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Seismic vulnerability assessment of power grid systems

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Electric power systems play a critical role in assuring modern society's functionalities. Earthquakes are one of the most destructive natural hazards that affect the serviceability of electricity transmission systems. The earthquake excitations applied to each component of a power grid system (e.g., plants, substations and transmission lines) are spatially correlated by nature due to common causes. Yet limited attention has been paid to the impact of this spatial correlation on power grid system vulnerability. This paper presents an approach for estimating the seismic vulnerability of power grid systems using the network flow theory to model the power flow allocation over the grid components. A stochastic ground motion model is employed to represent the spatial characteristics of earthquake excitations. The proposed method is illustrated through an application to the seismic vulnerability assessment of the national power grid of Italy. The overall vulnerability is measured and evaluated through a proposed metric, and the critical components of the grid system are identified. The impact of spatial correlation of earthquake ground motion on the grid system vulnerability is also investigated.

Keywords: Power grid system, seismic vulnerability, earthquake excitation, spatial correlation, network flow theory.

1 Introduction

Electric power systems are crucial for supporting a community's functionalities due to their wide distribution and indispensable role in modern society. It has been demonstrated historically that a large-scale outage of a power system can lead to a catastrophic impact on a community's social, industrial, residential and commercial services (Bompard et al., 2007). In-service power systems are unavoidably exposed to many sources of hazards/attacks that essentially impair the system serviceability. Existing works on the vulnerability assessment of power grid systems have, for the most part, considered the load effects as spatially statistically independent for the whole system (e.g., Ouyang and Dueñas-Osorio, 2014, Salman and Li, 2017), which may differ from the realistic case due to both spatial variability and correlation of load effects, especially when considering a large-scale system. Some researchers have revealed that neglecting the load spatial correlation may lead to an overestimated system reliability and further underestimated damage losses (e.g., Goda, 2008). Thus, the assessment of seismic vulnerability of power grids needs to consider the spatial correlation of earthquake excitations applied to each component so as to better reflect the reality, especially for the case where scale of the grid system is large.

This paper assesses the seismic vulnerability of electric power systems in the presence of spatial correlation of earthquake excitations. The network flow theory is used to model the power flow allocation over the grid components, and a stochastic ground motion model is employed to represent the spatial variability and correlation of earthquake excitations. A metric is developed to measure the post-hazard state of the grid system, defined as the ratio of post-hazard weighted electricity consumption of end users to pre-hazard state. Illustratively, the seismic vulnerability assessment of the national power grid of Italy is presented to demonstrate the applicability of the proposed method. The impact of spatial correlation of earthquake excitations on grid vulnerability is investigated by comparing the results with those associated with fully correlated and statistically independent load effects.

2 Network flow model for electricity transmission systems

Power grids have been modeled as a complex network in earlier works due to their massive size and complex interactions among components and thus the topological characteristics such as small-world and scale-free features (Watts and Strogatz, 1998; Barabási and Albert, 1999) and cascading failure modes (Buldyrev et al., 2010). More recent works have as well considered the physical properties of power grids such as the power flow allocation over lines, instantaneous balance between power production and consumption and line flow limits (e.g., voltage modules and angles) to better describe the real-world systems (Bompard et al., 2011). In this paper, an electricity distribution system is modeled based on a complex network where the physical features and constraints of the power grid are also incorporated.

Figure 1(a) presents an illustrative electric power system, consisting of generation facilities, substations and distribution circuits. Figure 1(b) shows the national power grid system of Italy, where two types of transmission lines, namely 380kV and 220kV lines, are considered. We model an electric power system such as that in Figure 1(b) as a complex network with nodes being the plants and substations, and transform the multi-source multi-sink graph into a one-source one-sink problem by introducing a source vertex v_0 and a sink vertex v_1, as shown in Figure 1(c). Further, the electricity flow is described by a maximum-flow minimum-cost model, which can be solved using some well-documented methods such as the simplex algorithm (e.g., Bazaraa et al., 2010; Dwivedi and Yu, 2013).

3 Stochastic model of earthquake excitations

Stochastic ground motion models have been studied for seismic risk assessment of civil infrastructures subjected to earthquake excitations (Gidaris et al., 2015). Such a model is typically represented by a stochastic sequence (e.g., white noise) modulated by a function that accounts for the spectral characteristics of the ground motion. The inputs of both excitation model and structural vulnerability model complete the risk assessment through stochastic simulation techniques, where the uncertainties arising from both the seismicity characteristics and the functional relationship shall be captured under a probability-based framework (Ellingwood, 2001).

A stochastic ground motion to predict the ground motion intensity (e.g., the peak ground motion, PGA) at site i caused by earthquake j, Y_{ij}, generally takes the form of (Jayaram and Baker 2009)

$$\ln(Y_{ij}) = \ln(\overline{Y}_{ij}) + \varepsilon_{ij} + \eta_j \tag{1}$$

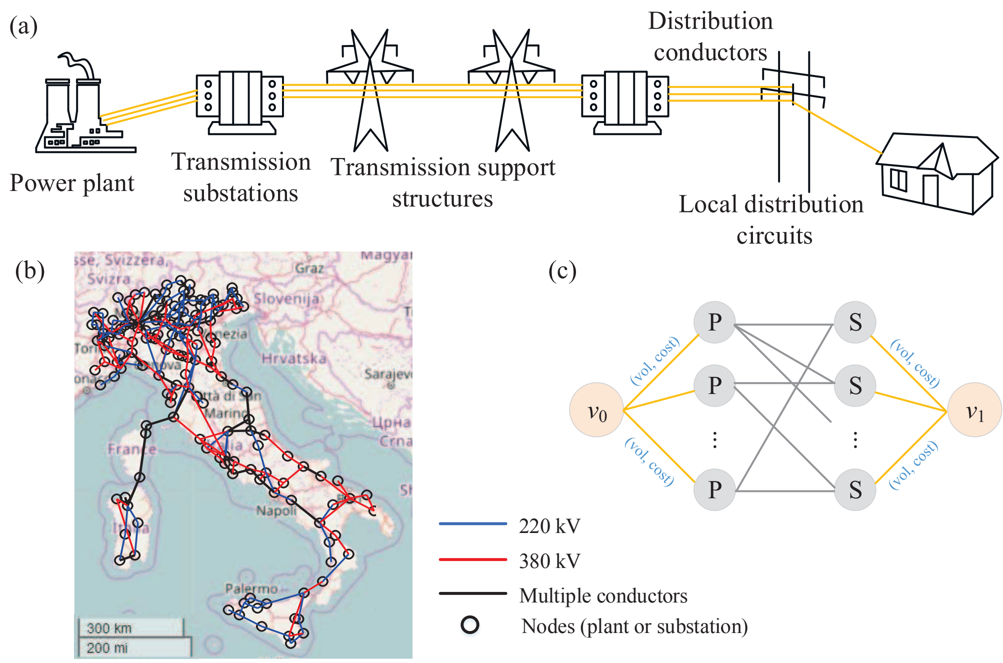


Figure 1. (a) Schematic figure of power system components. (b) Topological network of Italy electric power system. Grid data are from Global Energy Network Institute (GENI) at http://www.geni.org, and the geographic map is reproduced from the Open street map at http://www.openstreetmap.org. (c) Illustration of topological structure of network-based power grid system considered in this paper. The circled P and S denote the power plant and transmission substation respectively; v_0 and v_1 are (imaginary) source vertex and sink vertex in the topological network. Each transmission line (edge) has a transmission capacity and a cost (consumption), which further form a capacity matrix and a cost matrix for the whole grid system.

where $\overline{Y}_{ij}$ is the predicted median ground-motion intensity, ε_{ij} is the intra-event residual (a random variable) and η_j is the inter-event residual which is a common random variable for all sites conditional on the occurrence of one earthquake event. Sabetta and Pugliese (1996) developed a stochastic attenuation model for Italy using historical data, which is given by

$$\ln(Y) = a_1 + a_2 M + a_3 \ln(R^2 + h^2) + a_4 \varepsilon_1 + a_5 \varepsilon_2 + \Lambda \qquad (2)$$

where M is the earthquake magnitude, R is the epicentral or fault distance (in km), L is a zero-mean residual reflecting the variation of ln(Y), h is a fictitious depth determined by regression analysis, ε_1 and ε_2 are site classification indicators, taking a value of 1 for shallow and deep alluvium sites and 0 otherwise, a_1 through a_5 are constant, and Λ is the residual term. Eq. (2) can be used to describe the random field of earthquake excitations (e.g., PGA) in seismic vulnerability assessment of Italian electric power system, as will be adopted later.

4 A metric for seismic vulnerability of power grid systems

Components of an electric grid system such as plants, substations and transmission support structures may be impaired during an earthquake event. In order to reflect the seismic vulnerability of the grid system, this paper proposes a post-hazard vulnerability indicator, γ, defined as

$$\gamma = \sum_{i=1}^{n_S} \omega_i r_i^* \Big/ \sum_{i=1}^{n_S} \omega_i r_i^* \tag{3}$$

where r_i^* and r_i denote the post-hazard and pre-hazard electricity consumptions of the ith substation respectively, n_S is the number of substations, and ω_i is the importance weight of the ith substation (predicted by the importance level of the attached consumers). The indicator γ utilizes the electricity consumption of each substation to represent the total consumption of the associated end users (consumers) for simplicity, due to the consideration that individual end users are usually connected to a single substation. Despite this simplification, it is notable that the post-hazard damage of local distribution circuits (c.f. Figure 1) may affect the electricity transmission from substations to consumers and thus impair the electricity consumption of end users, which is not considered in this paper. In the following, the complementary of γ, $\gamma_c = 1 - \gamma$, will also be used to measure the reduction of the post-hazard performance of the grid system.

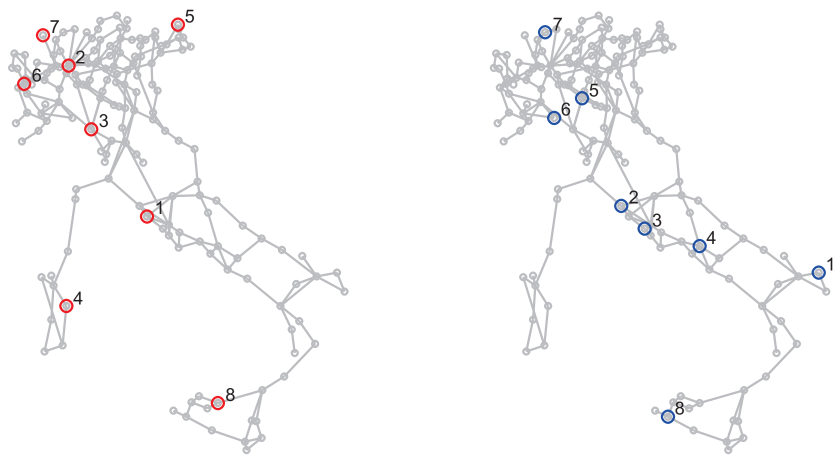
5 An illustrative example

We consider the seismic vulnerability assessment of the national electric power system of Italy, as shown in Figure 1(b). The seismic vulnerability is measured and evaluated through the indicator γ as in Eq. (3). The critical components of the grid system are identified, and the impact of spatial correlation of earthquake ground motion on the system vulnerability is investigated.

In order to model the seismotectonic structure of Italy, historical records with both rupture location and magnitude, which are available from the National Geophysical Data Center/World Data Service (https://www.ngdc.noaa.gov), are used herein. For the purpose of seismic vulnerability assessment, provided a randomly chosen pair of epicenter and magnitude from historical records, Eq. (3) can be used to model a random field of PGA.

Figure 2 shows the locations of critical power plants and substations which have a significant impact on system vulnerability. The labeled numbers denote the importance ranking of each component. For instance, the failure of plant 1 in Figure 2(a) leads to the largest reduction of γ compared with the failures of other plants. The post-failure indicator γ_c equals 0.0065 given the failure of plant 1 and 0.00076 if plant 8 fails. It is noticed that the electricity productions of the plants indicated in Figure 2(a) are not the highest among all the plants of the system, implying that the critical plants do not necessarily refer to those associated with high electricity productivity. The locations of critical substations are shown in Figure 2(b). While the substations 1 to 7 have different volumes of electricity consumption, their failures surprisingly lead to an identical reduction of γ, indicating that the importance rank of each substation is not necessarily determined by the electricity consumption uniquely.

The most critical transmission lines that have the most significant impact on γ can also be identified (not shown here). The failure scenarios can be classified into three categories: (1) the failed lines lead to the isolation of some substations; (2) the failed lines change local structure of power distribution (for example, a topologically closed structure becomes a series one); (3) the combination of the above two mechanisms. These results can be used by local governments and asset owners to make strategies aimed at maintaining normal use of the grid system and mitigating the effects of localized attacks.



(a) Critical power plants (b) Critical substations

Figure 2. Critical power plants and substations whose failure affects system vulnerability indicator most.

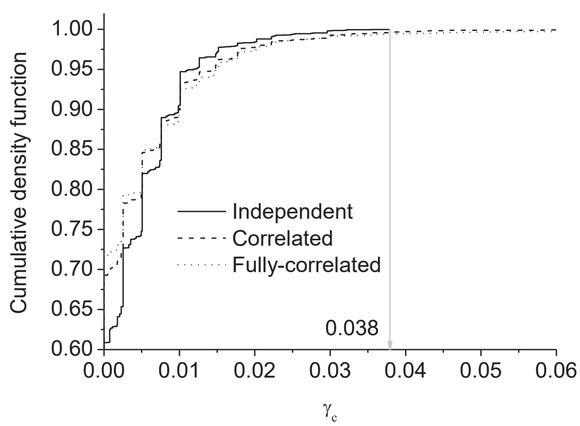


Figure 3. Comparison of probability distributions of γ_c associated with fully-correlated, realistic (correlated) and statistically independent earthquake excitations.

In order to investigate the impact of spatial correlation of earthquake excitations on the post-earthquake performance of the electric power system, Figure 3 compares the CDFs of γ_c for the cases of fully correlated, realistic (correlated) and statistically independent earthquake loads on the spatial scale. It is seen that at the lower tail of γ_c (e.g., $\gamma_c < 0.005$), the exceeding probability associated with independent earthquake loads is the highest, followed by those associated with the realistic and fully correlated excitations. At the upper tail (e.g., $\gamma_c > 0.020$), however, this observation is reversed. The CDF associated with the independent case reaches 1.0 at the region around $\gamma_c = 0.038$, implying that the assumption of an independent earthquake field underestimates the extreme damage of the grid system. The probability that $\gamma_c > 0.05$ conditional on the occurrence of an earthquake event is 0.36% for the case of fully correlated earthquakes, which is three time that associated with the realistic earthquake excitations, showing that the assumption of a fully-correlated earthquake random field essentially overestimates the grid system damage.

6 Conclusions

This paper has presented a probability-based framework for vulnerability assessment of power grid systems subjected to seismic hazards. A metric is developed to represent the seismic vulnerability of an electric power system, which can be used to identify the most critical components within the grid system in the presence of earthquake excitations. The applicability of the proposed method is illustrated through an application to the seismic vulnerability assessment of Italian national grid system. The probability distributions of the proposed vulnerability indicator associated with fully correlated, partially correlated, and statistically independent earthquake excitations are compared. It is found that the assumption of a fully-correlated earthquake random field underestimates the system seismic vulnerability, while the assumption of a statistically independent field overestimates the vulnerability.

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