Physica A 460 (2016) 105–115

Contents lists available at ScienceDirect

Physica A

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

A power flow based model for the analysis of vulnerability in power networks

Zhuoyang Wang [a], Guo Chen [b,*], David J. Hill [a,c], Zhao Yang Dong [a]

[a] School of Electrical and Information Engineering, The University of Sydney, Australia
[b] School of Electrical Engineering and Computer Science, The University of Newcastle, Newcastle, Australia
[c] School of Electrical Engineering, The University of Hong Kong, Hong Kong

HIGHLIGHTS

- A new model for the analysis of power system vulnerability is proposed.
- A new vulnerability index is presented to identify the vulnerable lines.
- The proposed model can have a closer approximation to a real power grid.
- Simulations show the proposed model is more effective in vulnerability analysis.

ARTICLE INFO

Article history:
Received 9 January 2016
Received in revised form 22 April 2016
Available online 11 May 2016

Keywords:
Power system
Vulnerability analysis
Complex network
Max-Flow
Power flow

ABSTRACT

An innovative model which considers power flow, one of the most important characteristics in a power system, is proposed for the analysis of power grid vulnerability. Moreover, based on the complex network theory and the Max-Flow theorem, a new vulnerability index is presented to identify the vulnerable lines in a power grid. In addition, comparative simulations between the power flow based model and existing models are investigated on the IEEE 118-bus system. The simulation results demonstrate that the proposed model and the index are more effective in power grid vulnerability analysis.

1. Introduction

It is well known that a power grid plays an indispensable role in modern society. Lately, the competitive electricity market environment, with rapidly rising distributed generation and renewable energy sources, increases the stress of the whole power system, bringing a new risk of cascading events [1]. Power system security is always an important issue in the power industry and much work has been implemented to enhance the grid security and reliability. However, large scale blackouts all over the world still occur from time to time [2] due to the continuous evolution of power grids. Thus, it is necessary to further develop new tools and models so as to meet the new situations and mitigate potential large scale blackouts.

In recent years, complex networks (CN) theory has been studied intensively in solving practical problems of large-scale complex systems. A power grid has evolved into one of the most complex human-made systems. According to recent research, it can be described as a small-world network [3] which is highly clustered. In other words, although many nodes are not neighbors of one another in the network, one can be reached from others by only a few steps [4,5]. In the case of

* Correspondence to: School of Electrical Engineering and Computer Science, The University of Newcastle, Newcastle, Australia.
E-mail address: guochen@ieee.org (G. Chen).

http://dx.doi.org/10.1016/j.physa.2016.05.001

a power system, this structure can maintain a short electrical distance between loads and generators even if the grid size is very large. It may imply that the power transmission capacity of a power network would reduce greatly when a failure occurs in these paths. In addition, a power grid has also been shown to exhibit the properties of a scale-free network [6]. It is well known that scale-free networks are robust to random failures but vulnerable to targeted attacks [7]. Thus, these above characteristics may imply that the removal of a few of important lines and/or nodes in a grid would cause cascading failures and severe blackouts [8]. That is to say, a power system is vulnerable when some important nodes and/or lines are attacked. However, how to accurately identify these nodes and lines is still an open question.

It is obvious that new development in the CN field has provided an innovative direction for power system vulnerability analysis [9]. Currently, most research is focused on network topological structure. The large-scale blackouts in North American and Italy were studied by the network structural vulnerability method in Refs. [10,11] respectively. In these studies, indexes and methodologies from graph theories, such as degree distribution, shortest path and diameter are widely used to identify the vulnerable lines in power grids. The analyzing result of an American power grid based on this methodology is given by Refs. [12,13]. Based on these basic concepts, the mechanism of cascading failures has been explained in Ref. [14] and an efficiency based model of cascading failure was proposed. Herein, the efficiency is defined as harmonic composition of the efficiency of edges. Ref. [15] reviewed some basic modeling and traditional methodologies in structural vulnerability. Furthermore, based on topology and load distribution, two criteria to identify the critical lines are proposed in Ref. [16]. The results explain how a link and its location can affect the network's capability. Unlike these traditional physical topology models, an electrical efficiency model is proposed in Refs. [17,18], where a power grid is depicted as a weighted graph based on the electrical topology. Furthermore, in these models, it is assumed that the power flow is transmitted across the line with least resistance. Thus, the admittance is used to weight lines in a power system. Based on this electrical model, a lot of research has been carried out in recent years. Net-ability, a measure of power system performance under normal operating conditions, is considered in Ref. [19]. Also a cascade-based model is proposed in Ref. [20]. Several critical power system features are included in Ref. [21], such as Kirchhoff's Laws and power angle, and thus this model can have a closer approximation to a real power grid.

However, some important issues still exist. Most work just analyzes a power system considering the efficiency or the shortest path based algorithms from the CN theory. In these studies, a power grid is described as an undirected graph weighted with efficiency or shortest path. However, in a real power grid, the power is driven by the generation and load distribution, voltages and rotor angles etc. Thus the power flow always has a direction. Moreover, the power neither flows along the shortest path nor any efficient path. Actually, the power flows from the generation rich side to the load rich side through parallel paths determined by complex interaction of all factors, which can be observed by power flow analysis. To the best of our knowledge, no prior analyses have investigated in terms of the flow feature and its directions together.

With this consideration, the main contribution of this paper is to develop a new model and analysis approach that aim to analyze the vulnerability of a power system. Firstly, a power flow based model is proposed. This model considers more power system features compared with previous ones. Consequently, it is a closer approximation to a real power grid. Then, a new definition of vulnerability index is introduced to identify the set of vulnerable lines in a power system. The lines with a higher vulnerability index ranking are considered to have more damage to a power grid when they trip off. It is shown in later sections that this innovation can form better approximation models for the vulnerability analysis of a power system.

This paper is organized as follows. Section 1 gives the introduction and rationale of this research. The main ideas of the topological structure model and the efficiency based model are introduced in Section 2. Section 3 presents the deficiencies of those models by the actual measurement comparison in a power grid test system. Then a new power flow based model for power system vulnerability analysis is introduced in Section 4. Numerical simulations are displayed in Section 5 to show the performance of the new model. Conclusions and future work are discussed in Section 6.

2. Topological and electrical efficiency analysis models

2.1. Traditional topological structure model

A power grid contains a certain number of buses with transmission lines connected to them. Based on the topology of a power grid, a graph G with N nodes and K edges can be formed, where nodes represent buses and edges represent the transmission lines respectively. The graph G defines an $N \times N$ adjacency matrix, whose elements A_{ij} describe the physical connections of the network. The key physical characteristics of a network can be gained from the adjacency matrix. The connectivity of a network is mainly defined by the nodal degrees and clustering coefficients. Analyzing these characteristics can give an indication of the structural vulnerability of a power grid [14].

2.2. Electrical efficiency model

The topological model can only describe the physical structure and connections of a power system. However, a power grid is more than just a simple network structure. There are several electrical features such as current and voltage, which can impact the performance of the whole system. Thus, based on the physical model, an updated electrical efficiency based model was proposed. In the electrical efficiency model, the power network G is denoted by an $N \times N$ admittance matrix,