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Multi-Hazard Risk Assessment of Electric Power Systems Subjected to Seismic and Hurricane Hazards

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Abstract

Electric power systems are susceptible to damage due to natural hazards such as earthquakes, hurricanes, flooding, and storm surges. Among these hazards, earthquakes and hurricanes are the most damaging to power systems. Considerable effort have been made to develop methodologies for assessing the reliability of critical civil infrastructure systems such as electric power systems under single hazards such as earthquakes or hurricanes. However, there are parts of the world that are vulnerable to both seismic and hurricane hazards. In such regions, more accurate risk assessment is only possible when focus is shifted from single-hazard to multi-hazard analysis. There is therefore a need to develop methods for quantifying the risk posed by combined effect of multiple hazards on infrastructure systems in these regions. This is essential for pre-disaster decision making regarding strengthening of existing systems. This paper presents a framework for multi-hazard risk assessment of electric power systems subjected to earthquakes and hurricanes. Parts of the framework include hazard analysis, component fragility, system reliability analysis, and multi-hazard risk assessment. For the hazard analysis, a probabilistically weighted deterministic hazard scenarios approach is also employed to overcome the limitations of scenario-based and probabilistic hazard analysis approach for spatially distributed infrastructure systems. A notional electric power network assumed to be located in Charleston and New York is used to demonstrate the proposed framework.

Keywords: multi-hazard; earthquake; hurricane; electric power systems; probabilistically weighted deterministic hazard analysis

1. Introduction

The vulnerability of civil infrastructure systems subjected to perturbations is a major concern to stakeholders. Electric power systems are among the most critical infrastructure systems that are subjected to numerous disturbances ranging from small disturbances caused by common cause failures to major disturbances caused by natural and man-made hazards. Natural hazards such as hurricanes and earthquakes can cause considerable damage to electric power systems. For example, the 1994 Northridge earthquake caused damage to electric power systems causing over 2.5 million customers to lose power [1]. Similarly, the 1995 Great Hanshin earthquake, 2008 Wenchuan earthquake, as well as the 2010 Chile earthquake caused various levels of damage to electric power systems [2-4]. In 2005, hurricanes Katrina, Rita, and Wilma struck the U.S. causing extensive damage to power systems across several states [5-7].

Hazards can be concurrent/non-concurrent and dependent/independent. Seismic and hurricane hazards can be described as independent and non-concurrent hazards. Regardless, within the life span of infrastructure systems located in regions vulnerable to both hazards, there is a possibility of such infrastructure being subjected to such independent hazards that are different in nature. Hazard events differ in nature, intensity, return periods, and magnitude measurement method. Therefore, the first challenge of multi-hazard risk analysis is comparability of hazardous events. Hazards with different probabilities of occurrence, such as earthquakes and hurricanes, are difficult to compare. For example, a low probability/high consequence earthquake can cause as much damage as recurrent high probability/low consequence hurricanes. The second difficulty in multi-hazard risk analysis is comparison of vulnerabilities of exposed elements. Different hazards can affect different elements in a region or different components of a system. For example, substations and transmission lines can be more vulnerable to different hazards and the parameters used to measure their vulnerabilities are not the same.

Multi-hazard risk assessment of independent non-concurrent hazards is usually carried out through comparative approach using a common index. This is feasible because risk is not measured in hazard-specific units but in damage or loss-specific units such as damage to properties or disruption to economic activities [8]. While development of multi-hazard risk analysis framework for buildings and bridges have been ongoing in recent years, risk analysis of spatially-distributed civil infrastructure systems such as electric power and water systems have so far been limited to mostly single-hazard considerations (e.g. Salman, Li [9], Adachi and Ellingwood [10], Winkler, Dueñas-Osorio [11], Duenas-Osorio and Hernandez-Fajardo [12]). As these systems usually cover large areas and can be subjected to multiple hazards within their lifetime, there is a need to develop a framework to study the impact of multiple hazards on such systems. This is essential for pre-disaster decision making regarding mitigation strategies as certain mitigation strategies for one hazard might be ineffective or even increase the risk for other hazards.

This paper presents a framework for multi-hazard risk assessment of electric power systems under seismic and hurricane wind hazards. As part of the framework, a topological-based system reliability model is developed that relates components (substations and transmission lines) failure with power delivery. Two multi-hazard risk assessment methods are also presented. The first method is a comparative approach using proposed risk curves due to multi-hazard, while the second method is a cumulative approach based on the annual probability of system failure. The proposed multi-hazard risk assessment models can be used to prioritize investment in mitigation strategies by ranking hazards based on the level of risk they pose in the short- and long-term. Fig. 1 shows a flowchart of the proposed framework. The framework is demonstrated using a notional power system assumed to be located in Charleston, SC and New York, NY.

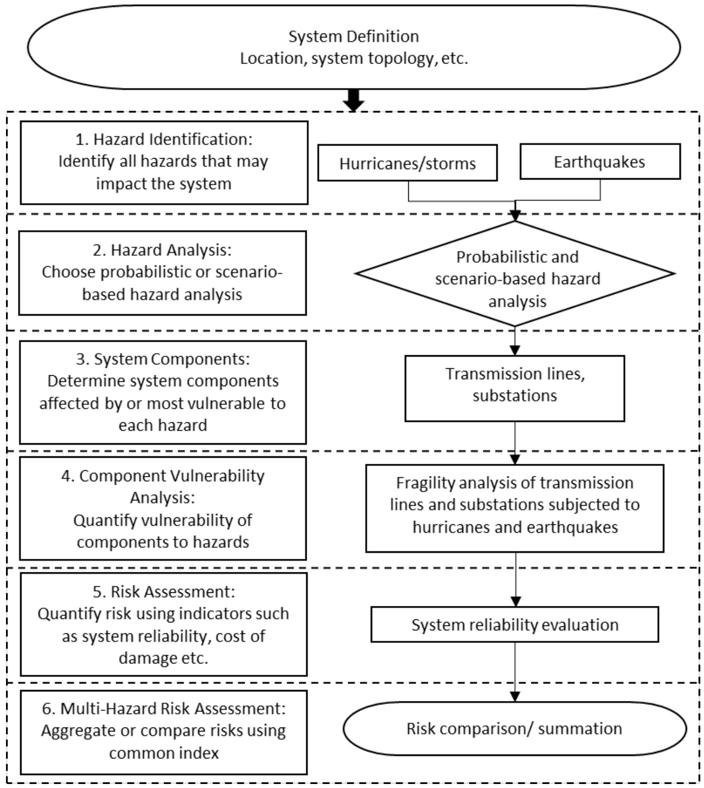

Fig. 1: Flowchart of proposed multi-hazard risk assessment framework

2. Hazard Analysis

Hazard analysis for structures and infrastructure systems can be carried out in two ways, namely probabilistic analysis and scenario-based analysis. Probabilistic analysis considers the aggregated effect of all possible hazard levels. In a probabilistic analysis, hazard levels are weighted by their respective probability of occurrence. In a scenario-based approach, the effect of a specific hazard level is considered (e.g. 200-year return period hurricane or a magnitude 6.5 earthquake).

In the context of multi-hazard analysis where risks due to different hazards are compared using an index, adopting a scenario-based approach such as comparing worst case scenarios of various hazards can be biased [13]. In such a case, all possible intensities of hazards should be considered which makes probabilistic hazard analysis more suitable for multi-hazard risk assessment. However, application of probabilistic seismic hazard analysis to spatially distributed infrastructure systems has been shown to be limited by Adachi and Ellingwood [10]. This is because the spatial variation of intensity for a severe earthquake is lost in the aggregation process of probabilistic analysis. The probabilistic approach, however, allows risks to be annualized which is essential in decision making regarding long-term investment in mitigation strategies. This approach also provides a way for risk comparison due to different competing hazards.

The limitation of both scenario-based and probabilistic hazard analysis can be overcome by adopting a probabilistically weighted deterministic hazard scenarios approach. This entails selecting a suite of hazard events under which risk analysis can be performed. The risk assessment is performed by weighing each hazard with its respective probability of occurrence. Consequently, the probabilistic nature of hazard occurrence and spatial variation of hazard intensities are reconciled. In this research, the probabilistic hazard analysis and the probabilistically weighted deterministic hazard scenarios approach are considered and compared.

2.1 Seismic hazard analysis

2.1.1 Probabilistic seismic hazard analysis

The annual rate of exceedance of seismic intensity measure, IM, is often modeled by a power law expression such as the one given by Eq. (1) [14].

$$v(IM) = k_0(IM)^{-k} \tag{1}$$

where $v(IM)$ is the annual probability of exceeding intensity measure, IM; and k_0 and k are empirical constants. The power law in Eq. (1) is linear on a log-log space. Bradley, Dhakal [14] demonstrated that the above power law overestimates the hazard within the low and high-intensity regions of the hazard curve and underestimates the hazard between the design basis earthquake (DBE) and maximum considered earthquake (MCE) intensity levels (see Fig. 2). To remedy such anomaly, Bradley, Dhakal [14] proposed a hyperbolic function in a log-log space as given by Eq. (2).

$$\hat{v} = a \cdot exp\left[b\left\{\ln\left(\frac{PGA}{c}\right)\right\}^{-1}\right] \tag{2}$$

where $\hat{v}$ is the annual probability of exceeding a certain peak ground acceleration; a, b, and c are constants determined by fitting the above Eq. over a hazard curve such as the one obtained from USGS [15]. Fig. 2 shows the hazard curve plotted using data from USGS [15] for a location in a coastal area of South Carolina. The power model in Eq. (1) is fitted to the USGS hazard curve using the method proposed by Jalayer [16] while the hyperbolic model in Eq. (2) is fitted using non-linear least square regression analysis. The constants k_0 and k in Eq. (1) are found to be 0.000192 and 1.072, respectively. The constants a, b, and c in Eq. (2) are found to be 0.33, 30.02, and 42.36, respectively. It can be seen from Fig. 2 that the hyperbolic function is more suited to the curve and it is therefore adopted for use in this research.

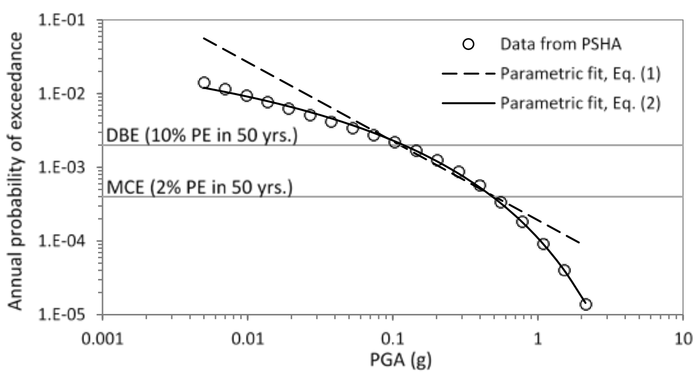

Fig. 2: Seismic hazard curve for Charleston, SC (32.8°N 79.9°W)

2.1.2 Probabilistically weighted deterministic seismic scenarios approach

To model the seismic hazard in this approach, a suite of earthquake scenarios with their corresponding annual probabilities of occurrence is required. The aim is to select enough earthquake scenarios to closely replicate the seismic hazard curves obtained from USGS [15]. The scenarios should be selected to represent all seismic source zones in the area, as well as the range of damaging earthquakes that are possible in the area as suggested by Chang, Shinozuka [17]. The application of this approach is detailed in Section 6.2.

2.2 Hurricane hazard analysis

2.2.1 Probabilistic hurricane hazard analysis

The hurricane annual maximum wind speed is assumed to be modeled by a Weibull distribution given by Eq. (3). The validation of this assumption can be found in [18].

$$f_v(v) = \frac{\alpha}{u}\left(\frac{v}{u}\right)^{\alpha-1} \exp\left[-\left(\frac{v}{u}\right)^{\alpha}\right] \tag{3}$$

where v is the wind speed, and u and α are the parameters of the Weibull distribution. The wind speed, v, is related to the return period (T) of the hurricane by Eq. (4). This equation is used to estimate the Weibull parameters for any given location by using two or more wind speeds and their corresponding return periods obtained from wind maps in ASCE-7 [19] or similar maps.

$$v = u\left[-\ln\left(\frac{1}{T}\right)\right]^{\frac{1}{\alpha}} \tag{4}$$

2.2.2 Probabilistically weighted deterministic hurricane scenarios approach

For this approach, a hurricane simulation model is used. This entails using site-specific statistics of key hurricane parameters and Monte Carlo simulation for assessing hurricane hazard level. Based on the site-specific parameters, thousands of scenario hurricanes can be generated and the wind speed at points of interest calculated.

3. Component Vulnerability Analysis

The structural components of electric power systems considered in this study are the substations and transmission structures/lines. Since the objective of this study is to model multi-hazard risk assessment, the fragilities of the system components are taken from existing literature.

3.1 Substation Fragility

Due to the nature and weight of substation components, substations are rarely damaged by hurricane winds. Rather, flooding resulting from storm surge is of greater concern for substations [20]. Since only hurricane winds are considered in this research, it is assumed that substations are not affected by hurricanes. Substations are however vulnerable to earthquakes due the presence of brittle components that have considerable mass [21, 22].

FEMA [23] modeled the seismic fragility of substations using lognormal distribution and provided the fragility parameters. This model is adopted for use in this research. Five damage states, namely: none, slight/minor, moderate, extensive, and complete were considered by FEMA [23]. In this study, it is assumed that substations in *extensive* or *complete* damage states will lose their functionality and are considered failed [24].

3.2 Transmission Line Fragility

Transmission towers are rarely damaged by the actual shaking of the ground during earthquakes as they are designed for severe loads such as combined wind and ice, extra loads due to the collapse of adjacent towers and so on. Instead, the damage is mostly due to foundation failures caused by landslides, ground fracture, and liquefaction. However, there is a lack of data to include such failures in analytical studies [25]. Therefore, it is assumed in this research that the transmission structures are not affected by earthquakes.

Brown [20] developed a fragility curve for transmission support structures subjected to hurricane winds based on 10-year storm-related damage data provided by four coastal utility companies. According to the data, a total of 1,947 transmission structures were damaged or replaced in the 10-year period. The exponential model fitted to the damage data is given by Eq. (5). It should be noted that the fragility of transmission structures depends on the type of structure as well as the conductor span. The fragility function given by Eq. (5) however did not take these factors into account. Rather, it based on general damage data collected by the utility companies. Therefore, the adoption of Eq. (5) here is for the purpose of demonstrating the proposed framework.

$$P(C < D) = min\{[(2 \cdot 10^{-7})e^{0.0834 \cdot v}], 1\} \tag{5}$$

where C is capacity; D is demand; and $P(C < D)$ is the probability of failure at a given wind speed, v. The span of transmission lines is usually long enough that the failure of one support structure will lead to service failure of the line. If a transmission line is modeled as a series system, the lower and upper bounds of the probability of failure are given by Eq. (6).

$$max[P_S] \leq P_{fL} \leq 1 - \prod_{i=1}^{N}[1 - P_S] \tag{6}$$

where P_{fL} is the probability of line failure; P_S is probability of failure of a single structure; and N is the total number of structures in the line. In this research, full independence is assumed between the failure modes. This is reasonable due to the long span between structures.

4. Risk Assessment

The seismic risk to infrastructure components is evaluated by convolving component fragility with the seismic hazard curve. The annual probability of exceeding a certain damage state is given by Eq. (7) [13].

$$P_A = \int_0^\infty F_R(IM) \cdot \left|\frac{d\hat{v}}{d(IM)}\right| d(IM) \tag{7}$$

where P_A is the annual probability of exceeding a specified damage state; $F_R(IM)$ is the fragility function given certain level of intensity measure, *IM*; and $\hat{v}$ is the seismic hazard function given by Eq. (2). For the hurricane hazard analysis, the risk to infrastructure components is quantified using the annual probability of failure which is estimated by convolving the structural fragility with a hurricane wind speed model as [26]:

$$P_A = \int_0^\infty F_R(v) f_v(v) dv \tag{8}$$

where $F_R(v)$ is the CDF of the structural fragility given a wind speed v which is modeled by Eq. (5) for transmission structures in this case; and $f_v(v)$ is the PDF of the hurricane wind speed given by Eq. (3).

5. System Reliability Model

For electric power systems, models of performance measure can range from purely topological-based models that only consider how the components of the system interrelate to complex power flow-based models that takes into account capacity limits of components and other engineering details of the system [27]. While power flow-based models provide more accurate description of system performance, they are computationally complex and often impractical [12, 27, 28]. Advantages of topological-based models include ease of computation especially for large systems and also little information about a system is needed to perform risk analysis. A topological-based model developed in [29] and [30] is therefore adopted in this research. The system reliability is given by Eq. (9).

$$R_S = 1 - \sum_{i=1}^{N} Q_i \frac{C_i}{C} \tag{9}$$

where Q_i is the probability that power is not delivered to the ith substation; C_i is the load served by ith demand substation (kVA, kW, or number of customers); C is the total load served by the system (kVA, kW, or number of customers); and N is the total number of demand substations in the system.

6. Illustrative Example

6.1 Electric Power System

The electric power system adopted to demonstrate the proposed framework is shown in Fig. 3 and is based on the electric power system of Shelby County, Tennessee modified from Shinozuka, Rose [31]. It is assumed herein that the system is located in two cities, namely Charleston and New York. The power system is superimposed on the map of the two locations using the georeferencing tool in ArcGIS. This allows the coordinates of each substation or any point within the system to be determined.

The system consists of 8 high voltage gate stations, 17 medium voltage substations, and 16 low voltage substations. The gate stations are assumed to be the source nodes while the medium and low voltage substations are the demand nodes. Power flow through the network is modeled so that edges connected to supply nodes are unidirectional while all other edges are bidirectional except those supplying terminal substations such as L5 and M5 in Fig. 3. The system is located such that gate station G1 is at latitude 33^{o}N and longitude 80.2^{o}W in Charleston, and 40.71^{o}N and 74^{o}W in New York. The system covers an area of approximately 1,000 sq. miles and transmission line span is assumed to be 800 ft. Number of customers is adopted for use in evaluating system reliability. Based on information of actual number of customers served by the system in Shelby-County [32], all the low voltage substations are equally assumed to serve 10,000 customers each while the medium voltage substations are assumed to serve 14,000 customers each. The total number of customers served by the system is therefore 398,000.

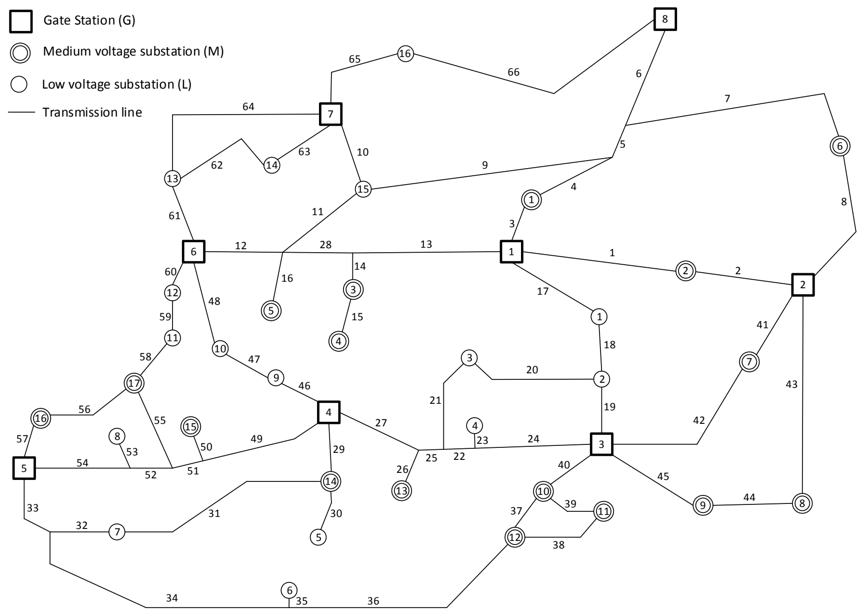

Fig. 3: Notional electric power system

6.2 Hazard Analysis

6.2.1 Seismic hazard analysis

For the probabilistic seismic hazard analysis, the seismic hazard curve data is obtained at each substation location through the hazard curve application from USGS [15] by inputting the coordinates of each substation. The hyperbolic function given by Eq. (2) is then fitted to the hazard curve which is used to calculate the annual probability of failure for each substation using Eq. (7).

For the probabilistically weighted deterministic seismic scenarios approach, the scenario earthquakes are selected from a catalog of earthquakes for Central and Eastern United States (CEUS) compiled in the Central and Eastern United States – Seismic Source Characterization (CEUS – SSC) for Nuclear Facilities report [33]. Nine and eight scenario earthquakes from a shortlist are selected for Charleston and New York, respectively, from the CEUS-SSC report. The selection is made so as to cover all possible hazard levels as accurate as possible and also to reduce computational effort. The selected scenario earthquakes from CEUS-SSC are from historical records and might not represent the entire risk in a given location, i.e., earthquake events of higher magnitude than those recorded are possible. Therefore, the maximum probable earthquake (MPE) from de-aggregation analysis of earthquakes from USGS [34] at a risk level of 2% in 50 years is also included in the list of scenario earthquakes for Charleston. The MPE corresponding to a risk level of 2% in 50 years and 1% in 200 years are selected for New York. The MPEs account for future events of higher magnitudes as MPE is defined as the largest predicted earthquake a fault is capable of generating. This makes a total of 10 scenario earthquakes for both locations.

For each scenario earthquake, the peak ground acceleration (PGA) at any location within the power network is evaluated using the attenuation relationship developed by Toro, Abrahamson [35]. An initial annual probability of exceeding the calculated PGA level is assigned so as to closely match the hazard curve from USGS [15] at a particular site. The annual probability of exceedance is then revised iteratively to minimize the error between the actual hazard curve from USGS [15] and the hazard curve based on the chosen scenario earthquakes. The locations of the 8 gate stations (G1 – G8) are used as control points to adjust the annual probabilities of exceedance. This is because if only one location is used to assign the probabilities, the resulting scenarios and their corresponding probabilities might not accurately model the hazard curves in other locations. Using 8 control points will ensure that the resulting scenarios and their corresponding probabilities can model the hazard in the entire area covered by the electric power system. Note that the annual probability of exceedance assigned to each seismic event or PGA level is cumulative of the probabilities of occurrence of events that will produce the same level of PGA or higher. Therefore, the probability of occurrence of an event is found by subtracting the appropriate annual probabilities of exceedance.

6.2.2 Hurricane hazard analysis

For the probabilistic hurricane hazard analysis, the wind speeds corresponding to several return periods are found for the mid-points of each transmission line from ATC [36] by inputting the coordinates of the mid-points of the lines. All the structures in an entire line are then assumed to be subjected to the same wind speed. The Weibull parameters for each line are then calculated using Eq. (4). The annual probabilities of failure of the individual transmission structures are calculated using Eq. (8) which is then used to calculate the annual probability of failure of an entire line using Eq. (6).

For the probabilistically weighted deterministic hurricane scenarios approach, the hurricane simulation model described in [18] and [37] is used. The required parameters for the hurricane simulation in South Carolina are taken from [38]. The parameters for New York City are found by fitting probability distributions to histograms of the parameters from Lin, Emanuel [39]. The simulation is carried out for 10,000 hurricane seasons. For each hurricane, the maximum wind speeds at the middle of each transmission line are recorded as the hurricane passes through the study region. The maximum wind speed at the location of G1 is also recorded based on which the annual probability of exceedance is assigned to each recorded wind speed so as to match the resulting hazard curve with that obtained from ASCE 7-10 model which can be accessed from ATC [36] for any location.

7. Multi-Hazard Risk Assessment

7.1 Risk Comparison Based on Risk Curves

For comparison of seismic and hurricane risks, it is imperative to use some kind of a common risk indicator. In this research, system reliability is used. Here, the concept of a multi-hazard risk curve is introduced. Such a risk curve shows a plot of system reliabilities against corresponding return periods (or exceedance probabilities). This allows direct quantitative comparison of the risks for the range of return periods covered by both hazards. To construct the multi-hazard risk curves for the probabilistic hazard approach, several return periods (or annual probabilities of exceeding various hazard levels) are selected. The corresponding PGA and wind speed at locations of all substations and lines are then found using Eq. (2) and (4), respectively. System reliability corresponding to each hazard level is then evaluated. The multi-hazard risk curves of the power system using the probabilistic hazard analysis are shown in Fig. 4.

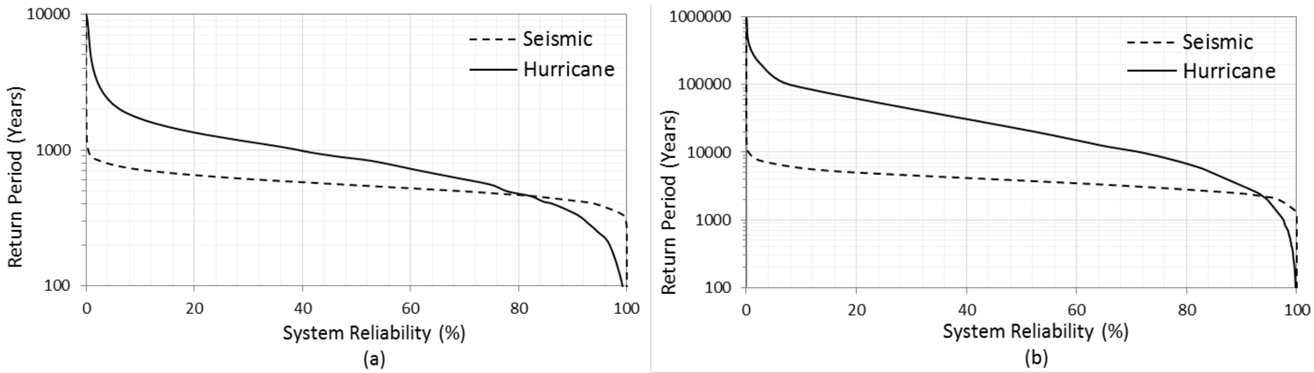

Fig. 4: Multi-hazard risk curves based on probabilistic hazard analysis; (a) Charleston, (b) New York

From Fig. 4(a), it can be seen that at higher return periods (lower exceedance probabilities) greater than about 460 years, the risk is clearly dominated by seismic hazard in Charleston. For instance, at a return period of 700 years, the system reliability due to seismic hazard is 12% compared to 62% due to hurricane hazard. It can also be seen that a 2000-year return period earthquake will cause a complete shutdown of the system (0% reliability) as compared to a 10,000-year return period hurricane that will cause the same impact. For more frequent events with return periods less than 460 years, it can be seen from Fig. 4(a) that hurricane hazard has more impact on the system than the seismic hazard. Both hazards have the same effect on system reliability at a return period of about 460 years. From Fig. 4(b), it can be seen that the pattern in New York is similar to that in Charleston with seismic hazard dominating the risk at return periods higher than 2,200 years. Compared to Charleston, however, it can be seen that both the seismic and hurricane risks are lower in New York.

Fig. 5 shows the multi-hazard risk curves using both the probabilistic hazard analysis and probabilistically weighted deterministic hazard scenarios approach for Charleston. It can be seen that risk curves from the two methods are similar. Relatively, the probabilistically weighted deterministic scenarios approach overestimates the risk in some sections of the curves. The comparison for New York is shown in Fig. 6 where the probabilistically weighted deterministic scenarios approach results in higher risk than the probabilistic analysis.

The advantage of the probabilistic analysis used is that it considers the entire range of hazard levels. However, the hazard levels corresponding to different return period at different locations does not necessarily occur at the same time or during the same hazard event. This is why the spatial variation of hazard intensity is lost in the aggregation process. The probabilistically weighted deterministic scenarios approach on the other hand models the spatial variation of hazard intensity during each event. However, due to the limitation on computational effort, the number of hazard events that can be considered is limited. Consequently, the approach might not cover the entire range of possible hazard levels.

The information gathered from the multi-hazard risk curves is valuable in decision making regarding risk mitigation investment as it gives information on the impact of both low-probability high-consequence events as well as frequent events on system reliability.

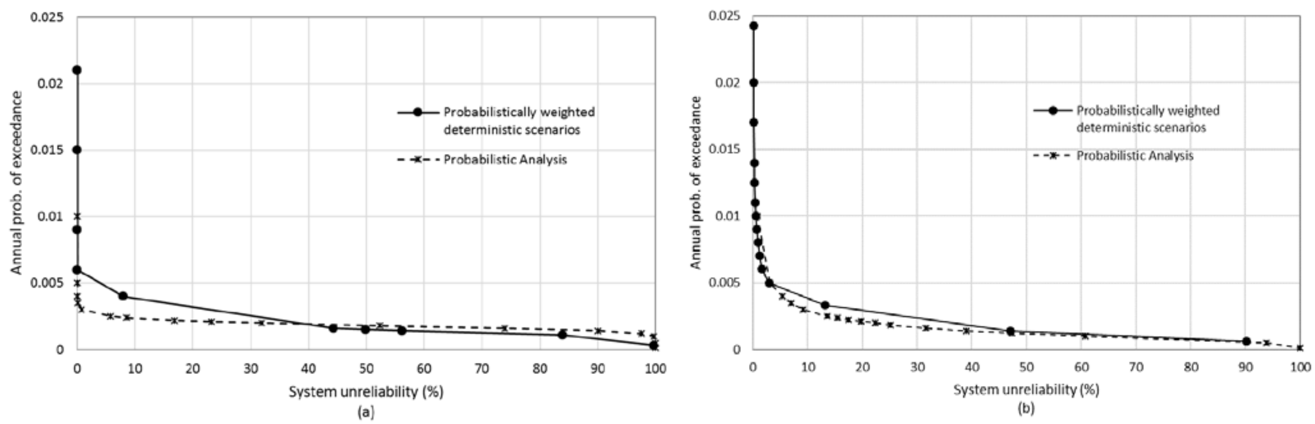

Fig. 5: Comparison between probabilistically weighted deterministic scenarios method and probabilistic method for Charleston (a) Seismic curves (b) Hurricane curves

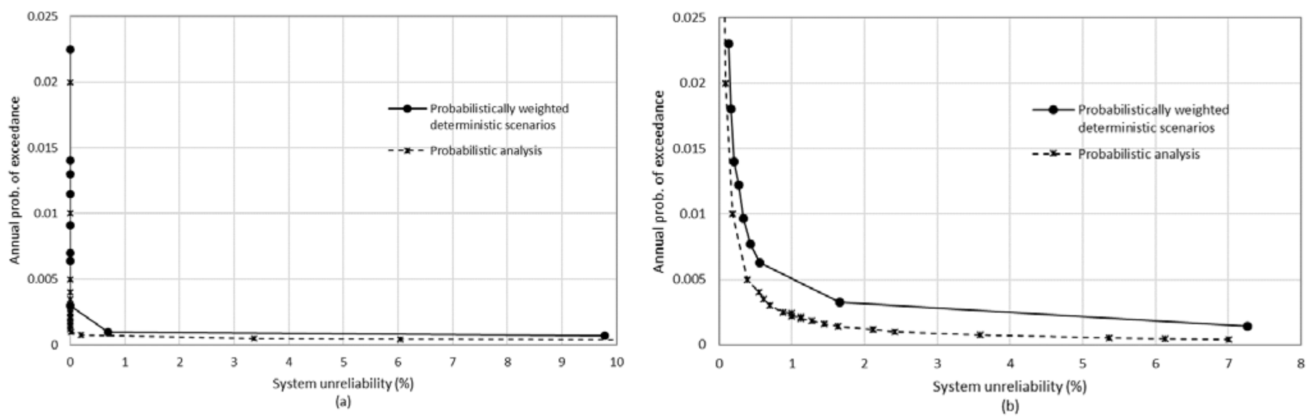

Fig. 6: Comparison between probabilistically weighted deterministic scenarios method and probabilistic method for New York (a) Seismic curves (b) Hurricane curves

7.2 Multi-Hazard Risk Based on Annual Probability of System Failure

The annual probability of system failure, defined as the complement of system reliability is plotted in Fig. 7. The annual probability of system failure is computed using the annual probability of components' failure from the probabilistic hazard analysis. The results show that in Charleston, seismic hazard has greater effect on system reliability, unlike in New York where hurricane hazard has a slightly higher effect. Considering the combined effect of both hazards, the system has a higher annual probability of failure in Charleston than in New York. Even though hurricanes and earthquakes are independent non-concurrent hazards, annualizing the risk (measured as system unreliability in this case) allows for the summation of the risks due to both hazards. For example, in the case of Charleston, there is a 0.11 annual probability of system failure due to earthquakes and 0.04 annual probability of system failure due to hurricanes. The total annual probability of system failure due to both hazards is thus 0.15.

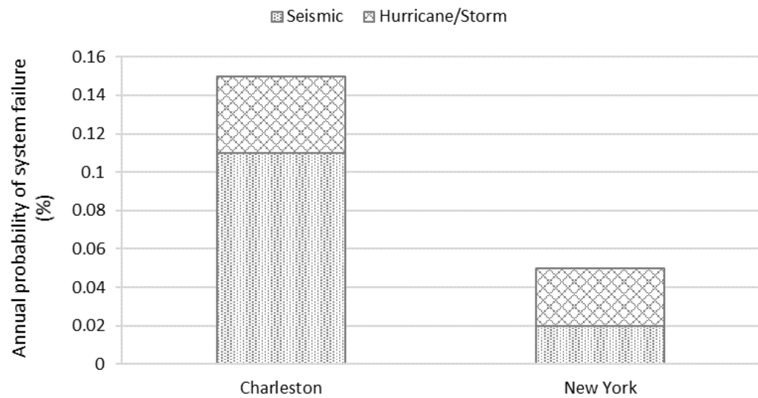

Fig. 7: Annual probability of system failure

8. Conclusions

A multi-hazard risk assessment framework has been presented in this paper for considering the impact of seismic and hurricane hazards on electric power systems. A more comprehensive risk assessment that takes into account the potential impact of all possible natural hazards on power systems will help to guide pre-disaster preparation as well as decision making regarding cost-effective mitigation strategies. A notional electric power system assumed to be located in Charleston, SC and New York, NY was used to demonstrate the proposed framework. The case study considered shows that multi-hazard risk assessment enables the comparison and/or aggregation of different risks to electric power systems and can reveal the contribution of each hazard to the overall risk to the system. The case study also shows that probabilistic hazard analysis and probabilistically weighted deterministic hazard scenarios approach can give similar results.

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