Seismic Performance Analysis of Electric Power Systems

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Research Objectives

The objectives of this research are to evaluate the seismic performance of the Los Angeles Department of Water and Power's (LADWP's) electric power system, particularly its substations, and recommend appropriate rehabilitation measures. More specifically, it will provide the analytical and empirical foundation to estimate direct economic losses, as well as indirect economic losses suffered by society at large due to seismically induced degradation of the LADWP's power system. Indirect losses include commercial and industrial activities in the Los Angeles metropolitan area affected by service interruption of the electric power system. This research will use the results from the inventory survey and equipment rehabilitation study being performed concurrently primarily by the members of this research team to examine the extent of mitigation enhancement such rehabilitation work can produce. The analysis requires a somewhat elaborate systems analysis of LADWP's power system with primary emphasis on the substation performance under damaging earthquakes such as the 1971 San Fernando and 1994 Northridge earthquakes.

While emergency repair and power supply was accomplished rapidly in the aftermath of the 1994 Northridge earthquake (one day) and the 1995 Kobe earthquake (three days), the costs of full restoration of their electric power systems was extremely high. Estimated direct costs were said to be approximately $500 million and $4 billion for the Northridge and the Kobe earthquakes, respectively. Since the "big one" appears to be imminent in California, a much longer and more costly interruption of electric power may have to be anticipated, which could have overwhelming socioeconomic impacts in the affected region. This research will help find rehabilitation measures to mitigate such impacts.

Sponsors

MCEER/NSF

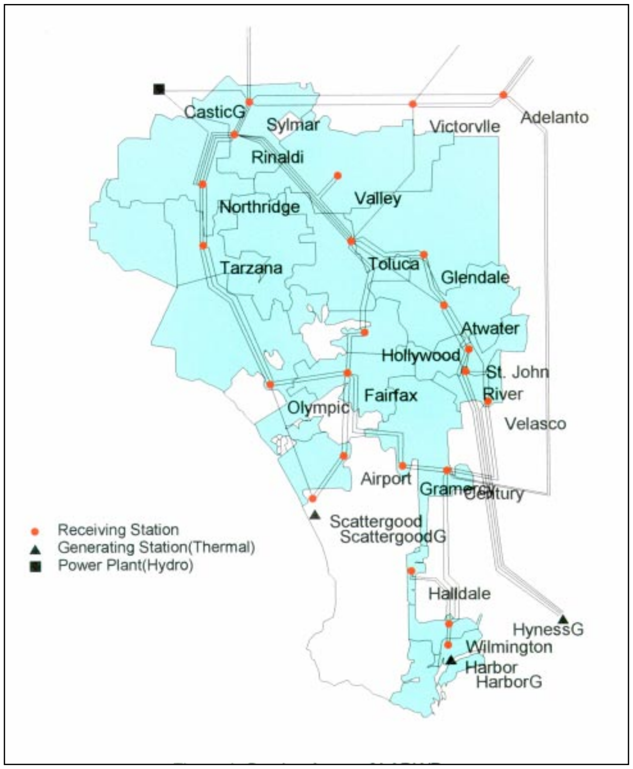
Collaborative Partners

***Min-Hsiung Chien**, formerly of the Los Angeles Department of Water and Power*
***Nobuo Murota**, Bridgestone Company, Japan*
***Donald Penn**, Los Angeles Department of Water and Power*

The MCEER research team on system performance evaluation has a unique capability of modeling lifeline systems and carrying out a seismic performance evaluation, given inventory data, system configuration and fragility information with or without rehabilitation. The evaluation requires the delicate coordination of various technologies involving interpretation and manipulation of sophisticated and voluminous inventory data, utilization of highly specialized computer codes for systems analysis, estimation of fragility enhancement resulting from the advanced rehabilitation

Links to Current Research

- *LADWP is an important partner in this effort, providing the MCEER research team with inventory and operational information of its electric power system and some statistics of the damage sustained by the system from the past earthquakes.*
- *Effort is being made to entice Southern California Edison to participate in MCEER's research as an industry partner.*
- *A Memorandum of Understanding is being prepared between MCEER and the National Center for Research on Earthquake Engineering (NCREE) in Taipei, Taiwan to perform a joint experimental study on transformers using the shaking table in Taipei.*
- *MCEER investigator **M. Feng**, University of California, Irvine, is collaborating with **N. Murota**, on leave from Bridgestone Company, in the planning and preparation of shake table testing.*



■ Figure 1. Service Areas of LADWP

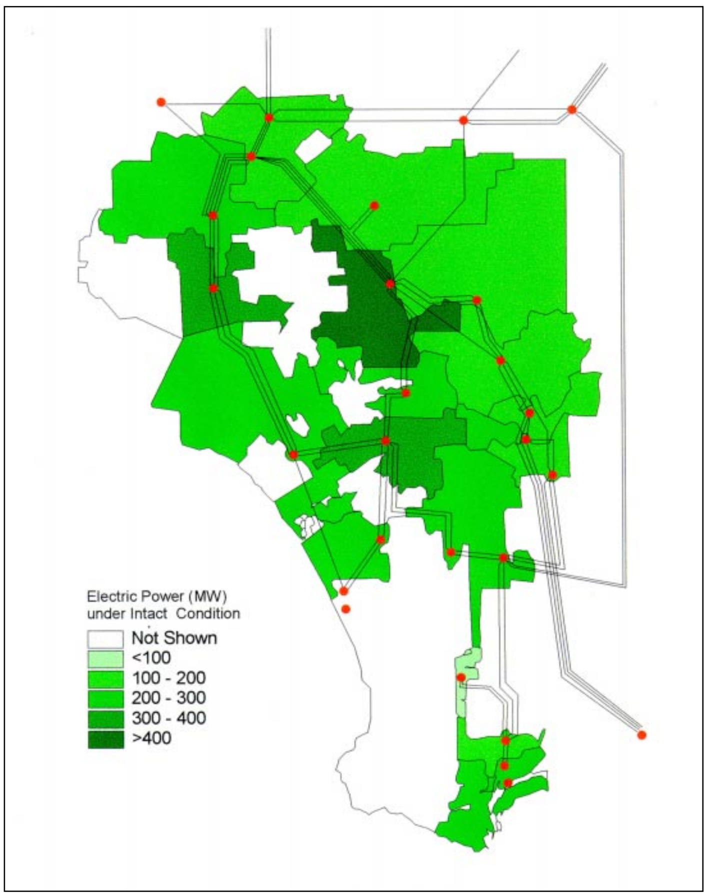
technology and integration of all the above into a GIS platform for demonstration. This capability itself represents an advanced technology and the purpose of this research effort is to make use of this technology on the Los Angeles Department of Water and Power (LADWP) electric power system.

The Los Angeles Department of Water and Power electric power service areas and the power output under usual operating conditions in each service area are shown in Figures 1 and 2. The area not colored is serviced by the Southern California Edison. Figure 3 is the Northridge PGA map developed on the basis of the contour map provided by David Wald, U.S. Geological Survey and Figure 4 demonstrates how the system deteriorates under the ground shaking shown in Figure 3 under the hypothesis that only the transformers are vulnerable to the earthquake with the fragility curves assumed in Figure 5. This is based on the observation that the transformer is one of the most critical pieces of equipment for the functionality of the power network system. The effect of other equipment such as circuit breakers, disconnect switches and buses on the system performance is currently being studied. These hypotheses are introduced to demonstrate the

Primary users of this research include both LADWP's power division and water division because of potential interactive effects, as well as utility companies throughout the U.S. and elsewhere. The research results can further be used by government agencies such as the California State Office of Emergency Services for pre-event and post-event mitigation planning and by private-sector organizations including insurance and financial companies. Another important group of users include researchers in lifeline earthquake engineering, and providers of information for loss estimation databases and methodologies such as HAZUS.

proof of concept in relation to the analytical simulation work used in this research. Figure 4 shows the system deterioration by computing the average ratio of power output relative to that associated with the system under undamaged conditions for each service area. The system analysis utilizes a Monte Carlo simulation method under the hypothetical fragility curves (Cases 1, 2, and 3) provided in Figure 5. Fragility curves (Case 1) were used by Tanaka et al. (1996) for substation equipment. The sample size is equal to 20 for each Monte Carlo simulation analysis. The increasingly improved system performance as fragility curves move to the right (Case 1 to Case 2 and to Case 3) indicates the extent to which the rehabilitation or retrofit of transformers as represented by enhanced fragility curves contributes to improved system performance. This is conceptually not an unreasonable approach for evaluation of the effect of the rehabilitation or retrofit. In fact, M. Shinozuka (1998) gave an example (Figure 6) of such fragility curve enhancement involving a typical Memphis bridge retrofitted by a base isolator in which major damage was assumed to occur when the ductility demand at all the bridge columns exceeded 2.0.

In the present research, reliable fragility curves for the transformers rehabilitated or not rehabilitated are still in the process of being developed. The FPS (Friction Pendulum System) was considered for enhancing the fragility of the LADWP's transformers. Analytical simulations were performed for a typical transformer weighing 230,000 lbs. subjected to the ground acceleration time histories observed at the Sylmar substation during the 1994 Northridge earthquake. To evaluate the effectiveness of the FPS for a wide range of earthquake intensities, time histories were linearly scaled up to achieve higher PGA values for the development of fragility information. Figure 7 shows that the degree of reduction in the inertia exerted on the transformer depends on the time histories with differing levels of PGA (0.5 g, 1.0 g, and 1.5 g). The trend observed from Figure 7 is that: (1) the FPS is more effective



■ Figure 2. Electric Power Output for Service Areas Under Intact Condition for earthquakes with larger PGA's; (2) the reduction of acceleration exerted on the transformer is more significant when FPS' radius is larger at the expense of larger displacements. Since most transformers are installed outside and have sufficient clearance with neighboring equipment and buildings, larger displacements may not represent a serious obstacle in deploying FPS devices; and (3) in general, for a reasonable size of radius (say 15 inches), the reduction ranges from 30% to 50% depending on the earthquake intensity between 0.5 g to 1.5 g in terms of PGA. This result was generally consistent with hypothetical fragility curve enhancement introduced in Figure 5.

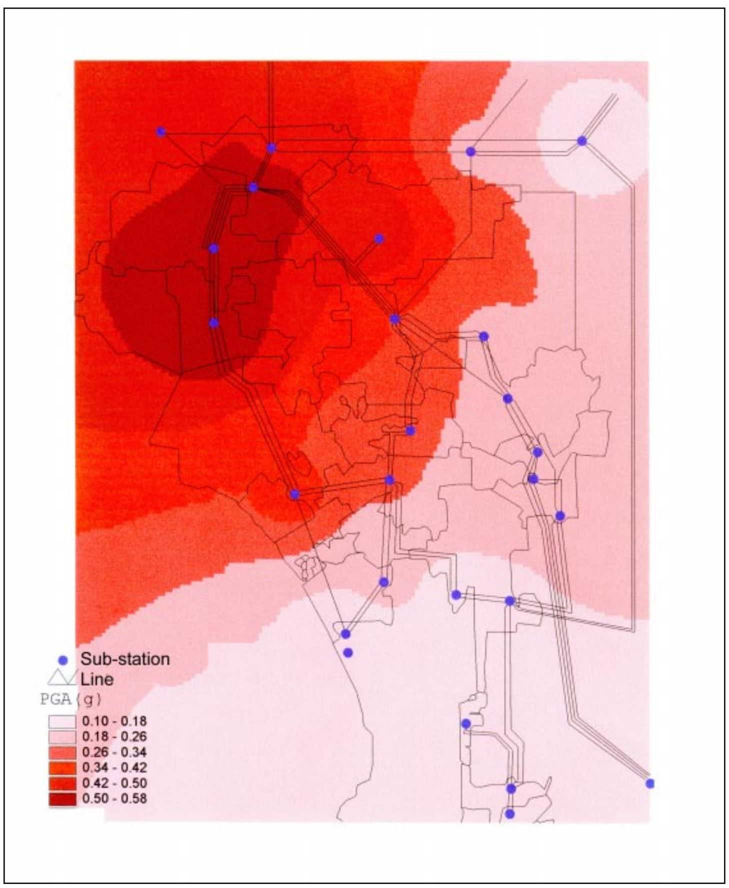
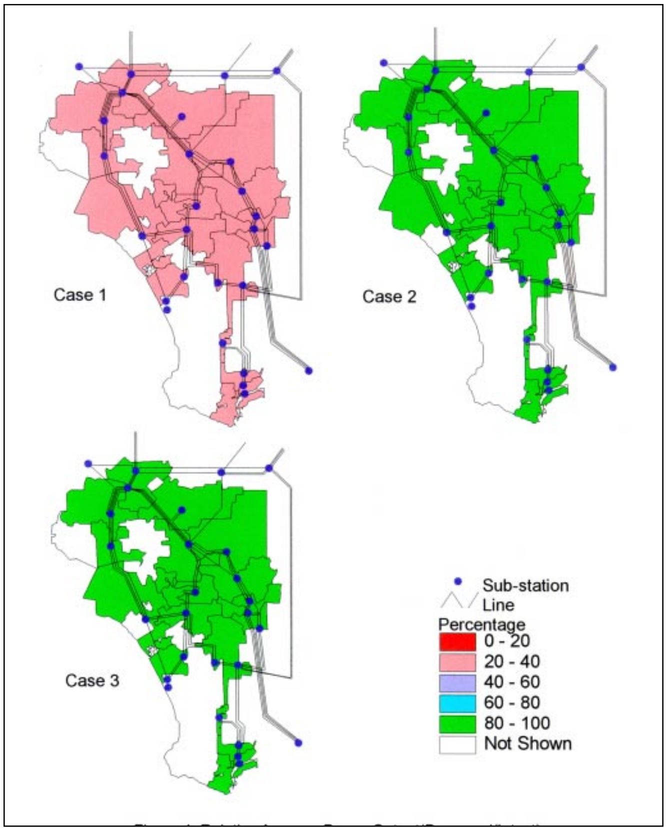


Figure 3. PGA Under Northridge Earthquake

LADWP's Power System

There are two electric power networks serving the Los Angeles region operated by different organizations, Los Angeles Department of Water and Power, and Southern California Edison. Basically, these networks are managed independently. However, for coping with the fluctuating power demand, they cooperate with each other at several substations and operate the system from a regional point of view. In addition, since the networks are a part of the very large Western Systems Coordinating Council's (WSCC) power transmission network covering 14 western states, two Canadian provinces and northern Baja California, the analysis was performed by taking all the substations and transmission facilities covered by the WSCC network into account. Indeed, the fact that a black-out condition was observed over several states after the Northridge earthquake demonstrates the far-reaching impact of a local system failure throughout the network.

In analyzing the functional reliability of each substation, the following modes of failure were taken into consideration: (1) loss of connectivity, (2) failure of the substation's critical components, and (3) power system imbalance. It was noted that most of the transmission lines of the LADWP's power system are aerial supported by transmission towers. While by no means this implies that the transmission lines are completely free from seismic vulnerability, it was assumed in this study that

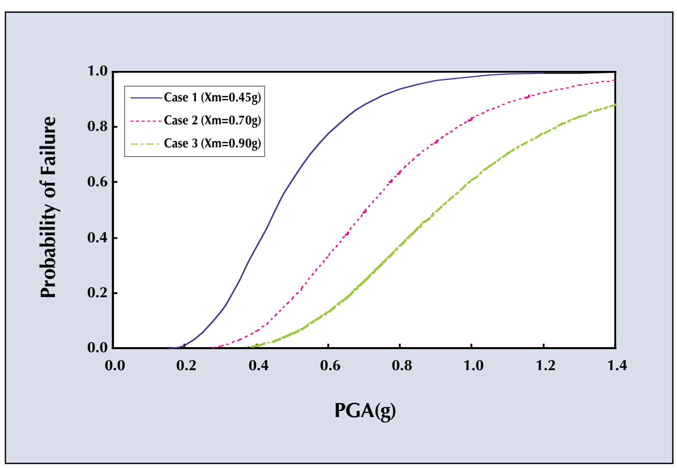


■ Figure 4. Relative Average Power Output (Damaged/Intact) with Transformers Vulnerable

they were, primarily for the purpose of analytical simplicity. Figure 8 shows an abbreviated system flowchart for LADWP's power system with all the substations identified together with the nodes, generators and transformers. Thick horizontal bars represent the nodes (buses with all other associated equipment) in substations as described by a model shown in Figure 9. In the systems analysis pursued here, however, substation data were taken from the WSCC's database and used for the systems analysis in conjunction with the computer code IPFLOW, (version 5.0), licensed by the Electric Power Research Institute (EPRI) to the University of Southern California.

Monte Carlo Simulation

Using the ARC/INFO GIS capability, the electric transmission network map was overlaid with the PGA map (Figure 3) to identify the PGA value associated with each substation under the Northridge earthquake. The fragility curves assumed in Figure 5 were then used to simulate the state of damage involving the transformers at all the substations of the LADWP's power system. For each systems analysis, the connectivity and power flow were examined with the aid of IPFLOW, where LADWP's power system was treated as a part of WSCC's overall system.



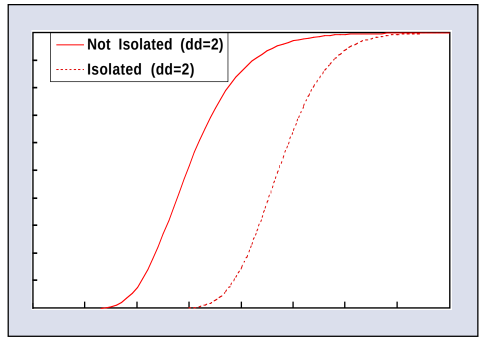
■ Figure 5. Fragility Curves

Related MCEER Research Activities

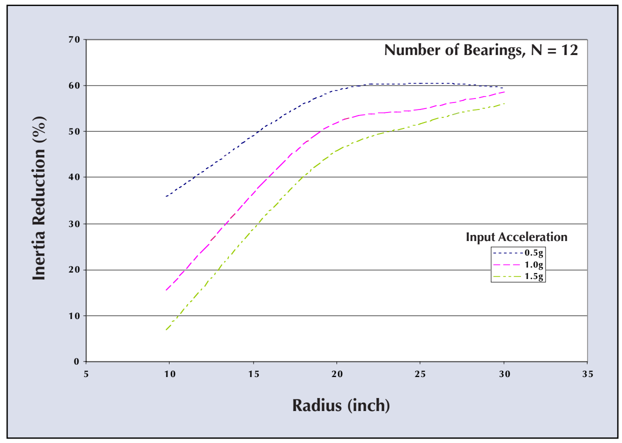
- *Seismic Reliability Analysis for Southern California Power Systems, **T.C. Cheng**, University of Southern California*
- *Rehabilitation Strategies for Lifelines: LADWP Water Systems, **T.D. O'Rourke**, Cornell University*
- *Seismic Retrofit Methods for LADWP Power Systems, **S.T. Mau**, New Jersey Institute of Technology and **M. Feng**, University of California, Irvine*
- *Socioeconomic Impacts of Lifeline Systems, **S. Chang**, University of Washington*

> **"The research results can be used by government agencies such as the California State Office of Emergency Services for pre- and post-event mitigation planning and by private-sector organizations including insurance and financial companies."**

Loss of connectivity occurs when the node of interest survives the corresponding PGA, but is isolated from all the generators due to the malfunction of at least one of the nodes on each and every possible path between this node and any of the generators. Hence, the loss of connectivity can be confirmed on each damage state by actually verifying the loss of connectivity with respect to all the paths that would otherwise establish the desired connectivity.



■ Figure 6. Fragility Curves for Bridges with and without Base Isolation



■ Figure 7. Acceleration Reduction by FPS Bearings

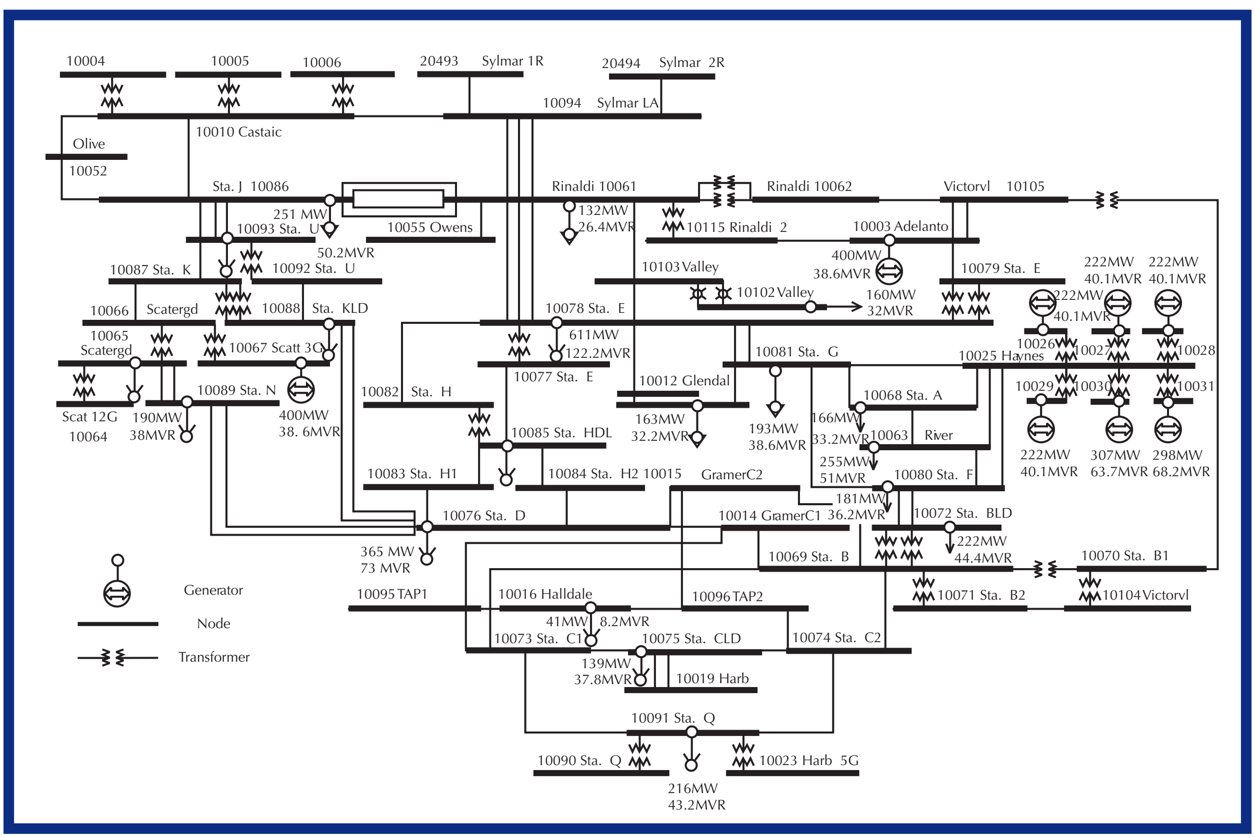
As for abnormal power flow, it was noted that the electric power transmission system was highly sensitive to the power balance and ordinarily some criteria are used to judge whether or not the node continues to function immediately after internal and external disturbances. Two kinds of criteria are employed at each node for the abnormal power flow: power imbalance and abnormal voltage. When the network is damaged due to an earthquake, the total generating power becomes greater or less than the total power demand. Under normal conditions, the balance between power generation and demand is within a certain range of tolerance. Actually, the total power generation must be between 1.0 and 1.05 times the total demand for normal operation even accounting for power transmission loss.

In this study, it was assumed that if this condition was not satisfied, the operator of the electric system must either reduce or increase the power generation to keep the balance of power. However, in some cases, the supply cannot catch up with the demand because the generating system is unable to respond quickly enough. In this case, it was assumed that the power generation of each power plant cannot be increased or reduced by more than 20% of the current generating power. When the power balance cannot be maintained even after increasing or reducing the generating power by 20%, the system was assumed to be down due to a power imbalance. In this respect, the effect of the emergency management systems used for power flow management will be incorporated in the systems analysis in the future study.

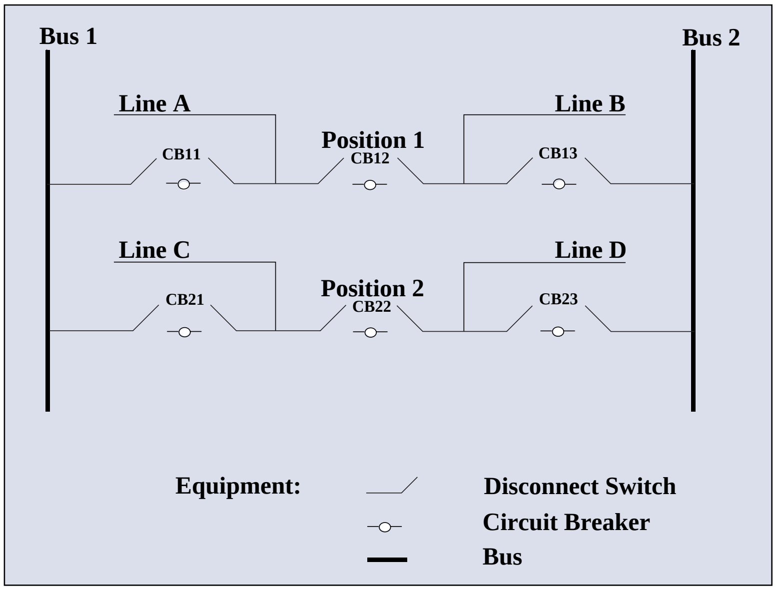
As to the abnormal voltage, voltage magnitude at each node can be obtained by power flow analysis. Then, if the ratio of the voltage of the damaged system to the intact system is out of a tolerable range (plus/minus 20% of the voltage in the intact system), it was assumed that a blackout will occur in the area served by the substation.

For the Monte Carlo simulation of system performance under the Northridge earthquake, each substation was examined with respect to its possible malfunction under these three modes of failure for each simulated damage state. Thus, each simulation identifies the substations that will become inoperational.

The simulation was repeated 20 times on the network. Each simulation provided a different damaged network condition. Figure 4 shows the ratio of the average output power of the damaged network to that associated with the intact network for each service area. The average was taken over the entire sample size equal to 20. It was concluded from Figure 4 that the rehabilitation that lead to the fragility curve labeled as Case 2 was good enough to protect the transformers, and hence the entire power system, very well under the assumption that structures and other equipment were not vulnerable to earthquake ground motion.



■ Figure 8. LADWP's System Flowchart



■ Figure 9. Typical Node Configuration Model

On-going Research Activities

Figure 4 is based on the hypothesis that transformers are the only vulnerable equipment under the earthquake and that their fragility curves are given by the three curves in Figure 5. Other equipment such as circuit breakers, buses, and disconnect switches are currently being incorporated into the systems analysis.

In order to examine the adequacy of the fragility assumptions for transformers and other equipment, a walk-down at LADWP's Sylmar substation is scheduled on June 11, 1999 by S.T. Mau (and/or Professor M.A. Saadeghvaziri) of the New Jersey Institute of Technology, M. Shinozuka (and/or Mr. X. Dong and Professor F. Nagashima) and T.C. Cheng (and/or Mr. X. Jin) of the University of Southern California, and Professor M. Feng (and/or Mr. N. Murota) of the University of California, Irvine.

In cooperation with Professor C.H. Loh, Director of the National Center for Research on Earthquake Engineering (NCREE) in Taipei, Taiwan, the MCEER team with Bridgestone Company as an industrial partner, is participating in an experiment to verify the effectiveness of FPS and hybrid friction and elastometric base-isolators designed, manufactured and tested by Bridgestone. The experiment will be performed in July 1999 on a transformer model installed with a typical porcelain bushing. For the experiment, NCREE's 5 m x 5 m triaxial shaking table will be used.

Future Research

Now that all the analytical tools are in place, in the year immediately following and beyond, the research will continue to proceed on three fronts. The first is to refine the systems analysis methodology by incorporating all significant substation equipment and validating the results of the analysis with data from power interruption experiences caused by the Northridge and Kobe earthquakes. Upon validation, other scenario earthquakes will be considered for the systems analysis to examine the seismic performance of LADWP's power system under a wide variety of earthquake magnitudes, epicentral locations and seismic source mechanisms. Interaction between LADWP's power and water systems will also be considered. This requires, however, additional effort for inventory and other database development.

The second is to further study seismic vulnerability of the equipment and develop their fragility curves. In this regard, the results from the research carried out by the MCEER investigators on fragility information will be used as they become available. Rehabilitation measures can then be expressed as fragility curve enhancements, which can in turn be directly reflected on the systems analysis with the aid of Monte Carlo techniques. In this connection, rehabilitation measures other than those by base isolation will be explored. Possibilities include use of advanced semi-active dampers. The shaking table tests for transformers will be completed and the continued MCEER-NCREE collaboration will lead to additional tests involving other equipment to determine their fragility characteristics and enhancement measures.

The third area of future endeavor involves direct and indirect economic loss estimation arising from physical damage to the system facilities and resulting possible system interruption. This endeavor expands the MCEER team's capability in this area demonstrated by the study of the seismic vulnerability of the Memphis area's electricity lifelines (see Shinozuka et al., 1998). To assist the MCEER investigators in loss estimation, the Monte Carlo simulation will be performed in such a way that direct and indirect loss estimation will be pursued by recording a specific inventory of equipment damage observed for each realization of system damage. As detailed in Shinozuka and Eguchi (1997), this allows statistics on direct and indirect losses based on individual states of damage associated with corresponding simulation to be obtained, rather than based on the average of the power output taken over the entire sample of simulation.

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