Fragility of the Electric Power Grid

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Perspective

• In nearly every M 5+ earthquake, there are reports of “Power Outages”

• 1971 - 2013. Many earthquakes damage high voltage equipment at substations. Outcome: IEEE 693 (1997) (ShakeTable tests at PGA = 0.5g for 220 kV - 500 kV equipment)

• 2014. Napa M 6.0 earthquake. No damage at high voltage substations (PGA ~0.2g to 0.4g). Still, 90,000 customers still lose power.
What is Happening that Still Causes Power Outages?
The Model

• SERA: risk model to quantify power outages at substations, transmission towers and the distribution system

• SDG&E, SCE, PG&E, PPL, BPA, BC Hydro (90% of the power grid from Mexico to the Yukon)

• Inventory includes every component at every substation; every transmission circuit; every transmission tower; every wood pole; every overhead and underground distribution feeder
The Issues

- Interactions between Equipment. Still a problem at many substations. A major problem in the distribution system.

- Fragility. Over 2 million “exposures” of equipment in actual earthquakes.

- Towers. Landslides present a significant risk (fault offset, liquefaction are relatively smaller risks).

- What is an “acceptable” power outage? Customer-Minutes (CM)

- Mitigation Benefits. If we can reduce CM, there is less economic impact. For California use $0.11 per CM outages.

- Cost. Rate payers want low cost / kilowatt-hour.

- Benefit. Present value of Mitigation Costs should be < Present value of future Benefits.
Test PGA = 1.00g, Broad Band, IEEE 693
Loma Prieta Power Outages
Feeder Service

FEEDER IN SERVICE
Median Response
- 80% + Chance
- 60 - 80% Chance
- 40 - 60% Chance
- 20 - 40% Chance
- 00 - 20% Chance
SERA Forecasts vs 18 significant Earthquakes, 1980 - 2017
Petrolia 1992, San Simeon 2003, Eureka 2010, etc.
Equipment Performance in Historical Earthquakes
Figure 3-21. Epicenters of Historical Earthquakes in Northern California 1980 – 2018, $M \geq 5.0$
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12 EQs with PGA > 0.40g in 38 Years (Return period is 3.2 years for the “475” year EQ)

9 EQs with PGA > 0.60g in 38 Years (Return period is 4.3 years for the “975” year EQ)
Fragility Exposures
Substation Equipment

20 Equipment Classes
(CB, TR, CT, DS, EG, etc.)

4 Voltage Ranges
500 kV
230 kV
115 kV
66 kV

Well anchored / installed
Marginal Installation
Poor Installation

Every Major Equipment Vendor

Over 70,000 Installations
100s of Shake Table Tests
100s of Qualification Reports
Component-Specific Slack
Over 2,200 Fragility Models
Cumulative Number of Exposures, 20 Equipment Classes

- 14,018 equipment exposures to PGA = 0.10 or higher
- 5,068 equipment exposures to PGA = 0.20 or higher
- 1,928 equipment exposures to PGA = 0.30 or higher
- 175 equipment exposures to PGA = 0.40g or higher
- 100 equipment exposures to PGA = 0.50g or higher
- 34 equipment exposures to PGA = 0.60g or higher
- 32 equipment exposures to PGA = 0.70g or higher
- 17 equipment exposures to PGA = 0.80g or higher
Number of Exposures, Seismic Battery Racks
Number of Exposures, 115 kV SF6 CB
Conclusions

• To forecast Power Outages, the SERA model needs to include all Substations, Transmission Towers, Distribution

• To get Restoration Times: Add up the damage, divide by the repair crew size

• How big a Repair Crew is ideally needed for “The Big One”? 1,000 people is “not enough”. 10,000 people is a better. 25,000 or more might be best.

• What is an acceptable power outage? 40 million customer-minutes should be “okay”. With 1,000 repair crew, “billions and billions of CM” is a possibility.
What to Do?

- **Mitigation.** Much of the “inertial” upgrades is already done at high voltage substations. (some fine-tuning, and old equipment replacements, Tuned Mass Dampers / bushing fixes, will solve the remainder). 10 more Years for California.

- **Cable Slack:** A big remaining vulnerability. With time and good installation practices, this too can be solved for substations. 10 Years for California if pursued aggressively.

- **Towers.** Landslides are an open item. At least 10 Years for selective relocations.

- **Distribution.** There are no seismic standards. Cable Slack is the biggest open issue. Undergrounding will help (50 Years). Big repair crews will help.
Questions?

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