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Topological interactive analysis of power system and its communication module: A complex network approach

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HIGHLIGHTS

- Interactive power and telecommunication network are considered.
- Centrality measures of complex networks are briefly reviewed.
- Novel interactive statistical measures are proposed for the interactive network.
- Case studies about the interactive power and telecommunication network of one province in China are carried out.

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ABSTRACT

Power system and its communication system, which can be called a cyber-physical system, are interconnected and interdependent on each other. This paper considers the interaction problem between power system and its communication module from the perspective of the topological structure. Firstly, some structural properties and centrality measures of complex networks are briefly reviewed. Furthermore, novel interactive measures are proposed to describe the interactive system in terms of topologies. Finally, based on these metrics, the statistical properties and the interactive relationships of the main power system and its communication module (abstracted as two complex heterogeneous networks) of one province in China are investigated.

1. Introduction

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The past decade has witnessed great efforts to build a *strong and smart grid*, that is, strong Ultra High Voltage (UHV) AC/DC hybrid transmission system and smart power telecommunication system, which in turn make the power system more controllable and observable [1,2]. A characteristic of these two critical infrastructure systems is that they are highly interconnected and mutually dependent which has formed a coupled system, while the decoupled systems are functional different. It has been widely agreed that there are inseparable interdependencies among the reliability, robustness, survivability, and some efficient operations of the power system and the corresponding communication system [3],

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meanwhile the performance of the power system is also assured by the global monitoring and control through the services of the communication system [4].

At present, smart grids are becoming increasingly dependent on its communication system (i.e. power telecommunication system) to process electrical information which could provide safe-stable services for power systems. While the power telecommunication system is not alone but interdependent on the power system, such interdependencies truly enhance the performance of the entire smart grid system; on the other hand, it may also increase the potential for cascading failures. Buldyrev et al. [5] have developed a framework for understanding the robustness of interactive networks subject to cascading failures and demonstrated a cascade of failures by using real-world data from a power network and an internet network. While this conclusion may not be appropriate for the interactive power grid and the power telecommunication network. Most of the realistic blackouts are caused by the initial failure of some substations in power grids, and only small fraction of cascading failures in power grids are caused by the failure of communication equipments [6]. That is the failure of substations in power grids may not influence the corresponding communication equipments in the same location, instead, the failure messages can be detected rapidly and forwarded to the control center. The communication network is just like a mirror of the power grid, if there is an initial failure in the communication network, then the failure of the power grid may not be observable and controllable. Interactive cascading failures in the power grid and the power telecommunication network are not similar to the power grid and the internet network due to the fact that lots of communication equipments are not strongly dependent on the power supply. Meanwhile, most of the transmission equipments for the power telecommunication system are always equipped with backup powers, a short-term power outage may not degrade the performance Q3 or paralyze the communication system.

By abstractly denoting the power system and its communication system, one can derive two complex networks, that is, the power grid [7] and the communication network [8]. These two networks are interdependent on each other, and such coupled network can present structural and dynamical composite features which are different from those observed in isolated networks. It has also been shown that the coupling of the function in each of these two networks enhances the resilience of cooperation across the interdependent layers [9,10]. One of our research problems is how the failures of the communication network contribute to potential perils to the power grid? The research proposal includes the interactive topology/business analyses between the power grid and the communication network; vulnerability of individual/composite components in the power grid and the communication network; the effects of the communication delay, the communication error rate and the communication interruption to the power grid. Taking the communication interruption as an example, when one of the communication equipments or communications lines breaks down or even the communication subnetwork in one control area breaks down, which will make the corresponding power grid in this control area become not observable and controllable. Once the malfunction of the power grid in this area occurs, the power grid is running in an unhealthy environment.

It is worth mentioning that some of the existing research results about the interactive network always assume that there are the same number of nodes in two networks [5,11,12,1], while the actual cases are not the same and they are assumed to be different in this paper. We will do some research based on the practical regional power grid and communication network. For such kind of hybrid coupled network, one can investigate the basic topology properties, network correlation, static/dynamic vulnerability, cascading failures, interactive simulation, etc. The present manuscript is concentrated on the topological analyses and interactive centrality-differences, centrality correlation coefficients so that we can have a clear comprehending of the studied interactive network. Recently, percolation theory has attracted much attention in the investigation of cascading failures in the interactive network, such as Refs. [13,14], which will provide some guidelines for our research in dynamical cascading process.

The remaining part of this paper is organized as follows. In Section 2, some topological properties and centrality measures of nodes/links of complex networks are summarized. In Section 3, by defining the interactive network, some novel interactive statistical measures including contact ratios of nodes and links, centrality-difference, centrality correlation coefficient are proposed. In Section 4, statistical properties as well as important stations and lines of the power grid and its communication network in one province of China are given. Furthermore, the interactive relationships between the power grid and the communication network are formulated by the proposed interactive metrics. Some conclusions are drawn in Section 5.

2. Statistical metrics of complex networks

The understanding of network structures, functions and their relationships has become of great importance in such a networked era. It has been shown that many mechanisms such as cascading failure, information spreading and network synchronization in a large network are highly affected by a tiny fraction of influential nodes [15,16]. So how to locate these critical nodes is of theoretical significance. In this section, some structural properties of complex networks including basic topological characteristics and centrality measures of nodes/links are given.

For a network, one can use $\mathcal{G} = \{\mathcal{V}, \mathcal{E}\}$ to represent its topology structure, where $\mathcal{V} = \{1, 2, \ldots, N\}$ is the set of nodes and $\mathcal{E} = \{e_{ij}\}$ is the links' set. The adjacency matrix $A = (a_{ij}) \in \mathbb{R}^{N\times N}$ of the network $\mathcal{G}$ is defined as $a_{ij} \geq 0$ in which $a_{ij} = 1 \Leftrightarrow e_{ji} = (j, i) \in \mathcal{E}$ while $a_{ij} = 0$ if $e_{ji} \notin \mathcal{E}$. The Laplacian matrix of a network is defined as $L = D - A$, where $D = \mathrm{diag}\{d_{ii}\}$ is a diagonal matrix with $d_{ii} = \sum_{j\neq i} a_{ij}$.

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