Research Article

The relationship between the damage rate of high voltage electrical equipment and instrumental seismic intensity

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Abstract:

Wenchuan earthquake that occurred in China in 2008 caused severe damage to a large number of electric substations. In this paper, Kriging interpolation method was used to calculate the impact area of the instrumental seismic intensity in Wenchuan earthquake, and to compare the intensities based on strong motion observation against the instrumental seismic intensities at locations where the observation data is available. The instrumental seismic intensities were calculated for the Wenchuan Earthquake at substations in the national power grid with voltage of 110kV or higher in areas of Mianyang, Deyang, Guangyuan and Chengdu. The cumulative Gaussian distribution function was then used to fit the relationship of the curves of the damage probabilities of high-voltage electrical equipment such as transformers, voltage mutual inductors, current mutual inductors, circuit breakers, isolating switches and lightning arrester with their instrumental seismic intensities. The damage probability density distribution curve of high-voltage electrical equipment based on the instrumental seismic intensities was obtained. The results showed that: (1) In the lower seismic intensity region, the mean instrumental seismic intensity was in good agreement with the traditional seismic intensity, but there was noticeable dispersion; in regions of intensity IX and above, the instrumental intensity was lower than the seismic intensity, but there was a lower degree of dispersion. (2) Among high-voltage electrical equipment, the transformers were most vulnerable to damage and they had some damage even under lower instrumental intensity. More damage would be produced when the instrumental intensity reached VIII or above; the second most vulnerable equipment was the circuit breaker, and the damage was most likely to occur when the instrument intensity was IX or above . (3) The damage rate curves of lightning arresters, current mutual inductors, voltage mutual inductors and isolating switches were relatively close to each other and the damage probability was the highest when the instrumental intensity was about X.

Keywords: substation; high voltage electrical equipment; damage rate; instrumental seismic intensity; statistical curve

1. Introduction

Various disastrous earthquakes at home and abroad have caused serious damage to high-voltage electrical equipment in the transformer substations, resulting in the failure of power grid function in the disaster areas, which has caused great difficulties for post-event emergency rescue efforts, the lives of the affected people and the resettlement of the people after the

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disaster. Researches on the vulnerability of high voltage electrical equipment in the transformer substations are of great significance for improving the seismic performance of electrical equipment, assessing the damage and functional failure of power facilities and emergency repair after earthquake.

The researches on the vulnerability of high-voltage electrical equipment are mainly divided into three categories: theoretical and numerical calculation methods, shaking table experimental method and statistical method for seismic damage [1]. The first two are main methods and means for studying the seismic capability of the equipment, simulating seismic response process and damage mechanism, developing techniques for earthquake resistance, earthquake damage mitigation and seismic base isolation [2-4]. The statistical method for seismic damage is to study the damage rates of the equipment under different ground motion intensities through statistical analysis on the basis of samples of high-voltage electrical equipment damaged in earthquakes, so as to obtain the vulnerabilities of the equipment. This method is directly linked to the actual seismic damage and is often used for seismic equipment damage risk analysis, seismic damage estimation and economic loss assessment.

In the 1990s, the Pacific Earthquake Engineering Center (PEER) and Pacific Gas and Electric Company in US jointly established the Database of Seismic Performance of Transformer Substation Equipment for California, which recorded the damage data of electrical equipment of 60 substations of different voltage classes with 220 kV and above in 12 earthquakes in California. They statistically calculated the vulnerability curves of high voltage electrical equipment and the result was widely used in post-disaster assessment in electrical power system [5]. The Applied Technology Council (ATC) in US provided seismic vulnerability curves for various lifelines, which were used in the seismic risk analysis system of Federal Emergency Management Agency (FEMA) [6-7].

In recent years, some scholars in China have studied the seismic vulnerability of substation electrical equipment with oil-immersed high-voltage transformer connected to the pipe busbar [8-9]; Hailei He et al provided seismic vulnerability curves of transformers, busbars and power transmission towers based on seismic damage data [10]; Zhenlin Liu used the Weibull distribution function to fit the seismic vulnerability curves of electric porcelain electrical equipment [11]; Changqing Yang studied the relationships of the damage probabilities of various high-voltage electrical equipment with the peak ground acceleration and acceleration response spectrum, and analyzed the functional failure modes of transformer substations under different peak ground accelerations [12].

At present, rapid progress has been made in the construction of seismic intensity rapid reporting system in various regions of China [13], and the system can quickly produce spatial distribution information of instrumental seismic intensity after the earthquake. The rapid assessment of seismic disaster based on output information of instrumental seismic intensity is an urgent need for earthquake emergency response and engineering rescue. The research on the vulnerability of high-voltage electrical equipment based on instrumental seismic intensity is the basis of rapid seismic disaster assessment of power facilities.

However, the results of the research on the vulnerability of aforementioned electrical equipment are based on peak acceleration, acceleration response spectrum or traditional intensity. At present, there are no published reports on the research on the vulnerability of substation high voltage electrical equipment based on the instrumental seismic intensity.

To study the vulnerability of substation high-voltage electric equipment, this paper first calculated the instrumental intensities at strong motion observation stations in Wenchuan earthquake, and Kriging interpolation method was used to calculate the instrumental seismic intensities in a total of 121 110kV and above substations in national power grid in the worst-hit areas of Mianyang, Deyang, Guangyuan and Chengdu in Wenchuan earthquake, and then according to the seismic damage data of high-voltage electrical equipment, a cumulative Gaussian distribution function was used to fit the damage rate -

instrument intensity relationship curve of high-voltage electrical equipment such as transformer, circuit breaker, voltage mutual inductor, current mutual inductor, isolating switch and lightning arrester and construct a vulnerability curve based on instrumental seismic intensity, in order to provide a basic reference for seismic risk assessment and emergency response of power facilities.

2. Instrumental seismic intensity of strong motion observation stations

The instrumental seismic intensity is the intensity calculated using the strong motion observation records according to a specified method, and it can directly reflect the ground motion intensity of the observation site and can be quickly obtained after the earthquake [14]. Rapid seismic intensity reporting systems have been established and different algorithms for instrumental seismic intensity have been specified in countries and regions such as United States, Japan and Taiwan. The national seismic intensity rapid reporting and early warning projects in China are under construction, and the seismic intensity rapid reporting network has already been constructed in a few selected regions, and the interim regulations for the calculation of instrumental seismic intensity have been promulgated.

In accordance with the interim regulations in China, the calculation method for instrumental seismic intensity is defined as follows: baseline correction, band-pass filtering and three-component synthesis of three-component seismic acceleration or velocity records at the observation sites are performed to calculate the peak ground acceleration (PGA)and the peak ground velocity (PGV), and then they are brought into equation (1) and (2) to calculate IPGA for the peak seismic acceleration and IPGV for the peak seismic velocity.,Instrumental seismic intensity I is finally determined by the equation (3). The instrument seismic intensity is categorized into scales from I to XII.

$$I_{PGA}=\begin{cases}3.17lg\left(PGA\right)+6.59, & \textit{When the PGA was synthesized from three directions}\\ 3.20lg\left(PGA\right)+6.59, & \textit{When the PGA was synthesized from two horizontal directions}\\ 3.23lg\left(PGA\right)+6.82, & \textit{When the PGA was synthesized from single}\end{cases} \quad (1)$$

$$I_{PGV}=\begin{cases}3.00lg\left(PGV\right)+9.77, & \textit{When the PGA was synthesized from three directions}\\ 2.96lg\left(PGV\right)+9.78, & \textit{When the PGA was synthesized from two horizontal directions}\\ 3.11lg\left(PGV\right)+10.21, & \textit{When the PGA was synthesized from single}\end{cases} \quad (2)$$

$$I=\begin{cases}I_{PGV}, & I_{PGA}\geq 6.0 \; and \; I_{PGV}\geq 6.0\\ (I_{PGA}+I_{PGV})/2, & I_{PGA}<6.0 \; or \; I_{PGV}<6.0\\ 1.0, & I\leq 1.0\\ 12.0, & I\geq 12.0\end{cases} \quad (3)$$

A total of 255 strong motion observation stations in four provinces of Sichuan, Gansu, Ningxia and Shaanxi obtained strong-motion acceleration records in Wenchuan earthquake. According to the above mentioned calculation methods, the data obtained at these strong motion observation stations were processed, and the instrumental seismic intensities at these locations were calculated. The comparison between the seismic intensity at strong motion observation stations and the instrumental seismic intensity at the same sites was shown in Figure 1.

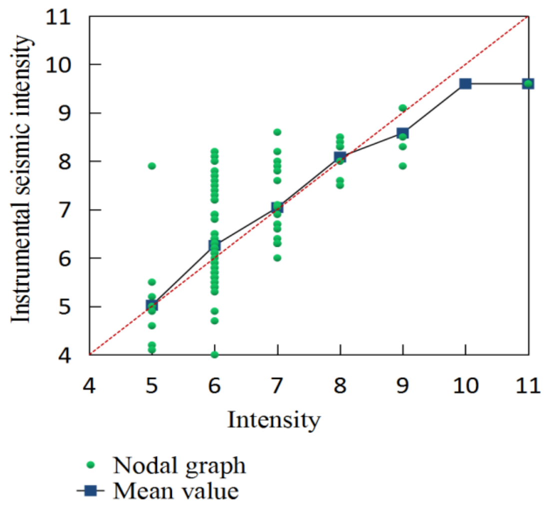

Fig.1 The contrast figure of seismic intensity and instrumental seismic intensity of strong motion observation stations

From Fig. 1the following can be stated. (1) The mean instrumental intensity was in good agreement with the traditional intensity in regions of intensity VIII or below, while the instrumental intensity was lower than the traditional intensity in regions of intensity IX or above. (2) The instrumental intensity had some dispersion from the traditional intensity, and the dispersion was relatively large in the low-intensity regions. As the intensity increased, the dispersion decreased. There were more data points in regions of intensity between V and VII, the maximum difference of the instrumental intensity from traditional intensity was close to 2, and the dispersion in intensity VIII region was relatively small.

3. Interpolation of instrumental seismic intensity at substations

The Kriging interpolation method is used to calculate the instrumental intensity of the substation based on the instrumental intensity and position coordinates of the strong motion observation station.

Kriging interpolation method is an interpolation method named after South African geologist P. G. Krige by French scientist Matalon [15], which is widely used in contour line in many fields. The theoretical basis is the regionalized variable theory and the variogram theory, and the estimated values are obtained under the premise of ensuring that the estimated values satisfy the unbiased condition and the minimum variance condition. The Kriging interpolation method not only considers the positional relationship between the points to be evaluated and the sample points, but also considers the spatial correlation of all known points near the point to be evaluated, thus it greatly reduced the systematic error in instrumental intensity fitting.

It is assumed that $f(x)$ is the regionalized variable in the space where the interpolation point and the sample point are located, and it is intrinsic, and $f_i(i=1,2,\ldots,n)$ is the corresponding value at the sampling point $x_i(i=1,2,\ldots,n)$. The estimated value of f_0 is f_0^*, and f_0^* meets the following conditions:

$$f_0^* = \sum_{i=1}^{n} \lambda_i f_i \ , i = 1,2,\ldots,n \tag{4}$$

The coefficient $\lambda_i(i=1,2,\cdots,n)$ could be calculated according to the principle of unbiasedness and minimum variance of error.

According to the principle of unbiasedness, there is:

$$E\left[f_0^* - f_0\right] = 0 \tag{5}$$

Thus it could be concluded:

$$\sum_{i=1}^{n} \lambda_i = 1 \tag{6}$$

The error variance was:

$$\begin{aligned} S_E^2 &= E\left[f_0^* - f_0\right]^2 - \left\{E\left[f_0^* - f_0\right]\right\}^2 \\ &= \sum_{i=1}^{n}\sum_{j=1}^{n} \lambda_i \lambda_j C_{i,j} - 2\sum_{i=1}^{n} \lambda_i C_{i,0} + C_{0,0} \end{aligned} \tag{7}$$

The partial derivative for the error variance was calculated:

$$\frac{\partial S_E^2}{\partial \lambda_i} = 2\sum_{j=1}^{n} \lambda_j C_{i,j} - 2C_{i,0} \tag{8}$$

To minimize the error variance, the extreme value of the error variance was calculated. The Lagrangian multiplier method was used. Assume :

$$F = S_E^2 - 2t\left(\sum_{i=1}^{n} \lambda_i - 1\right)$$

(9)

We can calculate the partial derivatives respectively for λ_i and t, and set them to be equal to zero:

$$\begin{cases} \dfrac{\partial F}{\partial \lambda_i} = 2\sum_{j=1}^{n} \lambda_j C_{i,j} - 2C_{i,0} - 2t = 0 \\ \dfrac{\partial F}{\partial t} = -2\left(\sum_{i=1}^{n} \lambda_i - 1\right) = 0 \end{cases} \tag{10}$$

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The equation (10) was arranged to to be the following:

$$\begin{cases} \sum_{j=1}^{n} \lambda_j C_{i,j} - t = C_{i,0} \\ \sum_{i=1}^{n} \lambda_i = 1 \end{cases} \quad (11)$$

λ_i and t could be resolved from equation (11). When the regionalized variable couldn't satisfy the second-order stationary hypothesis, but satisfied the intrinsic assumption, the variogram and covariance functions should have the following relationships:

$$C(m) = C(0) - y(m) \quad (12)$$

Substituting equation (12) into equation (11) we should have the following:

$$\begin{cases} \sum_{j=1}^{n} \lambda_j y(x_i - x_j) + t = y_{i,0} \\ \sum_{i=1}^{n} \lambda_i = 1 \end{cases} \quad (13)$$

λ_i could be calculated from equation (13), and then it was brought into equation (4) to obtain the estimated value of f_0^*.

The power supply system in Sichuan Province is composed of State Grid and power grids administered by local power companies, and State Grid is the main body. The Wenchuan earthquake caused severe damage to the power grid in Sichuan Province[16]. A total of 121 substations with voltage of 110kV and above in the State grids in all areas of Deyang, Mianyang and Guangyuan and selected areas of Chengdu such as Dujiangyan, Pengzhou, Chongzhou, Wenjiang and Pixian and those in Aba autonomous region but managed by State Grid Company were selected as the statistical analysis samples for the study on vulnerability of high-voltage electrical equipment. According to the spatial distribution of the strong motion observation stations and the instrumental intensity, the instrumental seismic intensities of the substations calculated by the above Kriging interpolation method were shown in Table 1.

Table 1:Substations samples of 110kv-and-above and instrumental seismic intensity

Region	Name oftransformer substation	Voltage degrees	Instrumental seismic intensity	Region	Name oftransformer substation	Voltage degrees	Instrumental seismic intensity
Deyang	Tanjiawan station	500	8.3	Chengdu	Shuzhou station	500	8.1
Deyang	Mengjia station	220	8.5	Chengdu	Danjing station	500	7.7
Deyang	Wulidui station	220	8.3	Chengdu	Longxing station	220	7.8
Deyang	Gucheng station	220	8.1	Chengdu	Huilong station	220	8.7
Deyang	Wan'an station	220	8.4	Chengdu	Yufu station	220	7.6
Deyang	Xinshi station	220	8.6	Chengdu	Juyuan station	220	9.0
Deyang	Yunxi station	220	8.8	Chengdu	Datian station	110	7.5
Deyang	Chengnan station	110	8.4	Chengdu	Chongzhou station	110	7.9
Deyang	Deyang station	110	8.2	Chengdu	Wangchang station	110	8.0
Deyang	Feng'guang station	110	8.6	Chengdu	Yongkang station	110	7.8
Deyang	Jinghu station	110	8.3	Chengdu	Guangming station	110	8.3
Deyang	Qingping station	110	8.4	Chengdu	Taiqing station	110	8.2
Deyang	Tianyuan station	110	8.4	Chengdu	Tianpeng station	110	8.4
Deyang	Yangjia station	110	8.5	Chengdu	Linwan station	110	7.9
Deyang	Binglinggong station	110	8.2	Chengdu	Pixian station	110	7.7
Deyang	Datang station	110	8.1	Chengdu	Gongping station	110	7.6
Deyang	Gaoxin station	110	8.4	Chengdu	Haike station	110	7.7
Deyang	Guanghan station	110	8.6	Chengdu	Liucheng station	110	7.6
Deyang	Jinxing station	110	8.3	Chengdu	Guanxian station	110	9.7

Deyang	Lianshan staion	110	8.2	Chengdu	Jinjiang station	110	9.2
Deyang	Luocheng station	110	8.2	Chengdu	Xujia station	110	9.3
Deyang	Sanxing station	110	8.2	Mianyang	Gufeng station	220	7.8
Deyang	Xiangyang station	110	8.1	Mianyang	Jiaqiao station	220	7.6
Deyang	Xiaohan station	110	8.3	Mianyang	Yongxing station	220	8.1
Deyang	Banzhu station	110	8.4	Mianyang	Dakang station	220	9.1
Deyang	Yuying station	110	8.3	Mianyang	Tianming station	220	8.4
Deyang	Minzhu station	110	9.0	Mianyang	Baisheng station	220	8.0
Deyang	Yanshi station	110	8.5	Mianyang	Anxian station	220	9.1
Deyang	Bajiao station	110	9.4	Mianyang	Sanyuan station	110	7.5
Deyang	Xiaoquan station	110	8.6	Mianyang	Gaoshui station	110	7.9
Deyang	Baimiao station	110	8.4	Mianyang	Mianyang station	110	7.9
Deyang	Dongbei station	110	8.7	Mianyang	Nanta station	110	7.8
Deyang	Longqiao station	110	8.6	Mianyang	Puming station	110	7.9
Deyang	Mianzhu station	110	8.7	Mianyang	Santai station	110	7.4
Deyang	Lianglukou station	110	8.8	Mianyang	Shiqiaopu station	110	8.0
Deyang	Shuangsheng station	110	8.7	Mianyang	Tangxun station	110	7.9
Deyang	Tutang station	110	8.6	Mianyang	Tieniu station	110	8.1
Deyang	Wanchun station	110	8.9	Mianyang	Xinzao station	110	8.0
Deyang	Yongning station	110	8.5	Mianyang	Yuanyi station	110	8.1
Deyang	Xiangshan station	110	9.0	Mianyang	Hongren station	110	7.7
Deyang	Hanwan station	110	9.1	Mianyang	Changqing station	110	7.7
Deyang	Chuanxindian station	110	9.1	Mianyang	Weicheng station	110	7.6
Guangyuan	Chihua station	220	9.8	Mianyang	Xianrenqiao station	110	7.8
Guangyuan	Hongjiang station	220	7.8	Mianyang	Xiaojian	110	7.8
Guangyuan	Baishiyan station	220	9.7	Mianyang	Youxian station	110	7.9
Guangyuan	Yuanjiaba station	220	10.0	Mianyang	Xiaoting station	110	8.2
Guangyuan	Lingjiang station	110	8.0	Mianyang	Huagai station	110	8.1
Guangyuan	Lantupo station	110	9.1	Mianyang	Jiepai station	110	8.0
Guangyuan	Chengjiao station	110	9.0	Mianyang	Erlangmiao station	110	9.7
Guangyuan	Jiange station	110	9.3	Mianyang	Ganxi station	110	8.5
Guangyuan	Saxiba station	110	9.5	Mianyang	Majiaoba station	110	10.0
Guangyuan	Xiasi station	110	9.0	Mianyang	Sanhe station	110	8.2
Guangyuan	Shangxi station	110	8.6	Mianyang	Shawo station	110	8.4
Guangyuan	Songlinpo station	110	8.1	Mianyang	Taibai station	110	8.3
Guangyuan	Chaotian station	110	9.4	Mianyang	Zhongba station	110	8.5
Guangyuan	Zhuyuan station	110	10.3	Mianyang	Jushui station	110	9.1
Guangyuan	Sandui station	110	10.4	Mianyang	Xiaoba station	110	8.9
Guangyuan	Muyu station	110	11.2	Mianyang	Yongan station	110	9.4
Guangyuan	Qiaozhuan	110	11.1	Mianyang	Yuanmen	110	9.2

	g station				ba station		
Aba station	Maoxian station	500	8.0	Mianyang	Leigu station	110	10.0
Aba station	Yinxing station	220	10.5				

4. Statistical methods for damage probability of various high-voltage electrical equipment in substations

All high-voltage electrical equipment outside the substations such as circuit breakers, isolating switches, voltage mutual inductors, current mutual inductors and lightning arresters belong to porcelain-column type structure. The damage patterns in earthquakes are mainly cracks and oil leakage occurring in porcelain components or direct fracture of porcelain columns. Once these types of equipment with porcelain column structures are destroyed, they cannot be repaired and thus need to be completely replaced. Therefore, the damage patterns of the equipment can be divided into two types, damaged and intact, and it is not necessary to divide them into five damage grades as used for building structures. The damage patterns of transformers in earthquakes are mostly porcelain casing damage. The oil pillow damage, radiator damage and wheel and rail fixture damage occur in high intensity areas, and sometimes the transformers could be overturned. However, the inside of the main body is not easy to be destroyed, and no damage occurred in the inside of any transformer in Wenchuan earthquake. No matter what kind of damage occurs in the transformer, it can be regarded as damage limited within a small range. Therefore, it can be considered as that the transformer has two damage states such as damaged and non-damaged, the same as other porcelain-type high-voltage electrical equipment, and no finer damage grades are needed.

A substation usually has 1 to 3 working transformers, and many sets for other types of high voltage electrical equipment. The damage rate R of a certain type of high-voltage electrical equipment in a substation was shown in equation (14):

$$R = n / N \tag{14}$$

In equation (14), n is the number of such type of equipment damaged in the substation; N is the total number of such equipment in the substation.

If we assume that the damage rate obtained for a type of high voltage electrical equipment in each substation as one sample, the least square fitting was performed using a functional expression for all substation samples in Table 1, the damage rate-instrumental seismic intensity fitting curves of various high-voltage electrical equipment could be obtained and they were the vulnerability curves of the equipment based on the instrumental seismic intensity. There have been studies on the relationships of the damage probability of the transformers and the busbars with the peak ground motion, and the studies used a logarithmic cumulative Gaussian distribution function to fit the relationship curves [9]. In addition, other scholars have studied the seismic vulnerabilities of basic components and structures of reinforced concrete under earthquakes. It is found that the use of a logarithmic cumulative Gaussian distribution function to express the relationship between their damage and the ground motion peak acceleration has a better rationality [17-18]. The instrumental seismic intensity has a linear relationship to some extent with the logarithms of the peak acceleration and the peak velocity. From the relationship between Gaussian distribution and logarithmic Gaussian distribution, it can be seen that the relationship between the damage probability of high-voltage electrical equipment and the instrumental seismic intensity can be fitted using the cumulative Gaussian distribution function.

If a random variable x follows Gaussian distribution with an expected value of μ and a standard deviation of σ, the probability density function is:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} exp[-\frac{(x-\mu)^2}{2\sigma^2}] \tag{15}$$

The cumulative Gaussian distribution function is:

$$F(x) = 0.5 + 0.5 erf(\frac{x-\mu}{\sigma\sqrt{2}}) \tag{16}$$

Wherein the *erf(x)* function is:

$$erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt \tag{17}$$

The damage rate of high-voltage electrical equipment in each substation and instrumental seismic intensity of the substation location were fitted by the formula (16) using the least squares method, and the damage rate curves of various types of high-voltage electrical equipment under different instrument seismic intensities could be obtained.

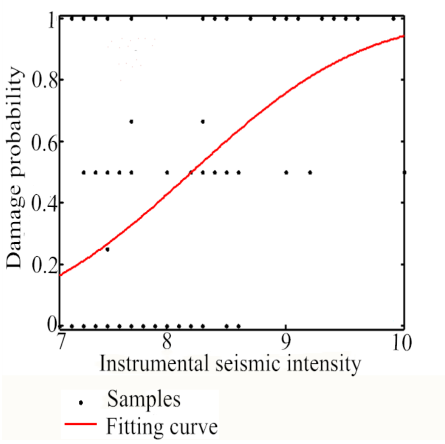
5. Results of vulnerability curve fitting for various types of high-voltage electrical equipment

Using the substations listed in Table 1 as the samples, the damage probability – instrumental intensity relationship could be fitted for transformer, circuit breaker, isolating switch, current mutual inductor, voltage mutual inductor and lightning arrester to derive parameter values μ and σ of cumulative Gaussian distribution function curves for these 6 types of high-voltage electrical equipment, as shown in Table 2.

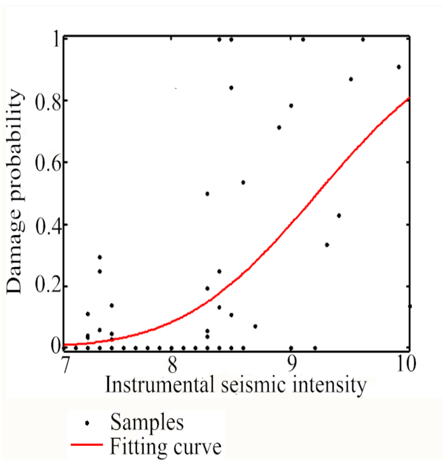
The fitted damage probability curves and original data samples of various high-voltage electrical equipment were shown in Fig. 2(a)-(f). It can be seen from Fig. 2 that: (1) For transformers, the damage rate was close to 20% when the instrumental intensity was VII, about 40% when the instrumental intensity was VIII, above 80% when the instrumental intensity was IX, and close to 100% when the instrumental intensity was X; (2) Although damage occurred in other types of equipment other than the transformers when the instrumental intensity was VII, the damage rate was very low, not exceeding 5%, and the damage rate was below 15% when the instrumental intensity was VIII; the damage rate was about 40% when the instrumental intensity was IX; the damage rate of circuit breakers reached 80% and the damage rates of transformers, isolating switches and lightning arresters basically ranged between 45% and 60% when the instrumental intensity was X; (3) the dispersion of damage rates for various types of high-voltage electrical equipment in substations was still large under different instrumental seismic intensities. For example, the damage rate for transformer in some substations had reached 100% within the instrumental intensity range of VI-VII, while no damage occurred in other substations. From the fitted curve, the damage rate of transformers was less than 30%; (4) Since the maximum number of transformers in a substation did not exceed 3, the damage rate values were only concentrated in several limited fixed values under various intensities, while there were usually more sets for other types of equipment in a substation, there were more sample points shown in the figure for these types of equipment.

Table 2:Gaussian distribution accumulation functioncurve parametervalues of high voltage electrical equipment damage rate

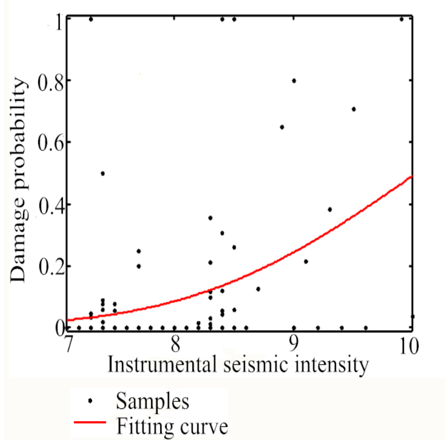
Equipment type	*μ*	*σ*
Transformer	8.21	1.14
Circuit breaker	9.26	0.88
Isolating switch	10.03	1.48
Lightning arrester	9.68	1.26
Current mutual inductor	9.92	1.36
Voltage mutual inductor	9.67	1.22



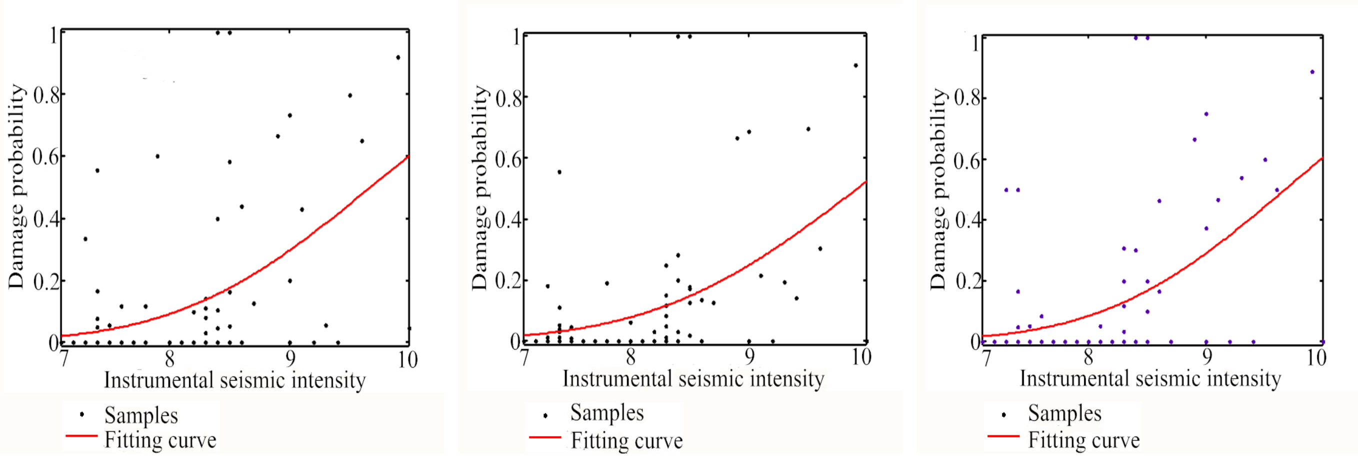
(a)Transformer



(b)Circuit breaker



(c)Isolating switch



(d)Lightning arrester (e)Current mutual inductor (f)Voltage mutual inductor

Fig.2 Damagerate fitted curves and samples distribution of high voltage electrical equipmen

The damage rates and probability density distribution curves of various types of equipment were compared respectively, as shown in Fig. 3 and 4.

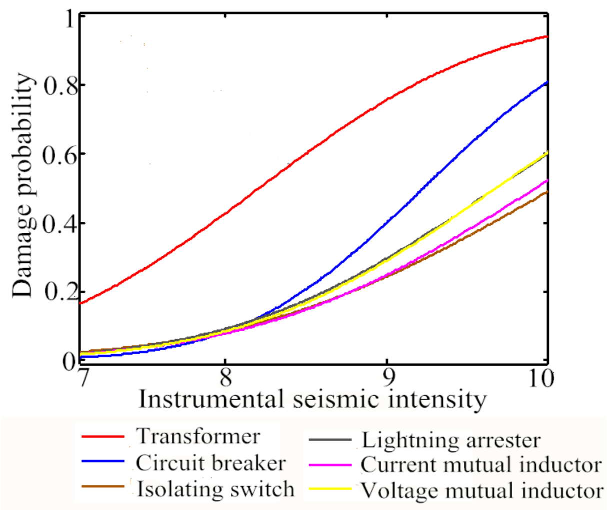


Fig. 3 Damage probability curves for all kinds of high voltage electrical equipment

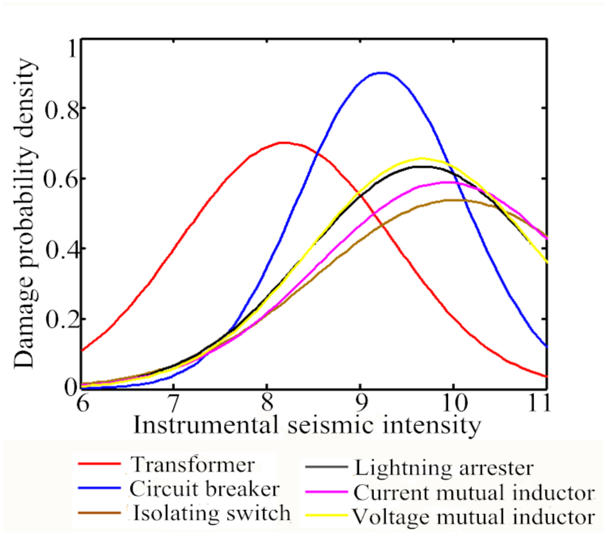


Fig. 4 Damage probability density curves for all kinds of high voltage electrical equipment

It could be seen from the comparison diagram in Figure 3 that the transformer was the most vulnerable to damage than other types of high-voltage electrical equipment, and its vulnerability was significantly higher than those for other types of equipment; the circuit breaker was the second most vulnerable in other types of equipment, and the damage rate curves of lightning arresters, mutual inductors and isolating switches were close to each other.

It could be seen from Fig. 4 that the damage probability density of transformers reached a peak value when the instrumental intensity was VIII, and the number of damaged transformers increased rapidly. The damage probability density of circuit breakers reached a peak value when the instrumental intensity was IX, and the number of damaged circuit breakers increased the most; the damage probability densities of isolating switch, lightning arrester, current mutual inductor and voltage mutual inductor reached peak values when their instrumental intensities were X, and the numbers damaged sets for these types of equipment increased rapidly. Fig.4 illustrated that on

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the one hand, different types of equipment had their respective damage-resistant strengths as the ground motion intensity increased; on the other hand, the damage of each type of equipment around this intensity value was disperse under the influences of various incidental factors.

6. Conclusion

According to the strong motion acceleration records of Wenchuan earthquake, Kriging interpolation method is used to calculate the instrumental seismic intensities at locations of a total of 121 110kV and above substations in affected areas of Mianyang, Deyang, Guangyuan and Chengdu in Wenchuan earthquake, and then the Gaussian distribution cumulative function is used to fit damage probability - instrumental intensity relationship curve for six kinds of equipment such as transformer, circuit breaker, voltage mutual inductor, current mutual inductor, isolating switch and lightning arrester in these substations to form vulnerability curves of high voltage electrical equipment outside the substations based on the instrumental seismic intensity. The fitting results show that the transformers have the highest vulnerability during earthquakes, and have a certain damage probability under lower instrumental intensity. The secondly most vulnerable equipment is the circuit breaker, followed by lightning arrester, transformer and isolating switch, the transformer and the isolating switch, and the seismic vulnerability curves of these types of equipment are relatively close to each other. The fragile link in the substations is mainly the transformer, which is the most important factor for the substations to lose their functions in the earthquakes. It is necessary to speed up the researches on measures to improve the seismic capacity of the transformer or enhance the shock absorption and seismic isolation performances.

At present, construction of a rapid seismic intensity reporting system is being vigorously promoted and developed in China, and a rapid reporting network has been formed in some provinces and regions, which can be used to timely release the rapid reporting information of the intensity after an earthquake. Instrumental seismic intensity will be widely used in earthquake emergency related efforts and disaster assessment. The vulnerability curve based on high-voltage electrical equipment can be used for rapid assessment of seismic damage and economic loss of power equipment, and can also provide reference for equipment emergency repair in power industry after an earthquake.

Wenchuan earthquake had a wide impact and heavy seismic damage. Many seismic damage samples have been obtained in regions with different levels of intensity, which provide a wealth of basic information for the study of the vulnerability of high-voltage electrical equipment. Due to sparse distribution of strong earthquake observation stations during Wenchuan earthquake, the instrumental intensity values in locations of substations cannot be directly obtained. However, the instrumental intensity values of substations estimated by the interpolation method must have certain errors compared with the actual values, which will bring some errors to the vulnerability statistics of high voltage electrical equipment based on instrumental intensity. At the same time, the fitting of vulnerability curves needs to be further enriched by accumulating more seismic samples in the future, especially the samples in high intensity regions of intensity X and XI need to be further enriched.

Date Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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