Optimum seismic fortification level forelectrical equipment in substation

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Abstract. We determined the seismic fortification level of electrical equipment in this paper according to the features of seismic failures in substation, provisions about seismic fortification level standard, and decision about optimum seismic fortification for electrical equipment, we also classified the seismic fortification level according to seismic reliability calculations and reliability results, put forward a high, medium and low seismic fortification level system.

1 Introduction

Seen from earthquake hits home and abroad, one of the disastrous consequences is the extensive long-time power outage caused by the wrecked electrical equipment, which arouse people’s consciousness on safeguarding the safety of power grid by boosting the seismic capacity of electrical equipment, which mainly depends on the seismic fortification level. Now the seismic design of electrical equipment in our country mainly refers to Code for Seismic Design of Electrical Installations(GB 50260—2013)[1],seismic fortification grade, and site parameters are taken from Seismic Ground Motion Parameter Zonation Map of China(GB 18306—2001)[2] and Code for Seismic Design of Buildings(GB 50011—2010)[3].

However, Seismic Ground Motion Parameter Zonation Map of China(GB 18306—2001) and Code for Seismic Design of Buildings(GB 50011—2010) are applicable for seismic design for ordinary construction project and a special building rather than electrical equipment because of their high universality, if classified in details as those for building structures,it shall be unfavorable for massive production of electrical equipment, so will design and selection for engineers, what’s more, this may as well repeat the unnecessary seismic safety appraisal, postpone the joint debug and operation of equipment. For all above, some foreign countries and regions set out the combination of seismic ground motion parameter zonation map and divide into a high, medium and low grade system, which is more suitable for electrical equipment[4][5].

Hereby we defined the seismic failure degree for electrical equipment according to relative standards home and abroad, power grid optimum seismic fortification level decision-making method, and calculated seismic reliability results, discussed the grading of seismic capacity for electrical equipment, recommended the grading principle for our country’s electrical equipment seismic fortification.

2 Seismic level in foreign related seismic codes for electrical equipment

Generally, many foreign countries have established their seismic fortification grades for electrical equipment, including Japan, who has only one seismic fortification type, for small and narrow area of land, and relatively single type of earthquake.IEC62271-2 specifies three of high, medium and low grades, with seismic level equivalent to S2 earthquake magnitude, which requires a nuclear power station to safety shutdown, with annual exceeding probability10^{-4}. US IEEE693 also specifies three of high, medium and low grades, but its seismic fortification level is classified on the basis of 50-year exceeding probability2%, shown as Tab.1.

Tab.1 Comparison of seismic level in foreign related seismic codes for electrical equipment

Foreign standard and code		Seismic level	PGA(g)
Japan Guide of Seismic Design for Electrical Equipment[6] JEAG 5003-1998	Porcelain electrical equipment	—	0.3g
	Insulating bush of transformer	—	0.5g
IEC62271-2:2003High-voltage switchgear and controlgear—Part 2: Seismic qualification for rated voltages of 72.5kV and above		AG2: low to medium intensity	0.2g
		AG3: medium to high intensity	0.3g
		AG5: high to high high intensity	0.5g
USA substation seismic design code IEEE Std 693-2005		Low level:<0.1g	0.1g
		Medium level:0.1g~0.5g	0.25g
		High level:>0.5g	0.5g

3 How to specify the optimum seismic fortification level for electrical equipment

3.1 Objective function of optimum seismic fortification level. The optimum seismic fortification level of power grid is the min. value calculated by objective function considering short-term investment (construction cost) and long-term income (loss expectation),that is

$$W(I_d) = C_{min}(I_d) + L(I_d) \rightarrow min \tag{1}$$

Where,W,Cmin and L are respectively total investment, lowest construction cost and loss expectation for design $\bar{x}(I_d)$,all of them are functions of single variable Id. For each seismic fortification intensity Id, the design of lowest construction cost for structure $\bar{x}(I_d)$ is unique, so both formula (1) and formula (2) are equivalent

$$W(I_d) = C_{min}(I_d) + L(I_d) \rightarrow min \tag{2}$$

Because other designs themselves have some factors of waste, considering the optimization of objective functions, the seismic fortification with the lowest construction cost is feasible.

3.2 Method for solving the lowest construction costcurve. There are two methods for solving lowest construction costcurve Cmin-Id(i.e., function $C_{min}(\bar{x}(I_d))$).

(1) Precise

First, under the specified seismic fortification intensity Id, resolve the structure design $\bar{x}(I_d)$, let the construction cost meet with the formula below

$$C_{min}(\bar{x}(I_d)) \to \min \quad (3)$$

and all applicable provisions and requirements.

Then work out the respective lowest construction cost Cmin with different Ids to get several points on function $C_{min}(\bar{x}(I_d))$ orcurve Cmin-Id, and lowest construction cost curve Cmin-Id by using a statistical regression method, shown as Fig.1.The lowest construction cost $C_{min}(\bar{x}(I_d))$ increases with the increasing of seismic fortification intensity.

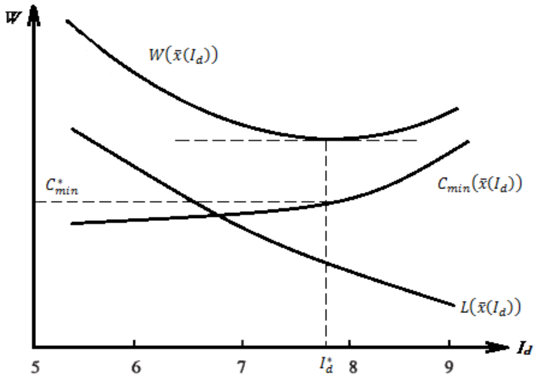

Fig.1 optimum seismic fortification level decision-making graph

(2) Simplified

Although it is easy to calculate function $C_{min}(\bar{x}(I_d))$(i.e.,Cmin-Id curve), quite a lot workload shall be paid for, to keep stay away from this case, substitute the lowest construction cost curve Cmin-Id with empirical curve C-Id for giving structure cost and seismic fortification intensity according to designed and calculated empirical and statistical data. The simplified method can calculate the real structure cost $C(I_d)$in details according to normal method (e.g., budgeting) according to seismic fortification intensity Iddesign, this shall be more suitable for the actual situation.

3.3 Loss expectation of electrical equipment. The loss of power grid under type-Bifailure can be expressed in a formula below

$$D_i = D_i^{(1)} + D_i^{(2)} \quad (4)$$

Where, $D_i^{(1)}$ is the direct loss from the failure of structure itself, $D_i^{(1)}$ is the indirect loss accompanied with the structure. For total loss of structure under multi-level failure criterion, it can be worked out with equation below

$$L(\bar{x}(I_d)) = \sum_{i=1}^{5} P_f[\tilde{B}_i, \bar{x}(I_d)] \cdot D_i \quad (5)$$

So, with different seismic fortification intensity Ids, the loss expectation curve L-Id can be drawn, shown as Fig.3-3. The loss expectation $L(\bar{x}(I_d))$ decreases with the increasing of seismic fortification intensity Id.

3.4 Decision-making of optimum seismic fortification level. After worked out the lowest construction costcurve Cmin-Id and loss expectation curve L-Id, then the illumination on Fig.3 or single unbound variable minimization method can be used for calculating as per objective function

$$W(\bar{x}(I_d)) \rightarrow \min \tag{6}$$

Get the optimum seismic fortification intensity, which is corresponding to the lowest point of curve $W(\bar{x}(I_d))$, i.e., the optimum seismic fortification level shall be finally decided.

Take a 110kV new-built substation as an example, it was designed and built in degree 7 fortificationlevel, with equipment purchasing cost 21.1712 million Yuan RMB, equipment installing cost 2.1815 million Yuan RMB, building construction cost 5.5695 million Yuan RMB, and others6.4022 million Yuan RMB, total investment for this substation was estimated about 35.3244 million Yuan RMB. Its optimum seismic fortification level was finally appraised in seismic fortification intensity 6,7,8, and 9 degrees, see Fig.4-32 for the optimum seismic fortification level decision-making graph for this substation.

For substations under different seismic fortification intensities, the estimation of construction cost at a low intensity area depends on equipment installation cost and others, rather than equipment purchasing cost, equipment installation cost, building construction cost and others at high earthquake intensity area. The loss of substation caused by earthquake includes direct loss and indirect loss. The direct loss decreases with the increasing of seismic fortification intensity, relates to seismic reliability and construction cost of substations themselves, the indirect loss further concerns with direct loss, for the verification is applied to but a substation, its acting range is uniform.

Seen from Fig.2, this substation, despite its seismic fortification was designed up to degree 7, its optimum seismic fortification level is degree 8.Seen from Code for Seismic Design of Electrical Installations(GB 50260—2013), the design basic acceleration of a degree 8fortification is twice that of degree 7.This is almost the ratio between a peak acceleration at 50-year exceeding probability2% and a peak acceleration at 50-year exceeding probability10%.

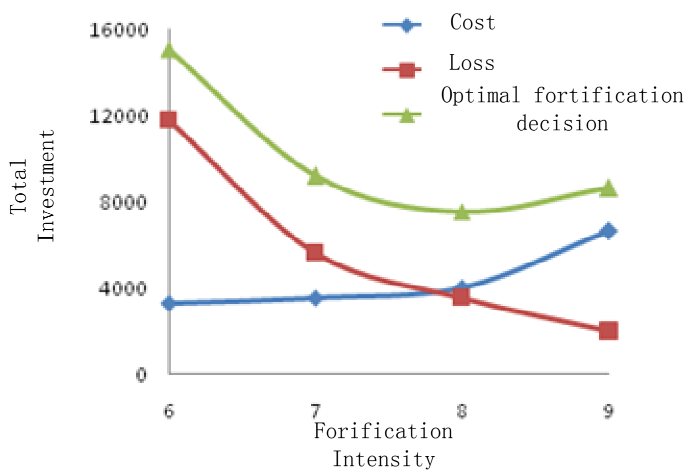

Fig.2 optimum seismic fortification level decision-making graph for an 110kV substation

Furthermore, for grade VI, if an electric equipment increases its seismic fortification intensity 1 degree, then its corresponding 50-year exceeding probability ranges between 3% and 2%; for grade VII, and grade VIII areas, if increasing seismic fortification intensity 1 degree, then the corresponding 50-year exceeding probability is between 2% and 1%, approximate 1%.Considering a medium-rigid site, and importance of power facilities, the design of 50-year exceeding probability shall be between 5% and 2%, so the seismic fortification level for power grid is recommended as 50-year exceeding probability2%.

4 Seismic reliability and seismic failure degree

The electrical equipment usually suffer brittle failure, their limit state equations are linear, their seismic reliability shall be calculated with a first-order second-moment method, assume that both equipment resistance and response should obey the law of Gaussian distribution, then the seismic reliability index β , failure probability P_f andreliability P_r are

$$\beta = \frac{\mu_R - \mu_S}{\sqrt{\sigma_R^2 + \sigma_S^2}} \tag{7}$$

$$P_f = \phi(-\beta) = 1 - \phi(\beta) \tag{8}$$

$$P_r = \phi(\beta) \tag{9}$$

Where, $\phi(\bullet)$ is the standard Gaussian Distribution function, μ_R and σ_R are respectively the mean value and mean standard deviation of equipment resistance R, σ_R and σ_S are respectively the mean value and mean standard deviation of response[9].After worked out the mean value and variance of response at weak points of electrical equipment affected, the equipment reliability and failure probability can be calculated.

This paper takes typical electrical equipment for analyzing their seismic reliabilities under type I_0,I_1,II, and III sites by a first-order second-moment method as mentioned above.

4.1 How to select the earthquake acceleration value. Our country's prevailing seismic group motion parameter zonation map only offers the peak ground acceleration at 50-year exceeding probability10%, but many designers pay much attention on how to get the peak ground acceleration value at 50-year exceeding probability2%~3%.Seen from standard89 version and relating documents, a large earthquake is average 1 degree higher than that of medium earthquake, for peak acceleration, large earthquake is twice that of medium one [10].Seen from version 01seismic group motion parameter zonation map, a large earthquake is 1.6~1.7 times that of medium one [11].For higher safety of equipment, a peak ground acceleration at 50-year exceeding probability2% is feasible, shown as Tab.2.

Tab.2peak ground acceleration under different exceeding probabilities

50-year exceeding probability	Degree VI	Degree VII		Degree VIII		Degree IX
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

4.2 Seismic reliability of voltage transformer. 500kV voltage transformer has 3 groups of hollow porcelain cylinder and pad. Each pitch of cylinder is 1.8m high, and pad0.639m high. The porcelain bush is OD 0.355m and ID 0.265m, this equipment is 6.039m high, total weight 2184.6kg, shown as Fig.3.The Young's modulus of porcelain takes 110GPa.Its bottom is cemented. No support on the model, its magnification coefficient takes 1.2, and calculates by response spectrum method.

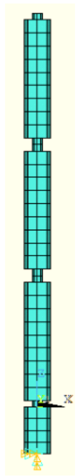

Fig.3 model of voltage transformer

The seismic reliability of 500kVordinary porcelaintransformer is basically insusceptible to classification of design earthquake, with identical seismic reliabilities for both type II, and type III sites. At the peak acceleration0.1g and 0.2g, the reliability is almost 100%.At the peak acceleration up to 0.3g,the lowest reliability presents at type III site, which falls to 93.7%. At 0.4g, the lowest reliability is also up to 70% and above, at peak acceleration0.5g and 0.6g,the reliability keeps falling, with lowest values respectively 47.2% and 28.4%, shown as Fig.4.

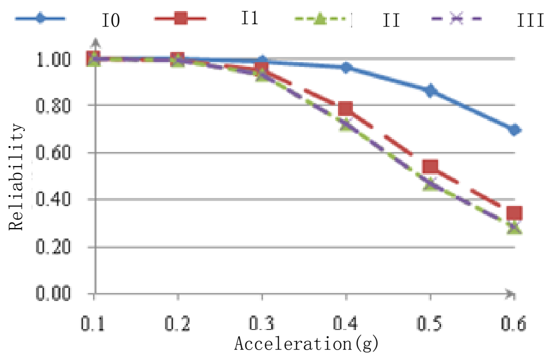

Fig.4Earthquake reliabilities of ordinary porcelain voltage transformers

4.3 Seismic reliabilities of disconnectors. 220kVdisconnectorhas 3 groups of solid porcelain cylinders and 1 steel-pipe support. Each porcelain cylinder group has two segments, the upper one is R0.06m,the lower one is R0.07m, the disconnector is 2.915m high, total 214.03kg,its support is 3.50m high, with the Young's modulus of porcelain100Gpa, shown as Fig.5.

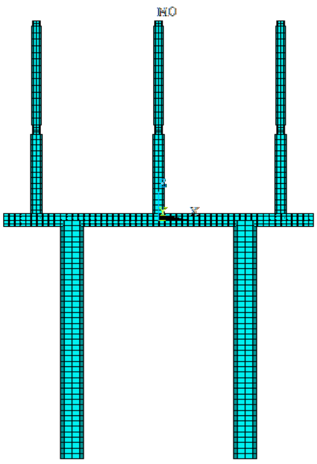

Fig.5 model of disconnector

For 220kVdisconnector, its seismic reliability is basically insusceptible to classification of design earthquake, the reliability of equipment at type I0 site is basically equal to those in other types of sites. At 0.1g,its reliability is still up to about 100%, with equipment completely intact. If the acceleration is up to 0.2g, its mean value lowers to 78.5%, approximate to 80%.Then if its acceleration is up to 0.3g,the reliability level falls abruptly, so far as to that of type I0 site been fallen to 40% and below, with mean value 28.5%.after0.4g,the reliability level completely falls to 10% and below, at 0.5g, its lowest value is 3.5%, at 0.6g, its lowest value is 1.8%, shown as Fig.6.

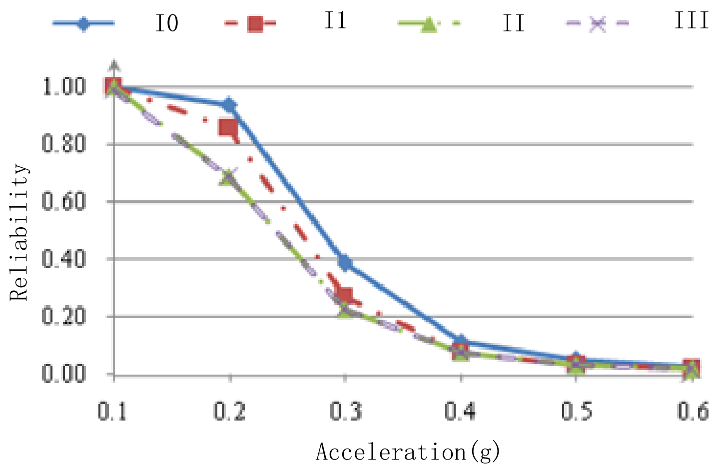

Fig.6Seismic reliabilities of 220kV ordinary porcelain disconnectors

4.4 Seismic failure degree. According to the seismic reliability of electrical equipment, the classification of failure to power grid facilities defines as per seismic reliability, including three types of basically intact, moderate, severe and destroy, with corresponding reliabilities as followings:

(1)Basically intact: equipment components and parts are intact, or individually slightly damaged, suitable for continuous service without repair. The range of seismic reliability is $0.00 \le Pr < 0.05$;

(2) Moderate failure: a few equipment components and parts are spotted with slight fracture, and most of them with obvious cracks, usually unsuitable for continuous service without repair, the seismic reliability ranges $0.05 \le Pr < 0.70$;

(3) Severe failure and destroy: most of components have severe failures, uneasy or unable reusing, with seismic reliability ranging $0.70 \leq Pr < 1.00$.

Wherein, some quantitative words are defined as below:

(1) The “individual” is 5% and below;

(2) The “minority” is 5%~45%;

(3) The “majority” is 40%~70%;

(4) The “most” is 60%~90%.

5 Grading of seismic fortification

Seen from the degree of seismic failure to typical electrical equipment, classify the seismic capacity into three grade:0.1g and below is specified as the first grade, a low grade of seismic verification level, which is corresponding to seismic fortification intensity magnitude VI and below area, considering provisions of Code for Seismic Design of Electrical Installations(GB50260-96): electrical equipment330kV and above shall have seismic design under seismic fortification grade VII and above, electrical equipment220kV and below shall have seismic design under seismic fortification grade VIII and above, with peak acceleration value 0.1g; take 0.1g~0.4g as the second verification level for moderate seismic failure, which is corresponding to seismic fortification intensity magnitude VII~VIII zones, with peak acceleration value 0.4g; take 0.4g and above as the third verification level for severe seismic failure, which is corresponding to seismic fortification intensity magnitude IX and above zones, with peak acceleration value 0.6g.

6 Conclusions

Our country’s prevailing substation electrical equipment seismic fortification zonation comes from Seismic Ground Motion Parameter Zonation Map of China(GB18306-2001), which is mainly suitable for seismic design of buildings, because the building structure is significantly different from electrical equipment on materials, structural type and production process,especially more precision the classification for buildings is more unfavorable for massive and batch production of electrical equipment.

By analyzing the seismic fortification level of electrical equipment with optimum seismic fortification level decision-making procedure, we recommended a 50-year exceeding probability2%.

Seen from results of electrical equipment seismic reliability calculations, and seismic failure classification for typical high voltage electrical equipment, our country’s high voltage electrical equipment have three seismic fortification classification of high, medium and low grades.0.1g and below belongs to low seismic verification level, with acceleration0.1g;0.1g~0.4g belongs to medium level, with peak acceleration value 0.4g;0.4g and above belongs to high level, with peak acceleration value 0.6g.

References

[1]GB50260-2013.Code for Seismic Design of Electrical Installations[S].Beijing:China Planning Press,2013.

[2]GB18306-2001.Seismic Ground Motion Parameter Zonation Map of China [S].Beijing: China

standard press,2001.
[3]GB 50011—2010.Code for Seismic Design of Buildings[S].Beijing: China Building Industry Press,2010.
[4] JEAG 5003—1998.Guide of Seismic Design for Electrical Equipment[S].Japan Electrical Technology Standard Investigation Committer,1998.
[5] IEC62271-2:2003.High-voltage switchgear and control gear—Part 2: Seismic qualification for rated voltages of 72.5kV and above[S].
[6]IEEE Std 693-2005.IEEE Recommended Practice for Seismic Design of Substations[S].IEEE Power Engineering Society,2005.
[9] Chen Huai, Li Jie. Method for analyzing the seismic reliability of high voltage electrical equipment[J].World earthquake engineering,2006,16(2):19-23.
Chen Huai, Li Jie. Seismic Reliability Analysis of High Voltage Electrical Equipments[J].World Information on Earthquake Engineering,2006,16(2):19-23.
[10] China Academy of Building Research. Provisions of Code for Seismic Design of Buildings[M].Beijing: Liaoning Science Press,1990,1-2.
[11] State Standardization Administration Committee.GB18306-2001 textbook of Seismic Ground Motion Parameter Zonation Map of China[M].Beijing: China standard press,2001,106.