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Vulnerability analysis of power grid with the network science approach based on actual grid characteristics: A case study in Iran

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HIGHLIGHTS

- We do not just use the centrality measure. We combined use of grid network topology and centrality measures with real and physical characteristics of power grid.
- The advantage of this approach is that it eliminates complex and time-consuming differential calculations.
- We used real dataset and the results were compared with dispatching center and verified.

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ABSTRACT

The vulnerability analysis of power grids has long been of paramount interest to researchers and authorities. Network vulnerability analysis refers to beforehand evaluation of the impact of local failures on the network as a whole so that proper measures could be adopted before occurrence of any major crisis. Previous studies on power grid vulnerabilities that are based on network science concept have been mostly concentrated on topological measures and unweighted networks. In this paper, grid vulnerability identification is carried out by combined use of grid network topology and centrality measures along with real and physical characteristics of power grid. Namely line load and failure rate, with the help of Weighted PageRank algorithm. The main advantage of this approach is that it eliminates complex and time-consuming differential calculations, which results in reduced computation time, and allows real-time updating of the result based on changes in the actual grid characteristics. The proposed model was validated by implementation over a section of Iranian 400 kV and 230 kV power grids. The striking accuracy of the achieved result was confirmed by comparison against results that obtained through calculations by Iran's national dispatching body.

1. Introduction

Power grid is one of the most vital infrastructures of any country, and due to the dependency of a whole nation on this public utility, utmost reliability and constant availability of power supply is a basic necessity. Power grid topology refers to the network of high-voltage transmission lines that transmit electricity over long distances within and between countries. The vertices of aforementioned network are the generators and substations and its edges are high-voltage lines. While all

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transmission substations are important components of power grid, position and operating condition of some substations make them more essential for network stability, which in turn make their reliability, safety, and security all the more imperative. In this context, the term vulnerability analysis refers to the process of identifying key substations and evaluating their role in the reliability of electricity grid [1].

Two important aspects of power grid vulnerability analysis are: network topology and network operating condition. Network topology is concerned with how its components are connected while network operating condition deals with how the load is distributed over the grid. Network topology is essentially static while operating condition is dynamic and in constant change depending on grid characteristics such as peak load.

The majority of published works on power grid vulnerability analysis that employ the network science approach have focused on network topology and paid little attention to weights and directions of its components [2]. In the few cases where direction is taken into account, lack of attention to core characteristics of a power grid, namely line load and line failure rate, have made the results inconsistent with network reality.

In this paper, we first introduce a novel power grid vulnerability prediction method and then use this method both to analyze the condition, structure and vulnerabilities of Iran's 400 kV and 230 kV power grids and to predict their vulnerabilities at different time horizons.

The following section, firstly, the literature on power grid analysis that is based on the network science is reviewed. Secondly, weighted power grid is considered based on the proposed method and identify power grid vulnerabilities by taking both network topology and grid characteristics. In the next section, the proposed method is applied for a fragment of Iranian power grids at 400 kV and 230 kV, and the results are evaluated against those obtained by engineers at the dispatching centers.

2. Power grid analysis based on the network science

In recent years, power grid vulnerabilities have received increasing attention from researchers in the field of complex networks and have been a topic of immense research. For example, vulnerabilities of US power grid were studied by Albert [1] (2004), Chassin (2005) [2], Wang (2009) [3], Hines (2010) [4], and Xu (2014) [5], and those of European power grid were explored by Rosas-Casals [6–9] (2007–2010). This same concern in Italy was investigated by Crucittia (2004) [10], Bompard (2010) [11] and Fenua (2014) [12], and in China, their counterparts; Mei (2011) [13], Ding (2006) [14] and Guohua (2008) [15] dealt with it. In our native Iran, the challenge was tackled by Monfared (2014) [16]. Moreover, Sun et al. (2016) [17] and Chowdhury et al. (2016) [18] evaluated the applicability of centrality measures aimed at analyzing critical lines by using IEEE 57-bus 118-bus test systems.

The primary centrality measures utilized in the aforementioned studies are Degree centrality, Betweenness Centrality, and Path length. Degree centrality was used by Chassin [2] to analyze the vulnerabilities of North American power grid. Degree centrality is a simple local centrality measure based on the extent of connectivity. This centrality is widely used for static graphs and problems where the goal is to find the nodes with greatest number of direct links to other nodes. Degree centrality of a node is defined as [19]:

$$d(v) = \sum_{u} m_{vu} \tag{1}$$

where $m_{vu} = 0$ if there is no edge between nodes v and u, and $m_{vu} = 1$ if such edge exists. Fig. 1 illustrates the degree centrality of nodes in European power grids.

Betweenness Centrality was used by Fenua [12] to analyze Italy power grid. This centrality refers to the number of times a node or edge is part of the shortest path between two other nodes. Betweenness centrality of the vertex x equals the number of shortest paths passing through it and is given by [19]:

$$b(x) = \sum_{s,t \in V \wedge s \neq x \neq t} \frac{\sigma_{st}(x)}{\sigma_{st}} \tag{2}$$

where σ_{st} denotes the total number of shortest paths from the node *s* to the node *t*, and $\sigma_{st}(x)$ denotes the number of those paths that pass through *x*.

Finally, Path length is The walk of minimal length between two nodes which is the shortest path length where a walk from the node *i* to the node *j* is a sequence of adjacent nodes that begins with *i* and ends with j. Based on the shortest path efficiency of power grid is to be can be computed by the following formula [20]:

$$E = \frac{1}{N(N-1)} \sum_{i \neq j} \frac{1}{d_{ij}} \tag{3}$$

where *N* is the number of nodes and d_{ij} is the shortest path between the nodes *i* and *j*.

As summarized in Table 1 most previous studies on power grid vulnerability that are based on the network science concept have typically utilized topological criteria without considering the network weights. An exclusively topological approach means studying electrical power grid as a graph and ignoring its real characteristics. But in reality, power grid is a weighted and directed network whose loads need to be taken into account.