Evolution of Electrical Grid Seismic Resiliency

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ABSTRACT

This paper describes chronological mitigation efforts (before, during and after) to the Southern California Edison (SCE) electrical grid (Transmission, Substation and Distribution) after major earthquakes in Southern California. "Before the earthquake" describes the seismic standard and designs at that time. "During the earthquake" describes real time mitigation efforts to continue emergency power flow of the electrical grid even in the midst of chaos, and documents how the grid can operate during an emergency situation and help guide future methods of operation during emergency. "After the earthquake" illustrates how SCE and the industry changed seismic standards for the electrical grid, in the interest of increasing seismic resiliency, and summarizes actual mitigation.

The history behind a lot of today's (2018) "common" seismic design practices for the Electric Grid is not well documented. This paper provides a historical perspective of how real-world earthquakes help shape industry codes, company standards and emergency protocol.

INTRODUCTION

Southern California Edison (SCE) is the largest subsidiary of Edison International. SCE is the primary electricity supply company for much of Southern California. SCE's electrical system serves about 4.97 million customers (average, 2016-2017), with a population of about 14 million people, across a service territory of about 50,000 square miles. The record peak demand recorded in 2007 was just over 23,600 MW. Figure 1 shows SCE's service area (heavy black outline), along with main transmission lines (red = 500 kV, blue = 220 kV, green = 115 kV, grey = 66 kV). Names reflect locations discussed in this paper.

Today (2018), the SCE system includes nearly 900 transmission level substations (66 kV to 500 kV), over 1,000 transmission circuits (66 kV to 500 kV), nearly 5,000 distribution feeders (about half underground and half overhead, total length over 100,000 km), nearly 140,000 transmission and sub-transmission towers and poles, and about 2 million distribution poles. SCE owns and operates over 80 hydro-electric power plants in the Sierra Nevada Mountains. SCE also occupies many office buildings, service centers, and maintenance yards. All of this inventory is exposed to seismic hazards, including ground shaking, liquefaction, landslide and surface faulting. Nearly 85% of this inventory is exposed to PGA > 0.9g, assuming a 2,475-year return period motion.

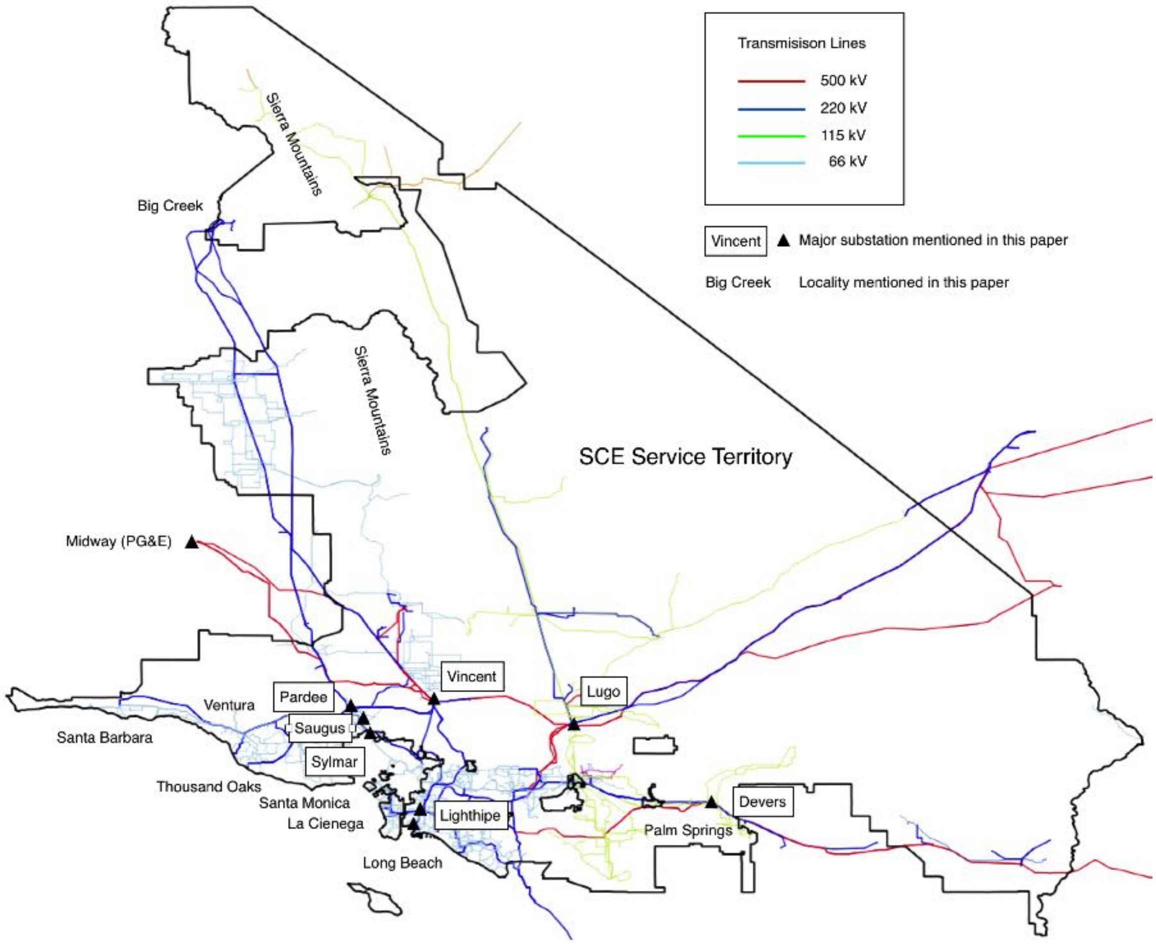

Figure 1. SCE Service Area and Transmission and Subtransmission System

BEFORE THE EARTHQUAKE

The SCE system has been exposed to a number of damaging earthquakes over the past century, see Table 1. There are many publications that examine the specific damage at many of the above facilities, notably substations. Not all the damaging earthquakes are listed in Table 1. Herein, we examine the root causes of the damage and what SCE "learned" and then put into practice.

Prior to 1930, the SCE system included many hydro electric power plants in the Sierra Mountains, as well as a variety of small steam plants. Seismic design, per-se, did not exist, even though it was clearly understood that earthquakes were a fact of life in Southern California. The 1920 and 1925 earthquakes partially or fully collapsed moderate size (about 5,000 square feet) unreinforced masonry buildings that housed steam plants and indoor substation equipment. Prior to 1930, lateral load resisting systems were designed for wind loads (commonly 20 to 30 pounds per square foot), transmission towers were design for wind (70 miles per hour, working stress design with a factor of safety of 1.25 to 1.5 against yield). Substation equipment, like circuit breakers, were commonly anchored for short circuit loads, but larger power transformers were often unanchored or located on railroad ties.

Name	Date	M	Highlights
Inglewood	Jun 21 1920	5.0	Collapsed substation in Inglewood.
Santa Barbara	Jul 21 1925	6.7	Collapsed steam plant in Santa Barbara.
Long Beach	Mar 10 1933	6.5	Collapsed Rigid Bus at 220 kV Lighthipe and Long Beach substations.
San Fernando	Feb 9 1971	6.7	Rebuild San Fernando distribution system. Damaged 66 kV tower.
North Palm Springs	Jul 8 1986	6.0	Heavy damage at 500 kV Devers substation. Palm Springs area was without service for approximately 5 hours.
Whittier	Oct 1 1987	5.9	Moderate damage at 2 substations including damage to live tank circuit breaks and post insulators. Moderate damage to SCE office buildings in Rosemead.
Joshua Tree	Apr 23 1992	6.1	No significant damage recorded.
Landers	Jun 28 1992	7.3	10 feet of right lateral fault offset through a 220 kV tower. Minor structural damage to a generating station and service centers. Bushing leakage at 4 substations. Sudden pressure false operations at three substation banks.
Northridge	Jan 17 1994	6.7	Heavy damage at 220 kV Pardee substation. Damage at Saugus 220 kV and Vincent 500 kV substations. A few collapsed and many damaged towers. Minor damage to a SCE office building in Rosemead. Moderate damage to a SCE office building in Santa Monica.
Hector Mine	Oct 16 1999	7.1	Transmission Line outages caused by slapped wires and relay tripping. Minor damage at substations with brief outages to distribution circuits.
Parkfield	Sept 28 2004	6.0	
Chino Hills	July 29 2008	5.4	Fire at substation in La Habra. Power outages in Chino Hills, Chino, Diamond Bar and Pomona. One outage to distribution circuit in Brea.
Brea	Mar 29 2015	5.1	No damage at Olinda 220 kV modern design (PGA ~0.35g). Minor damage at a few 66 kV substations.

Table 1. Notable Historic Earthquakes in the SCE Service Area

By 1928, SCE had just constructed a major new transmission line, to bring in large quantities of hydro power from Big Creek powerhouses in the Sierra Nevada Mountains, to the heart of the SCE service area. This line was designed at 220 kV (highest voltage in the SCE system at that time). Two large 220 kV – 66 kV switchyards were constructed, both in Long Beach (Lighthipe substation and the step-up switchyard at the Long Beach power plant). The March 10, 1933 Long Beach earthquake heavy damaged both of these 220 kV yards. The estimated motions were about PGA = 0.30g at both yards. The 66 kV switchrack at Lighthipe, Figure 2, apparently suffered little damage, and much of this 800-foot long structure remains in service today (2018); back-calculation suggests this 1920s-era steel switchrack can sustain about PGA = 0.5g near yield. However, a variety of rigid bus connections were used to connect 220 kV circuit breakers with disconnect switches and electrical bus, and these failed badly; about 600-feet of rigid bus collapsed entirely, Figure 3.

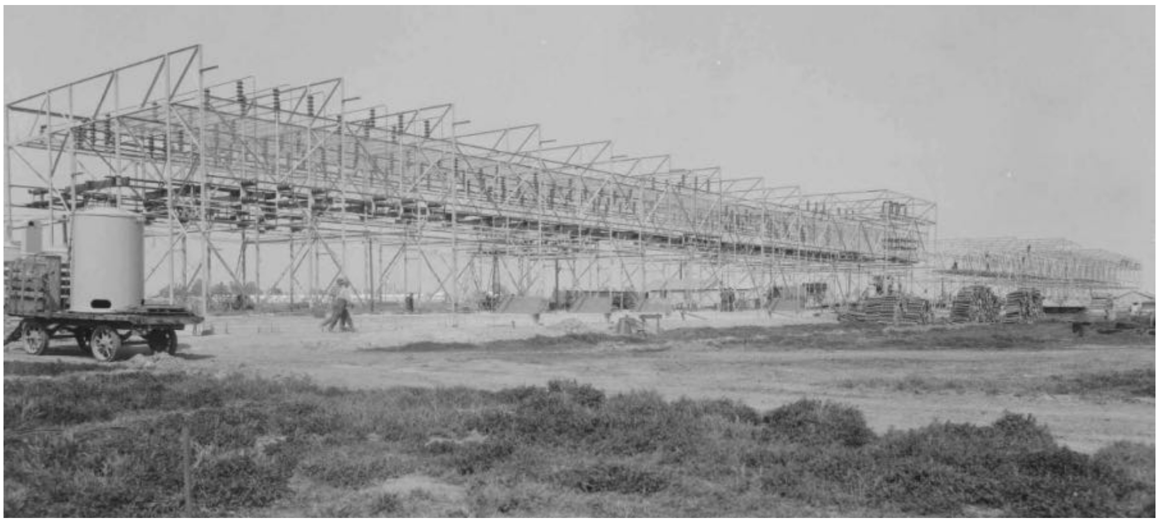

Figure 2. Lighthipe Steel 66 kV Switchrack (photo dated 1927)

Figure 3. Long Beach 220 kV Rigid Bus (photo dated March 10 1933)

DURING THE EARTHQUAKE

This paper highlights some of the more significant damage during past earthquakes. In this paper, we do not attempt to document every piece of damage. There are many publications that document the past damage at the substations; see Eidinger and Ostrom (1994) and Agnanos (2001) for overviews and statistics of that damage.

In this section, we document a few examples from the 1994 Northridge earthquake of what type of damage reports look like, from an operator's perspective, and what it cost to make short term (within a month or so) repairs.

In the 1994 Northridge earthquake (January 17 1994, 4:31 am local time), ground shaking at the 500 kV Vincent substation was about PGA = 0.16g. This yard had (3) three 500 kV lines to Midway (PG&E), and (2) two 500 kV lines to Lugo (SCE). The earthquake interrupted service to over one million of SCE's 4.2 million customers, most of them in the Ventura, Thousand Oaks, and Santa Barbara areas. Service was restored to one-fourth of these customers within one minute as automatic equipment re-energized facilities. Eight hours after the event service had been restored to 600,000 of the interrupted customers. Within 24 hours, service had been restored to all but 2,500 customers. All service was restored within 55-1/2 hours of the earthquake.

By 10:30 am local time on January 17, SCE operators had inspected the Vincent substation, with the following description of the main damage in the 500 kV yard:

- Circuit Breaker (CB) 962 was open (open means that current cannot flow through the CB). The breaker looked normal and pressures of the SF6 gas were normal.
- CB 952 was open. Pressures looked normal. All adjacent disconnect switches (DS) collapsed.
- CB 862 was open. The C-phase head had a leak; the column pressure was zero.
- CB 852 was open. Pressures looked normal. Adjacent DS B Phase collapsed.
- CB 822 was closed. Pressures looked normal. CB 822 was carrying load from the 500 kV Bank 2AA.
- CB 812 was open. Pressures looked normal. Adjacent DS A Phase collapsed.
- CB 762 was open. Pressures looked normal. Adjacent DS B Phase had broken porcelain.
- CB 752 was open. Pressures looked normal. Adjacent DS A and C Phases collapsed; B Phase had broken porcelain.
- CB 722 was open. Pressure was zero. Phase A Interrupter head collapsed. Adjacent DS A Phase collapsed.
- CB 712 was open. Pressure was zero. Adjacent DS A and B Phase collapsed.

- CCVTs and Wave Traps for the 5 transmission lines: most had line grounds open.
- South bus. In service.
- North bus. CCVT / PTs open. A Phase ground switch open.
- Series Capacitors (to PG&E interconnection at Midway). All 3 appear normal. All are by-passed internally and cleared and grounded. Some broken porcelain posts, but the structures remain standing.

By 11:24 am, one 500 kV line was inspected, breakers and switches re-set and put back into service. By 22:41 pm, one 220 kV line was inspected, switches re-set and put back into service.

January 19 1994. By 21:16 pm, Bank 3AA (500 kV) returned to service; Breakers 862 and 762 repaired and OK for service.

January 20 1994. One 500 kV line to Lugo returned to service. One more 220 kV line returned to service.

January 21 1994. 20:29 pm. One 500 kV line to Midway returned to service, including its series capacitors.

January 22 1994. 03:37 am. Second 500 kV line to Lugo returned to service.

January 24, 1994. 18:33 pm. Remaining 500 kV lines to Midway returned to service. This restored the PG&E – SCE 500 kV intertie, total time = 7 days, 14 hours, 1 minute.

A breakdown of the "short term" (within month or so) repairs required from this earthquake include (costs in $1994):

- Pardee (220 kV). Replace 8 CBs. Replace 14 DS. Repair / inspect 32 DS. Replace all "shotgun" ACSR (Bluebird) bus splices. Repair / inspect 15 CBs. Repair control room. Approximate cost: $5.7 million.

- Vincent (500 kV). Replace 1 CB. Replace 3 DS. Repair / inspect 11 CBs. Repair/inspect 19 DS. Repair control building. Repair capacitor banks. Approximate cost: $4.0 million.

- Saugus (220 kV). Replace 2 DS (220 kV). Repair / inspect 70 DS (66 kV). Repair / inspect 36 CB (66 kV). Repair / inspect DS and CB (220 kV). Clean up oil spill from two spare transformers. Temporary repairs to 66 kV switchrack. Approximate cost: $0.9 million.

- San Fernando (66 kV). Replace control building. Approximate cost: $1.2 million.

- Several other 66 kV and 220 kV substations and miscellaneous. Various repairs. Approximate cost: $0.05 million (Pardee area); $0.24 million (La Cienega area); $0.09 million (Orange County).

- Transmission lines (220 kV). Replace 1 tower and footings. Replace insulators, repair conductors, replace dampers at various locations. Approximate cost: $2.3 million.

- Transmission lines (66 kV). Replace 13 towers and footings. Install 4 crib walls. Replace insulators, repair conductors at various locations. Approximate cost: $3.0 million.

In this particular earthquake, there was very strong shaking (PGA > 0.5g) at hundreds of SCE transmission towers (66 kV and 220 kV lines). Many of these towers were situated at or near ridge tops. In a few cases, there were deep-seated landslides that damaged or collapsed towers. In many cases, the ridge tops looked like "plowed ground", with many fissures that sometimes impacted the tower foundations. 4 towers collapsed outright (2 initiations, 2 adjacent from pull downs); about 40 towers had various levels of damage, including buckled primary members, buckled secondary members, etc.

The total "short term" repair cost for SCE from the Northridge earthquake was about $17 million, needed to restore service to pre-earthquake levels, and mostly completed within two months after the earthquake. In approximate terms, this corresponded to about 100 man-years of work using a crew of about 1,000 people over two months to accomplish the bulk of the work. In the longer term, SCE made many changes to its seismic design practices, and many components that had minor damage (or appeared weak) were later replaced with new seismically qualified components. It is difficult to put a specific cost to these longer term upgrades, as most are incorporated into the regular maintenance cycle.

As an outcome of the 1986 Palm Springs and 1994 Northridge earthquakes, there were many changes to seismic design practices, and many long term equipment changes; these will be described in the next section.

AFTER THE EARTHQUAKE

A major finding from the 1933 earthquake was that "220 kV rigid bus" was no longer to be used for new construction. Today (2018), all transmission level substations use "flexible bus"; nearly all of the rigid bus (like Figure 3) has been removed and replaced over the past 85 years, with just a few remnants left at lower voltage substations; eventually, those too will be replaced.

Over much of the late 1930s until the 1971 earthquake, SCE adopted a seismic design approach that approximates V = 0.20W for small stiff structures (like transformers) (seismic base shear equals 20% of the component's weight). A similar approach was used the other large California power utility (PG&E) at the time. In comparison, the regular building seismic code evolved to require small stiff structures to be constructed for V = 0.10W (1930s), V = 0.14W (1960s), V = 0.18W (1980s). So it would seem that the V = 0.20W approach was relatively conservative as compared to the approach for most building structures. However, the 1971 earthquake proved that this approach was insufficient, for a variety of reasons, including: many substation components use porcelain that is relatively "brittle"; near-field earthquakes can produce much stronger shaking than presumed by V = 0.20W; equipment interactions through conductors due to relative motions are not addressed; design-by-analysis does not always factor in all the moving parts or electrical insulation requirements for substation equipment.

The 1971 earthquake was a very strong localized earthquake, centered in the neighboring LADWP electric system. This earthquake caused severe damage at the recently-built 500 kV Sylmar converter station, operated by LADWP; PGA > 0.5g and there was liquefaction at the yard. SCE's system had some distribution damage, but as there was relatively little SCE inventory in the strong shaking area, the impacts were modest. Soon after this earthquake, representatives of SCE, LADWP, PG&E, SDG&E, BPA and cognizant industry experts began to meet regularly to discuss the seismic issues and lessons learned. One outcome was that new 500 kV equipment would be procured with a requirement for seismic qualification for PGA = 0.5g horizontal acceleration and 0.33g vertical acceleration; which could be demonstrated by structural analysis. Another outcome from this earthquake was the development for an “Earthquake Recorder Program” at SCE facilities. SCE worked with California Institute of Technology to develop the TRINET system which was a real time earthquake motion monitoring system.

The 1986 earthquake produced PGA ~0.9g at the recently-built Devers substation. The brand new 500 kV yard (which included seismic design for PGA = 0.5g) sustained heavy damage, including many toppled "seismically qualified by analysis" circuit breakers; pulled down 500 kV bus runs; broken anchorage systems for 500 kV transformers, etc. The lessons learned suggested that "qualification by analysis" of equipment with porcelain posts was not always satisfactory, and a push was made to require shake table qualification tests of 220 kV to 500 kV equipment. This earthquake created “The Palm Springs Earthquake Task Force” that built on the lessons learned from various organizations within SCE and helped improve equipment specifications, component interaction, and robust foundation anchorages of transformers and shunt reactors. One of the most important studies performed by the task force was to examine component-to-component interaction. The recommendations of the task force included details to help reduce the impacts of conductor dynamic loading by providing adequate slack in conductors and the use of higher cantilever strengths for post insulators.

1991 marked the birth of the State of California's Seismic Safety Commission (SSC) which was responsible for reporting the progress of California’s earthquake hazards reduction program. This program was monitored by the California Public Utilities Commission (CPUC). The CPUC has jurisdiction of investor-owned natural gas, electric, telecommunication and water utilities; including the establishment of rates; and issues General Orders which outline recommended design practices such as wind loading for transmission towers. SCE's response to these efforts included development of uniform emergency response criteria and procedures, extensive replacement of live-tank circuit breakers, equipment seismic hardening, System Earthquake Risk Assessment (SERA) vulnerability analyses, and the study of relative deflection between equipment during earthquakes.

Along with damage at the Vincent substation, the 1994 earthquake produced PGA ~ 0.6g at the Pardee switchyard. There was major damage at Pardee yard, owing to toppled live tank circuit breakers, swinging wave traps, bus-slack interactions, all compounded by liquefaction that occurred in and near the yard. LADWP's re-built Sylmar 500 kV yard was again exposed to PGA > 0.6g, and against suffered heavy damage. More than (20) twenty 230 kV transformer bushings were broken at substations where PGA > 0.4g or so.

The 1986 and 1994 earthquakes galvanized action. A committee (IEEE 693) put together and issued, in 1997, the first industry-based seismic guideline for substation equipment, including requirements for shake table testing and, where suitable, qualification by analysis. Since 1997, this guideline has undergone continual review, with updates in 2005 and 2018 (in progress). In parallel, IEEE 1527 was created to provide guidance as to how to design flexible bus between adjacent pieces of equipment in high voltage substations.

After the 1994 earthquake, the focus was to continue and accelerate the milestones set in the 1991 by the CPUC and SSC. By the four year anniversary of the 1994 Northridge earthquake, SCE had replaced all live-tank circuit breakers, upgraded transformer anchorage at critical substations, dedicated spare parts inventory for earthquakes, retrofitted 500kV transformer bank jack buses, relocated seismically vulnerable high voltage surge arrestors and continued the Earthquake Recorder Program.

Starting in the mid-1980s and continuing through 2018, SCE has performed a variety of System Earthquake Risk Analyses (SERA). The SERA model includes a database of about 40,000 substation components, including essentially every piece of equipment at every 500 kV and 220 kV substation, and most of the equipment at 115 kV and 66 kV substations; every transmission tower; every distribution feeder. Every component is evaluated for its likely performance in any of 50 possible future scenario earthquakes, including forecasts of system-wide damage, repair efforts and outage times. These 50 scenarios represent large earthquakes on essentially every known active fault in the SCE service area. The model also produces damage forecasts for probabilistic earthquakes (like 100 year, 475-year, 975-year, 2,475-year, etc.), and can produce estimates of damage within a minute after any earthquake that triggers a ShakeMap from real instrumental recordings of ground motion (about ten M 3 to M 4 events per year in the SCE service area). The SERA model factors in local site conditions, liquefaction, landslide and surface faulting hazards. The SERA model helps SCE make rational planning forecasts, forecast power outages from various types of earthquakes, assess the cost effectiveness of various mitigation and emergency planning strategies, increase awareness of remaining seismic vulnerabilities, and overall become better prepared.

CONCLUSIONS

SCE is located in earthquake country. As earthquakes occur, SCE strives to learn its lessons, both of what "worked well" and "what had weaknesses". These lessons learned, coupled with ongoing efforts to purchase and install seismically qualified equipment, are geared towards reducing power outages in future earthquakes.

It would be nice to get to a configuration such that, one day in the future, a major earthquake on the nearby San Andreas fault or on one of the blind thrust faults under the densely populated portions of the SCE territory, will cause no more outages than a typical winter storm. It is doubtful that in 2018, that any power utility in the world is at this level of readiness. With this in mind, SCE continues to work to identify and implement those cost effective strategies that will help SCE move ever closer towards this goal.

UNITS, CONVERSIONS AND ABBREVIATIONS

The data presented in this paper uses both US customary and SI units. Conversions and abbreviations are as follows: 1 mile = 1.6 km; 1 inch = 25.4 mm; 1 mile = 5,280 feet; 1 foot = 12 inches; PGA = Peak Ground Acceleration, 1 g = 32.2 feet / sec^2 = 981 cm/sec^2 = 981 gal. kV = kiloVolt. km = kilometer. CB = Circuit Breaker. DS = Disconnect Switch. CCVT = Capacitance Coupled Voltage Transformer. PT = Potential Transformer. SF6 = Sulfur Hexafluoride gas. MW = Megawatt. ACSR = Aluminum Conductor Steel Reinforced conductor. M = Magnitude (moment). V = seismic base shear force. W = weight. SCE = Southern California Edison. PG&E = Pacific Gas and Electric. BPA = Bonneville Power Administration. SDG&E = San Diego Gas and Electric. LADWP = Los Angeles Department of Water and Power. SSC = Seismic Safety Commission. CPUC = California Public Utilities Commission. SERA = System Earthquake Risk Assessment.

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