— Displacement of cashing and converter transformer and oil tank (mm)

Working condition		Direction	Base displacement	Bottom of oil pillow	Cashing3	Cashing4
0.31g	El Centro wave	X	1.439	0.393	8.001	9.797
		Y	0.605	0.528	5.142	4.444
	Kobe wave	X	11.828	0.994	33.257	36.667
		Y	20.109	1.878	37.494	40.733
	Taft wave	X	18.589	1.235	19.20	23.204
		Y	19.390	1.298	25.942	26.883
0.51g	El centro wave	X	2.656	0.83	15.98	16.541
		Y	1.615	0.801	11.20	8.458
	Kobe wave	X	27.290	2.384	75.071	71.662
		Y	45.137	5.208	78.047	82.746
	Taft wave	X	39.123	2.281	38.448	45.194
		Y	38.962	5.974	45.840	50.54

Table—4 Acceleration at the top of cashing (g) and converter transformer

Working Condition		Direction	Cashing 3	Cashing 4	Bottom of body	Dynamic magnification factor		
						Cashing3	Cashing4	body
0.31g	El Centro wave	X	0.916	0.946	0.363	2.936	3.032	1.171
		Y	0.981	0.989	0.371	3.259	3.286	1.197
	Taft wave	X	0.966	0.985	0.373	3.178	3.240	1.203
		Y	0.954	0.967	0.369	2.991	3.031	1.190
	Kobe wave	X	0.924	0.922	0.376	2.952	2.946	1.213
		Y	0.987	0.959	0.381	3.123	3.035	1.229
Average		X	0.952	0.954	0.371	3.330	3.330	1.196
		Y	0.984	0.958	0.374	3.316	3.316	1.205
0.51g	El Centro wave	X	1.742	1.890	0.632	3.363	3.649	1.239
		Y	1.609	1.823	0.613	3.106	3.519	1.202
	Taft wave	X	1.598	1.991	0.633	3.115	3.881	1.241
		Y	1.595	1.796	0.621	3.085	3.474	1.218
	Kobe wave	X	1.646	1.847	0.631	3.209	3.600	1.237
		Y	1.695	1.959	0.702	3.317	3.834	1.376
Average		X	1.685	1.962	0.632	3.225	3.731	1.239
		Y	1.710	1.827	0.645	3.180	3.677	1.265

4. ANALYSIS FOR THE SHAKING TABLE TEST OF HIGH-VOLTAGE CONVERTER TRANSFORMER

4.1 The design of statistic testing scheme

The hybrid-similar model is used in this experiment, the emphasis of this simulation is to ensure that the stiffness of structure is similar. Therefore, whether the structure is into the elastic-plastic state that can be sure based on strain response in this experiment. he similarity relation of shaking table test of high-voltage converter transformer model is built according to the basic equations of motion, this similar relation should meet the similarity for particle motion balance equation, the similarity for boundary condition and the similarity for motion initial condition.

The similar relation can be given based on dimensional analysis, as shown in the following formula

$$\sigma = f(l, E, \rho, t, u, v, a, g, \omega) \tag{2}$$

Where σ is reaction stress, l is member sizes, E is elastic modulus, ρ is mass density, t is time, μ is response displacement, v is response speed, α is response acceleration, g is gravitational acceleration, ω is self vibration frequencies. l , E, α are regarded as base quantity. A in the prototype structure is defined as A_y, which is Am in the model. So the similarity ratio of A is A_m/A_y. The model proportion is 1/4, the model design is based on the similarity theory.

According to the carrying capacity of shaking table and the total weight of structure, the similarity relations between model and prototype is shown in Table 5.

Table 5— the similarity relations between model and prototype

Similarity coefficient	Symbol	Formula	Ratio（model/prototype）
Size	S_L	Model(L) / Prototype(L)	1/4
Elastic modulus	S_E	Model(E)/Prototype(E)	1
Acceleration	S_a	Model(a)/Prototype(a)	1/0.6
Mass	S_m	$S_m = S_E S_L^2 / Sa$	1/26.7
Time	S_t	$S_t = \surd S_L/Sa$	0.387
Frequency	S_f	$S_f = 1/S_t$	2.582
Velocity	S_v	$S_v = \surd S_L Sa$	0.6455
Displacement	S_u	$S_u = S_L$	1/4
Stress	S_σ	$S_\sigma = S_E$	1
Strain	S_ζ	$S_\zeta = 1$	1
Force	S_F	$S_F = S_E S_L^2$	1/16
Stiffness	S_K	$S_K = S_E S_L$	1/4
Energy	S_{EN}	$S_{EN} = S_E S_L^3$	1/64

The model of converter transformer body is made by steel plate, and water is used to simulate the oil in converter transformer inner. According to arrange the lead evenly to increase the density of effective model material in structure. The model of converter transformer cashing is made by steel pipe, the reduced-scale model of cashing system is designed by stiffness similarity, according the stress of the steel pipe to judge the state of the prototype casing system. Fig.7 is the experimental model.

Fig7 — Experimental model

Fig.8 Location of lead rubber bearing

4.2 Analysis of vibration table test results for converter transformer

The model is a 800kV converter transformer, as shown in Fig.1, and it is located in the II site class, field basic earthquake intensity is 8(0.30g). El Centro wave, Taft wave and Kobe wave are used to analyze the seismic responses of transformer for isolation and non-isolated structural and the inputting excitation wave is white noise with a band width of 0.1 to 50Hz and its peak acceleration is 0.1g.

4.2.1 Analysis of the acceleration response

Fig.9 is layout of measuring points, and The maximum acceleration response at different locations of the seismic isolation and consolidation are shown in Fig.10

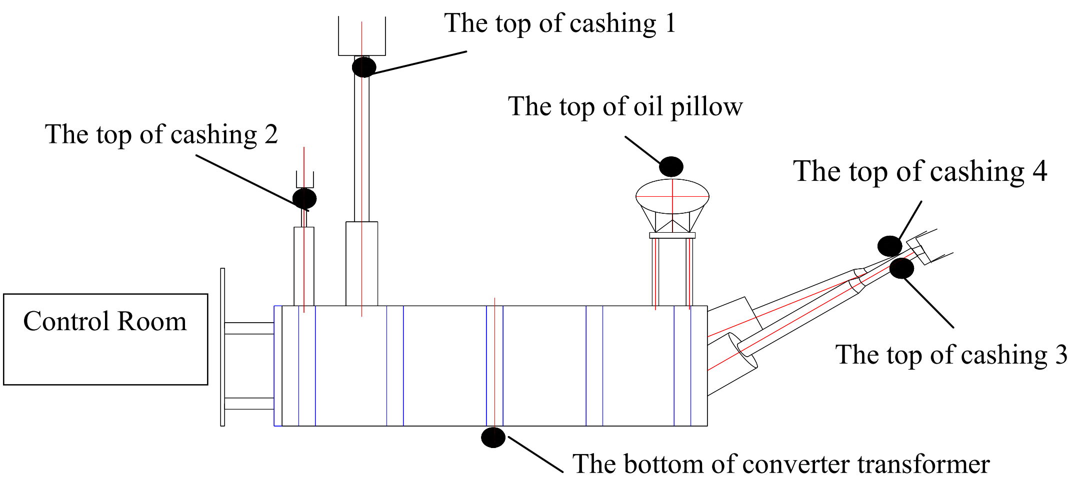
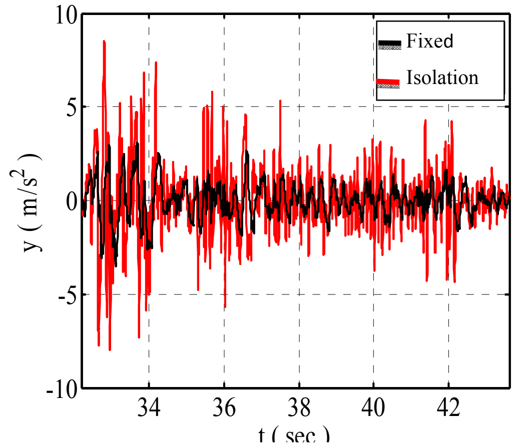
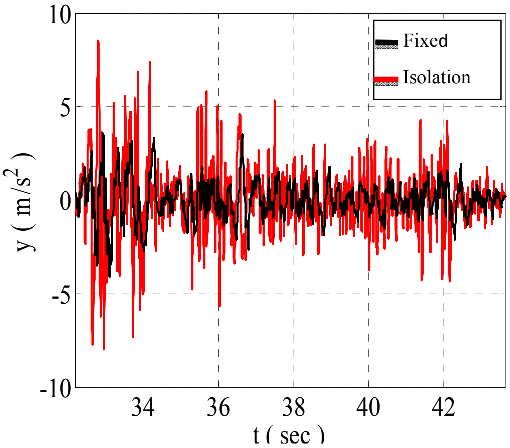


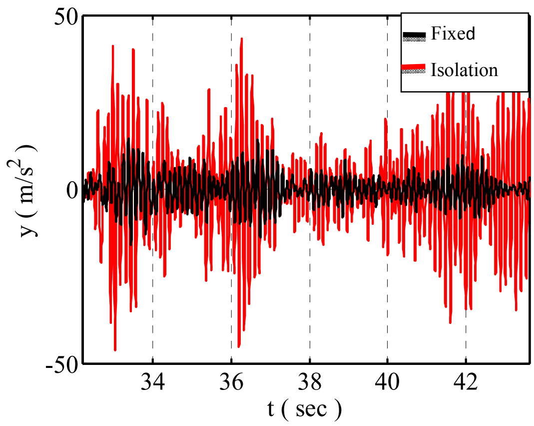
Fig.9 — layout of measuring points



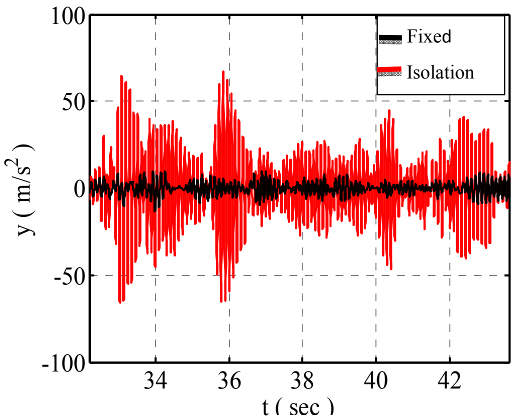
The bottom of converter transformer



The top of oil pillow



The top of cashing 2

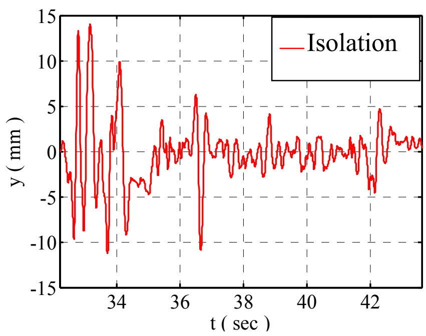


The top of cashing 4

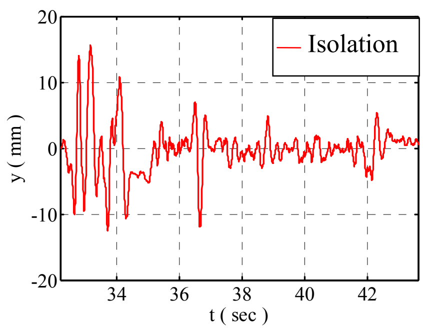
Fig.10 —Acceleration of cashing (g) and converter transformer

4.2.2 Analysis of displacement for isolation layer

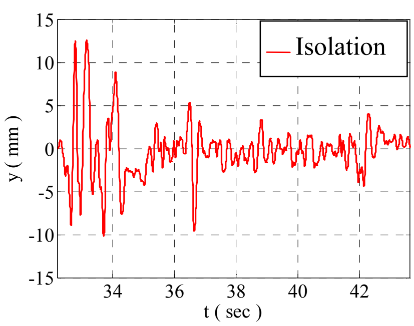
Under strong earthquake, when the El Centro wave inputting is x direction, the displacement response of isolation layer is shown in Fig.11, and when the El Centro wave inputting is y direction, the displacement response of isolation layer is shown in Fig.12.



central place of X direction

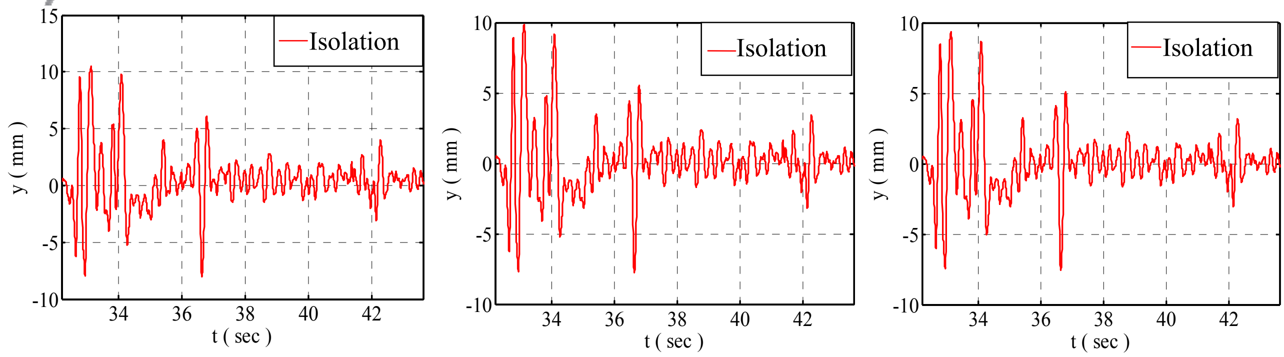


left place of X direction



right place of X direction

Fig.11—Displacement of isolation layer in inputting X direction El Centro wave



central place of Y direction   left place of Y direction   right place of Y direction

Fig.12－Displacement of isolation layer in inputting Y direction El Centro wave

5. CONCLUSION

（1）According to the investigation results of earthquake damage in Wenchuan earthquake, There are three main damage forms: the transformer body has large displacement or the transformer fall off from platform because shear force at the bottom of the body is too large, medium-voltage and high-voltage bushing fracture because the stress at the bottom of cashing is beyond the ultimate strength, and transformer occurs short circuit because the acceleration response of transformer body is too large.

（2）According to the finite element analysis for a actual ±800kV converter transformer, We may conclude that the weakest part of cashing is at the bottom of cashing and the middle part of cashing under strong earthquake. In these two positions, the maximum value of tensile stress and compressive stress appear alternatively, when the maximum stress of converter transformer is beyond the yield strength of material, it will get into plastic state.

（3）According to the shaking table test of high-voltage converter transformer, the acceleration of converter transformer adopting based isolation should be reduced to below 37% under strong earthquake. Except for cashing 2, the acceleration response of each part of converter transformer adopting isolation should be less than the 34% response of seismic converter transformer under the excitation of earthquake wave in x direction, and that is less than the fixed structure 49% under earthquake at y direction.

6. ACKNOWLEDGEMENT

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