Defining and quantifying the resilience of electric power systems to natural hazards

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Motivation

Power systems, as the backbone of modern industry, have been equipped with sophisticated analytical tools such as power flow, state estimation, and transient stability analysis to ensure reliable and economic operation. However, none of these tools consider natural hazards, which can pose a significant threat to reliable and efficient operations of power systems, despite their low probability of occurrence. Infrastructure networks are also increasingly reliant on each other for their functionality, as presented in Figure 1. In a New Zealand context, simulation of network disruption showed that approximately 53% of user disruption was due to direct disruption to an infrastructure network (Figure 2). However, indirect disruption due to infrastructure dependencies was dominated by dependence on the electric power systems. This project aims to define and quantify resilience of electric power distribution infrastructure to natural hazards in terms of degradation of system function.

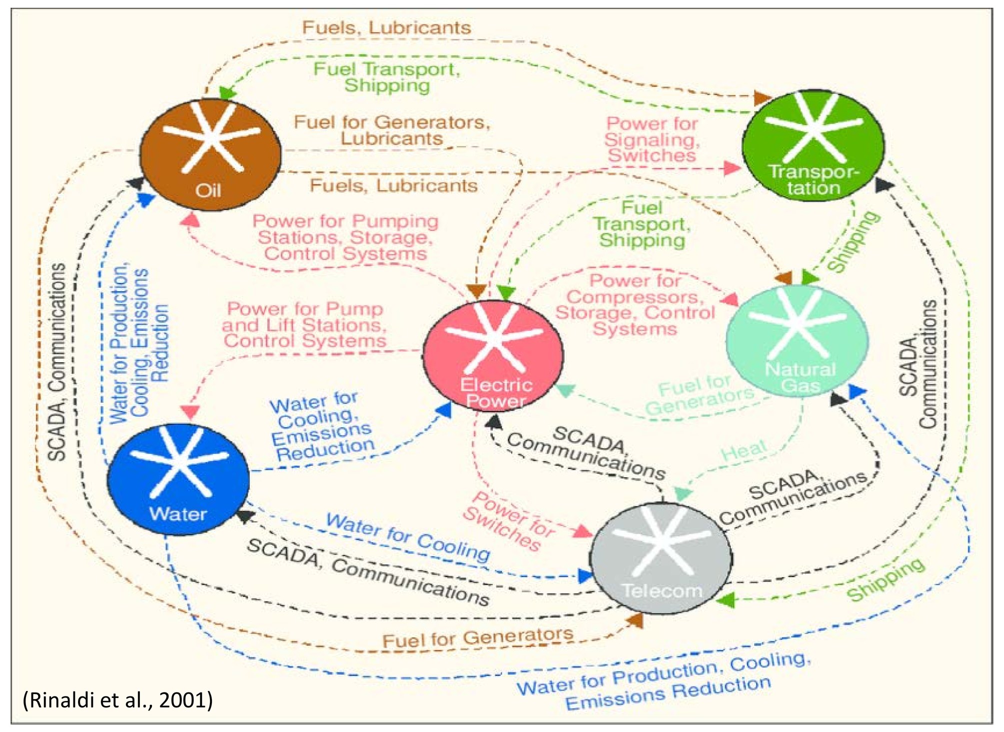

Figure 1. Examples of infrastructure interdependencies

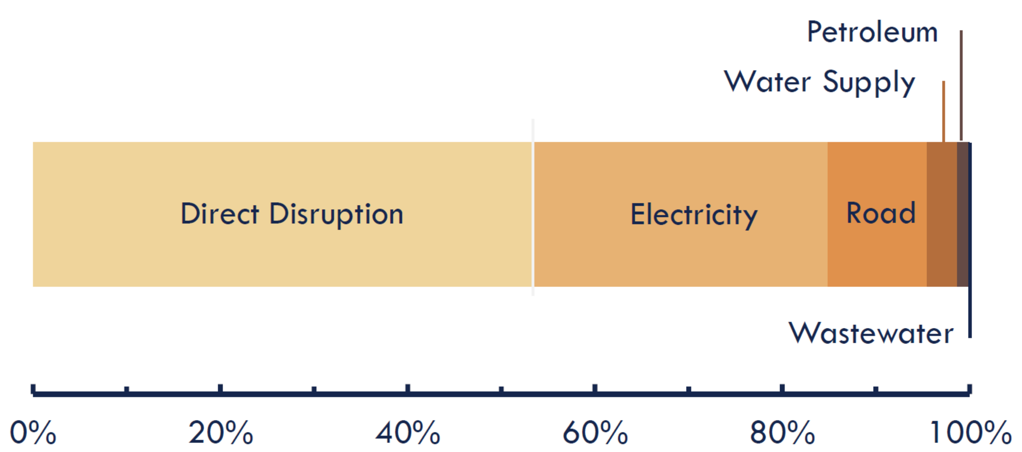

Figure 2. The proportion of direct disruption to infrastructure networks compared to indirect disruptions due to dependencies across NZ national infrastructure networks (Zorn)

Model

System failures due to natural hazards is simulated taking into account hazard intensity, component fragility and their configuration. The model considers functionality level of each individual component, interactions between components within the network and the ultimate impacts on the whole network (Figure 3). The model and simulation tools are developed under Python scientific computing environment.

Simulation and Outputs

Hazard impacts are simulated using Monte Carlo method given failure probability of each system component, which is jointly characterized by fragility functions and hazard intensity. The power distribution system resilience is measured in terms of loss of load (in kW or kVA) and/or number of lost service points. Simulation output is a number of probable scenarios with impacts measured by the resilience metrics and the probability for each scenario to occur i.e. probability mass function of the resilience metrics. Base on simulated distribution of the resilience metrics, unserved demand can be estimated with varying confidence interval. A simple standard distribution test feeder shown in Figure 4 is simulated as an illustrative example. The test system contains a regulator, a transformer, a switch, 12 poles and 8 overhead lines. The total load of the system is 3266 kW. Figure 5 shows a set of probability mass functions of lost loads with varying sample sizes and component failure rates. Increasing sample size leads to decrease in coefficient of variation indicating convergence. A higher component failure probability results in increase in both lost demand and the probability that it is likely to occur.

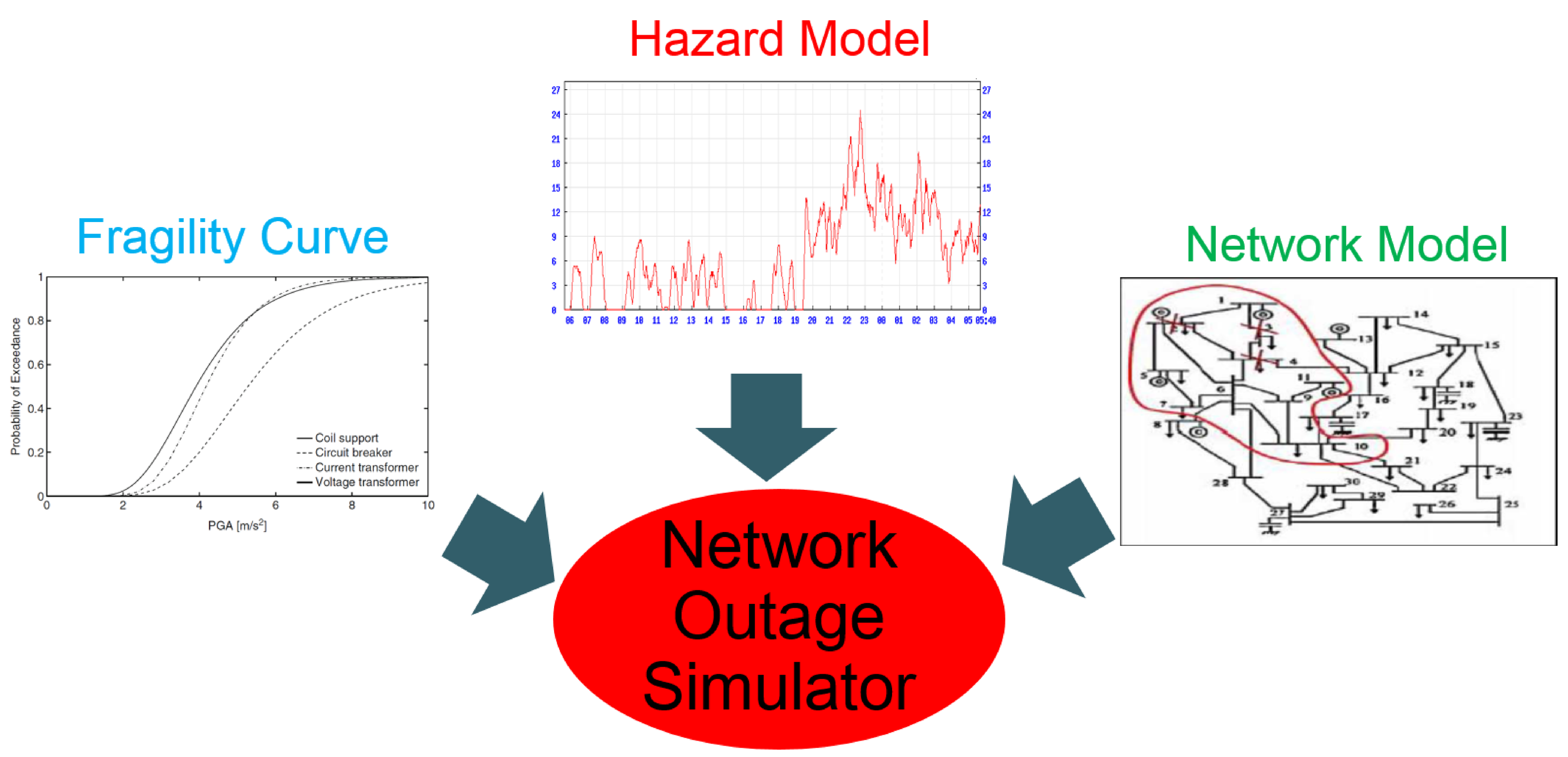

Figure 3. Simulation framework

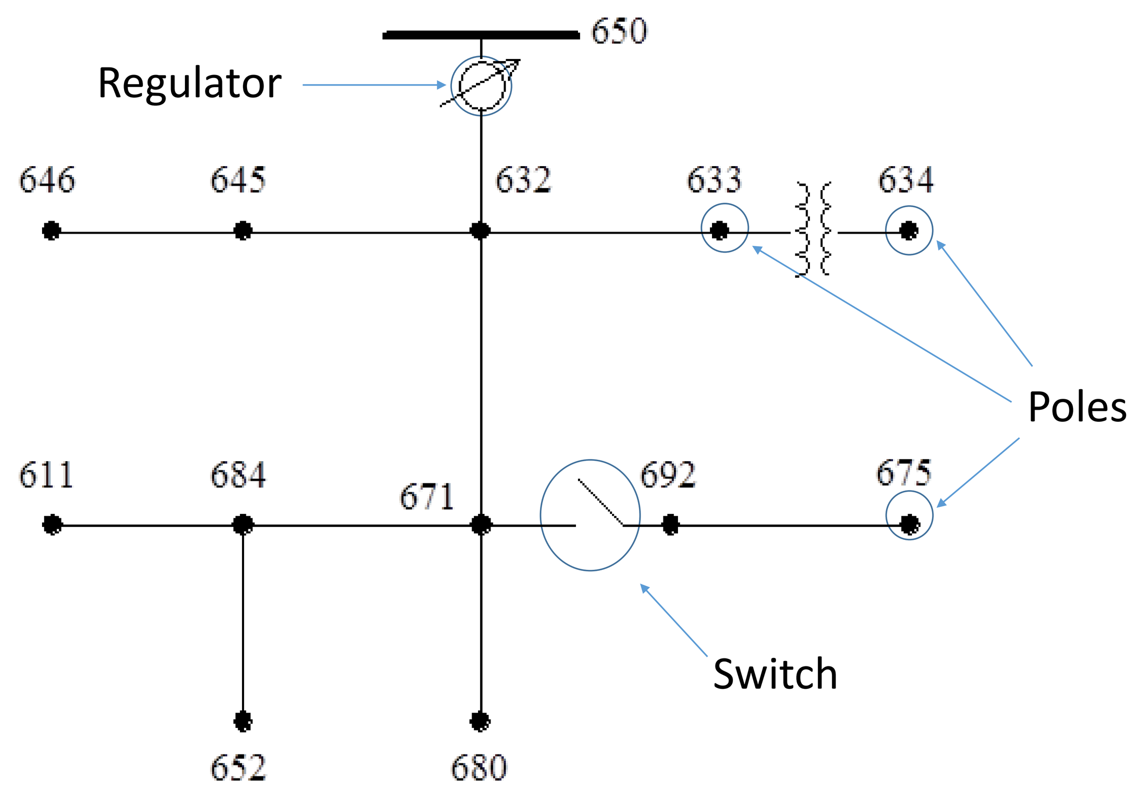

Figure 4. IEEE 13 node distribution test feeders

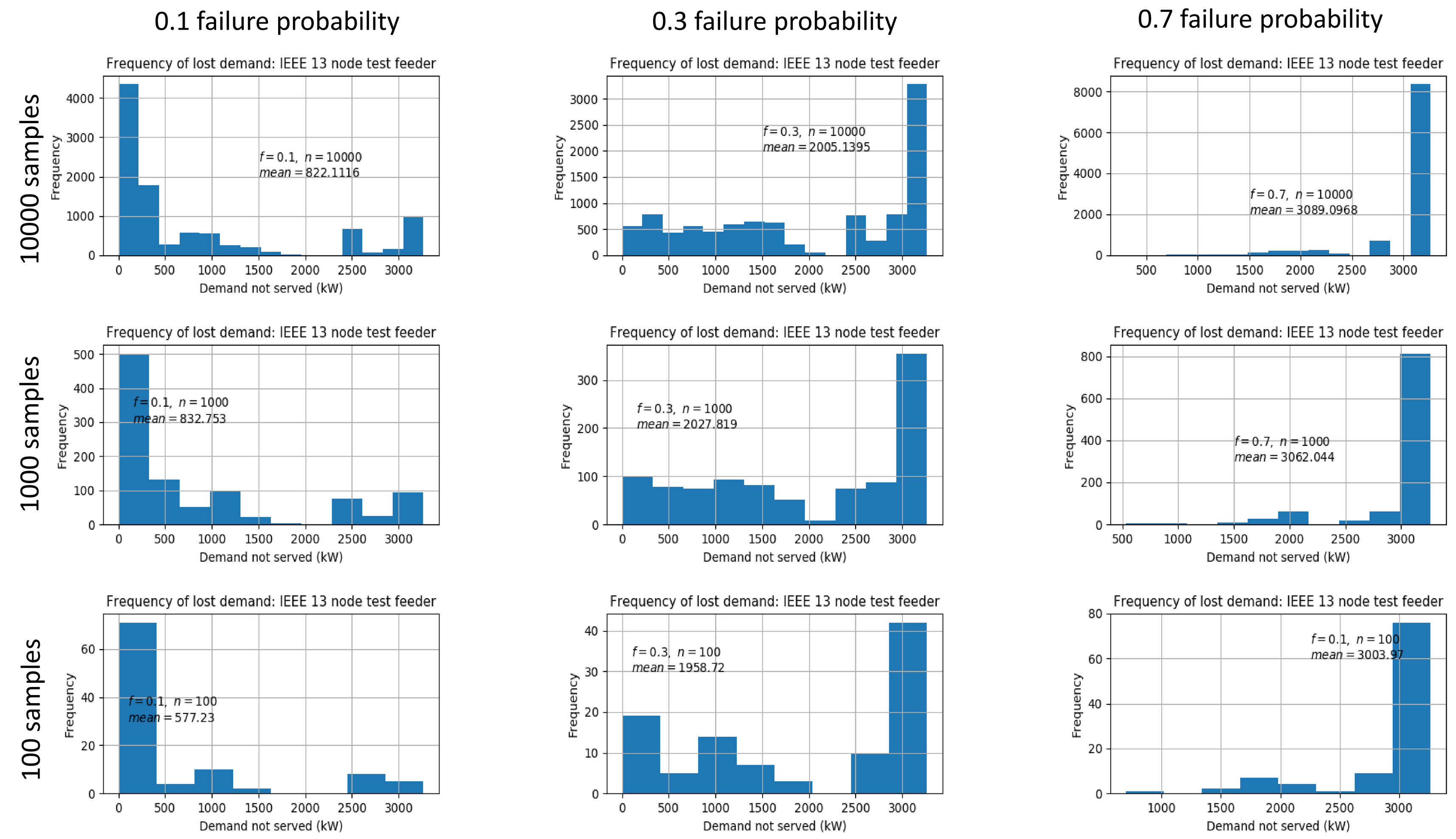

Figure 5. Distribution of demand not served for different sample sizes and component failure probabilities

The sub-plot sitting in the first row second column shows the prediction of lost load when 10k samples are generated for estimation and failure probability of each components is assumed to be 0.3. In this case, the lost demand is estimated to be between 1990 kW and 2022 kW.

Usage

The model and simulation tool will be used:

1. **By distribution companies to simulate and estimate hazard impact in terms of lost loads.**
2. **By transmission system operator to re-evaluate reserve requirements factoring in hazard impacts based on the anticipated loss of load or supply.**
3. **To perform cost-benefit analysis. Benefits of hazard mitigation investments can be directly measured by loss of load or number of lost customers.**

Future/Ongoing Work

1. Electricity Distribution Resilience Framework informed by West Coast Alpine Fault Scenario (2017-2019).
2. Electricity generation and transmission expansion planning to mitigate natural hazard risk.
3. Power system restoration factoring network interdependencies e.g. communication, transport & water.

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