SEISMIC RISK OF A HIGH VOLTAGE ELECTRIC TRANSMISSION NETWORK

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ABSTRACT

A model of Bonneville Power Administration's (BPA) 230 kV to 500 kV substations in the Puget Sound area was developed using the SERA GIS-based risk model computer program. The model includes more than 5,000 individual components, including transformers, circuit breakers, disconnect switches, capacitor banks, instrument transformers, control buildings, backup power equipment, as well as conductor and bus connections. More than 380 fragility estimates are used to describe the equipment, including various types of flexible connections between adjacent components. The transmission network was evaluated for impact from several scenario earthquakes. While all the scenario earthquakes have the potential to cause damage, the study found that the power system is rugged enough to be able to restore power within a few days, after most crustal earthquakes. However, worst case subduction zone events can cause widespread damage to many substations at the same time, that power restoration to 90% of pre-earthquake levels might take a much longer time.

Introduction

BPA operates one of the nation's largest high voltage transmission networks spanning four states, with more than 250 substations, and 15,000 transmission circuit miles. Figure 1 shows the transmission system in western Washington and northern Oregon, highlighting the Puget Sound area selected for discussion in this paper.

The basic steps in the evaluations are to collect inventory information; assign fragility functions to components; estimate the seismic hazards for each component; compute the damage in scenario earthquakes; develop restoration times given available repair capability; and estimate economic impact to the community due to resultant power outages. If outcomes are deemed to be unacceptable, a utility can develop a seismic upgrade program that would reduce damage and outage times. With the results obtained from SERA, utilities can use a benefit-cost analysis to establish if the cost of a seismic upgrade program is justified by the benefits.

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Scenario Earthquakes

The network is exposed to multiple earthquake sources (crustal faults, deep intraplate events, and an interplate subduction zone). For this paper, we present some detailed findings for two scenario earthquakes, including one crustal event and one Cascadia subduction zone (CSZ) event. The M 7.1 crustal event is on the Seattle Fault; the interplate event is a M 9.0 CSZ event that ruptures from Canada in the north to California in the south.

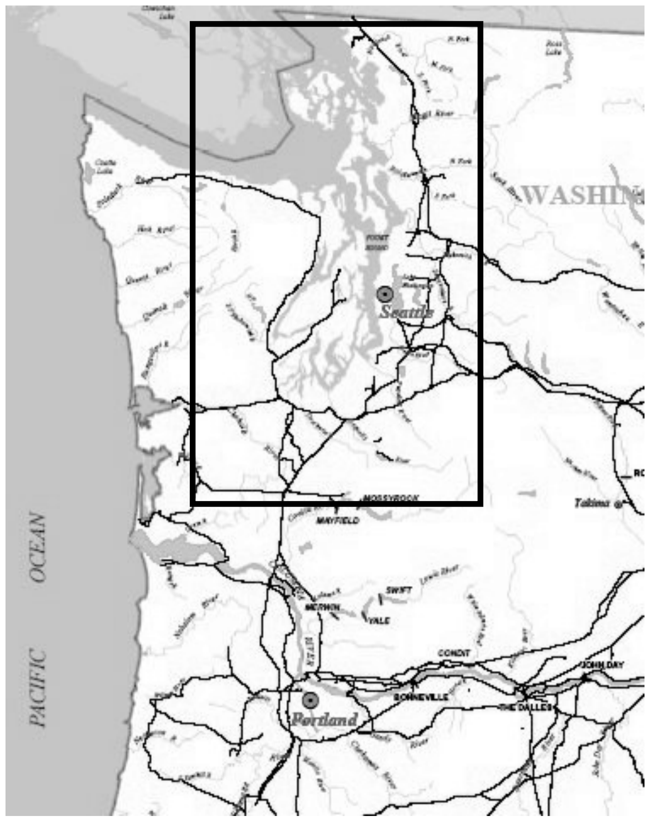

Figure 1. Map of Regional Power Transmission System and Study Area

Table 1 shows the expected horizontal-direction peak ground accelerations (PGA) at the 20 substations studied in the Puget Sound area. It is important to understand the performance of the BPA system by examining the variation in ground motions at the individual substations. For example, in either the Seattle Fault or south Whidbey Island Fault crustal events, one or two substations will experience high PGAs (over 0.3g) but many will feel only modest motions (under 0.10g). For the CSZ Interplate event, almost all substations studied will feel ground motions over 0.20g. Surface fault and landslide hazards generally do not exist at BPA substations, but liquefaction is important at a few substations in the study region.

Inventory

Possibly the most challenging aspect of a risk assessment of substations is the development of an accurate inventory of substation components to be evaluated. For this effort, we had earthquake knowledgeable engineers visit every substation and develop detailed inventory of every facility and component that might be of interest during earthquakes. The inventory was processed into a relational database, including photographs of each component. The inventory was divided into 17 sub-classes of equipment. Each class of equipment was then further subdivided into sub-classes, depending on the style of construction as it might affect the seismic fragility. The classes of components were: circuit breakers, current transformers, disconnect switches, circuit switchers, voltage transformers, surge arrestors, bus risers, capacitor banks, power transformers, reactors, rigid bus, station service, control equipment (important to operation), other equipment (not essential to operation), emergency generators and batteries, occupied buildings and non-occupied buildings. Including sub-classes, fragilities were assigned to 389 different types of equipment and/or components.

Fragility

The fragility functions for the equipment were expressed in terms of a ground shaking parameter,: peak ground acceleration, PGA; spectral acceleration parameter, SA; or permanent ground deformation parameter, PGD. The fragility functions are expressed as lognormal distributions described by a median ground motion and a dispersion β. In some cases, where the fundamental frequency of the damage mode is important, and where suitable fragility data was available, fragility functions were expressed in terms of spectral accelerations (SA's) instead of PGA's.

Table 1. Ground Motions (Median, firm soil)

Substation	Seattle Fault M 7.1 PGA, g	South Whidbey I. M 7 PGA, g	CSZ Interplate M 9 PGA, g	CSZ Intraplate M 7.5 PGA, g
1	0.02	0.05	0.25	0.10
2	0.20	0.08	0.22	0.25
3	0.02	0.04	0.28	0.09
4	0.31	0.11	0.20	0.22
5	0.02	0.05	0.29	0.10
6	0.14	0.21	0.21	0.21
7	0.07	0.16	0.22	0.19
8	0.06	0.03	0.32	0.21
9	0.19	0.08	0.21	0.22
10	0.09	0.04	0.35	0.19
11	0.14	0.33	0.22	0.23
12	0.14	0.06	0.24	0.26
13	0.14	0.07	0.25	0.26
14	0.32	0.12	0.23	0.25
15	0.04	0.02	0.31	0.22
16	0.03	0.02	0.32	0.20
17	0.09	0.04	0.25	0.26
18	0.20	0.52	0.23	0.25
19	0.03	0.02	0.31	0.21
20	0.04	0.02	0.40	0.15

Each equipment item has at least one damage state, an associated damage factor, and functionality code. The damage state is a description of the type of damage expected for the particular piece of equipment. The damage factor is the ratio of the repair cost (and man-hours) of the equipment and its replacement value. The functionality code describes whether the equipment is functional; should the damage state occur.

The decision to use the lognormal distribution as the basis of the fragility functions was based on two main reasons. First, the lognormal distribution is mathematically convenient in that the probability of failure at PGA = 0.0g is zero (never negative), no matter what median or dispersion beta value is chosen. Second, an argument can be made that the shape of the lognormal distribution function (skewed towards the left, with a long tail to the right) often matches the observed damage patterns of many kinds of physical equipment.

In most cases, a unique component was defined for each phase of a circuit. For example, each circuit breaker in a 500 kV circuit was defined as one component. The only exception was for three phase transformers, which were defined as one component (but the fragility curves for a three phase component include separate damage states for all three high voltage bushings). If a three phase circuit breaker had been defined as a single component, then each of the six bushings would have been modeled separately, and the resulting damage forecast would be similar.

The fragility of each component was established using a variety of techniques. A review of available literature for catalogues of high voltage substation fragilities, including Agnanos (1999), Eidinger and Ostrom (1994), and procedures used by other power utilities (Matsuda et al 1991) was completed. A review of actual seismic qualification tests of more than 100 types of substation components was also performed. Adjustments were made to the fragilities to consider known damage (or non-damage) to BPA-specific equipment in past earthquakes, including the Nisqually M 6.8 2001, Satsop M 5.7 1999, Duvall M 5.1 1996, Seattle-Tacoma M 6.5 1965, and Olympia M 7.1 1949 earthquakes. Each of these prior earthquakes in the greater Puget Sound area damaged BPA equipment. For example, the Duvall earthquake resulted in damage at one substation (PGA about 0.10g) that included: damage to three of nine 500 kV instrument transformers; three 500 kV risers with welds failed, but nine other risers did not fail; most (15 units) of the step-arc suppression resistors on the 500 kV disconnect switches were damaged; one phase (one of 63 phases damaged) of a 500 kV disconnect switch failed and two additional disconnect switches had broken insulators; one phase of an older live-tank circuit breaker had a damaged current transformer; another phase of the circuit breaker developed an SF6 gas leak; a 230 kV rigid bus tap connection to a disconnect switch failed; a 34.5 kV station service fuse holder stand-off insulator broke causing the fuse to fall breaking the holder.

A comparison of the fragility recommendations in the literature with the observations of actual equipment in the BPA system was completed. In doing so, it was decided to update the fragility database taxonomy, to reflect the styles of equipment in use at BPA. Damage states were delineated to reflect the common styles of damage observed. For a power transformer, up to nine damage states were included, to cover the range of damage to bushings (broken, slipped/leaking), surge arrestors (broken), radiators (leaks, breaks), anchorage (damaged and transformer remains in service, or broken and transformer moves sufficiently to break bus connections or bushings).

Findings – Seattle Fault M 7.1

The SERA GIS software was used to estimate the damage to the substations and ensuing power outage and recovery times. One hundred simulations of each scenario earthquake were performed, in order to capture the likely range of damage due to randomness in earthquake motions and uncertainty in equipment fragility. A sampling of the type of damage is described in Table 2, for the Seattle Fault M 7.1 scenario earthquake. The results are listed by type of component. Each row in Table 2 shows six types of components (the third row has five), for a total of 17 types of components.

Table 2. Seattle Fault M 7.1 Component Damage

	CIRCUIT BREAKER			CURRENT TRANSFR			DISCNCT SWITCH			CIRCUIT SWITCH			VOLTGE TRANSFR			SURGE ARRESTOR		
	# CB	# CB	# CB	# CT	# CT	# CT	# DS	# DS	# DS	# CS	# CS	# CS	# VT	# VT	# VT	# SA	# SA	# SA
SIM NUM	NO LOSS	PART LOSS	TOTAL LOSS	NO LOSS	PART LOSS	TOTL LOSS	NO LOSS	PART LOSS	TOTL LOSS	NO LOSS	PART LOSS	TOTL LOSS	NO LOSS	PART LOSS	TOTL LOSS	NO LOSS	PART LOSS	TOTL LOSS
AVG	812	0	23	108	0	14	2263	9	24	57	1	0	192	0	2	389	0	5
MIN	784	0	7	83	0	1	2170	0	0	48	0	0	181	0	0	366	0	0
MAX	829	0	52	122	0	40	2296	46	84	60	10	6	195	0	14	395	0	29
16%	791	0	14	89	0	7	2190	7	13	49	1	0	183	0	2	370	0	4
84%	821	0	44	115	0	33	2275	38	70	58	8	5	192	0	11	390	0	24
STD	10	0	10	8	0	8	27	10	19	3	2	1	3	0	3	6	0	6
-1S	801	0	12	99	0	5	2235	-1	4	53	-1	-1	188	0	-1	382	0	-1
+1S	822	0	33	116	0	22	2290	19	43	60	3	1	195	0	5	395	0	11

	** BUS RISER **			CAPACITOR BANKS			PWR TRANSFRMERS			SHUNT REACTORS			STATION BUS			STATION SERVICE		
	# RS	# RS	# RS	# CP	# CP	# CP	# TR	# TR	# TR	# RE	# RE	# RE	# RB	# RB	# RB	# SS	# SS	# SS
SIM NUM	NO LOSS	PART LOSS	TOTAL LOSS	NO LOSS	PART LOSS	TOTL LOSS	NO LOSS	PART LOSS	TOTL LOSS	NO LOSS	PART LOSS	TOTL LOSS	NO LOSS	PART LOSS	TOTL LOSS	NO LOSS	PART LOSS	TOTL LOSS
AVG	593	0	21	284	0	15	92	1	0	16	0	0	16	0	0	30	0	0
MIN	568	0	9	254	0	1	82	0	0	10	0	0	15	0	0	30	0	0
MAX	606	0	47	299	0	46	95	9	7	17	7	2	17	2	0	30	0	0
16%	574	0	15	261	0	8	84	1	1	11	1	0	15	0	0	30	0	0
84%	599	0	40	291	0	38	92	7	5	15	5	1	16	1	0	30	0	0
STD	7	0	7	10	0	10	3	2	1	1	0	0	0	0	0	0	0	0
-1S	585	0	13	273	0	4	88	-1	-1	14	0	0	15	0	0	30	0	0
+1S	600	0	28	294	0	25	95	3	1	17	0	0	16	0	0	30	0	0

	** BUILDINGS **			** BLDG NON OCC **			CNTL COM EQUIP			OTHER EQUIPMNT			BATTERY + GENS			** OTHER EQUIP **		
	# BL	# BL	# BL	# BX	# BX	# BX	# EQ	# EQ	# EQ	# XQ	# XQ	# XQ	# EG	# EG	# EG	# AT	# AT	# AT
SIM NUM	NO LOSS	PART LOSS	TOTAL LOSS	NO LOSS	PART LOSS	TOTL LOSS	NO LOSS	PART LOSS	TOTL LOSS	NO LOSS	PART LOSS	TOTL LOSS	NO LOSS	PART LOSS	TOTL LOSS	NO LOSS	PART LOSS	TOTL LOSS
AVG	18	0	0	4	0	0	152	0	1	69	0	0	54	0	0	0	0	0
MIN	16	0	0	4	0	0	146	0	0	67	0	0	52	0	0	0	0	0
MAX	19	2	1	5	1	0	154	2	7	70	2	2	55	3	0	0	0	0
16%	16	0	0	4	0	0	147	0	1	67	0	0	52	0	0	0	0	0
84%	18	1	0	4	0	0	152	1	5	69	1	1	54	2	0	0	0	0
STD	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0
-1S	17	0	0	3	0	0	150	0	0	68	0	0	53	0	0	0	0	0
+1S	18	0	0	4	0	0	153	0	2	69	0	0	54	0	0	0	0	0

For each type of component, there are three result columns: No Loss; Part Loss; and Total Loss. By "No Loss", it is meant that the component suffers no damage that leads to material functional impairment. By "Part Loss", it is meant that the component suffers some damage that leads to some functional impairment; the damage is either so slight that the component can continue to operate without outage; or at most the equipment can be rapidly returned to service with some minor workaround (less than $1,000 repair cost). For example, the contacts might become mis-aligned for a disconnect switch. By "Total Loss", it is meant that the component suffers some damage that leads to full functional impairment. The equipment must usually be totally replaced at full replacement value in order for it to be restored to normal service. For example, the posts of a disconnect switch might break, causing collapse of the switch and attached conductors.

By reviewing Table 2, it can determined that the most likely amount of (average, avg) functional damage at the substations in the Puget Sound study Area is:

23	Circuit breakers
14	Current transformers
24	Disconnect switches
0	Circuit switchers
2	Voltage transformers (CVTs, PTs, etc.)
5	Surge arrestors
21	Bus risers
15	Capacitor banks
0	Power transformers (the most important items) (1 might suffer a radiator leak)
0	Shunt reactors
0	Station bus (this type of component was not always included in the SERA model at every substation, although all unanchored installations were included in the model)
0	Station service
0	Control buildings
0	Non-occupied emergency generator buildings
1	Control room item important for operation
0	Non-critical pieces of equipment
0	Emergency generators and battery components

To make temporary repairs and bypasses, if 30 high-voltage construction crew staff can be mobilized, plus 20 from contractors, and assuming, on average, 10 hour work days, 7 days a week, until all equipment is bypassed / temporarily repaired, then it will take between 2.1 and 6.8 days to restore some level of service to all circuits. If 100 high-voltage construction crew staff can be mobilized, plus an equal amount from contractors, and assuming, on average, 10 hour work days, 7 days a week, until all equipment is repaired, then it will take between 19 and 63 days to restore the system to its pre-earthquake condition.

It should be mentioned that there can be a lot of difference in damage outcomes between two different simulations of a single scenario earthquake, Cumulatively, with over 100 simulations, it is possible to get a reasonable picture of likely performance.

Findings – Cascadia Subduction Zone M 9.0

The BPA system in the Puget Sound study area was also evaluated for other scenario earthquakes, including a "worst case" CSZ M 9.0 event. The average component damage is described below.

75	Circuit breakers
38	Current Transformer
242	Disconnect switches
3	Circuit switchers
23	Instrument transformers (CVT's, PT's, etc.)
45	Surge arresters
103	Bus risers
47	Capacitor banks
13	Power transformers (the most important items)
1	Shunt reactors
0	Station bus (this type of component was not rigorously included in the analysis, so the results should not be viewed as totally representative)
4	Station service
1	Control buildings
0	Non-occupied emergency generator buildings
16	Control room items important for operation
0	Non-critical pieces of equipment
0	Emergency generators and battery components

To make temporary repairs and bypasses, if 30 high-voltage construction crew staff were mobilized, plus 20 from contractors, and assuming, on average, 10 hour work days, 7 days a week, until all equipment is <u>bypassed / temporarily repaired</u>, then it will take between 11.2 and 42.2 days to restore some level of service to all circuits. If 100 high-voltage construction crew staff were mobilized, plus an equal amount from contractors, and assuming, on average, 10 hour work days, 7 days a week, until all equipment is <u>repaired/replaced</u>, then it will take between 117 and 410 days to restore the system to its pre-earthquake condition.

Network Considerations

The key components that must remain functional post-earthquake are high voltage power transformers and control room buildings and equipment within the control buildings. Generally speaking, damage to almost any other component in a substation can be readily bypassed in a few hours once repair crews are available.

Substation switchyards are designed with substantial redundancy. For example, the commonly used breaker-and-a-half bus configuration can lose one of the three circuit breakers and associated disconnect switches in a position and not cause any disruption. Power networks also have redundant circuits so that some circuits can be lost with no disruption of service.

In the Seattle Fault M 7.1 earthquake, it is not likely that any (or not more than one) power transformers will be functionally damaged, and no control buildings are severely damaged.

In the Cascadia Subduction Zone (interplate) M 9.0 earthquake scenario, it is likely that 13 power transformers will be functionally damaged; and possibly one control building severely damaged. At almost all substations, there is at least a 50% chance of functionally damaging one or more transformers. Coupled with extensive damage to disconnect switches and circuit breakers, this worst case scenario could result in the bulk of the Puget Sound BPA transmission network being out of service immediately after the seismic event. Few substation circuits will be undamaged. The post-earthquake strategy to repair damage will have to be set once good estimates of system-wide damage are available. Based on the assumptions in the analyses, it would take about 11 days (possibly much longer depending on the specifics of transformer damage) to make a sufficient number of repairs to bypass all damaged equipment and restore power (possibly without many circuit breakers and disconnect switches) to all circuits.

Benefit Cost Analyses

Reasons for an electric power utility to implement a seismic mitigation program are for investment protection of power equipment and minimize recovery time to limit the potential for economic harm to the regional community. The question arises: how much should a utility spend to seismically-strengthen its transmission network? And, is it cost effective for a utility to do so?

The results from SERA can be used to investigate the cost and benefit of performing a seismic mitigation program. An example Benefit Cost Analysis (BCA) of implementing an ongoing seismic mitigation program was performed. The BCA analysis presented *only* takes into account the potential for economic disruption in the Puget Sound area due to earthquake-damage to the transmission system. Other benefits of a seismic mitigation program, such as reduction in repair cost, life safety issues and indirect economic impacts were excluded from the analysis. Overall, these benefits, while important, are secondary to the larger impact of loss of power to the region for multiple day earthquake-induced outages.

The following are the main points and assumptions used in the example benefit cost analysis for seismic mitigation of the transmission substations studied in the Puget Sound area.

1. Assume that gross regional product (GRP) in the Puget Sound area represents about 1.5% of the USA GRP.2. Assume USA GRP = $10 trillion / year ($2004).
2. Then the Puget Sound GRP = $150 billion per year, or $410 million per day.
3. Assume a CSZ M 9 event once every 300 years and a CSZ M 7.5 event once every 150 years.
4. Assume CSZ M 9 results in 11 days to restore power to all transmission circuits (current condition), with a linear restoration curve; 6.8 days for a CSZ M 7.5; 2.1 days following Seattle fault M 7.1; 2 days following South Whidbey Island M 7.
5. Assume local electric utilities can restore the bulk (90%+) of their local transmission and distribution systems in 2 days following any earthquake.

6. Assume generation requires use of the transmission system studied.
7. Assume complete loss of the studied transmission capability results in 75% slowdown in local economic activity.

Given these assumptions, the CSZ M 9.0 would result in, a worst case scenario, an equivalent significant loss of transmission capability for 3.79 days *beyond the first two days after the earthquake.* Given these assumptions, the CSZ M 7.5 would result in, a worst case scenario, an equivalent significant loss of transmission capability for 1.68 days *beyond the first two days after the earthquake, covering about 60% of the local Puget Sound region.*

For CSZ M 9.0, scenario economic loss = $410 million * 3.79 days = $1.55 billion. Given a 300-year return period, this translates to an annualized loss of $5,174,000. Similarly, for a CSZ M 7.5, this translates to an annualized loss of $2,755,000. Assuming that the existing BPA and local electric utility systems are fairly robust to restore power to 90% of end user customers within 48 hours after any crustal earthquake.

Total annual loss that could be mitigated = $7,929,000. Assume that any seismic mitigation measures would have a useful economic lifetime of 50 years, and assume a discount rate of 7%. The net present value of $1 invested for 50 years at 7% is $13.80. The total economic benefit of a seismic mitigation program to meet a maximum 2 day outage for 90% of demand is therefore: 13.8 * $7,929,000 = $109,000,000. In other words, a $109 million investment to seismically strengthen the transmission network in the Puget Sound area to a point where power could be restored within 48 hours would have a benefit cost ratio greater than 1.

Conclusions

The capability to perform a high-voltage electric transmission line system study to investigate the seismic vulnerability of the power system was presented. With a program like SERA a utility has the capability to investigate the seismic vulnerability of the power system, obtain damage estimates, and perform cost benefit evaluations for seismic hardening and mitigation.

The presented benefit cost analysis was simplified, and relied on the outage times developed in the current SERA analyses. Both these assumptions are open to refinement. However, based on these analyses, the following observations can be made:

The study considered both seismic mitigation solutions completed by BPA and the performance of the power system without any seismic mitigation. BPA's seismic mitigation program to date (2005) has resulted in measurable improvement to high-voltage power transformers, emergency backup power systems and control room equipment.

Given network redundancies, it appears that the current system has a reasonable expectation of not being so damaged as to result in more than about 48 hour outage for more than 10% of the load, given any large crustal earthquake in the Puget Sound area. But, transmission line systems in the Pacific Northwest remains vulnerable to much longer outage times for a CSZ M 9.0 interplate (or worst location CSZ M 7.5 intraplate) earthquake, possible 11 or 7 days, respectively.

The SERA analysis shows that a seismic mitigation program with a target to be able to restore power to 90% of its normal capacity within 48 hours after a CSZ M 9.0 earthquake would provide significant benefits to reduce the vulnerability of the high-voltage electric power transmission system. This would involve a combination of strengthening equipment, adding redundancy, and improving emergency response capability.

This analysis tool demonstrated the advantage of a seismic mitigation program. As an example assuming a seismic mitigation program of $7.4 million per year, the benefit cost ratio of implementing the seismic mitigation program is $109 million / $7.4 million = 15. This type of information can be used by a utility, such as BPA, to determine the benefits and potential results of performing a seismic mitigation program on an existing high-voltage electric power transmission line system.

BPA will continue to develop the SERA model of their Pacific Northwest high-voltage electric transmission system. Results from scenario earthquakes will be used to investigate seismic vulnerabilities and for developing seismic mitigation recommendations that will provide significant benefits to BPA's power system and the Pacific Northwest region.

It should again be mentioned that there could be a lot of difference in damage outcomes between different simulations of earthquake scenarios. The results from a study such as presented in this paper should be interpreted by experts in power system earthquake engineering, high-voltage transmission engineers, maintenance specialists, and power system operation personnel.

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