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Shaking Table Test of an Isolated UHV Capacitor Structure with FPS Bearings

K. Yao(1), J. Qian(2), E. Muho(3)

(1) *Ph.D Candidate, Tongji Universtiy, yaokun@tongji.edu.cn*
(2) *Professor, Tongji Universtiy, jqian@tongji.edu.cn*
(3) *Post Ph.D, Tongji Universtiy, edmondmuho@gmail.com*

Abstract

Power system is pivotal to the national economy and public welfare. Past earthquakes have highlighted the vulnerability of the power system with catastrophic consequences. Ultra-high voltage direct current (UHVDC) technology bring great benefit for operation security and economy of the whole power system. Such technology is developing rapidly in the seismically active regions including China. The UHV capacitor towers are critical equipment of the UHVDC converter station. Their failure may have consequences to the local network and the entire grid. UHV capacitors are mainly consists of porcelain support insulators and steel bearing benches. The construction includes therefore a combination of components some extremely brittle and some ductile. The structures have heavy weight, large height, limited deformability and small damping ratio, which renders them seismically vulnerable. With the development of isolation technology, as a novel isolation bearing, the friction pendulum system (FPS) bearings have been successfully used in civil engineering projects. However, so far little information on the FPS application for the seismic protection of the UHV capacitor towers.

A shaking table test of an isolated UHV capacitor structure using FPS bearings has been completed in Tongji University. The experiment's results indicate that FPS is an effective way to reduce the earthquake effect on the UHV capacitor structure. The shaking table test is based on a 1000kV capacitor tower which is 4.0m long, 2.2m wide, 12.4m high and weighs 32.7t. Considering the laboratory condition and specification limits for porcelain insulators, the length similarity ratio is 0.55. The UHV capacitor tower has large slenderness ratio and its isolation test design has special features. The grasp of its particularity will directly affect safety and results of the test. This paper presents the model design and development of the shaking table test. UHV electrical equipment weighs far less than buildings. Therefore, the size of the FPS bearings is not controlled by the structural weight but by the ultimate displacement requirement. FPS bearings were optimized according to the characteristics of the equipment. The displacement limit and anti-overturning devices have been specially designed for safety. The similitude rules for the general test model, the determination of the model bearings' parameters and the installation of the models were studied in this paper. This paper is aimed to be useful for the future shaking table test model design of friction pendulum bearing isolated UHV electrical equipment with large slenderness ratio and check the possibility of the FPS application for the seismic protection of the UHV capacitor towers.

Keywords: Ultra-high voltage*; capacitor tower; shaking table test; friction pendulum; seismic isolation*

1. Introduction

Power networks have undergone considerable damage during past strong earthquake and the statistical results of earthquake reveal that the seismic fragility of the power system is extremely high[1]. Power transmission and distribution systems are vital lifelines for the society and their failure can lead to serious economic and societal consequences[2]. Power networks have undergone considerable damage during past strong earthquakes with direct losses in the range of hundreds of millions of dollars for each event and other collateral costs[3]. Ultra-high voltage direct current (UHVDC) technology bring great benefit for operation security and economy of the whole power system.[4] Such technology is developing rapidly in the seismically active regions including China.[5] The UHV capacitor towers are critical equipment of the UHVDC converter station. Their failure may have consequences to the local network and the entire grid. With the development of isolation technology, as a novel isolation bearing, the friction pendulum system (FPS) bearings have been successfully used in civil engineering projects[6]. However, so far little information on the FPS application for the seismic protection of the UHV capacitor towers.

A shaking table test of an isolated UHV capacitor structure using FPS bearings has been completed in Tongji University. The test results indicate that FPS is an effective way to reduce the earthquake effect on the UHV capacitor structure. This paper is aimed to be useful for the future shaking table test model design of friction pendulum bearing isolated UHV electrical equipment with large slenderness ratio and check the possibility of the FPS application for the seismic protection of the UHV capacitor towers.

2. Design of the tested Model

2.1 Prototype equipment

Test prototype is a 1000kV filter tower. Its elevation diagram and plan diagram are shown in Figure 1. The height of UHV capacitor tower is 12.4m and its total weight is 33t. The tower mainly consists of support insulators and bearing benches. Insulators are made of high tension porcelain and girders are welded with Q345 steel. Based on modal analysis, its basic frequency is 1.6Hz.

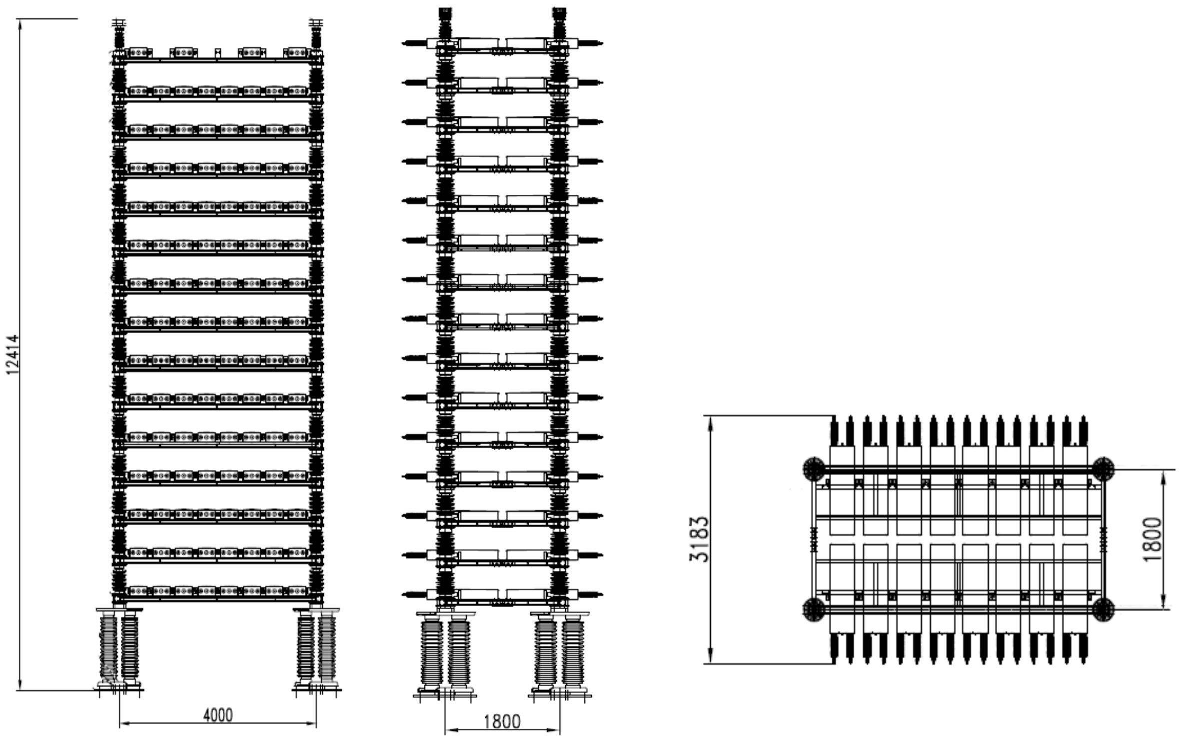

Fig. 1 –1000kV filter tower

2.2 Description of the shaking table

Shaking table model test is carried out using MTS shaking table facility at the State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China. The table can input three-dimensional and six degree-of-freedom motions. The dimension of the table is 4m×4m, and the maximum payload is 25 000 kg. The shaking table can vibrate with two maximum horizontal direction accelerations of 1.2g and 0.8g, with a maximum acceleration of 0.7g vertically.

Its frequency ranges from 0.1 to 50Hz and there are 96 channels available for data acquisition during testing progress.

2.3 Model design

The basic equation of the dynamics is equation (1). For the test similarity design, in addition to length L and force F, time t need to be considered. From this, we can derive the equation that the similar constants need to satisfy. According to the laboratory condition, the length similarity ratio is 0.55. Since the load-bearing members of UHV capacitor towers are high-strength ceramics, their mechanical properties are largely discrete and not fully understood. In order to make the model have similar stress-strain relationship with the prototype, the model is made of the same material as the prototype of the equipment. The similarity ratio of elastic modulus and density are 1. Other similarity constants are obtained by the dimensional analysis method and the similar is shown in the Table. The full-scale prototype tower is scaled down according to the similitude rule which is shown in Table 1.

$$m\left(\ddot{x}(t)+\ddot{x}_g(t)\right)+c\dot{x}(t)+kx(t)=0 \tag{1}$$

Table 1 –Similarity rule

Parameter	Relationship	Model/prototype
Length	S_l	0.55
Young's Modulus	S_E	1
Stress	$S_\sigma = S_E$	1
Strain	$S_\varepsilon = S_\sigma / S_E$	1
Density	S_ρ	1
Force	$S_F = S_\sigma * S_l^2$	0.303
Frequency	$S_f = \sqrt{S_a / S_l}$	1.82
Acceleration	S_a	1.82

The dimensions of insulator pillars, load-bearing channel steel beams and their nodes are designed according to the similar ratio of length. The dimensions of the pillar insulators are shown in Table 2. The dimensions of steel structural members such as channel steel beams and conversion tables are shown in Table 3. The insulators and bearing benches are prefabricated at the factory. There are many electrical components installed on the bearing benches of the prototype UHV capacitor tower. These electrical components only increase the weight of the equipment but not affect the rigidity of the structure. Therefore, the quality of the electrical components is designed according to the quality similarity ratio design. Therefore, the quality of the electrical components is simulated by weight plates designed according to the mass similarity ratio. All the components are assembled on site by installation workers. The insulators are brittle and the weight plates had been. The structure is too heavy. The shake during installation must be minimized. Flexible restraint was set between the slings and the structure with cloth bands and wooden sticks during lifting.

Table 2 – Dimensions of insulators

Size(mm)	Prototype		Model	
	height	diameter	height	diameter
145kV insulator	1400	395	770	217
40.5kV insulator	560	355	305	195
24kV insulator	460	320	255	180

Table 3 – Dimensions of steel frames

Size(mm)	Prototype				Model			
	length	width	height	thickness	length	width	height	thickness
Conversion platform	1270	550	145	38	700	300	80	20
Frames for layers 1-10	4000	1800	110	8	2200	990	60	5
Frames for layers 11-15	4000	1800	110	5	2200	990	60	3

2.4 Friction pendulum bearing

Friction Pendulum bearings were purchased from Shanghai Lubo Shock Absorption Technology Co., Ltd. UHV electrical equipment weighs far less than buildings. Therefore, the size of the FPS bearings is not controlled by the structural weight but by the ultimate displacement requirement. FPS bearings were optimized and therefore the upper plate of the support is smaller than the lower plate. The bearing capacity of each support is 55kN. The design friction coefficient of the sliding surface is 0.08. The radius of the sliding sphere is 1350mm. And the period is 2s.

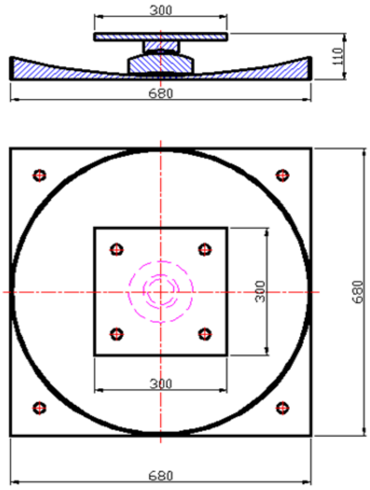

Fig. 2 – dimension of the friction pendulum support

2.5 Design of anti-overturning device

This test equipment has a large aspect ratio and weak anti-overturning ability. In order to prevent extreme situations such as abnormal loading of the shaking table during the test, safety measures should be taken to limit the model displacement during the test and prevent the equipment from overturning. Two steel beams anchored by high-strength bolts are adopted to limit the displacement of the model under extreme conditions and prevent the model from overturning damage. The dimensions of the steel beam are shown in Figure 3.

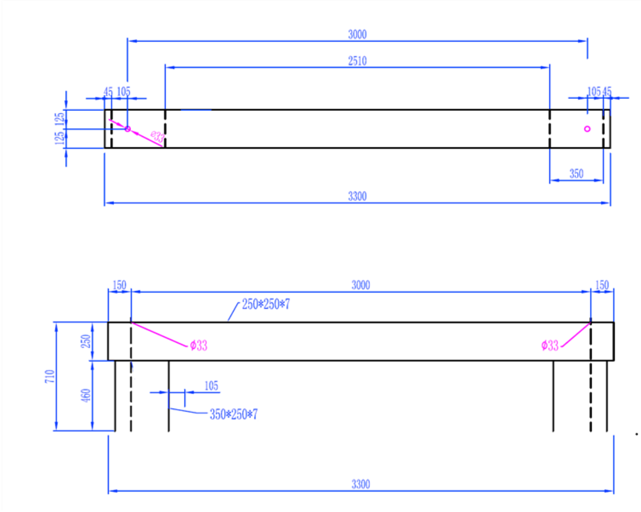

Fig. 3 – dimension of anti-overturn device

3. Vibration input

Five ground motion records with different spectral characteristics and development mechanisms were selected as vibration inputs, Elcentro wave, Taft wave, Wenchuan wave, CHICHI wave, Shanghai artificial wave. The response spectrum of these waves are shown in Figure 4. The records were scaled based on peak ground acceleration (PGA). The tests were conducted with 0.364g peak ground acceleration. The model has a large difference in the aspect ratio between the X and Y directions. It is hoped that the effect of the aspect ratio on the isolation effect can be studied at the same time. Therefore, the model is applied with X, Y, and unidirectional ground motion, XZ two-direcional ground motion and three-dimensional ground motion. For multi-directional ground motion input, the magnitude of each seismic excitation is adjusted by a ratio of 1: 0.85: 0.65.

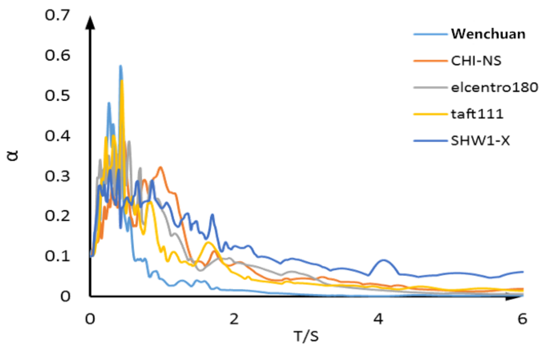

Fig. 4 – Response spectrum

4. Test Results

The shear force of the structure in the test can be approximated from the acceleration response and the mass distribution of the model. In most cases, the maximum ratio of the shear force between the isolated and non-isolated structures appears at the bottom. The base shear forces in X direction and

Y direction of isolated system and fixed structure under different input condition are shown in Table Analyzing the data, the following conclusions can be drawn.

Table 4 – Base shear force in X direction under different seismic waves (kN)

Load case / Wave	X direction			X and Z direction			three dimisional input		
	isolated	fixed	reduction rate	isolated	fixed	reduction rate	isolated	fixed	reduction rate
Elcentro	19.4	34.2	43.3	21.7	33.5	35.2	18.2	34.7	47.6
Taft	9.7	36.4	73.4	13.5	37.3	63.8	11.7	35.8	67.3
Chichi	14.8	48.1	69.2	18.4	45.2	59.3	21.7	48.4	55.2
Wenchuan	10.1	18.5	45.4	17.0	23.8	28.6	16.5	20.9	21.1
SHAW	20.5	36.5	43.8	15.9	47.0	66.2	21.1	44.7	52.8

Table 5 – Base shear force in Y direction under different seismic waves (kN)

Load case / Wave	Y direction			three dimisional input		
	isolated	fixed	reduction rate	isolated	fixed	reduction rate
Elcentro	7.6	37.0	79.5	10.0	32.2	68.9
Taft	7.6	34.5	78.0	9.5	26.5	64.2
Chichi	15.4	40.6	62.1	16.2	33.0	50.9
Wenchuan	6.3	20.9	69.8	6.1	16.1	62.1
SHAW	11.3	35.0	67.7	10.8	29.5	63.4

(1)The FPS system showed excellent damping efficiency under unidirectional excitation. The FPS system performed best under Taft wave. Base shear in the X direction of isolated system is 73.4% lower than fixed model and base shear in the Y direction of isolated system is 78% lower than fixed model. The damping effect is slightly weak under the vibration of Shanghai artificial wave containing more energy of long period. Base shear in the X direction of isolated system is 43.8% lower than fixed model and base shear in the Y direction of isolated system is 67.7% lower than fixed model. The FPS performs better in the Y direction than X direction.

(2) The vertical excitation has influence on the shear response of the friction pendulum system. The vibration reduction effect under multi-directional input is generally slightly weaker than the unidirection input. Under three-dimensional input, base shear in the X direction of isolated system is 67.3% lower than fixed model and base shear in the Y direction of isolated system is 64.2% lower than fixed model under the taft wave. Compared with the unidirectional input the damping efficiency is reduced by 8.3% in the X direction and 17.7% in the Y direction. Under the Shanghai artificial wave three-dimensional input, base shear in the X direction of isolated system is 52.8% lower than fixed model and base shear in the X direction of the isolated system is 63.4% lower than the fixed model. Compared with the unidirectional input, the damping efficiency in the X directional increases by 20.5% and the damping efficiency in the Y direction decreases by 6.3%. The pressure on the bearings changes greatly under vertical excitation. The friction force is closely related to the pressure and friction force directly affects the seismic force transmitted by the support to the upper structure and the energy dissipation capacity of the support. The increase in vertical

force causes the increase in friction, that results in increase the force transmitted to the superstructure.But at the same time the energy consumption of the support increases.

5. Summary

A shaking table test of an isolated UHV capacitor structure using FPS bearings has been completed in Tongji University. The model has a large aspect ratio and weak anti-overturning ability. In order to prevent extreme situations such as abnormal loading of the shaking table during the test, safety measures should be taken to limit the model displacement during the test and prevent the equipment from overturning. The experiment's results indicate that FPS is an effective way to reduce the earthquake effect on the UHV capacitor structure and the vertical excitation has a certain influence on the shear response of the friction pendulum system. Full consideration should be given to the possible negative impact of vertical ground motions when designing for isolation.

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