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Q1 A study of the impacts of flow direction and electrical constraints on vulnerability assessment of power grid using electrical betweenness measures

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HIGHLIGHTS

- We analyze the effect of electrical properties on assessment of grid vulnerability.
- Flow direction impacts the identification of critical elements.
- Line limits also affect the identification of critical elements.
- Flow direction and line limits have more significant effects than node constraints.
- Combined electrical betweenness is more effective for detecting critical elements.

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ABSTRACT

In this paper, we analyze the impacts of major electrical properties, including node constraints, line limits, and flow direction, on vulnerability assessment of power grid using several types of electrical betweenness measures. Specifically, we first propose a set of new electrical betweenness measures, which takes into account flow direction in power grids. Then, the impacts of major electrical properties on vulnerability assessment of power grid are analyzed by comparing the identification results of critical components based on the proposed electrical betweenness measures with those based on the other two types of electrical betweenness measures reported in the literature, which take into consideration node constraints and line limits, respectively. Analysis results show the important impact of flow direction on the identification of critical components. The results lead us to introduce a set of combined electrical betweenness measures that take into account node constraints, line limits, and flow direction together. Simulation results on the IEEE 300-bus system and the Italian power grid show that the combined electrical betweenness measures are superior in identifying critical components and more useful in assessing power grid vulnerability.

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1. Introduction

Network scientists have applied network theory to the vulnerability analysis of power grid. Various measures have been used for this purpose. Betweenness centrality is one of the widely used measures. The betweenness measures are typically calculated based on the shortest paths between node pairs, assuming that information spreads along shortest paths between node pairs in a network. The betweenness measures have been used to identify critical components in real power grids such as North American power grid [1], Italian electric power grid [2], Dutch electric power grid [3], and East China power grid [4]. Also, these measures have been used to develop models for cascading failure analysis in real power grids such as Italian electric power grid [5], Western US power grid [6], North American power grid [7], and Northern China power grid [8].

However, the betweenness measures may not be directly applied to power grid vulnerability analysis. Since they do not take into account essential electrical properties of power grids, analysis results based on the betweenness measures may not accurately describe the characteristics of real power grids [9–13]. In Ref. [10], the betweenness measures have been modified with electrical betweenness measures in which the shortest paths between node pairs are replaced with the electrical paths. Recently, some new electrical betweenness measures have been proposed by taking into account additional electrical properties of power grids. For instance, the electrical betweenness measures reported in Ref. [11] take into consideration node constraints including generation capacity and maximum load demand; the electrical betweenness measures proposed in Ref. [12] include line limits, i.e., line power transmission limits. In these papers, the importance of the electric properties, i.e., node constraints and line limits, in power grid vulnerability analysis has been shown.

In this paper, we first introduce new electrical betweenness measures by taking into account flow direction in power grids. Then, we analyze the impacts of major electrical properties, including node constraints, line limits, and flow direction, on vulnerability assessment of power grid by performing comparative studies of the proposed electrical betweenness and those electrical betweenness reported in Refs. [11,12]. Analysis results show the important impact of flow direction on the identification of critical components. Thus, we further propose a set of combined electrical betweenness measures by including the electrical properties of node constraints, line limits, and flow direction together. We show the effectiveness of the combined electrical betweenness measures in the identification of critical components by performing vulnerability analysis on the IEEE 300-bus system and the Italian power grid.

The rest of the paper is organized as follows. In Section 2, we summarize recent works on the application of complex network concepts in the vulnerability analysis of power grids. In Section 3, models and measures for power grid vulnerability analysis are presented. In Section 4, new electrical betweenness measures with flow direction are introduced, and comparative studies based on simulations are provided. In Section 5, we further propose a set of integrated electrical betweenness measures and provide comparative studies. We conclude in Section 6.

2. A review of power grid vulnerability analysis using complex network concepts

Cascading failures are common in large complex networks such as internet networks, transportation networks, and power grids [6,14–17]. In a power grid, a cascading outage may affect a wide area or even the whole power grid, which causes catastrophic consequences. Thus, the study of cascading failures has become a vibrant research topic in power grid vulnerability analysis [18–23]. Recently, complex network concepts have been used to analyze the vulnerability of power grids against cascading failures. Following the recent reviews presented in Refs. [24,25], we classify related works in the area into two different categories: the purely topological approach and the hybrid approach.

The purely topological approach is mainly based on topological concepts. In this approach, the measures that are used to analyze large complex networks are directly applied to power grids to identify critical components and assess topological vulnerability [26]. This approach has been used to investigate various power grids such as European power grids [27–29], the North American power grid [1], the US Western power grid [30], and the New York power grid [31]. The investigations show that the power grids have a behavior similar to scale-free networks when nodes are removed. That is, the power grids are vulnerable to attacks on the most connected nodes but are robust against random loss of nodes. Thus, the failure of one of the small number of nodes may trigger large-scale blackouts in the power grids. In addition, the purely topological approach has also been used to analyze the structure of power grids. The research in Ref. [32] points out that the US Western power grid seems to be a small-world network. The nature of small-world networks is also found in other power grids such as the Shanghai Power Grid [33], the Italian 380 kV, the French 400 kV and the Spanish 400 kV power grids [34] and the Nordic power grid [30]. The work in Ref. [35] suggests that the degree distribution of the power grid seems to be scale-free following a power law distribution function, but exponential cumulative degree distribution functions are found in Californian power grid [36], the whole US power grid [1], and thirty-three different European transmission power grids [28]. While the purely topological approach is widely used to analyze the vulnerability of power grids, it may lead to inaccurate results since the purely topological approach does not capture electrical properties of power grids [24,25].

To improve the purely topological approach, the hybrid approach has been developed by combining the electrical properties with the topological concepts. In the hybrid approach, various topological measures in complex network analysis have been extended as electrical measures by incorporating the electrical properties [25]. For example, topological measures, such as efficiency, betweenness, and degree, were extended as net-ability, electrical betweenness, and entropy degree in Refs. [13,37–39]. It has been found that the extended electrical measures are more effective to identify critical components in power grids than topological measures. The work in Ref. [40] shows the connection between the analysis results of

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