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# Issues of Seismic Response and Retrofit for Critical Substation Equipment

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## Summary

*This study focuses on a means to reduce the seismic hazard for transformer-bushing systems and different issues of the response and rehabilitation of transformers. The primary means of seismic mitigation investigated is the use of Friction Pendulum System (FPS) bearings to seismically isolate transformers. This is done by developing a finite element model representing the behavior of FPS bearings and implementing this model in an ADINA finite element package for further use in analytical studies. This model is used to study the behavior of isolated primary-secondary systems and the effects of parameters like different FPS radii or vertical excitations. Also studied are the effects of isolation on forces applied to the foundations and the corresponding design of foundations compared to the commonly used fixed-base forces. Further, the interaction of transformer-bushings with interconnecting equipment in the substation is studied and corresponding graphs indicating the amount of required slack in connecting cables are presented. Finally, the behavior of internal components of transformers under seismic excitation has been studied. Possible failure and damage modes are identified and a model is developed and analyzed to assess damage risk.*

## Introduction

Electric substations are among the most important parts of any electric power network. In societies deeply dependent on electric energy, any damage to these substations, or anything interrupting their functioning, has immense adverse effects on the society. Such effects include economic damage, disruption of life, interruption in provision of services, and safety problems. Especially in case of earthquakes, the uninterrupted functioning of electric power systems is an integral condition for all activities aimed at recovery, restoration, and reconstruction of the seismically damaged environment.

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 to improve the seismic resiliency of substations and to perform research addressing structural and functional problems that are unique to a substation facility.

This research deals with different issues of behavior and improvement of electric substations under earthquake conditions (Ashrafi 2003). Transformers and bushings are diagnosed as the most important components of an electric substation. Hence, the study is focused on a means to reduce the seismic hazard to transformer-bushing systems and different issues concerning the response and rehabilitation of transformers. The primary means of seismic mitigation chosen here is the use of the Friction Pendulum System to seismically isolate transformers. This job is done by developing a finite

**Figure 1. Typical substation**

element model representing the behavior of FPS bearings and implementing it in the ADINA finite element package for further use in analytical studies. This element is used to study the behavior of the isolation system on primary-secondary system responses for a wide range of frequencies with emphasis on frequencies close to those of real transformers and bushings. The effects of parameters such as FPS radii, and vertical excitation on different responses are studied. Also studied are the effects of isolation on forces applied to the foundation and the corresponding design of the foundation, compared to the commonly used fixed-base forces. Comparisons are made in terms of foundation cost and size and economic benefits of use of FPS. Furthermore, the interaction of transformer-bushing with interconnecting equipment in the substation is studied and interaction effects on various elements are evaluated. Corresponding graphs are provided showing the amount of slack required for different levels of peak ground acceleration and FPS radius. The seismic behavior of internal components of transformers is also investigated. Possible modes of damage and failure are identified for the internal components and seismic analyses are performed to assess the risk.

## Details and Results

Studying the behavior of a complex structure isolated through the use of an FPS requires an analytic model that can take into account complex behavior on a curved low-friction surface including the effects of changes in normal force, interaction of friction behavior in different directions, changes in friction behavior due to change in sliding velocity and normal force, and large displacement effects. This model should be accompanied by a structural modeling tool that permits modeling of nonlinear structures with all their details. Hence, the behavior of the FPS is modeled through a finite element model using the user-supplied element subroutine CUSERG in ADINA.

The response of a wide range of fixed and isolated primary-secondary systems is analyzed. The system characteristics were chosen based on previous studies (Ersoy 2002, Gilani et al., 1999) in such a way to represent the actual transformer and bushing characteristic range. The primary systems are also flexible in the vertical direction to include the effects of vertical excitation in different response parameters as well. The results show the effectiveness of FPS in reducing bushing response for all frequencies. Isolation is effective, even for high system frequencies, and prevents bushing response resonance when its frequency is close to that of the transformer. The base shear force and response of the transformer are also reduced considerably by use of FPS. Figure 2 shows the bushing response for bushings mounted on a transformer with a horizontal frequency of 8 Hz.

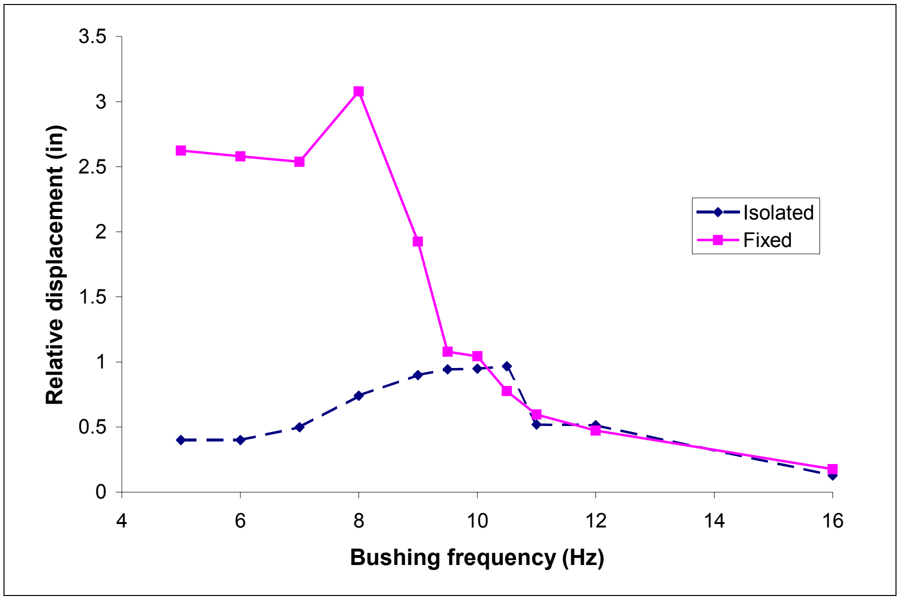


**Figure 2. Response of a bushing mounted on a transformer**

The foundation design is performed for fixed and isolated cases and it is observed that isolation can make the footing size much smaller and remove the need for big piles that can cost $50,000 to $100,000. This might make the use of FPS economical, even on initial cost basis.

To study the interaction between transformer-bushing and other interconnecting equipment, a simplified model is used. The cable connection to the interconnecting equipment can be taut or have different amounts of slack. The interaction between transformer-bushing and interconnecting equipment is observed to have an adverse effect on different responses, particularly bushing response. This effect exists independent of the relative value of the FPS frequency to that of the interconnecting equipment. This phenomenon is even observed when these frequencies are equal. The FPS response is the predominant factor determining the behavior of the various interacting components. Figure 3 shows the significant effects on bushing and interconnecting equipment, caused when the FPS slides away from the interconnecting equipment, causing tension loads in the connecting cable. Even the slightest interaction has significant adverse effects. Therefore, interaction of the transformer-bushing with the interconnecting equipment must be prevented at any cost. One way to insure this is to provide a slack equal to the sum of the maximum absolute values of FPS and the interconnecting displacements in the connecting cable. To help choose the appropriate FPS radius and slack amount, numerous analyses were performed for several earthquake records and different soil conditions, FPS radii, and ground accelerations. Graphs are developed showing the FPS displacement and the inertia reduction for different situations and suggestions are made, based on these graphs, on how to choose the proper FPS radius. Figure 4 shows such a graph, providing the average inertia reduction versus ground acceleration for records on soil.

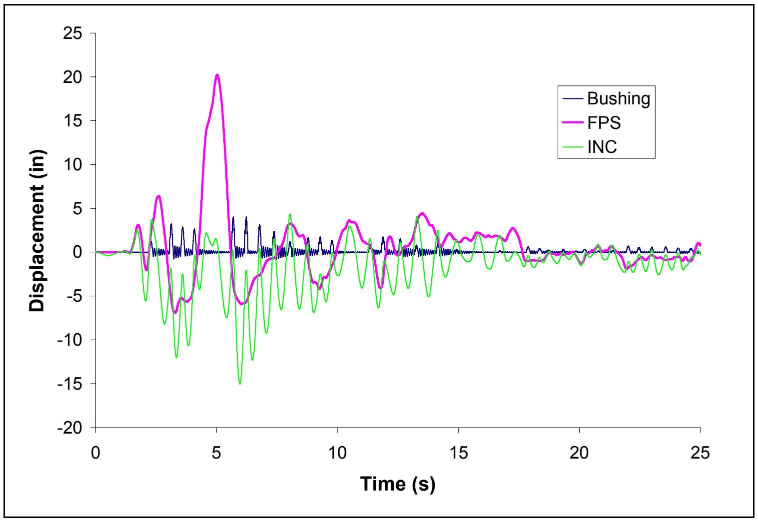


**Figure 3. Time history responses in the interaction of transformer-bushing and interconnecting equipment**

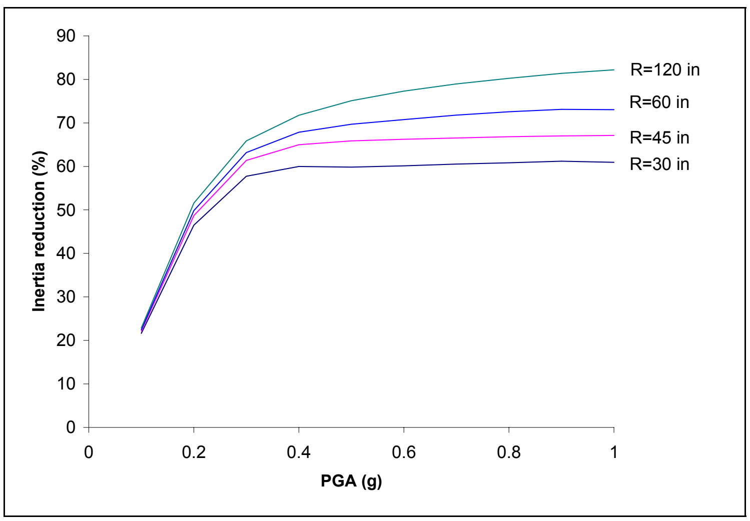


**Figure 4. Average inertia reduction versus peak ground acceleration for soil**

The seismic behavior of internal components of a transformer is studied to ensure that they are not structurally damaged and can continue their electrical function after an earthquake. Four modes of damage and failure are identified for the internal components, of which the sliding of key spacers and loss of close fitting tolerances between limbs and yokes are investigated as the most critical cases. Both of these damage modes can be attributed to loss of prestressing. The tensile forces in windings and core caused by vertical excitation are modest, and are easily offset by the typical prestressing forces. Therefore, it seems that failures of internal components in earthquakes for structural reasons is very unlikely, unless the prestressing is lost before the earthquake occurs. This also suggests that more focus should be put on other reasons to explain the occasional internal damage observed in past earthquakes in the form of slipping of key spacers. This subject is still under study and further analyses are being conducted. Figure 5 shows the internal components of a transformer.

**Figure 5. Internal components of a transformer**

## Concluding Remarks

Proper functioning of transformers and bushings during and after an earthquake is crucial to the electric power network. The Friction Pendulum System is shown to be a good seismic improvement and retrofit tool for transformers. Its use considerably reduces the response of a bushing and transformer and the forces transferred to the foundation. This reduction will also result in large reductions in footing size and economic savings. Use of the FPS should be accompanied by provision of sufficient slack in the connecting cable to prevent any interaction with interconnecting equipment. The initial studies on the behavior of the internal components of transformers show no damage, except when the prestressing is lost in the core before the earthquake. The behavior of the internal components still requires further study, which is in progress.

## Acknowledgements

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