Physica A 413 (2014) 11–24

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

Vulnerability of the large-scale future smart electric power grid

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HIGHLIGHTS

- A bidirectional power flow based electric power grid vulnerability analysis has been presented.
- The consequence of removing critical nodes found from the analysis has been presented through various metrics.
- A modified centrality measure to identify critical elements of the grid has been discussed.

ARTICLE INFO

Article history:
Received 21 February 2012
Received in revised form 30 December 2013
Available online 5 July 2014

Keywords:
Centrality measure
Bidirectional power flow
Path length
Connectivity loss
Load loss

ABSTRACT

The changing power flow pattern of the power system, with inclusion of large-scale renewable energy sources in the distribution side of the network, has been modeled by complex network framework based bidirectional graph. The bidirectional graph accommodates the reverse power flowing back from the distribution side to the grid in the model as a reverse edge connecting two nodes. The capacity of the reverse edge is equal to the capacity of the existing edge between the nodes in the forward directional nominal graph. Increased path in the combined model, built to facilitate grid reliability and efficiency, may serve as a bottleneck in practice with removal of certain percentage of nodes or edges. The effect of removal of critical elements has been analyzed in terms of increased path length, connectivity loss, load loss, and number of overloaded lines.

1. Introduction

Utilities around the world are integrating smart and new technologies towards making the existing electrical power transmission grid much more smarter [1]. The scope of smart grid includes various generation options, primarily in the distribution side—near consumers. Engagement of customers with the energy management systems is the most lucrative part of smart grid from the point of view of regulating energy usage. Excess of generation after local use can be transmitted long distance to meet the energy shortage of the destination area.

This introduces a new concept of power flowing from customer end towards the grid. The bidirectional power flow changes the whole power flow pattern of the existing grid [2]. Analytical methods, technical strategies, control system and protecting devices need to be changed along with, to mention a few. Metering and protecting equipments will experience flows coming from the reverse side. Proper operation of the equipments used earlier can be ensured either by changing the instruments themselves or by incorporating new measurement techniques [3].

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http://dx.doi.org/10.1016/j.physa.2014.06.024
0378-4371/

Recent years have seen several very large scale blackouts initiating from small disturbances. In August 1996, a cascading outage occurred in the Western power grids of North America in USA and Mexico [4]. More than 4 million people suffered the consequences. Most affected areas were out of electricity for about 4 days. Another large scale blackout which affected around 55 million people happened in August 2003 [5]. Several northeast and midwestern states of USA and some provinces of Canada were affected.

The move towards the smart grid started after the blackouts happened all around the world [6]. From the frequent events of large scale-blackouts it is clear that the existing dynamics security assessment and monitoring system has not been working well [7]. The motivation of complex network framework based analysis approach comes from the necessity of new, alternative and improved methodology to assess the risk involved with cascading events in power system.

Degree centrality, betweenness centrality and closeness centrality measures are commonly used in social network research to find a person with most influence. [8]. The person who has most number of links is the most central according to degree centrality. Betweenness centrality measures the importance of a person as an intermediary. The person who comes across a path of communication between two other persons most of the times is considered as central in between centrality. A person is said to be closeness central if he or she is closest to all other persons relative to other persons in the network of interest.

Connectivity of the network is hampered, when nodes with higher degrees are taken out from the system. Removing a node takes out with it many links, which degrades the performance of network. Betweenness central node is important because it has the most ability to control communication between other nodes. The node which has least distance from all other nodes is closeness central. This node is the most independent one since it can communicate with other nodes without the need of intermediate nodes.

Power grid topology has been analyzed by various researchers recently to explore its strength and weakness using complex network framework. The strength of the grid is found to be, from a pure topological analysis of USA power grid, small-world property [9]. This implies that various nodes within the system can be reached easily, which will make the communication that comes along with the smart grid easy and effective. The scale freeness of the topology of the grid is shown to be a weakness of the grid since it makes the system very much vulnerable to targeted attack [10]. This targeted attack can trigger cascading failure which will lead to blackout.

The research on power grid from a system point of view has been triggered after the publications of the preliminary topology based analysis results. Since results from pure topological approach is quite misleading [11], several researchers have a mix of both topological and electrical characteristics based complex network analysis of power system to find reasonably improved results [12,13].

Motivated by the topological result that found the power grid robust against random failure but vulnerable to targeted attacks [10], critical node and link analysis of power grid have been carried out to explore the criticality of the power grid. If critical components can be spotted out which can initiate cascading effect, special preventive actions could be exercised so that to prevent large scale blackouts from happening.

Network efficiency, a topological measure of performance change after the inclusion or removal of nodes or lines from a grid, is analyzed in Ref. [14]. A weighted line betweenness based approach is utilized to find out critical lines responsible for spreading of large scale blackouts from small initial shock [15]. Vulnerable regions of power system is identified employing complex network theory based qualitative simulation in Ref. [16]. Transmission line reactance is incorporated to compute a new vulnerability index to identify critical lines [17].

A link is explored between power system reliability and small world effect [18]. Maximum flow based centrality approach is used to find out critical lines which removes the shortcoming of the assumption of power flowing through the shortest paths between source and load nodes [19]. This method has slow convergence but can be useful when used in conjunction of planning issues. A DC power flow model is used and hidden failure of protective equipment is considered to model the structural vulnerability of power grid [20]. Electrical parameters are incorporated extensively to improve the centrality indices for power system [21].

An extended topological approach proposed in Ref. [22] takes into consideration traditional topological metrics as well as operational behavior of power grids like real power flow allocation and line flow limits. Power Transfer Distribution Factor (PTDF) is used to simulate cascading event in an attempt to identify correlated lines [23].

All these analysis are carried out for electric grids where power flow is directed from generating nodes to load nodes. But since with the inclusion of distributed generations the power flow pattern is going to change, new methodologies have to be proposed which takes into account bidirectional power flow. Since communication is an important factor in smart grid, identifying those nodes in the system would be very much useful which are important for communication. These issues have not yet been addressed in literatures as per authors best knowledge.

In this paper, a method based on complex network theory has been proposed to identify critical components in smart grid. This method is a modification of closeness centrality which takes into account power flow distribution among various power lines during steady state. This is a reasonable extension of previous work carried out by researchers since it captures the power flow in smart grid environment. Rank similarity analysis result is carried out to verify that the proposed index is useful although there is a slight change in network. The impact of removing critical components are identified using well known impact metrics like path length, connectivity loss and load loss.

The organization of the rest of the paper is as follows. Section 2 provides a model for the analysis of smart power grid under complex network framework. A new model based on bidirectional power flow is considered and a method is discussed