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Article

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Response of a 230 kV outdoor termination according to the frequency characteristics of input seismic waves

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Abstract

Even in disaster situations like earthquakes, power facilities must maintain their structural stability without losing their own functions. In this study, the seismic performance of a 230 kV outdoor termination, a power facility, was assessed using the shaking table test and finite element analysis. The shaking table test was conducted in accordance with the procedure of IEEE Std. 693-2005, and the finite element model was updated based on the test results. Moreover, two artificial seismic waves were prepared, and seismic response analysis was conducted to examine the influence of low- and high-frequency seismic motions on the 230 kV outdoor termination. The von Mises stresses for the seismic waves were also compared.

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Keywords: Power facility; Outdoor termination; Shaking table test; Seismic response analysis; IEEE Std. 693-2005

1. Introduction

With the recent development of technologies and industries, the numbers and scales of power generation and industrial facilities are increasing worldwide, and so is the number of power facilities. Power facilities that distribute and supply power to entire social infrastructures, including homes and power plants, must maintain their functions even in national disaster situations. Severe damage to power facilities due to the large-scale earthquakes that occur worldwide, however, may further amplify seismic damage with a secondary wave owing to the non-operation of social infrastructures and the delay of damage recovery. The cases of damage to power facilities due to earthquakes include the 1994 Northridge earthquake in the United States, the 1995 Kobe earthquake in Japan, the 1999 Chi-Chi earthquake in Taiwan, and the 2008 Sichuan earthquake in China. These confirmed that serious damage may occur when the functions of power facilities are lost [1].

In the event of an earthquake, the major failure modes of an outdoor termination include falling off and slippage due to the breakage of the anchor that fixes the facility body, damage to the bushing and oil leakage, and damage

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to the components attached to the facility. The bushing is an important device that protects the insulation of power facilities by allowing overvoltage with an impact to flow to the ground. The bushing is generally made of a brittle material with little energy absorption capacity, and is made up of porcelain. Therefore, damage to the bushing occurs due to stress concentration, the lift of the bushing, and the slippage of the gasket. As the bushing is one of the facilities vulnerable to earthquakes, seismic stability must be secured by examining and assessing the seismic performances of the bushing and its connections. Japan Electric Association Guide (JEAG) 5003-2010 [2], the guideline on the seismic design of the substations in Japan, emphasizes the examination of the seismic safety of the anchorage zone and the bushing because the rigidity of the transformer main body is high. IEEE std. 693-2005 [3] of the United States suggests a seismic test procedure for the bushing of transformers.

In this study, a shaking table test was conducted on a 230 kV outdoor termination in accordance with the procedure of IEEE Std. 693–2005, and the finite element model was updated using the test results. Moreover, finite element analysis was conducted using the spectrum that referred to NRC Regulatory Guideline 1.60 (RG 1.60) [4] and the Uniform Hazard Spectrum (UHS) [5] of the Ulsan area of South Korea to examine the influence of low- and high-frequency seismic motions on the 230 kV outdoor termination.

2. Test and analysis method

In this study, a shaking table test was conducted on a 230 kV outdoor termination, which is an ultra-high-voltage power facility, in accordance with IEEE Std. 693:2005, a seismic test standard for substations. Moreover, the finite element model was updated using the test results. To examine the influence of low- and high-frequency seismic motions, the von Mises stresses were compared for the vulnerable parts of the 230 kV outdoor termination. The 230 kV outdoor termination consisted of a bushing structure at the top, a steel structure that supported the bushing structure, support insulators, and a steel plate, as shown in Fig. 1. Fig. 2 shows the finite element model of the 230 kV outdoor termination. It had a 1212 mm width, a 6000 mm height, and a 2108 kg weight. The support insulator placed between the bushing structure at the top and the steel plate was made of porcelain and had a variable thickness. The steel structure and steel plate member were made of SS400 of the KS standards. For the members of the steel structure, right-angled equilateral L-shaped steel was used. Moreover, the cracks in the bushing structure, oil leakage, and bolt loosening were examined by performing visual inspection before and after the shaking table test.

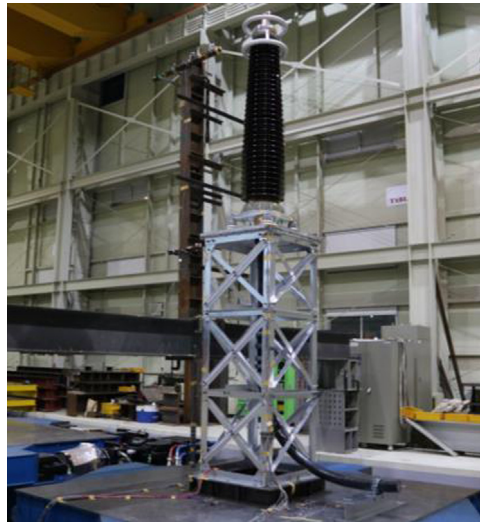


Fig. 1. 230 kV outdoor termination installed on a shaking table.

The seismic waves required for the seismic performance assessment that used the shaking table test were prepared to meet the high-performance required response spectrum (RRS) for the 2% damping ratio suggested by IEEE Std. 693:2005. Moreover, the input seismic waves in the shaking table test were applied to the finite element model to examine the possibility of assessing the seismic performance using analysis. To examine the influence of low-

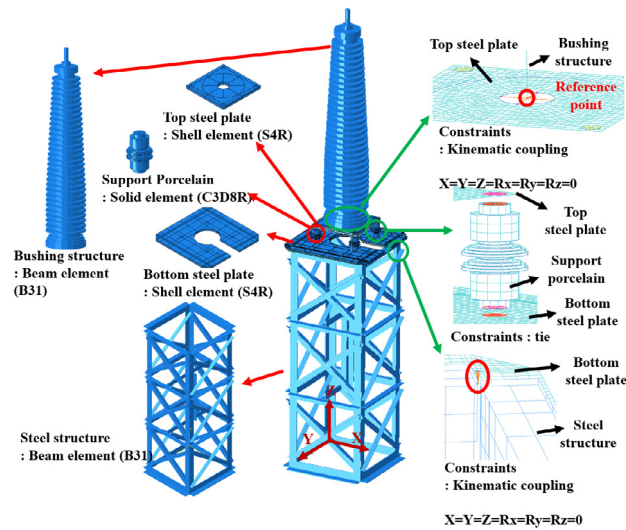


Fig. 2. Finite element model.

and high-frequency seismic motions, finite element analysis was conducted by preparing seismic waves considering RG 1.60 and UHS. Fig. 3 shows the RRS of the seismic waves used in the shaking table test and finite element analysis.

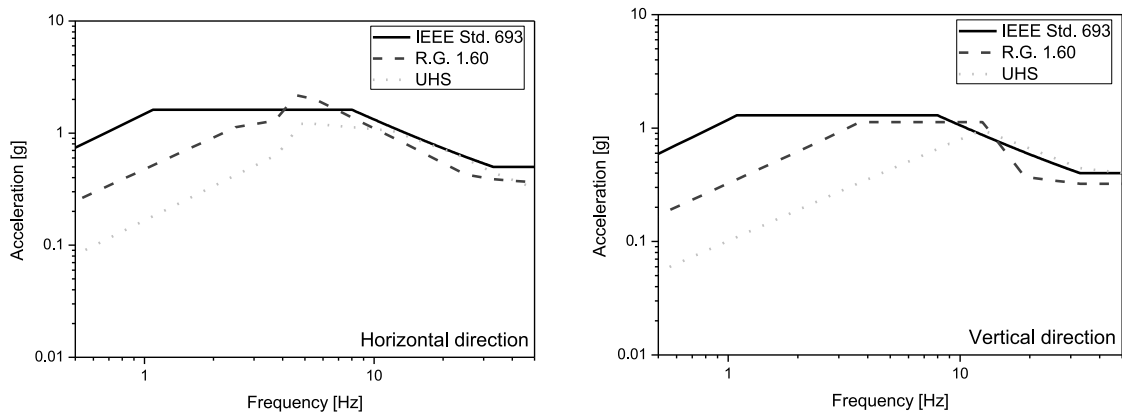


Fig. 3. Required response spectrum.

For finite element analysis, the 230 kV outdoor termination was modeled using ABAQUS, as shown in Fig. 2. As the bushing and steel structures were long and thin and corresponded to the entire structural system, they were modeled using a beam element (B31). The support insulators were relatively small and corresponded to the vulnerable parts. Therefore, they can be considered for plasticity and large deformation, and they were modeled using a solid element (C3D8R) to conduct nonlinear analysis. The steel plate member was modeled using a shell element (S4R) because it was a plate-shaped member with a thickness significantly smaller than the other dimensions. Table 1 shows the material properties defined in the finite element model.

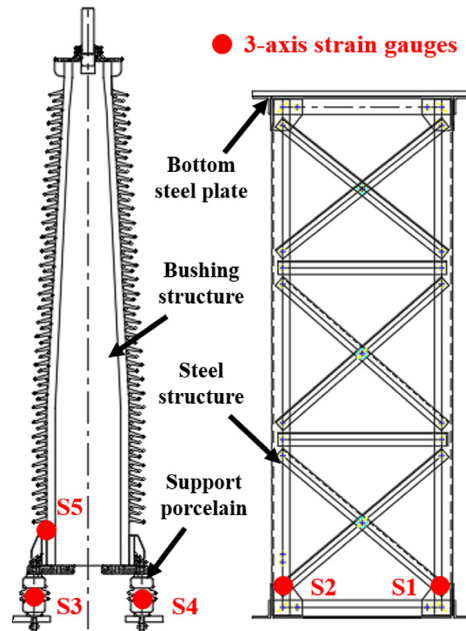
In the finite element model, the tie option was used for the support insulators and steel plate to constrain the surfaces of the solid and shell elements. The coupling option was used for the steel structure connected to the steel plate and the bushing structure to constrain the beam elements using nodes. As the power cable inside the bushing structure had little influence on the entire structural system, the mass of the power cable was evenly distributed to the steel structure and was applied using the non-structural mass option.

During the shaking table test, 3-axis strain gauges were installed on the vulnerable parts of the 230 kV outdoor termination to measure the responses, and von Mises stress was calculated using the results. The selected locations

Table 1. Material properties of finite element model.

Member	Material	Density (t/mm ³)	Young's modulus (MPa)	Poisson's ratio
Steel structure	SS400	7.85e−9	205 940	0.3
Steel plate				
Bushing structure	Porcelain	2.7e−9	120 000	0
Support porcelain				

for the assessment of the von Mises stress were the lower parts of the steel structure, the support insulators, and the end of the bushing structure, which were parts vulnerable to earthquakes, as shown in Fig. 4.

**Fig. 4.** Installation locations of the 3-axis strain gauges.

3. Test and analysis results

In this study, a 230 kV outdoor termination was installed on a shaking table, as shown in Fig. 1, and the resonance search test was conducted using sine sweep. The test was conducted in the vertical and horizontal directions. The 230 kV outdoor termination was a flexible structure with a high center of gravity. Therefore, a low input acceleration (0.05 g) was used to prevent damage to the structure during the resonance search test, and the search range was 1–35 Hz. Moreover, the finite element model was updated using the natural frequencies measured in the resonance search test. Fig. 5 shows the mode shape in each direction according to the eigenvalue analysis, and Table 2 shows the natural frequencies and weights of the finite element model and the real structure. The error of the weight between the real structure and the finite element model was 0.17%, and the difference of the natural frequency in each direction was less than 3%.

Table 2. Comparison of weight and resonant frequency.

Category	Weight (kg)	Resonant frequency (Hz)		
		X	Y	Z
Real structure	2108.1	7.13	7.19	36.75
FEM	2111.7	6.97	7.19	36.09
Difference (%)	0.17	2.24	0.00	1.80

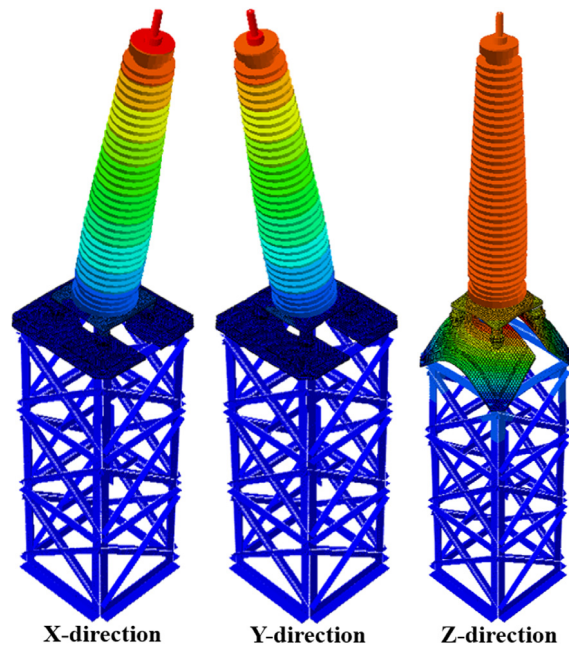


Fig. 5. Mode shape of eigenvalue analysis.

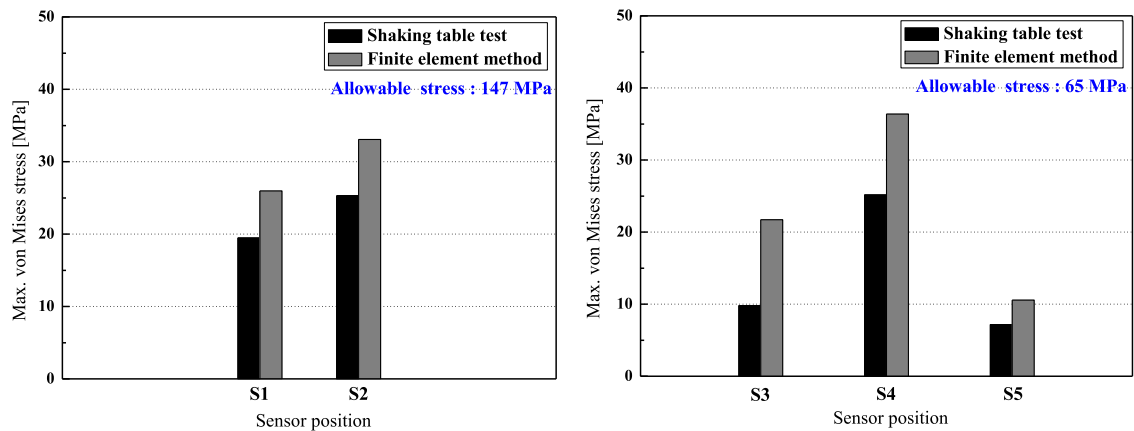


Fig. 6. Comparison of the results of the shaking table test and finite element analysis.

Before and after the shaking table test, in which the seismic waves that met the RRS suggested by IEEE Std. 693:2005 were used, external changes of the 230 kV outdoor termination, such as deformation, damage, and bolt loosening, were not found. The von Mises stress was calculated using the measured 3-axis strain responses as well as Young's modulus and Poisson's ratios of porcelain and steel presented in Table 1. The allowable stress of steel is three-fifths of the yield stress according to the allowable stress design (ASD) while that of porcelain is half the ultimate strength according to IEEE Std. 693:2005. As the ultimate strength of porcelain is 130 MPa, 65 MPa was used as the allowable stress. The yield stress of steel was 245 MPa, and its allowable stress was 147 MPa. As shown in Fig. 4, the stress values calculated at the 3-axis strain gauge installation locations of the 230 kV outdoor termination met the allowable stresses of steel and porcelain. Moreover, the results of the finite element analysis exhibited higher stress values than those of the shaking table test. In the results of the shaking table test and finite element analysis shown in Fig. 6, the maximum stress was lower than the allowable stress and thus

met the acceptance criterion suggested by IEEE Std. 693:2005. For the outdoor termination that requires seismic verification, it was found that its safety could be assessed using finite element analysis.

Fig. 7 shows the stress for the vulnerable parts of the 230 kV outdoor termination obtained through finite element analysis considering IEEE 693, RG 1.60, and UHS. The stress was assessed to be higher in NRC RG 1.60, which considered low-frequency components, than in UHS, which considered high-frequency seismic motions. The maximum stress in the finite element analysis that considered UHS, a response spectrum that may actually occur, was higher in RG 1.60 than in UHS at all of the locations.

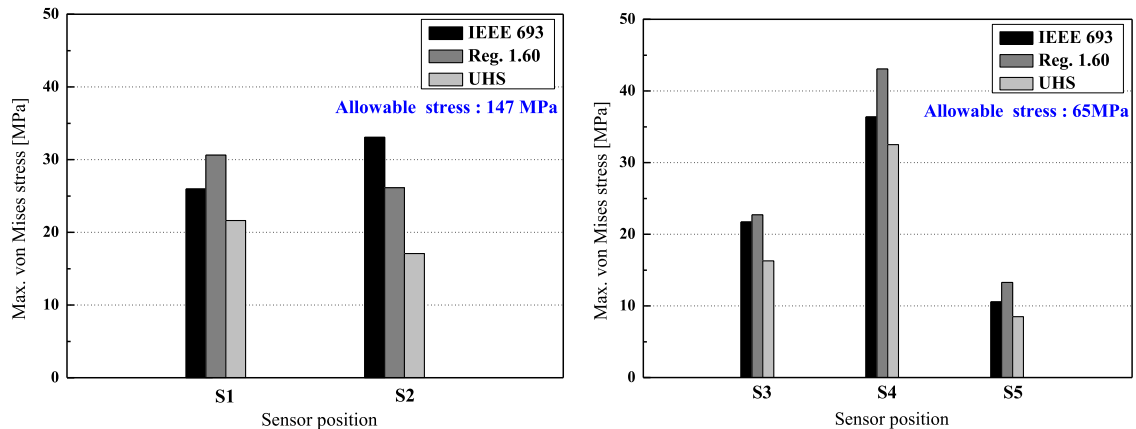


Fig. 7. Stress comparison considering high- and low-frequency seismic motions.

4. Conclusions

In this study, a shaking table test was conducted in accordance with the procedure of IEEE Std. 693:2005 to assess the seismic performance of a 230 kV outdoor termination. No external changes of the 230 kV outdoor termination, such as deformation, damage, and bolt loosening, were found before and after the shaking table test, and the soundness of the seismic verification test was secured. In addition, for the finite element model, the accuracy of the analysis could be confirmed by comparing the results with those of the shaking table test.

For the 230 kV outdoor termination, the von Mises stresses were compared for the vulnerable parts by conducting finite element analysis using the spectrum that referred to NRC Regulatory Guideline 1.60 (RG 1.60), a low-frequency seismic motion, and the uniform hazard spectrum (UHS) of the Ulsan area in South Korea, which is a high-frequency seismic motion. The maximum von Mises stress at the vulnerable locations obtained through finite element analysis was higher in RG 1.60, which is a low-frequency seismic motion, than in UHS, which is a high-frequency seismic motion that may actually occur. This indicates that the application of the conservative response spectrum must be considered for a test to verify the performance of a device even though it is desirable to reflect the characteristics of the actual seismic load for the assessment of a device according to the purpose of the performance test of a power facility.

Acknowledgments

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