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Seismic analysis under SL-1 of high-power DC reactor prototype for ITER poloidal field converter

Chuan Li^{a,b}, Yong Yang^{a,b,*}, Yuanxu Liao^c, Ming Zhang^{a,b}, Zhiquan Song^d, Peng Fu^d

^a State Key Laboratory of Advanced Electromagnetic Engineering and Technology, Huazhong University of Science and Technology, Wuhan 430074, China

^b School of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

^c Jiangxi Electric Power Design Institute, Nanchang 330096, China

^d Institute of Plasma Physics, Chinese Academy of Science, Hefei 230031, China

HIGHLIGHTS

- Response spectrum approach is adopted in seismic analysis of high-power dc reactor prototype.
- The results of seismic analysis such as the displacement, stress and reactive force under seismic level one (SL-1) with damping factor of 2% and 4% are presented in detail.
- This analysis could provide reference for the foundation design of stacked reactors, as well as make a contribution to the similar seismic design work.

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ABSTRACT

This paper mainly introduces the seismic analysis of the high-power dc reactor prototype, whose functions are to limit the ripple current and the increasing rate of fault current in the ITER poloidal field (PF) converter. The stacked reactors with the assembly dimension ($L \times W \times H$) of 2955 mm \times 1639 mm \times 3296 mm and weight about 5 tons are fixed to the steel base by five support components. In order to evaluate the seismic response of the structure under specific seismic excitation, a method based on response spectrum is adopted in this paper. The design earthquake spectrum of seismic level one (SL-1) with damping factor of 2% as well as 4% provided by ITER is applied as load. In addition, the simulation analysis is introduced in detail and the results as the displacements, stresses and reactive forces are also presented. This analysis could provide reference for the foundation design of dc reactor, as well as make a contribution to the similar seismic design work.

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1. Introduction

ITER (International Thermonuclear Experimental Reactor) is an international nuclear fusion project to realize an experimental fusion reactor based on the concept of ‘tokamak’. The poloidal field (PF) converter module plays a significant role in the plasma shape and position control in vertical and horizontal direction [1–3]. As a significant inductive component, the main functions of dc reactor is to restrain circulating current, ripple current and limit the dc short-circuit current and its increase rate [4]. The stability and reliability

of dc reactor is essential for the normal operation and safety of PF converter.

According to the requirements of ITER organization, the equipment of PF converter unit should restart without special maintenance and test after the specific seismic events. Therefore, it is of importance to provide the seismic response information under specified seismic excitation. In this paper, finite element method software ANSYS Workbench is adopted in seismic analysis [5]. The seismic excitation is defined by ITER in the forms of design response spectrum (DRS) for SL-1 seismic event.

In this paper, the assembly prototype structure and technical parameters of the prototype reactor are introduced. Based on response spectrum approach, the seismic analysis for SL-1 with damping factor 2% and 4% are introduced.

* Corresponding author at: State Key Laboratory of Advanced Electromagnetic Engineering and Technology, Huazhong University of Science and Technology, Wuhan 430074, China.

E-mail address: yangyong0919.hust@126.com (Y. Yang).

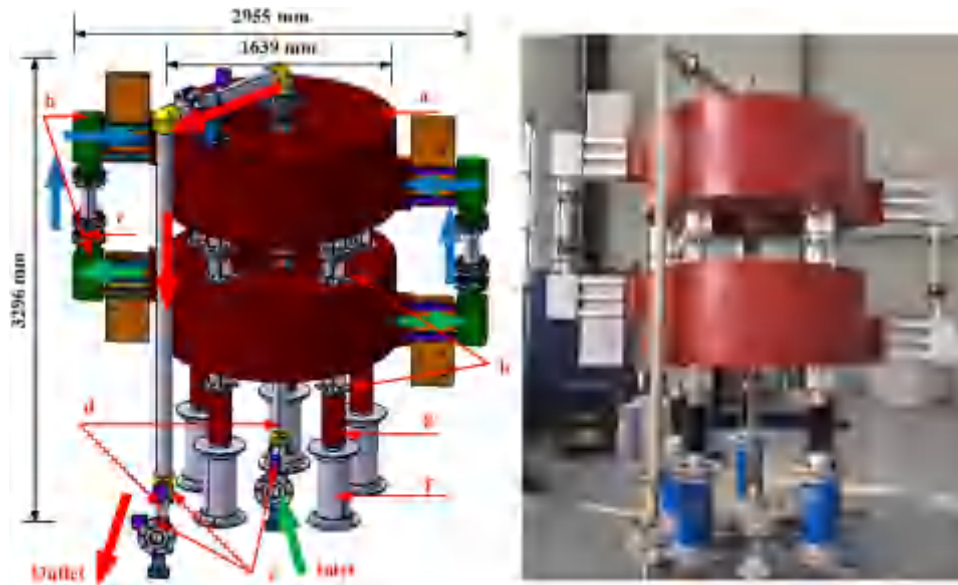


Fig. 1. Model and actual prototype of stacked reactors (**main body** (a): coils, busbar, epoxy resin; **water system**: collecting water box (b), regulator (c), water pipes (d), instruments for water (temperature, pressure and flow) (e); **auxiliaries**: epoxy resin support components (f), 35 kV insulator (g), 316L stainless steel support components (h)).

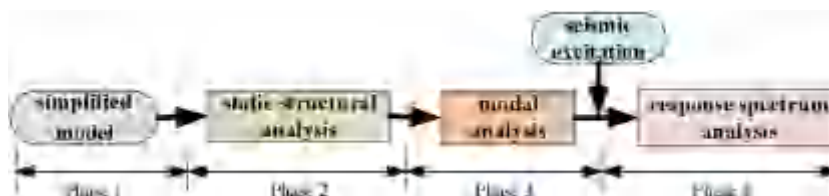


Fig. 2. Analysis flow of response spectrum approach in Workbench.

Table 1
Main parameters of dc reactor.

Parameters	Values
Rated inductance (μH)	193
Rated continuous current (kA)	27.5
Peak current (kA)	196
Insulation level, Nominal/testing/impact (kV)	AC, 12/28/60; DC, 30
Size ($L \times W \times H$) (mm)	1639 \times 800 \times 630
Cooling medium	Deionized water
Conductor material	Aluminum 6063-O
Location	Indoor

Table 2
List of components of stacked reactors.

Description	Material	Mass (t)
Coil	Al 6063-O	2.80
Busbar	Al 6063-O	0.26
Cooling System	deionized water	0.46
Insulator	ceramic	0.50
Insulating Material	epoxy resin	0.70
Others	/	0.22
Total mass (appr)	/	5.00

2. Prototype structure

According to the operating modes and potential fault modes of PF converter, the final parameters of dc reactor prototype are listed as Table 1 described. The measured rated inductance is 193 μH . Temperature rise test and transient fault current test demonstrate that dc reactor have a good performance under continuous current 27.5 kA and fault pulse current up to 196 kA. The other parameters are listed in Table 1.

DC reactor has adopted a structure of dry-type air-core water-cooling reactor with epoxy resin casting technique. To obtain high strength and ductility, the material of coils is aluminum 6063-O. The conductor section is square with a hollow, which is for cooling water. The stacked reactors with the assembly dimension ($L \times W \times H$) of 2955 mm \times 1639 mm \times 3296 mm and weight about 5 tons are composed of two reactors and fixed to the steel base by five support components.

Fig. 1 shows the model and actual structure of the stacked reactors prototype. The prototype can be divided to be three parts, i.e. main body, cooling water system and auxiliaries. The main body consists of aluminum coils, connecting busbar and epoxy resin with vacuum pressure impregnation (VPI) technology to enhance the structural strength. The cooling water system aims to taking away the heat diffused to the deionized water. Due to the limitation of the installation space, the upper reactor and the lower reactor share a common water system, since the two reactors do not work simultaneously. The status of the water system are monitored by several instruments. The other components are categorized into auxiliaries, such as epoxy resin support components, 35 kV insulators and 316L stainless steel support components. Table 2 lists the main components of stacked reactors and corresponding weights. The more detailed information about the prototype can refer to Ref. [6].

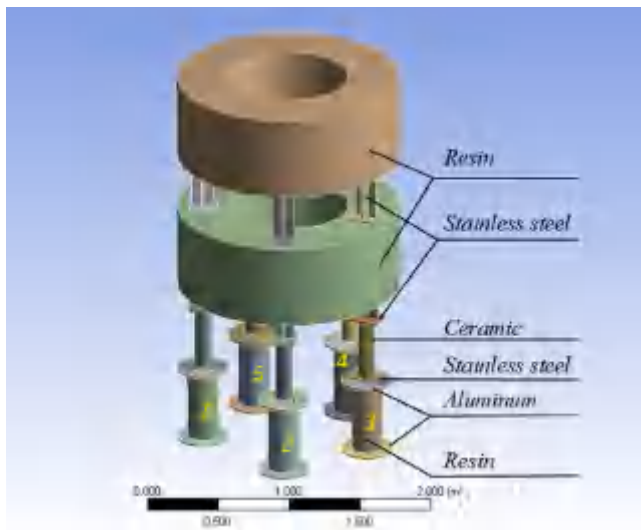


Fig. 3. Simplified model and main materials.

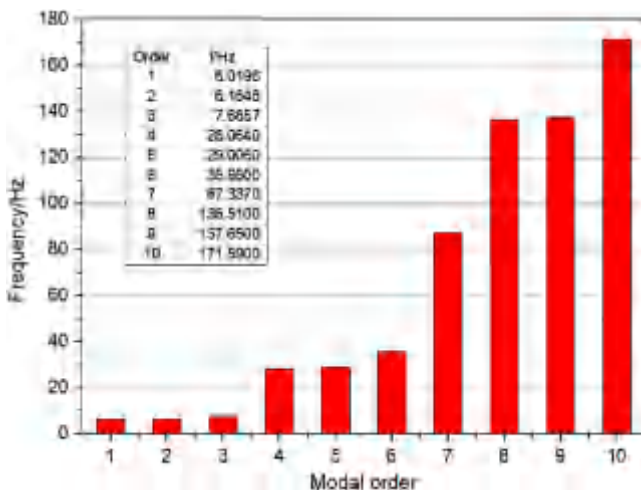


Fig. 4. Vibration frequency and modal order (order less than 11).

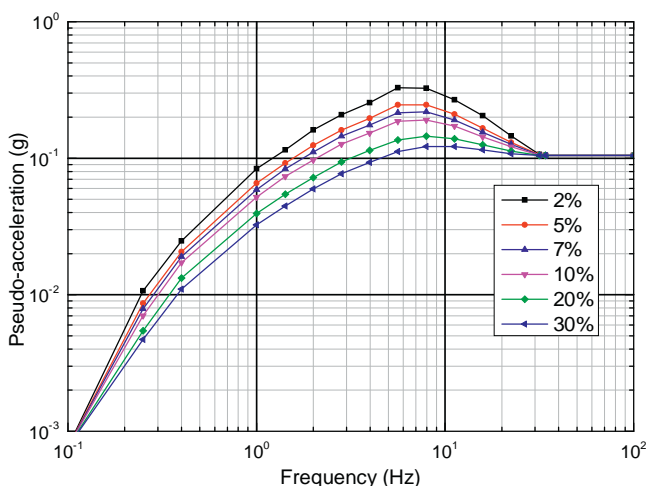


Fig. 5. Earthquake spectrum of SL-1 with various damping factors in horizontal direction for ITER site Cadarache.

Table 3
Physical-mechanical properties of materials.

Material	Young's modules (GPa)	Poisson's ratio
Aluminum 6063-O	70.7	0.32
Ceramic	221.0	0.22
Resin	3.0	0.42
Stainless Steel	200	0.3

Table 4
Reactive forces of five supports.

	F ₁ (kN)	F ₂ (kN)	F ₃ (kN)	F ₄ (kN)	F ₅ (kN)
F _x	2.52	3.00	3.24	3.25	2.99
F _y	3.10	3.05	3.06	3.06	3.05
F _{z+}	25.44	25.86	28.12	28.14	25.88
F _{z-}	-7.99	-7.46	-7.75	-7.81	-7.47

3. Analysis methods

Generally, there are three typical methods for seismic analysis, such as static approach, time-history approach and response spectrum approach. The static approach takes the structure as a rigid body and the inertia force as static load which is equal to the product of structural mass and seismic acceleration. Thus, the calculation is easy but the accuracy is low. Time-history approach is adopted by most countries since 1970s. In this method, the whole time history response of the earthquake can be obtained by the integral solution based on the basic equation of structure motion and the recorded ground acceleration. Due to the integral solution, it has relatively more calculation amount. Besides, the calculation results only apply to the given seismic excitation, which limits its wide application. Thus, it is usually applied in some specified situations. The third method is response spectrum approach, which is first put forward in 1940s by M Biot. The method takes the structure as a linear elastic multi-degree-of-freedom system. Thus, the linear elastic seismic response is equivalent to solving the largest earthquake response of each independent equivalent degree of freedom [7,8]. The maximum response exists in the combinations of the results of each analysis [9]. Due to the equivalent solution of the largest response and model simplification, the response spectrum approach has the advantages of small calculation amount and wide range of applications.

Fig. 2 shows the analysis flow of the response spectrum approach used in finite element method software (Workbench), which consists of four phases. Phase 1 is the establishment of the simplified model. In this phase, the actual prototype needs to be simplified for simulating calculation. Phase 2 is the static structural analysis, which aims to obtain the initial state of the module, the anti-force of support components under gravity and provide pre-stress for the next phase. Phase 3 is the modal analysis, which focus on the natural vibration frequency and vibration mode of stacked reactors. Phase 4 is the response spectrum analysis combined with the seismic excitation. In this phase, the seismic excitation is applied on the module in three orthogonal directions, two horizontal (x, y) and one vertical (z). Each directional response spectrum (RS) analysis can get the amplitudes of the response for each mode. However, the phase angles of the modes are unknown, so a combination rule is a must to obtain the final results of each analysis. The SRSS (square root of sum of squares) rule is adopted in each RS analysis. After the completion of three orthogonal directional RS analyses, a spatial combination rule called Newmark's rule is applied to the results of the three RS analyses to obtain the final results. For a given variable S, the final result can be obtained by Formula (1).

$$S = \max(\pm S_x \pm 0.4S_y \pm 0.4S_z, \pm 0.4S_x \pm S_y \pm 0.4S_z, \pm 0.4S_x \pm 0.4S_y \pm S_z) \quad (1)$$

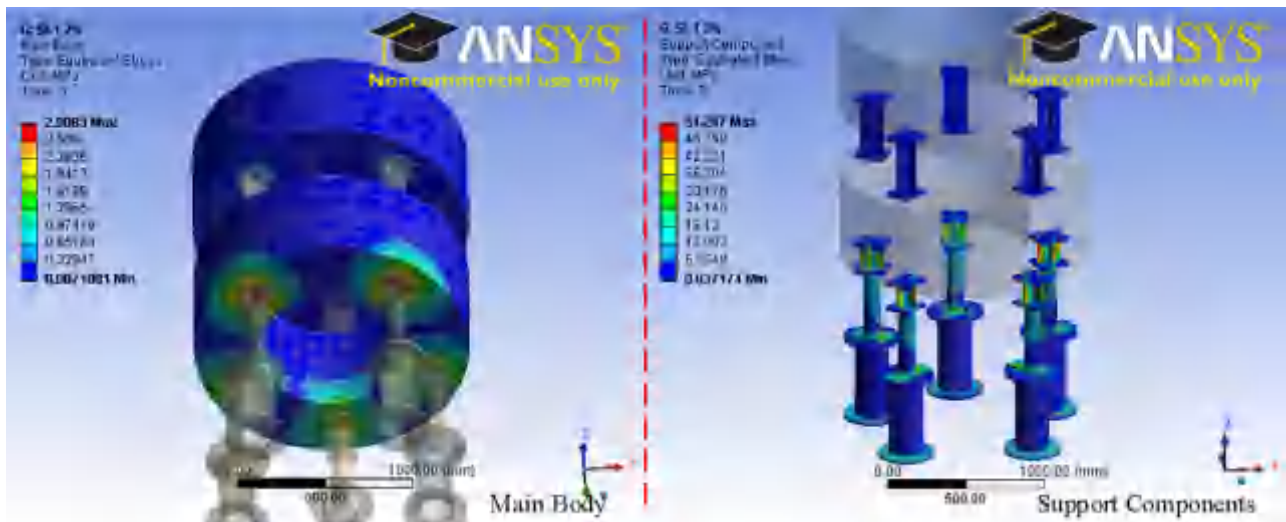


Fig. 6. Equivalent stress distribution under seismic excitation (SL-1 with damping factor 2%).

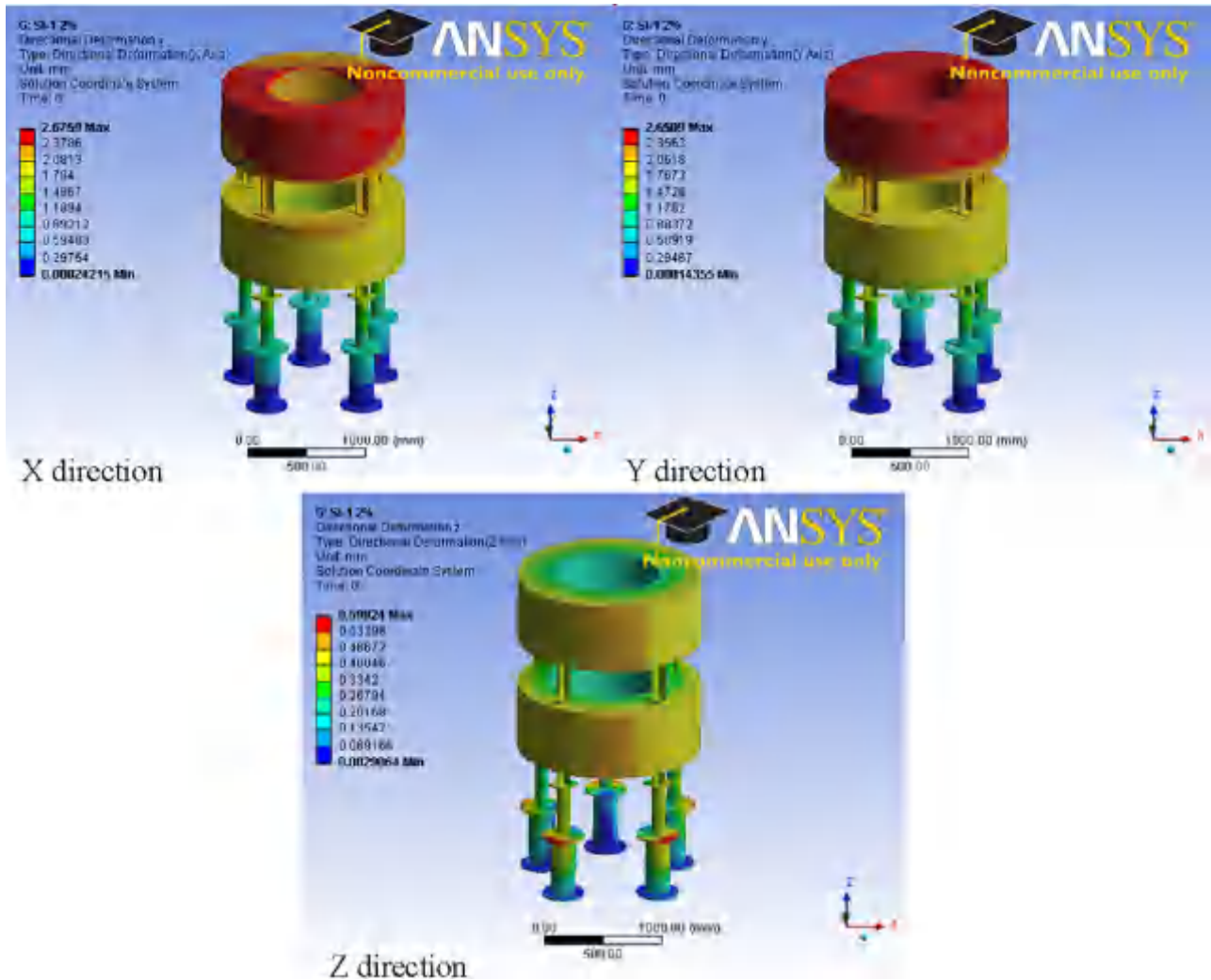


Fig. 7. Deformation distribution in each direction under seismic excitation in corresponding direction (SL-1 with damping factor 2%).

Table 5
Comparison with various damping factors under SL-1.

Damping factor	Max. deformation (mm)	Max. stress of main body(MPa)	Max. stress of support components (MPa)
2%	2.7	2.9	54.3
4%	2.2	2.4	44.0

S_x , S_y and S_z represent the maximum responses under three orthogonal directions, when applied excitation separately. It means S is the maximum value of 24 combinations.

4. Seismic analysis

4.1. Model and static structural analysis

As described above, the stacked reactors include three parts and each part has kinds of equipment. In order to reduce the computation of the simulation, the actual prototype has been simplified and reduced, such as the mass of aluminum busbar, collecting water box, regulator, water pipes and the water in water pipes are reduced and added to the mass of aluminum coils. The simplified model and main materials is as shown in Fig. 3. Table 3 lists the physical-mechanical properties of main materials used in the prototype.

4.2. Modal analysis

The modal analysis with pre-stress is to obtain the natural vibration frequency and vibration mode of stacked reactors. Based on the simplified 3D model, the natural vibration frequency with modal order less than 11 can be simulated by Workbench, and the results are shown in Fig. 4. The otherness of natural vibration frequency with modal order less than 7 is small.

4.3. Seismic excitation

Based on the geographical conditions of ITER site, three levels, such as SL-2 (seismic level 2), SMHV (seismic maximum historically probable earthquakes) and SL-1 (seismic level 1) of ground motion are considered. SL-2 is also called SSE (safe shutdown earthquake) and in this event it shall be demonstrated that all safety functions are maintained. SMHV is equivalent to occur over a period of about 1000 years. SL-1 is also called OBE (operating basis earthquake). SL-1 corresponds to an event with a probability in the order of 10^{-2} per year and represents an investment protection earthquake level. The facility needs to be designed to restart and operate after an SL-1 event without special maintenance or test [10].

This paper focuses on the anti-seismic property of stacked reactors under SL-1. Seismic excitation reflects the strength and type and is defined in term of FRS (floor response spectrum) which consists of displacement, velocity and acceleration response spectra [11]. The pseudo-acceleration response spectra is adopted to describe the seismic excitation in this paper. The design response spectrum for SL-1 with various damping factors for the site of Cadarache provided by ITER is as shown in Fig. 5. It reflects the relation of pseudo-acceleration and frequency (or natural vibration period). Different ground structures have various damping factors. For stacked reactors, 2% and 4% are adopted in the seismic analysis simulation, and the latter can be deduced from the curves by using interpolation. For vertical direction, the value of pseudo-accelerations are equal to 2/3 of the horizontal [10,12].

4.4. Results

Table 4 shows the reactive forces from the 24 combinations by Newmark's rule with the gravity taken into consideration. F_n means the reactive force of support with No. n as defined in Fig. 3. The symbol of F_z depends on the directions of seismic excitation and gravity, i.e. '+' means the same, and '-' means the opposite.

Fig. 6 describes the equivalent stress distribution under SL-1 with damping factor 2% in three directions synchronously. Indicated from Fig. 6, the maximum equivalent stress of main body and support components are 2.9 MPa and 54.3 MPa, respectively. Both of them are under the allowable stresses of the corresponding materials, which demonstrated the reliability of structures.

Fig. 7 shows the deformation distribution in three orthogonal directions (x , y and z) under seismic excitation (SL-1 with damping factor 2%) in corresponding directions separately. The maximum deformation is located at the upper reactor and is about 2.7 mm for horizontal direction (x , y). The deformation in vertical direction is relatively small.

To evaluate the impact of various damping factors on seismic properties, the seismic analysis with damping factor 4% are also simulated by the same method. Earthquake spectrum of SL-1 with damping factor 4% can be deduced by the values of 2% and 5%. The detailed results are shown in Table 5. Obviously, the impact of 4% is less than that of 2%, since the excitation of 4% is less.

5. Conclusion

Based on response spectrum method, the seismic response of the stacked DC reactors is evaluated under the design earthquake spectrum of seismic level one (SL-1) with damping factor of 2% and 4% provided by ITER Organization. The results show that the maximum deformation and equivalent stress of stacked reactors are 2.7 mm, 2.9 MPa (for main body) and 54.3 MPa (for support components), which are less than the allowable stress. It means that the stacked reactors have good anti-seismic performance and no damage under the SL-1 with damping factor 2% and 4%. This analysis could provide reference for the foundation design of dc reactor, as well as make a contribution to the similar seismic design work.

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