17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

Experimental Studies of Transformers Isolated with Friction Pendulum System

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Abstract

Power transformers are pieces of equipment essential for the operation of a substation. Together with bushings, which are critical components for their functionality, they have been shown to be particularly susceptible to damage during past strong earthquakes. Traditional seismic design methods usually improve the seismic performance of the transformer-bushing system by the following reinforcement methods: improving the strength of the tank and bushing; using new materials; changing transformer installation type to prevent the transformer from dumping during the earthquake. However, due to the functional requirements of the components of the transformer and the limitations of the materials of manufacture, these reinforcement methods may not effectively to improve the seismic safety of the transformers. The fact that the transformers were seriously damaged in the 2008 Wenchuan earthquake proves that the traditional seismic reinforcement and design methods are invalid. The base isolation system isolates the superstructure from the foundation without changing the superstructure equipment, thereby reducing the seismic response of the superstructure and ensuring the safety and functionality of the superstructure, which has been studied and applied in conventional engineering structures. In this work, base isolation for the seismic protection and retrofit of the power transformers and their bushings was proposed and studied.

Although the technology of base isolation is widely used in the building and the bridge engineering nowadays, the feasibility of the base isolation for the large transformers has not been fully demonstrated yet. Differences between the power transformers and the conventional engineering structures lead to more constraints in the design of isolation systems for the power transformer. Such constraints involve the requirement for small displacement of the isolation system due to the limited slack of high voltage conductors connected to the power transformer; convenience for the connection method of the isolation base to the power transformer; torsion effect caused by highly asymmetric distribution of mass and stiffness of the power transformer tanks. In light of these constraints,the friction pendulum system (FPS) is selected in this work for the seismic isolation of electrical power transformers.

This paper presents a shake table experiment to demonstrate the effectiveness of the selected FPS. Tests were performed on a power transformer-bushing system with/without the FPS. The results show that top acceleration and strain responses of the bushing in the base-isolated transformer-bushing system reduced to 50% of those in the non-isolated system. Meanwhile, the relative displacement of the top of the bushing under the ground motions with the peak ground acceleration of 0.4 g was within 75 mm, which satisfies the slack limitation of the conductors. Therefore, the test validates the effectiveness of FPS for the transformer-bushing system.

Keywords: friction pendulum system; power transformer; shaking table test; base isolation system

1. Introduction

Large power transformers are the core equipment in substations. However, seismic damage data show that large power transformers and their high voltage bushings are extremely vulnerable during strong earthquakes, with various damage types , difficult post-disaster recovery and long recovery period[1-5]. Therefore, improving the seismic capacities of large power transformers is a very important research topic. Seismic responses of high-voltage bushings were studied in the past decades[6]. The Pacific Earthquake Engineering Research Center (PEER) has comprehensively investigated the seismic performances of the 196kV[7], 230kV[8], and 550kV[9] transformer bushings mounted on the rigid steel frames through earthquake simulator experiment and analysis. However, it is difficult to meet the seismic requirements of higher voltage transformers only by relying on traditional seismic design methods such as increasing the strength of materials or strengthening the structure[10,11,12]. What's more, due to the power transformers are not standardized and present high variability in their designs, which makes it difficult to promote the method of local reinforcement[13,14], researchers have turned their attention to the application of base isolation in large power transformer-bushing systems.

The basic isolation technology has the characteristics of clear damping mechanism, obvious effect, simple layout and so on. In the past 30 years, more and more scholars have carried out research on this application for large transformers. As early as 2000, Liu Jiyu, Selahattin Ersoy and others carried out a batch of shaking table tests on the transformer-bushing system including both isolated and fixed at the National Earthquake Engineering Research Center in Taiwan[15,16]. These are the first experimental tests on base isolated transformer models. They chose two base isolation systems: (a)the hybrid isolation system consists of four sets of sliding bearings and two sets of rubber bearings, (b)the friction pendulum system(FPS). Experimental results indicate that both two base isolation systems have good isolation effect on the transformer model. In addition, the mathematical model of isolation bearings and transformer-bushing system were also studied by system identification. Kostis Oikonomou et al.[17] put forward the isolation design method of power transformer through transformer-bushing-isolation system shaking table test and finite element analysis. Ma Guoliang et al.[18] verified the effectiveness of the composite isolation system through the shaking table test. However, these studies are mainly based on the commonly used hybrid bearings, and the test model sizes are often different from the actual ones. Therefore, the full-scale shaking table test data of large power transformers using sliding friction pendulum bearings is still lacking.

In this paper, sliding friction pendulum isolation bearings are used for basic isolation of large power transformers. Through a full-scale shaking table test, the seismic responses of the transformer-bushing system with isolation and without isolation were compared and the isolation efficiency of the DFP bearing was verified.

2. Experimental Program

2.1 Test specimen and isolation system

The shaking table test was conducted at the Chinese State Key Laboratory (SKL) of disaster reduction in civil engineering. The specimen was a full-scale simulated transformer-bushing system, including main components such as tank, turrets, bushings, oil pillow and radiator, as shown in Fig.1. In order to investigate the seismic performance of the bushing in two different installation methods, installed on the turret of the tank roof and installed on the L-shaped turret protruding from the side wall of the tank, the transformer tank was designed as shown in Fig.1. Two same real 220 kV porcelain bushings, the lateral bushing (LB) and the top bushing (TB), were mounted on the turrets.

The outer contour length, width and height of the transformer-bushing system are 4.58m ×3.88m× 6.90m, respectively. The long axis direction corresponds to the x direction in Fig.1, and the y direction is perpendicular to the paper. To simulate a real transformer tank filled with insulating oil, the total weight of the transformer-bushing system after water injection is 19.80t. The total length of each bushing is 4.58m, the length of air-side porcelain bushing is 2.33m, and the length of oil part is 1.38m. The section of the bushing is a circular ring, with its inner diameter of 240 mm and outer diameter of 280mm. The length of oil pillow is 3.00m, and the outside diameter is 0.80m.

The arrangement of the transformer-friction pendulum isolation system is shown in Fig.1. The bottom plate of the transformer tank was welded to two foundation beams, and the double friction pendulum(DFP) bearings were connected to both ends of each foundation beam (i.e., 4 DFP bearings in total). The DFP bearing, designed by ourselves, consists of a top plate, a bottom plate, and an inner cylindrical slider. Bottom plates of all the DFP bearings were mounted on a 4 m × 4 m shaking table. The profile of the DFP bearing are also given by Fig.1. The exterior of the DFP bearing is a cuboid of 310 mm × 310 mm × 120 mm. Spherical surfaces of the top and the bottom plate have the same radius of 775 mm, and the distance between the center of the slider and the center of the spherical surface equals 40 mm. The maximum allowable horizontal relative displacement between the top and the bottom plates is 176.8 mm, which occurs when the slider collides with the bulging rim of the plates. The DFP bearing was not designed to constrain the uplift; thus, for the purpose of safety, four square-tube restrainers were mounted above the foundation beams — with a space of 20 mm between them in case of the potential uplift of the isolation system.

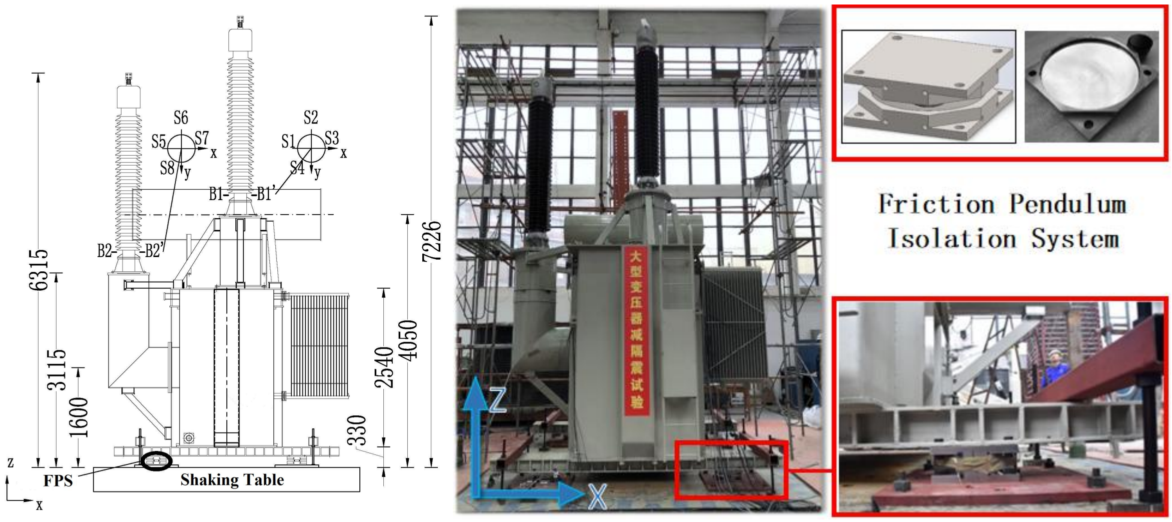


Fig. 1 – Transformer-bushing system and friction pendulum isolation system

2.2 Instrumentation

Location of the sensors in the testing are also shown in Fig.1. Accelerometers and displacement meters were arranged at the top and root of the two bushings, the root of the turrets, the bottom of the box wall, and the top plate of DFP. The accelerometer can measure the three-dimensional acceleration response and displacement, while the displacement meter measures the displacement response in the x and y directions. In addition, four equidistantly pasted strain gauges are arranged on the sections of B1-B1 'and B2-B2' at the root of the air-side porcelain bushing roots, respectively, as shown in Fig.1. In order to monitor motions of the bearing and evaluate the rigid-body rotation of the isolated system, accelerometers and displacement sensors were placed at the top plates of two diagonal DFP bearings.

2.3 Ground motions and test procedure

Three ground motions were employed: Bajiao, Takatori, and the artificial wave IEEETH (Pacific Earthquake Engineering Research Center 2005). Information of these input ground motions is listed in Table 1. Test response spectra (TRS) of these input ground motions, 2 % damped, are shown in Fig.2, and the IEEE 693 required response spectrum (RRS) at the high performance level is also plotted in Fig.2 for reference. and the demand response spectra (RRS) specified in Chinese standard, Code for seismic design of electrical installations (GB 50260-2013), are also drawn in Fig.2 for reference.

Table 1 – Information of input ground motions

Input ground motion	**Year**	**Earthquake event**	**Magnitude**	**Recording station**	**Significant duration**
IEEETH	1992	Landers, America	7.3	Joshua Tree station	25.9 s
Takatori	1995	Kobe, Japan	6.9	Takatori station	9.9 s
Bajiao	2008	Wenchuan, China	8.3	Bajiao station	34.5 s

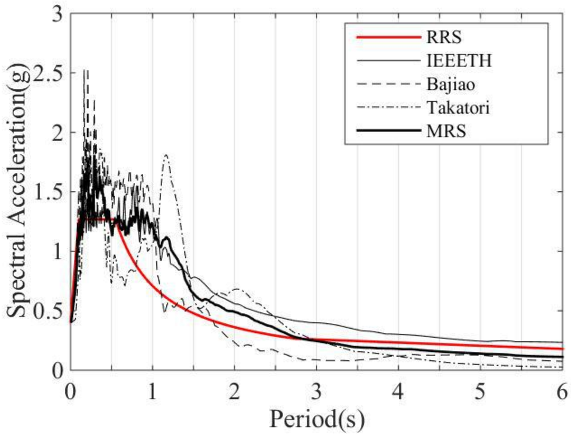


Fig. 2 – TRS of input ground motions, and IEEE 693 RRS

According to each ground motion, the seismic excitation in one-direction, two-direction and three-direction under different PGA was carried out respectively. In the case of multi-direction excitation, the ratio of the peak ground acceleration (PGA) in the X, Y, and Z directions is 1:0.85:0.65. Procedures of the testing under three-direction seismic excitation are listed in Table 2. Except the test of 0.6 IEEETH, the transformer was exited in both the configurations with/without the isolation.

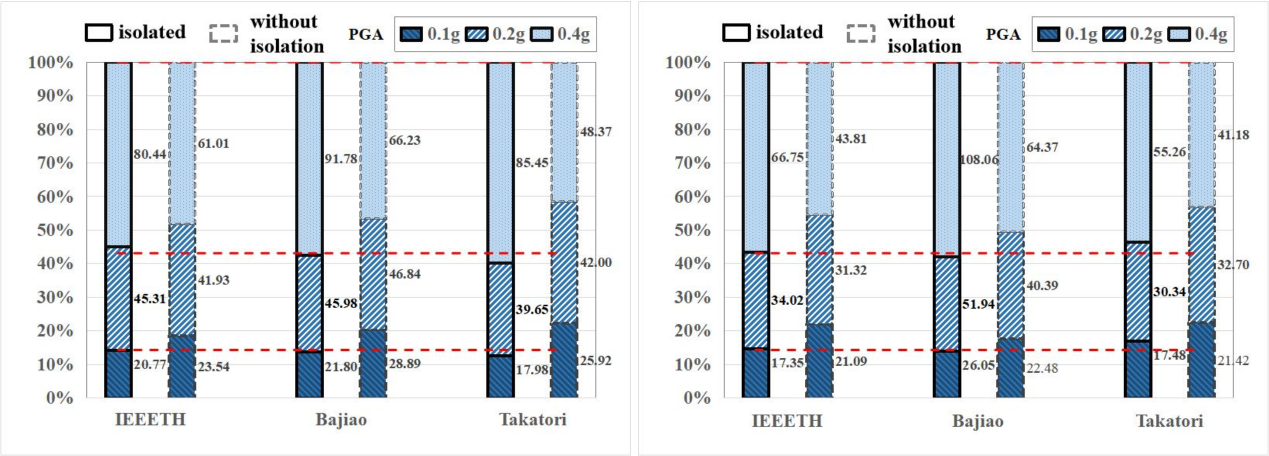
Table 2 – Testing procedures

No.	**Input ground motion**	**PGA (g)**			**State of transformer**
		X dir.	**Y dir.**	**Z dir.**	
1	IEEETH	0.100	0.085	0.065	with/without isolation
2	Bajiao	0.100	0.085	0.065	with/without isolation
3	Takatori	0.100	0.085	0.065	with/without isolation
4	IEEETH	0.200	0.170	0.130	with/without isolation
5	Bajiao	0.200	0.170	0.130	with/without isolation
6	Takatori	0.200	0.170	0.130	with/without isolation
7	IEEETH	0.400	0.340	0.260	with/without isolation
8	Bajiao	0.400	0.340	0.260	with/without isolation
9	Takatori	0.400	0.340	0.260	with/without isolation
10	IEEETH	0.600	0.510	0.390	with isolation

3. Test Results and Evaluation

3.1 Maximum strain responses and isolation efficiency

In order to evaluate the isolation efficiency of the DFP bearing, the maximum seismic responses with/without the base isolation were compared. As the bushings are the most vulnerable components of a transformer-bushing system, the maximum stress of the bushing is adopted as the key criterion for the seismic qualification in current codes. The maximum strain of bushings measured in the testing are shown in Fig.3.



(a) (b)

Fig. 3 – Maximum strain of (a) TB and (b) LB with/without isolation

Fig.3 compares the maximum strain response of TB and LB with and without isolation by using percentage accumulation histogram. The purpose of this is to clearly show the variation of strain response with and without isolation with the increase of PGA. The red dashed line in figure XXX is 1/7 and 3/7, respectively, corresponding to the cumulative strain percentage of 0.1g and 0.2g of PGA without isolation. That is, without isolation, the maximum strain response of both TB and LB is linearly correlated with PGA. With isolation, the strain response showed obvious nonlinearity, that is, when the PGA reached 0.4g, the growth rate of the maximum strain response greatly decreased. When the PGA was 0.4g, the maximum strain of both TB and LB in the case of base isolation was much smaller than the maximum strain without isolation. The maximum isolation efficiency of TB and LB was 41.31% and 41.38% respectively. There are two possible reasons for this phenomenon: first, there is an error between the actual vibration table acceleration and the design acceleration, and the error is more obvious when PGA is small. When PGA is 0.1g, the average ratio of peak acceleration on shaking table to peak acceleration on shaking table without isolation is 112.33% under the same seismic wave input. Another reson is that when the PGA is small, the DFP may not slip.

Furthermore, with the nonlinearity of the DFP bearings, the isolated transformer-bushing system is able to sustain the extremely strong earthquake. Subjected to the IEEETH wave, the maximum strain of the bushings against the PGA are shown in Fig.4. The maximum PGA in the tests with isolation was 0.6 g, whereas without the isolation system was 0.4 g. Because the responses of the non-isolated system are almost linear functions of the PGA, responses of the non-isolated system can be extended to the PGA of 0.6 g, through the linear fitting. The linear fitted responses are given by the dotted lines shown in Figure 9. With the increase of the PGA, the DFP bearing is more effective, and can reduce about 50 % of the seismic responses with the PGA of 0.6 g.

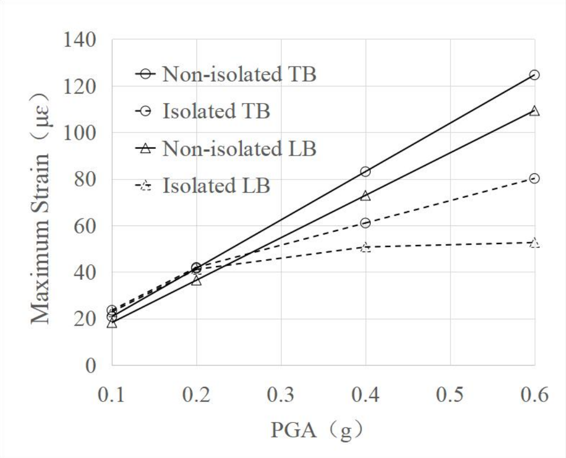
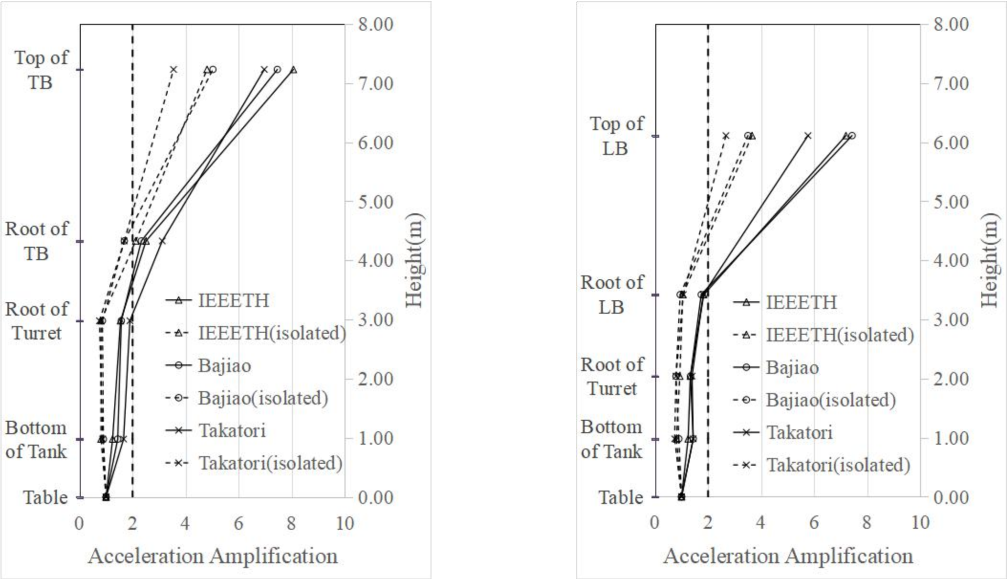


Fig. 4 – Maximum strain of TB and LB subjected to IEEETH

3.2 Acceleration amplification

As mentioned above, due to the error between the actual input peak acceleration on the table and the designed input peak acceleration, the direct comparison of the peak seismic response cannot truly reflect the isolation efficiency. In order to eliminate the input error, the ratio of the peak acceleration at the measuring points at different heights to the input peak acceleration at the shaking table, as another evaluation index of the isolation efficiency.

Acceleration amplifications with the PGA of 0.4g were calculated, as shown in Fig.5. In the non-isolated system, no matter which ground motion input, the amplification at the base of the TB exceeds 2.0 specified by the IEEE 693, and it even reaches 3.0 with Takatori input. With the base isolation, amplifications at the bases of the TB and LB are lower than 2.0. Comparing the amplifications of the TB and LB, it is found that the isolation effects on the TB and LB are not identical. For the TB, the amplification at the root of the turret, i.e., the amplification aroused by the flexible top plate of the tank, was almost eliminated by the isolation; while amplification aroused by the top turret was still existed the isolated system. For the LB, the amplification caused by the side plate of the tank was also eliminated. However, different from the top turret, amplification factors of the base and top of the side turret were closed, suggesting that the side turret would not amplify the accelerations input to the LB. Moreover, the slope of amplification curves of the isolated bushings (except the TB with Bajiao) is obviously larger than that of the non-isolated bushings, indicating the base isolation can significantly reduce deformations of the bushings.



(a) (b)

Fig. 5 – Acceleration amplifications with PGA of 0.4g for (a) TB and (b) LB

3.3 Maximum displacement responses

As the DFP bearing can produce a large-amplitude slide during the sever earthquake, displacement responses of the isolated transformer are also concerned by designers or engineers. For the interconnected electrical equipment, if energy-dissipation mechanism of the isolation devices are unable to alleviate the large displacement, the conductor could be tensed during the earthquake, and could produce great interaction forces between the adjacent equipment[19]. Therefore, the base isolation which significantly enlarges the displacement responses will not be applied to the electrical equipment. When PGA is 0.4g, the maximum seismic response of the transformer casing system is shown in Table 3. In Table 3, "-1", "-2" and "-3" in the case column correspond to single-direction excitation, two-direction excitation and three-direction excitation, respectively. "(I)" represents isolation condition. Even subjected ground motions of 0.4 g, with which the DFP bearings moved considerably, displacement responses of the isolated LB and TB were less than those of the non-isolated system, except subjected to the 0.4g Bajiao record. Displacement responses with the isolation can be reduced by nearly 30%, when the 0.4g Takatori wave was input. Therefore, the energy-dissipation capability of the DFP bearing is sufficient to ensure acceptable displacement responses.

Table 3 – Summary of experimental results with PGA of 0.4g

Case	**Maximum acceleration response(m/s^2)**				**Maximum displacement response(mm)**				**Maximum strain response(με)**	
	Top of TB	**Root of TB**	**Top of LB**	**Root of LB**	**Top of TB**		**Top of LB**			
					X dir.	**Y dir.**	**X dir.**	**Y dir.**	**TB**	**LB**
IEEETH-1	3.00	0.93	2.68	0.68	59.52	9.49	58.42	12.27	46.98	49.12
IEETH-1(I)	1.89	0.83	1.44	0.41	53.78	7.20	53.96	9.18	31.40	43.81
IEEETH-2	3.13	1.13	3.05	0.67	65.47	39.99	65.07	42.57	69.96	59.22
IEETH-2(I)	2.16	0.90	1.55	0.41	55.74	31.50	55.07	37.36	64.33	58.61
IEEETH-3	3.09	1.03	3.15	0.73	65.07	43.93	64.60	46.58	80.44	66.75

IEETH-3(I)	2.59	0.86	1.54	0.52	58.89	38.98	58.67	44.77	61.01	50.70
Bajiao-1	3.23	1.01	3.22	0.76	71.31	9.06	69.81	11.85	55.89	61.28
Bajiao-1(I)	2.47	0.83	1.72	0.47	56.24	10.06	55.89	12.77	39.98	53.59
Bajiao-2	2.72	1.07	3.11	0.75	65.25	38.46	63.73	45.90	91.87	111.78
Bajiao-2(I)	2.39	0.69	1.89	0.46	57.61	33.80	58.21	34.10	71.43	73.71
Bajiao-3	3.02	1.38	3.22	0.85	72.57	40.13	70.54	46.80	91.78	108.06
Bajiao-3(I)	2.37	0.79	1.62	0.48	60.30	35.70	60.16	35.60	66.23	64.37
Takatori-1	3.08	1.45	2.49	0.78	69.82	8.59	68.61	8.33	56.52	40.80
Takatori-1(I)	1.57	1.13	1.15	0.46	53.85	4.20	53.07	8.33	17.26	26.01
Takatori-2	3.21	1.44	2.58	0.75	71.33	48.43	67.87	48.97	78.42	54.62
Takatori-2(I)	1.47	0.70	1.29	0.40	53.86	34.50	52.83	33.92	47.40	41.68
Takatori-3	2.92	1.16	2.41	0.74	71.63	49.22	67.43	47.71	85.45	55.26
Takatori-3(I)	1.69	1.03	1.53	0.67	59.09	34.69	57.74	34.00	48.37	41.18

4. Conclusions

To demonstrate the effectiveness of the DFP bearing for large transformers in high seismic intensity areas, shaking table testing were performed in the present research.

In the shaking table testing, a transformer-bushing system was isolated by the DFP bearings, and the results suggested that the tested bearings was able to alleviate the seismic responses during strong earthquakes and showed the nonlinear characteristics. When the PGA was 0.4 g, strain responses of the isolated bushings was about half of those of the non-isolated bushings.

In order to eliminate the input error, the ratio of the peak acceleration at the measuring points at different heights to the input peak acceleration at the shaking table, as another evaluation index of the isolation efficiency. When the PGA was 0.4g, the acceleration amplification factor of the superstructure with isolation significantly decreased compared with that without isolation, and the maximum isolation efficiency at the root of TB was 45.79%, while the maximum isolation efficiency at the root of the LB was 60.39%.

The relative displacement of the top of the bushing under the ground motions with the PGA of 0.4 g was within 75 mm, which satisfies the slack limitation.

5. Acknowledgements

This study was financially supported by the National Key R&D Program, China (Grant No.2018YFC0809400) and the National Natural Science Foundation, China (Grant No. 51878508). Their support is greatly appreciated.

6. Copyrights

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