Seismic Resilience Assessment of Electric Power Systems Using a Substation Bay-level Model

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***Abstract*—Substations are among the most vulnerable components when earthquakes occur, and thus models to assess the risk of substation outages in resilience studies are becoming critical. In this context, this paper proposes an approach to model substation outages using a bay-level representation. Hence, substation outages can take many forms depending on the specific configuration of bays unavailable after an earthquake strikes. Thereafter, we simulate the system operation under many outage scenarios and quantify system resilience through various metrics. Our proposal is applied on the IEEE RTS 24-bus and Chilean transmission systems. Furthermore, we compare our proposed bay-level approach with a monolithic method currently used to model substation outages in power system resilience. The results show that the bay-level approach is more practical and accurate for modeling substation outages in power networks.**

***Index Terms*—Substation outages modeling, substation bays, seismic resilience, power system resilience, Monte Carlo simulations.**

I. Introduction

A. Motivation

Substations are considered the most vulnerable points in the power system when an earthquake occurs [1], [2]. For example, in 2008, the Wenchuan earthquake caused extensive damage to approximately 900 substations and 270 transmission lines [3]. In the 2010 earthquake in Chile, only 2 km of transmission lines failed, while 25% of the substations at the transmission level presented some level of damage [4], [5]. In 2011, the Tohoku earthquake in Japan affected 75 substations and damaged 37 transmission towers [6]. Consequently, substation outage modeling is key to assessing the power system resilience against natural hazards. Furthermore, resilience assessments are highly dependent on how outages of substations are modeled. There are two main polar approaches to model substation outages after earthquakes. The first one is based on a detailed model of every substation component, and the second is based on a simplistic model that considers the entire substation as a single monolithic block. The first one can capture the complex set of interconnected equipment, but the model is more complicated and time-consuming. Also, the availability of data is usually an issue. Hence, the monolithic approach is the most used practice to model substations outages in resilience analysis. This, however, is too simplistic and inaccurate. Hence, an approach to better balance accuracy and complexity is needed.

B. Literature review

Modeling substation outages within seismic resilience assessments becomes increasingly important to both operational and planning studies. Various resilience planning studies, such as in [7] and [8], use a monolithic approach to substations. In the monolithic model, the substation is assumed to be a single asset or block, in which a derating factor (between 0 and 1) is applied to the capacity of every component connected to the substation to model different degrees of impacts after an earthquake occurs. This factor equally derates the capacity of all lines, generation, and demand components connected to the substation (and transformers that are part of the substation).

Although this way to model impacts of earthquakes on substations is less realistic, it is simple and serves to model complex power networks with a relatively low computational burden.

In terms of operational resilience assessment studies, the reference [9] consider a monolithic approach to model substations to assess the seismic resilience on an illustrative electricity network. Similarly, [10] and [11] propose a seismic resilience assessment using the monolithic model for substations applied on the Chilean power system. On the other hand, in [12] and [13] present an approach to model the effect of individual equipment outages within a substation for seismic resilience analysis. This model is more accurate and provides more granularity in terms of substation-related outages. However, the main disadvantage of this approach is that, as the system increases in size and complexity, modeling every piece of equipment in all substations may become prohibitively costly in computational terms.

One way to address the increasing complexity in component outage modeling caused by natural hazards in large networks with many substations is clustering individual components into bays. Clustering components is a middle point between the monolithic approach (where all substation components behave like a single, monolithic body) and the component-by-component approach, where every single component is modeled. Clustering individual components into bays also

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considers the physical reality of the substations, which are naturally divided into bays. Electrical bays group various elements (such as switches, circuit breakers, etc.) that are connected to incoming or outgoing lines, power transformers, and busbars, among others. We assume that if one element within the electrical bay fails, all the elements connected in series will fail. Consequently, the complete electrical bay would be out of service.

This paper proposes a framework to model substation outages triggered by earthquakes, using an electrical bay-level approach. This modeling approach includes the risk of bays outages of substations in resilience assessment against earthquakes, considering outages of different bays that may affect the overall capacity of the substation. Thereafter, we simulate the system operation under outage scenarios (lines, substations, generating units, etc.) and quantify the system resilience. Hence, our approach increases the levels of details compared with the monolithic approach, widely used in resilience assessment. On the other hand, it reduces the level of complexity compared with the component-by-component approach. Thus, our model attempts to balance accuracy and computational burden, becoming particularly attractive for resilience applications on large power networks.

Finally, note that although we assess the proposed modeling framework on earthquakes, this framework can also be applied to other hazards.

C. Contributions

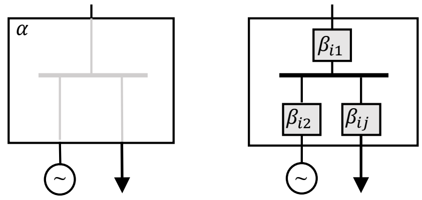
We provide a practical framework to model outages within a substation, grouping components into different bays that ultimately form the substation. Hence, the availability of different bays will affect the overall performance of the substation depending on its internal connections among bays and the external connections with other components (e.g., lines, generating units). We illustrate the benefits of this approach against the widely used monolithic approach, where the substation is modeled as one monolithic block. We do so in the IEEE RTS 24-busbar system. We also demonstrate the applicability and scalability of our approach, applying it to the Chilean power network.

D. Article Structure

The rest of this paper is organized as follows. Section II describes our bay-level and the monolithic approach to model substation outages. Section III describes the probabilistic methodology used for seismic resilience assessment. Section IV presents the case studies and results. Section V summarizes the main conclusions and future research efforts.

II. Frameworks for Substation Outage Modeling

Substation outage modeling is key to assessing the power system resilience against natural hazards. In this sense, we compare two frameworks to model substation outages after earthquakes. The first is the monolithic approach, the most used practice to model substations outages in resilience analysis. This model considers that all substation components behave as a single monolithic block. The second one is the proposed bay-level approach. This modeling approach includes the risk of bays outages within substations, considering that bay outages may affect the overall performance of the substation depending on its internal connections among bays and the external connections with other components (e.g., lines, generating units). Fig. 1 illustrates the differences between these two substation outage modeling approaches.



(a) (b)

Fig. 1. Modeling substation outage, (a) Monolithic approach, (b) Bay-level approach.

A. Monolithic approach

The monolithic approach is a simplistic model that considers the entire substation as a single monolithic block. The representation of this substation model is depicted in Fig. 1(a). In this case, the impact of hazard events is usually represented by a derating factor (α). This derating factor (between 0 and 1) is applied to the capacity of every component connected to the substation to model different degrees of impacts after an earthquake occurs. This factor equally derates the capacity of all lines, generation, and demand components connected to the substation (and transformers that are part of the substation). Considering a seismic hazard, the derating factor can be obtained through fragility curves and Hazus criteria [14]. The fragility curves express the probability of system components reaching different damage states, conditioned to the occurrence of a natural hazard. Hazus criteria define five damage states for fragility curves, expressed in terms of the derating factors of component functionality. These are (i) none (fully functioning), (ii) slight, (iii) moderate, (iv) extensive, and (v) complete damage. The power available capacities associated with the (i)–(v) states are 100%, 95%, 60%, 30%, and 0%, respectively.

The assignment of the damage states to the vulnerable components is done through a probabilistic method (e.g., Monte Carlo Simulation), as explained in Section III-B.

B. Bay-level approach

In order to incorporate the risk of bays outages of substations in resilience assessment against earthquakes, it is necessary to develop a model to determine the unavailability of the bays after an earthquake strikes. In Fig. 1(b), the bay-level representation of the substation is presented. The network components are connected to the bays and the same type of bays are independent of each other.

The bay-level outage approach relates to the unavailability of the bays and the available capacity of each network component connected to the substation. β_{ij} represents the availability of the bays in scenario i, that is, if $\beta_{ij} = 0$, the bay j is unavailable and if $\beta_{ij} = 1$ indicates that bay j is available. The available capacity (AC_i) of the substation in the scenario i is determined by summation of the product of the power capacity of each network component connected to the bay (P_j) with its availability parameter βij. Table I shows the substation capacity outage based on electrical bays. The first column of the table indicates the scenarios of possible combinations of unavailability of the bays. The second column contains the combination of all possible bay unavailability states, and the third column contains the corresponding AC_i for each scenario i.

TABLE I
SUBSTATION CAPACITY OUTAGE BASED ON ELECTRICAL BAYS

Scenario	$i = 1, ..., 2^{N_{Bays}}; j = 1, ..., N_{Bays}$				AC_i
S_1	β_{11}	β_{12}	$\cdots$	β_{1j}	$\sum_{j=1}^{N_{Bays}} P_j \cdot \beta_{1j}$
S_2	β_{21}	β_{22}	$\cdots$	β_{2j}	$\vdots$
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$
S_i	β_{i1}	β_{ji}	$\cdots$	β_{ij}	$\sum_{j=1}^{N_{Bays}} P_j \cdot \beta_{ij}$

Once all possible scenarios of bay outage states in the substation and their respective AC_i are identified, they are classified considering the power available capacity as seen in Table II. The five damage states considered this way are none, slight, moderate, extensive, and complete. The available capacity is divided according to Hazus criteria. If the AC_i of the substation is greater than 95% and less than or equal to 100%, the substation is considered undamaged. Likewise, if the AC_i is greater than 60% and less than or equal to 95%, the substation is considered slightly damaged. If the AC_i is greater than 30% and less than or equal to 60%, the substation is considered moderately damaged. If the AC_i is greater than 0% and less than or equal to 30%, the substation is considered extensively damaged. If the AC_i is equal to zero, the entire substation is considered completely damaged. Finally, the bay outage states are classified in a set of outage scenarios depending on the substation damage states. The sets of outage scenarios obtained are none (Ω_N), slight (Ω_S), moderate (Ω_M), extensive (Ω_E) and complete (Ω_C). In order to obtain the bay outage scenario (S_i) within the set of outage scenarios, we generate a uniformly distributed random integer number that returns a random scalar integer between 1 and the maximum size of the set of outage scenarios. Thus, we assign the bays outage scenario based on the chosen random scalar integer. If the status of a bay is one, the component connected to it is available. Conversely, if the status of a bay is zero, the component connected to it is unavailable.

III. METHODOLOGY FOR SEISMIC RESILIENCE ANALYSIS

In this paper, we use a probabilistic methodology with four stages to simulate the hazard (including its occurrence and spatio-temporal propagation profile) and its impacts on the power system (i.e., the system response and quantification of system resilience). Following the proposal in [9], we refer to these stages as follows: 1) Hazard modeling, 2) Vulnerability of the system components, 3) System response, and 4) Resilience quantification. These four stages are run sequentially in a Monte Carlo method in order to obtain a detailed simulation of the power system during the natural hazard. The methodology for seismic resilience analysis is depicted in Fig. 2. The description of each of the stages is detailed below.

TABLE II
CLASSIFICATION OF OUTAGE SCENARIOS BY DAMAGE STATES

Damage state	**Hazus criteria**	**Classification by available capacity**
None	100%	$\forall S_i \in \Omega_N \leftrightarrow AC_i > 95\% \wedge AC_i \leq 100\%$
Slight	95%	$\forall S_i \in \Omega_S \leftrightarrow AC_i > 60\% \wedge AC_i \leq 95\%$
Moderate	60%	$\forall S_i \in \Omega_M \leftrightarrow AC_i > 30\% \wedge AC_i \leq 60\%$
Extensive	30%	$\forall S_i \in \Omega_E \leftrightarrow AC_i > 0\% \wedge AC_i \leq 30\%$
Complete	0%	$\forall S_i \in \Omega_C \leftrightarrow AC_i = 0\%$

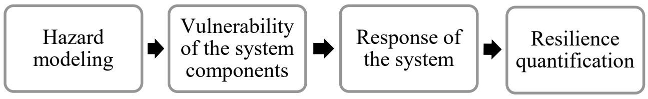


Fig. 2. Methodology to seismic resilience analysis.

A. Hazard modeling

In the first stage, we simulate the seismic hazard using the peak ground acceleration (PGA) profiles as a seismic intensity parameter for each of the locations of the system components. To calculate PGA attenuation, we use the model proposed by Boroschek [15] (suitable for Chile) as follows (1):

$$\begin{aligned}\log_{10}(PGA(x, y; ex, ey, h, M)) = -1.55 + 0.26M \\ +0.01h - 0.01R - (1.52 - 0.10M)\log_{10}(R)\end{aligned} \quad (1)$$

where M is the moment magnitude and h is the focal depth. Given the hypocenter (ex, ey, h), then $r = \sqrt{(ex - x)^2 + (ey - y)^2}$ and R is $\sqrt{r^2 + (0.07 \cdot 10)^{0.36 \cdot M}}$. The results is on units of [g], the gravity acceleration constant.

B. Vulnerability assessment

We assess the vulnerability of system components by using fragility curves [14], which are hazard intensity dependent. In this stage, we incorporate the two frameworks for substation outage modeling. For both the monolithic approach and the bay-level approach, we use fragility curves for power substations, as shown in Fig. 3, which correspond to a substation of medium voltage (150 kV to 350 kV). We then determine the hazard-dependent failure probabilities of every network component. After we have determined the outage/state probability of every network component, we use Monte Carlo simulations to generate various scenarios where network components are outaged/derated. In details, the failure probability obtained from fragility curves is compared with a uniformly distributed random number $r \sim U(0, 1)$ for each component at each simulation. If the failure probability is equal or greater than the random number, the damage state is assigned. After we have determined the damage state of every network component, we fix the condition (outaged/derated) for each one. For these network conditions (where each may present several simultaneous outages), we model the system response as explained below.

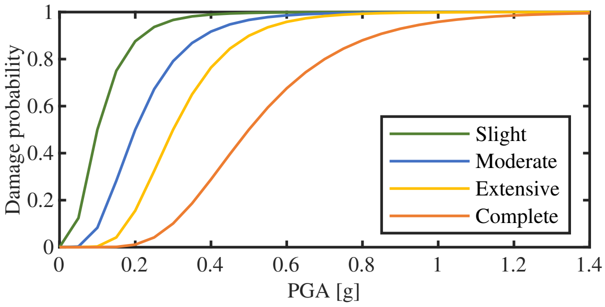


Fig. 3. Fragility curves for medium voltage substations [14].

C. System response

We determine the system response through two power system models: a pre-contingency optimal power flow (OPF) and a post-contingency OPF, where the latter is subject to the results obtained by the former. We first run the pre-contingency OPF model in order to define the intact system condition. After such intact system operation has been obtained, a set of input outage scenarios due to earthquakes are defined. We model the system response considering optimal corrective actions by means of the post-contingency OPF model. In fact, this OPF model is used for undertaking corrective actions right after the outages occur (by using generation changes, e.g., ramp rate limits or load shedding). The amount of load shedding in all buses represents the energy not supplied (ENS) in this study.

D. Resilience quantification

To quantify the system resilience, we use the expected energy not supplied (EENS) and the $\Phi\Lambda E\Pi$ framework [16] as resilience metrics. On the one hand, EENS is defined as the expected amount of energy not being served to consumers by the system during the period considered due to system capacity shortages or unexpected severe power outages [17]. The metric is detailed in (2), where ENS_k is the energy not supplied with a probability π_k of occurrence of outage scenario k during the time frame of the study.

$$EENS = \sum_{k=1}^{N_k} ENS_k \cdot \pi_k \tag{2}$$

On the other hand, the $\Phi\Lambda E\Pi$ framework allows measuring the performance of the different phases that a power system may experience during an extreme event. For seismic analysis, when the power systems are hit by an earthquake whose duration is seconds to minutes, a sharp and immediate resilience decrease occurs. Hence, we select Λ-metric that measures how low resilience drops when the extreme event hits a power system. For this, Λ-metric represents the difference between the pre-disturbance resilience state indicator (R_0) and post-disturbance resilience state indicator (R_{pd}) as shown in (3).

$$\Lambda = R_0 - R_{pd} \tag{3}$$

Furthermore, this metric allows to quantify operational and infrastructure resilience degradation after the earthquake occurs. We use the following indicators for operational resilience: lost production and lost load. While for infrastructure resilience, we use the following indicators: outaged lines and outaged substations.

IV. Case Studies and Results

To demonstrate the applicability of the proposed substation modeling approaches in the seismic resilience analysis methodology, two case studies are analyzed: i) the IEEE RTS 24-bus system and ii) Chilean Transmission System.

A. IEEE RTS 24-bus system

1) Input data: The case study described in this section is based on the IEEE RTS 24-bus system. This test system consists of 24 buses, 33 transmission lines, 5 power transformers. and 33 generators with a total capacity of 3405 MW. Using the substation bay considerations described in Section II-B, the bay-level RTS 24-bus system will consist of 20 substations. Buses 9, 10, 11 and 12 formed a substation, and buses 3 and 24 formed another substation. The electrical data and network component locations on the map can be found in [18].

For the seismic resilience analysis, we use the probabilistic methodology introduced in Section III. To calculate the PGA for each of the locations of the system components, we evaluate an earthquake with a magnitude of 7.5 M_W and a depth of 20 km. The epicenter at $(60, 60)km$ on a fictitious map with an area of 210 $\times$ 210 km^2. We then generate 10000 scenarios to simulate network outages triggered by earthquakes, via Monte Carlo simulation. Once the status of the components (outaged/derated) is obtained, we model the system operation during peak demand. The analysis allows to quantify the resilience of the power system. The methodology is implemented in MATLAB, making use of MATPOWER, which is an open-source power system optimization library [19].

2) Results and discussion: Table III shows the resilience metrics obtained for the IEEE RTS 24 bus system. These metrics are divided into three groups to visualize how the system is affected in terms of EENS, operational resilience, and infrastructure resilience. On the one hand, the proposed bay-level approach provides an EENS value that is approximately 49% higher than the monolithic approach. To illustrate the EENS results, Fig. 4 shows that the number of scenarios where ENS values are highest (placed in the right "tail" of distribution) is caused by the bay-level approach (see Fig. 4(b)) and is significantly higher compared to the monolithic approach (see Fig. 4(a)). On the other hand, the results obtained for the infrastructure (outaged lines and outaged substations) and operational (lost production and lost load) resilience indicators show that the bay-level approach caused more significant resilience drops than the monolithic model.

The results demonstrate that the bay-level approach causes greater degradation in infrastructure and operation resiliency metrics due to a greater number of simultaneous network component outages caused by the failure of individual bays, and thus, increases the number of higher ENS scenarios.

TABLE III
RESILIENCE QUANTIFICATION FOR IEEE RTS-24-BUS SYSTEM

Approach	EENS (MWh)	*Operational resilience*		*Infrastructure resilience*	
		Λ-lost production (% MW lost)	**Λ-lost load (% MW lost)**	**Λ-outaged lines (% Lines tripped)**	**Λ-outaged substations (% subs. outaged)**
Monolithic	478.73	16.53	15.24	7.79	7.74
Bay-level	935.01	26.75	24.16	31.11	15.10

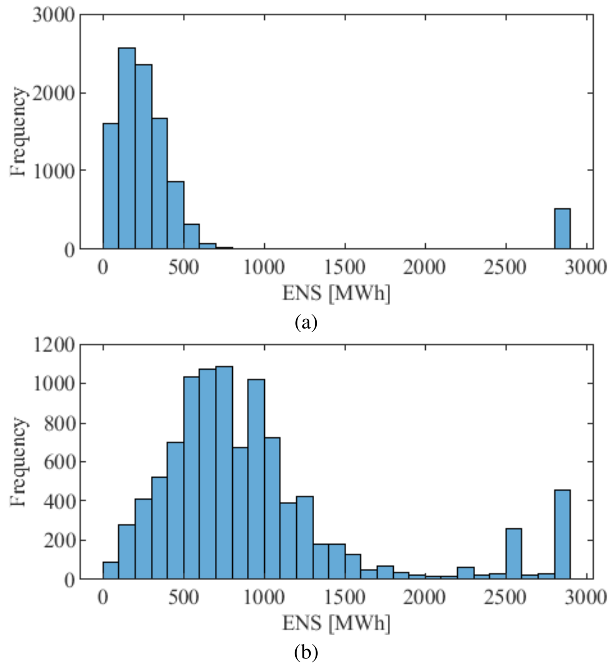


Fig. 4. ENS Histogram for IEEE RTS 24-bus system (a) Monolithic approach, (b) Bay-level approach.

B. Chilean Transmission System

1) Input data: The case study described in this section is based on the Chilean transmission system [18], considering its infrastructure in 2018. For that year, the total installed generation capacity is 24 GW, and generation supply included mainly hydro [23 TWh (30%)], coal [30 TWh (39%)], and gas [11 TWh (15%)] units, with minor participation from wind [4 TWh (5%)] and solar resources [5 TWh (7%)]. The electricity peak demand is approximately 10 GW. The Chilean transmission system is represented by nodes/substations, with their real geographical coordinates; and links are the transmission lines connecting substations as shown in the Fig. 5.

For the seismic resilience analysis, we use a earthquake intensity equal to 8.8 M_W and a depth of 35 km, the epicenter of the event was located at the coordinates latitude: $-35.846°$ and longitude: $-72.719°$, equalizing the conditions of the most recent 2010 earthquake (which was one of the worst earthquakes experienced in Chile). The PGA is determined at the location of each system component as shown in the Fig. 5.

2) Results and discussion: Table IV shows the resilience metrics obtained for the Chilean transmission system. These metrics are divided into three groups to visualize how the

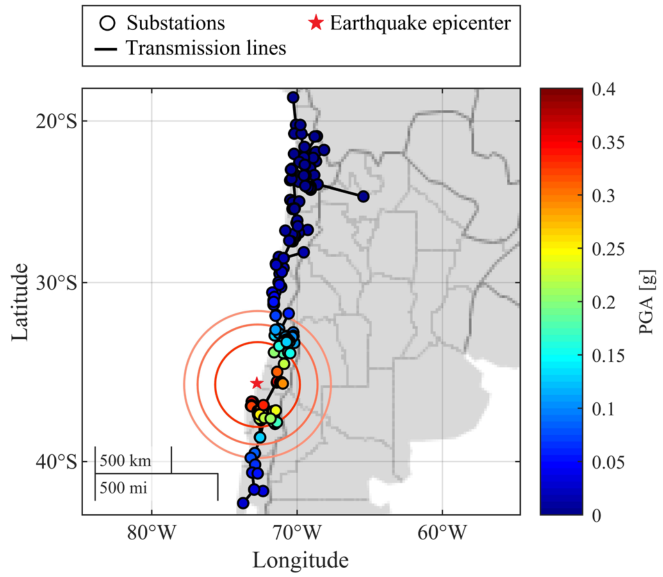


Fig. 5. The Chilean transmission network diagram considering earthquake of 2010.

system is affected in terms of EENS, operational resilience, and infrastructure resilience. The amount of EENS for the bay-level approach is approximately 48% greater than the monolithic approach. Furthermore, Fig. 6 shows the ENS histograms for both approaches, it is observed that for the bay-level approach (see Fig. 6(b)) the critical scenarios increase and present a greater amount of ENS compared with critical scenarios obtained by the monolithic approach (see Fig. 6(a)). On the other hand, the operational and infrastructure resilience results show that the bay-level approach caused greater drops in resilience indicators than the monolithic approach.

Interestingly, from the perspective of validating the proposed bay-level approach, the percentage of outaged substations obtained is close with empirical evidence observed in the 2010 Chile earthquake, where 25% of the substations at the transmission level were damaged. It is, therefore, more realistic to model substation outages through a bay-level model. Furthermore, it is important to highlight that this example demonstrates the applicability and scalability of the proposed approach for large power networks.

TABLE IV
RESILIENCE QUANTIFICATION FOR CHILEAN TRANSMISSION SYSTEM

Approach	EENS (MWh)	*Operational resilience*		*Infrastructure resilience*	
		Λ-lost production (% MW lost)	**Λ-lost load (% MW lost)**	**Λ-outaged lines (% Lines tripped)**	**Λ-outaged substations (% subs. outaged)**
Monolithic	1846.00	20.00	16.50	9.40	9.37
Bay-level	3538.00	34.30	27.60	29.40	26.20

V. CONCLUSIONS

We propose a resilience framework to model earthquakes' impacts on substations that groups electrical components into

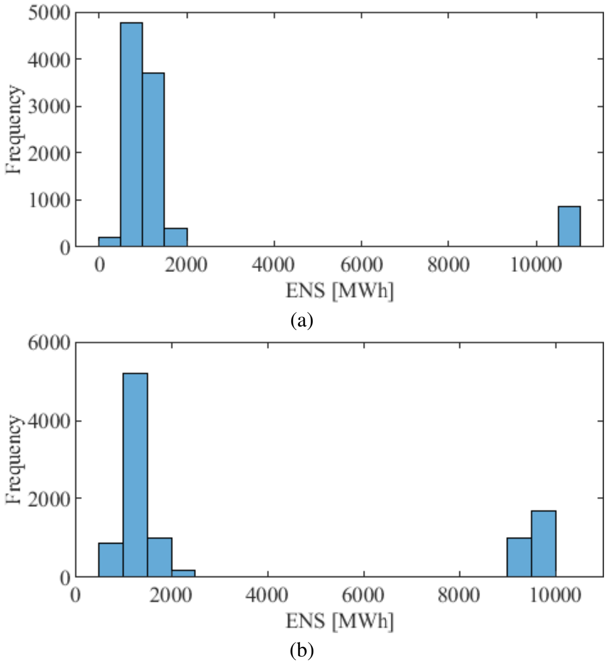


Fig. 6. ENS Histograms for Chilean transmission system (a) Monolithic approach, (b) Bay-level approach

bays. This opposes the widely used approach that models outages of substations as a single monolithic block with different degrees of availability. We use this framework to assess resilience in power networks, simulating, via Monte Carlo, network outages (lines, substations, etc.) triggered by earthquakes. Hence, we can quantify the risks to which consumers in different points of the networks are exposed. The proposed approach based on grouping elements into bays is compared with the monolithic approach. Hence, we use both substation models to quantify resilience on the IEEE RTS 24-bus and the Chilean transmission systems.

The results show that the monolithic approach significantly underestimates risks. This is a critical problem in resilience analysis. Furthermore, the bay-level approach can more accurately capture the greater number of simultaneous outages of network components caused by the failure of individual bays. The monolithic approach neglects this. Therefore, a higher granularity level is needed when modeling substation components, although this level has to be carefully decided not to increase computational burden prohibitively. Our proposal attempts to reasonably balance these two conflicting objectives (accuracy and computational burden).

We propose as future work to incorporate our proposed framework to model substation outages into resilience planning models like that in [7].

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