Seismic resilience assessment and adaptation of the Northern Chilean Power System

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***Abstract*—Even though the concept of resilience is becoming widely used in electric power systems, there is no consensus on how to systematically model or quantify it. This article begins by proposing a classification for different types of system risk analyses, associating them to the concept of power systems resilience. Thereafter, it describes and applies a resilience assessment and adaptation framework to the Northern Chilean electric power system in the context of its exposure to seismic events. This time-dependent analysis is evaluated throughout the disaster's impact and the network's operation and restoration timeframes with two indices: Energy not Supplied and Energy Index of Unreliability. Finally, the article compares a base case with three resilience adaptation strategies, namely, robust, redundant and responsive cases, in terms of their expected energy annual loss and the return period of different levels of network performance.**

***Index Terms*—Adaptation strategies, earthquakes, resilience, resiliency, seismic risk assessment.**

I. INTRODUCTION

The electric power systems of Chile and various countries located in the Pacific Ring of Fire are used to being tested by earthquakes and subsequent tsunamis. For instance, the strongest earthquake registered in modern history took place in Valdivia, south of Chile, in 1960 with moment magnitude (M_w) of 9.5. Furthermore, only between 2010 and 2015, three earthquakes M_w 8.8, 8.2 and 8.4 struck the country. Therefore, since power systems are critical infrastructure for countries' public security and economic prosperity [1], it is a necessity to develop risk assessments and particularly resilience analyses as it is proposed in this article.

The impact of natural disasters on power systems presents a complex problem to analyse. Hence, researchers have traditionally focused in particular branches of the problem; such as hazard studies, component vulnerability studies, system operation studies, system restoration studies and adaptation studies; which are not risk analyses and in this article will be referred to as (i) "System single-stage analyses" (see Fig. 1). Even though these approaches are useful, an integral perspective, combining all single-stage analyses, can result in a better understanding of the whole problem.

Several researchers have integrated the studies mentioned above and performed system risk analyses. For instance, [2]-[4] co-modelled in a modular way the threat study and the system topology. This (ii) "System fragility analysis" (see Fig. 1) enables the understanding of the system capacity post-disaster after a disastrous event by identifying which components will commonly fail and which may continue working. The work in [5] integrated in a single study the hazard modelling, the system topology and the system operation, which may be considered as (iii) "System serviceability analysis", because it permits to know the actual capacity of the system to supply the service required over a time frame. Finally, in the past few years, a number of authors [6]-[10] have started to integrate the hazard characterization, the system topology, the system operation and also the system restoration thus performing (iv) "System resilience assessment analysis". Moreover when adaptation measures are included in the procedure, it becomes a (v) "System resilience assessment and adaptation analysis". The previous classifications are presented to comprehensively capture and measure the resilience concept as "the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions" [11]-[12].

Despite the growing public interest, resilience is still an emerging and debated concept, which is treated in a wide range of ways, without including all the necessary aspects, and usually not systematically quantified. Therefore, the objective of the present work is to outline a comprehensive seismic resilience model and apply it to the Northern Chilean system.

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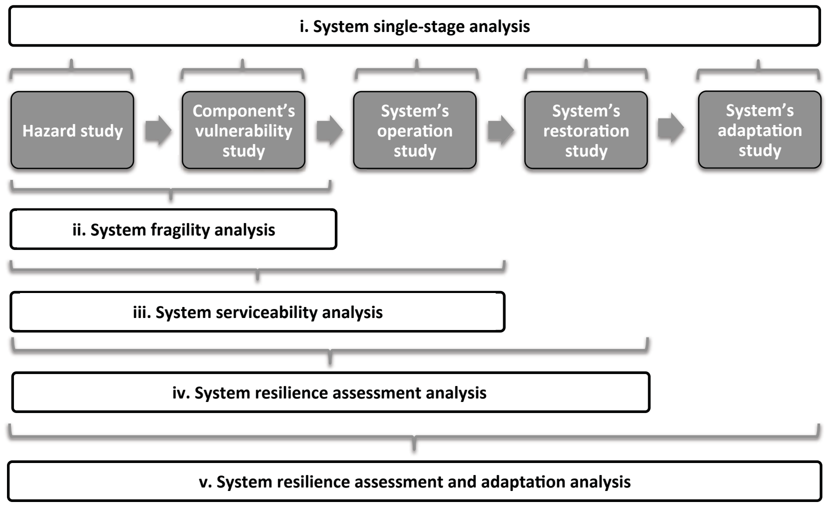

Figure 1. Steps for comprehensive seismic resilience analysis. Partial assessments are classified as single-stage analysis (i) and risk analyses (ii-v).

II. Multi-stage seismic resilience assessment and adaptation framework

Works that have analysed the impact of seismic events on electric power systems are: [3], where the IEEE 118 Bus Test Case was stressed by earthquake epicenters uniformly spatially generated in a circular area of 150 km diameter; [4], that uses a single return-period hazard map, which is parameterized, to obtain the electric network fragility curve and assess the vulnerability of the interdependent European gas and electric network; [5], which studies the power system of Sicily, and includes stochastically-generated seismic scenarios and a power-flow formulation for the system operation to calculate the connectivity loss of the system; [8], which analyses the power system of the city of Los Angeles (US) where micro-components within substations are stressed by historic seismic events to assess the resilience of the system; [10], that presents a resilience assessment analysis considering the interdependence of lifelines; and [13], which incorporated a retrofit model as an adaptation study to [3], and would be classified as a resilience assessment and adaptation analysis but lacks the system operation.

The methodology is based on the five stages of the comprehensive resilience assessment and adaptation framework, which is discussed in [6] for windstorms and floods and in [9] for hurricanes. They are presented hereafter for seismic events.

A. Stage 1: Hazard characterization

The objective of this stage is to model the magnitude, probability of occurrence and spatiotemporal profile of seismic events. This is carried out by sampling a stochastic catalogue of earthquake scenarios by the use of Monte Carlo Simulations (MCS), which will then be used to assess the performance of the network. This methodology is explained in detail in previous work [14], and is briefly summarized here.

The first step of the methodology consists in sampling earthquake magnitudes from a truncated exponential distribution, derived from the Gutenberg-Richter law. Then, the seismic source that generates each earthquake is selected and the hypocentral location is sampled from a uniform distribution in each source, enabling the computation of the distance to the source for all network components. Finally, the local intensities at all sites and for each earthquake scenario, characterized in this study by the Peak Ground Acceleration (PGA), are sampled using the ground motion prediction equation proposed by Abrahamson et al. [15], which depends on earthquake magnitude, source to site distance, focal depth, and local soil conditions, amongst others.

High magnitude earthquakes contribute more to the overall risk of the system than low magnitude earthquakes, but since magnitudes are sampled from a truncated exponential distribution, high magnitude earthquakes will be sampled less frequently. Therefore, importance sampling with a uniform distribution of earthquake magnitude is used to improve computational efficiency.

B. Stage 2: Component's vulnerability

The aim of the second stage is to determine the damage state of each vulnerable component by the use of fragility curves, which express the probability of system components reaching different damage states, conditioned to PGA.

As shown in Table I, the electrical components modelled as vulnerable are substations and power plants, in contrast, line towers are not included since past experience in Chile shows that they resist well earthquakes impact. Their associated lognormal fragility curves where retrieved from the technical manual of the Hazus software, from the US Federal Emergency Management Agency [16]. To select the fragility curves, all facilities were considered as "anchored" because the Chilean electric normative indicates that high voltage facilities must fulfill the ETC 1.015 standard of the IEEE 696-1997 standard at "High Performance Level". For each component classification, fragility curves assign one of five different damage states: None, Minor, Moderate, Major or Collapse

Damage states are modelled differently for each vulnerable component identified. Substations with minor/moderate/major damage and collapse disconnect 5%/40%/70% and 100% of adjacent generators and lines. Power plans with any damage are disconnected from the system until restored.

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TABLE I. NETWORK COMPONENTS MODELLED AS VULNERABLE

Vulnerable components	*Classification*
Substations	Anchored medium voltage (150 to 350 kV)
	Anchored low voltage (34.5 to 150 kV)
Power plants	Anchored large power plant (>200 MW)
	Anchored small power plant (<200 MW)

C. Stage 3: System's operation

The aim of this stage is to assess the amount of energy that will not be supplied by the system while it is exposed to seismic events, when several components may be unavailable.

In this work, two dispatch models with an hourly resolution are used: (i) a simplified unit commitment, where the scheduling of power generation units status (on/off) is decided and (ii) a DC Optimal Power Flow (DC-OPF) with loss of load represented by expensive generation units in every bus, where the dispatching of the online generators is carried out subject to grid constraints.

Unit commitment is performed once prior the earthquake by considering 70 MW of primary reserves during the study period, which is one week, and running a DC-OPF every hour in order to supply all demand in normal (no damage) state.

DC-OPF, which has been discussed at length in the electric power system's literature, can be modelled as a linear optimization problem with specific modelling assumptions and limiting constraints. In this case, reactive power and voltage magnitudes are omitted from the problem, and active power flows are modelled as linear functions of the node voltage angles (Θ_k - Θ_j). The decision variables of the problem are the power generated by of each generation unit i (p_i) and the voltage angle of each node k (Θ_k). The problem is described as follows:

$$\min_{p_i,\Theta_k} \sum_{i=1}^{n_g} C_i\,(p_i) \tag{3}$$

subject to

$$(k \in 1 \ldots \text{K nodes}, \quad j \in 1 \ldots \text{J connected nodes}, \quad i \in 1 \ldots n_g \text{ generators})$$

$$g_k(p_i, \Theta_k) = p_k^{load} - \sum_{i=1}^{n_g} A_k^i * p_i + \sum_{j=1}^{J} B_{kj} * (\Theta_k - \Theta_j) = 0, \quad \forall k \tag{4}$$

$$h_{from}(\Theta_k) = B_{kj} * (\Theta_k - \Theta_j) - F_{max} \leq 0, \quad \forall k, j \tag{5}$$

$$h_{to}(\Theta_k) = -B_{kj} * (\Theta_k - \Theta_j) - F_{max} \leq 0, \quad \forall k, j \tag{6}$$

$$\Theta_k^{ref,min} \leq \Theta_k \leq \Theta_k^{ref,max}, \quad \forall k \tag{7}$$

$$0 \leq p_i \leq p_i^{max}, \quad \forall i \tag{8}$$

The objective function (3) is to minimize the generation polynomial costs, assumed as linear in this study, subject to: (4) real power balance constraints for each node k, where, as stated by Kirchhoff's laws, demand minus nodal generation plus net branch active power flow has to be zero (A_k^i is a generation connectivity matrix; where its elements are equal to 1 if generator i is connected to node k and 0 otherwise); (5)-(6) real power thermal constraints for each branch, where B_{kj} represents line susceptances; (7) voltage angle constraints; and (8) real power production constraints for each generator. Importantly, every node presents an extra, costly generator that represents the unserved energy, which is included in n_g.

D. Stage 4: System's restoration

The quantitative indices for resilience are highly affected by the duration of equipment damage. Restoration times are strongly related to the damage caused, human and material resources available, and accessibility of the affected area.

Related to the Unit Commitment performed, the offline generation units that were not damaged by the seismic event are included in the DC-OPF respecting their start-up times.

For simplicity reasons, this study assumes that component restoration times only depend on their damage states. These times are sampled for power plants and substations from normal distributions with parameters estimated by Hazus [16] as detailed in Table II. In this stage, components that fulfill their restoration time are available again.

TABLE II. RECOVERY PARAMETERS (NORMAL DISTRIBUTIONS)

Components	*Damage state*	*μ (days)*	*σ (days)*
Substations	Minor	1.0	0.5
	Moderate	3.0	1.5
	Extensive	7.0	3.5
	Collapse	30.0	15.0
Power plants	Minor	0.5	0.1
	Moderate	3.6	3.6
	Extensive	22.0	21.0
	Collapse	65.0	30.0

E. Stage 5: Adaptation strategies

According to the resilience definition, it is important not only to recover rapidly but also be able to adapt. For stages 2-4 strategic adaptation cases, arbitrarily selected, are proposed:

- Robustness strategy (stage 2): seeks to improve the resistance of the system, such as a modification in the seismic building code or the use of seismic protection technologies. In this work, as it has been employed before in literature, this adaptation solution is modelled by shifting the lognormal fragility curves to the right-hand by 50% of their median, which means a significant decrease in the probability of being damaged.
- Redundancy strategy (stage 3): includes backup components or spare capacity that enables the diversion of power flows to alternative routes. This could be applied by doubling certain power plants, substations or lines. In this work this is modelled by doubling (in parallel) all system lines.
- Responsiveness strategy (stage 4): enables a faster response by improving spares stock, preparedness and number of recovery teams, and crew coordination,

amongst others. In this work this is modelled by decreasing 50% the average recovery times and their respective standard deviations of components.

Finally, since resilience is a time-dependent process, metrics that are able to incorporate the impact from the seismic shock until the complete restoration of the system are required. In this study, two indices are used: Energy not Supplied (ENS) and Energy Index of Unreliability (EIU), the latter associated with the portion of Energy not Supplied over the study period's demand [17].

III. Application to the Northern Chilean Electric Power System

The case study is a close representation of the 220 kV northern Chilean network (SING), which covers 25% of the national continental territory but only 7% of its population. Almost all consumption comes from mines, as SING supplies approximately 60% of the Chilean mining industry; therefore, any interruption in electricity is economically sensitive.

By the beginning of 2014, the SING was entirely a thermal system comprised of 3744 MW of installed capacity, where 2100 MW was coal (56%), 1180 MW was diesel (31.5%) and 436 MW was LNG (11.5%). There were no interconnections with other systems and the peak demand in 2014 was 2363 MW, as the most stressful condition, the demand for the modelled week includes this demand peak. Fig. 2(a) presents geographically the most important components of the system and Fig. 2(b) presents the detailed network with 36 main substations, 14 auxiliary substations, 69 lines (220 kV and 110 kV), 43 generation units and consumers.

The system is located in a seismic gap, segment of an active plate boundary that has not ruptured recently, which can be roughly defined between latitudes 19°S and 23°S. This gap had not been activated since a megathrust earthquake in 1877 [18]. In 2014, an earthquake swarm struck the area, with the largest earthquake, M_w 8.2, occurring on April 1st 2014. However, the sequence only ruptured about 20% of the gap, and hence the area still remains highly hazardous [18].

As explained in the previous section, MCS were used to sample a set of approximately 32,000 earthquake scenarios, computing the performance of the system to each of them in terms of unsupplied energy (ENS and EIU). All scenarios are then used to estimate the resilience of the system, which was characterized, as in [14], by: (i) Expected Annual Loss (EAL); i.e. the expected unsupplied energy in a year, which is displayed in Table III with a 95% confidence interval since a finite number of scenarios were used; and (ii) return period curves for different levels of network performance, which are illustrated in Fig. 3 (a). Furthermore, the results are also characterized by probability distributions of the accumulated amount of ENS from all earthquakes that occur in specific time windows, illustrated in the cumulative distribution functions (CDFs) of Fig. 3 (b). The assessment was first performed for the base case and then repeated for the three adaptation strategies.

Return periods are associated to the likelihood of events. For example; in Fig. 3 (a), the value associated to a return period of 10^2 means that, for the base case, events with a loss that exceeds 33.4 GWh of ENS occur in average once every century; whereas, for the base case in Fig. 3 (b), the probability that the amount of unsupplied energy due to all earthquakes will be up to 300 GWh in the next 50 years is 0.7.

Given the assumptions of the adaptation cases, and that a more comprehensive understanding would require a cost-benefit analysis, the results of Fig. 3 (a) and Table III show that, from an average perspective, the robust case was the most effective strategy in reducing losses, followed by redundancy and finally responsiveness. Although, this order might change depending on the return period of interest, as evidenced by the intersection of the responsive and redundant curves at high return periods in Fig. 3 (a). This may be explained by the fact that for rare events the impact is so high that most components are impacted and become unavailable for the first hours, and thus shorter restoration times would become more effective. Therefore, the selection of suitable indicators (average or focused on the tail) becomes important.

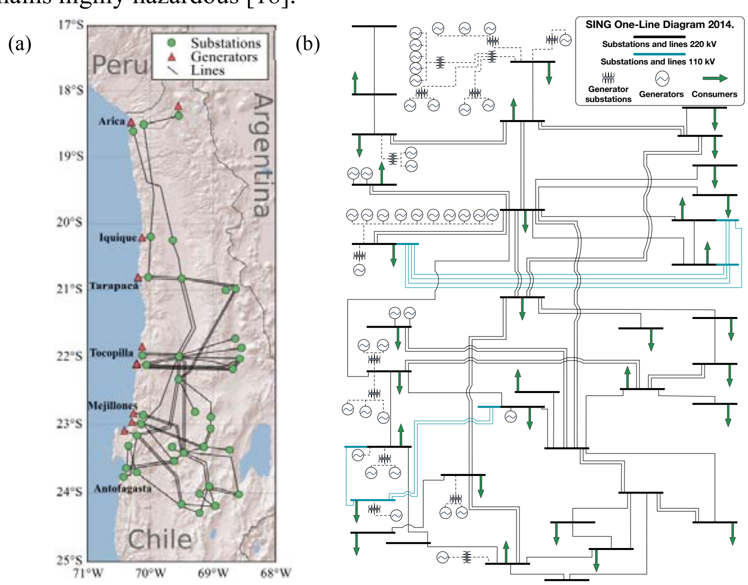

Figure 2. Northern Chilean System (a) geographic diagram and (b) network diagram. Reprinted from [14].

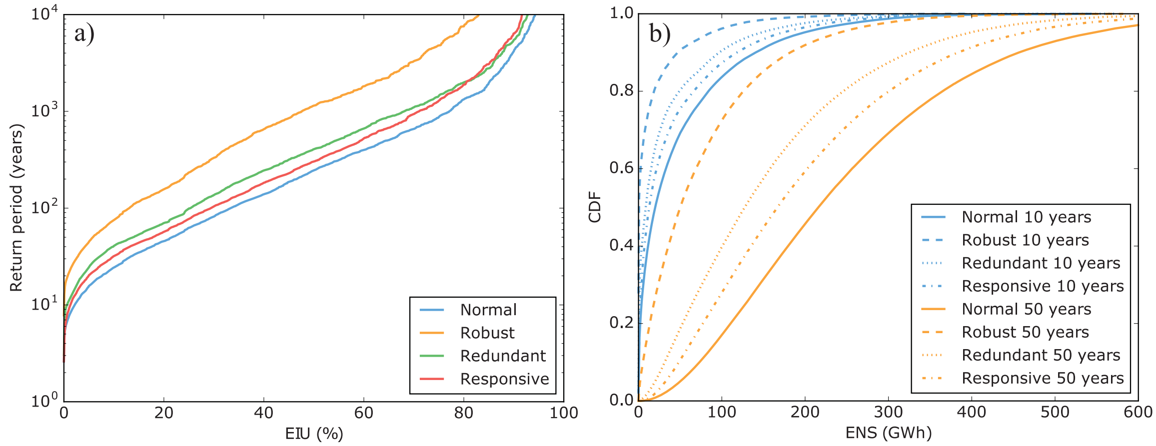

Figure 3. Results of study cases in terms of: (a) return period of events exceeding certain EIU values; and (b) CDFs of accumulated ENS for 10 and 50 years.

TABLE III. EXPECTED ANNUAL LOSS FOR ADAPTATION CASES WITH 95% CONFIDENCE INTERVALS

Study case	*EAL (GWh)*	*EAL (%)*	*100-year loss (GWh)*	*1,000-year loss (GWh)*
Base	4.90 ± 0.21	1.46 ± 0.06	33.4 ± 1.1	77.1 ± 1.5
Robustness	1.52 ± 0.08	0.45 ± 0.02	13.1 ± 0.9	47.6 ± 2.0
Redundancy	3.13 ± 0.14	0.93 ± 0.04	25.3 ± 0.9	68.0 ± 2.4
Responsiveness	3.91 ± 0.17	1.17 ± 0.05	29.4 ± 1.1	71.0 ± 2.0

IV. CONCLUSIONS AND FUTURE WORK

This work presented a classification for different types of system risk analyses for electric power systems. A seismic resilience assessment and adaptation framework was then applied to the electric network of northern Chile. This represented a challenge due to the multi-disciplinary work required. The methodology uses Monte Carlo Simulations to stochastically generate earthquake scenarios and operates the system with DC-OPF while computing the resilience of the system to all scenarios in terms of Energy not Supplied and Energy Index of Unreliability during the first week following each seismic event. Finally, three adaptation strategies are evaluated.

It is important to highlight that this analysis summarises the impacts of earthquakes of various magnitudes and frequencies on the security of supply. Hence, one can determine the effectiveness of adaptation strategies considering events with various probabilities and impacts, such as Low Impact High Probability events (those that happen several times in a decade) and High Impact Low Probability (HILP) events (those that happen once in a century/millennium); thus moving away from the focus on "average" indicators (e.g. expected energy not supplied, which is widely used in power systems) towards effective risk/resilience assessment. This is critical for planners and policy makers who prefer robust solutions that are tested using risk analyses that include all possible scenarios rather than those effective only under a specific event.

Ongoing developments and future works include evaluating the adaptation strategies using cost-benefit analysis, considering seismic aftershocks and tsunami hazards, and incorporating more complex dispatch and recovery models.

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