RESILIENCY OF POWER SYSTEMS: EARTHQUAKES, WIND AND FIRE

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Abstract

Electric Power Systems are the backbone of our communities. High voltage substations (commonly 230 kV to 500 kV) have been shown to be extremely vulnerable in many earthquakes; some modern designs failed (Laguna Salada California 2010) and some modern designs did great (Napa California 2014). Power outages due to future windstorms in California can last many months. The western United States and Canada are exposed to severe forest fires, and these can cause power outages approaching a year or more.

The report examines some of the causes of these long power outages. Some are man-made (we build fragile systems and we skimp on rigorous design) and some are ignorance made (we pretend we think rare hazard events are rare…. except when they are not).

There is no single ideal post-earthquake (earthquake, wind, fire) restoration time that is cost effective for every community. While some idealists would like power to mandate that power be restored in a day (or so) after a rare event, the reality is that there are many hazards that can lead to power outages lasting months (or more) in rural areas; and possibly weeks in high density urban areas.

Our community's goal should be to implement cost effective strategies that reduce the time of these outages, while not materially increasing current costs to buy power. Should these strategies be set by self-regulating power utilities? Or should the goals be set by the Government?

Wind

In California, General Order 95 sets the requirements for building transmission towers. Essentially, nearly every tower in California has been designed for a nominal 56 mile per hour (MPH) wind speed, at elastic working stresses, with a factor of safety against yield of either 1.5 (more important towers) or 1.25 (less important towers) (similar for buckling). Since we commonly design regular buildings in California for 85 mile per hour winds, is something wrong here?

General Order 95 was developed by knowledgeable transmission system engineers in 1948, with the recognition that over the prior 2 or 3 decades, "not many" towers fell down in California. Thus, the 56 mph wind speed was presumed to be cost effective. Today, if one wants to build a tower in California, one can build for a higher wind speed, but the regulatory agency may not allow the extra costs to be passed onto the rate payer.

This state of affairs has served California well for the past half century. Not many towers fall over every year. Yet, a small thunderstorm recently knocked over a few towers on the 500 kV DC Intertie between Oregon and California. And for those towers that do fall over, the "N-1" rule means that the transmission network remains reliable with the loss of one transmission line. But, a recent wind storm in Pasadena had wind speeds measured at 140 mph, and there was a lot of power system damage… and the electric company crews making repairs in Pasadena were sometimes scared at the hostility shown by people who were suffering power outages exceeding a couple of days.

In Oregon, Washington and Idaho, the Bonneville Power Administration (BPA) owns and operates most of the high voltage network. Transmission tower failures due to wind and ice are not that uncommon. Figure

1 shows the history of failures to BPA's towers from 60 kV to 500 kV). Figure 2 shows a 500 kV tower that collapsed in 2010… it has been designed for 100 MPH winds, but the nearest weather stations recorded only 50 MPH. The American current building code requires regular buildings to be built for 85 MPH in these states. BPA designs their towers for 120 MPH / 100 MPH (on the tower / on the conductor). Yet, towers keep failing.

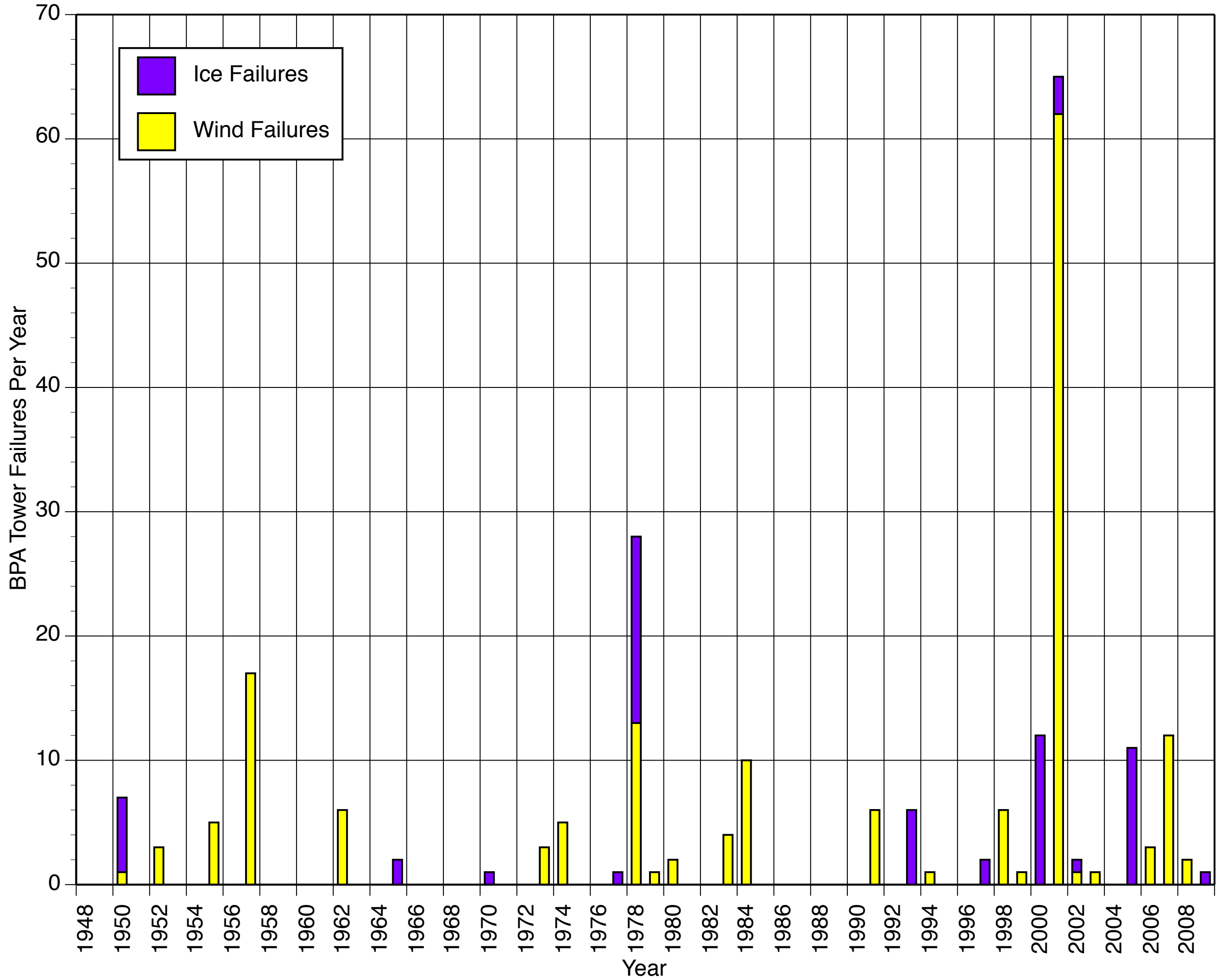

Figure 1. Transmission Tower Failures in Oregon, Washington and Idaho

Figure 2. Collapsed 500 kV Transmission Tower due to High Wind, 2010

Fire

California regularly suffers from forest fires. Figure 3 shows the areas of California that have burned one or more times (red areas) in the last century. The red areas correspond to nearly 100% of the forested and high fuel areas of California. The annual rate of forest fires is increasing. About 97% of these fires are man-made. Given this story, we can assume that nearly every forested and high fuel area of California will burn again…. And when that happens, how much of the power system will burn down with the fire?

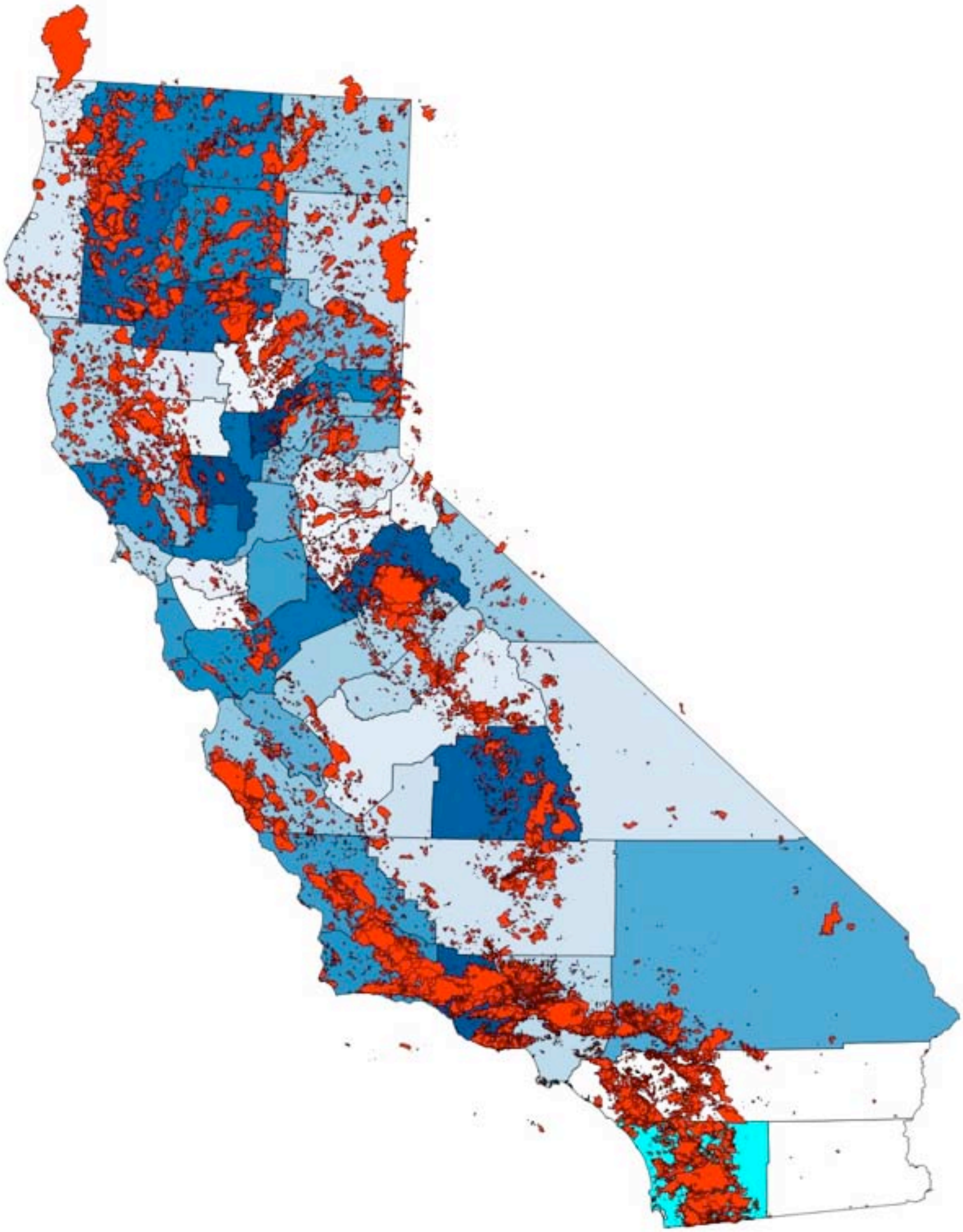

Figure 3. Historical Large Forest Fires (10 acres or more, red zones) in California, 1878 – 2013. (Blue colors refer to county boundaries).

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The primary threat to power systems is on three fronts: the burning of individual overhead structures (most of them are wood poles) with corresponding failure of the circuit; the ultimate size of the fire, in that larger fires burn multiple circuits at the same time; and the repair capability of the utility after the fire. In the past, the number of overhead structures within a single fire is about 100 poles every year someplace in California, 1,000 poles every 5 to 10 years, and more than 10,000 poles about once a decade or so. The open questions for establishing restoration times are: given that a wood pole is located within a forest fire, what is the chance it will burn sufficiently as to require immediate or delayed replacement? how many spare poles does a utility keep on hand? How many crews can a utility muster to re-build burned poles and circuits? New research shows that about 80% of wood poles survive California's forest fires without replacement; of the remaining 20%, about half are burned sufficiently that the fail immediately (or with a light gust of wind); and the other 10% are replaced as part of the overall restoration process. This last 10% represents a thorny question, as the poles are not damaged by the fire, so why should the California Public Utilities Commission authorize payment? Once the decision is made to replace poles, should the "rapid and low cost" process of replacing "like for like" be done (putting up a new wood pole for a burned wood pole), or should a more expensive (about ten-fold or more) process of undergrounding be done? One can readily imagine future fires in California that will spread to engulf 20,000 to 30,000 or more wood poles. In Ontario and Quebec in 1998, a ice storm damaged 30,000 wood poles, and it took 6 months for some of the largest North American power utilities to complete the rebuild effort.

When face with the fire threat to the wood pole power system, one can ask: why not require a boundary around each pole where vegetation growth is controlled? In California, the de-facto rule is that for poles supporting power transformers, fuel load must be curtailed within a 10 foot radius from the pole. This strategy comes from the idea that the transformer may ultimately fail, and sparks from the transformer should not start a fire. In urban and suburban areas, it is not uncommon for about half of all poles to have a transformer; whereas is low density rural areas, one a tenth to a quarter or so of poles have transformers, and thus the majority of poles have no clear fuel load "sort of defensible" space.

The fire threat is further complicated as suburban areas have spread into high fuel load areas, where a fire ignition that starts many miles away can eventually spread into a conflagration that encroaches on the urbanized area. This encroachment into urbanized areas happens almost annually in California, happening almost annually in southern California. In northern California, such fires occurred in 1923 (burning about 550 homes in Berkeley) and 1991 (burning about 3,000 structures in Oakland). In such cases, overhead poles burn too, and the performance of underground lines remains an open issue: in the 1991 Oakland fire, undergrounded telecom lines were still damaged by the fire, as the high heat induced high heat in metallic conduits, thus failing the cables within.

Figure 4 illustrates the fire threat for San Diego County. The average number of large fires per year is now about 17. While most of these fires encompass just 1 to 5 wood power poles, some have encompassed more than 10,000 wood poles. There is a trend for the size of fires to get larger, even while more and more fire stations are built. A large fire in California can easily encompass 100,000 acres, with the larger fires encompassing about 1,000 square miles. The great San Francisco Fire after the 1906 earthquake only encompassed about 4 square miles. As the human population continues to rapidly expand into the high fuel load areas, the chance of mega-fire disasters increases. The established fire practices for overhead power lines (wood poles, only maintain clear fuel load space for poles with transformers) will not address this risk. New concepts, like using only steel poles, building greater space between phases of power lines, more undergrounding, etc. are approaches that can reduce the fire threat to and from power systems in fire zones. All these concepts require heavy capital investment, and the benefits (the reduction of future losses) are not clearly understood.

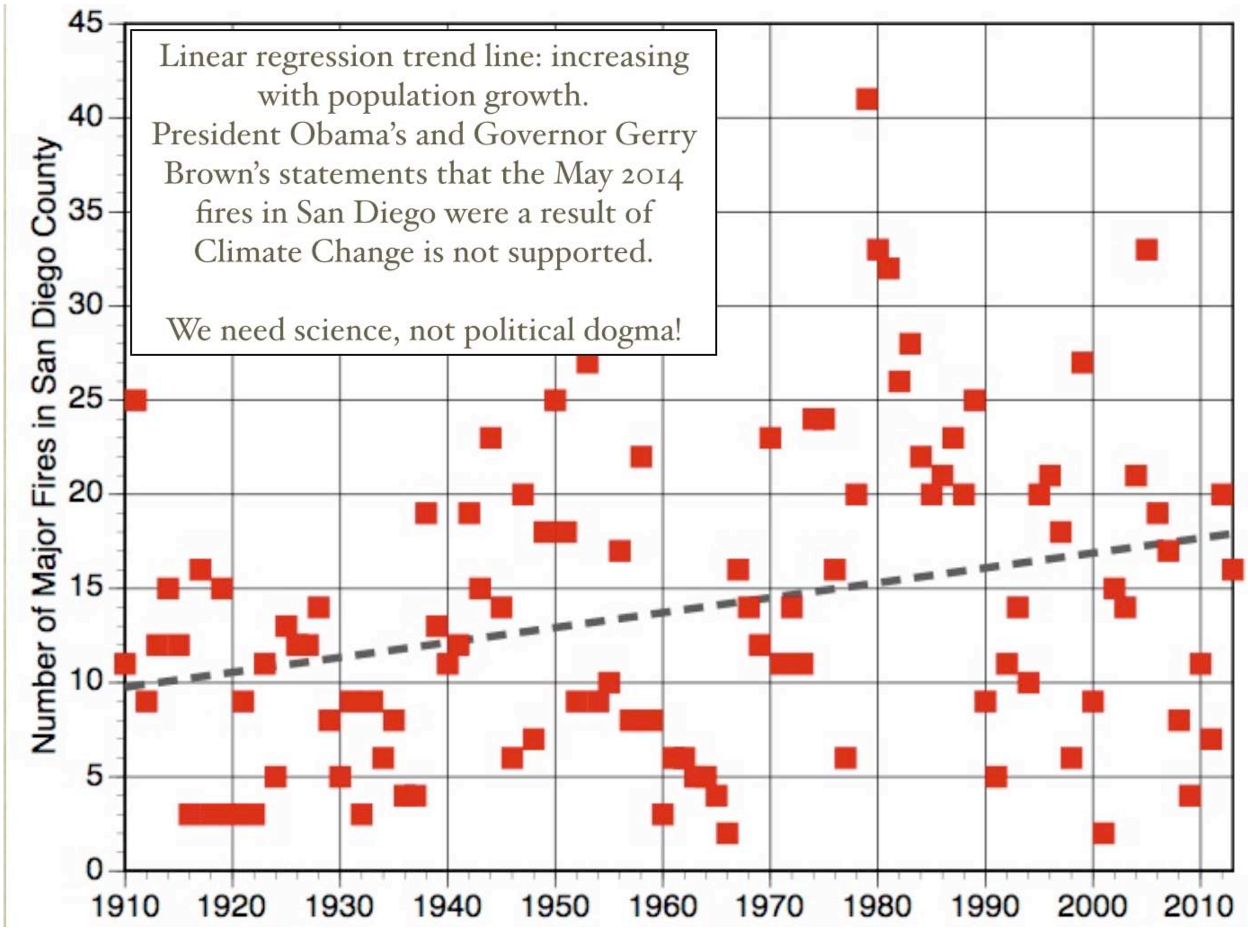

Figure 4. Annual number of large fires (10 acres of more) in San Diego County, 1910-2013

Earthquake

The issues with earthquake-induced damage to power systems has been well documented. The Taft 1952 M 7.7 earthquake failed more than 800 distribution transformers, and toppled over a number of 115 kV transformers in substations… and served as a clear guideline to anchor transformers. Today, nearly all of PG&E's transformers are well anchored, but in countries like China, unanchored 110 kV to 500 kV transformers continue to break in every earthquake, and the State Grid informs us that "unanchored transformers are safe". Can both America (PG&E with anchored transformers) and China (State Grid with unanchored transformers) both be right?

But the earthquake issue for power systems goes far beyond anchorage of transformers. There are many areas of continuing development of better seismic practices, ranging from how bushings are connected to aluminum castings; cable slack between components in substations; the amplification and beating effects of multiple similar-frequency appendages (bushings, surge arrestors, radiators, oil tanks) on transformers; and the like. Outside the substation, the damage to buried cables in liquefaction zones is now well documented, with more than 500 buried cable failures in Christchurch New Zealand earthquake sequence of 2010-2011. Wire slapping and cable slack issues remain the primary ways that overhead power systems fail. In the recent 2014 Napa earthquake, PG&E's customer power outage were as shown in Figure 5. Every PG&E substation that had ground motions with PGA > 0.20g was inspected, and not a single piece of equipment was functionally damaged. The power outages were almost entirely due to wire slapping-related issues in the overhead distribution system (about 97% of outages) and failures of underground cables (about 3%).

In Figure 5, the PGA levels in the various communities were about:

- Napa. PGA 0.3g to 0.5g
- Saint Helena. PGA < 0.05g
- Santa Rosa PGA < 0.05g
- Sonoma. PGA 0.1 to 0.2g
- Vallejo. PGA 0.15g to 0.25g

Not all customers in Napa lost power.

Current thinking is that long period motion is the controlling hazard parameter for damage to overhead circuits, and not Peak Ground Acceleration.

When doing the surveys of the PG&E system in the days following the earthquake, people uniformly thanked PG&E crews for their efforts to restore power.

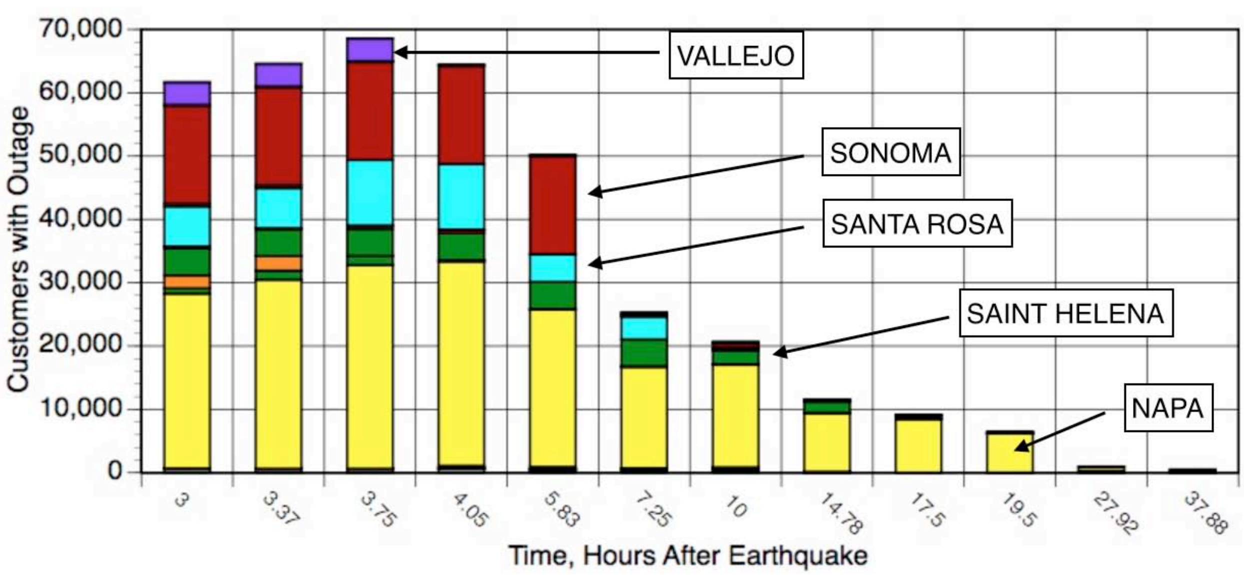

Figure 5. Power Outages, PG&E, Naps Earthquake of August 23 2014

In the years prior to 2014, PG&E had substantially re-built its high voltage substations in the Napa area. A few PG&E substations were exposed to PGA = 0.3g to 0.35g. No item that had been designed for PGA = 0.5g (the current IEEE seismic guideline for high voltage equipment in California) was damaged at these substations, which indicates that PG&E, and the IEEE 693 seismic guidelines, are beneficial.

The April 2010 earthquake in southern California (Laguna Salada M 7) seriously damaged a modern designed 500 kV substation. This substation was originally constructed in the 1980s, and every component that had been installed had been subject to seismic qualification, typically for PGA = 0.5g. The actual ground motions at the substation were about PGA = 0.3g. The 500 kV yard suffered widespread damage, and all power transformer banks had one or more damaged units. The 500 kV yard was reconstructed rapidly (in a day or so), but repair of the transformers took months. No customers in San Diego lost power due to the damage, as the N-1 capability allowed power from alternate sources serve the entire load. Today, it appears that a primary reason for the damage was impacts between equipment due to inadequate cable slack, and mitigation at this substation is ongoing. Many shake table tests are being conducted to better understand and quantify the forces in the cables due to impacts caused by differential movements of adjacent pieces of substation equipment.

What are Acceptable Outage Times, and Who Pays?

Each hazard (wind, fire, earthquake) impacts and can damage power systems. Loss of power supply results in loss of economic activity to customers, affecting the economic well being of the community.

In the open forum of the workshop, it is hoped that the following questions / issues will be discussed.

- There are those amongst us who would like to adopt a policy like: "restore power to 99% of all customers in the affected region, within 24 hours after the earthquake (fire / storm)".
- Intelligent consideration shows that this policy might be seriously flawed: what is the return period? Should the restoration time be different in urban and rural areas? How much will it cost to achieve this policy?
- Is it technically achievable to achieve this policy?
- When is it cost effective to do seismic (wind, fire) mitigation, and when is it best to "clean up after the fact"?
- Should the power industry self-regulate (as it now does with IEEE 693), or should the Government impose the guidelines?
- If Government leaders make public statements in May 2014 that the fires in San Diego County were a result of Climate Change, within a day of the fires, and before even examining the facts, can Engineers trust the Government to make sound public policy in areas of extreme natural hazards?
- No matter who makes the policies, who will enforce them, and will the ratepayers be eager (or mandated) to pay?

Photo Credits

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