



UTILITY POWER NETWORK SYSTEMS

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SUMMARY

This paper addresses the issues of security, system behavior, and socio-economic efficiency of utility power networks based on a multitude of research interests. In this paper, a general GIS based methodology is developed to analyze the behavior of large electric utility systems under a catastrophic event, such as a severe earthquake, a technological accident or a terrorist attack. The extent of performance degradation under simulated disaster scenarios is evaluated in order to gain quantitative insight and to develop a software package that can be used to evaluate performance immediately after an actual disaster. Repair and restoration process is also modeled. The power network of the LADWP (Los Angeles Department of Water and Power) and SCE (Southern California Edison) have been used as benchmark test systems for modeling and analysis of system behavior. The system risk evaluation includes a socio-economic analysis relative to the communities served by the test-bed power systems.

INTRODUCTION

Electric power is essential for virtually every urban and economic function. Failures of electric power networks and grids – whether from natural disaster, technological accident, or man-made disaster such as terrorist attack – can cause severe and widespread societal and economic disruption. In the 1994 Northridge earthquake that struck Los Angeles, some 2.5 million customers lost electric power. For the first time in its history, the entire city of Los Angeles was blacked out. Power outages were experienced in many areas of the western U.S. outside the earthquake region and as far away as Canada (Hall[1]). On August 14, 2003, blackout of unprecedented proportions rippled out from Akron, Ohio, across the northeastern U.S. and parts of Canada, affecting an area with a population of some 50 million (U.S.-Canada Power System Outage Task Force [2]). In September of 2003, a power outage that began in Switzerland cascaded over a large region of Italy. Examples such as these indicate the importance of being able to anticipate potential power system failures and identify effective mitigation strategies.

Modeling the impacts of electric power disruption is, however, a highly complex problem. Many of the inherent challenges relate to the need to integrate across disciplines – not only civil, mechanical, and

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electrical engineering, but also economics and other social science disciplines. For example, one must assess how damage to individual pieces of electric power equipment affects power flow across the network. One must model how a damaged network would be repaired and how electric power would be restored over space and time. Additionally, one must capture how the loss of electric power would affect households, businesses, and other units of society.

While numerous studies have addressed portions of the problem, very few have attempted to model regional impacts. For example, Nojima and Sugito [3] modeled power restoration times based on empirical data from Japanese earthquakes using geographical information systems (GIS); however, they did not evaluate power outage and impacts in an actual urban area. The current study builds on a long-standing research program led by the second author of the paper and carried out by a group of researchers. Their results (e.g., Shinozuka et al[4, 5]; Tanaka et al[6]) laid the foundation for the development of a method by which utility transmission network performance can be rationally analyzed, taking into account power flow in a seismically damaged network. Related research developed methods for assessing how power system failures would impact regional economies (Rose et al[7]).

The objective of this study is to evaluate the seismic performance of electric power system, recommend appropriate seismic rehabilitation measures and estimate associated socio-economic impacts. The Los Angeles Department of Water & Power's (LADWP's) power system was taken as a test-bed in this research. Figures 1 and 2 show LADWP's electric power service areas and the power supply under normal operating conditions. The areas not colored are serviced by Southern California Edison (SCE). To develop the analysis methodology and gain insight into the performance of the power system, fragility curves for electrical power equipment, such as transformers in the transmission network, were developed on the basis of damage information from the 1994 Northridge earthquake. This paper also uses results from an inventory survey and equipment rehabilitation study being performed concurrently by members of the research team, supported by the Multidisciplinary Center for Earthquake Engineering Research (MCEER). With the aid of systems analysis procedures, a performance analysis of LADWP's power system was conducted for actual and simulated earthquakes, using a network inventory database, available fragility information, and Monte Carlo simulation techniques. This is a unique research work in which the Western System Coordinating Council's (WSCC) database are used for the systems analysis, in conjunction with the computer code IPFLOW (version 5.0), licensed by the Electric Power Research Institute (EPRI).

In addition to transformers, the seismic vulnerability of other equipment and components such as circuit breakers disconnect switches and buses, and their impact on system performance are integrated into the analysis by representing their vulnerability in terms of respective fragility curves.

To gain a more complete understanding of the performance of LADWP's power system under the possible seismic action in the study area, 47 scenario earthquake events were selected and simulated. By including each scenario's associated annual "equivalent probabilities" of occurrence, they represent the full range of the regional seismic hazard curve[8]. Based on the power analysis results from these 47 events, the risk curves for system performance degradation, for example, related to reduction of power supply, households without power and reduction in GRP (Gross Regional Product) immediately after an earthquake in LADWP's service areas were developed.

A repair and restoration model was developed to predict and evaluate the restoration process of the power systems. The system restoration process was simulated and restoration curves were developed from the results of the power analysis. Finally, this study demonstrates that a relatively simple disablement of key transmission components can lead to a disastrous consequence. A case in point is the disastrous August

14, 2003 power blackout throughout the Western Grid due to an accident that disabled a segment of high voltage transmission line.

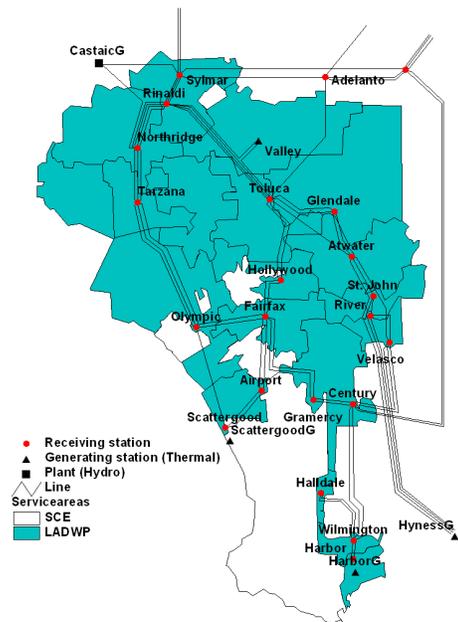


Figure 1. Transmission Network and Service Areas of LADWP's Power System

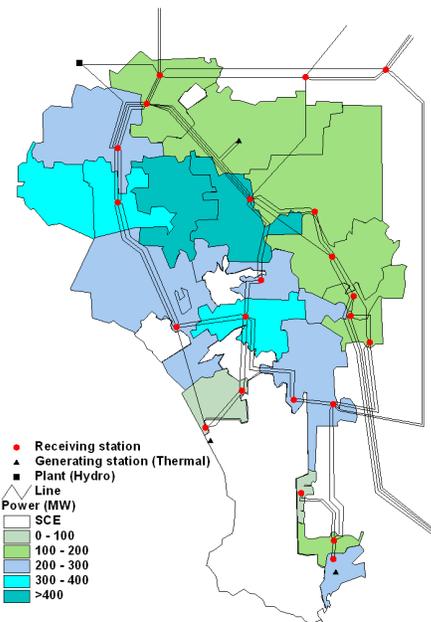


Figure 2. Electric Power Output for LADWP's Service Areas Under Intact Condition

SEISMIC PERFORMANCE OF LADWP'S POWER SYSTEM

LADWP's network is part of the very large WSCC power transmission network, covering 14 western states in the USA, two Canadian provinces in Canada and northern Baja California in Mexico. The present analysis considers 52 receiving stations within the WSCC network that are subjected to significant ground motion intensity under the 47 scenario earthquakes. Recently, the WSCC network has been expanded to include more facilities and is now renamed as the Western Electricity Coordinating Council (WECC)[9]. Using ArcGIS platform, the map of 52 receiving stations in Figure 3 is overlaid on the map of peak ground acceleration (PGA) from the 1994 Northridge earthquake as shown in Figure 4(a) to identify the PGA value at the location of each receiving station. The fragility curves provided in Figure 5 were then used to simulate the damage state for transformers at each of the 52 receiving stations (some in LADWP and others in SCE power systems). Note that 3 fragility curves (labeled Case 1, 2 and 3) are given in Figure 5 where Case 1 curve is obtained empirically from the Northridge earthquake damage data, Case 2 curve represents improvement on Case 1 curve by 50% (in terms of median value) and Case 3 curve by 100%. These improvements are deemed possible on the basis of analytical and experimental studying by Feng and Saadeghvaziri [10]. For each system analysis, connectivity and power flow were examined with the aid of IPFLOW, where LADWP's power system was treated as part of the overall WECC system.

The methodology used to evaluate the seismic performance of the electric power network is described in the following steps:

- (1) Use 47 scenario earthquakes [8](13 Maximum Credible Earthquakes and 34 User Defined Earthquakes)
- (2) For each scenario earthquake, simulate equipment damage using fragility curves representing conditions with and without rehabilitation

- (3) Simulate damage to the transmission network
- (4) Calculate power flow using IPFLOW under network operational criteria

$$1 \quad \text{Balance of Power:} \quad 1.05 < \frac{\text{total supply}}{\text{total demand}} < 1.1 \quad (1)$$

$$2 \quad \text{Normal voltage} \quad \left| \frac{V_{\text{int act}} - V_{\text{damage}}}{V_{\text{int act}}} \right| < 0.1 \quad (2)$$

- 3 Frequency change (IPFLOW does not check this criteria)
- 4 Loss of connectivity

(5) Compute the seismic performance of the power network in terms of percentage of power supply and number of households in the entire area of service as well as each service area under each scenario earthquake

- (6) Evaluate reduction in the seismic performance
- (7) Develop seismic risk curve (which plots the annual probability that system performance will be reduced more than a specified level due to earthquake as a function of each level)
- (8) Examine system performance relative to performance criteria, with and without rehabilitation.
- (9) Determine the effectiveness of rehabilitation

Utilizing Monte Carlo simulation techniques involving the fragility curves in Fig. 5, the power flow analysis is performed on LADWP's network 20 times under each scenario earthquake. Each simulation result represents a unique state of network damage. Figure 4(b) shows the ratio of the average power supply of the damaged network to that associated with the intact network for each service area, when only transformers are considered to be vulnerable. The average is taken over all simulations. The extent to which the rehabilitation of transformers contributes to improvement of system performance is evident if we compare the power supply ratio under Case 1 (not enhanced), Case 2 (50% enhanced) and Case 3 (100% enhanced), as shown in Figure 5.

In addition to transformers, there are other important types of electrical equipment in the power network that are vulnerable to earthquake ground motion. They include circuit breakers and disconnect switches. Figures 6 and 7 present the results of the seismic performance analysis when other components are also assumed to be vulnerable, using with the same fragility characteristics as transformers. The results show that if we consider transformers and circuit breakers (Fig. 6) or transformers and disconnect switches (Fig. 7) to be seismically vulnerable, the power output is reduced significantly throughout LADWP's service areas under the Northridge earthquake. This result matches the actual outcome in the 1994 Northridge earthquake. It should be noted that the after the Northridge earthquake, power outages were brief because of effective crisis management on the part of LADWP. The fact that a black-out condition was observed not only for LADWP service areas and also over several states demonstrates the far-reaching impact of a local system failure throughout the network.

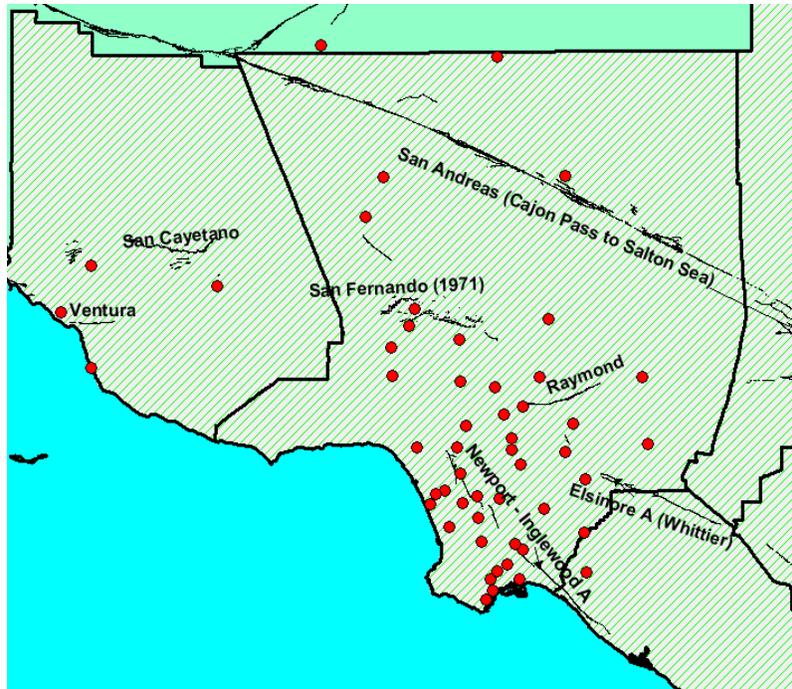


Figure 3 Locations of Earthquake Faults and 52 Receiving Stations

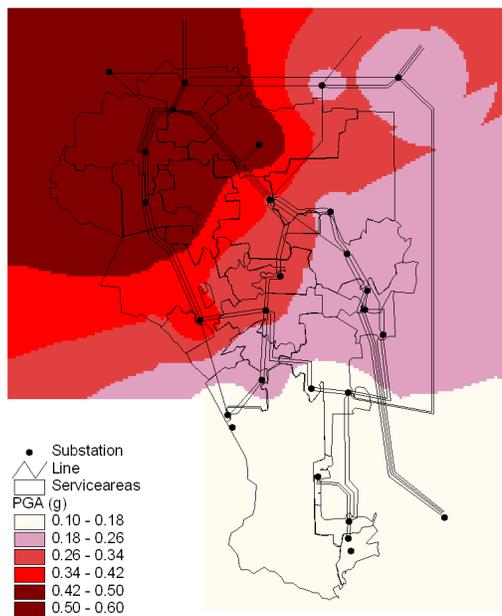


Figure 4 (a). Spatial PGA Distribution in the 1994 Northridge Earthquake

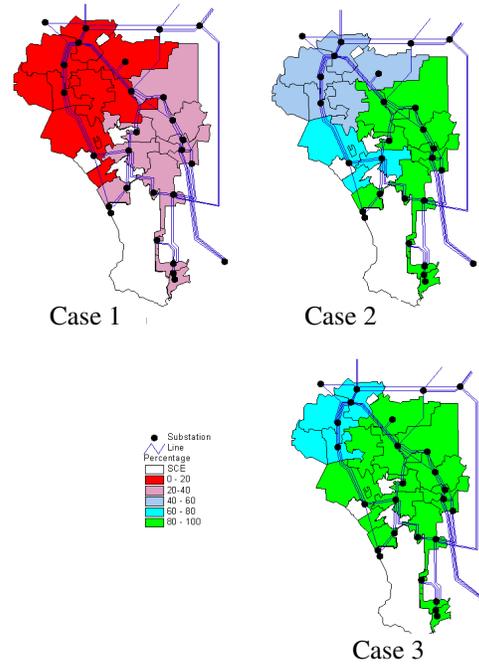


Figure 4(b). Relative Average Power Output with only Transformers Assumed to be Vulnerable (Sample size=20)

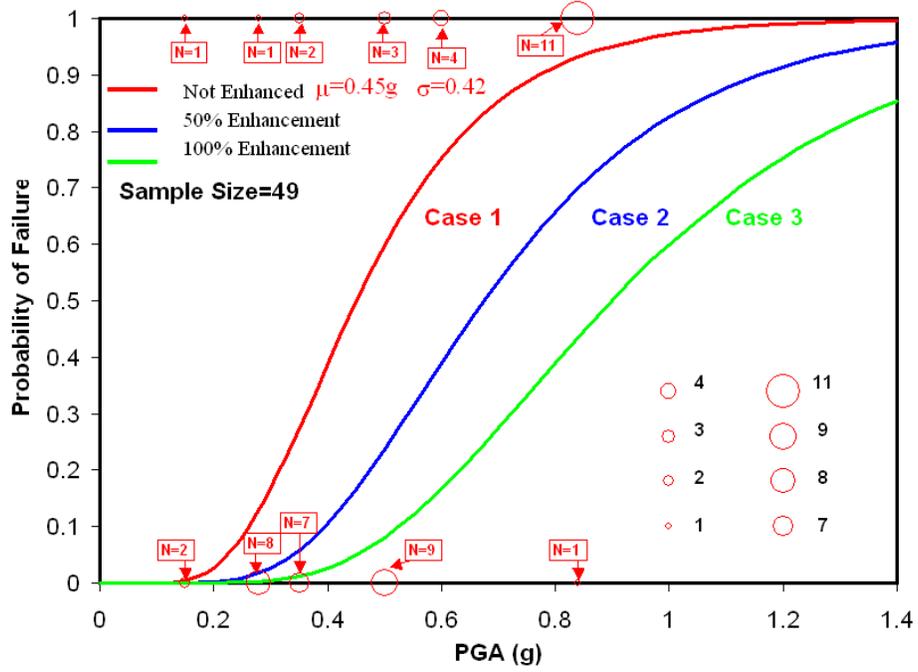


Figure 5. Fragility Curves for Transformers With and Without Enhancement

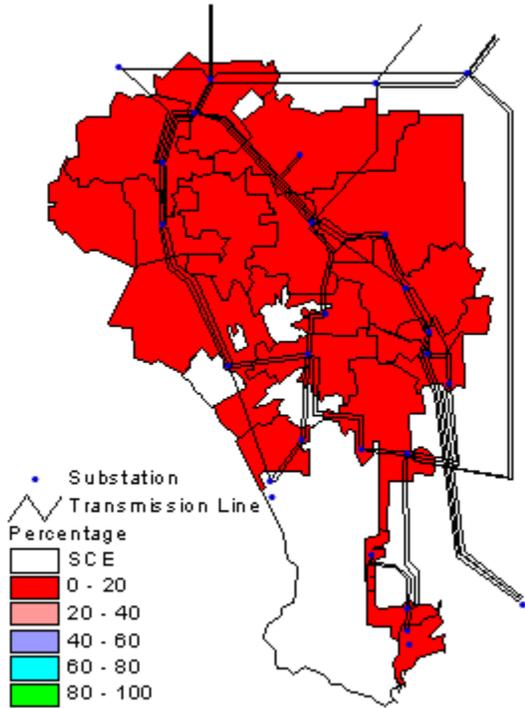


Figure 6. Relative Average Power Output with Transformers and Circuit Breakers Vulnerable

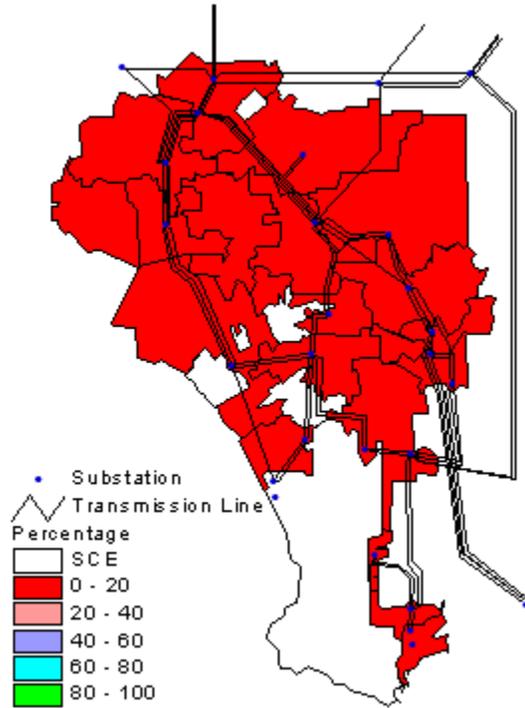


Figure 7. Relative Average Power Output with Transformers and Disconnect Switches Vulnerable

RISK EVALUATION OF POWER SYSTEMS

Scenario Earthquakes

For electric power and other urban infrastructure systems, evaluating potential impacts of damage is complicated by the fact that the networks are spatially distributed across a wide area. Risk analysis must account for how the system performs given that the hazard (e.g., earthquake ground motion) is not only spatially variant across a wide area but also, for any given disaster, spatially correlated. Hence, traditional probabilistic methods that can readily be applied for site-specific facilities such as individual buildings cannot be used for these spatially distributed networks.

The current study therefore analyzes system functionality and impacts in the context of scenarios of individual earthquake events, then combines the scenario results probabilistically to gain a complete understanding of the seismic performance of LADWP's power system. In total, 47 scenario earthquakes for the Los Angeles region are selected and simulated, as discussed later in detail. These scenarios were developed by Chang *et al.* (2000) [8], applying a loss estimation software tool, EPEDAT[11], based on K. Campbell's attenuation law (Campbell, 1994)[12], which was used to generate regional ground motion patterns for given earthquake epicenter, magnitude, and depth (USC-EPEDAT, 1999).[11] The 47 events include 13 maximum credible earthquakes (MCEs) on various faults in the Los Angeles region and 34 other events of magnitude 6.0 or higher. These scenario earthquakes are associated with annual "equivalent probabilities" of occurrence so that collectively, they represent the full range of the regional seismic hazard (Chang *et al.*, 2000)[8].

Analysis using these probabilistic earthquake scenarios allows the estimation of "risk curves" that graphically summarize system risk in terms of the likelihood of experiencing different levels of performance degradation in disasters. Risk curves can be developed for performance parameters associated with different dimensions of resilience, including the technical (e.g., power supply in each service area), societal (e.g., rate of households without power supply), organizational (e.g., repair and restoration efficiency), and economic (e.g., regional output or employment loss). Examples of risk curves are provided later in this chapter.

Risk Curves for LADWP's Power System

The locations of LADWP and SCE receiving stations relative to faults in and around the Los Angeles area indicate that many are near active faults (Figure 3) and have a high likelihood of suffering damage due to an earthquake. To evaluate the risk and costs associated with potential future earthquakes, the performance of the power system in 47 (deterministic) earthquake scenarios was evaluated, as noted earlier. Based on these scenarios, together with their hazard-consistent probabilities, the seismic risk to LADWP's power system performance due to earthquake-induced performance degradation is evaluated in terms of "risk curves." Figures 8-10 shows the risk curves in terms of the severity of power loss for Case 1 (no fragility enhancement) and for Cases 2 and 3 (enhancement index 50% and 100% respectively) for reduction in power supply, number of households without power and reduction in GRP. One can develop similar risk curves for each service area. The significant improvement due to seismic retrofit is clearly seen in Figures 8-10.

Reduction in power supply, households without power and reduction in GRP immediately after an earthquake are risk measures of technical, societal and economic concern, and the associated risk curves are plotted in Figures 8-10. These risk curves indicate the percentages of reduction in power supply, households without power and reduction in GRP immediately after earthquake, and are computed utilizing the results of power flow analysis and census data on the spatial distribution of households across

LADWP's service areas. As for the details of evaluation in GRP, readers are referred to Shinozuka and Chang [13].

Percentage of power supply P_w

$$P_w = \frac{\sum_{m=1}^M \frac{1}{N} \sum_{n=1}^N Pd(m, n)}{\sum_{m=1}^M P(m)} \quad (3)$$

Percentage of reduction in power supply P_{wo}

$$P_{wo} = 1 - P_w \quad (4)$$

Percentage of households with power H_w

$$H_w = \frac{\sum_{m=1}^M \frac{1}{N} \sum_{n=1}^N Rd(m, n) \times Hshld(m)}{\sum_{m=1}^M Hshld(m)} \times 100 \quad (5)$$

Percentage of households without power H_{wo}

$$H_{wo} = 1 - H_w \quad (6)$$

where:

m = service area number (1,2,...,M); M=21 in this example

n = simulation number (1,2,...,N); N=20 in this example

$Pd(m,n)$ = power output in service area m under n -th simulation

$P(m)$ = power output in service area m under normal condition simulation

$Rd(m,n)$ = power output ratio in service area m under n -th simulation

$Hshld(m)$ = total number of households in service area m

The risk curves in this study plot the expected annual probability that loss of system power supply in Figure 8, the percentage of households without power in Figure 9 the reduction of GRP in Figure 10 after an earthquake. Each point in the figures represent one of the scenario events with their occurrence probabilities cumulatively added backward beginning from the scenario earthquake producing the largest percentage so that the risk curve represents a complimentary (or 1 minus) cumulative distribution function of the performance variable (such as percentage of power supply reduction). The risk curve approach is also useful for economic impact analysis, as well as cost-benefit analysis to determine the effectiveness of enhancement technologies (see the curves with solid triangles and squares) (Dong [14]). Of equal importance is the use of the risk curve in relation to the development of performance criteria and their verification.

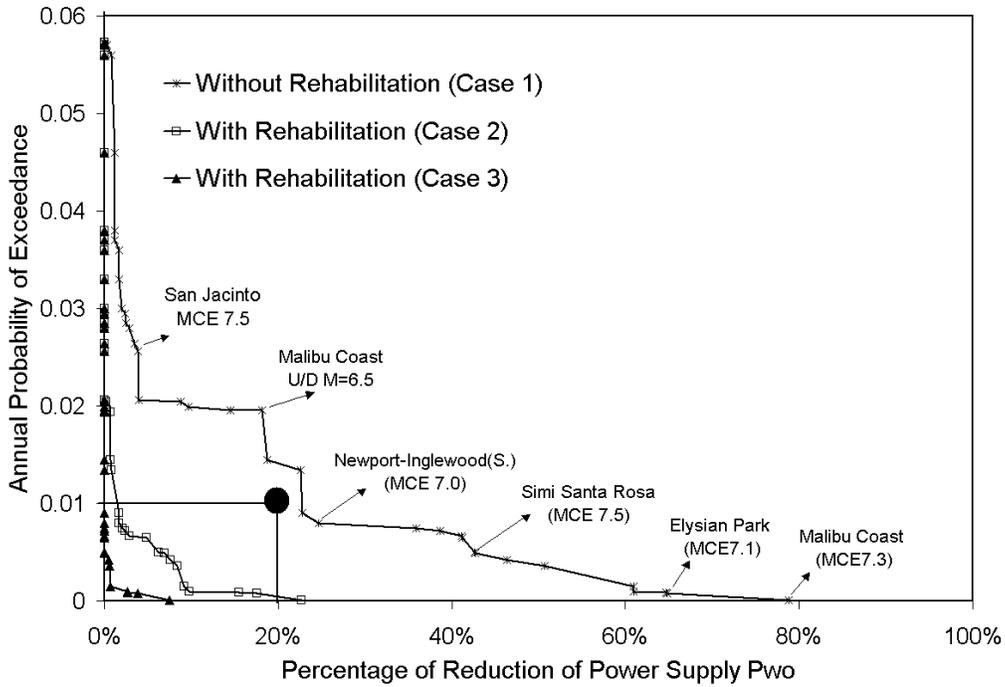


Figure 8 Risk Curves for Power Supply Reduction

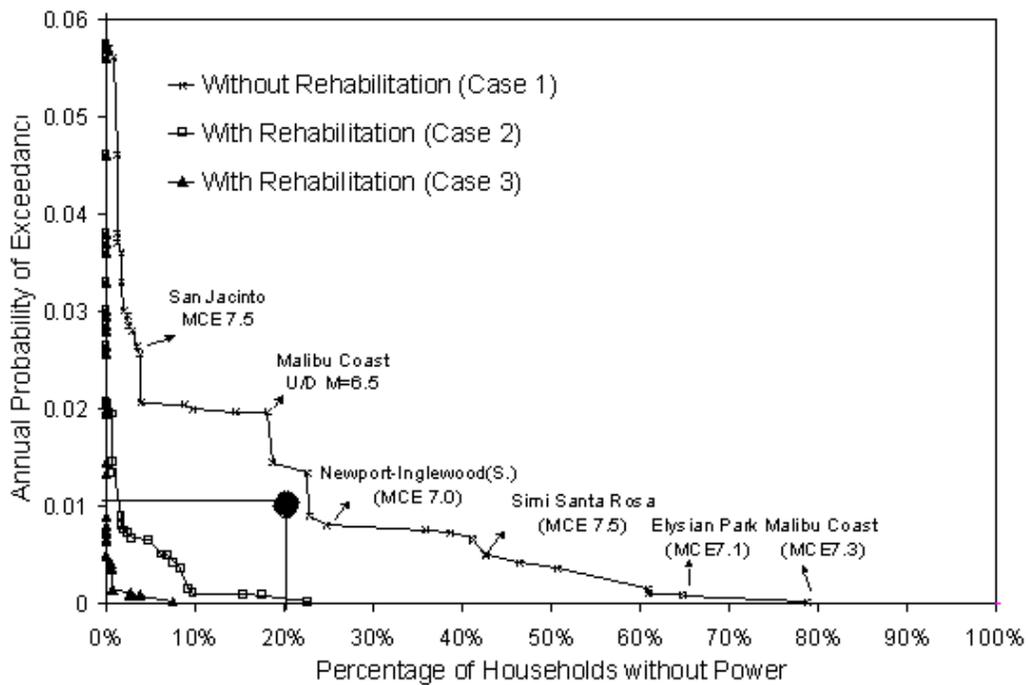


Figure 9 Risk Curves for Household Power Outage

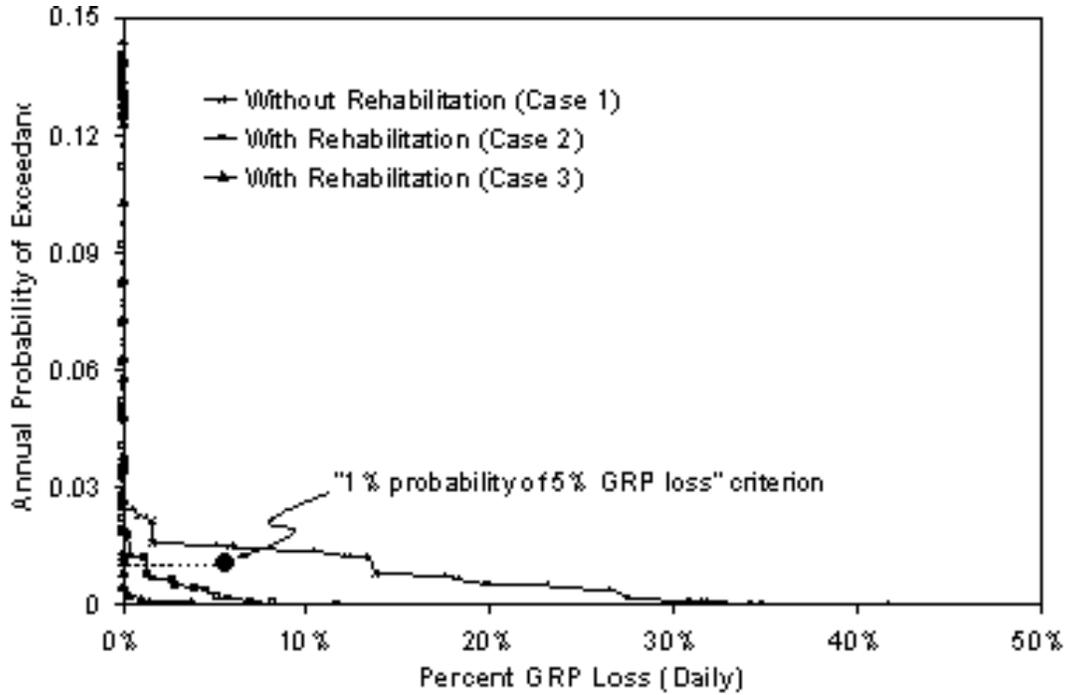


Figure 10 Risk Curve for Economic Loss

The solid circles in the figures 8-10 indicate example performance criteria for the electric power system in technical, societal and economic terms. In these cases, the criteria specify that percentage of reduction of power supply, of households without power and of GRP loss immediately after earthquake should not exceed respectively 20 percent, 20 percent and 5 percent all with 1 percent annual probability. In these instances, the unmitigated system (Case 1) will not meet the stated performance criteria. However, rehabilitated systems (both Cases 2 and 3) will satisfy the performance criteria.

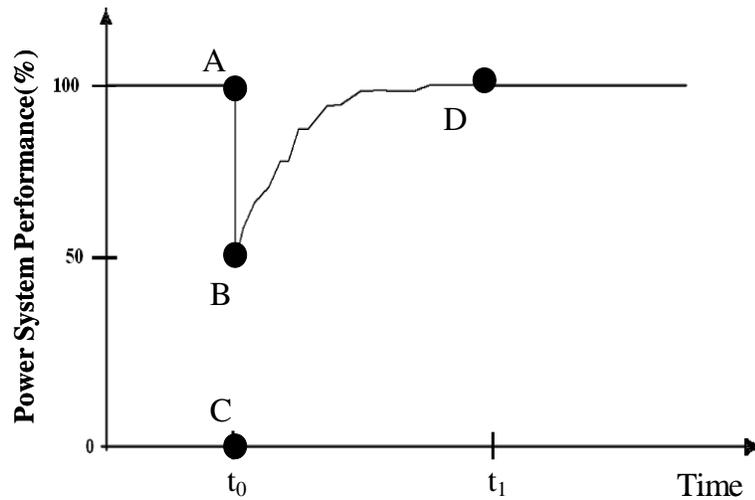
RESILIENCE FRAMEWORK AND SYSTEM RESTORATION

Resilience is an important concept for the disaster management of infrastructure systems. Two key dimensions of resilience can be referred to as robustness and rapidity in restoration. These can be expressed utilizing a restoration curve typically having characteristics as shown in Figure 11.

The curve plots system performance as a function of time. The reduction in performance from 100% at point A (time t_0) to 50% (in this example) at point B results from the damaging seismic impact to the system. The restoration curve starting from the initial distress point B, to the complete recovery point D (back to 100% at time t_1), demonstrates the process of restoration. Hence, the performance percentage corresponding to B (or B-C, with C associated with zero performance) represents robustness (Equation 7), and the elapsed time for the total restoration ($t_1 - t_0$) can be used to quantify rapidity (Equation 8), although Equation 8 may admittedly be too simplistic.

$$\text{Robustness} = B - C \quad (\text{in percentage}) \quad (7)$$

$$\text{Rapidity} = \frac{A - B}{t_1 - t_0} \quad (\text{recovery in percentage /time}) \quad (8)$$



t_0 = Time at which an earthquake occurs
 t_1 = Time at which power supply is restored 100%

Figure 11. Power Supply as A Function of Time

It has been demonstrated that the restoration for power systems tends to be rapid compared with that for water, gas and transportation systems. Figure 12 shows the assumed repair or replacement curves for the LADWP system after the Northridge earthquake. The curve plots the probability of damaged equipment being restored (repaired or replaced) as a function of time (in days). It is postulated that circuit breakers and disconnect switches are more rapidly restored with uniformly distributed probability density over the first one day period, and transformers and buses over the first two days. This not only reflects the relative ease with which each component is repaired /replaced but also the cost of its replacement. The resulting curve indicates for example that a damaged transformer can be replaced or repaired within a half day with a probability of 25%. This is merely an assumption on which we initiate and gain numerical insight for the restoration simulation. In reality, a transformer probably cannot be replaced or repaired with such rapidity unless the degree of damage is moderate. We follow the fragility simulation and power flow analysis as outlined in earlier sections and add an extra layer of Monte Carlo simulation where damaged components are restored in accordance with the restoration probability function assumed in Figure 12. The resulting simulation of restoration (in % of households) is represented by four points in Figure 13, which underestimates the speed of restoration (in % of customers) actually observed in the aftermath of the Northridge Earthquake. The difference between household- and customer-based percentage restoration is assumed negligible here. Figure 13 also includes simulated restoration curves for two other less damaging scenario earthquakes. Note their shapes are, in essence, the same as the curve BD in Figure 11. We note that power system restoration procedures will repair or replace damaged components in an order reflecting the priority established by the utility for the purpose of accelerating the entire network restoration. If such a procedure were taken into consideration, the simulation performed here might have more closely agreed with the empirical curve.

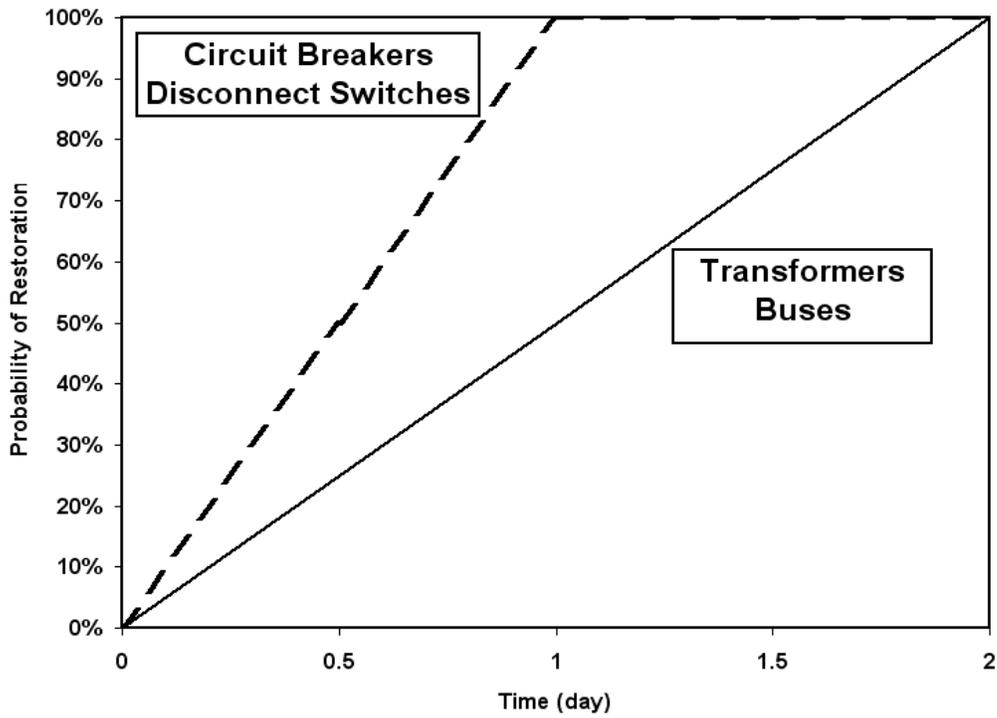


Figure 12. Restoration Curve for Transformers, Circuit Breakers, and Disconnect Switches

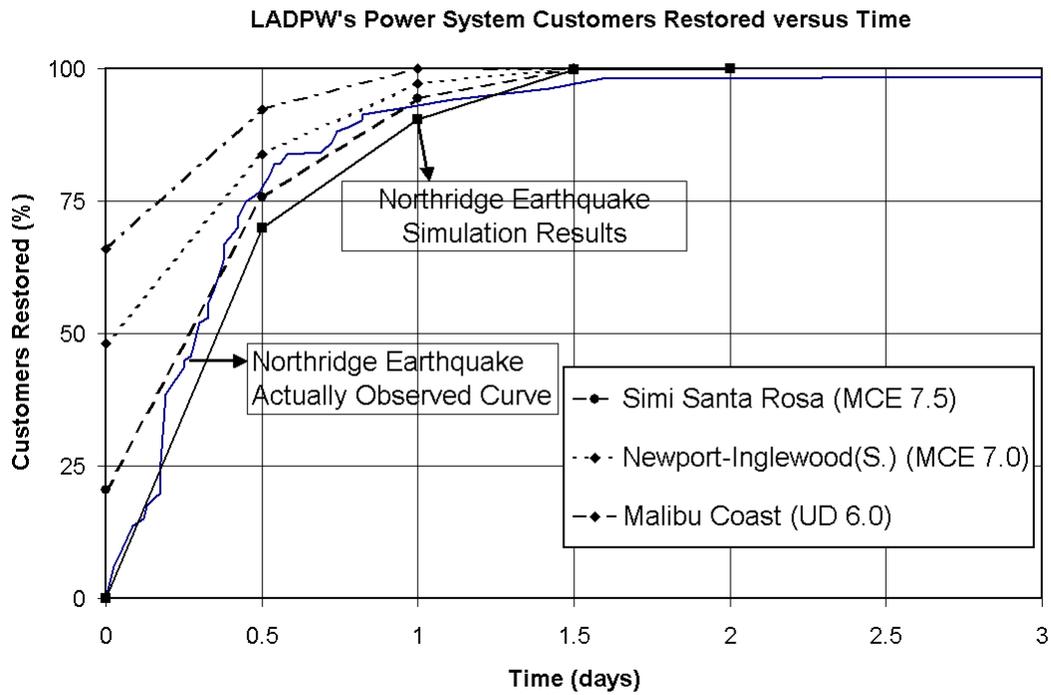


Figure 13. LADWP Power System Customers Restoration

EFFECT OF A DISABLING EVENT ON PERFORMANCE OF LARGE SYSTEMS

A general methodology has also been developed to analyze the behavior of large electric utility networks or grids under a catastrophic event, such as a severe earthquake or an intentional disablement of system components. In this respect, we are working on the outages recently experienced in the Midwest and northeastern part of the U.S. and southern Canada on August 14, 2003 in order to analyze and simulate what happened, not only to the power grid, but also to transportation, water supply, and other infrastructure systems and the associated socio-economic disturbances. Initially, the research was motivated by an accident in August 1996, in which a tree came into contact with a high-voltage aerial power line at a location in the State of Oregon, disabling its transmission capability. The result was a widespread blackout in several states and cities, including part of Los Angeles. We were able to simulate outage in Los Angeles under the Oregon scenario, making use of grid inventory data and an electric power flow simulation code. The simulation dealt with two scenarios (A and B) involving disabled 500kV transmission lines between Washington State and Idaho (A) and between Washington State and Oregon (B) as shown in Figure 14 (a) for Scenario A and Figure 14 (b) for Scenario B. The red cross in the WECC Grid in the figures indicates the locations of the interruptions. In Scenario A, there are only minor impacts on the power supply to the LADWP service areas. The power supply to most LADWP service areas is maintained at above 90%. In one centrally located service area, power supply drops to a value between 85% and 90%. The reason is that the disabled 500kV transmission line in Scenario A is a more redundant segment of the grid, relative to the LADWP power system. The power supply reduction to the LADWP service areas results from power-load balance requirements within the entire WECC system. For Scenario B, however, the disabled transmission line at the border of Washington and Oregon States is a less redundant component, and influences the LADWP power system through two 500kV AC transmission lines and one 500kV DC transmission line. From Figure 14 (b), it is seen that the entire LADWP service area is blacked out when this component is disabled. This is indeed a disaster to the LADWP service area, in spite of various redundancies and tolerances built into the system between the Pacific Northwest and Southern California.

This type of accident often creates a chain of events such as power imbalances and abnormal voltages leading to blackout. This research took on a new significance after the tragic September 11 event from the homeland security point of view, and the August 14, 2003 power outage adds another layer of relevance. This is because network outages can be man-made, either accidental or malicious, and can have a devastating negative impact on the socio-economic welfare of the directly affected regions in the short term, and on the nation as a whole in the long run.

CONCLUSION AND FUTURE RESEARCH

This paper integrated many of the data and methods developed by the authors over the years, including GIS inventory data of the LADWP electric power transmission system, multiple scenario earthquakes representing the Los Angeles area seismic hazard, fragility characteristics of system components with and without seismic retrofit, systems analysis techniques using WECC's database and EPRI's IPFLOW computer code. This integration leads to the capability to evaluate the performance of power systems and the consequences of system interruptions caused by earthquakes. Additional study will be undertaken to further establish performance criteria that can be quantitatively mapped into the response space, in terms of the technological, economic, organizational, and social dimensions of disaster resilience. Future study will also include the development of probabilistic procedures to estimate the reliability of the seismic resilience of the community. Also, integration with other critical systems such as water systems, emergency response organizations, medical care systems (e.g., acute care hospitals) and highway transportation systems will be carried out to evaluate the community resilience. Finally, the application of SCADA in the inverse analysis of power system performance is of significant future

interest. This is to improve the time it takes to achieve restoration of system function degraded by the earthquake, which represents the rapidity aspect of the resilience criteria. An added dimension to our future research is to provide recommendations to prevent, protect and quickly restore the power network and grid from outages due to natural, technological and malicious causes.

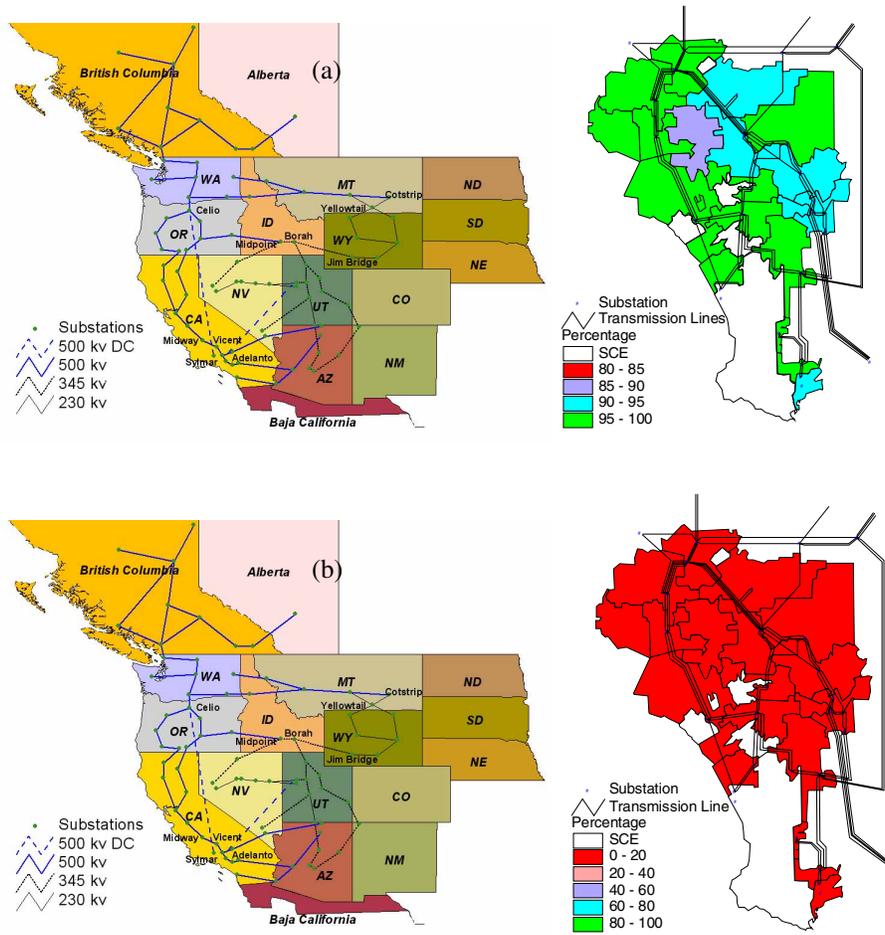


Figure 14 (a) Disabled Location A and Reduction (b) Disabled Location B and Reduction in Power Supply

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