Physica A 512 (2018) 316–329

Contents lists available at ScienceDirect

Physica A

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

Novel complex network model and its application in identifying critical components of power grid

Chong Chen, Xuan Zhou, Zhuo Li, Zhiheng He, Zhengtian Li *, Xiangning Lin

State Key Laboratory of Advanced Electromagnetic Engineering and Technology, School of Electrical and Electronic Engineering, Huazhong University of Science and Technology (HUST), Wuhan 430074, China

HIGHLIGHTS

- The power flow transmission network of the power grid is defined.
- The proposed model captures both the structure and operating status of the grid.
- A more systematic grid critical components identification model is proposed.
- Extensive simulations show the effectiveness and superiority of the proposed model.

ARTICLE INFO

Article history:
Received 8 January 2018
Received in revised form 28 April 2018
Available online xxxx

Keywords:
Complex network model
Power flow transmission network
Transmission capability
Critical component identification
Capability degree
Betweenness

ABSTRACT

A novel power grid complex network model in order to in-depth characterize the power grid with its complexity is proposed in this paper, based on the power flow transmission network (PFTN). With novel definitions, considering the path, distance and capacity of power transmission comprehensively, the complex network model can comply with the basic electrical law and the physical constraints of power grid. On this basis, an index set for identifying critical buses and branches within the power grid is designed. The index set includes distance and capability degree, hub, distance and capability betweenness, which can fully evaluate the role of nodes or branches in composing the structure and maintaining the system operation of the power grid. Simulations on both IEEE benchmark systems and a provincial power grid in China are conducted using the proposed model, with critical components identification yielding good results. By comparison with existing methods, the effectiveness and superiority of the proposed model are verified.

1. Introduction

With the gradual construction of UHV transmission and the increase of large-scale power transmission cross regional power systems, interconnection between regional power grids is becoming more tight, increasing the size of power grid and complicating its form [1]. Although large-scale power grid improves the economy and reliability of power transmission, it increases the possibility of tremendous power outages and catastrophic accidents caused by partial failures [2–5]. The theory of complex networks (CN) provides a tool to analyze power grid characteristics from the perspective of the overall topology [6,7]. However, existing works are mainly based on the basic complex network model or with limited consideration regarding physical features of the power grid, which still have a big gap before being applied in actual power grid [8].

In order to appropriately analyze the successive blackouts of power grids, CN is introduced into the modeling and simulation of the large scale power grid [9,10]. Since then, a lot of research has been carried out to analyze the vulnerability

* Corresponding author.
E-mail address: lizhengtian@hust.edu.cn (Z. Li).

https://doi.org/10.1016/j.physa.2018.08.095
0378-4371/

of power grid against cascading failures with concepts from CN theory. Basic concepts form CN theory, such as mean path length, clustering coefficient, efficiency, degree distribution, betweenness distribution, small-world property and scale-free property, has been introduced directly to analyze structural properties of power grids [11–14]. This approach is based solely on the topological structure that a power grid is modeled as a graph, with identical nodes representing stations and substations, and un-weighted branches modeling transmission lines between nodes, which is classified as the purely topological approach by the recent reviews [15,16]. And in this approach, the physical quantity between two nodes is supposed to be transmitted through the shortest path (path consisting of least nodes). From the conclusions drawn from numerous related works it can be found out the approach provides a total new perspective to analyze the power grid, making important contributions to understanding the structural characteristics [6,9,10]. However, there also exist many deficiencies in this quite simplified model, with which results may be not very credible since there is a huge difference between this model and the actual power grid. To improve the purely topological approach, some electrical properties are introduced to combine with topological concepts, such as branch impedance and simplified power flow models, which is classified as the hybrid approach [15,16]. In the hybrid approach, extended metrics of entropy degree, electrical betweenness and net-ability are proposed to substitute conventional ones, and the Power Transfer Distribution Factors (PTDF) or the Maximum-Flow concept are used to replace the shortest path [17–21]. These improvements make a huge progress to analyze the vulnerability of components in power grid with CN theory from both a global and a local point of view [22]. And it has been found that the extended electrical measures are more effective to identify critical components in power grids than topological measures [23,24].

In the information network, the dissemination of information is "atomic", but the current transmitted in the power grid is "divisible". Despite being constrained by the physical topology, the power grid is more of a flow-based network than a topological network. It is the PFTN between generator–load pairs hidden under the topological structure that can truly reflect the structure and operation characteristics of the power grid. In the actual power grid, the final power transmission path of a generator–load pair only pass some of the branches due to the superposition of the flow in different directions, and not all the branches bear the task of power transmission. Therefore, the establishment of the power grid CN model based on the power flow transmission network (PFTN) with AC power flow not simplified power flow models (e.g. the shortest path, the PTDF method, or the Maximum-Flow) is of great significance for accurately analyzing and revealing the structure and operation characteristics of the power network. What is more, branch impedance, capacity and other electrical properties should be properly modeled.

In recent years, blackouts occurred worldwide, which tend to be caused by initial failures of a few components. However, if affecting critical components of the grid in operating state, it will cause expansion of the accident [2,3]. Therefore, identification of the critical components (nodes and branches) within the power grid in real-time state and improving monitoring and protection for them accordingly have great significance in restraining the size of a power system accident. Also, during the stage of power grid planning, by lowering high criticality of individual components, balance and robustness of power grid can be increased [8]. It is proposed on the basis of small-world model of grid, which declares that nodes or branches of high degree or betweenness play an important role in the cascading failure occurrence and expansion [10–12]. Identification of critical components within the power grid from the respect of grid structure by the complex network theory is an effective way to achieve the above goal, of which core indexes include degree and betweenness. Degree, betweenness and other centrality measures derived from purely topological models have been widely used to identify critical components in real power grids such as North American power grid [10], Italian electric power grid [25], Dutch electric power grid [26], and Swiss transmission grid [27]. Considering the graph-based centrality measures cannot take into account essential electrical properties of power grids, extended metrics of entropy degree, electrical betweenness based on hybrid models have been proposed, which can be better used to rank and identify critical components of the power grid [23,28–30]. The work in [31] shows the connection between the analysis results of the extended metrics and real blackout data of German, Italian, French and Spanish power grids. However, due to reasons aforementioned, these indexes proposed by previous research based on the purely topological approach or hybrid approach cannot accurately measure changes in the structure and operating conditions of the power grid. At the same time, the indexes defined previously are not systematic or comprehensive, for instance, node betweenness cannot fully reflect the input and output power flow, capacity and activity level of nodes in the grid [8].

With considerations above, the main contribution of this paper is to develop a novel power grid CN model and then a comprehensive and systematic model for identifying critical components is established based on it. Firstly, the flow of the power grid under current operating conditions was traced between all generator–load pairs. Consequently, the PFTN of the power grid under specific structure and operating conditions is obtained. Then, in order to better analyze the power grid, a novel power grid CN model is established with 3 new definitions put forward based on the PFTN: Power Transmission Path, Weighted Power Transmission Distance and Path Transmission Capability. At last, a more comprehensive and systematic model for better identifying critical components of the grid is proposed based on the novel power grid CN model.

This paper is organized as below. In Section 2, a novel power grid CN model is proposed with 3 new definitions. Based on the novel power grid CN model, critical components identification model is established in Section 3. In Section 4, numerical simulation are displayed, followed by conclusions in Section 5.