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Evaluation of power substation equipment seismic vulnerability by multivariate fragility analysis: A case study on a 420 kV circuit breaker

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ABSTRACT

Recent earthquakes have shown that Electrical Power Substations apparatuses are seismically vulnerable. This causes to disrupt the power supply in many cases, and therefore their seismic evaluation with high reliability is significantly important. Using fragility curves is a common practice for assessing seismic vulnerability. In general, fragility curves are based on only one intensity measure (IM), such as peak ground acceleration (PGA). This study has attempted to propose multivariate fragility analysis. One of the major advantages of this developed multivariate fragility analysis is to more reliably determine the seismic vulnerability of a region. A 420 kV circuit breaker (CB) was modeled and analyzed by using finite element technique. The results show that by adding another IM as peak ground velocity (PGV) the dispersion of the created data decreases to a great extent and therefore, the developed fragility surfaces helps conducting the seismic risk evaluation of electric power system components with higher level of reliability. Based on the obtained numerical results it can be expressed that for moderate damage state the fragility values are not much dependent on the PGV variation, while for severe damage state the dependence of fragility values on PGV is noticeable, particularly for PGA values in range of 0.1–0.7 g.

1. Introduction

Inspired by lessons from the past earthquakes, it is clear that the existence of electricity during and after seismic events has a substantial effect on rescue and relief operations, resulting in saving lives in emergencies. Major losses resulting from vulnerability of electric power system subjected to earthquake include: a) direct loss which comprises the costs of repairing damaged parts of the electric system; and b) indirect loss due to service interruption of other lifelines, particularly those notably dependent on electric power such as water supply systems [18,21,28,29,31]. Among the electric power network's elements, power substations are more vulnerable and play a vital role in stability, controllability, and serviceability of electric power system [10,11,25,26].

The studies conducted by the researchers about seismic vulnerability of the electrical apparatuses can be classified into three main sections: the studies conducted on physical damages of either one or several special equipment in the past earthquakes, the studies conducted through experimental and analytical methods, and the studies dealt with evaluating the power substation's equipment vulnerabilities by means of numerical and probability based methods such as fragility curves.

Vulnerability of power substations may be due to the following reasons [19,20,22,23].

- Using brittle materials (porcelain) to support electrical wires and buses,
- Improper mass distribution along the equipment height,
- Heavy elevated masses,
- Inadequate anchorage,
- Insufficient lateral stiffness of supporting equipment,
- Low redundancy of structures and networks as a whole,
- Interaction between adjacent devices and structures and their different parts,
- Aging of the equipment, and
- Lack of seismic design of equipment and the structures

The dynamic behavior of power substation apparatuses were studied by some other researchers. In 2015, Alessandri et al. introduced a novel wire rope base isolation system protect high voltage (HV)

Abbreviations: CB, Circuit Breaker; PGA, Peak Ground Acceleration; PGV, Peak Ground Velocity; DS, Disconnect Switches; CT, Current Transformer; CVT, Capacitor Voltage Transformers; LA, Lighting Arrestor; PTR, Power Transformer; THA, Time History Analysis

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porcelain circuit breakers (CBs) during earthquakes. At the beginning, experimental tests were performed to assess the mechanical properties of the porcelain column (strength and elastic modulus). A series of time-history analyses were performed and demonstrated the effectiveness of this isolation system in both serviceability and ultimate limit conditions. The displacements obtained were compatible with the electrical insulation requirements and a reduction in the bending moment by 80% was observed. The new wire rope base isolating system seems particularly suitable when the elongation of the period is generated by a rocking effect rather than horizontal shear deformations [36].

In a companion paper the experimental characterization of the previously discussed base-isolation system was addressed. The comparison between experimental and numerical results showed a consistency for all response quantities (displacements, moments, and deformations), while the maximum values were systematically underestimated about 20%. The results also illustrated that the wire rope base isolation system reduces approximately of 75% the maximum stress level in the porcelain column, which highly increases the safety level of this apparatus against earthquakes [37].

Mosalam and Günay (2013) proposed a real-time hybrid simulation system (RTHS) for cost-effective and time efficient dynamic testing of high voltage disconnecting switches (DS). In the developed RTHS system, a single insulator post used in the 245 kV vertical-break DS was tested as the experimental substructure on the smart shaking table and a single degree of freedom system representing the support structure was employed as the analytical substructure. The test results of RTHS system were also compared with those from a conventional shaking table test [38]. In another companion research the results of a parametric study consisting RTHS tests were presented. The purpose of the parametric study was to evaluate the effect of support structure damping and stiffness on the response of DSes with two different insulator materials, namely porcelain and polymer insulator posts [39].

One of the common methods for assessing seismic vulnerability of power substation equipment is using fragility curves. There are several studies in which fragility curves have been developed for electrical equipment [4,8,12,24]. In 1999, Anagnos assessed the performance of twelve power substations equipment in California using fragility curves. Using the peak ground acceleration (PGA) as the input ground-motion parameter, she compared failure probabilities with opinion-based fragility curves for a few selected equipment classes. Her study also showed that most of the damage in power substations has resulted from CBs and DSes [5].

Regarding to the experimental analysis, Paolacci and Giannini [9] investigated the seismic vulnerability of 380 kV vertical DS. They performed numerical analyses to obtain fragility curves on the equipment, and evaluated the influence of significant parameters on the probability of its failure. Their results showed that the equipment was quite vulnerable to an extremely intense earthquake (i.e., for a spectral acceleration of 1*g*; corresponding to a PGA value of about 0.35 g) [9].

Generally, a substation comprises many components such as power transformers (PTRs), CBs, DSes, current transformers (CTs), and etc. Inevitably, all the equipment must function safely and the entire substation must qualify for performance and normal serviceability. But in the case of severe earthquake events, some equipment are more critical and the overall performance of substation depends on their functionality. Zareei [27] has evaluated the seismic vulnerability of power substation equipment. It was tried to find the critical components in a power substation by analytical hierarchy process. According to that study, after PTRs on which the whole performance of substation greatly depends, CBs have a considerable effect on the substation performance [27]. Considering the important role of CBs in a power substation, it is necessary to evaluate their seismic vulnerability more reliably. Inside the CB's porcelains, there is gas or oil, or in some cases, the porcelain is vacuumed. Thus, existence of even fine cracks will annihilate its insulation capability and then its performance will be affected [2,3]. In this study, seismic evaluation of a 420 kV CB in terms of fragility curves has been conducted using analytical method, based on a set of time history analysis (THA). Then, observing the high dispersion of the data obtained from THA calculations, an attempt has been made to decrease the dispersion by developing two-variable fragility functions. For this purpose two hazard intensity measures (IMs), including PGA and peak ground velocity (PGV), instead of PGA alone, have been employed. Details of the study are presented in the following sections.

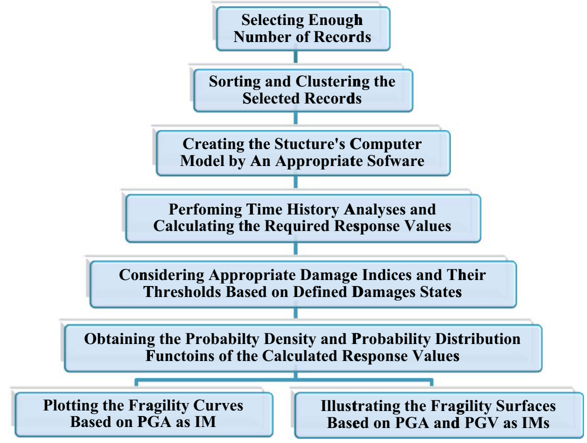

Fig. 1. Flowchart of the required process for seismic fragility assessment.

2. The process of developing seismic fragility functions

Fig. 1 shows a flowchart of the required process for developing the seismic fragility functions for a structural system.

2.1. Single-variable fragility function (fragility curves)

By definition, seismic fragility curves are natural logarithmic functions which give the probability of exceedance of a specific response of the structure from a specific performance level for different values of a specific IM of the earthquake. Some types of fragility curves have been discussed in previous researches [1,14,33–35] which include:

- Empirical fragility curves,
- Fragility curves developed based on engineering judgment, and
- Analytic fragility curves.

In the present study, analytical fragility functions are developed by using THA. Several methods have been developed to calculate analytical fragility curves such as: conventional incremental dynamic analysis (IDA), multiple strip analysis (MSA), and endurance time method (ET). Incremental dynamic analysis involves scaling each ground motion in a suite until it causes collapse of the structure. It requires many structural analyses to be performed with increasing IM levels, in order to finally observe a collapse. Also, the large-IM results are less practically relevant, as the fragility function values at large IM levels are of less interest than values at small IM levels. Finally, it is questionable whether scaling typical moderate-IM ground motions up to extreme IM levels is an accurate way to represent shaking associated with real occurrences of such large IM levels. MSA produces more efficient fragility estimates than other methods for a given number of structural analyses and evaluates structural seismic responses in different IM levels [6]. In this section MSA process is described:

Probability of exceedance of a specific structural response versus a specific IM values have often a log-normal distribution [6,16], mathematically expressed as: