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Seismic risk mitigation of cylindrical electrical equipment with a novel isolation device

Yongfeng Cheng, Sheng Li*, Zhicheng Lu, Zhenlin Liu, Zhubing Zhu

China Electric Power Research Institute, No.33 Nanbinhe Rd., Xicheng District, Beijing 100055, China

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ABSTRACT

Cylindrical electrical equipment is common in substations and vulnerable in earthquakes. Isolation technique, as an important method to mitigate seismic demand, has attracted less attention in electrical substation. This study aims at filling the knowledge gap by introducing a novel isolation device for cylindrical electrical equipment. The device is a combination of circularly arranged lead alloy isolator units installed at the bottom of equipment. A 1000 kV capacitor voltage transformer is adopted as specimen, and both non-linear time history analysis and shaking table test are incorporated in examining seismic mitigation effect. Probabilistic seismic demand analysis is carried out with two set of ground motions: recorded ground motions with spectral acceleration's corner periods around 0.85 s and scaled ground motions with corner periods around 1.7 s. Results show that for recorded ground motions, the failure probabilities on both flexural moment and displacement demand are lowered significantly; for scaled ground motions, the mitigation on flexural moment demand is significant but the effect on displacement demand is negligible, revealing that mitigation effect on displacement demand is promising but more conditional on properties of input. In shaking table test, a code spectrum compatible wave is adopted as excitation, and results show that the device is successful to reduce the acceleration, displacement and stress responses by more than 50% under a 1.4 × 0.5 g PGA input. Besides mitigation effects on earthquake induced flexural moment and displacement, the isolation device also avoids residual deformation after shaking and does not increase vibration amplitudes under wind. Numerical model of the isolation device is proposed with a validation by shaking table test result, providing a useful tool for parameter design of the device. The isolation technique and device in this paper offer an important option for seismic enhancement of cylindrical equipment in substations.

1. Introduction

In recent decades, the demand for clean energy has triggered another round of electrical grid construction [1,2]. Large clean energy bases, i.e. hydro power plant and ocean wind farm, are often located far from electrical power demand centers such as urban agglomeration [3]. The geometrical dis-matching between them requires long distance electrical power transmission. Higher voltage level electrical grids, such as Ultra High Voltage (UHV) grid with larger transmission capacity and less line losses [4], have been developed enormously in recent years to meet the demand. As the UHV grid serves vaster areas, its seismic safety becomes more significant for the resilience of society.

Substations are important nodes in electrical grids, which are a complex of electrical equipment in various types. The seismic fragility of substation equipment has attracted attention after many earthquakes, such as 2008 Wenchuan Earthquake [5] (as seen in Fig. 1) and 1994 Northridge Earthquake [6]. Due to requirement on electrical functionality, the material adoption and structural type are usually similar for a kind of equipment in different voltage levels. However, the structural scale of equipment in a higher voltage level can be significantly larger. In the substation, a 1000 kV surge arrester can reach 13 m in height and 9 t in weight, which is nearly 2 times taller and 5 times heavier than a 500 kV surge arrester [7]. It results in much larger earthquake induced forces, making it more challenging to achieve seismic safety.

Isolation technology is an effective method for seismic mitigation of substation equipment, especially for two main kinds of them. One is the isolation of bulky equipment such as electrical transformer and shunt reactor, as seen in Fig. 2. This kind of equipment has large equipment body at base and flexible bushing installed in vertical or tilt direction at top. The other is the isolation of cylindrical equipment in slender shape, as seen in Fig. 3. This kind of equipment is an assembly of insulator units and often installed on supporting structure in vertical direction. A substation contains large number of the slender cylindrical equipment,

* Corresponding author.
E-mail address: lisheng@epri.sgcc.com.cn (S. Li).

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Fig. 1. Failure of cylindrical electrical equipment in 2008 Wenchuan Earthquake [8].

Fig. 2. Electrical transformer installed in ± 800 kV Zhalute Convertor Substation in Inner Mongolia, China.

such as capacitor voltage transformer, post insulator and surge arrester [7]. There is also equipment of different structural characteristics other than these two categories, such as outdoor gas insulated switches or equipment installed indoor. The seismic isolation of those equipment should be discussed more specifically.

For electrical transformers as seen in Fig. 2, seismic isolation is aimed at reducing responses of bushing [9] and avoiding excessive acceleration or overturning of equipment body [10]. Base isolation systems in different types have been used and proved to be efficient. For isolation in horizontal direction, Saadeghvaziri et al. [11] and Oikonomou et al. [12] installed friction pendulum system for reducing the seismic responses of the transformer. Cheng et al. [13], Murota et al. [14] and Oikonomou et al. [12] have adopted Lead Rubber Bearing (LRB) for reducing response of the transformer body and bushing. It was pointed out by Lee et al. [15] that for the common seismic isolation technique of electrical transformer, vertical ground motions were transmitted through the isolation system unchanged or even magnified. Probabilistic seismic assessment carried out by Kitayama et al. [16,17] proved that systems which were isolated in both horizontal and vertical directions can be further effective in enhancing the reliability of transformer. Lee et al. [15,18] designed a novel horizontal–vertical seismic isolation system for the electrical transformer, which was a combination of two separate systems, friction pendulum isolators to achieve horizontal seismic isolation and spring damper units to achieve vertical seismic isolation. Shaking table test validation of the system showed it was effective and reliable.

For cylindrical equipment in slender shape as seen in Fig. 3, the failure of this kind of equipment was repeatedly observed in earthquake events in form of insulator facture [5,19], indicating that flexural moment at bottom was key for seismic safety [20]. The seismic isolation technique for this kind of equipment has not been fully studied, and it is the main object of this paper. Alessandri, et al. [21,22] introduced an application of wire rope isolators to form a base isolation system. It took advantage of flexibility and friction between the wires to provide mechanical isolation properties. In that system, reducing the stress of electrical equipment would result in larger displacement of superstructure in wind load, so that a balance should be met to avoid displacement induced problem. It is an intention of this paper to introduce and validate a novel isolation system for slender cylindrical equipment which has excellent mitigation effect on seismic responses, while keeping the structural rigidity unchanged in operational load such as wind. On the other hand, cylindrical electrical equipment of different dynamic properties needs to be connected with each other by conductor buses or cables to form circuits of different functionalities. If displacement at the top of equipment is too large, slackness of the conductor between equipment might be not adequate and significant dynamic interaction may occur and cause damages [23,24]. Many researches

Fig. 3. Cylindrical electrical equipment in 1000 kV Beijing East Substation in Beijing, China.