Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Analytical Models for Electrical Equipment Connected by Rigid Buses* — **401**		
Start/End Dates	5/1/02 – 6/30/04	Budget/ Funding Source	$82,121/ PG&E/CEC
Project Leader (boldface) and Other Team Members	**Der Kiureghian (UCB)**		

1. Project goals and objectives

This project aimed at developing analytical models and methods for assessing the seismic response of electrical substation equipment connected by assemblies of rigid bus (RB) and flexible strap connectors (FSC) or slider connectors (SC). Also developed is a method to estimate the reliability of electrical substation systems subjected to stochastic earthquake loading.

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 project resulted in mechanical models and dynamic analysis methods of equipment items connected by RB-FSC's or RB-SC's. The model and analysis approach allow accurate prediction of the behavior of connected equipment items by properly accounting for the nonlinear behavior of the connectors and the interaction effect between equipment items. This study also introduced a new S-shaped FSC, called *S*-FSC, which has enhanced flexibility and is highly effective in reducing the adverse effect of dynamic interaction between the connected equipment items. Through extensive parametric investigations, simple design guidelines are suggested for reducing the hazardous effect of the seismic interaction in practice. In order to assess and improve the seismic reliability of electrical substation systems, a new method is developed for computing bounds on the reliability of general systems by use of Linear Programming (LP). These results will help identify and reduce the seismic vulnerability of electrical substation equipment and systems.

3. Brief description of the accomplishments of the project

Considering the plethora of equipment types and configurations in a substation, and the dearth of available information about their characteristics, simple modeling of equipment items is essential. In this study an electrical substation equipment item is idealized as a single-degree-of-freedom (SDOF) oscillator by use of a displacement shape function. In order to examine the accuracy of the SDOF idealization for interaction studies, a connected system consisting of a disconnect switch and a bus support is examined in great detail. The response ratios predicted by the SDOF models are compared with those obtained by 3D finite-element dynamic analysis. Based on these results, recommendations are made on the best choice of the shape functions for the SDOF idealization.

The hysteretic behavior of rigid bus connectors is described by differential-equation-type models for use in nonlinear time history and random vibration analyses of the interconnected electrical substation equipment. For the existing designs of FSC's, a generalized Bouc-Wen model is developed that is capable of describing the highly asymmetric hysteresis behavior. This model is appropriate for use in conjunction with nonlinear random vibration analysis by the equivalent linearization method (ELM). For SC, a bi-linear model in the form of a differential equation is adopted. The hysteretic behavior of the *S*-FSC is modeled by the original Bouc-Wen model. These theoretical models are fitted to available experimental results conducted at UC San Diego and finite element predictions, and then are used to conduct a comprehensive parametric study of the interaction effect.

Analysis methods are developed for estimating the seismic response of equipment items connected by nonlinear rigid bus conductors. The analysis methods use the SDOF models for equipment items and the differential-equation-type hysteresis models for the rigid bus connectors. For deterministic time-history analysis, the adaptive Runge-Kutta-Fehlberg algorithm is used. For stochastic dynamic analysis, the ELM is used. For each connector hysteretic model, closed-form expressions are derived for the coefficients of the equivalent linear system in terms of the second moments of the response. Numerical simulations verify the accuracy of the proposed models and methods as demonstrated in Figure 1.

Employing nonlinear random vibration analysis with the developed models and methods, the effect of interaction in the connected equipment system is investigated through extensive parametric studies. For each connector, parametric charts of the amplification in the response of the higher-frequency equipment item relative to its stand-alone configuration are developed, which describe the influences of important system parameters over wide ranges of values. The performances of the various connectors under identical conditions are then compared in terms of the amplification in the response of the higher-frequency equipment item. Based on this parametric investigation, simple design guidelines are suggested for reducing the adverse effect of the seismic interaction in practice. The design guidelines utilize the parametric charts and an interpolation/extrapolation formula for easy estimate of the interaction effect in practice.

In order to assess and improve the seismic reliability of electrical substation systems, a method is developed for computing bounds on the reliability of general systems by use of LP. The usefulness of the methodology for assessing the seismic reliability of complex electrical substation systems is demonstrated by applications to three transmission-line-substation examples. It is also shown that the proposed LP formulation provides a convenient framework for a systematic identification of critical components and cut sets of the system. Numerical examples with the two-transmission-line substation system demonstrate the proposed methodology.

In order to obtain narrow bounds on the reliability of an electrical substation system under stochastic loading, the new concept of “joint first-passage probability of a vector process” is introduced and new formulations for Gaussian vector processes are derived. The accuracy of the proposed formulas is verified by comparing analytical predictions with Monte Carlo simulation results. By synthesis of the analytical models and methods developed in the study, a general methodology for estimating the reliability of an electrical substation system subjected to a stochastic ground excitation is proposed. The methodology is demonstrated for an example electrical substation system. Figure 2 shows the marginal and system fragility curves of the example system.

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

PG&E has funded the manufacturing and testing of prototypes of the *S*-FSC. The tests have verified the advantages of this FSC as predicted by our analytical models. We hope that this improved design will be used in practice in the near future.

5. Methodology employed

We used and developed differential-equation type models for describing the hysteresis behavior of the connectors. For deterministic dynamic analysis, the adaptive Runge-Kutta-Fehlberg algorithm was used. For nonlinear random vibration analysis by use of ELM, closed-form coefficients were derived for each connector. The LP bounds methodology is newly developed to estimate the reliability of electrical substation systems subjected to earthquake loadings. To obtain narrow bounds on the reliability of an electrical substation system under stochastic loading, the joint first-passage probability of a vector process is introduced and new formulations for Gaussian vector processes are derived. Design charts and interpolation formulas are developed for easy assessment of the interaction effect in practice.

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

Experimental work parallel to this study was conducted at UC San Diego by Professor A. Filiatrault. Comparisons between the experimental results and analytical predictions based the model developed are presented in this study.

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

In order to improve the applicability of the proposed methods in practice and to improve their efficiency and accuracy, the following topics are recommended for future research.

- Develop a method for assessing the reliability of large systems by use of the LP bounds methodology. The idea of employing "super-components" to reduce the size of the LP problem should be explored. Specifically, it is desirable to develop a method for the optimal selection of "super-components," which achieves the objective of problem size reduction, while minimizing the information loss.
- Develop a rigorous and practical decision framework for optimal upgrading of systems relative to specified performance and safety criteria and load hazard. This problem may take the form of a mixed integer-linear programming algorithm that aims at identifying the most effective and economical scheme for strengthening the components of a system to enhance its reliability, subject to prescribed constraints. Such an algorithm may also be used for developing optimal inspection and maintenance strategies for an electrical substation system.
- It would be highly desirable and instructive to apply the methods developed in this research to a real-world electrical substation system. Such an application would highlight the power and usefulness of these newly developed or extended methods, as well as identify shortcomings and areas needing further development. Furthermore, the system analysis methods developed in this research are applicable to any system, and applications to other lifelines may produce fruitful results. In particular, consideration may be given to applying these techniques to an entire power transmission network, or a subset of such a network, consisting of generation nodes, transmission lines, substations, and consumption nodes.

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

Junho Song, Armen Der Kiureghian and Jerome L. Sackman, "Seismic Response and Reliability of Electrical Substation Equipment and Systems," *will be published soon*.

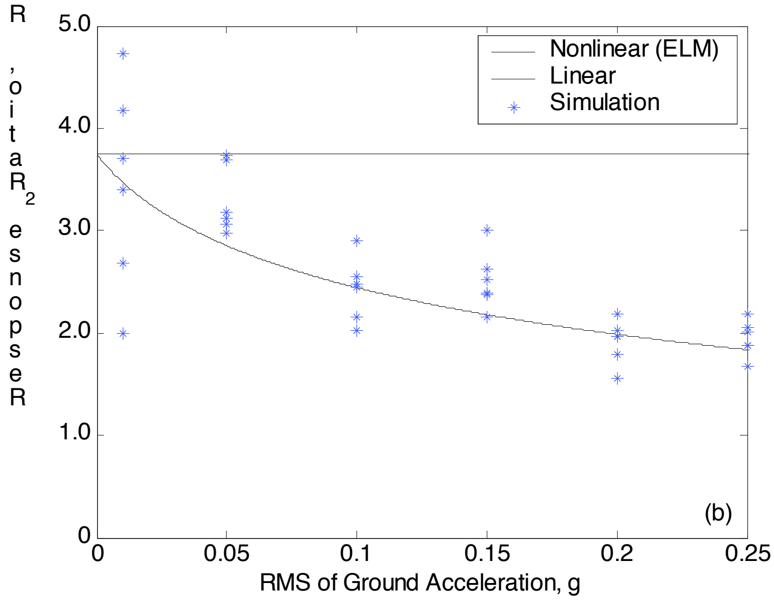

Figure 1. Response ratios for higher-frequency equipment item connected by *S*-FSC

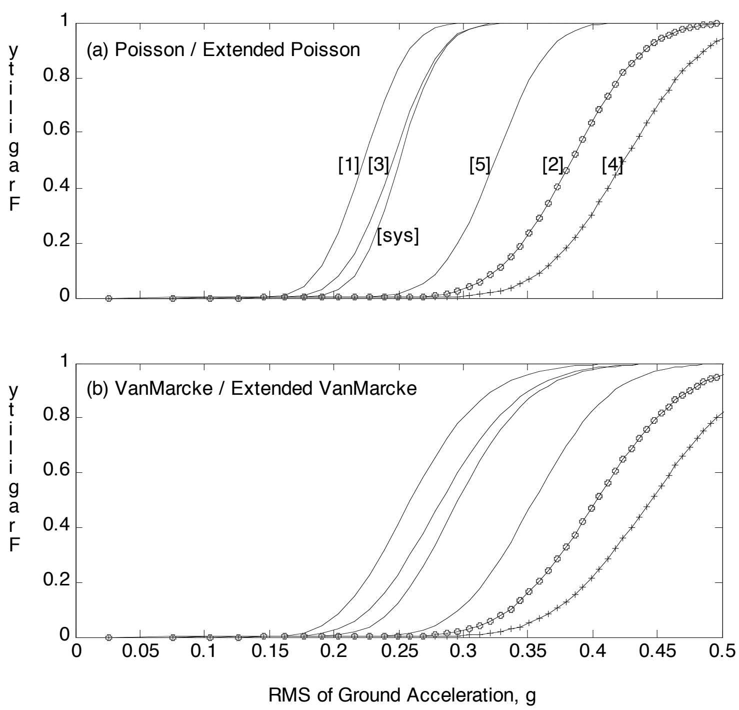

Figure 2. Equipment and system fragility estimates by (a) extended Poisson approximation; (b) extended VanMarcke approximation