Parameter Analysis and Shaking Table Test on Seismic Isolation System of Transformer with Bushings

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SUMMARY:
Earthquake damage many times in history indicate that the destroy type of large power transformer is diverse in earthquake and vulnerability is very high. Isolation technology can effectively reduce seismic response of the transformer and bushings, but transformer isolation layer design and parameter selection have a larger impact on the isolation effect. Firstly, one transformer model installing 220,500 kV real bushings for testing and analysis is designed which its structural dimension is closer to true transformer. Multi-particle analysis model of the transformer with bushings isolation system (TBIS) and the equations of motion are established, and calculation procedures are compiled using MATLAB program. Secondly, impacts analysis on equivalent horizontal stiffness and damping ratio of the isolation layer are carried out subjected to earthquake. Reasonable ranges of stiffness and damping parameters have been determined. Earthquake simulator testing of the transformer with real bushings is implement which transformer tank filled with water in the test. Acceleration, displacement and stress response of transformer and bushings with or without isolation bearings were obtained. Analysis and experiments show that the rational designing isolation layer parameters can effectively reduce the seismic response of transformers and bushings. In conclusion, mentioned above research have reference role to seismic isolation design and application for power transformer and bushings for the future.

Keywords: transformer and bushing; seismic isolation technology; earthquake response; parameter analysis; earthquake simulator testing

1. GENERAL INSTRUCTIONS

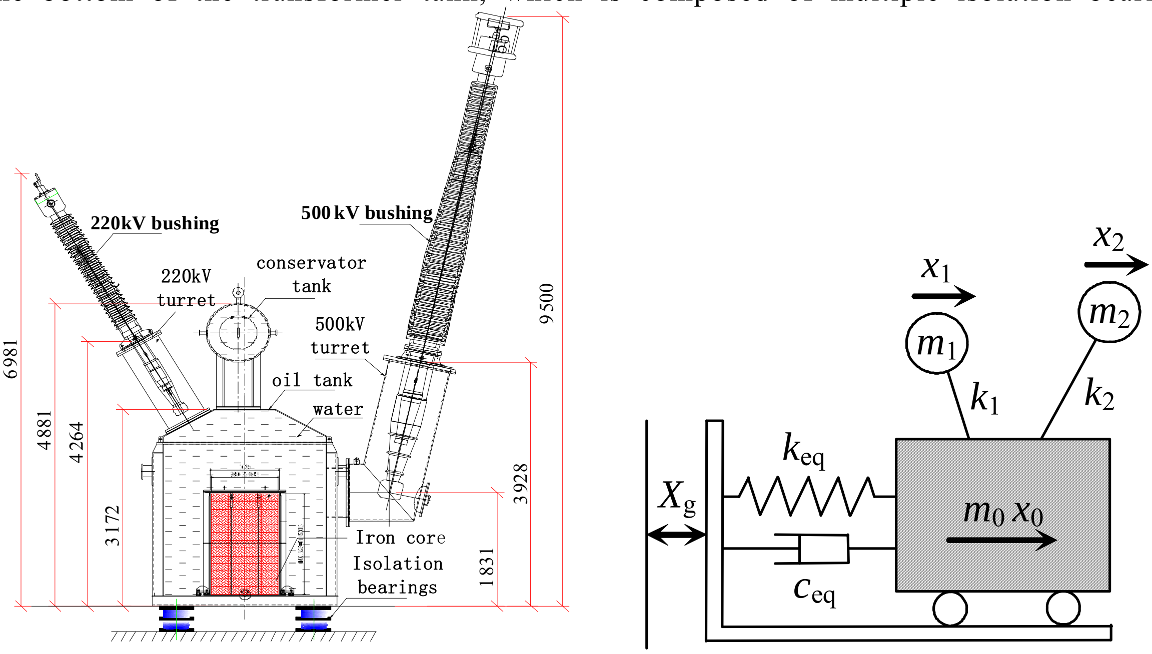
Significant damage in the 2008 Wenchuan earthquake in China indicate that the destroy type of large power transformer is diverse in earthquake and vulnerability is very high. Disaster recovery is difficult, long recovery cycle, and higher cost of restoration. Reducing acceleration response of the transformer and bushing system is crucial to improving the transformers and bushings seismic capacity and reducing all kinds of earthquake disaster. The transformer with bushings isolation system (TBIS) with bushings is set up isolation layer between the bottom of transformer tank and top of basic, forming the isolation system for complex structure. The TBIS is mainly composed of the upper structure (tank, casing, radiator and ancillary facilities), the isolation layer, substructure, or foundation. Compared with the stiffness of the upper structure, the stiffness of the isolation layer is very small. The structural horizontal deformation is mainly concentrated in the isolation layer under the earthquake. By adjusting stiffness, damping and other parameters of the isolation layer, the natural vibration period of the structural system will be extend, and the seismic response of the acceleration and internal force of the structure or equipment will be reduce. However, as the stiffness of isolation layer is lower, the displacement of the structure will be increasing under the earthquake. As important electrical equipment of the power system, it is not only to reduce the acceleration and internal force response of the upper structure, but also to limit the displacement response of the TBIS. If the displacement response is too large, there will be arise some new problems, such as inadequate electrical insulation distance, conductor pull bad adjacent equipment. Thus, compared to the building structure, bridge, common equipment structure, there is a large difference about the transformer seismic isolation design.

Studies have shown that as long as selecting the appropriate design scheme and determining reasonable isolation layer parameters, base isolation can effectively reduce the transformer tank and the bushing acceleration, internal force response, and effectively control the displacement of the isolation layer and the top of the bushing. Otherwise, not only cannot get a better isolation effect, but may enlarge the seismic response. Therefore, it is necessary to carry out impact studies of the transformer isolation layer parameters. In addition, Since the transformer has a complex structure, the huge size and heavy weight, and Limited to the constraints of the existing shaking table test, there are greater difficult about the real transformer shaking table test study. Analysis of existing research found that it has been often a great simplification of the transformer structure, not a true reflection of the seismic response of the transformer and bushing system.

Firstly, one transformer model installing 220,500 kV real bushings for testing and analysis is designed, and mathematical model of the transformer casing isolation system is established. Using MATLAB software, numerical calculation procedure of the TBIS are compiled under The earthquake, impacts analysis on isolation layer parameters are carried out subjected to earthquake, and reasonable range of stiffness and damping parameters have been determined. Secondly, earthquake simulation tests transformer with bushings with or without isolation bearings are carried out. The characteristics of the transformer isolation technology and response law are further understand, and the parameter values of reasonable obtained by the analysis of the isolation layer parameters has been verified.

2. CALCULATED MODEL OF TRANSFORMER WITH BUSHINGS ISOLATION SYSTEM

As shown in figure 2.1(a) that one transformer model installing 220,500 kV real bushings for testing and analysis is designed. its structure dimensions: length is 3.524 m, wide is 2.424 m and height is 3.172m, the total assembly weight for transformer and bushing system is 45 315kg. Through the flange installed on the elevated seat, Two 220,500 kV true type oil impregnated paper capacitor bushings which filled insulating oil is mounted on transformer tank shell, and installation angle is respectively 30° and 12°. Transformers and bushings isolation system is set up one isolation layer in the bottom of the transformer tank, which is composed of multiple isolation bearing.



(a) Structural designing of TBIS (b) Calculated model

Figure 2.1 Structural designing of TBIS and calculated model

Compared to the tank, the transformer bushing is relatively high and soft. The relative movement is present between the bushing and tank under seismic action. Connected to adjacent electrical equipment through the conductor, the top of displacement of bushings have to be limited, so isolation layer horizontal stiffness are often not designed too small. Based on the above 2 points, to simplify the seismic response analysis of the transformer bushing isolation system, the relative movement between the bushing and tank cannot ignore. Generally, the oil tank, storage tanks, radiator are simplified as single-particle, while bushing equivalent analysis are simplified as multi-particle or single-particle system. As shown in the Figure 2.1 (b) that three particles analytical model of the transformer bushing isolation system is established, which 220,500 kV bushing is respectively simplified to a single particle m_1 and m_2, and the tank is simplified to a single particle m_0. In the model, m_1 is 689 kg, m_2 is 2 813 kg, m_0 is 41 813 kg. k_{eq}, c_{eq} are respectively represented as equivalent horizontal stiffness and the equivalent damping coefficient of the isolation layer. k_1, k_2 are respectively represented as the integrated flexural rigidity of 220,500 kV bushing and turret system.

According to D'Alembert principle, equation of motion of multi-particle analysis model for the transformers with bushings isolation system are established under earthquake:

$$\boldsymbol{M}\ddot{\boldsymbol{X}} + \boldsymbol{C}\dot{\boldsymbol{X}} + \boldsymbol{K}\boldsymbol{X} = -\boldsymbol{M}\ddot{x}_g \tag{2.1}$$

Where: $\ddot{x}_g$ is earthquake ground motion acceleration; $\boldsymbol{X}$ $\dot{\boldsymbol{X}}$ $\ddot{\boldsymbol{X}}$ is respectively the particles displacement, velocity and acceleration vectors; $\boldsymbol{M}$、$\boldsymbol{K}$、$\boldsymbol{C}$ is respectively the mass, stiffness and damping matrix of system. No considering the damping of the upper structure, $\boldsymbol{M}$、$\boldsymbol{K}$、$\boldsymbol{C}$ can be expressed in the following form:

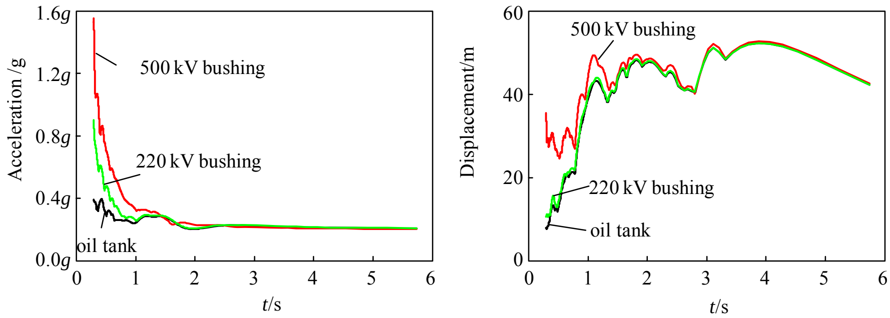
$$\begin{cases} \boldsymbol{M} = \begin{bmatrix} m_0 & 0 & 0 \\ 0 & m_1 & 0 \\ 0 & 0 & m_2 \end{bmatrix} \\ \boldsymbol{C} = \begin{bmatrix} c_{eq} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \\ \boldsymbol{K} = \begin{bmatrix} k_{eq} + k_1 + k_2 & -k_1 & -k_2 \\ -k_1 & k_1 & 0 \\ -k_2 & 0 & k_2 \end{bmatrix} \end{cases}$$

Generally, transformer isolation system is made from different types of isolation bearing. There are a variety of restoring force model of the isolation bearing which two most commonly used is linear and bilinear, such as the restoring force curve of laminated rubber bearings is linear, high damping or lead rubber bearings is bilinear, friction skateboard bearings is ideal elastic, flexible skateboard bearings is the ideal bilinear model. Bilinear model is widely used, the equivalent level of stiffness (k_{eq}) and equivalent damping ratio (ξ_{eq}) can be obtained by equivalent linearization method. In this paper, using MATLAB, multi-particle model calculation procedure for transformer and bushing system is written in which the numerical integration method is Newmark β and Wilson θ, and the restoring force of isolation layer is any multi-linear model.

3. TRANSFORMER ISOLATION LAYER PARAMETERS IMPACT ANALYSIS

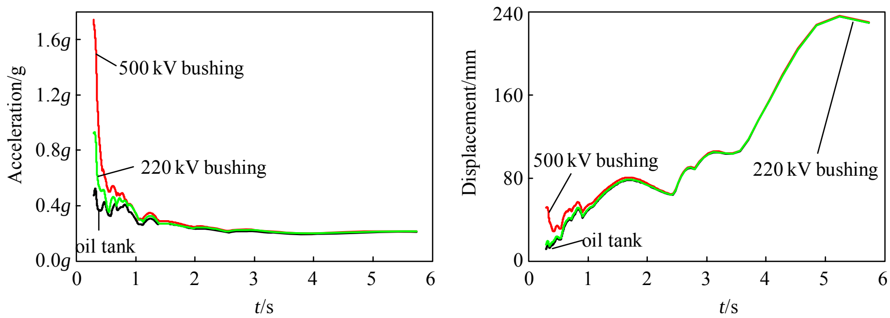
3.1. Impact analysis of the equivalent horizontal stiffness

Assumed no consider the damping of the upper structure, and Assumed as 10% for the isolation layer damping ratio in the analysis, acceleration and displacement response peak of TBIS are acquired When k_{eq} changing 0.05 to 20kN/mm under earthquake. Figure 2 is acceleration and displacement response curves with variable T_{eq} subjected to artificial wave (PGA=0.2g). Figure 3 is acceleration and displacement response curves with variable T_{eq} subjected to Taft wave (PGA=0.2g). As shown in Figure 3.1 and Figure 3.2 that some conclusion are acquired. When T_{eq} less than 1s acceleration response peak of oil tank and 220, 500kV bushing have great attenuation amplitude. When T_{eq} greater than 1s change of acceleration response peak tends to be straight. In general, displacement response peak increases with T_{eq}, but T_{eq} is large enough displacement response have declining trend. When T_{eq} greater than 1.5s oil tank and bushings have the same displacement response which approximated to a whole movement. Therefore, it can be preliminarily determined reasonable range T_{eq} of transformer isolation system is 1-2s.



(a) Acceleration response (b) Displacement response

Figure 3.1 Maximum seismic response curves with variable T_{eq} subjected to artificial wave



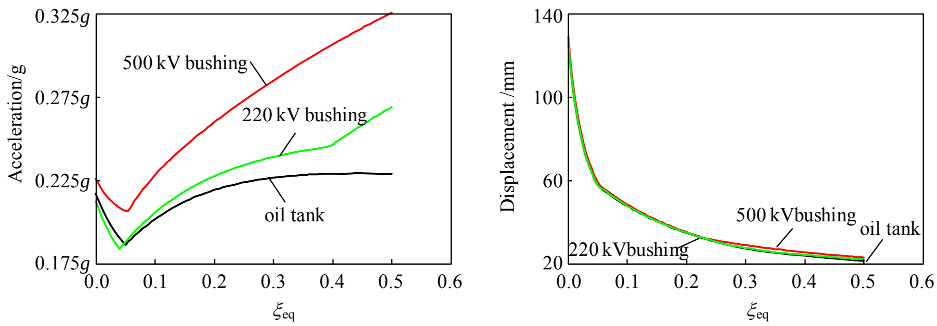
(a) Acceleration response (b) Displacement response

Figure 3.2 Maximum seismic response curves with variable T_{eq} subjected to Taft wave

3.2. Impact analysis of isolation layer equivalent damping ratio

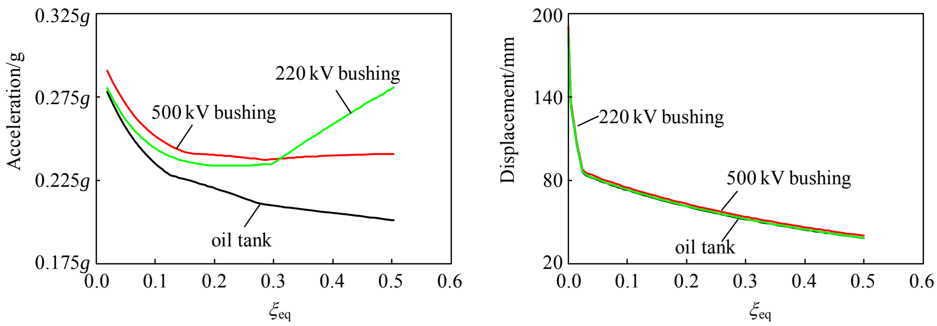
In general, seismic response of base isolated structure has a larger relationship with equivalent damping ratio (ξ_{eq}) of isolation layer. Assumed no consider the damping of the upper structure, and Assumed as 0.41 kN/mm for k_{eq} in the analysis, namely, the natural period of vibration (T_{eq}) is 2.09s. Acceleration and displacement response peak of TBIS are acquired When ξ_{eq} changing 0.5% to 50% under earthquake. Figure 3.3 is acceleration and displacement response curves with variable ξ_{eq} subjected to artificial wave (PGA=0.2g). Figure 3.4 is acceleration and displacement response curves with variable ξ_{eq} subjected to Taft wave (PGA=0.2g). As shown in Figure 3.3 and Figure 3.4 that some conclusion are acquired.

From the point of displacement response, displacement response of oil tank and bushing decreases with ξ_{eq} increasing subjected to inputting whether artificial wave or Taft wave. When ξ_{eq} less than 5% displacement response decreased very fast, but displacement response rate of decline slowed down after ξ_{eq} greater than 5%. And oil tank and bushings have the same displacement response which approximated to a whole movement. From the point of acceleration response, acceleration response and damping ratio relation is more complex which there is have different performance about different structural components and subjected to different earthquake inputting. Although the damping ratio ξ_{eq} can effectively reduce transformer displacement response, but it cannot increase the damping, or there may be magnifying transformer acceleration response. Analysis shows that reasonable rangeξ_{eq} of transformer isolation system is 15%~25%.



(a) Acceleration response (b) Displacement response

Figure 3.3 Maximum seismic response curves with variable ξ_{eq} subjected to ART wave



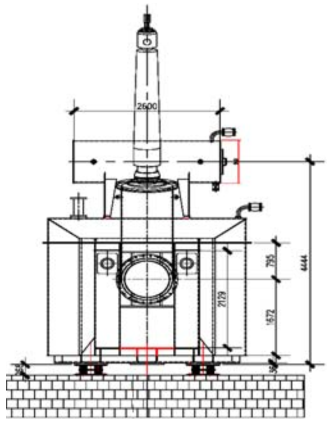
(a) Acceleration response (b) Displacement response

Figure 3.4 Maximum seismic response curves with variable ξ_{eq} subjected to Taft wave

4. COMPARATIVE ANALYSIS OF EARTHQUAKE SIMULATION TEST

Shaking table testing on large power transformer is very difficult. There are two major reasons that transformer structure have large body size, weight heavy, price expensive, and vibration table bearing capacity and geometrical dimensions cannot meet. Therefore, it is often required to greatly simplified or carry out partial seismic test on transformer. In this paper, vibration table testing of transformer with or without isolation are done which transformer testing model shown in figure 2.1(a). The weight and size of testing transformer are the largest in the world. The liquid boundary of transformer tank was filled with water in place of insulating oil, considering the difficulties on transformer tank oil filling during test. Transformer vibration table test as shown in Figure 4.1 was conducted on a large earthquake shaking table which has MTS 6m × 6m three directions and six degrees of freedom in State Construction Engineering Quality Supervision and Inspection Center in Beijing. Three different seismic wave were adopted in the testing which respectively is Taft wave, Shifang wave (SF) and artificial seismic wave (ART). SF wave is the real seismic record of 2008 Wenchuan earthquake in China. ART is designed as artificial wave according to the response spectrum which originated from GB50260-1996 (China Code for Design of Seismic of Electrical Installations). During the earthquake tests, we can get acceleration and displacement responses of the critical parts by setting the acceleration sensor at the transformer, such as the top or bottom of oil tank, the top of bushings and so on. We also can get strain response of bushing bottom by setting strain meters at 220, 500kV bushing bottom.

(a) Transformer on shaking table



(b) Isolation layer layout in testing

Figure 4.1 500kV transformer and bushings system installed on shaking table

4.1. Transformer isolation layer layout

Assumed transformer with bushings isolation system to the single-particle system, calculation formula as shown in Formula 1 for the transformer acceleration response attenuation rate can be deduced.

$$R_a = \sqrt{\frac{1+(2\xi\omega/\omega_n)^2}{\left[1-(\omega/\omega_n)^2\right]^2+(2\xi\omega/\omega_n)^2}} \tag{4.1}$$

Where: ω/ω_n is the ratio of the predominant frequency of seismic input and isolation structural vibration frequency ratio, ξ is the damping of the isolation layer. After repeated calculation, the two new type bearings designed by author have been selected which their models were MRB-110 and MRB-130 as shown in Table 4.1. The isolation bearing arrangement of transformer is shown in Figure 4.1 (b) which average compressive stress of isolation bearing in is 2.50MPa.

Table 4.1 Mechanical performance parameters of designed transformer isolation bearings

Types	Designed area pressure/MPa	Designed bearing capacity/ kN	Horizontal yield force/kN	Post yield stiffness/ ($kN \cdot mm^{-1}$)	Vertical stiffness/ ($kN \cdot mm^{-1}$)	Allowable Horizontal displacement/ mm
MRB-110	8	380	0.0	0.35	372	180
MRB-130	10	530	0.0	0.45	595	192

4.2. Testing results and analysis

4.2.1 Dynamic characteristics of detection results

Inputting white noise, the natural frequency of transformer and bushings with isolation or without isolation are acquired as shown in Table 4.2. The stiffness of the transformer tank is relatively large without isolation bearing which X, Y direction natural vibration frequency are respectively 16.5Hz and12.3Hz.The X, Y direction natural frequency of the transformer with isolation bearing is 1.30Hz, and the isolation layer damping ratio $\xi_{eq} \leqslant$ 12%. The natural frequency of the transformer has a great reduce because of lower stiffness of the isolation layer. However, whether or not the isolation, the natural frequency of the bushings changes very small.

Table 4.2 The natural frequency of transformer and bushings /Hz

Structural component	X direction		Y direction	
	without isolation	with isolation	without isolation	with isolation
Oil tank	16.5	1.30	12.3	1.30
220kV bushing	4.81	4.76	7.10	6.82
500kV bushing	3.67	3.88	3.30	3.27

4.2.2 Acceleration and displacement response results

Definition of response reduction coefficient λ as shown in formula 4.2:

$$\lambda = \frac{R_{iso} - R_{anti}}{R_{anti}} \times 100\ \% \tag{4.2}$$

Where: R_{iso} is seismic response of transformer and bushings with isolation; R_{anti} is seismic response of transformer and bushings without isolation.

Table 4.2 Acceleration peak and reduction coefficient of the bushings with and without isolation /g

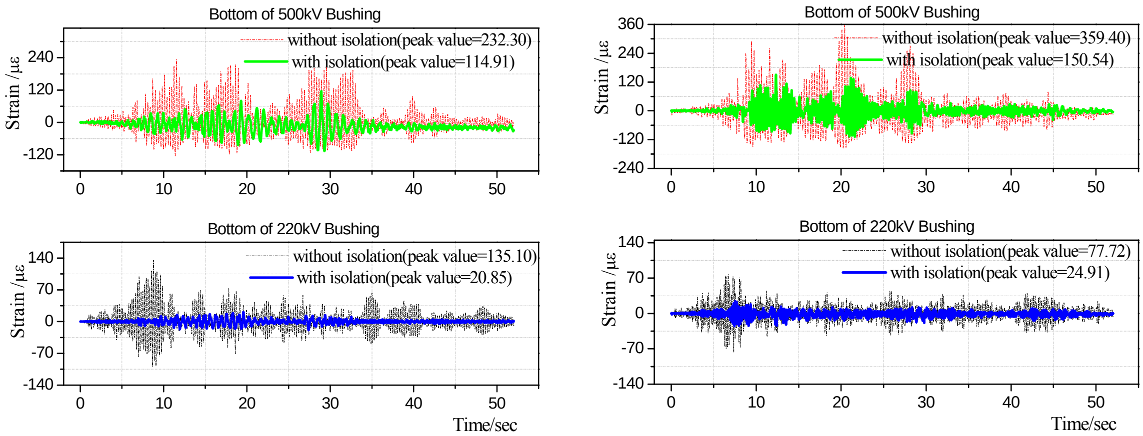
Measure point \ Seismic input		Taft wave (PGA=0.3g)		ART wave (PGA=0.4g)		SF wave (PGA=0.3g)	
		X direction	Y direction	X direction	Y direction	X direction	Y direction
Top of 220kV bushing	without isolation	2.316	1.375	3.473	3.389	3.116	2.441
	with isolation	0.911	0.973	0.866	1.024	0.933	0.632
	λ_a	-60.66%	-29.24%	-75.07%	-69.79%	-70.06%	-74.11%
Top of 500kV bushing	without isolation	1.932	1.70	3.62	3.41	3.258	3.574
	with isolation	1.392	1.28	1.23	1.112	1.514	1.54
	λ_a	-27.95%	-24.71%	-66.03%	-67.39%	-53.52%	-56.91%

Table 4.3 Displacement peak and amplification coefficient of the bushings with and without isolation /mm

Measure point \ Seismic input		ART wave (PGA=0.4g)		SF wave (PGA=0.3g)	
		X direction	Y direction	X direction	Y direction
Top of 220kV bushing	without isolation	30.3	21.32	40.07	16.05
	with isolation	71.46	83.2	76.76	47.3
	λ_d	2.36	3.9	1.92	2.95
Top of 500kV bushing	without isolation	47.21	68.83	71.66	82.75
	with isolation	203.38	119.31	210.8	86.15
	λ_d	4.31	1.73	2.94	1.04

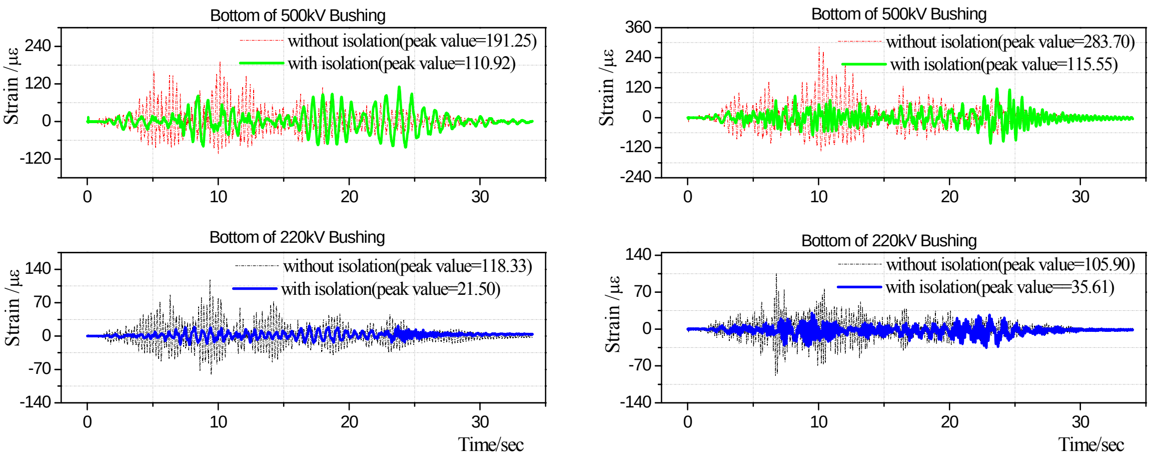
Table 4.4 Strain peak and reduction coefficient of the bushings with and without isolation bearings / $\mu\varepsilon$

Measure point \ Seismic input		Taft wave (PGA=0.3g)		ART wave (PGA=0.4g)		SF wave (PGA=0.3g)	
		X direction	Y direction	X direction	Y direction	X direction	Y direction
Top of 220kV bushing	without isolation	94.0	43.1	126.86	108.24	131.81	78.49
	with isolation	19.55	35.44	24.67	34.83	22.35	25.45
	λ_s	-79.20%	-17.77%	-80.56%	-67.83%	-83.04%	-67.57%
Top of 500kV bushing	without isolation	114.9	136.9	205.15	290.23	226.63	363.03
	with isolation	124.31	126.68	110.64	113.01	123.24	154
	λ_s	8.19%	-7.47%	-46.07%	-61.06%	-45.62%	-57.58%



(a) X direction (b) Y direction

Figure 4.2 Strain response time-history curve of the bottom of bushing: SF /X/Y/0.4g



(a) X direction (b) Y direction

Figure 4.3 Strain response time-history curve of the bottom of bushing: ART /X/Y/0.4g

Because of the limit of the article space, the parts of test results are listed. As shown in Table 4.2 to Table 4.4 that response peak and reduction coefficient λ of transformer and bushings with or without isolation are acquired subjected to above mentioned seismic wave. As shown in Figure 4.2, Figure 4.3

that strain response time-history curve of 220, 500kV bushings are also acquired. Analysis of the above figure and table, we can get the following two points:

1) The seismic response of transformer with bushing isolation systems has close relationship with inputted seismic waves. The isolation layer design in the test can significantly reduce acceleration and strain response of transformer and bushings subjected to ART and SF wave. Compared with ART and SF wave, reduction efficiency of the acceleration and strain response were not satisfactory subjected to Taft wave, and sometimes response are even more enlargement. The main reason is the stiffness of transformers and bushing isolation systems was designed too high. The natural period of the TBIS ($T_{eq} \leq 1s$) and predominant period of Taft is too closer to making response attenuation is small, and even play an enlarged role.

2) The displacement response of transformer and bushings with isolation has larger magnification than transformer without isolation under different seismic input. For example, the maximum displacement of the 500kV bushing reaches 210mm under SF wave. The main reason is damping of the isolation layer in the test (damping ratio $\xi_{eq} \leq 12\%$) is too small, so hysteretic energy dissipation of the isolation layer is insufficient. the displacement response of transformer and bushings will effectively reduce if the isolation layer damping are appropriate increased or various types of damping devices be worked together isolation bearings.

5. CONCLUSION

In this paper, the multi-particle analysis model of the transformer with bushings isolation system and the equations of motion are established, and calculation procedures are compiled using MATLAB program. Impacts analysis on equivalent horizontal stiffness and damping ratio of the isolation layer are carried out subjected to earthquake, and reasonable range of stiffness and damping parameters have been determined. Shaking table test on transformer with bushings with or without isolation are conducted which acceleration, displacement and strain response are acquired and mutual compared.

1) Isolation layer parameters analysis and seismic simulation testing show that as long as determined reasonable design parameters of isolation layer which can effectively reduce the seismic response of the transformer and bushings. But seismic responses have greater relationship with earthquake inputting and isolation layer parameters. It is necessary to reduce the acceleration and strain response to carry out seismic isolation design, but also to limit the displacement response of the transformer and bushings.

2) It can significantly reduce the acceleration response of transformer and bushings by extending the natural period T_{eq} of isolation layer. The greater the value of T_{eq}, isolation effect will be more obvious. However, isolation effect will be no obviously improved and the displacement of isolation layer will be significantly increased when T_{eq} reaches a certain value. It shows that the ideal natural period T_{eq} of transformer with bushing isolation system are in the range from 1 to 2s.

3) The isolation layer damping ratio ξ_{eq} can effectively reduce the displacement response of transformer and bushings. But with the increase of the ξ_{eq} valued, the acceleration response of transformer and bushings cannot be predicted which may increased or reduced. Therefore, it is important to determine the damping of isolation layer in order to reduce displacement of transformer; otherwise, the excessive damping could amplify acceleration response of transformer and bushings. It shows that the ideal isolation layer damping ratio ξ_{eq} of transformer with bushings isolation system are in the range from 15% to 25%.

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