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Study on Seismic Fortification Grading Level and Distribution Diagram of Substation Electrical Equipment

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Abstract

The seismic fortification levels of electrical equipment have been more and more attention after Wenchuan earthquake. The current seismic requirement level of electrical equipment in China is lower than other international standards, such as IEEE 693, IEC 62271 and JEAG 5003. And the seismic level of electrical equipment is decided by combining several conditions of fortification intensity, site condition, and classification of design earthquake in China, which is not easy to determine the seismic level of electrical equipment quickly and conveniently. According to the characteristics of substation electrical equipment for high gravity center, large quality, soft structure and brittle material, and comparing domestic and foreign related codes about seismic fortification level of electrical equipment, the advantages of grading fortification were summarized, which would be more conducive to the work of production, call, qualification, and design for the electrical equipment. So grading fortification for electrical equipment in China was proposed. In order to obtain the grading fortification principle, the seismic reliability of electrical equipment was determined to calculate. Design earthquake accelerations of exceeding probability of 2% in 50 years which were higher than the norm value and obtained by survey were used as calculation parameters, two typical pillar electrical equipment were chosen as calculation modals, seismic reliability of electrical equipment in ordinary porcelain and high-strength porcelain was calculated using the FOSM method. The use of design earthquake accelerations of exceeding probability of 2% in 50 years will meet the seismic target of no collapsing with strong earthquake that will further assure seismic safety of electrical equipment. The seismic reliability of high-strength porcelain equipment was obviously higher than the value of ordinary porcelain equipment. So it is an effective method to improve equipment seismic capacity through replacing ordinary porcelain by high-strength porcelain. And the reliability results were as indexes to determine the low, medium and high levels. 0.1g and below was as low assessment level, peak acceleration was taken 0.1g. 0.1g~0.4g was as medium assessment level, peak acceleration was taken 0.4g. Above 0.4g was as high assessment level, peak acceleration was taken 0.6g.Comparing the peak acceleration with IEEE and IEC, it is found that the proposed seismic fortification for electrical equipment is more reasonable in whole district compared with IEEE and IEC, the acceleration value of each seismic level is moderate which is slightly lower than the value of IEEE and IEC. According to the grading level of seismic fortification, using ArcGIS technology, the distribution was mapped, and the applications of the series map will provide the dicision-making basis for reasonable planning electrical equipment.

Keywords: seismic fortification level, electrical equipment, seismic reliability

1. Introduction

Electrical equipment damage is one of the main factors that cause power network failure during an earthquake. People have realized the importance of the electrical equipment seismic capacity after the large-scale power failure, caused by the damage of electrical equipment, in Wenchuan earthquake. In China, the seismic design of electrical equipment is mainly based on GB 50260—2013“Code for seismic design of electrical installations” [1]. The seismic fortification level and site parameters are determined according to GB 18306—2015 “China earthquake parameter zoning map”[2] and GB 50011—2010 “Code for seismic design of buildings”[3].

As references of seismic design for general constructions, GB 18306—2015 “China earthquake parameter zoning map” and GB 50011—2010 “Code for seismic design of buildings” are applicable to the design of specific buildings. Both the peak ground acceleration and characteristic period are specified by considering different fortification intensities and different site conditions as well as the classification of designed earthquake, respectively. For building structures, this detailed classification is feasible because of the protracted nature and immobility of structures. However, for electrical equipment that has strong universality, this detailed classification will bring a lot of troubles in design, production and damage recovery. Considering the characteristics of electrical equipment, foreign countries/regions have given seismic zoning map for electrical equipment, which are divided into three levels including high, medium, and low[4,5], by combining structure seismic zoning maps.

In this paper, the domestic and foreign relevant specification of electrical equipment seismic fortification levels are compared, the advantages of classification fortification are analyzed, and the seismic fortification grading level of China is suggested.

2. Comparison of seismic level of electrical equipment in domestic and foreign codes

Many countries and regions have set up the seismic codes for electrical equipment, in which the seismic rating and fortification objectives are provided, as shown in Table 1. Foreign seismic fortification provisions for electrical equipment are confirmed by means of establishing levels, for example, Japan establishes one level. Both IEC standard and IEEE standard have established three levels including high, medium, and low, but they have different criteria for the classification and fortification level. Seismic level of IEC 62271-2, corresponding to level S2 earthquake, is equivalent of safety shutdown earthquake in nuclear power station, the annual exceedance probability is 10^{-4}. IEEE 693 is classified on 10% exceeding probability in 50 years.

Table 1 – Comparison of seismic level in foreign related seismic codes for electrical equipment

<table>
<tr><th colspan="2">Foreign related seismic codes</th><th>Seismic level</th><th>PGA（g）</th></tr>
<tr><td colspan="2" rowspan="3">IEEE Std 693-2005
“IEEE Recommended Practice for Seismic Design of Substations”</td><td>low：<0.1g</td><td>0.1g</td></tr>
<tr><td>medium：0.1g~0.5g</td><td>0.25g</td></tr>
<tr><td>high：>0.5g</td><td>0.5g</td></tr>
<tr><td colspan="2" rowspan="3">IEC62271-2:2003“High-voltage switchgear and controlgear—Part 2: Seismic qualification for rated voltages of 72.5kV and above”</td><td>AG2：Mild to moderate earthquake</td><td>0.2g</td></tr>
<tr><td>AG3：moderate to strong earthquake</td><td>0.3g</td></tr>
<tr><td>AG5：strong to extra strong earthquake</td><td>0.5g</td></tr>
<tr><td rowspan="2">Japan“Guide for seismic design of electrical equipment”[6]
JEAG 5003-1998</td><td>Porcelain type electrical equipment</td><td>—</td><td>0.3g</td></tr>
<tr><td>transformer insulation bushing</td><td>—</td><td>0.5g</td></tr>
</table>

Most seismic codes in China distinguish particularly the general equipment and the important equipment, take the 50 year exceedance probability of 10% as the fortification level, and take the fortification intensity as the standard. However, GB/T 13540—1992 “Seismic qualification for high-voltage switchgear and controlgear” is a exception, which cites IEC 62271-2:2003 and is same to the specification on seismic level. It does not match current codes in China, thus the seismic level specification of electrical equipment is far from uniform in China.

3. Seismic reliability analysis of typical electrical equipment

The failure mode of electrical equipment is usually brittle failure, the limit state equation is linear, and it is sufficient to calculate the seismic reliability using FOSM. Both the resistance and response of equipment follow the normal distribution. Thus, the reliability index β, the failure probability P_f and reliability P_r are:

$$\beta = \frac{\mu_R - \mu_S}{\sqrt{\sigma_R^2 + \sigma_S^2}} \tag{1}$$

$$P_f = \phi(-\beta) = 1 - \phi(\beta) \tag{2}$$

$$P_r = \phi(\beta) \tag{3}$$

where, $\phi(\bullet)$ is the standard normal distribution function, μ_R and σ_R are the mean value and standard deviation of the equipment resistance, respectively[7]. After calculating the mean value and standard deviation of electrical equipment response under earthquake, the reliability index and failure probability will be calculated.

3.1 Selection of seismic acceleration values

Fortification target of GB 50260—2013 “Code for seismic design of electrical installations” can be summarized as “undamaged under moderate earthquake, repairable under strong earthquake”. However, due to the characteristics of electrical equipment, it is difficult to achieve “repairable under strong earthquake”. Thus the objective of “undamaged under strong earthquake” is more able to ensure the safety of equipment. The “moderate earthquake” and “strong earthquake” are relative concept, which refers to 50 year exceedance probability of 10% and 2%~3%, respectively.

Relevant documents held that the average ratio of the strong earthquake was more than 1 degree than moderate earthquake, on the peak acceleration, the strong earthquake was roughly 2 times than the moderate earthquake [8].Relevant materials of “China earthquake parameter zoning map” indicated that the strong earthquake was 1.6 to 1.7 times than moderate earthquake [9]. Some scholars have also made the relative relationship between strong earthquake and moderate earthquake. According to their research, the ground motion peak acceleration of 50 year exceedance probability 2% in this paper is shown in Table 2.

Table 2 – Peak ground acceleration of different probability of exceedance

50 year exceedance probability	**VI degree**	**VII degree**		**VIII degree**		**IX degree**
10%	0.5g	0.1g	0.15g	0.2g	0.3g	0.4g
2%	0.1g	0.2g	0.3g	0.4g	0.5g	0.6g

3.2 The basic characteristics of porcelain material

Allowable stress of porcelain is statistical calculated according to equation (4)

$$[\sigma] = \bar{X} - 3\sigma \tag{4}$$

where $[\sigma]$ is allowable stress, $\bar{X}$ is the average value of damage stress, σ is standard deviation.

According to GB 50260—2013“Code for seismic design of electrical installations”, the safety factor of porcelain bushing and porcelain insulator under earthquake or other loads is 1.67, thus equation (4) can be expressed as

$$[\sigma] = \bar{X} - 3\sigma = \frac{\bar{X}}{1.67} \tag{5}$$

3.3 Reliability Analysis of electrical equipment

The equipment was made up by three sections of porcelain bushing with the bottom consolidated. The inner and outer diameters of the bushing are 125 mm and 205 mm, respectively. The total height is 4.7925m and the total weight is 825.72kg. The elastic modulus of porcelain is 90 GPA. The response spectrum method is used, and the fundamental frequency is 3.18 Hz.

Figure 1 shows equipment seismic reliability under different peak accelerations and different site conditions using ordinary porcelain. The reliability of class II and class III are the same under the same peak acceleration. When the acceleration is 0.1g, the reliability is 100%. When the acceleration is 0.2g, the reliability is declining. When the acceleration reaches 0.4g, the reliability decreases rapidly from 88% to 21%. As the acceleration continues to increase, the level of reliability of the equipment will reduces to below 20%.

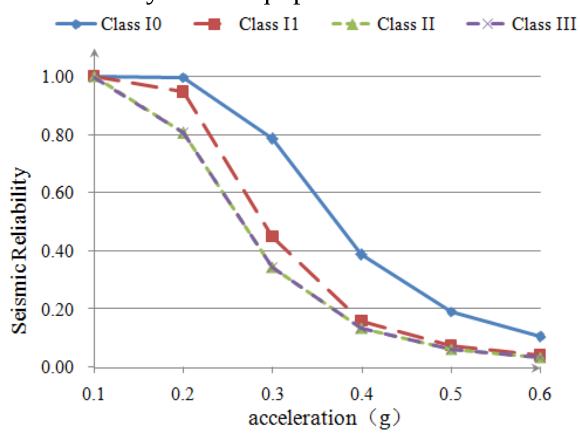

Fig.1 – Seismic reliabilities of ordinary porcelain arresters

Figure 2 shows equipment reliability under different peak accelerations and different site conditions is using high-strength porcelain. The equipment seismic reliability is greatly improved. Taking site of class III as an example, when the acceleration is 0.3g, the reliability increases from 34.5% to 91.5%. Even the acceleration reaches 0.6g, the minimum reliability is above 20%.

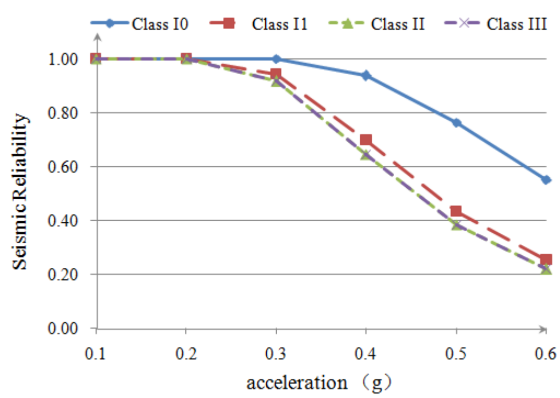

Fig.2 – Seismic reliabilities of high-strength porcelain arresters

In summary, considering the site conditions and classification of designed earthquake, if the acceleration is 0.1g, the seismic reliability is 100%. If the acceleration is 0.4g, the seismic reliability ranges from 20% to 40%, and the equipment is in medium damage. If the acceleration reaches 0.6g, the seismic reliability is declined below 10%, and equipment is in serious damage. The use of high-strength porcelain will improve the seismic reliability of equipment to a certain extent, ensuring the safety of equipment.

4. Classification of seismic fortification level of electrical equipment

According to the results of seismic reliability, the damage level of electrical equipment is divided into three categories: largely intact, moderate damage, and serious damage. The corresponding reliability is as follows: basically intact, medium damage, serious damage or destruction.

(1) Basically intact: the equipment component is in good condition, or individual equipment is slightly damaged but can be used without repair. The corresponding seismic reliability range is 0.00≤Pr<0.05;

(2) Medium damage: a small number of equipment components have minor cracks, most of them have obvious cracks, which can be used after repair. The corresponding seismic reliability range is 0.05≤Pr<0.70;

(3) Serious damage or destruction: most members have severe damage, they are difficult to repair or beyond of repair. The corresponding seismic reliability range is 0.70≤Pr <1.00.

Thus, based on the damage level, the seismic capacity of electrical equipment is divided into three levels: 0.1g and below is the first low level, corresponding to the region of fortification intensity VI and below, with the peak acceleration of 0.1g; 0.1g~0.4g is the second medium seismic level, corresponding to the region of fortification intensity VII ~VIII, with the peak acceleration of 0.4g; 0.4g and above is the high seismic level, corresponding to the region of fortification intensity IX, with the peak acceleration of 0.6g.

Compared with IEEE and IEC, the proposed electrical equipment seismic fortification level is reasonable, the seismic level is moderate, and is slightly lower than the acceleration values of IEEE and IEC.

According to the grading level of seismic fortification, using ArcGIS technology, the distribution was mapped, and the applications of the series map will provide the dicision-making basis for reasonable electrical equipment planning.

5. Conclusions

It is found that the high-voltage electrical equipment in China can be divided into three categories though the seismic reliability analysis of typical high-voltage electrical equipment: 0.1g and below is the first low seismic level, the peak acceleration is 0.1g; 0.1g~0.4g is the second medium seismic level, the peak acceleration is 0.4g; 0.4g and above is the high seismic level, the peak acceleration is 0.6g.

Compared with the seismic fortification level of existing codes at home and abroad, the proposed seismic level in this paper is higher than that of the existing codes in China, but is slightly lower than that of foreign codes.

6. Acknowledgements

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