Shaking Table Test on Seismic Performance of Combined High Voltage Circuit Breaker

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Abstract. This paper focused on the experimental characteristics of seismic performance on a typical combined high voltage (HV) circuit breaker. Through the shaking table test of the scale model of a “T”-type circuit breaker, the results indicated that the test model could better reflect the main force characteristics of the prototype structures. Meanwhile, the dynamic characteristics of the model structure were reflected by white noise sweep frequency, and the seismic response of the model structure under the excitation of different seismic waves with different intensities were studied. It is concluded that the vulnerable parts of the model structure appeared at the root of the structural insulation porcelain column, the top and the bottom of the structure. Generally, the magnification coefficient of acceleration is about 1.1-2.7.

1. Introduction
The experiences obtained from recent earthquakes showed that some components of the substation were extremely vulnerable. As an indispensable part of the substation, the electro-ceramic circuit breaker also was suffered from unpredictable damages. Thus, a number of researches paid much attention on the seismic performance of electrical equipment systems in recent years [1-3].

In the past, the researchers mainly focused on the dynamic characteristics, anti-seismic design and damping control of electric porcelain-type structures [4-6]. Günay and Mosalam conducted a parametric study using real-time hybrid simulation tests[7,8], and the results indicate that the high vulnerability of these elements was confirmed, and the use of proper seismic protection systems were necessary. Xie Qiang et al. carried out a simulated seismic vibration table test on a full-scale model of a 220kV single-column circuit breaker[9], which further comprehensively determined the seismic performance of the circuit breaker structure based on the dynamic characteristics and the mechanical performance.

As mentioned above, various researches on the seismic performance of electric porcelain-type electrical equipment mainly focused on the structure of single-column electro-ceramic equipment, while the research on the seismic performance of the combined electro-ceramic electrical equipment structure with more serious damage in the earthquake is rarely found. In this paper, the “T”-type and “Y”-type combined circuit breaker structures were designed and fabricated, and the dynamic characteristics and seismic response of such structure under the excitation of ground motion were obtained through the shaking table test. Meanwhile, the vulnerable parts of the structure were identified additionally, which provides a reference for the seismic design and seismic isolation research of the electro-ceramic structure.

2. Experimental Program

2.1. Specimen design
In shaking-table tests, scale models are often used due to the large size of the prototypes. Based on the prototypes of LW15A-363/Y HV circuit breaker, a 1/4.5 “T”-type scale model was designed and fabricated. The detailed dimensions of the model are illustrated in Table 1. The “T”-type circuit breaker model is composed of four porcelain columns, three connection flanges, and one chassis support. Two of porcelain columns are support porcelain columns (abbreviated as SP column) and the other two are insulation porcelain columns (abbreviated as IP column). The porcelain columns, the SP columns and the chassis support are all connected by flanges, while chassis support and the top of shaking table are connected by bolting. The assembled structure is shown as Figure 1. Meanwhile, the porcelain columns all adopt high-strength porcelain, and the flanges all are made of steel.

![Figure 1. Assembled structure diagram](image1)

![Figure 2. Test setup and instrumentation](image2)

### 2.2. Overview of the shaking table

The WS-Z50 Small Precision Vibration Table System used in this test consists of electromagnetic vibration exciter, power amplifier, shaking table, controller and sensor of shaking table, computers etc. The main technical parameters of the shaking table are shown in Table 2. The direction of the maximum acceleration is horizontal in Table 2.

| Specimen | Length/mm | Maximum outer diameter/mm | Inner diameter/mm | Thickness/mm | Weight/kg |
|----------|-----------|---------------------------|-------------------|--------------|-----------|
| IP column | 430       | 75                        | 60                | 5            | 5.3       |
| SP column | 450       | 50                        | 45                | 5            | 2.1       |

### 2.3. Selection of input

In accordance with IEEE Standard 693 Recommended Practice for Seismic Design of Substations in the USA[10], EL-Centro seismic wave, Lanzhou seismic wave, and Taiwan Chi-Chi seismic wave recorded were selected in this paper. Before starting the shaking table test, the selected seismic waves were amplified according to the required maximum acceleration value. In this paper, the seismic intensities of 0.60g and 0.80g were used as the inputs for the circuit breaker model.

### 2.4. Test setup and instrumentation

In order to obtain the actual ground motion input at the bottom of the circuit breaker model, one acceleration sensor (abbreviated as AS) was placed at the position above. Subsequently, for the purpose of obtaining the vibration modes of the circuit breaker model, five acceleration sensors were arranged along with the entire height of the model, and further to obtain the power amplification factor of the SP columns. In addition, the “T”-type combined circuit breaker belongs to the single-axis symmetrical
structure, so the circuit breaker model was excited in the X or Y directions respectively. The test setup and instrumentation are shown in Figure 2.

3. Results and discussion

3.1. Dynamic characteristics analysis

Table 3. The basic frequencies of “T”-type circuit breaker (unit: Hz)

| The sequence of white noise | Level (g) | “T”-type first-order frequency | “T”-type second-order frequency |
|-----------------------------|----------|-------------------------------|-------------------------------|
| 1<sup>st</sup>              | -        | 10.7825                       | 15.5468                       |
| 2<sup>nd</sup>              | 0.14     | 10.7825                       | 15.5468                       |
| 3<sup>rd</sup>              | 0.22     | 10.7824                       | 15.5467                       |
| 4<sup>th</sup>              | 0.28     | 10.7822                       | 15.5467                       |
| 5<sup>th</sup>              | 0.40     | 10.7819                       | 15.5465                       |
| 6<sup>th</sup>              | 0.60     | 10.7816                       | 15.5465                       |
| 7<sup>th</sup>              | 0.80     | 10.7813                       | 15.5462                       |

The basic frequencies of the “T”-type circuit breaker model measured for each input excitation of white noise is shown in Table 3. The first-order frequency of the “T”-type circuit breaker model is 10.78 Hz, while the second-order frequency is 15.55 Hz. Meanwhile, it is obvious that the frequency and stiffness of the model does not change significantly under various excitations.

3.2. Acceleration response analysis

It could be seen from Table 4 and Table 5 that, under the same seismic wave with the same intensity, the acceleration amplification factor at the root of the SI column of the “T”-type circuit breaker model has the smallest value, conversely, the factor has the largest value at the end of the IP column. Moreover, the acceleration amplification factors, at the root of the SP column, the top of the structure and the end of the IP column, all increase as the peak acceleration increases. Besides, the maximum acceleration amplification factor of the model under excitation of X-direction is 2.104, which occurs at the end of the IP column. Relatively, the maximum acceleration amplification factor of the model under the Y-direction excitation is 2.189, which occurs at the end of the IP column as well. It is indicated that the single-axis symmetrical circuit breaker model is more vulnerable when subjected to a seismic action in parallel with the symmetry plane, and the IP column is more likely to be damaged by the excitation of seismic wave in this direction. The acceleration versus time curves of the EL-Centro wave with the peak accelerations of 0.60g and 0.80g are shown in Figure 3 respectively, in the excitation of X-direction.

![Figure 3.](image-url)
Table 4 Peak of acceleration response and dynamic amplification factor of “T”-type circuit breaker model under excitation of X-direction

| Intensity | Location                  | EL-Centro wave | Chi-Chi wave | Lanzhou wave |
|-----------|----------------------------|----------------|--------------|--------------|
| 0.60g     | mesa                       | 0.627          | 0.616        | 0.631        |
|           | The root of SP column      | 0.645          | 0.630        | 0.664        |
|           | The top of model           | 1.151          | 0.978        | 0.991        |
|           | The end of IP column       | 1.164          | 1.008        | 1.016        |
| 0.80g     | mesa                       | 0.814          | 0.796        | 0.853        |
|           | The root of SP column      | 0.900          | 0.823        | 0.868        |
|           | The top of model           | 1.620          | 1.391        | 1.438        |
|           | The end of IP column       | 1.713          | 1.458        | 1.463        |

\(a\) Maximum acceleration.
\(b\) Amplification factor.

Table 5 Peak of acceleration response and dynamic amplification factor of “T”-type circuit breaker model under excitation of Y-direction

| Intensity | Location                  | EL-Centro wave | Chi-Chi wave | Lanzhou wave |
|-----------|----------------------------|----------------|--------------|--------------|
| 0.60g     | mesa                       | 0.625          | 0.637        | 0.631        |
|           | The root of SP column      | 0.673          | 0.718        | 0.683        |
|           | The top of model           | 1.233          | 1.174        | 1.187        |
|           | The end of IP column       | 1.240          | 1.208        | 1.225        |
| 0.80g     | mesa                       | 0.843          | 0.825        | 0.851        |
|           | The root of SP column      | 0.949          | 0.877        | 0.913        |
|           | The top of model           | 1.833          | 1.575        | 1.685        |
|           | The end of IP column       | 1.845          | 1.591        | 1.692        |

3.3. Displacement response analysis

Table 6. Peak displacement of each test-point in the excitation of X-direction (unit: mm)

| Direction | Input                  | The root of SP column | The top of the model | The end of the IP column |
|-----------|------------------------|-----------------------|----------------------|-------------------------|
| X         | EL-Centro wave         | 6.3                   | 8.6                  | 10.5                    |
|           | Chi-Chi wave           | 6.4                   | 8.7                  | 10.3                    |
|           | Lanzhou wave           | 5.7                   | 8.3                  | 9.9                     |
| 0.80g     | EL-Centro wave         | 7.7                   | 10.7                 | 11.9                    |
|           | Chi-Chi wave           | 7.5                   | 10.3                 | 11.9                    |
|           | Lanzhou wave           | 7.1                   | 9.9                  | 11.1                    |
Table 7. Peak displacement of each test-point in the excitation of Y-direction (unit: mm)

| Direction | Input       | The root of SP column | The top of the model | The end of the IP column |
|-----------|-------------|------------------------|----------------------|--------------------------|
| Y         | 0.60g       | EL-Centro wave 9.3     | 12.5                 | 13.7                     |
|           |             | Chi-Chi wave 9.4       | 12.7                 | 13.5                     |
|           |             | Lanzhou wave 9.1       | 11.9                 | 13.1                     |
|           | 0.80g       | EL-Centro wave 12.3    | 15.7                 | 19.5                     |
|           |             | Chi-Chi wave 11.9      | 15.3                 | 19.8                     |
|           |             | Lanzhou wave 11.5      | 14.9                 | 19.1                     |

As shown in Table 6 and Table 7, under the same seismic wave with the same acceleration, the peak displacement response at the root of the SP column has the smallest value and it has the largest value at the end of the IP column. Meanwhile, the peak displacement response at the root of the SP column, the top of the model and the end of the IP column, all increases with the increase of the acceleration. In addition, the peak displacement response peak under excitation of the Y-direction is larger than that under the excitation of X-direction, which means that the power amplification of the model under the excitation in Y-direction has more significant effect due to the different stiffness in and out of the plane of the un-axial-symmetrical structure. Also, the model reaches a peak displacement of 11.9 mm under the excitation of Chi-Chi wave in X-direction, and a peak displacement of 19.8 mm in the excitation of Y-direction, both of which occur at the end of the IP column.

4. Conclusion

By using a shaking table test campaign, the seismic performance of a typical “T”-type combined HV circuit breaker was studied. The in-depth analysis of the shaking table test aims to explore the dynamic characteristics, acceleration response and displacement response of the model under different seismic excitations. The following conclusions are derived:

Through the vibration frequency measured by the sweep of the white noise, it shows that the basic frequency of the model does not change obviously under each excitation, indicating that the internal stiffness of the model does not change significantly. Under the same seismic wave with the same acceleration, the peak acceleration response and peak displacement response at the root of the SP column both reach the smallest values, and it has the largest value at the end of the IP column. Meanwhile, the peak acceleration response and peak displacement response at the root of the SP column, the top of the model and the end of the IP column, all increases with the increase of the intensity. The dynamic amplification effect of the “T”-type circuit breaker is more significant under the seismic excitation in Y-direction, and the peak displacement response of the circuit breaker appears at the end of the IP column. The corresponding measures should be taken to control the structural displacement response to prevent the IP columns from being damaged due to the relative motion between the devices.

References

[1] Zareei S A, Hosseini M, Ghafoory-Ashtiany M. Evaluation of power substation equipment seismic vulnerability by multivariate fragility analysis: A case study on a 420 kV circuit breaker[J]. Soil Dynamics & Earthquake Engineering, 2017, 92: 79-94.
[2] Alessandri S, Giannini R, Paolacci F, et al. Seismic retrofitting of an HV circuit breaker using base isolation with wire ropes. Part 2: Shaking-table test validation[J]. Engineering Structures, 2015, 98: 263-274.
[3] Shah A M, Bhalja B R. A Laboratory Prototype and Simulation of Ground Constant Measurement of Circuit Breaker[J]. Journal of the Institution of Engineers, 2014, 96(1): 1-8.
[4] Hallested R, Murase S, Kishida R, et al. Evaluation of the effect of mechanical operations on seismic qualification test of SF/sub 6/circuit breakers[C]/ Transmission and Distribution
Conference, 1991. Proceedings of the 1991IEEE Power Engineering Society. IEEE, 2002:473-477.

[5] Thuries E,Girodet A,Serres E, et al.Seismic behavior of ‘candle’ type SF 6, outdoor circuit breakers and associated SF 6,insulated current transformers[J].Power Delivery IEEE Transactions on,1989,4(4):2100-2108.

[6] Miri A M,Kuhner A,Reinhardt P,et al. Seismic Qualification Of High-Voltage Substations (420-kV Circuit Breaker With Coupled Poles)[C]//International Conference on Optimization of Electrical and Electronic Equipments.IEEE, 2002:225-230.

[7] Gü nay, Selim, Mosalam K M . Seismic performance evaluation of high-voltage disconnect switches using real-time hybrid simulation: II. Parametric study[J]. Earthquake Engineering & Structural Dynamics, 2014, 43(8):1223-1237.

[8] Mosalam K M, Gü nay S. Seismic performance evaluation of high voltage disconnect switches using real-time hybrid simulation: I. System development and validation[J]. Earthquake Engineering & Structural Dynamics, 2014, 43(8):1205-1222.

[9] XIE Qiang, WANG Yafei, WEI Sihang. Cause analysis of damage of flexible -busbar-connected switchgears under earthquake[J]. Electric Power Construction,2009, 30(4):10-14.

[10] IEEE Standard 693 Recommended Practice for Seismic Design of Substations[S]. Institute of Electrical and Electronic Engineers,USA,2005.