IMPROVING DISTRIBUTION NETWORK RESILIENCE AGAINST EARTHQUAKES

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Abstract
Historically, reliability analysis has ignored the occurrence of natural hazards such as those associated with extreme weather, flooding, earthquakes and tsunamis, which are becoming more and more relevant due to recent events. In this context, we present an assessment methodology to determine the resiliency levels of a distribution system exposed to a major earthquake. The proposed 4-stage methodology models (i) the earthquake, (ii) the fragility of network components, (iv) the network outages, and (v) the impacts on network operation (including the energy not supplied) through sequential Monte Carlo simulations. This methodology is used to study the resilience of distribution networks under two particular strategies: one that hardens substations infrastructure in order to reduce their fragility levels, and the other one that uses additional network infrastructure in the form of transfer cables to shift load among substations in case a major event occurs. Through several case studies based on a real distribution network in Chile, we demonstrate that hardening substations infrastructure may be a more resilient way to deal with earthquakes, even when compared to an alternative, extreme case where a vast number of transfer cables are installed to support damaged substations.

1 Introduction
Power systems, including transmission and distributions networks, have been historically designed to satisfy certain levels of reliability, dealing with the occurrence of the so-called credible outages, such as the disconnection of a large power plant, disconnection of one or more transmission lines and/or power transformers (N-1 or N-2), etc. This reliability framework has been critical in power system, being focus mainly on adequacy and security [1]. Adequacy refers to the system capability to supply the peak demand (i.e., enough installed capacity) and security refers specifically to the system ability to recover after a contingency (i.e., enough reserve to overcome credible outages) [2].

That traditional reliability framework (adequacy/security) ignores high impact and low probability (HILP) events, common mode failures and natural hazards [3] and hence, these types of contingency are not usually considered for planning (e.g., sizing and redundancy levels of transmission lines and further infrastructure) and operational purposes (e.g., sizing of maintenance crews, tele-control manoeuvre devices for topological configuration). In this context, Power System Resilience, defined as the capability of a system to recover the original state, as fast and as much as possible, after a severe disturbance [4], emerges as a promising concept to overcome effects of HILP events such as those originated from earthquakes, floods, tsunamis, etc.

The resilience of key infrastructure (communication, roads, water, and power systems) is a topic getting increasing attention from the policy making and academic community. Particularly on power systems, a pioneer study about the seismic vulnerability of power transmission network was presented in [5]. Then, the authors in [4] present a comprehensive framework to assess resilience at generation and transmission levels, showing specific example applications in [6] by using a simplified version of the bulk UK system. However, only a few studies have been reported on distribution networks [7],[8].

The distribution network is very important since, after a large disturbance occurs (e.g., earthquake) and after generation and transmission networks have been fully recovered, load may remain unserved due to failures in the distribution systems that can last longer than those in the generation and transmission networks. In fact, this situation happened after the 8.8 Mw earthquake in Chile, where it took almost two weeks to reconnect the load nearby the epicentre area, albeit generation and national transmission network infrastructure did not present any important failure [9].

Hence, this paper will focus on distribution network resilience and the application of two mitigation actions to increase resilience, namely, i) hardening the primary substation infrastructure and ii) smart tele-control manoeuvre devices for load transferring among substations. This modelling allows assessing the effects of an earthquake and thus properly quantify the energy not supplied (EENS) that can be used in tandem with generation-transmission resilience models to assess the whole-system effects of natural hazards. Furthermore, we demonstrate the value of hardening infrastructure and the utilization of smart grid technologies in terms of minimising the expected energy not supplied (EENS) under severe and rare events, which can be used to informing
review and development of innovative security standards and network incentive frameworks.

The rest of the paper is structured as follows. Section II describes the proposed methodology to evaluate resilience at distribution networks. The case study and the corresponding sensitivities are developed in section III. Section IV presents the simulation results for a real distribution system and finally, the main conclusions are drawn in section IV.

2 Methodology

To assess potential mitigation actions to reduce the impacts of earthquake at distribution networks, it is important to properly model the distribution system, the effect of the earthquake on the electrical infrastructure and then, the corresponding impacts on power system operation. In fact, given the large scale characteristic of these systems with substations and loads located in a widespread area, the only way to assess the impact of an earthquake is through the topological modelling of the network infrastructure. As an example, Fig. 1 shows the geographic information system (GIS) representation of a portion of a distribution system.

In general terms, the core of the proposed methodology to comprehensively assess the impacts of earthquakes and the potential mitigation actions can be summarised in the following steps:

1. **Earthquake modelling**: Given an earthquake location and intensity, the model must be able to calculate the distance attenuation from the epicentre for each network element, this means the intensity at each point (i.e., X and Y coordinates on a 2-dimensional map) in the distribution network will be determined. This requires the GIS representation of the distribution network, which corresponds to the specific location (e.g., universal transverse Mercator –UTM– coordinates) for each distribution network element (e.g., power substations, distribution transformers, loads, etc.)

2. **Fragility Modelling**: Having the intensity of the earthquake at each point, it is possible to determine the intensity in each infrastructure element, and then, through the analysis of Fragility curves [5],[6] determine the level of damage in each of them.

3. **Outage Modelling**: After determine the outage status of each element, the effect in the system operation can be determined. Indeed, if certain infrastructures are partially or totally outaged/damaged, and the reconfiguration strategies are in place, the amount of customers not served and the energy not supplied can be determined and minimise.

![Figure 1: Distribution Network Example](image)

4. **Sequential Monte Carlo Simulations**: the impacts on the distribution system operation will depend on the period of time when the event occurs (with certain probability) and the restoration times for the damaged infrastructure (according to distribution probabilities). Thus, the time series analysis is fundamental to assess the resilience performance of distribution networks. Furthermore, the impacts on the infrastructure are also probabilistic, in fact, a particular magnitude can produce a problem with a given probability. Consequently, to cope with the time-series dimension of the problem and the stochasticity of the model, a Sequential Monte Carlo is implemented.

2.1 Earthquake Modelling

In order to measure the intensity of a particular earthquake on a widespread area, such as a distribution network, the magnitude attenuation from the epicentre is modelled. This attenuation can be determined by using the peak ground acceleration (PGA) equation.

PGA corresponds to the input magnitude in the Fragility Curves (i.e., X axis) of power infrastructure due to the action of an earthquake. The PGA attenuation used in this work was presented in [10] based on an extensive ground motion data base (i.e., 697 PGA values for the regression analysis) for the subduction zone in the Pacific. Thus, the equation obtained is representative for the Chilean distribution network used in this work.

\[
\ln PGA = 6.36 + 1.76M - 2.73 \ln(R + 1.58e^{0.608M}) + 0.00916h
\]

Where M is the moment magnitude (earthquake intensity), R is the distance to the epicentre in km, and h is the focal depth in km. PGA is the peak ground acceleration in gals. Hence, given a combination of magnitude and depth is possible to calculate the PGA magnitude in each position of the distribution system.
As an example, Fig. 2 shows a realistic distribution system used in [11]. For visualization purposes, only the poles and underground chambers are represented (black dots). The total dimension for the system is 4,485 km2 (65 km times 68 km), supplying approximately 1,700,000 customers with a yearly consumption of 12,477 GWh. Here, an 8.0 Mw earthquake is simulated with a focal depth of 23 km in the northeast of the city, indicating the PGA for each position in the map through colours (brown refers to higher PGA and blue refers to lower PGA).

It is important to highlight that the earthquake model used in this work is a good approximation to the phenomena but it is not the full earthquake representation (i.e., consideration of the soil mechanical structure [12]) and therefore the impacts determined here are only referential. Nonetheless, they still allow the comparison among different case studies.

### 2.2 Fragility Curves and Restoration Time Curves

After having the PGA values for each position in the network (Fig. 2), the impact on the power system infrastructure can be determined. Those effects are calculated from fragility curves, which relate the PGA magnitude with a damage state. Mathematically speaking, the fragility curve describes the cumulative probability of reaching or exceeding different states of damage for a specific peak ground acceleration. These fragility curves are modelled as cumulative lognormal distributions [13].

Fig. 3 shows the fragility curve for primary substations specified in [13]. Here, four possible damage states can be observed, namely, minor, moderate, extensive and complete substation damage. Hence, for example, if the PGA is 0.6 g, then the probability of being or exceeding the minor damage state is 0.99 (i.e., almost certainly the substation is having minor problems) and the probability of being in a complete damage state is about 0.3. This implies that the probability of being in a particular state is the difference between the probabilities of exceeding the particular state and the probability of exceeding the above damage state. Finally, the probability of having no damage is the difference between one and the probability of exceeding the minor damage state.

Each damage state represents a specific percentage of damage of the corresponding infrastructure. For instance, in the case of primary substation, according to Hazus report: Multi-hazard Loss Estimation Methodology [13], the minor, moderate, extensive and complete damage states imply a capacity substation reduction of 5%, 40%, 70% and 100%, respectively.

It is important to remark that a particular PGA does not produce always the same problem, on the contrary, a specific PGA can cause different consequence with certain probabilities, adding a stochastic dimension to the impact assessment. In this line, another source of stochasticity to be considered is the restoration time for the failed infrastructure.

In fact, according to the Hazus report, the probability for these restoration times follows a normal distribution and it is different for different damage states. For instance, Fig. 4 indicates the probability distribution of restoration times for minor, moderate, extensive and complete damage state. These curves have a median and standard deviation values of 1 and 0.5, 3 and 1.5, 7 and 3.5 and 30 and 15 days, respectively.
2.3 Sequential Monte Carlo Simulations

From the previous subsection is clear that the stochasticity added by fragility and restoration curves must be incorporated.

Given the large number of elements included in a distribution networks and their widespread location, it is not possible to model all the potential scenarios with their corresponding probabilities through an analytical formulation (i.e., large number of combinations when considering damage states, infrastructure elements and earthquake realizations). Thus, to avoid the full enumeration of all combinations, a Monte Carlo simulation is used for sampling, representing adequately the stochastic nature of this distribution network problem [14]. Moreover, since the time-series dimension is important in this analysis due to the interdependence among the event occurrence, the demand variation and the recovery period for different infrastructure elements with different damage status, a Sequential Monte Carlo Simulation (SMC) is implemented, and therefore the chronological time dependence is fully considered [15]. Specifically, for this work the SMC has fixed-intervals of one hour for a total period of one month. The main steps are described below:

1. Set the inputs:
   a. Fragility and restoration time curves for each network infrastructure and damage state.
   b. Definition of the set of earthquakes to test, indicating location, magnitude and depth (e.g., set of most likely earthquakes in the zone, worst case scenario: strongest one, etc.).
   c. Failure rates and recovery times for the so-called credible outages at distribution level (i.e., low impact and high probability events).

2. Earthquake representation:
   a. Select randomly one of the earthquake from the feasible set.
   b. Calculate the PGA at each network location for the selected earthquake.
   c. Select randomly the occurrence of the earthquake between 1 and T (T refers to the last hour in the simulation horizon).

3. Sequential steps for hour t over the horizon 1 to T.
   a. If there is an earthquake in t:
      i. For every network element b in B (set of indexes of network elements): Generate a random number, Z. Having Z and the PGA for b determine the damage state of b and consequently the available installed capacity.
      ii. Determine the restoration time from the probability distribution curves.
      iii. Check time in failure and time left to be recovered for b.
      iv. Update b status (damaged or recovered)
   b. If there is not an earthquake in t:
      i. For every network element b in B: Generate a random number, Z, and compare the failure rate (λ) with Z.
      ii. Check time in failure and time left to be recovered for b.
      iii. Update b status (damaged or recovered)
   c. Update case with the status of all elements.
   d. Quantify the energy not supplied for the period t and moves to t+1.

When t reached the last hour of the simulation horizon T, one Sequential Monte Carlo simulation has been completed. For each Monte Carlo run, the power system case is reset to its default values. Thus, after N Monte Carlo simulations (we run steps 2 and 3, N times), it is possible to obtain a probability distribution for the energy not supplied during period 1 to T.

3 Case Study

To test the proposed methodology and to use it to improve the resilience of distribution network against earthquakes, a realistic distribution network is implemented (Fig. 2). In this case study, the specific SMC characteristic are i) one earthquake realization is simulated (8.0 Mw, 23 km of depth, Northeast location as the one shown in Fig. 2), ii) 100,000 Monte Carlo simulations are run, iii) the time step is set in one hour and the total horizon is 1 month (720 hours) and iv) the network infrastructure considered corresponds to the set of primary substations (i.e., 41 for the real network under analysis). A base case plus two strategies to improve the resilience of the distribution system are examined.

3.1 Base Case

The base case is given by the consideration of the fragility curves presented in Fig. 3 and the restoration times of Fig. 4 without any capability of transferring load among substations (i.e., this represents a counterfactual scenario where all the substation are isolated from each other).

3.2 Improving Resilience – Case 1

This alternative represents the possibility of hardening the substations design in order to be more resistant to the earthquake action. To do that, a new set of fragility curves is incorporated from [13]. These curves represent the cumulative distribution of being or exceeding a damage state, namely, minor, moderate, extensive and complete, for a certain PGA in a substation with seismic considerations (Fig. 5). Hence, for a given PGA, the probability of being in a state of complete damage is larger in the base case than under this case 1.

To allow a fair comparison with the base case, this action does not include load transfers among substations. It is also worth mentioning that this structure reinforcement is feasible in reality and the fragility curve used come also from [13].
3.3 Improving Resilience – Case 2

This alternative adds to the base case, the possibility of transferring load among substations (i.e., unanchored substations) when there are connections and power capacity available. This availability condition is particularly important for the earthquake modelling because in a city, neighbours substations are close enough to face similar PGA values, and therefore having similar chances to be in a similar state of damage. Hence, the transfer of load will be possible if only if the substations expected to provide backup have enough capacity to do so (i.e., the damage state still allow the transfer of a de-rated amount of power).

In order to model a system in which every substation is backed up for at least three substations, the Delaunay triangulation is determined among all the primary substations in the distribution network under analysis and this is shown in Fig. 6. By using this triangulation (green lines in Fig. 6), all the interconnections are made only among neighbours substations. These neighbouring areas corresponds to Voronoi Diagrams whose centres are the substation location [16]. As observed, the support network formed from transfer cables in Fig. 6 is very interconnected and this provides an extreme case against which case 1 can be compared.

4 Results

The proposed methodology indicated in section 2.3 with the specifications defined in section 3 is applied over the three cases under analysis: i) Base Case, ii) Case 1: Hardening Infrastructure and iii) Case 2: Load Transfer Capability, obtaining the histograms for the energy not supplied (ENS) presented in Fig. 7, 8 and 9, respectively. There, it is possible to observe that both mitigation actions increase the resilience of the distribution network. Moreover, hardening the infrastructure seems to have a better performance in the reduction of the ENS. With the purpose of having a better comparison, several statistical metrics are determined for the three cases and summarised in Table 1. Here, it can be seen that for all the metrics, both mitigation actions have less energy not supplied than the base case and also for all the metrics, the Case 1 has a better performance.

![Figure 5: Fragility Curve for Seismic Substations, Case 1.](image)

![Figure 6: Delaunay Triangulation among Substations, Case 2.](image)

![Figure 7: ENS Histogram for Base Case.](image)

![Figure 8: ENS Histogram for Case 1.](image)

![Figure 9: ENS Histogram for Case 2.](image)
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### References


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