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A Comparison of Domestic and Foreign Seismic Fortification Standards for Electrical Equipment[1]

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It is of great significance to make comparative analyses of seismic fortification criteria at home and abroad for improving the anti-seismic capability of electrical equipment and revising the relevant national standards. A brief overview of American, Japanese, IEC standards and Chinese seismic design codes for electrical equipment is presented. Differences between these seismic fortification standards of electrical equipment are compared and analyzed in respect of the goal and level of seismic fortification and the seismic design spectrum. The advantages and disadvantages of Chinese standards are pointed out. Through learning from foreign experience on the determination of seismic fortification standards, recommendations are made for the improvement and revision of Chinese seismic fortification standards for electrical equipment.

Key words: Electrical equipment; Seismic fortification standard; Comparative analysis; Recommendations for improvement

INTRODUCTION

Destructive earthquakes occurring in recent years have proven once again that electrical equipment is highly vulnerable to earthquakes (Yu Yongqing et al., 2008). In order to reduce losses caused by earthquakes, absorb timely new research and draw lessons, seismic design codes or criteria related to electrical equipment have been revised constantly in all countries. It is of great significance to make a comparative analysis of seismic fortification standards at home and abroad for improving the anti-seismic capability of electrical equipment and revising the relevant national standards.

The USA *Recommended Practice for Seismic Design of Substations* (IEEE, 2005) has been developed from IEEE Std 693-1984 to IEEE Std 693-1997, and the current version in effect is IEEE Std 693-2005. At the moment, new revisions are in progress. The seismic environment in

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the US is similar to that in China, thus IEEE Std 693 provides an important reference for the revision of Chinese relevant standards. The Japan *Guideline for Seismic Design for Electric Equipment at Substations* (Japan Electrotechnical Standards and Codes Committee, 2010) was developed from JEAG 5003-1980 to JEAG 5003-1998, and the current version in effect is JEAG 5003-2010. Meanwhile, the International Electrotechnical Commission also continues to launch new IEC relevant standards, which have been introduced into our country and become national standards. The occurrence of the Wenchuan earthquake promoted the compilation of Chinese seismic codes for electrical equipment. The national standard *Seismic Qualification for High-voltage Switchgear and Controlgear* (GB/T13540-2009) (PRC National Standard, 2009) and *Code for Aseismic Design of Electrical Facilities in Industrial Plants* (GB50556-2010) (PRC National Standard, 2010a) are newly revised, and *Code for Seismic Design of Electrical Installations* (GB50260-2013) has also been worked out.

Takhirov et al. (2009), You Hongbing et al. (2009) introduced seismic fortification standards of electrical equipment in USA according to IEEE Std 693-2005; Eric Fujisaki (2009) compared the difference between seismic design standards for substation electrical equipment in IEEE Std 693-2005 and IEC 62271-300; Lu Zhicheng et al (2010) analyzed load combination parameters in Chinese, American and Japanese seismic design codes; Ji Ye et al (2010) studied dynamic amplification factors of supporting structures, and compared it with Chinese and Japanese codes; Xie Qi et al. (2009) analyzed the features and differences of the dynamic amplification of electrical equipment, the design of the porcelain insulators and the shake table test of electrical equipment in Chinese, American and Japanese codes, and put forward suggestions for the improvement of Chinese seismic design codes. Still, little study on Chinese relevant standards has been done in the above research with respect to the goal and level of seismic fortification and the seismic design spectrum. A brief overview of American, Japanese, IEC standards and Chinese seismic design codes for electrical facilities is presented. Differences are analyzed on the fortification goal, level and seismic design spectrum among the seismic fortification standards of electrical equipment. The disadvantages of Chinese related standards are pointed out, in hopes of improving the anti-seismic capability of electrical facilities in China as soon as possible.

1 RELEVANT STANDARDS AND CODES FOR SEISMIC FORTIFICATION OF ELECTRICAL EQUIPMENT

1.1 Relevant Standards and Codes Abroad

(1) The USA *Recommended Practice for Seismic Design of Substations* IEEE Std 693-2005

The *Recommended Practice for Seismic Design of Substations* IEEE Std 693-1984 was stipulated by the Institute of Electrical and Electronics Engineers (IEEE) in 1984, and serves as a key reference document for seismic design and performance testing of electrical equipment in US substations. The main contents of the current IEEE Std 693-2005 include: Overview, Normative references, Definitions, Instructions, Installation considerations, Design considerations, and Seismic performance criteria for electrical substation equipment, etc. Minimum requirements for the seismic design of substations are specified, which are applicable to seismic design and performance testing of electrical equipment in substations and their structural supports.

(2) The Japan *Guideline for Seismic Design for Electric Equipment at Substations* JEAG 5003-2010

The Japan Electric Association stipulated the *Guideline for Seismic Design for Electric Equipment at Substations* JEAG 5003-2010 in 2010, which serves as the main document for seismic design and performance testing of electrical equipment. Chapter 1 of the *Guideline for Seismic Design for Electric Equipment at Substations* is the general principles, the content of which includes goals, scope of application, relevant laws and regulations etc. Chapter 2 is about seismic design, concerning the outdoor, indoor electrical equipment, transformers, and other equipment, etc.; "Reference data I" provides design conditions specified in the text part and methods for standard designs, with design examples offered. "Reference data Ⅱ" systemizes seismic design and evaluation methods of ground and foundation. There are 10 appendices, the fifth of which is detailed data of 16 major earthquakes occurring in recent years in Japan and earthquake damage they caused to electric power systems, which are of significant reference value.

(3) IEC series of standards

IEC (International Electrotechnical Commission), founded in 1906, is the world's first international electrotechnical organization for standardization, which is responsible for international standardization work in the field of electrotechnics concerning electric power, electronics, telecommunications and atomic energy. Now more than 3000 international electrotechnical standards have been formulated, and the IEC series of standards are mainly applied in European countries.

Standards related to aseismic testing of electrical equipment mainly include: Environmental testing. Part 3 Guidance Seismic test methods for equipment (IEC, 1991), Part 2: Vibration-time history method (IEC, 1999), and vibration (sinusoidal) (IEC, 2007a), etc.

Standards related to seismic requirements of high voltage switchgear and control gear mainly include: high voltage switchgear and control gear, Part 2: Seismic requirements for rated voltage of 72.5kV and above (IEC, 2003), high voltage switchgear and control gear, Part 207: Seismic qualification for gas-insulated switchgear assemblies for rated voltages above 52 kV (IEC, 2007b), high voltage switchgear and controlgear, Part 300: Seismic qualification of alternating current circuit-breakers (IEC, 2006), etc.

1.2 Domestic Relevant Standards and Codes

(1) National standard *Code for Seismic Design of Electrical Installations* (GB50260-2013)

In 1996 China promulgated and implemented the mandatory national standard *Code for Seismic Design of Electrical Installations* (GB50260-96) (PRC National Standard, 1996), which is mainly applicable to electric power facilities in the electrical power system and serves as the main basis for seismic design of substation electrical equipment. It has played an active role in reducing earthquake damage and loss of electrical equipment. In order to absorb the advanced scientific achievements and draw experience and lessons from earthquakes in time, the *Code for Seismic Design of Electrical Installations* (GB50260-2013) has been worked out.

Major modifications of seismic fortification criteria for electrical equipment in the *Code for Seismic Design of Electrical Installations* (GB50260-2013) are as follows: 220kV key substations and 750kV substations are put into the category of important electric power facilities. The provision that "One degree higher than the seismic fortification intensity is required for the important electrical facilities, but will be no longer increased when the design intensity reaches degree 8 and above" is revised as "One degree higher than the seismic fortification intensity is required, but will be no longer increased when the design intensity reaches degree 9 and above"; the maximum value of the dynamic amplification factor of the design response spectrum increases from 2.25 to 2.5; Characteristic periods of the design response spectrum shall accord with that in current *Code for Seismic Design of Buildings*, and etc.

(2) National standard *Code for Aseismic Design of Electrical Facilities in Industrial Plants* (GB50556-2010)

Once electrical facilities in industrial plants are damaged in earthquakes, it will result in large economic losses, and may cause serious secondary disasters such as fires, explosions etc. To reduce earthquake damage and loss of electrical facilities in industrial plants, and to avoid loss of life, the national standard *Code for Aseismic Design of Electrical Facilities in Industrial Plants* (GB50556-2010) (PRC National Standard, 2010a) was drafted in 2010, which specifies the seismic fortification goals, criteria, seismic design methods, and aseismatic constructions of electrical equipment in industrial plants. The Code also serves as the basis for seismic design of power transformation and distribution equipment in industrial plants.

(3) National standard *Seismic Qualification for High-voltage Switchgear and Controlgear* (GB/T13540-2009)

Some IEC standards have been successively introduced into China as national standards. The *Seismic Qualification for High-voltage Switchgear and Controlgear* (GB/T13540-2009) (PRC National Standard, 2009) has replaced *Anti-seismic Characteristic Test for High-voltage Switchgear* (GB/T13540-92). The revisions mainly refer to IEC series of standards, such as IEC 62271-2: 2003, lEC 62271-207: 2007, IEC 62271-300: 2006, etc. This standard is applicable for all indoor and outdoor high voltage switchgear and controlgear operating in electrical power systems with rated voltage of 3kV and above and frequency of 50Hz and below, including the supporting structures rigidly connected with the ground.

2 SEISMIC FORTIFICATION GOALS AND LEVELS

A seismic fortification goal refers to the specific goals required to achieve seismic fortification of construction according to fortification principles. Seismic fortification level means the determination of the fortification parameters to be used, based on actual fortification environment and the set fortification goals, and taking into account the social and economic conditions, that is, how much strength of an earthquake should be adopted. For example, the China *Code for Seismic Design of Building* (GB50011-2010) (PRC National Standard, 2010b) adopts the three-level design goal as "no damage to the building in small earthquakes, repairable damage in moderate earthquakes and no collapse in large earthquakes", and the corresponding seismic design levels are respectively exceeding probability of 63%, 10% and 2 ~ 3% in the future 50 years. For comparative purposes, Table 1 presents seismic fortification goals and levels of electrical equipment in different standards, and Table 2 provides the values of design basic acceleration of ground motion for important electrical equipment in different standards.

2.1 *Seismic Fortification Goal*

There is a slight difference in the seismic fortification goal adopted in standards of all countries, as seen in Table 1. Two-levels of fortification are applied for electrical equipment both in the US IEEE693 and the China *Code for Seismic Design of Electrical Installations.* For ordinary electrical equipment in China, the seismic fortification goal can be referred to as "No damage in moderate earthquakes", "Repairable damage in large earthquakes". With regard to essential electrical equipment of substations, seismic fortification should be increased by 1 degree higher than the seismic design intensity, that is, "no damage in large earthquakes". One-level of fortification is adopted in the IEC series of standards and the Japan JEAG 5003, which requires no reduction of equipment functions, and the corresponding seismic fortification goal is "Repairable damage in large earthquakes". One-level of fortification is also used in the *Code for Aseismic Design of Electrical Facilities in Industrial Plants*, and the fortification goal is "No damage in moderate earthquakes". Design basic seismic acceleration of essential electrical equipment is increased by 0.05g, which is no longer increased after reaching 0.2g and above.

Electrical equipment is mostly slender with insulators, which are often damaged in earthquakes due to breakage of insulators. Insulators are made of hard brittle material, which will not be able to be put into use once damaged, and there is no "repairable" state. "Repairable" means that secondary components or plastic materials of electrical equipment can still be used again after repair. Therefore, with regard to "repairable" in the second level of fortification, stress on insulators must be ensured to be less than failure stress, to be sure that they won't be destroyed. The fortification goal of a "no destruction guarantee" of insulators is consistent in all standards above.

The US IEEE Std 693-2005 sets the basic seismic test level, and provides relevant required response spectra (Required Response Spectra, RRS for short), also known as RRS test level. It is required that under RRS testing, the stress on insulators should be 50% lower than failure stress, and when the seismic effect is doubled, that is, at the seismic performance level (Performance Level, PL for short), stress on insulators shall be less than failure stress. A safety factor of 2.0 is taken under RRS level, which can be expected to ensure insulators won't be destroyed under PL, and in combination with other measures, the fortification goal of "Repairable" can be achieved.

The *Code for Seismic Design of Electrical Installations* (GB50260-96) and the newly revised code (GB50260-2013) provide specific requirements for checking computations of seismic effect and intensity, etc., which ensures the realization of the first-level fortification goal of "No damage". But no specific measures to achieve the goal "Repairable" are given in the code, which makes it difficult to achieve the second-level fortification goal. This is the deficiency of the code with respect of earthquake fortification. For example, some insulators can ensure that equipment won't be damaged in moderate earthquakes; but it can't be assured that insulators won't be damaged in large earthquakes, thus the goal of "Repairable" cannot be realized. A safety factor of 1.67 is given under moderate earthquakes in the code, only considering the discreteness and brittle failure of failure stress of electric porcelain products, but the fortification goal of "Repairable in large earthquakes" is not taken into account. By referring to the US IEEE Std 693 relevant regulations, the seismic fortification goal of "Repairable" can be realized by increasing the safety factor and using proper computing methods of failure stress of insulators.

2.2 *Seismic Fortification Level*

Sin waves with peak acceleration 0.3g (electroceramics equipment) and 0.5g (transformers) are employed in Japanese standards, and their amplification coefficient is about 1.3 times the time history of the same peak acceleration, which, converted to ground motion time histories, are respectively 0.39g (electroceramics equipment) and 0.65 (transformer).

The USA IEEE 693-2005 defines three seismic qualification levels (RRS) of high, medium and low, with peak ground accelerations of 0.5g, 0.25g and 0.1g respectively; and two seismic performance levels (PL) of high and medium, with peak ground accelerations of 1.0g and 0.5g, which are double the corresponding RRS. For RRS levels, selection can be done according to the PGA value of engineering sites with exceeding probability of 2% in the future 50 years: the low level is taken when PGA is less than 0.1g, medium level when PGA is between 0.1g ~ 0.5g, and high level when PGA is greater than 0.5g; for PL, medium level is taken when PGA is between 0.1g ~ 0.5g, and high level when PGA is more than 0.5g. It is observed that the test level of IEEE 693 in a large scope is on the high and not the low end, with high seismic fortification levels. According to seismic risk analysis in China, PGA with exceeding probability of 2% in the future 50 years in region of 8 degrees and 0.2g is usually less than 0.5g, and in Table 2, 0.25g is picked; PGA with exceeding probability of 2% in the future 50 years in degree 8, the 0.3g region is generally larger than 0.5g, and 0.5g is selected.

Table 1 Comparison of the seismic fortification goals and levels

Standards and codes		Fortification goal	Fortification level
The US *Recommended Practice for Seismic Design of Substations* IEEE Std 693-2005		Completely undamaged and continuing to function for a given RRS level. With little or no significant structural damage， and most equipment will continue to function for a given PL level	To determine low， medium， and high seismic qualification level according to PGA of engineering sites with exceeding probability of 2% in the future 50 years
GB/T13540-2009 IEC 62271-2-2003 lEC 62271-300-2006 lEC 62271-207-2007		No failure on the main circuits， the control and auxiliary circuit， including the relevant mounting structures， should occur. Permanent deformations are acceptable provided that they do not impair the functionality of the equipment	The selected qualification level shall be in accordance with expected earthquakes at maximum ground motions for the location of the installation. This level corresponds to an S2-earthquake
The Japan JEAG 5003-2010		No abnormal phenomenon of functions of electrical equipment happens	Resonant three cycle sine wave with 0. 3g （electroceramics equipment） and 0. 5g （transformer）
Code for Seismic Design of Electrical Installations GB50260-96	General equipment	Under the earthquake with intensity equivalent to or below the fortification intensity， equipment are not damaged and can continue to function； Under the earthquake with intensity larger than the fortification intensity， equipment should not be not seriously damaged and can continue to function after repaired.	Fortification earthquakes： exceeding probability of 10% in the future 50 years Rare earthquakes： exceeding probability of 2 ~ 3% in the future 50 years
	Essential equipment		There shall be an increase of 1 degree higher than the fortification intensity， but where there is no longer an increase when fortification intensity reaches degree 8 and above
Code for Seismic Design of Electrical Installations GB50260-2013	General equipment	Under the earthquake with intensity equivalent to or below the fortification intensity， equipment are not damaged and can continue to function； Under the earthquake with intensity larger than the fortification intensity， equipment should not be not seriously damaged and can continue to function after repaired	Fortification earthquakes：exceeding probability of 10% in the future 50 years. Rare earthquakes：exceeding probability of 2 ~ 3% in the future 50 years
	Essential equipment		An increase of 1 degree higher than the fortification intensity， but there is no longer increase when fortification intensity reaches degree 9 and above
Aseismic Design of Electrical Facilities in Industrial Plants GB50556-2010	General equipment	Under the earthquake with intensity equivalent to or below the fortification intensity， equipment are not damaged and can continue to function	Fortification earthquakes： exceeding probability of 10% in the future 50 years
	Essential equipment		Seismic measures shall be taken by increasing 1 degree higher of the fortification intensity， but when the fortification intensity has reached degree 9， seismic measures higher than degree 9 are required. Design basic acceleration is increased by 0. 05g， and will no longer be increased when it reaches 0. 2g and above

Table 2 Comparison of the design basic acceleration values for different standards

Relevant standards		Intensity 6 (0.05g)	Intensity 7 (0.10g)	Intensity 7 (0.15g)	Intensity 8 (0.20g)	Intensity 8 (0.30g)	Intensity ≥9 (≥0.4g)
Synthetic seismic wave	GB50260-96	0.1g	0.2g		0.2g		0.4g
	GB50260-2013	0.1g	0.2g		0.4g		0.4g
	GB50556-2010	0.1g	0.15g	0.2g	0.2g	0.3g	0.4g
	IEEE Std 693-2005	0.25g			0.5g		
	GB/T13540-2009 and IEC standards	0.2g			0.3g		0.3g (9 degree) 0.5g (>9 degree)
JEAG 5003-2010		Sine wave with 0.3g(electroceramics equipment)，0.5g(transformer)					
IEEE Std 693-2005		Ten-cycle beat wave(breaker) 0.25g			0.5g		
Five-cycle beat wave	GB50260-96	0.075g	0.15g		0.15g		0.3g
	GB50260-2013	0.075g	0.15g		0.3g		0.3g
	GB/T13540-92	0.15g					0.3g

Fortification goals（Table 1） given in GB/T13540-2009 are generally the same as the PL fortification goals in IEEE 693 from the text description; and the corresponding fortification level is S2 earthquakes，which correspond to safe shutdown earthquakes in nuclear power stations. This level is higher than PL earthquakes in IEEE 693. However the peak value of acceleration（Table 2） given in GB/T13540-2009 obviously cannot reach to S2 earthquakes，even lower than PL earthquakes in some subareas. For example，it takes 0.2g when fortification intensity is degree 7，which generally corresponds to the 2% exceeding probability in the future 50 years in China. It differs a lot with S2 earthquakes (exceeding probability of 0.5% in the future 50 years)，and is also lower than the 0.25g given in IEEE 693. For intensity 8，0.3g areas，0.3g is taken in GB/T13540-2009 standards，which is equivalent to the exceeding probability of 10% in the future 50 years in China，and with greater difference from S2 earthquakes; while 0.5g is taken in IEEE693-2005，which is apparently higher than IEC standards. It can be seen that situations of earthquakes in China are not well combined in GB/T13540-2009 standards，and the fortification level and the peak value of acceleration are inconsistent，with rather low acceleration values.

In the *Code for Seismic Design of Electrical Installations*（GB50260-2013），design basic seismic acceleration of the intensity degree 6 area is 0.1g，which is obviously lower than the value in American and Japanese standards. In the intensity 8，0.2g area，it increases to 0.4g，which is higher than the value in American and Japanese standards. The seismic fortification level is approximately equivalent to the exceeding probability of 2% in the future 50 years，which basically accords with the actual conditions of China. Since the area of intensity degree 6 is quite large in China，seismic fortification levels of electrical equipment should be increased properly.

Design basic acceleration of essential electrical equipment in the *Code for Aseismic Design of Electrical Facilities in Industrial Plants*（GB50556-2010） is increased by 0.05g，and it will no longer increase when reaching 0.2g and above. The fortification level is lower than that in other standards，especially in regions of high intensity. Once electrical facilities in industrial plants are damaged，it can lead to serious secondary disasters such as fires，explosions，etc. Thus，compared with other standards，the seismic fortification level of electrical facilities in industrial plants should be increased appropriately.

3 SEISMIC DESIGN RESPONSE SPECTRUM

Seismic design response spectrum is the primary basis for seismic design of electrical equipment, and parameters that influence the design input ground motion the most are the maximum value of dynamic coefficient $\beta_{\max}$ and characteristic period T_g.

3.1 The Maximum Value of Dynamic Amplification Factor $\beta_{\max}$

Design spectrum is generally in the form of dynamic amplification factors in Chinese standards, and a uniform damping ratio of 5% is used. The maximum value of the dynamic amplification factor should be determined on the basis of statistical analysis of strong earthquake recordings and economic conditions. The teaching material "*Seismic Ground Motion Parameters Zonation Map of China*" points out that amplification factors of the plateau section of the response spectrum are dominantly distributed at 2.5. Zhou Xiyuan et al. (1984), Zhang Jiao (2008) and Mao Tianer et al. (2012) statistically analyzed strong earthquake recordings, also thinking that $\beta_{\max}$ should take the value of 2.5. At present, the maximum value of dynamic amplification factors is 2.5 in relevant standards of more developed countries and regions such as the United States, Europe and Taiwan etc.

In the compilation of seismic design code of 1974, the maximum value of dynamic amplification factor takes 2.25, which comprehensively reflects China's national conditions at that time. 2.5 is reduced by 10% for economic reasons. The dynamic amplification factor $\beta_{\max}$ in the current *Code for Seismic Design of Buildings* (GB50011-2010), *Code for Seismic Design of Electrical Installations* (GB50260-96) and other standards follows the result, and has not changed in nearly 40 years. But with the rapid development of economy in China, the maximum value of dynamic amplification factor in Chinese standards should be adjusted to 2.5.

For the seismic design of electrical equipment, a comparison of the maximum values of dynamic amplification factors in different standards is done, as listed in Table 3. When damping ratio is 5%, the maximum value of dynamic factors $\beta_{\max}$ in the US *Recommended Practice for Seismic Design of Substations* (IEEE Std 693-2005) takes 2.5. In order to link up with the new generation of the zonation map, $\beta_{\max}$ in the newly revised *Code for Seismic Design of Electrical Installations* (GB50260-2013) also takes 2.5, and $\beta_{\max}$ with other damping ratios are also basically the same as those in the US IEEE Std 693-2005.

Table 3 Comparison of maximum dynamic amplification coefficients of different standards

	Damping ratios		
	2%	5%	10%
GB/T13540-2009	2.8	1.74	1.28
GB50260-96	2.99	2.25	1.68
GB50556-2010	2.82	2.25	1.76
GB50260-2013	3.17	2.5	1.98
IEEE 693-2005	3.24	2.5	1.94

The current *Code for Aseismic Design of Electrical Facilities in Industrial Plants* (GB50556-2010) and the *Code for Seismic Design of Electrical Installations* (GB50260-96) take 2.25 as the maximum value of the dynamic amplification factor, mainly on account of their connecting with other standards of China which are currently in effect.

In the *Seismic Qualification for High-voltage Switchgear and Controlgear* (GB/T13540-

2009), a representative of IEC standards, the maximum values of dynamic amplification factors with different damping ratios are the smallest compared with those in other standards. Compared with IEEE Std 693, $\beta_{\max}$ in GB/T13540-2009 is reduced by 13.6% (damping ratio of 2%), 30.4% (damping ratio of 5%) and 34.0% (damping ratio of 10%), respectively.

By contrastive analysis, it is suggested that $\beta_{\max}$ is adjusted to 2.5 in future revisions of the *Code for Aseismic Design of Electrical Facilities in Industrial Plants*, and the maximum value of dynamic amplification factors with damping ratio of 5% in the *Seismic Qualification for High-voltage Switchgear and Controlgear* should be adjusted dramatically.

3.2 Characteristic Period T_g

The characteristic period refers to the period value corresponding to the starting point of the descending section of the response spectrum curve. The characteristic period is generally determined according to site classifications and combined effects of earthquakes in Chinese standards. With regard to seismic design of electrical equipment, rules of the characteristic period in Chinese standards and foreign standards such as America and Japan are obviously different, and a specific comparison is shown in Table 4.

To meet the requirements of standardized production of electrical equipment, the design response spectrum in the US IEEE Std 693-2005 is an envelope spectrum of site, with characteristic period of 0.91s (1.1Hz). For soft soil sites, special studies are proposed by the standard.

The characteristic period given in *Seismic Qualification for High-voltage Switchgear and Controlgear* (GB/T13540-2009) and other IEC standards is 0.42s, which is only applicable to sites of Class Ⅰ and Class Ⅱ in China. For sites of Class Ⅲ, Ⅳ, characteristic period takes the value of 0.42s which is significantly smaller.

Table 4 Comparison of the design characteristic period of different standards (unit: s)

Standards	Site classification				
	I_0	I_1	Ⅱ	Ⅲ	Ⅳ
GB/T13540-2009	0.42				
GB50260-96	0.2 ~ 0.24		0.25 ~ 0.35	0.36 ~ 0.51	0.51 ~ 0.65
GB50556-2010	0.2 ~ 0.35	0.25 ~ 0.4	0.35 ~ 0.45	0.45 ~ 0.65	0.65 ~ 0.95
GB50260-2013	0.2 ~ 0.35	0.25 ~ 0.4	0.35 ~ 0.45	0.45 ~ 0.65	0.65 ~ 0.95
IEEE 693-2005	0.91				

The *Code for Aseismic Design of Electrical Facilities in Industrial Plants* (GB50556-2010) and the *Code for Seismic Design of Electrical Installations* (GB50260-2013) both adopt the characteristic period given in the *Code for Seismic Design of Buildings* (GB50011-2010). However, compared with foreign standards, in the case of similar sites, the value of the characteristic period in Chinese standards is smaller by about 30% (Zhou Xiyuan et al., 1999). These two standards do not use the envelope spectrum of different types of sites, mainly considering their connecting with the current code for seismic design of buildings and design of electrical equipment supports. Because the characteristic period provided in the standards is small, it is apparently unsafe for electrical equipment with a longer natural vibration period, and meanwhile is not good for standardized production of electrical equipment and supports.

In the *Code for Seismic Design of Electrical Installations* (GB50260-96), the characteristic period is calculated on the basis of site index, by which the difference of site classifications caused by very small differences can be avoided. However, the influence of earthquake magnitudes and epicentral distances on characteristic period is not considered, thus the results are smaller.

Natural vibration periods of a large amount of electrical equipment are between 0.5s ~ 2.0s, which is close to the predominant frequency of seismic waves, and the smaller the damping of equipment is, the larger the dynamic amplification effect is. If the design characteristic period selected is too small, it will be unable to ensure the safety of equipment in earthquakes, and it is one of the reasons why electrical equipment was seriously damaged in the Wenchuan earthquake (Chinese Society for Electrical Engineering, 2009; You Hongbing et al., 2012).

On account of the uncertainty of future installation sites of electrical equipment and requirements for standardized production of equipment, it is suggested that Chinese relevant standards should use the US IEEE693 as a reference, using the envelope spectrum of sites of Class Ⅰ ~ Ⅲ, and the characteristic period can be determined according to statistics of strong earthquake recordings and by referring to relevant standards.

3.3 Comparison of Design Response Spectrum of Different Standards

In order to compare the influences of different maximum value of dynamic amplification factors and characteristic periods on the design response spectrum, the peak ground acceleration selected is 0.2g. Comparison of design response spectrum with different damping ratios (2%, 5%) in different standards is shown in Fig. 1. Site of Class Ⅱ is widely distributed in China and is most representative. In the diagrams, characteristic period in standards such as GB50260-2013, GB50556-2010 takes the maximum value corresponding to site of Class Ⅱ in Table 4. Natural vibration period of electrical equipment is usually between 0.2s ~ 1.0s, therefore, comparison of spectrum values in different standards with different periods of 0.2s, 0.4s, 0.6s, 0.8s and 1.0s etc. is especially done.

Compared with the *Code for Seismic Design of Electrical Installations* (GB50260-96), the value of response spectrum is significantly increased in the *Code for Seismic Design of Electrical Installations* drafted for approval (GB50260-2013). When damping ratios are respectively 2%, 5%, spectrum values at 5 periodic points between 0.2s ~ 1.0s are increased by an average of 30.8%, 41.7%. The main reason is that $\beta_{\max}$ is increased to 2.5 from 2.25 and characteristic period of site of Class Ⅱ is increased from 0.35s to 0.5s. The seismic fortification level in the revised *Code for Seismic Design of Electrical Installations* is evidently increased, which will effectively enhance the anti-seismic capability of electrical equipment. But when the natural vibration period of equipment is longer than 0.5s, the value of the design spectrum in GB50260-2013 is obviously lower than the corresponding spectrum value in the US IEEE693. Take the damping ratio of 2%, for example, spectrum values are respectively 0.52g, 0.65g when the characteristic period is 0.6s, with a difference of 25%; spectrum values are respectively 0.4g, 0.65g when the characteristic period is 0.8s, with a difference of 62.5%. Therefore, it is suggested that in future revisions of the *Code for Seismic Design of Electrical Installations*, envelope design response spectrum of different sites should be calculated according to characteristics of electrical equipment and requirements for standardized production, and should not simply copy the design response spectrum given in the *Code for Seismic Design of Buildings*.

Among all those standards, when peak accelerations are the same, the spectrum value at the plateau section of the design response spectrum in the *Seismic Qualification for High-voltage Switchgear and Controlgear* (GB/T13540-2009) is the lowest. When the damping ratio is 2%, the spectrum value at the plateau section is 3.6% ~ 16.1% lower than in other standards. When the damping ratio is 5%, the spectrum value at the plateau section is 29.4% or 47.1% lower than in other standards. If using this standard for seismic design or seismic performance testing, the anti-seismic capability of electrical equipment might be overestimated.

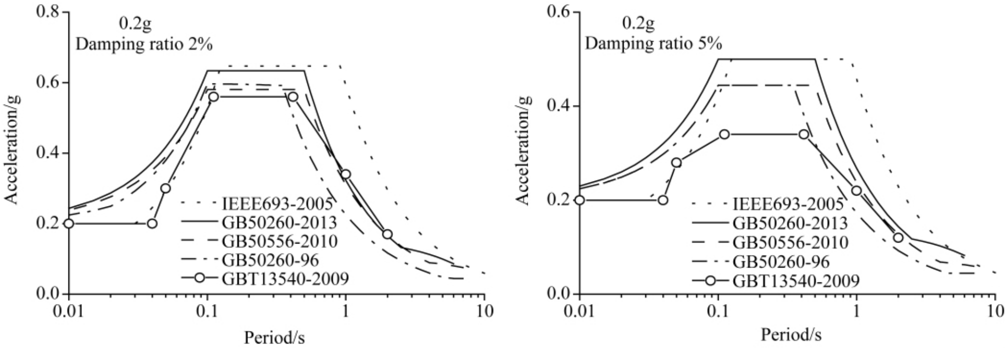

Fig. 1

Comparison of the design response spectra of different codes

4 COMPREHENSIVE COMPARISON OF SEISMIC FORTIFICATION STANDARDS OF ELECTRICAL EQUIPMENT

The allowable stress method is mostly adopted for seismic design of electrical equipment, and the safety factor is one of those key factors that can be used to evaluate seismic fortification levels. Damage to electrical equipment mainly results from damage of ceramic materials. In *Code for Seismic Design of Electrical Installations* GB50260-2013, for porcelain bushing shells and porcelain insulators, the total stress generated from seismic effect and other loads should not exceed the ratio of their failure stress to 1.67, that is, a safety factor of 1.67, while safety factors in other standards are all 2.0, which is 1.2 times that in *Code for Seismic Design of Electrical Installations*. According to the *Code for Seismic Design of Electrical Installations* (GB50260-96), 1.67 originally comes from the *Design Technical Rule for Selecting Conductor and Electrical Equipment* (DLGJ 14-80) (For Trial. Implementation). With the development of the economy and the increase of the importance of the power system, safety factors should be increased to 2.0 to coordinate with other relevant standards.

According to values of design basic seismic accelerations in different standards in Table 2, Fig. 2 provides design response spectrum of areas of intensity degree 6 and 0.05g, degree 7 and 0.1g, degree 8 and 0.2g, respectively, and damping ratios are 2%, 5% respectively. Characteristic periods in standards such as GB50260-2013, GB50556-2010 in the figure take the maximum value corresponding to the site of Class Ⅱ in Table 4.

Compared with GB50260-96, design basic acceleration of intensity degree area 8 in the *Code for Seismic Design of Electrical Installations* GB50260-2013, is increased from 0.2g to 0.4g, which is doubled. Meanwhile, $\beta_{\max}$ and the characteristic period are both increased to some extent, which effectively increases the seismic fortification levels and is of great significance in reducing earthquake losses.

According to the *Seismic Ground Motion Parameters Zonation Map of China* (GB18360-2001) (PRC National Standard, 2001), there are 904 cities and towns that fall in the 0.05g zone, accounting for 37.8% of the country. For the intensity degree 6 and 0.05g area, platform value of design spectrum in the *Code for Seismic Design of Electrical Installations* GB50260-2013 is 0.317, although it is higher than the platform value in the *Code for Aseismic Design of Electrical Facilities in Industrial Plants* (GB50556-2010), which is 0.29g, the safety factor differs by 1.2 times. Platform value of the design spectrum in GB50260-2013 will be reduced to 0.264, and its fortification level is lower than that of the *Code for Aseismic Design of Electrical Facilities in*

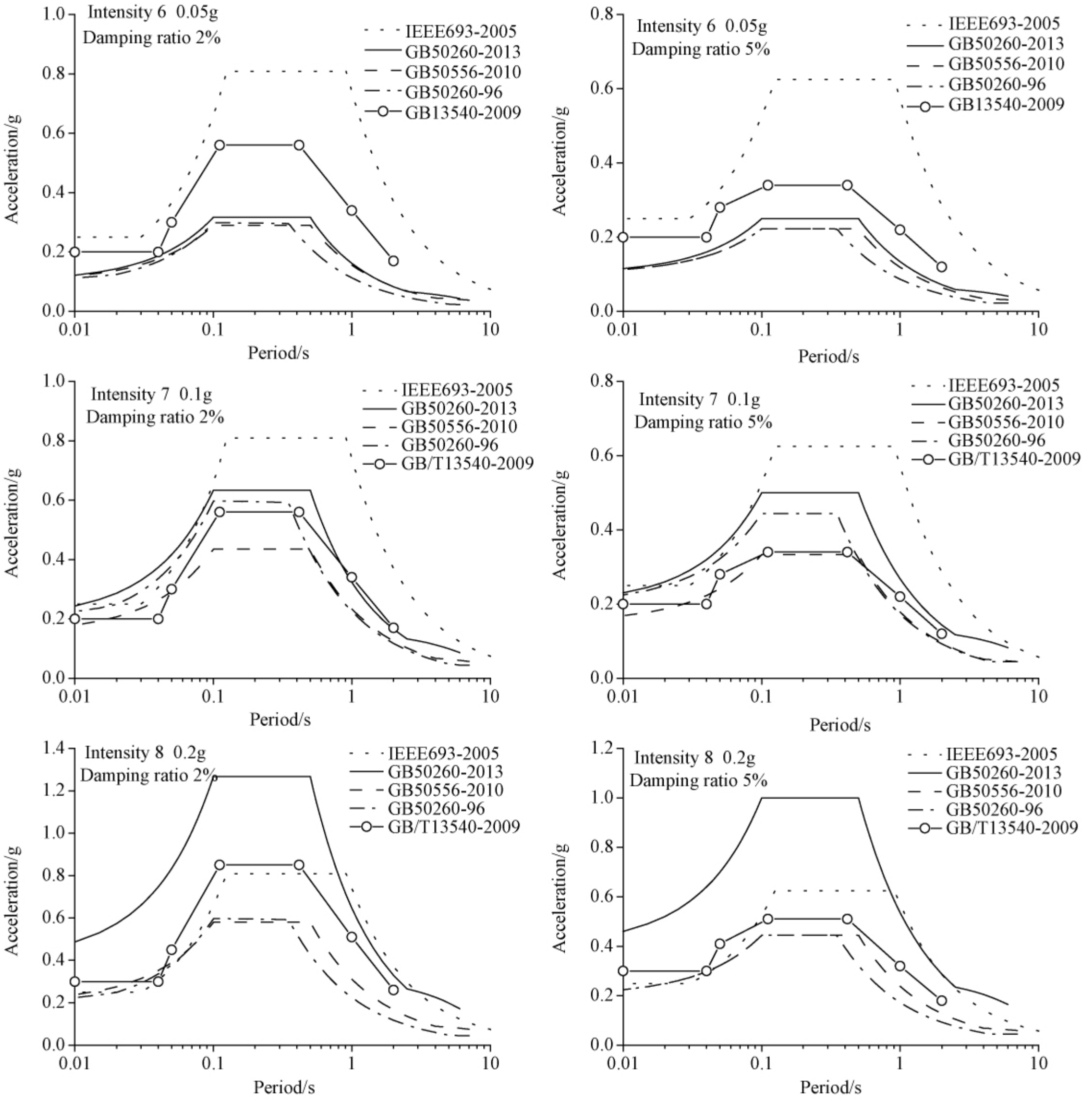

Fig. 2

Comparison of the seismic fortification standards of different codes

Industrial Plants, which is clearly a disadvantage for seismic resistance of electrical equipment in the 0.05g area which is widely distributed in China.

When the damping ratio is 2%, for intensity degree 6, 0.05g area, the platform value of design spectrum in IEEE693 is 0.809g, which is 2.55 times the platform value of 0.317g in the *Code for Seismic Design of Electrical Installations* GB50260-2013. For the intensity degree 7, 0.1g area, the platform value of the design spectrum in GB50260-2013 is 0.634g, which is about 78.4% of the corresponding spectrum value in IEEE693; for the intensity degree 8, 0.2g area, the platform value of the design spectrum in GB50260-2013 is 1.268g, which is evidently higher than the corresponding spectrum value in IEEE693. However, spectrum values with periods longer than 0.8s are equal to those in IEEE693. In consideration of safety factors, seismic fortification standards of electrical equipment in the *Code for Seismic Design of Electrical*

Installations are generally lower than that of the US IEEE693.

The platform height of the response spectrum with a 5% damping ratio given in *Seismic Qualification for High-voltage Switchgear and Controlgear* (GB/T13540-2009), a representative of IEC standards, is evidently lower, thus this standard is not recommended for seismic design or assessment.

5 CONCLUSION

A brief overview of American, Japanese, IEC standards and Chinese seismic design codes for electrical equipment is presented. From the goals and levels of seismic fortification, and seismic design spectrum, the difference between seismic fortification standards of electrical equipment is analyzed. The disadvantages of Chinese relevant standards are pointed out and suggestions for improvement of seismic fortification of electrical equipment in China are proposed, in the hope of improving the anti-seismic capability of electrical equipment in China as soon as possible.

(1) The newly revised the *Code for Seismic Design of Electrical Installations* (GB50260-2013) effectively increases the seismic fortification standards of electrical equipment. However, they are generally lower than American and Japanese relevant standards

(2) It is suggested that in future revisions of the *Code for Seismic Design of Electrical Installations*, the envelope design response spectrum of different sites should be included according to characteristics of electrical equipment and requirements for standardized production, and the value of safety factors should be increased.

(3) It is suggested that seismic fortification criteria of electrical equipment in intensity degree 6, 0.05g areas in the *Code for Seismic Design of Electrical Installations* should be improved.

(4) Compared with other standards, the seismic fortification level in the *Code for Aseismic Design of Electrical Facilities in Industrial Plants* (GB50556-2010) is slightly lower, which is suggested to be improved gradually in future.

(5) The fortification level and acceleration value given in the *Seismic Qualification for High-voltage Switchgear and Controlgear* (GB/T13540-2009) are not consistent. The value of acceleration is lower. It is proposed to increase the maximum value of dynamic amplification factor of response spectrum with damping ratio of 5%.

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