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Network topology and resilience analysis of South Korean power grid

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HIGHLIGHTS

- Detailed information on power grid may produce highly-skewed degree distribution.
- Resilience of KPG is analyzed with multiple approaches including recovery.
- KPG is revealed as most vulnerable compared to ER and BA networks.

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ABSTRACT

In this work, we present topological and resilience analyses of the South Korean power grid (KPG) with a broad voltage level. While topological analysis of KPG only with high-voltage infrastructure shows an exponential degree distribution, providing another empirical evidence of power grid topology, the inclusion of low voltage components generates a distribution with a larger variance and a smaller average degree. This result suggests that the topology of a power grid may converge to a highly skewed degree distribution if more low-voltage data is considered. Moreover, when compared to ER random and BA scale-free networks, the KPG has a lower efficiency and a higher clustering coefficient, implying that highly clustered structure does not necessarily guarantee a functional efficiency of a network. Error and attack tolerance analysis, evaluated with efficiency, indicate that the KPG is more vulnerable to random or degree-based attacks than betweenness-based intentional attack. Cascading failure analysis with recovery mechanism demonstrates that resilience of the network depends on both tolerance capacity and recovery initiation time. Also, when the two factors are fixed, the KPG is most vulnerable among the three networks. Based on our analysis, we propose that the topology of power grids should be designed so the loads are homogeneously distributed, or functional hubs and their neighbors have high tolerance capacity to enhance resilience.

1. Introduction

Infrastructure systems provide and maintain functions of transporting energy, material, human, and information, all of which are essential to modern society, through their networked structure. Some infrastructure systems, such as electric power transmission and distribution grids, are also called critical or lifeline infrastructure because they provide

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interconnected functions such as emergency response or the provision of essential resources, without which society cannot operate as intended [1]. As such, improving the structural and functional resilience of critical infrastructure systems (CIS) to various natural and man made hazards has always been an important problem to public and research disciplines [2].

One novel method for improving the resilience of a CIS is to study it as a complex network. This approach enables the identification of important underlying structures within the CIS and assessment of structural and functional robustness in multiple (e.g., meso- or macro) scales perspectives [3]. Many types of CIS, including power grids [4–6], roads [7], public transportation [8], natural gas supply [9], and water supply [10] have been studied as complex networks. Among those, power grids are one of the most important infrastructure systems to consider, as numerous other CISs depend on the reliable and stable provision of electricity for proper functioning [11].

In general, power grids have a centralized structure, where power plants generate large amounts of electricity and transmission lines direct power across vast regions for end-point consumption. This is evident in South Korea (Korea hereafter), where manufacturing facilities that use over 50% of total electric power generated nationally [12] are often located far from power generation, suggesting a strong spatial mismatch between electricity supply and demand. Thus, the negative impacts of a failure occurring somewhere in the power grid are not geographically isolated, but rather easily propagated to places far away from its origin. Furthermore, strong interdependency of the power grids with other infrastructure systems typically aggravates this situation, as a failure can propagate across multiple systems [13]. For example, the water distribution system uses electric power to pump water, and electric power plants, in turn, use this water for running turbines and cooling systems. The interdependency between these CISs increases their local vulnerability, as disruptions occurring in either system can trigger cascading of failures across both [11,14]. Moreover, recent blackouts in several countries (e.g., India in 2012; Korea in 2011; USA and Canada in 2003; Italy in 2003) were initiated by local malfunctioning but resulted in huge economic damages in multiple sectors across large spatial regions.

Recently, several studies analyzed the topological properties of real power grid networks, and some of those works try to link the topology of those networks with system vulnerability. In particular, we refer interested readers to Cuadra et al. [15], who provided a thorough review of extant literature on power grid network and robustness analyses research. Here we discuss several important works in detail to give background on the field. Also, note that we provide thorough descriptions of complex network terminology relevant to this work in the methods section.

Albert et al. [16] analyzed North American power grid (115–765 kV) – which is composed of 14,099 nodes and 19,657 edges – and found that, in spite of being characterized by exponential degree distribution, the network exhibits similar behavior as a scale-free network to errors and attacks. Rosato et al. [17] studied high-voltage electrical power transmission networks of three European countries – Italy (380 kV), France (400 kV), and Spain (400 kV) – all of which exhibit a very large clustering coefficient with a larger characteristic path length than random networks characterizing small world systems. Rosato et al. [17] also assessed the vulnerability of each network by evaluating the minimum number of links needed to break each power grid into two sub-networks (the "min-cut" problem). Their results conclude that the specific geography of each country has a strong influence on network topography and associated vulnerability. Rosas-Casals et al. [4] and Sole et al. [18] analyzed 33 networks within the Union of the Coordination of Transport of Electricity (UCTE) power grid (110–400 kV) and found that all the networks were characterized by exponential degree distributions. However, they concluded that most of the networks did not have a small world topology, and the networks displayed similar vulnerability behavior to scale-free networks under random and selective node removal.

The works described above are representative of the majority of complex network analyses in literature since they focus on high-voltage electrical transmission systems. While analyses often remain at this scale because of data availability, this macro-scale focus may result in an only partial realization of topological properties due to limited information. To obtain a more detailed view to a real system, it is better to analyze the power grid with a broader range of voltage classes, i.e., including sub-transmission and distribution circuits [19,20]. Moreover, many of these studies claim to assess power grid resilience [18,21–24], but their methods focus solely on the remaining system structure or function after the removal of individual components (either nodes or links), which only assesses network vulnerability or robustness Resilience, however, also requires information on how systems recover and adapt during or after failure scenarios [25,26].

In this work, we analyze the Korean power grid (KPG) as a complex network. The KPG data is composed of power generation plants, transformers, transmission substations represented as vertices (or nodes), and transmission lines represented as edges (or links). Our data is unique because it spans a much wider voltage range (3.3–765 kV) than those networks considered in the literature by including sub-transmission circuits that terminate at distribution substations and transformers. Using this network data, we investigate topological properties of the KPG and its structural vulnerability and resilience, including its recovery performance. The rest of this paper is organized as follows: Section 2 introduces the KPG data and methods for topological, vulnerability, and resilience analyses. Section 3 presents results and discussion for these analyses. Finally, Section 4 summarizes the results and recommends new design principles for more resilient power grids.

2. Methods

2.1. Korean power grid (KPG) dataset

We generated complex network representations of the 2011 KPG by digitally extracting it from PSS/E (power system simulation for engineering) data of the national electric power system provided by the Korean Power Corporation (KEPCO).