3

Analytical Study on Rehabilitation of Critical Electric Power System Components

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Summary

This paper describes an experimental and analytical research project intended to study the behavior of substation equipment under earthquakes and their response when isolated using FPS bearings. Results show that the interaction between components of substation equipment has a significant effect on the response of the system as a whole, and that incorporation of FPS bearings is a promising retrofit strategy.

Research Motivation and Research Objectives

Substations sustained significant damage during past earthquakes. Substation equipment is designed and qualified for a specified level of base excitation. If the design level is exceeded or if the interaction among various electrical and structural components aggravates the seismic response, damage to the equipment is almost certain. This results in direct and indirect losses and in a significant impact to the regional economy. Raising the level of the design seismic excitation, even if economically feasible, might not remedy the situation because the complicated interaction among the different components of the entire system when subjected to seismic events is not fully understood.

The objective of this research is to develop the tools and a framework to evaluate and assess the seismic performance of various substation components and the influence of their interaction on the response of the system as a whole. This research is also intended to evaluate the application of technologies for the improvement of the seismic resiliency of substations and to perform research addressing structural and functional problems that are unique to a substation facility.

Description of Research

In light of the abovementioned objectives, the research project described in this paper includes analytical and experimental studies on critical substation components intended to obtain a better understanding of their dynamic characteristics and to evaluate their seismic response in order to develop effective rehabilitation strategies. Transformers, bushings and disconnect switches are the key components in a substation. Individual behavior of transformers and bushings, as well as their interaction, was studied through time history analyses using 3-D finite element models. Results indicate that the transformer flexibility has a significant effect on the dynamic characteristics and seismic response of the bushings. This effect explains the discrepancy between the bushings' good-to-excellent performance when supported on rigid frames in laboratory experiments and their poor performance during past earthquakes. Analyses of typical transformer foundations indicate that it is very difficult to design foundations capable of resisting inertia forces caused by a major seismic event. New transformers tend to be even heavier due to the need for higher voltage transmission, which further compounds the design of seismically adequate foundations.

Shaking table tests were also performed to compare the response of a fixed-based transformer model supporting a bushing with that of the same system isolated with Friction Pendulum System (FPS) bearings (see Figure 1). 1-D, 2-D and 3-D excitations obtained from several earthquake records and scaled to different PGAs were used.

Experimental studies were followed by a parametric study on the response of a SDOF model of a typical transformer. Results demonstrate the effectiveness of base isolation using FPS bearings in reducing inertia forces and the response of the bushing. However, issues such as the effect of changes of the friction force due to changes of the normal force need further investigation. Large displacements associated with the use of base isolation can compound the interaction among transformer-bushing and interconnecting equipment. This can be addressed through proper design of conductor cables and possible modifications to the bushing flange. Based on analytical and experimental results, a simplified model has been developed to further study the interaction of the transformer-bushing system with interconnecting equipment. This interaction is studied parametrically for several earthquake excitations, isolation radii, interconnecting equipment frequencies, connecting cable stiffness and cable slacks for fixed-base and isolated cases (see Figure 2).

Figure 1. Experimental model of transformer-bushing on shaking table

Another ongoing task deals with the development of a finite element model for FPS bearings to be implemented into a general-purpose package such as ADINA. This element will be used to study the behavior of isolated transformer-bushing systems considering the effect of changes of the friction force on the transformer-bushing dynamic response (see Figures 3 and 4). It should be noted that FPS bearings have been widely investigated and some finite element formulations have already been presented. However, these are either not publicly available or possess restrictions on their applicability mainly because they were developed for building applications. Incorporation of the element into a general-purpose package will be beneficial to the general earthquake engineering community, since recent developments in seismic design of bridges will very likely require more use of advanced technologies such as FPS bearings.

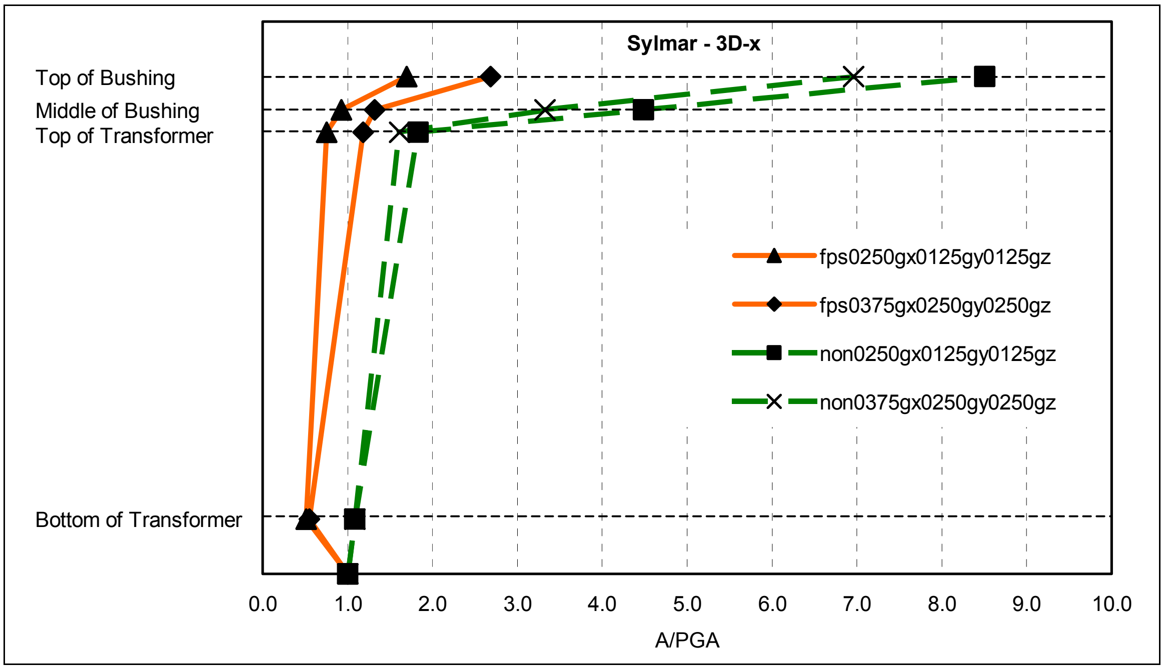

Figure 2. Acceleration response of transformer-bushing model to 3-D Sylmar excitation

Another task planned is the development of a new design criterion for the bushing flange so that the latter acts as a fuse during extreme events. In doing so, a yielding mechanism within the flange of the connection between the transformer/turret and the bushing prevents failure of the bushing and damage to the transformer should the relative displacement exceed the amount of slack provided. Future tasks include work on issues related to the seismic design of foundation and anchorage systems and cost-benefit analysis (vis-à-vis demand on foundations with and without base-isolation). The effect of seismic forces on the design of the anchorage between the core-coil assembly and the tank floor, as well as on the stability of these internal components, will be considered. On a long-term note, possible modifications of FPS bearings in order to minimize or eliminate displacements at the top of the bushing will be investigated.

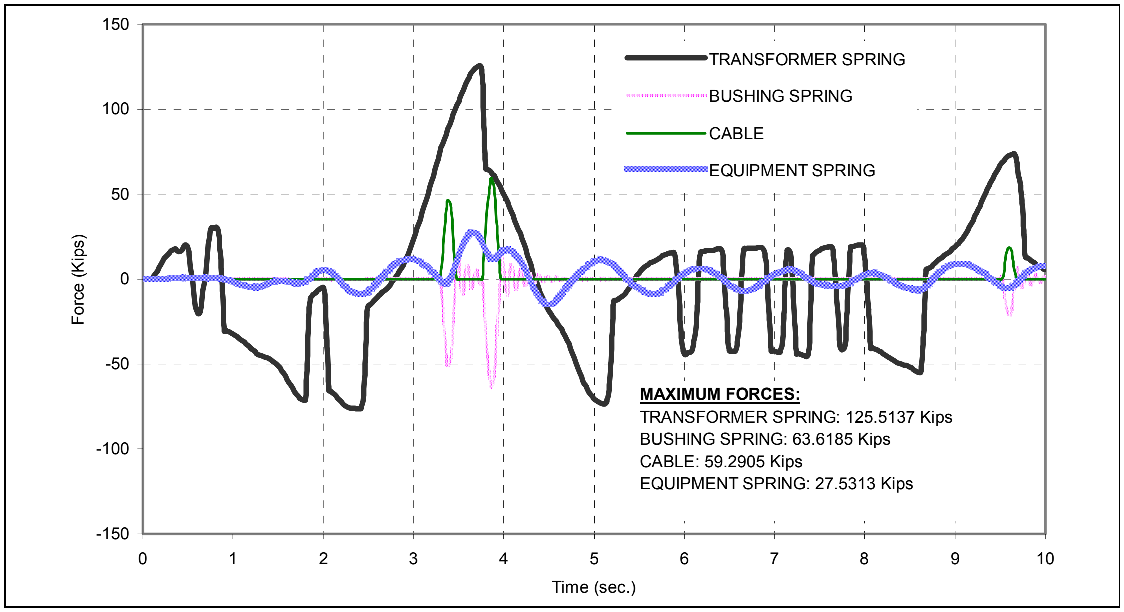

Figure 3. Time-history displacement response of a transformer-bushing system interacting with other elements in a power station

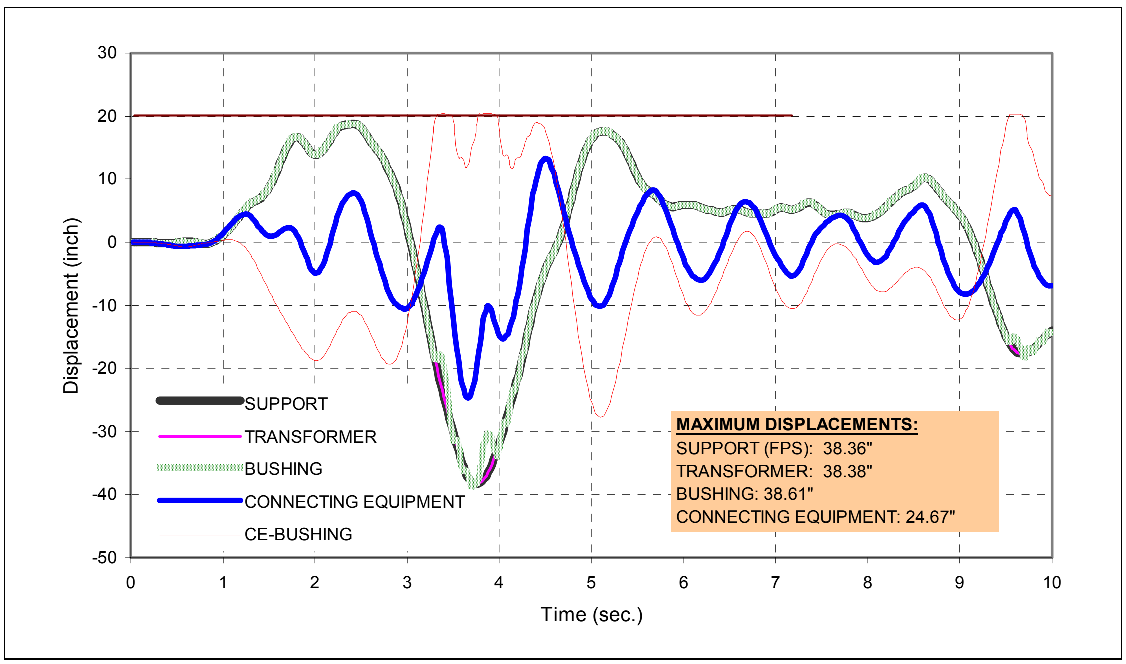

Figure 4. Time-history force response of a transformer-bushing system interacting with other elements in a power station

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