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Probabilistic seismic assessment of seismically isolated electrical transformers considering vertical isolation and vertical ground motion

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This study presents a probabilistic response analysis of seismically isolated electrical transformers with emphasis on comparing the performance of equipment that are non-isolated to equipment that are isolated only in the horizontal direction or are isolated by a three-dimensional isolation system. The performance is assessed by calculating the probability of failure as function of the seismic intensity with due consideration of: (a) horizontal and vertical ground seismic motions, (b) displacement capacity of the seismic isolation system, (c) limit states of electrical bushings, (d) details of construction of the isolation system, (e) weight of the isolated transformer, and (f) bushing geometry and configuration. Calculations of the probability of failure within the lifetime of isolated and non-isolated transformers at selected locations are also performed. The results of this study demonstrate that seismic isolation systems can improve the seismic performance for a wide range of parameters and that systems which isolate in both the horizontal and vertical directions can be further effective. The seismic assessment methodology presented can be used for: (a) deciding on the need to use seismic isolation and selecting the properties of the isolation system for transformers depending on the design limits, location, and configuration of transformer and (b) calculating the mean annual frequency of functional failure and the corresponding probability of failure over the lifetime of the equipment. The results may also be used to assess the seismic performance of electric transmission networks under scenarios of component failures.

1. Introduction

Electric power systems are important elements of the infrastructure. They are expected to supply electricity at any time, to have low vulnerability to disasters and to be resilient. Empirical evidence in past earthquakes demonstrates that electrical equipment is vulnerable to earthquakes and several have been reported damaged worldwide [1–5]. Failure to supply electricity following an earthquake causes degradation of public safety and quality of life, and results in economic losses. Estimated immediate economic losses in earthquakes such as the 1993 Kushiro-Oki, Japan, 1994 Northridge, USA, 1995 Kobe, Japan, 1999 Kocaeli, Turkey and the 1999 Chi-Chi, Taiwan were in the range of hundreds of millions of dollars for each event just due to interruption of electric power [6,7].

The electric power system consists of generating stations, transmission lines and distribution lines. Electrical transformers for step-up and step-down are located in-between these elements [8]. The key component of an electrical transformer is the high voltage bushing that is mounted on top of the transformer and provides electrical connection between the high-voltage lines and the transformer [9]. Bushings are most vulnerable to seismic shaking [7,8] so that many efforts have been undertaken in academia and the industry to develop means of seismically protecting the bushings and the transformers [8,10–13].

Past studies of the seismic performance of electrical equipment demonstrated that horizontal isolation systems can improve the seismic performance in terms of reduction of absolute horizontal acceleration and relative displacement of bushings and of the transformer body (e.g., [8,11,12]). These studies, however, (a) did not consider the effect of vertical ground motion or showed that the vertical ground motion was transmitted unchallenged through the horizontal isolation system, including some amplification, and (b) did not relate the reduction of the seismic performance index (e.g., acceleration at the bushing's center of mass) to the prevention of failure of the bushing or failure of the transformer itself.

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Moreover, other experimental studies [14,15] investigated the failure modes of electrical bushings but did not relate the findings of component failure to the seismic response of transformers.

The vertical ground motion affects a seismically isolated structure by (a) altering the behavior of the isolation system in the horizontal direction, and (b) magnifying (or at best not modifying) the vertical response of the structure above the isolators. The first effect is well documented and understood for sliding seismic isolation systems. For example, a review of the shake table test data reported in [8,16–18] for the friction pendulum isolation system reveals that the vertical earthquake causes a general increase in lateral forces, accelerations and drift (for strong excitation by an average of 15% but could be much larger for special cases) and that this increase is well predicted by analysis models. The earthquake vertical acceleration also has important effects on the lateral acceleration of structures isolated by elastomeric (lead-rubber) isolation systems as reported in [18–21], although we currently lack analytical models capable of predicting these effects. In general, the vertical excitation has insignificant effects on the isolation system displacement demands.

The second effect mentioned above is documented in experimental studies [8,18,20,21]. For sliding isolation systems which are vertically very stiff, the vertical acceleration is transmitted through the isolators with minor modification. It is then magnified in the vertically flexible components above the isolators leading to large vertical response and potential for damage to secondary systems. In elastomeric isolation systems which have some limited vertical flexibility, there is magnification of the vertical acceleration directly above the isolators and then further magnification in vertically flexible components. In general, it is well understood that current seismic isolation systems do not provide any protection in the vertical direction.

Providing for an effective vertical isolation system comparable to horizontal seismic isolation is a challenge. The main difficulty comes from the fact that the vertical isolation system must support the weight of the structure with limited static deflection so it becomes impractical to provide a sufficient low vertical frequency without excessive static deflections. A significant effort in Japan resulted in the development of three-dimensional seismic isolation systems by each of the large construction companies. These efforts are documented in [22] for applications related to nuclear structures and in [23] for buildings. These systems are often very complex consisting of combinations of air springs, elastomeric isolators, active components, vertical and horizontal coil spring and dampers. In the simplest and practical configurations, the systems consist of elastomeric isolators for horizontal isolation and a coil spring-damper system for vertical isolation, with the two separated by a stiff base. Additional vertical elements together with a stiff base ensure that there is no rocking in the isolation system. Typically, the vertical isolation system is stiff and highly damped but at least one tested design had the vertical frequency equal to 0.5 Hz, resulting in a static displacement of 1 m. Such an isolation system has a height of nearly 4 m, which is impractical. None has been implemented.

Some of the systems developed in Japan were intended for use in equipment. Given the light weight of equipment, the horizontal isolation system took forms of low friction sliding bearings and horizontal coil springs or multistage elastomeric bearings in order to achieve sufficiently low horizontal frequency-about 0.5 Hz. The resulting horizontal-vertical isolation systems were complex and of considerable height. They are considered impractical for use in electrical transformers where the height of the isolation system is important to be within acceptable limits so that easy access to the equipment is not compromised. Such considerations led to an effort at the University at Buffalo, funded by the Bonneville Power Administration (BPA), to develop a compact three-dimensional seismic isolation system for electrical transformers of weight in the range of about 1300 kN to 3500 kN, using readily available technologies. The system developed and tested consists of four triple friction pendulum isolators, each placed on top of a vertical coil spring-linear viscous damper assembly that is restrained by a telescopic system to only move vertically. This system allows for unrestrained rotation (rocking) of the isolation system. Another version of the system employs a stiff base in-between the friction pendulum isolator and the vertical spring-damper system so that rocking is restrained. The version of the system without the added stiff base is preferable as it is easier to implement, including the option of embedding the vertical spring-damper system in the foundation so that there is minimum gain in the transformer height.

This paper presents procedures for the analysis and results of an analytical study of the performance of electrical transformers with particular emphasis on comparing the options of a non-isolated transformer to one isolated only in the horizontal direction or a transformer with a three-dimensional isolation system. The isolation systems considered are those developed in the BPA-funded project and do not include any other possible alternatives. Details will be provided later in this paper. An important feature of this study is that the vertical ground motion is included in the analysis.

The study uses incremental dynamic analysis (IDA) [24], which gradually scales up a large number of ground motions, conducts nonlinear response history analysis for each set of scaled motions and calculates the number of times that a specified limit state (or states) is reached. The data are used for constructing fragility curves (probability of functional failure versus the seismic intensity) based on procedures in FEMA P695 [25], and then the probability of failure over the lifetime of equipment is calculated using procedures in FEMA P58 [26]. The numerical model of the analyzed transformers is based on information acquired in the testing of components of electrical transformers [5,14,15]. The limit states used to describe functional failure of transformers are based on information for the field performance of electrical equipment in past earthquakes ([27–30]). Particularly, [28] reports on the development of empirical fragility curves for conventionally supported electrical equipment which are used in seismic vulnerability assessments by electric utility companies in a program called SERA [28,29]. Information utilized in program SERA for non-isolated electrical transformers is used in this study to calibrate the failure model, which is then used for constructing fragility curves for seismically isolated transformers.

2. Methodology for seismic performance evaluation

IDA [24] is conducted for a set of ground motions, each one of which consists of a horizontal and a vertical component as originally recorded and progressively increased in intensity while maintaining the original ratio of peak vertical to peak horizontal acceleration. The intensity is defined as the peak value of the horizontal ground acceleration, the PGA, or per the terminology used in IEEE seismic design standard [31], the zero-period acceleration ZPA. Failure is defined when either the bushing transverse and longitudinal accelerations reach certain limits (based on calibration of the model using field empirical data) or the displacement of the isolators exceeds their stability limit either by too much horizontal displacement or too much uplift, whichever occurs first. The fragility curves (cumulative distribution functions) are then generated from information obtained in the IDA and analytical descriptions of the fragility curves are obtained by fitting the data with lognormal representations. The fragility curves present the probability of failure (i.e., the probability of exceeding a threshold of either acceleration or isolator displacement) versus the PGA, where the probability of failure is determined at each PGA level as the number of