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Seismic Response Analysis of UHVDC Converter Valves Based on Simulation and Test

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Abstract

Seismic performance of converter valve in high seismic intensity area is significant for the safety operation of ultra high voltage direct current (UHVDC) converter substations. There are still several aspects to be studied in depth. The actual motion characteristics of suspended valve towers under seismic waves are not yet clear by experiments, and the finite element simulation considering the motion characteristics was not carried out yet, while lots of simulation with dynamics technology were developed. These problems pose a great challenge to the stable operation of converter valves and converter stations.

This paper elaborates on the motion characteristics of suspended valve tower under seismic waves by experiments. Based on an UHVDC converter station, a 1/3 reduced-scale model of converter valve and hall was established and the earthquake simulation shaking table test was carried out. Several accelerometer and strain gauges were arranged and lots of experimental data has been obtained. The maximum swing occurs at the lowest end of the valve tower, and the maximum acceleration occurs at the top suspension points, which was nearly 4 times relative to the bottom input. The amplification of earthquake wave by hall leads to a rise of the horizontal acceleration response of valve. The results show that the strain of the middle section is smaller than that of the top and bottom sections, which indicates that the suspension insulator is not a two-force bar and torsion and bending effect should be concerned. Thus, the reliable of the top insulator is related to the seismic safety of the converter valve.

In addition to the experimental research, the simulation method based on multi-body dynamics is also studied in this paper. This paper analyzes the simulation technology of suspended valve towers, and established an 1/3 reduced-scale analysis model based on kinematics and dynamics technology by LMS, so that the motion characteristics can be achieved. Different kinematic pairs had been set and rigid-flexible coupling technology was used. Suspension insulators were set flexible and meshed, while electrical devices were set as rigid bodies. The analysis model could simulate the swing of the valve tower under earthquakes. Then the analysis results show the displacement of the valve tower and force of the insulators, which was consistent with the test results. The accuracy of multi-body dynamics simulation of valve tower is verified. Several simulation results can be obtained by this model, such as the acceleration and force of hinge joints, thus further analysis of the real valve tower under earthquake could be carried out.

Last but not the least, the paper compares the proposed analysis method with the traditional finite element simulation method for UHVDC converter valves, and it may be helpful for the further analysis of the seismic response analysis.

Keywords: UHVDC converter valves, shaking table test, seismic response analysis, multi-body dynamics

1. Introduction

Flexible DC transmission technology based on thyristor valve is suitable for long-distance power transmission as its strong controllability, so it is widely used in solving grid compatibility within cross region [1-3]. As the key equipment in the converter station, the quality and working voltage of the DC converter valve is great, therefore the seismic performance is directly related to the operation safety of the HVDC transmission system [4]. Considering the structure of the valve hall and valve tower, it is very important to carry out the overall seismic research to ensure the safe operation of the HVDC project.

Currently, the general structural design of the converter valve adopts the flexible suspension structure, with the valve tower suspended on the frame of the valve hall to meet the seismic requirements. The anti-seismic research and design of converter valve and converter station are becoming the research hotspot of HVDC Engineering [5].

For the experiment research of converter valves, Yi Wu and Chun Yang carried out the scale model test and simulation with ABAQUS of converter valve hall and valve tower [6], while the valve tower model is relatively simple, and the research focuses on the seismic behavior of the valve hall structure. Wei Wenhui, Wang Anyang also analyzed the swing characteristics of the valve hall structure in scale test with considering the valve tower just as suspension mass [7]. Compared with the experimental study of the valve hall structure, particularly seismic responses analysis with experiments of the valve tower under earthquake are much deficient.

On the other hand, considerable work has been done in simulation research based on dynamics theory. Ma Yongjie, Yu Ping established the analysis model and studied on the seismic response of converter station based on the finite element method [8-9]. Huang Lijun [10] analyzed the dynamic characteristics of the valve hall with simulation model and test. While all these analysis are focus on the characteristics of valve hall since the valve tower model is too simple. For the simulation of valve tower, Larder et al. optimized the structural design of valve tower and improved the seismic performance, Maison B F et al. carried out numerical simulation of ABB converter valve structure based on response spectrum analysis method and put forward the design method of setting damping to reduce the seismic response [11-13]. Wu Xiaofeng [14] conducted the finite element simulation analysis with a precise finite element model. All these analysis are based on dynamics theory, while there is few simulation analysis of suspended structure based on kinematic theory to obtain the motion characteristics.

In this paper, an 1/3 reduced-scale model was established and the seismic characteristics of suspended valve tower under seismic wave was tested on the shaking table, then the nonlinear dynamic time history analysis of the valve tower base on multi-body dynamics method was carried out by adopting LMS Motion software and the accuracy of simulation was verified. This study provides technical support for the structural optimization design of HVDC converter valve.

2. Shaking table test of reduced-scale model

2.1 Background of test

Reduced-scale model test is a kind of verification method often used in engineering research. Based on the elastic dynamic equation, the model could be consistent with the real object through reasonable test design. So the geometric similarity should be satisfied firstly, then the similarity ratio of physical parameters should be determined according to the theory of similarity.

Considering the suspended valve tower is too big to be tested on shaking table with physical structure directly, the reduced-scale model test of converter valve tower is an important way to analyze this kind of equipment.

As mentioned above, scholars carried out shaking table test mostly focused on the seismic response of the steel structure of the valve hall with considering the valve tower as suspended mass simply in the hall.

These researches are lack of in-depth analysis on the motion characteristics of suspended valve tower. Because of the complexity of the valve hall structure, the effect of hanging multi valve tower and single tower is different. So the in-depth study of the movement form and stress state of the valve tower under seismic waves is more important for the design in the engineering at this stage.

2.2 Experimental design

The purpose of this test is to study the seismic response of suspended valve tower, so it is important to make the model similar to the original valve tower as much as possible to reflect the movement and load under the earthquake excitation accurately. As shown in Fig 1, the valve tower is rather high, divided into 6 layers of devices and 2 shielding covers at upper and lower sides. The valve tower is suspended by composite insulators on the roof of the valve hall, and contiguous layers are connected by suspended insulators. Rotary pairs are set between connection positions of the insulators, which ensure sufficient freedom of rotation. Considering the parameters of the shaking table and test environment, a 1/3 reduced-scale model of converter valve was established and the parameters were listed in the table below.

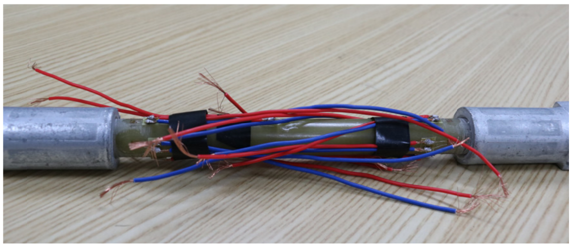
Fig. 1 –The suspended valve towers

Table 1 –Parameters of test model

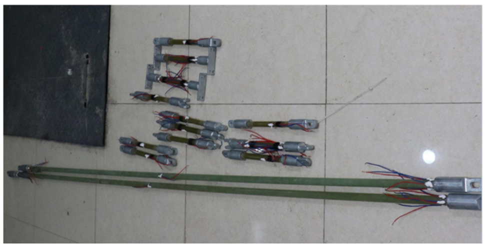
Item	Similarity parameter	Similarity coefficient
Geometric characteristics	Length	0.33
Material properties	Density	1.5
	Mass	0.06
Load	Force	0.11

This test was completed on the three-dimensional shaking table with the maximum acceleration to 1.5g.

The movement form of valve tower and the stress of core components are mainly investigated in this shaking table test. The acceleration state of the specific position of the valve tower was measured through 18 tri-axial acceleration transducers in total. One measuring point was arranged at the suspended position of the top frame to investigate the amplification effect of the valve hall, while the other measuring points were arranged at the top of the valve tower, within the layers and at the bottom of the test model. At the same time, 76 strain gages were arranged on insulators and insulation beams in total. As shown in Fig 2, measuring points of strain were arranged at both ends and middle positions of insulator, in order to investigate the tensile, bending and torsional loads. The final test model is shown in the Fig 3.



(a) strain gages of single insulator



(b) strain gages of different insulators

Fig. 2 –Layout of the strain gages on the suspensed insulator

Fig. 3 –Images of the whole test model

2.3 Conclusion of the test

The EL-Centro wave was selected as the input seismic waves for dynamic time history analysis, of which the peak acceleration was adjusted to 1.96m/s^2 according to the medium earthquake actions. For three-direction seismic wave input, the amplitude modulation coefficients for lateral, longitudinal and vertical directions, respectively, were 1:0.85:0.65, and the lateral directions was selected as the principal direction.

2.3.1 Acceleration response of the valve tower

Under the seismic wave, the peak acceleration of investigated points was listed in the table 2. Compared with the input acceleration on the ground, the acceleration at the top and bottom frame of the valve tower as well as the suspended point at the top of the valve hall were all shown below.

Table 2 – Acceleration response of the valve tower

Item	**X(m/s^2)**	**Y(m/s^2)**	**Z(m/s^2)**
Ground input	0.20	0.17	0.15
Suspended point	1.00	0.73	0.58

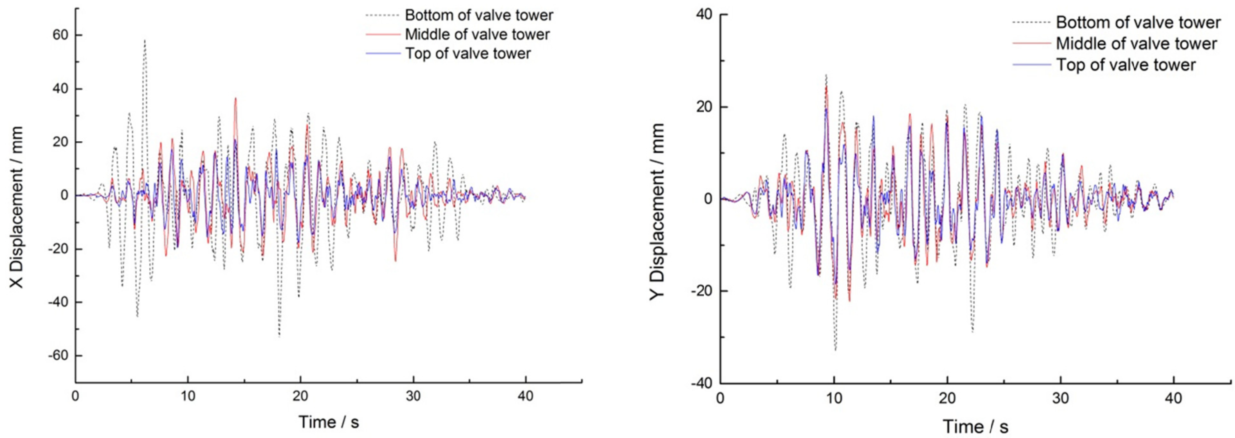
Top of valve	0.77	0.49	0.90
Bottom of valve	0.90	0.58	1.10

It can be seen from the table that the amplification coefficient of peak acceleration at the top of valve hall is nearly 4-5 times compared with the table input, while the peak acceleration at the top and bottom of valve tower is smaller than that at the top of suspended frame, which proves that the suspended structure has good seismic performance. The amplification of earthquake wave by valve hall structure leads to a rise of the horizontal acceleration response of valve.

Because of the redundant degree of freedom of the suspended structure, there is inevitably gap in the hinge position, which leads to the difference of force on different insulators and appearance of impact load. In the process of vibration, the impact load increases the peak acceleration, which makes the influence on Z direction greater than that on X and Y direction.

2.3.2 Displacement response

Under the earthquake, the swing of the valve tower should be evaluated particularly due to the flexible design. The peak acceleration of each layer in the valve tower was extracted and integrated to observer the swing under the seismic waves. The swing at the top, middle and bottom of the valve tower was extracted respectively and shown in the figure below.



(a) displacement of points in X direction (b) displacement of points in Y direction

Fig. 4 –Time-history curves of displacement on the valve tower under EL-Centro seismic wave

As is shown in the figure, the swing at the bottom of the valve tower is the largest, followed by the swing at the top of the frame. The maximum displacement of the bottom frame is about 2 times compared with that of the valve hall, and the swing in the middle is the smallest. There is little difference of maximum displacement between different layers.

2.3.3 Strain response

As the key component, the stress state of the suspended insulator directly affects the safety of the valve tower. The maximum strain of insulators in different layers was listed in the table below. These insulators were named from top to bottom in sequence.

Table 3 – Strain response of the valve tower

Item	**Top insulator**	**First layer insulator**	**Third layer insulator**	**Sixth layer insulator**

Point	Top	Middle	Bottom	Top	Middle	bottom	Middle	Middle
strain	132	108	136	105	86	89	56	37

The maximum strain response is located at the top suspended insulator of valve tower, which is 2-3 times compared with that of other interlayer suspended insulators. The results demonstrate that the strain of the middle section is smaller than that of the top and bottom sections, which indicates that the suspended insulator is not a two-force bar and torsion and bending effect should be concerned.

3. Multi-body dynamics simulation

3.1 Simulation theory

Multi-body dynamic analysis is a branch of mechanics which has developed rapidly in the past 20 years. It focuses on the interaction and coupling between the deformation of an object and its rigid motion as a whole, as well as the unique dynamic effect produced by the coupling. The simultaneous coupling of deformation and rigid motion are the core characteristics of multi-body dynamics.

It is very important on describing the elasticity of flexible body in multi-body dynamics. In engineering application, the modal synthesis technology of structural dynamics is introduced to divide the complex structure into several substructures according to the structural characteristics. The stress analysis of each substructure is carried out with the finite element method to obtain the mode, and a small number of modal coordinates are used as the generalized coordinates to reduce the degree of freedom of the system equation and reduce the solution scale.

At present, the simplified model of the valve tower is often established with the finite element method to carry out the response spectrum or time history analysis. But in fact, each component is connected by flexible rotating pairs, there is relative movement around the joints between components due to the particularity of suspension structure. Therefore, based on the time history analysis method of kinematics and dynamics, the rigid-flexible coupling model of the suspended valve tower could demonstrate the seismic performance of the structure more accurately.

3.2 Simulation model and input load

Considering the calculation scale and the purpose of verifying the simulation method, a multi-body dynamics simulation model was established and analyzed by adopting LMS Motion software with the tested seismic acceleration waveform at the suspended point from the shaking table test.

Based on the reduced-scale test valve model, the Cartesian coordinate system of the right hand was chosen in this analysis, of which the x-direction is the horizontal short side, the y-direction is the horizontal long side, the z-direction is the vertical direction of the valve tower. Then different constraint forms were set according to the motion characteristics as shown in table below.

Table 4 – Constraint forms of the simulation model

Item	Constraint Form (Based on test model)
Top suspended insulators	Revolute pairs
Interlaminar insulators	Revolute pairs
Insulator within layers	Sliding pairs

This study focused on the stress of the insulators and motion state of the valve tower, hence the reactors, valve string assembly and single-layer frame were set as rigid bodies to ensure their quality consistent with the actual model. While the top suspension insulator, interlayer insulator and internal insulator were flexible. Based on the method of substructure modal synthesis, meshing and flexibility analysis were carried out. The whole simulation model was shown in Fig 5.

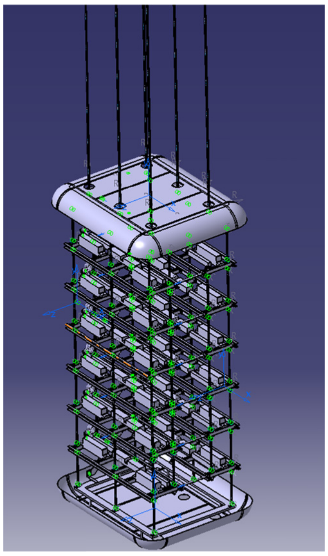
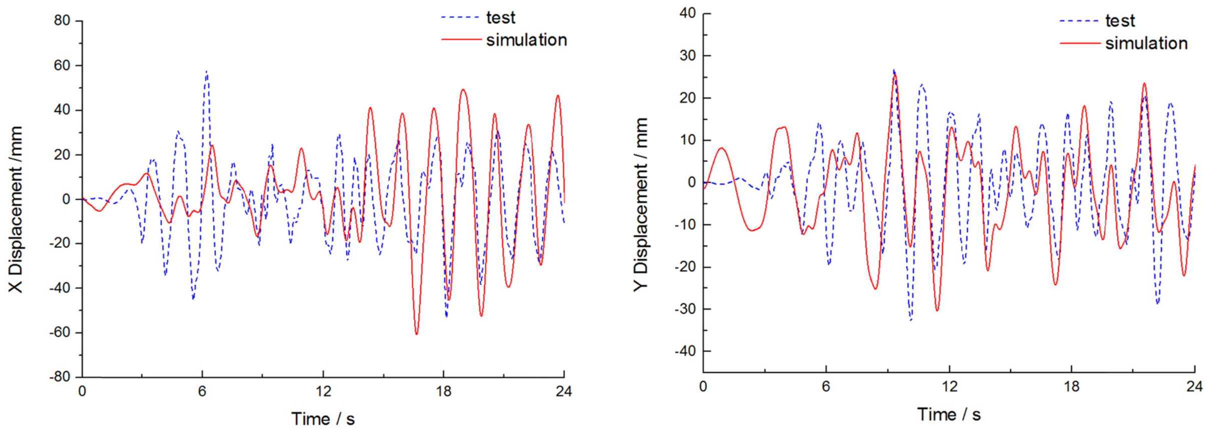


Fig. 5 –Simulation model of the valve tower

3.3 Simulation analysis

3.3.1 Displacement response of simulation

Figure 6 shows the contrast between numerical analysis and experimental results of displacement on point at the bottom of the valve tower under EL-Centro earthquake wave.



(a) comparison of displacement in X direction (b) comparison of displacement in Y direction

Fig. 6 –Time-history curves of displacement between test and simulation at the bottom of the valve tower

As shown in the figure, the numerical analysis results are in good agreement with experimental results. Under earthquake actions, the differential of the peak displacement is about 10%. The main reason for the differential of test and simulation is the damping and friction coefficient of motion pairs in the simulation model, which is more obvious in the X direction. Further research could be conducted in this respect later.

Therefore, the simulated results are of enough accuracy and the multi-body dynamic analysis model is feasible for investigating the seismic performances of the valve hall structure.

3.3.2 Stress analysis

As shown in Figure 7, the stress of top suspended insulators was demonstrated. There was significant bending deformation occurred under the earthquake wave, which was consistent with test results. As the core bearing component, the suspended insulator bears not only the axial load but also the radial bending effect under the earthquake wave, which was barely considered in other research. The forced state of the insulator could be simulated more accurately by considering as flexible beam element rather than link element, so it is more suitable for the seismic research of suspended valve towers based on kinematics and dynamics technology.

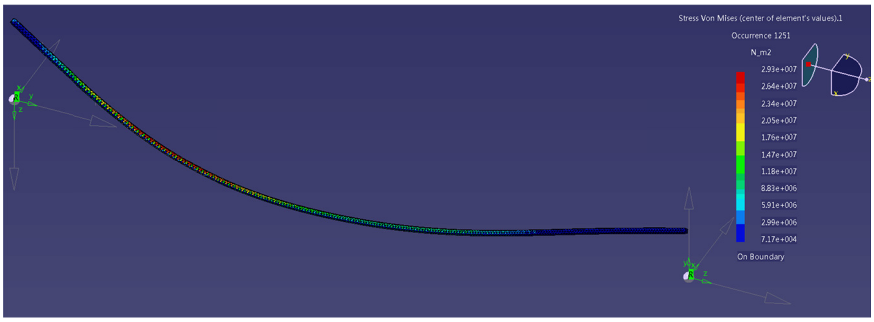


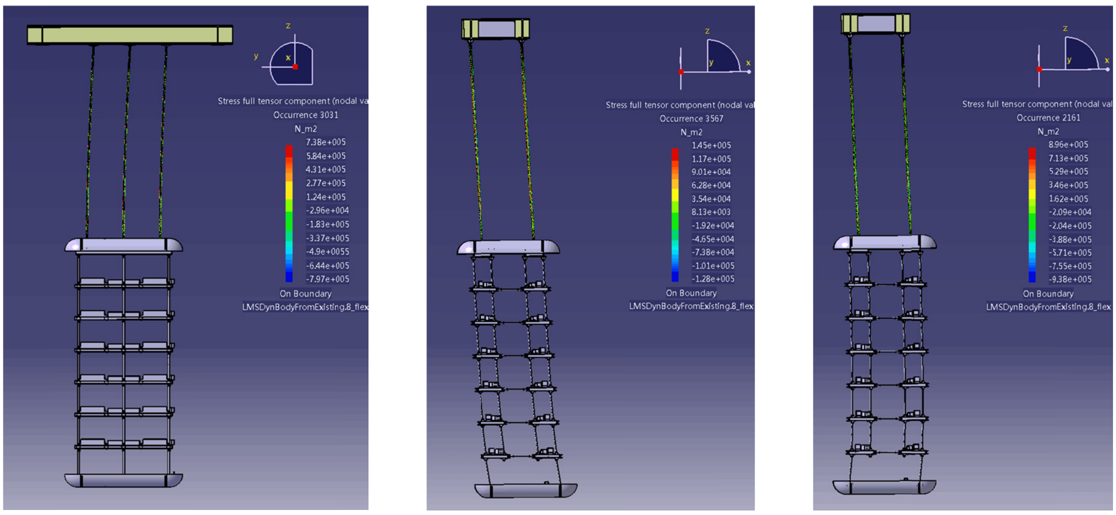
Fig. 7 –Stress analysis of the top suspended insulator

3.3.3 Motion characteristics

According to the previous research, it is quite signigicant that suspended valve has excellent seismic performance in acceleration because of the flexible structure. While on the other hand, the displacement of the suspended valve tower is relatively larger compared with the base-supported valve. Hence the motion characteristics should be investigated in deepth.

In contrast with the traditional finite element simulation method, the multi-body dynamic method proposed in this paper could demonstrate the motion characteristics of valve tower in detail. More simulation result for design could be obtained based on kinematics, such as the displacement, speed, and acceleration of any point at any time.

The swing state at some moment was demonstrated in Figure 8. As the freedom of interlaminar insulators were different with that of top insulators, the motion state of each layers was different in freedom release direction, while the difference could be ignored in Y direction. Due to the electrical connection between valve tower with wall bushing, further research of the swing is required for the safety of the system.



(a) Swing state in Y direction (b) Swing state in X direction (c) Swing state in X direction

Fig. 8 –Motion characteristics of the valve tower at any time

4. Conclusion

This paper focuses on the seismic behavior analysis of the valve tower. The actual motion characteristics of suspended valve towers under seismic waves was tested by an 1/3 reduced-scale model of converter valve and hall in shaking table test, compared with the simulation based on multi-body dynamics in this paper. The conclusions of the test and simulation results are as follows:

(1) The maximum swing occurs at the lowest end of the valve tower, and the maximum acceleration occurs at the top suspension points, which was nearly 4 times relative to the bottom input. The amplification of earthquake wave by hall leads to a rise of the horizontal acceleration response of valve, so the sudden change of acceleration should be considered in design and examination of the valve tower.

(2) The strain test indicates that the suspended insulator is not a two-force bar and torsion and bending effect should be concerned, which is often ignored in previous research. Thus more attention should be paid to the check of the insulators with considering the comprehensive loading.

(3) The displacement of the valve tower and force of the insulators was consistent with the test results. The accuracy of multi-body dynamics simulation of valve tower is verified. Thus further research can be carried out based on this model.

5. References

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