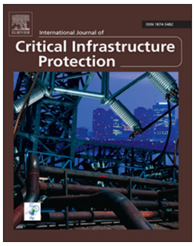
INTERNATIONAL JOURNAL OF CRITICAL INFRASTRUCTURE PROTECTION 12 (2016) 29–45

Available online at www.sciencedirect.com

ScienceDirect

www.elsevier.com/locate/ijcip



New centrality measures for assessing smart grid vulnerabilities and predicting brownouts and blackouts

Pravin Chopade[a,*], *Marwan Bikdash*[b]

[a]*Department of Computer Science, College of Engineering, North Carolina A&T State University, 526 McNair Building, 1601 East Market Street, Greensboro, NC 27411, USA*

[b]*Department of Computational Science and Engineering, College of Engineering, North Carolina A&T State University, 301 Fort IRC, East Market Street, Greensboro, NC 27411, USA*

ARTICLE INFO

Article history:
Received 21 July 2014
Received in revised form
1 October 2015
Accepted 25 November 2015
Available online 14 December 2015

Keywords:
Smart grid
Centrality measures
Admittance
Laplacian matrix
Vulnerabilities
Robustness

ABSTRACT

This paper proposes mathematical models based on the electrical properties of smart grids for conducting vulnerability analyses and predicting brownouts and blackouts. Definitions of pseudo-Laplacian, pseudo-adjacency and pseudo-degree matrices for smart grids are introduced to specify new centrality measures with electrical interpretations. The centrality measures are used to rank the relative importance of nodes (e.g., generating stations or substations) and edges (e.g., transmission lines or buses) of a graph corresponding to a power grid network and to assess the overall vulnerability of the network. The reliability of using the centrality measures to predict brownouts and blackouts is demonstrated in the face of random and targeted attacks. Monte-Carlo simulations are used to analyze attacks on smart grid networks and to assess the performance of the centrality measures. The simulations employ the IEEE 30-bus, IEEE 57-bus and IEEE 300-bus networks as well as the WSCC 4941-bus real power grid. Every scenario in the Monte-Carlo simulations involves the removal of a subset of buses and performing a complete nonlinear Newton–Raphson power flow analysis to compute the power traffic matrix and the corresponding centrality. The Monte-Carlo simulations conclusively demonstrate that electrical centrality measures based on the power traffic matrix are reliable indicators of the total unsatisfied load ratio (i.e., the load taken offline due to an attack divided by the total load demand). A key result is that, if the total centrality score of the removed buses exceeds a threshold estimated via Monte-Carlo simulation, then a sudden and dramatic jump to a blackout situation is ensured.

---

[*] Corresponding author.
E-mail address: pvchopad@ncat.edu (P. Chopade).

http://dx.doi.org/10.1016/j.ijcip.2015.12.001
1874-5482/© 2015 Elsevier B.V. All rights reserved.

1. Introduction

In many systems, the removal of certain critical components either accidentally or deliberately can cause system failure. In the case of a power system, a transmission line or generating station failure can seriously impact normal operations, possibly culminating in a brownout or even a blackout. Removing a transmission line shifts the load in the line to other intact lines in order to match the load demand. But this could overload other portions of the network, triggering relays that disconnect additional transmission lines in the power network. This could potentially lead to cascading effects that cause a large portion of the network to suffer total power loss [1,2].

More serious and rapid network loss can occur in the case of node removal. Nodes, especially generating stations, are connected to many other nodes via links such as transmission lines [32]. Large-scale faults can induce failures of several nodes and/or links. Localization indicates that the faulty nodes are located in the same neighborhood [18]. Unlike random graphs, scale-free networks display – on the global and local scales – high degrees of error tolerance as well as extreme vulnerability to attacks. Global and local efficiency may be unaffected by the failure of some randomly chosen nodes, but the networks can be extremely sensitive to the removal of a few nodes that are crucial to maintaining network connectivity [13].

Some of the centrality techniques proposed in recent years use concepts from network theory to study various properties of power grids. Centrality indices quantify the fact that some nodes and edges are more central or more important in a network than others [7,8]. This paper proposes mathematical models that are based on the electrical properties of smart grids for conducting vulnerability analyses and predicting brownouts and blackouts. Definitions of pseudo-Laplacian, pseudo-adjacency and pseudo-degree matrices for smart grids are introduced; this leads to the specification of new centrality measures for which electrical interpretations are developed. The new centrality measures are used to rank the relative importance of nodes and edges of a graph corresponding to a power grid network and to assess the overall vulnerability of the network. Monte-Carlo simulations employing random and targeted attacks on the IEEE 30-bus, IEEE 57-bus and IEEE 300-bus networks and the WSCC 4941-bus real power grid network are used to demonstrate the reliability of using the centrality measures to predict brownout and blackout scenarios. In particular, the simulations conclusively demonstrate that electrical centrality measures based on the power traffic matrix are reliable indicators of the total unsatisfied load ratio (i.e., the load taken offline due to an attack divided by the total load demand). A key result is that, if the total centrality score of the removed buses exceeds a threshold estimated via Monte-Carlo simulation, then a sudden and dramatic jump to a blackout situation occurs.

2. Related work

Network theory has been used to model and analyze several aspects of power system networks. The structural vulnerabilities of the North American power grid have received considerable attention after the North American blackout of August 2003. Large-scale blackouts and cascading failures have also motivated the analysis of the Italian power grid [6].

Bompard et al. [6] have developed an enhanced approach that uses traditional topological metrics (e.g., degrees of nodes and global efficiency) as well as the physical/operational behaviors of a power grid in terms of real power flow allocation on lines and line flow limits. In particular, they specified two new metrics, entropic degree and net-ability, that can be used to assess structural vulnerabilities in power systems. Andersson et al. [4] have summarized important reasons for blackouts such as the lack of reliable real-time data, insufficient time to take decisive and appropriate remedial actions, increased failure due to aging equipment and the lack of automated and coordinated controls to take immediate actions in an effort to prevent cascading failures.

Centrality measures the relative importance of a node or link in terms of network efficiency and network resource utilization. Koschutzki et al. [26] examined centrality indices based on distances and neighborhoods as well as on shortest paths. They presented several influential, classical centrality indices based on structural analysis, but they did not strive for completeness or provide a catalog of basic centrality indices along with their applications.

Borgatti [7] states that centrality measures can be regarded as generating expected values for certain kinds of node outcomes (e.g., speed and frequency of reception) given implicit traffic flow models. Borgatti regarded the formulas for centrality concepts such as betweenness and closeness as generating the expected values under specific unstated flow models for certain kinds of node participation in network flows. The principal contribution of Borgatti's work is that it provides assumptions underlying each measure and evaluates each measure using simulation. Node-centric measures are more convenient for computation and interpretation, and are, therefore, more common than edge-centric measures.

Centrality is commonly used in social network analysis to characterize social power and structural influence [28]. However, centrality plays a somewhat different role when studying faults and fault propagation in physical networks such as smart grids [42].

Zio et al. [42] have discussed the limitations that arise when neglecting the actual capacities of links, their failure probabilities and the fact that flows between network nodes are typically a global phenomenon, not restricted to direct or shortest paths as is typically assumed. To overcome some of these limitations, they developed a model of random flow propagation where the notion of betweenness centrality is extended to account for random flows in a network. Zio et al. state that the randomization of the flow out of a node is driven by the capacity values of its outgoing links and allows flows to travel along non-geodesic paths. However, they have not conducted an actual functional power flow analysis.