Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Improvements to Modeling Substation Equipment*—**404**		
Start/End Dates	7/15/01 3/31/04	Budget/ Funding Source	$130,000/ PG&E/CEC
Project Leader (boldface) and Other Team Members	**Pardoen (UC Irvine)**		

1. Project goals and objectives

Utilities use different types of substation equipment that have dynamic characteristics that are not well known for many classes of equipment. Manufacturer differences in design, method of structural support, physical dimensions, voltage class differences as well as differences at the component level are just some of the features that introduce variations of dynamic behavior. Although utilities have been specifying that equipment be seismically qualified by analysis for many years, there is uncertainty in the dynamic properties and methods of modeling used in these analyses. This project improves the methods used for modeling electric substation equipment through a combination of experimental and analytical studies of bushings and transformers.

The experimental program consisted of testing substation equipment in laboratory (UCI, UCSD) and in-situ, field conditions (BPA, SDGE) using force-calibrated hammer and shake table excitation techniques. The analytical program consisted of developing linear structural models based upon the experimentally-acquired data that can be integrated with existing finite element models as well as conducting parametric studies for bushing response under various support conditions observed in the field.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The research improves the modeling of bushings under dynamic loads. Specifically the research has determined the fundamental vibration characteristics for a wide range of bushings and, through its shake table tests, has identified a potential isolation retrofit that can substantially mitigate the destructive effects of earthquakes on most bushings.

3. Brief description of the accomplishments of the project

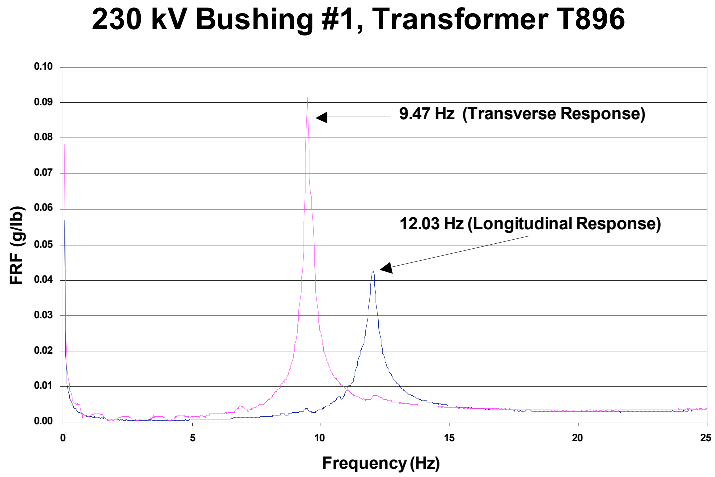
From the tests of more than 35 bushings, most in the transverse and longitudinal directions, it was determined that (a) almost all bushings could be characterized as a SDOF, lightly damped (< 1%) system, (b) bushing orientation and mounting location on the transformer had a significant natural frequency effect. UCI shake table tests of a wire-rope isolator confirmed that the damping characteristics could be significantly increased (< 1% to > 15%). The response of three transformers tested were found to be SDOF systems for frequencies < 35 Hz.

4. Describe any instances where you are aware that your results have been used in industry

Enidine (a former and/or current PEER BIP member) wants to market its wire-rope isolators as a retrofit to transformer-mounted bushings in seismically vulnerable areas.

5. Methodology employed

The experimental approach required a combination of laboratory and field-testing of substation equipment. The laboratory tests used both force-calibrated hammer and shake table excitations whereas the field-testing was confined to force-calibrated hammer and sledgehammer excitation. The experimental work was purposely divided into laboratory and field studies so that the vibration characteristics of the substation equipment can be investigated from two different perspectives. The laboratory test component provided more in-depth, iterative investigations using approximate support conditions whereas field-testing provided the correct support conditions for the substation equipment. Although the field tests at the BPA and SDGE sites did not permit in-depth investigations, the fundamental vibration characteristics of a transformer and more than 35 bushings of different sizes, orientations, and support configurations that were tested significantly adds to the database of such components.



The vibration characteristics of the 35+ bushings were interpreted using commercially available software (ME'Scope) in order to define the frequency, mode shape and damping characteristics of the equipment. Since the bushing's response due to the impact excitation was characterized as linear, ME'Scope determined the modal properties of the multiple degree-of-freedom, lumped parameter modal models from the experimentally-derived frequency response functions. The photo above denotes the force-calibrated excitation technique on a typical bushing at BPA whereas the graph depicts the longitudinal and transverse response for a 230 kV bushing on Transformer T896. It is significant to note that the response of these bushings (a) can be characterized as SDOF systems with low (< 1%) damping and (b) is dependent upon bushing orientation and location on the transformer.

These modal models can be integrated with standard finite elements to model structural response modifications due to mass or stiffness changes resulting from support structures. The linear analytic studies recommend methods for modeling equipment and major components. The significance of the experimentally-derived, modal model serves at least four purposes. First, the analytical models for bushings were found to be relatively simple compared to those that would have been derived from standard finite element techniques. Secondly, the effects of boundary conditions can be easily assessed by posing 'what if' questions to the ME'Scope Structural Dynamics Modification (SDM) software. Thirdly, the lumped parameter model of the substation equipment should be easily integrated with more elaborate finite element models of the support structure. Lastly, the modal models for the response of the bushings due to low- and moderate-level shake table excitation should provide some guidance regarding the appropriateness of assuming a linear analytical model.

Lastly, an MCEER-PEER cooperative effort to determine the vibration mitigation effects of bushings mounted with a variety of elastomeric pads and wire-rope isolators was conducted on the UCI shake table. The results were extremely encouraging. The Enidine wire-rope isolators were particularly effective in increasing the bushing's damping from < 1% to > 15%.

6. Other related work conducted within and/or outside PEER

An MCEER-PEER joint venture investigated the mitigation effects of bushings mounted with elastomeric pads and wire-rope isolators.

7. Recommendations for the future work: what do you think should be done next?

More experimental vibration tests of disconnect switches using experimental modal analysis techniques to supplement the work conducted at UCB. More shake table experimentation of bushings with wire-rope isolators should be conducted.

8. Author(s), Title, and Date for the final report for this project

Pardoen, G.C., Hamilton, C.H., "Improved Modeling of Electrical Substation Equipment for Seismic Loads", November 1, 2004.