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SEISMIC PROTECTION OF SUBSTATION PORCELAIN CYLINDRICAL ELECTRICAL EQUIPMENT

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Abstract

Porcelain cylindrical electrical equipment (PCEE), like current transformers, potential transformers, disconnect switches, circuit breakers, arresters, are critical components of substation. Past strong earthquakes have shown severe damage to PCEE. The PCEE failure is the major reason of power outage during earthquakes. Power outage may lead to many secondary disasters, like interrupt of water supply, transportation, communication and so on. Thus it is important to make sure that the PCEE could remain functional during earthquakes. This paper presents the state of art on seismic protection of substation porcelain cylindrical electrical equipment and proposes a novel protection method based on a synergetic protection strategy on base isolation (BI) and tuned mass damper (TMD). As for PCEE, it has several unique characteristics. Most PCEEs are connected with each other using conductors. Most PCEEs are tall while slender. All PCEEs have electrical function requirements. During past years, many researches focus on seismic protection of PCEE. New materials are advocated to replace porcelain. New type equipment is invented to replace traditional PCEE. Researches on seismic evaluation of PCEE are first presented and the reasons why PCEE is so fragile are explained. Major damping methods, including alloy dampers and TMD, used to enhance PCEE seismic resistance are presented and discussed. Characteristics among different damping methods and their affections on PCEE function are compared. Base isolation methods used to protect PCEE are also presented. Advantages and disadvantages of base isolation are introduced and compared. Pros and cons between isolation and damping methods are also compared. In order to reduce the adverse influences to PCEE function while fulfill efficient protection effectiveness and avoid excessive conductor deformation, an improved base isolation method is proposed. A TMD device is added between BI and PCEE as a stabilizer to help BI achieve better effectiveness and robustness and less absolute isolation displacements. In turn, BI reduces the frequency uncertainties of input ground motions and help TMD perform well facing these filtered motions. Dynamic responses of this method is plotted.

Keywords: Damping methods; Earthquakes; Isolation methods; Porcelain cylindrical electrical equipment; Substation;

1. Introduction

Power is indispensable for supporting reconnaissance efforts after natural hazards such as earthquakes. Blackouts and power outage have adverse effects on the community at large due to the interdependence between the power grid and other critical infrastructure such as water, gas, transportation, and communications, etc. [1]. Thus, avoiding blackouts or providing a robust way for immediate power restoration after earthquakes and other extreme events is necessary for resilient communities [2].

Porcelain cylindrical electrical equipment (PCEE), like current transformers, potential transformers, disconnect switches, circuit breakers, arresters, are critical components of substation. However, PCEEs did not perform well during past strong earthquakes [3-8]. During the 2008 Wenchuan earthquake, more than 90 substations with voltages of 110 kV and above went out of service [9]. Two weeks after the February 27, 2010 Chile earthquake, i.e. on March 14th, a widespread cascading blackout took place because of the disconnection of a 750 kV transformer bank that was attributed to a protection control cable on the transformer that got loosened during the earthquake [10]. The typical damage modes of PCEE include failure of the porcelain material and cracking of the lower flange of the insulator and oil leakage of facilities from the flange gaskets.

There are several reasons why PCEEs are so fragile. (1) Porcelain is a type of brittle material with little ductility. The maximum tensile strength of porcelain is low and the strength has obvious dispersion. (2) Most PCEEs are tall and slender and usually are cantilevered installed. Furthermore, PCEEs are usually installed on top of supports and some PCEEs even have heavy head parts. (3) The PCEE system damping is usually less than 2%. Some are even lower than 1%. Structures and equipment with smaller damping tend to experience larger responses under earthquakes. (4) The frequencies of PCEEs are usually between 1 Hz to 10 Hz, which are within the dominant frequency band of earthquakes. Resonance might happen under earthquake excitations. (5) PCEEs are connected with each other using conductors (buses), including rigid and flexible buses. Lack of proper slack might cause dynamic interaction among adjacent equipment. This might have adverse influences on PCEE equipment.

2. Seismic assessment analyses

Many researchers studied the PCEE seismic performance and dynamic characteristics, related codes are issued to guide the PCEE seismic design [11-14]. In this studies [15-23], the static and dynamic responses of PCEEs under different type of excitations are researched. The natural frequencies and damping ratios are calculated. The strain response at PCEE critical part, like bushing or insulator bottom, together with the acceleration and relative displacement responses are also of concern. Recent researches focus on increasingly high voltage classes, like ultra-high–voltage 1, 100 kV bushing [24]. To better evaluate the PCEE seismic performance, studies on input ground motions are conducted [25-28]. The interactions between PCEEs and related supports are also assessed [29-30]. Because some PCEEs are too big to be shake table tested, test methods, like real-time hybrid simulations, are advocated [31-33]. Considering the significant uncertainties of input ground motions and material strength, probability based seismic fragility methods are used to assess the PCEE seismic performance [34-41]. At each PGA level, the probability of PCEE failure is given. Different parameters, like peak ground acceleration (PGA) and peak spectral amplitude at resonant frequency, are used to index the ground motion intensity level. Besides fragility analyses on single PCEE, there are also researches on PCEE systems [42-46], which is not the focus of this paper.

Gas Insulated Switchgear (GIS), is a kind of metal enclosed switchgear. All the equipment of the electrical switchgear are enclosed by gas tight metal enclosure and SF_6 gas is used as insulation between live parts of the equipment and earthed metal enclosure. Compared with traditional PCEE, the GIS has better seismic performance. Besides, composite materials are used to replace porcelain. Compared with porcelain, composite material usually have better mechanical properties and lighter weight [47-54].

Another important factor is most PCEEs are connected with each other with conductors [55-71]. There are two types of conductors, which are rigid and flexible buses. Past researches and reconnaissance have shown that in some cases, the existence of conductor had adverse influences on adjacent PCEEs. The dynamic of flexible buses is difficult to be precisely simulated using numerical methods, tests are majorly used to study its mechanical behavior at beginning. Theoretical and numerical methods are then gradually used to give more research on conductors. The flexible bus connecting shapes are now recommended by IEEE 1527. Recent research demonstrate that given proper slack, the conductor influence to adjacent PCEEs could be reduced to an acceptable level.

3. Seismic protection methods

Although GIS and composite bushings (insulators) are becoming increasingly popular, PCEEs are still been widely used for function and cost reasons. Seismic protection techniques, used in civil engineering areas, like base isolation and dampers, are used to protect PCEEs.

Base isolation have been demonstrated as an effective seismic protection in structural engineering areas. The PCEE natural frequencies are usually in the range of 1 Hz to 10 Hz, which coincide with many ground motion dominant frequency band. Through adding a flexible layer between the ground and equipment. The PCEE frequency is decreased to avoid the ground motion dominant frequency band and related PCEE dynamic response is expected to be decreased. Many studies studied the effectiveness and robustness of base isolation on PCEE [72-83]. Wire rope isolators have been successfully used to reduce PCEE seismic responses. Compared with structures, there are some specific PCEE characteristics need to be considered. (1) Base isolation application usually increases the equipment lateral absolute displacement while the adjacent PCEEs are conductor connected. Sudden conductor stretch without enough slack might lead to PCEE failure. This factor should be considered at PCEE isolation design [82]. (2) PCEEs are tall and slender, overturning moment occurs under earthquake excitations. Tension devices may need to be designed and installed for PCEE isolation. (3) PCEEs are much lighter than structures, laminated rubber bearings, which are widely used in structures, might be inappropriate for PCEEs. Isolation of the whole substation might be a solution for the above three problems while cost might be an essential concern. (4) Some cantilevered PCEE bushings or insulators are lateral or inclined mounted. Vertical isolation may need to be carefully considered [83].

Another PCEE seismic protection method is using dampers. Many researches have illustrate the effectiveness of this method [84-91]. Compared with base isolation method, using dampers typically could reduce PCEE acceleration dynamic responses while not increasing the displacement responses. The PCEE acceleration and relative displacement response reduction effectiveness are generally weaker than base isolation. Typical dampers include alloy dampers, shear-type lead dampers and tuned mass dampers (TMD). TMD or MTMD is installed on top of the equipment and tuned according to the PCEE frequencies. The problem of this method is that extra components, which are the tuned masses, should be installed on top of PCEEs. This might have influences on PCEE functions. As for alloy damper and shear-type lead dampers, they are installed at the bottom flange to replace traditional bolts. The maximum strain at insulator bottom could be reduced. As PGA increases, the damper efficiency also increases. The equipment natural frequency usually decreases a little with the installation of dampers. Some early researches show that the effectiveness of this type of dampers might decrease facing long period ground motions and near fault impulsive ground motions. The most outstanding advantage of this method is that it has little adverse affections on PCEE.

For the above methods, base isolation is effective but will increase the equipment absolute displacement response. TMD has to be installed on top of the equipment and might have affections on PCEE function. Alloy damper doesn't perform well facing long period ground motions and near fault impulsive ground motions. An innovative damping method, which is combined by base isolation (BI) and tuned mass (TMD) is advocated, trying to fulfill stable response reduction effectiveness while not causing excessive displacement responses. The schematic diagram of the BI-TMD method is plotted in Fig. 1. The left figure is the traditional TMD installation and the middle is the traditional BI installation. The right figure is the combined BI-TMD method. The TMD in BI-TMD is installed at the PCEE bottom, on top of the base isolation plate. The ground motion is filtered by the BI and related frequencies are more concentrated at the isolation period. The TMD system perform better facing the filtered ground motion. Preliminary results under ground motion are plotted Fig. 2. In the preliminary simulation case, the PCEE frequency is 4.6 Hz. the isolation period is 1.5 s. The TMD tuned frequency is 75% of the isolation period. The mass ratio is 200%. The damping ratio of the BI-TMD system is 20%. The PGA of the input ground motion is 1.0 g. It should be mentioned that the mass ratio is much larger than conventional TMD mass ratio. Fig. 2 (a) gives the acceleration comparison at PCEE top at X direction between Non-control and BI under Chichi ground motion while Fig. 2 (b) between BI and BI-TMD. It can be seen that the acceleration amplitude at PCEE top is about 1.80 g without control, 0.95 g with BI and 0.40 g with BI-TMD. The BI-TMD performs well. More research will be further conducted in the future to validate the effectiveness of the BI-TMD method.

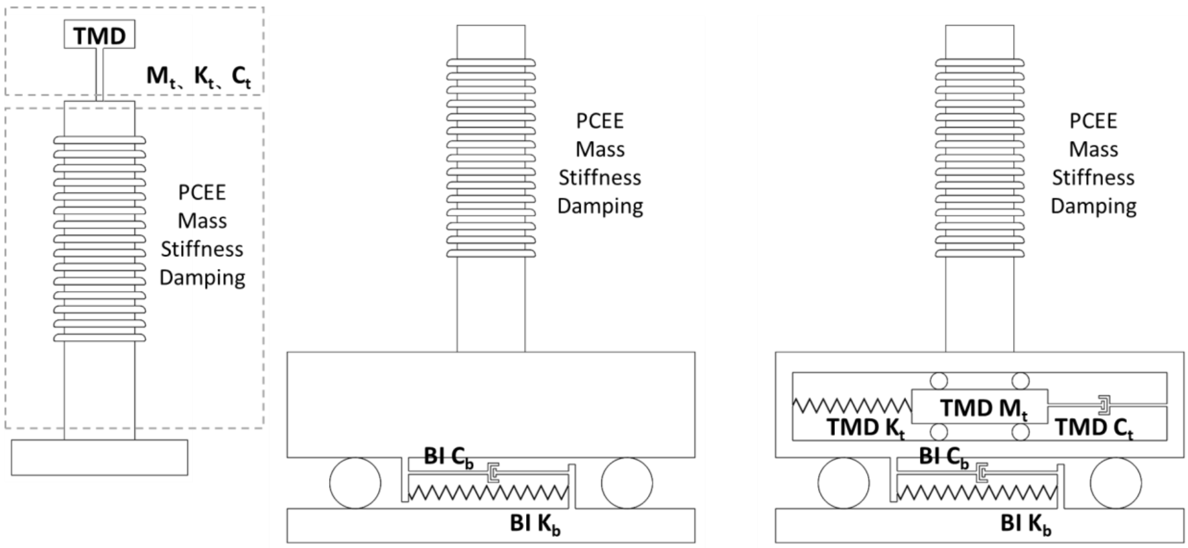
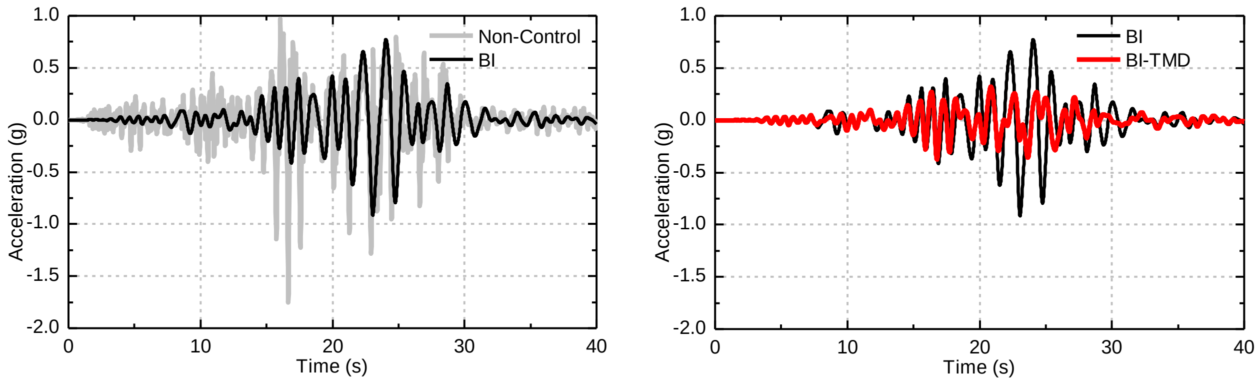


Fig. 1 BI-TMD schematic diagram



(a) Accelerations under Non-control and BI (b) Accelerations under BI and BI-TMD

Fig. 2 Acceleration responses with non-control, BI, BI-TMD [92]

4. Conclusions

PCEE, as important component of power supply system, its safety operation during earthquake is of great importance. This paper generally introduces current researches on PCEE seismic assessment. New material and innovative equipment systems are used to enhance PCEE seismic performance. Current methods used to protect PCEEs, including base isolation, tuned mass damper and alloy dampers, are also introduced. Advantages and disadvantages of this method are compared. A new method, based on BI-TMD, which might have some potential benefits on PCEE seismic protection, is preliminary introduced.

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The acknowledgements provide an opportunity to express appreciation to those who contributed significantly to the preparation of the paper. They may be written in free style, and must be brief.

5. Copyrights

6. References

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