Seismic Reliability of UHV Porcelain arrester with Damping System

Xuesong Zhang*, Meigen Cao and Zhicheng Lu

China Electric Power Research Institute of SGCC, No.33, Nanbinhe Rd, Xicheng District Beijing, China

Abstract: The vulnerability of the UHV porcelain arrester is very high under strong earthquake. To rise seismic reliability of the UHV porcelain arrester, a new type lead damper, which is a new patent product, is installed at the bottom of the equipment. To investigate the damping effect of the dampers, the experimental research and finite element analysis on seismic behavior of the UHV porcelain arrester with and without the dampers are carried out by means of single point input and single point output(SISO)measurement. The analyzed results show that the damper is well functioning, effectively decreasing stochastic earthquake response of the UHV porcelain arrester, thus the seismic reliability of porcelain arrester is improved. A seismic reliability analysis method is put forward based on the stochastic earthquake model .The mean and standard deviation of the seismic responses of the arrester with and without the dampers under the different site conditions are gained based on physical stochastic seismic motion model. Then its seismic reliability is calculated by the FOSM, and the fragility curves of the arrester are built. Calculation result shows that seismic reliability of the arrester with the dampers can be effectively enhanced under Ms 8.0 earthquake. A conclusion is given that the damper is capable to improve the seismic reliability of the UHV porcelain arrester effectively, and may be widely applied to the seismic design of the UHV porcelain arrester.

Keywords: UHV porcelain arrester, new type lead damper, physical stochastic seismic motion model, stochastic earthquake response, seismic reliability.

1. INTRODUCTION

The UHV porcelain arrester plays an important role in the power system, and it is crucial for ensuring the power system safety. It owns the features of intricate structure, complicate function, brittle material and small damping. Quite a few earthquake disasters both domestically and abroad shows that porcelain high-voltage electrical equipment is extremely easy to be destroyed in the earthquake [1, 2]. There are two major reasons: firstly, self-vibration frequency of this equipment is generally between 1Hz and 10Hz, which is extremely easy to generate resonance and lead to the body structure damage; secondly, the knob insulator of this equipment is of brittle material with small storage capacity [3, 4]. Based on the structural features of porcelain electrical equipment, it is effective to improve seismic reliability by installing vibration dampers on the bottom of equipment, since the vibration dampers can reduce the seismic response by changing dynamic features of porcelain electrical equipment. In order to enhance the seismic reliability of UHV porcelain arrester, China Electric Power Research Institute invented a new lead damper made of lead metal according to some patents at home and abroad [5-11], as shown in Fig. (**1**). Furthermore, this study investigates the seismic reliability method of the UHV porcelain arrester with and without the new lead damper, with a purpose of enhancing the safety performance of the equipment in an earthquake. This method is as follows: The first step is to generate synthetic artificial seismic wave suitable for different sites according to random seismic model. Secondly, the stochastic dynamical response of ultra-high voltage power facilities can be got by taking time history analysis. Finally, The reliability of the UHV porcelain arrester with damping system can be calculated based on reliability theory [12].

Fig. (1). New type lead damper.

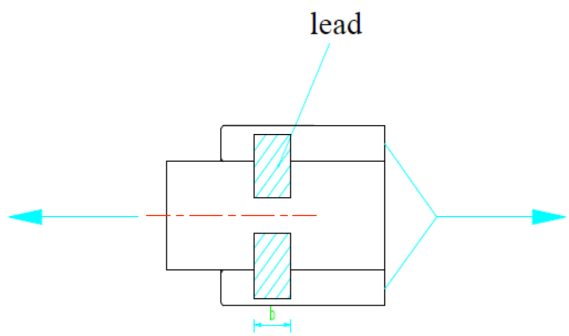


Fig. (2). Action principle of the new type lead damper.

2. DYNAMIC FEATURE OF THE UHV PORCELAIN ARRESTER WITH DAMPING SYSTEM

The dynamic features of the UHV porcelain arrester with damping system can be figured out by formula (1).

$$[M]\{\ddot{x}(t)\}+[C]\{\dot{x}(t)\}+[K]\{x(t)\}=-[H]\{u(t)\}-[M]\{I\}\ddot{x}_g(t) \quad (1)$$

In formula (1), [*M*], [*K*] and[*C*] a are the original structure's quality, stiffness and damping matrix; $\{\ddot{x}(t)\}$, $\{\dot{x}(t)\}$ and $\{x(t)\}$ are acceleration, velocity and displacement vector; $[I]$ is column vector; $\ddot{x}_g(t)$ is input earthquake acceleration; $[H]$ is the installation position matrix of the dampers; $\{u(t)\}$ is the control force vector provided by the damper, where the *i* th element is the control force generated by the *i* th damper. From formula (1), the damper provides additional damping force for high voltage electric equipment in an earthquake ($-[H]\{u(t)\}$), which is opposite to earthquake action (μ_R) and reduces the seismic response. Besides, the control principle of the damper can be further explained from the perspective of seismic response of high voltage electric power equipment.

Let $\{P(t)\}=-[H]\{u(t)\}-[M]\{I\}\ddot{x}_g(t)$, then formula (1) can be written as:

$$[M]\{\ddot{x}(t)\}+[C]\{\dot{x}(t)\}+[K]\{x(t)\}=\{P(t)\} \quad (2)$$

Formula (2) accords with the classical form of matrix structural dynamic analysis [16]. In general, let $P_f=\Phi(-\beta)=1-\Phi(\beta)$, and substitute it into formula (2), and the following formula are obtained:

$$x(t)=\frac{P_0/K}{\sqrt{[1-(w/w_n)^2]^2+(2\zeta w/w_n)^2}}\sin(wt-\phi)$$
$$=(P_0/K)R\sin(wt-\varphi) \quad (3)$$

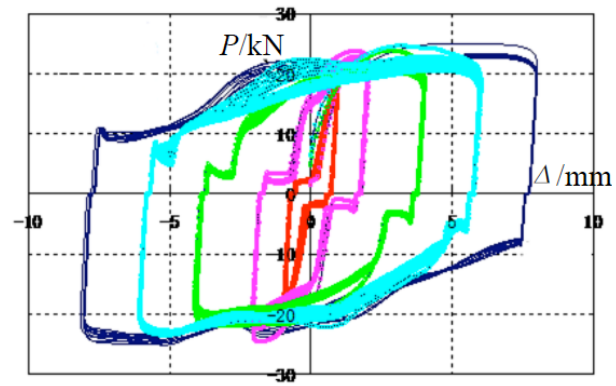


Fig. (3). Hysteretic loops of the new type lead damper.

In formula (3), *w* is ground acceleration input main frequency; w_n is natural frequency; ξ is total damping ratio, *R* is dynamic magnification factor, which can be written as follows:

$$R=\frac{1}{\sqrt{[1-(w/w_n)^2]^2+(2\zeta w/w_n)^2}} \quad (4)$$

In order to realize seismic control, damping or frequency of the UHV porcelain arrester is to be adjusted. As (Fig. **2**) shows, earthquake energy can be dissipated by shear deformation of the damper, which works through two lead body slide along one another and provides additional damping to the UHV porcelain arrester. The required parameters of the damper are shown in Table **1**. These parameters can be determined by hysteretic curve of the damper, as shown in Fig. (**3**).

3. EXPERIMENTAL VERIFICATION OF FINITE ELEMENT MODEL

3.1. Finite Element Model

The UHV porcelain arrester for voltage levels of 1100 kV mainly composes of bushing, grading rings and connecting flange. The dampers are installed at the bottom of the arrester, which the gross weight is 5863kg, as shown in Fig. (**4**). The material features of the UHV porcelain arrester are shown in Table **2**. Fig. (**5**) shows two finite element models, which are aseismic and damping structure of the UHV porcelain arrester established using ANSYS. The main equipment, equivalent flange, grading ring and are all simulated by beam 189 element [13]; the damper can be simulated by bilinear spring damping unit combin 40 [14]. The damp ratio of the UHV porcelain arrester is 2% while damping ratio of the UHV porcelain arrester with the dampers is 5% in time-history analysis. In order to prevent the UHV porcelain arrester from horizontal displacement, it is necessary to constrain the bottom

Table 1. Test parameters of the new type lead damper.

Pre-yield Stiffness K_1 (kN.m^{-1})	Post-Yield Stiffness K_2(kN.m^{-1})	Yield Force F_1(kN)	Maximum Force F_m(kN)	Ultimate Displacement D_u (mm)	Additional Damping Ratio(ξ)
85000	4250	17	23	8	0.541

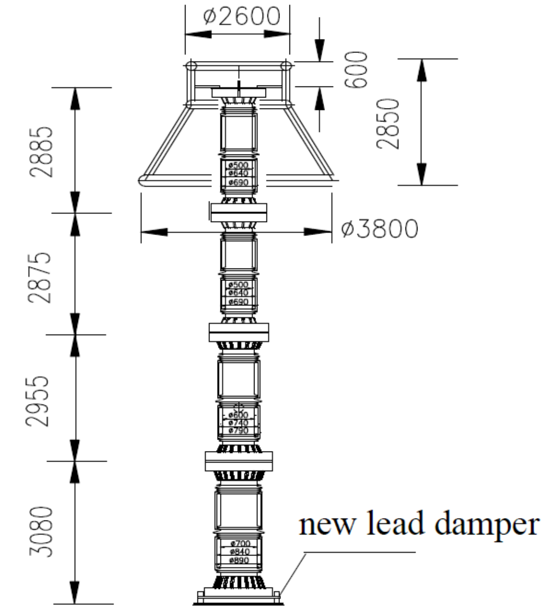


Fig. (4). Sketch of the UHV porcelain arrester.

Table 2. Material properties of the UHV porcelain arrester.

Material	Modulus of Elasticity (MPa)	Poisson's Ratio	Density (kg/ m^3)	Tensile Strength (MPa)
Porcelain bushing	0.90×10^{11}	0.3	2600	65
Ring-type aluminum tube	0.70×10^{11}	0.3	2700	145

Table 3. First 2 orders of frequency of the UHV porcelain arrester (Hz).

Frequency (Hz)	With Damper		Without Damper	
	Test Values	Calculated Values	Test Values	Calculated Values
First-order	2.28	2.14	1.78	1.72
Second-order	11.72	10.98	10.78	10.54

in the horizontal direction, and connect the bottom with four dampers vertically.

3.2. The Comparison Between Calculation Test Results and Calculated Results

By modal identification research of finite element model of the UHV porcelain arrester's aseismic structure and damping structure [15], the first two orders of frequency of the equipment are obtained, as shown in Table **3**. It can be seen from the table that the way of seismic vibration control of the damper is to provide additional damping and the damper has little effect on the equipments frequency. With regard to adopting time-history method to analyze the UHV porcelain arrester with and without the dampers, the UHV porcelain arrester is subjected to 0.15g sine-wave and the UHV porcelain arrester with the dampers is subjected to 0.30g sine-wave. The comparison between test results and calculated results is given in Table **4**. It is clear from data in Table **4** that the results obtained by adopting finite element analysis agree well with those test obtained by test. So, the finite element model of the UHV porcelain arrester is reliable and it can be used for the seismic reliability analysis.

4. RANDOM SEISMIC RESPONSE ANALYSIS

Due to the randomness of earthquake has great influence on the seismic response of the UHV equipment. the randomness of earthquake motion has to be taken into consideration in the analysis of the seismic response of the UHV porcelain arrester with damping system. This paper proposes a approach to synthesize random seismic wave based on the ramdom Fourier spectra corresponding to the physical random earquake model [16].

Table 4. Comparison between calculation test results and calculated results.

Bushing		Without Damper (0.15g Sine-wave)		With Damper (0.30g Sine-wave)	
		Test Values	Calculated Values	Test Values	Calculated Values
Stress (MPa)	Top bushing	4.2	3.9	4.8	4.5
	second bushing	12.9	12.0	14.5	14.1
	third bushing	14.0	13.0	16.9	15.8
	Bottom bushing	17.5	16.2	18.6	17.7
Top displacement (mm)		70.0	73.0	127.0	131.0

$$F(X,w)=H(X_w,X_\xi,w)\cdot F_o(X_{g1},...X_{gn},w) \quad (5)$$

$$H(X_w,X_\xi,w)=\frac{w_o^2+2\xi w_o wi}{w_o^2-w^2+2\xi w_o wi} \quad (6)$$

In Formula (6), w_0 is site fundamental frequency, ξ is site equivalent damping ratio.

$$F_0(w)=\begin{cases}\frac{f}{f_1}\cdot S_g & 0<f<f_1\\ S_g & f_1\le f\le f_2\\ -\frac{f-f_e}{f_e-f_2} & f_2<f<f_e\end{cases} \quad (7)$$

In Formula (7), f_1 and f_2 are break frequency, and 0.6 and 14.4 are chosen, respectively; f_e is the cut-off frequency, and 15 is chosen; and S_g is the parameter to determine the base amplitude spectrum. According to the relationship between Fourier coefficients and Fourier integral, artificial seismic wave can be generated based on stochastic Fourier amplitude spectrum.

$$A(w_i)=\frac{1}{2\pi}F(w)\Big|_{w=w_j}d_w \quad (8)$$

Owing to, $d_w\approx\Delta w$ formula (8) can be converted in the time domain,

$$x(t)=2\cdot\sum_{j=1}^{N}\left[\left(\frac{\Delta\omega}{2\pi}F(w)\Big|_{w=w_j}\right)\cdot\cos(\omega_j t+\varphi_j)\right] \quad (9)$$

In Formula (9), $F(w)\Big|_{w=w_k}$ is the Fourier amplitude spectrum corresponding to each frequency component of the discrete value. In organic synthesis, the random variable w_0、ξ and S_g take samples from a given value.

The model can not only reflect site characterization, but also simulate the earthquake randomness by changing initial value of the initial value of initial phase angle. When using the model to synthesize artificial random seismic wave, three random variables, circular frequency w_0, equivalent damping ratio ξ and initial phase angle θ, can be used,which can be selected by adopting the cut point method [17]. The seismic response of the UHV porcelain arrester with and without the damper obtains by inputting the artificial stochastic seismic wave based on physical stochastic seismic wave model into the finite element model of the equipments. Because of the limit of the article space, the parts of caulation results are listed. Table **5** lists the maximum stress near the root of the UHV porcelain arrester with and without the damper under the random seismic wave with different amplitude (0.2g of average peak ground acceleration values) and Fig. (**6**) shows time history curve of root stress the UHV porcelain arrester with and without the dampers. Comparison with aseismic structure of the UHV porcelain arrester indicates that the root stress of damping structure the UHV porcelain arrester is obviously reduced. Fig. (**7**) shows the stress distribution of the UHV porcelain arrester, which indicates the maximum stress of these two structures is distributed neer the root of the equipment.

5. SEISMIC RELIABILITY ANALYSIS

The 221 level stochastic earthquake wave can be generated based on the physical stochastic seismic motion model before carrying on the earthquake resistance reliability computation to the UHV porcelain arrester with and without the dampers. After inputting these level stochastic earthquake wave to finite element models of the UHV porcelain arrester with and without the dampers, the maximum random equivalent stresses obeying normal distribution of the root porcelain of the equiments can be got. Then the mean and variance of stresses can be got under the condition of different grades of artificial seismic wave. The failure stresses of high silicon porcelain after testing obey normal distribution. The average failure stress is 45MPa and the variance of the failure stress is 6.8MPa [18]. Finally, the earthquake resistance reliability of the UHV porcelain arrester with and without the dampers can be obtained by deviation in equation (10)~(12).

$$\beta=\frac{\mu_R-\mu_S}{\sqrt{\sigma_R^2+\sigma_S^2}} \quad (10)$$

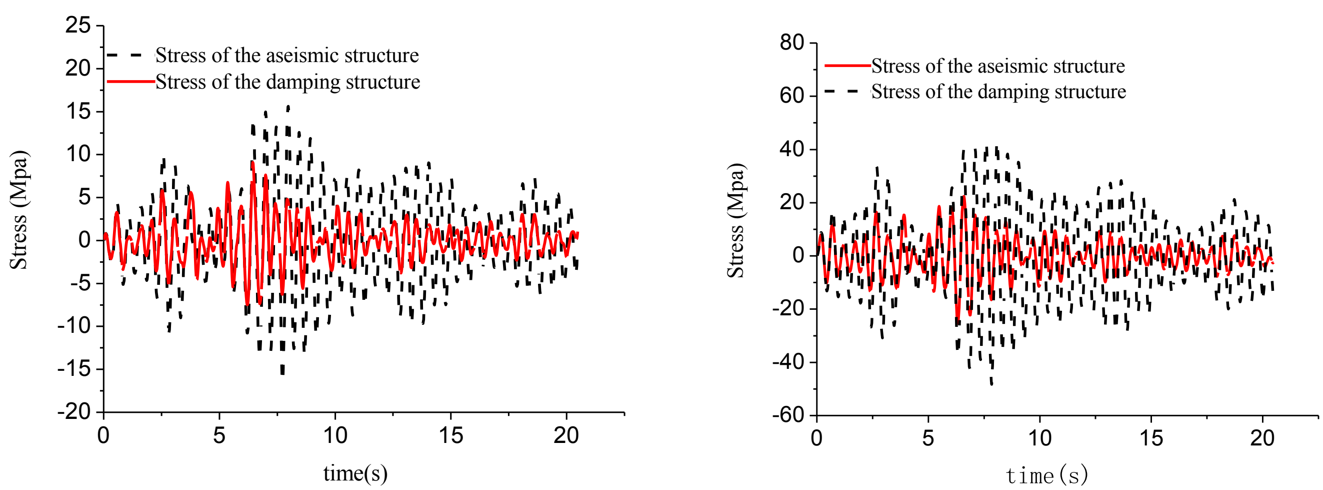
$$P_f=\Phi(-\beta)=1-\Phi(\beta) \quad (11)$$

Table 5. Maximum stress near the root of the UHV porcelain arrester (MPa)

Seismic Wave	Maximum Stress	
artificial random stochastic waves (0.20g)	without damper	11.90~48.53
	with damper	6.22~24.17

(1) Aseismic structure (2) Damping structure

Fig. (5). The finite element models of the UHV porcelain arrester.

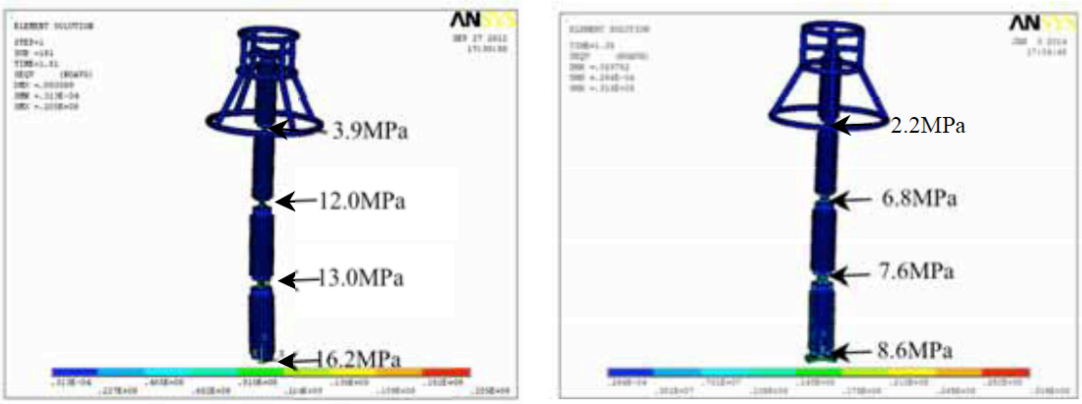


(1) Case (1) (2) Case (2)

Fig. (6). Stress time history near the root of the UHV porcelain arrester.

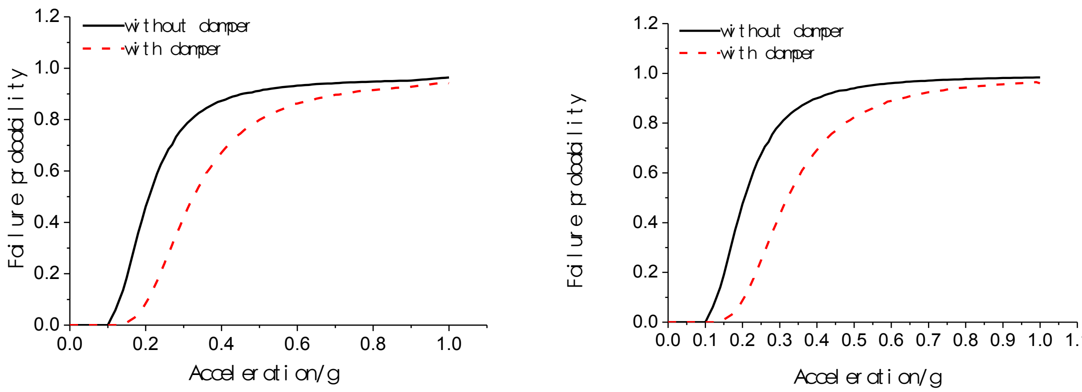
$$P_r = \Phi(\beta) \quad (12)$$

In formula (8)~formula (10), Φ(.) is standard normal distribution function, $\mu_R$is average value of the equipment resisting force, σ_R is standard deviation of the equipment resisting force; σ_S is average value of the equipment seismic response, σ_R is standard deviation of the equipment seismic response. P_f is equipment failure probability, P_r is equipment seismic reliability. The seismic damage rate curve of the UHV porcelain arrester with and without the dampers are shown in Fig. (**8**). The seismic reliability of the UHV porcelain arrester with and without the dampers is high under Ms 7.0 earthquake (0.1g of average peak ground acceleration values) but the seismic reliability of the UHV porcelain arrester is low under Ms 8.0 earthquake (0.2g of average peak ground acceleration values). The seismic reliability of the UHV porcelain arrester can be effectively enhanced under Ms 8.0 earthquake after installing the dampers at the bottom of the equipment under. Furthermore, the aseismic reliability of the UHV porcelain arrester with and without the dampers is different under the different site conditions.

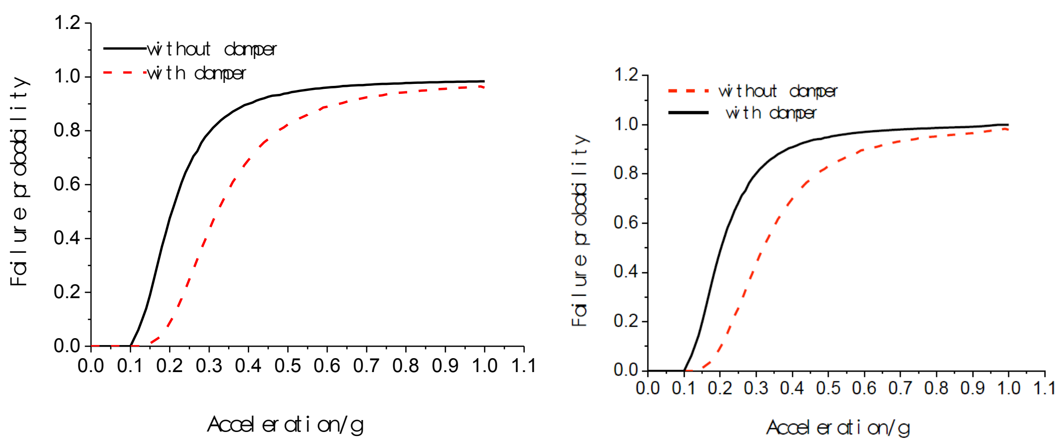


(1) Aseismic structure (2) Damping structure

Fig. (7). Stress contours of the UHV porcelain arrester.



(1) Class **I** site soil (2) Class **II** site soil



(3) Class III site soil (4) Class IV site soil

Fig. (8). Damage curve of the UHV porcelain arrester with and without the new type lead damper.

CONCLUSION

Some conclusions can be summarized by theoretically analyzing and calculating of the UHV porcelain arrester with damping system.

The fashion of vibration-reduction contro1 of the new type of lead damper is to provide additional damping to the equipment and the damper has little changed the frequency of the UHV porcelain arrester.

The results of UHV arrester obtained by test coincident well with the FEM results, the FEM model of UHV arrester is available and can be used for seismic reliability study of the UHV porcelain arrester with damping system.

Based on the stochastic earthquake model, a seismic reliability analysis method for evaluating the reliability of UHV porcelain arrester with damping system under different site conditions is presented.

(4) Comparison with the arrester without damping system indicates that the seismic reliability of the arrester can be effectively enhanced under Ms 8.0 earthquake after installing the new type lead damper.

CURRENT & FUTURE DEVELOPMENTS

The paper has reviewed the author's patent on a new lead damper made of lead metal for enhancing the seismic reliability of UHV porcelain arresters. The results of the test show that the lead dampers are well functioning, limiting the relative displacement and absolute acceleration at the top of bushing. There is a above reduction of 40% in the maximum strain of bottom porcelain pipe and the stronger the input ground motion is , the larger the reduction will be. The lead dampers can provide a definite initial stiffness to the arresters. Comparison with the arrester without damping system indicates that the seismic reliability of the arrester can be effectively enhanced under Ms 8.0 earthquake after installing the new type lead damper. Furthermore, the damper can be widely used in a variety of high voltage electrical equipment.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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