Fragility of the Electric Power Grid

J. Eidinger

ABSTRACT

This paper examines the reasons that earthquakes damage substations, transmission towers and distribution systems, highlighting the damage patterns that lead to power outages. Much of the past seismic evaluation work has concentrated on damage to equipment at substations. Recent earthquakes show that damage to distribution and transmission systems also plays an important part of causing actual power outages, especially lengthy outages. The paper reviews the performance of equipment due to actual earthquakes in California. The paper highlights component fragilities that factor in all the substation, transmission and distribution inventory as well as the shaking, liquefaction, landslide and fault offset hazards.

Introduction

After nearly every moderate or major earthquake, there are news reports that there are "electric power outages". This is true in California, and true everywhere else in the world. I am tired of hearing this, and something needs to be done.

Beginning after the 1971 San Fernando earthquake, there has been a concerted effort by all the major California power utilities to examine seismic vulnerabilities of equipment at high voltage substations. This was logical as this is where earthquake damage was concentrated and easily observed. After many earthquakes and more than two decades of research, the IEEE 693 [1] seismic design guideline was created, which provides *recommended* practices for seismic design of substations. IEEE 693 was first issued in 1997, then updated in 2005, and now being updated again, as of 2018.

There is now strong evidence that the actual application of IEEE 693 in California has resulted in considerable reduction or near elimination of functional damage to equipment at high voltage substations. However, power outages are still occurring after moderate to strong earthquakes in California. There still remain various weaknesses in substations due to the ground shaking hazard, mostly due to the influence of conductor dynamics, lack of slack between electrically-connected pieces of equipment, and bushing failures.

There also remains considerable weaknesses in the high voltage (66 kV to 500 kV) transmission network due to landslide, liquefaction or fault offset hazards. There also remains considerable weakness in the low voltage (4 kV to 33 kV) distribution network due to all four seismic hazards (shaking, landslide, liquefaction and fault offset) as well as damage to third party structures that result in pull-down of the overhead distribution network.

This paper presents examples of recent earthquakes that have impacted the large investor-owned California utilities.

South Napa M 6.0, 2014 – Distribution Damage

A magnitude 6 earthquake occurred just west of the City of Napa, California, on August 24 2014. Figure 1 shows a map of the region, highlighting place names and populations, and the level of shaking expressed using horizontal PGA. Along the strike of the fault, PGA was in excess of 0.7g. Most of the urbanized part of the City of Napa (population about 77,000 people) experienced PGA of about 0.3g.

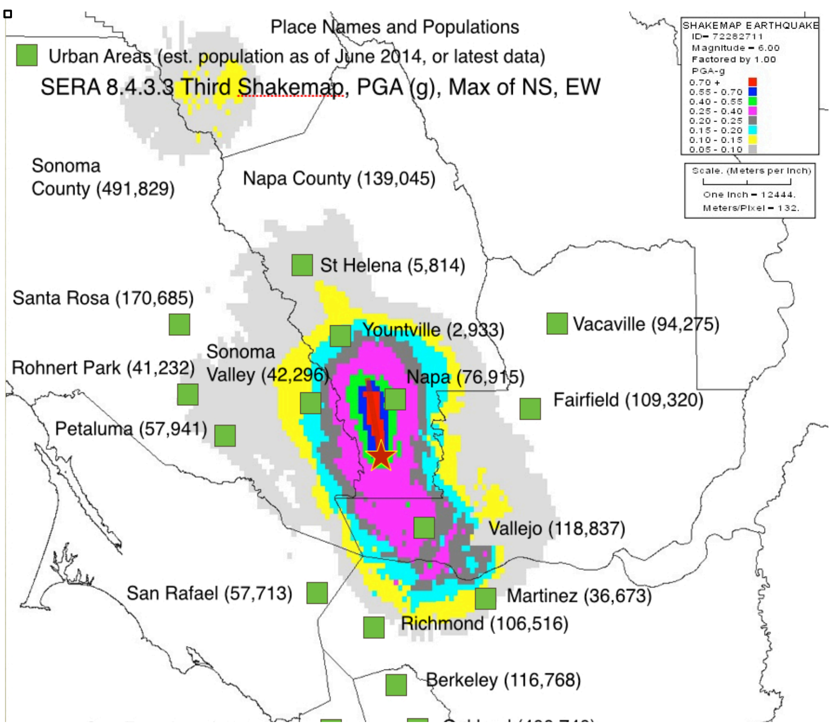

Figure 1. Place Names and Populations, SERA (PGA, g)

PG&E is the electric service provider for Napa. Nearly 90,000 PG&E customers in Napa and surrounding counties experienced one or more power outages during this earthquake. Figure 2 shows the power outage time chart for outages within Napa County.

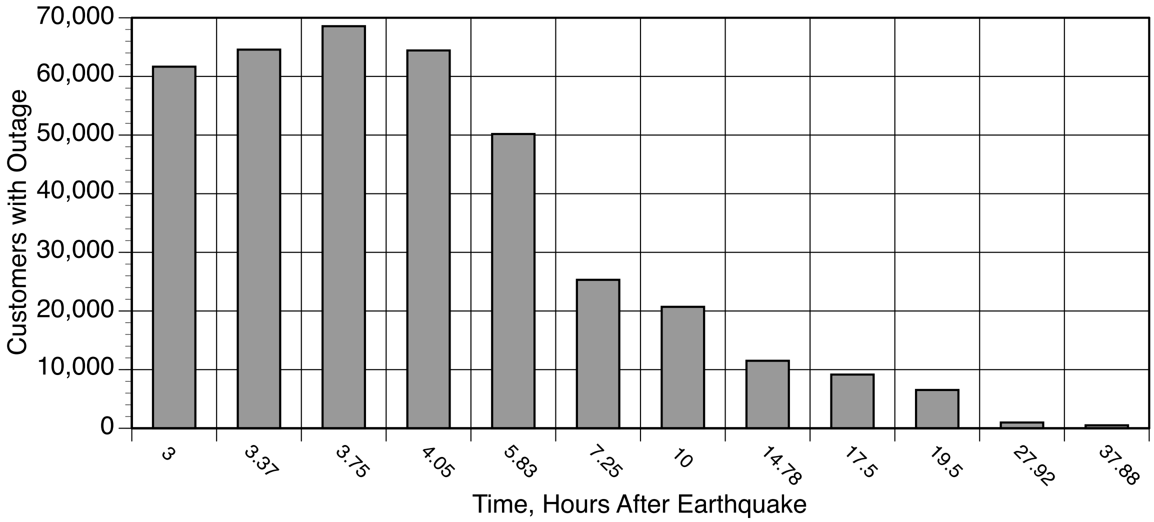

Figure 2. Power Outages, Napa County

The author visited all the large high voltage substations serving Napa within 48 hours after the earthquake. These substations included about 1,000 installations of 60 kV to 230 kV equipment, as well as several control buildings. These substations were exposed to horizontal PGAs between 0.16g and 0.35g. Most of this equipment had been installed in the prior 20 years. High voltage equipment (230 kV) had been installed to meet the seismic requirements of IEEE 693; lower voltage equipment had been installed with good anchorage, generally good slack provisions, and recognizing good seismic-detailing techniques. While there was some minor damage, there was *no damage of any sort in these substations* that resulted in any power outage to any customer [2]. We then examined the damage to PG&E's distribution system [3], and found about 120 locations where the earthquake had caused damage to low voltage (11 to 21 kV) overhead wire systems, and about 6 locations where the earthquake had caused damage to low voltage underground wire systems. There was no damage to the distribution system that could be attributed to the few third-party structure collapses. Several buried feeders crossed over the ruptured fault, but there were no wire failures, even though the wires were exposed to right lateral fault offsets of 3 to 9 inches. There was some liquefaction in the area, resulting in loss of bearing capacity and resulting in some tilted wood poles, but none of the pole tilting was severe enough to cause an outage. There was some landsliding, but none in areas where there was distribution system infrastructure. Reference [3] provides the fragility models that reflect the actual damage, and the key points are as follows:

- Buried distribution wire systems are seismically more rugged to ground shaking then overhead systems.
- The damage to the overhead system is well correlated to long period shaking (period about 3 seconds); and is not well correlated to high frequency motions (like PGA).
- The primary cause of the damage to overhead systems is that under strong shaking, the poles vibrate and deflect enough to exceed the available wire slack. Once wires become "tight", they impact high forces on their supports. Wood cross arms on poles can be broken due to high impact forces; damage to a cross arm can take a considerable amount of crew hours and time to repair. Small insulators and restraints at the customer's end of a

secondary line drop can be damaged when the available slack becomes tight.

- Other failure modes include overhead wire slapping and entanglements. Less than 25% of all the distribution damage could be attributed to wire slapping or entanglements.
- There were no cases of transformers "falling off" wood poles. This reflects PG&E's long-standing practice of bolting transformers directly to the pole.
- There were no cases of wood pole failures, even those with attached transformers.

Brea La Habra M 5.1, 2014 – Distribution Damage

A magnitude 5.1 earthquake occurred in Orange County on March 29 2014. Twenty substations were exposed to shaking with horizontal PGA from 0.17g to 0.42g. The corresponding long period (T = 3.0 seconds, 5% damping) spectral accelerations at these substations ranged from 0.007g to 0.021g. SCE is the electric service provider for this portion of Orange County.

The author visited all the larger substations that were exposed to PGA > 0.17g. Of these, the Olinda 220 kV substation was exposed to PGA > 0.3g, and had no damage. The bulk of the 220 kV and 66 kV yards at Olinda had been upgraded in the past 20 years, with all the new 220 kV equipment installed per IEEE 693. At a few of the older 66 kV yards, there was some minor damage (like rocking of weakly-anchored transformers), but none so severe as to cause an outage.

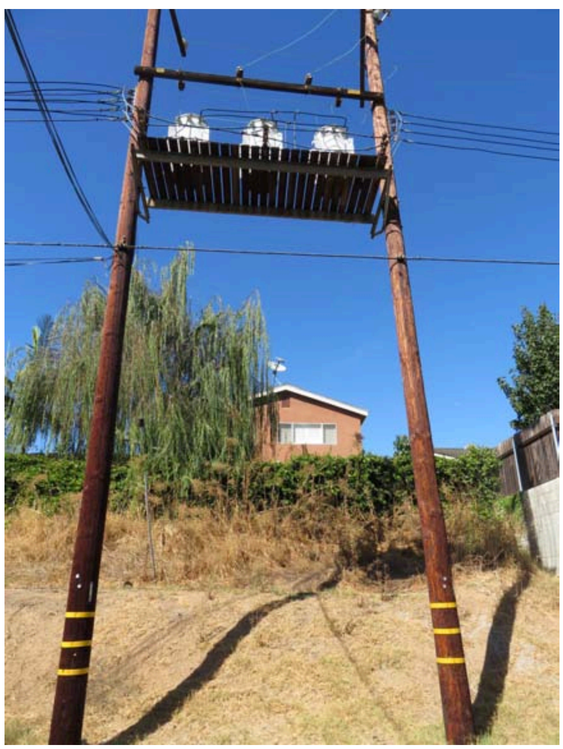

Figure 3. Unanchored Pole Top Transformers, Orange County

Unlike the Napa M 6.0 earthquake, power outages to customers were minimal. One distribution circuit faulted, serving perhaps 3,000 customers. That circuit was located in the epicentral area, where shaking likely exceeded PGA > 0.3g. The circuit outage was possibly (?) caused by rocking of an unanchored platform-mounted transformer, Figure 3. SCE currently has a program to identify all remaining unanchored platform-mounted transformers, with the intent to seismically strengthen them. In the 1952 Taft M 7.7 earthquake, more than 200 PG&E unanchored pole top transformers fell off their platforms, and the reason the ones in Figure 3 did not, even though exposed to high PGA, is attributed to the short duration of shaking (under 4 seconds) in this M 5.1 event. The actual shaking was likely high enough to initiate rocking and sliding of these transformers, possibly leading to a fault, but not long enough in duration to allow the transformers to slide far enough to fall.

Damage Statistics for High Voltage Substation Equipment

The author has developed a database of more than 100,000 substation components at nearly 3,000 substations, representing nearly every piece of high voltage equipment owned by the larger power utilities on the seismically active west coast of the USA and Canada. This includes nearly every component at more than 90% of all 500 kV substation as far south as the US - Mexico border and as far north as the Peace River in British Columbia. Every year, there are a number of earthquakes that shake these substations. The SERA software is used to compute and tally the level of shaking at each component for each earthquake, and from this, prepare statistics showing the performance of this inventory to various levels of shaking. Where there has been damage, or where shaking has been especially high, the substations are inspected to confirm the good performance, minor damage, or major damage as the case may be. The database has more than 2,000 separate fragility models for different types of equipment and with different installation practices (no, light or strong anchorage, tight, moderate or major slack, different types of bushings, etc.). Some statistics for Equipment from these analysis shows the following:

- 802,488 pieces of equipment have been exposed to shaking PGA > 0.001g in Southern California, and a additional 1.3 million pieces of equipment in Northern California.
- These pieces of equipment are grouped into 20 classifications, like power transformers, circuit breakers, disconnect switches, CCVTs, surge arrestors, etc. Each piece is further classified by voltage, manufacturer model number, and installation type (anchored, unanchored, with slack, no slack, type of bushing, etc.)
- Within the Southern California inventory of 802,488 exposures, 4,988 are dead tank 500 kV circuit breakers. Of these 4,988 exposures, 23 were at PGA = 0.16g; 12 at PGA = 0.14g; 43 at PGA between 0.06g and 0.10g; the remainder at PGA ≤ 0.05g. There were no functional failures in any of the 4,988 exposures.
- The most common 500 kV circuit breaker in this inventory is Mitsubishi, 500 kV SF6 dead tank type, Figure 4, with 2,349 exposures. Of these 2,349 exposures, 4 were at PGA = 0.16g; 12 at PGA = 0.14g; 25 at PGA between 0.06g and 0.10g; etc.
- This information establishes that this type of circuit breaker is seismically rugged up to at least PGA = 0.16g; probably much higher. Dead tank 500 kV breakers have been shake table tested and qualified per IEEE 693 for PGA = 0.5g, so these empirical observations are not surprising; but are reassuring. With time, as more earthquakes occur and produce strong shaking at equipment, these results can calibrate the various fragility models.

Figure 4. 500 kV SF6 Dead Tank Circuit Breaker

Damage to Transmission Towers

The failure of transmission towers in earthquakes remains one of the more problematic vulnerabilities that can lead to widespread and long duration outages in the power grid. The partial collapse of three 66 kV towers in the 2016 Kyushu, Japan earthquake [4] led to complete power outages for many smaller rural communities in the Mount Aso area. Ultimately, it required construction of more than 30 replacement towers to restore delivery of power to that area via the transmission grid; short term restoration took about a week, by using low voltage emergency generators to power undamaged segments of the distribution feeders.

Transmission tower failures have occurred in the 1999 Chi Chi earthquake (surface faulting), the 1994 Northridge earthquake (landslide), and can be expected in future earthquakes. Worldwide, transmission tower failures (and successes) have been tabulated for more than 30 earthquakes, with the following general observations:

- Strong ground shaking (PGA > 0.5g) does not collapse towers. At PGA > 0.2g, minor damage (bowing of secondary members, etc.) occasionally occurs, but this damage is not so severe as to cause a fault. Structural analyses of typical 115 kV towers (originally designed to reach initial yield at a wind speed of about 75 miles per hour) show initial yield or buckling of primary members is reached at about PGA > 1.25g, assuming the towers are not loaded by strong wind at the time of the earthquake. This is not surprising, as under dead weight, primary tower members are often loaded to under 4 ksi stress (less than 15% of yield).

- Deep-seated landslides can damage or fail towers. Structural analyses and empirical evidence show that most four-legged steel lattice-type towers can sustain more than 12 inches of differential movement between the four legs. One failure mode is column buckling, due to pull-down of one leg located within the landslide that induces high compression and buckling of another leg located outside the landslide.
- Liquefaction often occurs at towers. If there is no concurrent lateral spread, the towers generally sustain the ground deformations with only secondary member buckling. If a tower leg uses a heavy concrete foundation embedded in a sticky / stiff clay, and that formation is exposed to ground settlements, there is a higher potential for tower failure than if the tower uses light steel grillage-type foundations in granular materials. Liquefaction at poles will often result in some tilting of the pole due to the temporary loss of bearing capacity that is needed to resist unbalanced lateral line loads; most often, the tilting is not so severe as to cause a fault or ground clearance problem; this damage can be repaired months (or years) after the earthquake.
- Surface faulting can seriously damage or collapse a tower. This has happened just a few times, worldwide. The failure mechanisms are similar as for landslide or liquefaction. Surface faulting that occurs outside the boundary of the tower legs does not appear to be damaging. Most 4-legged towers can readily accommodate 1 to 2 feet of right lateral offset between the four legs. Single pole-type towers that have been exposed to several feet of offset are observed to tilt (but rarely break); but if the tilt is severe enough, then ground clearances and cable slacks can be impacted and repair is required.

Conclusions

With the implementation of IEEE 693, new substation equipment in California has performed very well (no functional damage) in recent earthquakes that have exposed such equipment to shaking with PGA = 0.3g to 0.4g. This is good progress. Over the next 10 to 20 years, as more and more substation equipment gets replaced with seismically-qualified equipment, the substation vulnerability will be materially reduced or nearly eliminated.

Transmission and distribution systems (towers, poles, overheads, underground cables) in California, and elsewhere in the world, essentially have no seismic standards. Recent earthquakes shows that these components are often damaged. Overhead distribution systems will sustain damage due to moderate to strong shaking. Underground cables will be damaged due to large imposed ground deformations. Transmission towers are especially vulnerable to landslides.

In California, there are more than 5 million distribution and transmission towers and poles. Some of these are exposed to landslide, surface faulting and liquefaction hazards.

Earthquakes with M ≥ 6.0 are large enough to damage overhead distribution feeder circuits; long duration energy (prevalent in M ≥ 7 events) causes the most damage. This damage can be widespread, and in longer duration earthquakes, will damage one or more locations on most overhead feeder circuits where PGA > 0.3g. Outages due to distribution system can be short (under a day or so) if the affected population is under 100,000 or so and the repair force large enough. Outages will be longer in higher magnitude earthquakes that produce strong long period shaking over major urban centers; or in situations where there is only a small repair force available. Most utilities have taken action to mitigate some distribution-system vulnerabilities, like unanchored pole top transformers; but much more work remains to be done. In the next 50 years or so, as more distribution feeders become undergrounded, the more common seismic weaknesses of the distribution system (due to cable dynamics) will be reduced; partially offset by increased issues with buried cables exposed to landslide, liquefaction or surface faulting. Seismic design requirements for new buried cable installations are needed. Modest cost seismic mitigation for poles in liquefaction zones can be implemented over time, by using longer embedment depths, which will cure some (but not all) of tower tilting. Reducing damage to overhead poles due to landslide is problematic, as the cost to mitigate (fix the landslide, avoidance) is often cost prohibitive, and such costs need to be paid for by the customer; residential customers served by distribution system that traverse landslide zones might just need to accept that risk; commercial customers with high-value economic activity may be willing to pay for mitigation.

Landslide hazards appear to be a considerable threat to transmission towers. A moderate M 6 to M 7 earthquake might damage a handful of transmission towers; each failure can lead to a lengthy power outage (days to a week or so). A large M 7.5 to 8 earthquake, if it occurs during the winter season when soils are saturated, can simultaneously trigger hundreds or thousands of landslides; and when coupled with concurrent surface faulting and liquefaction, a single earthquake could damage potentially dozens of towers. This could lead to very long outages for large populations, possibly weeks or more. Cost effective mitigation could include relocating the tower(s) outside the highest risk landslide / faulting zones; in-place mitigation for towers subject to liquefaction can often be effectively implemented.

Longer term mitigation strategies (10 to 20 years) should include the following: continue to implement IEEE 693 provisions for new installations; improve cable slack practices at substations; develop and implement seismic design standards for buried cables; continue to underground overhead distribution feeders where suitable based on non-seismic reasons; identify transmission circuits most vulnerable to landslides / faulting / liquefaction and establish new network redundancy or other emergency response strategies to avoid the potential for length (multi-week) outages to large population centers.

References

1. IEEE 693, Recommended Practice for Seismic Design of Substations, Substation Design Criteria Committee of the IEEE Power and Energy Society (1997, 2005, 2018).
2. Eidinger, J. (Ed.). South Napa 6.0 Earthquake of August 24 2014, TCLEE No. 1, April 2017.
3. Eidinger, J., Fujisaki, E., Sun, J., Trinh, R., Fragility of Power Distribution Systems, *16th World Conference on*

Earthquake Engineering, Santiago, Chile, January 2017.

4. Tang, A. and Eidinger, J. Kumamoto, Kyushu, Japan Earthquakes of M 6.0 April 14, 2016 and M 7.0 April 16, 2016, TCLEE No. 2, May 7 2017.

References 2, 3, 4 are available at *http://www.geEngineeringSystems.com*.