Evaluation of the seismic performance of isolated electrical transformers under pulse-like excitations

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ABSTRACT

Damage sustained by electrical transformers in past strong earthquakes led to irrecoverable and severe economic losses. The seismic performance evaluation is associated with the loss of proper functioning of the transformer. This study deals with modeling existing isolated electrical transformer structures to evaluate the effects of variables that may affect the seismic performance and dynamic characteristics. The results probabilistically determine the seismic performance acceptability of study isolated electrical transformer structures based on the impact of key structural response parameters on the seismic performance of the transformer. Analyses of systems for a wide range of parameters are performed. The effects of horizontal and vertical near-fault pulse-like ground motions, the displacement capacity of the seismic isolation system, limit states of electrical bushings, and details of the isolation system design are considered. Also, the probability of failure of the transformer under the near-fault excitations with pulse-like characteristics is investigated. The results of this study demonstrate that three-dimensional seismic isolation systems can improve the seismic performance for a wide range of parameters and can be further effective compared with only horizontal seismic isolation and offer the lowest probabilities of failure for all cases of transformer and isolation system parameters.

KEYWORDS

Electrical transformer, Three-dimensional isolation, Failure performance evaluation, near-fault pulse-like ground motions, fragility curves

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1. Introduction

Electrical transformers are the primary members of the lifeline engineering systems. They are meant to reserve electricity continually and have a low vulnerability to disasters. Empirical observations of past earthquakes illustrate that electrical equipment is vulnerable to earthquakes and various have been reported worldwide [1-5]. Failure to supply electricity following an earthquake leads to degradation of public safety and quality of life and results in economic losses.

This paper investigates the limitations of past studies by considering performing representative analyses with near-fault pulse-like ground motions [6,7] and evaluates the near-fault pulse-like excitations on the probability of transformer failure. It also compares the acceleration at the center of mass of the bushing in various situations, including fixed base and horizontal isolation only, and a three-dimensional seismic isolation system in near-fault pulse-like ground motions.

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 with rocking considering near-fault pulse-like ground motions.

2. Methodology

The failure performance evaluation is based on FEMA P695 provisions for collapse performance evaluation. These provisions mandate performing IDA and finding the collapse of the analyzed structure and failure of its critical components by seismic simulation [8,9].

The procedure followed is to conduct IDA to obtain data on the number of failures for each level of seismic intensity considered. In this paper, failure is considered either when the maximum value of acceleration at the center of mass of the upper part of the bushing in the transverse or the longitudinal directions reaches a determined limit or when the isolation system fails by exceeding the horizontal or the vertical (uplift) displacement capacity, whichever happens first. The ground motion intensity is measured in terms of the peak ground acceleration (PGA), or per the vocabulary used in the provisions by IEEE (2005), the zero-period acceleration ZPA.

It is necessary to mention that the number of analyses is determined by the PGA rate increase in each time step. Also, in this study, the number of ground motions is 40.

The analytical fragility curve (cumulative distribution function or CDF) representing the empirical data is calculated as:

$$CDF\left(x\right)=\int_{0}^{x}\frac{1}{s\beta\sqrt{2\pi}}exp\left[\frac{\left(\ln s-\ln PGA_{F}\right)^{2}}{2\beta^{2}}\right]ds \qquad (1)$$

Figure 1 shows the isolated transformer. The isolation system consists of triple FP bearings providing only horizontal isolation. The transformer is assumed to have three inclined bushings of as-installed frequencies of 4.3, 7.7, and 11.3 Hz, representing a broad range. Figure 2 shows the longitudinal and transverse direction sections of seismically isolated transformer with free rocking. This system is termed three-dimensional seismic isolation, which describes its seismic performance.

Figure 1. The seismically isolated transformer in Vancouver

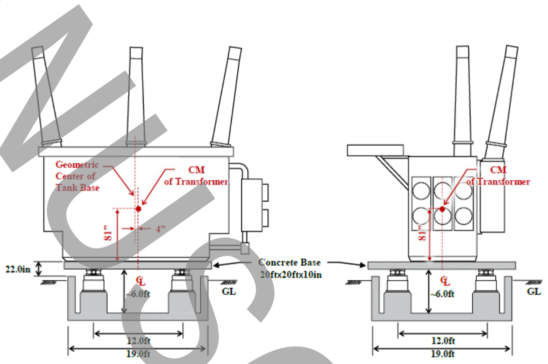

Figure 2. 3D isolated transformer with free rocking

For the isolated transformer, there is additional mass representing a concrete slab supporting the transformer on top of the isolators. This mass is $2m_C$ and is lumped at two locations on top of the supports. Small masses representing the triple FP isolators (m_{TFP}) and the spring-damper units (m_{SD}) are added at the isolator locations. The properties used in this study are summarized in Table 1.

Table 1 Characteristics of transformer models

Transformer height: H_T	2.05 m
Transformer length: L_T	2.80 m
Concrete slab height: H_C	0.15 m
Triple FP isolator height: H_{TFP}	0.13 m
Spring-damper height: H_{SD}	0.40 m
Bushing inclination angle: θ	0 or 20 degrees
clumped mass of transformer body: m_T	31740, 43080, 54410 kg
clumped mass of concrete slab: m_C	4535 kg
clumped mass of triple FP: m_{TFP}	320 kg
clumped mass of spring-damper: m_{SD}	230 kg
Total weight of isolated transformer: $W_T + W_C = (m_T + m_C)$. g, g= 9.81 m/sec^2	1425, 1870, 2315 kN

3. Results and Discussion

There is an increased risk of earthquakes in cities located near active faults. This area has an increased risk of earthquakes due to the built environment's proximity to a hazard source. Structures and buildings near fault lines are also affected by the seismic features of near-field earthquakes when it comes to their seismic performance. In various instances, forward directivity can cause pulse-like ground vibrations in the propagation direction of seismic waves.

IDA was performed using near-field motions for the transformers and bushings. The fragility curves for an 1870-KN transformer with a 7.7 Hz (#8) bushing inclined to 20° with triple FP isolators having a 450-in displacement capacity for the lower bound friction case, no inner restraint based on near-fault, pulse-like ground motions, and transverse acceleration limits of 1g are shown in Figure 3.

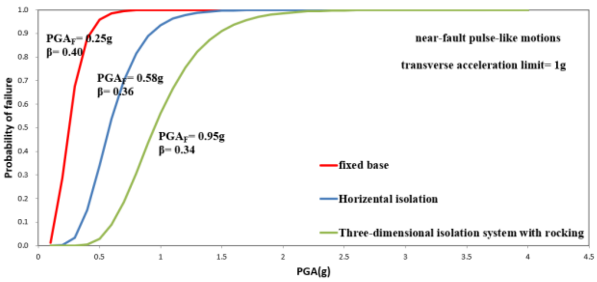

Figure 3. Fragility curves for 1870-KN transformer with a 7.7-Hz bushing (#8) inclined to 20° with an isolator ultimate displacement capacity of 450 mm based on near-fault, pulse-like ground motions, and a transverse acceleration limit of 1g.

4. Conclusion

This paper presents sample results for near-fault pulse-like ground motions. To investigate the effects of near-fault motions with pulse-like characteristics, the results of the analyses were evaluated. The results show a sharp increase in horizontal displacement of the triple FP and vertical displacement of the spring-damper unit compared to the far-field motions. The maximum horizontal displacement of the triple FP isolator reached about 380 mm (when the horizontal acceleration was scaled to 0.6g and vertical acceleration scaled to 0.48g), which increased more than three times compared to far-field motions.

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