Physica A 453 (2016) 84–98

Contents lists available at ScienceDirect

Physica A

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

Characterizing the topological and controllability features of U.S. power transmission networks

Jian Li [a,b,*], Leonardo Dueñas-Osorio [b], Changkun Chen [a], Benjamin Berryhill [c], Alireza Yazdani [d]

[a] *Institute of Disaster Prevention Science and Safety Technology, Central South University, Changsha, Hunan 410075, China*
[b] *Department of Civil and Environmental Engineering, Rice University, Houston, TX 77005, USA*
[c] *OneSubsea, Houston, TX 77041, USA*
[d] *Quantitative Risk Consultant, Boston, MA 02459, USA*

HIGHLIGHTS

- This paper studies the structural controllability of 58 power transmission networks.
- A small proportion of driver nodes are enough to control power networks topologically.
- Intermittent nodes tend to have low degree, triangular sub-graphs and betweenness.
- High degree and high betweenness nodes act infrequently as driver nodes.

ARTICLE INFO

Article history:
Received 13 January 2015
Received in revised form 16 May 2015
Available online 8 February 2016

Keywords:
Power transmission networks ensembles
Structural controllability
Driver nodes
Redundant nodes
Intermittent nodes
Smart infrastructure systems

ABSTRACT

Understanding the controllability of complex networks continues to gain traction across disciplinary fields, including the exploration of infrastructure systems such as power grids. Through topological principles, this paper investigates the controllability features of an ensemble of 58 U.S. city-level power transmission networks in seven U.S. states. To perform structural controllability analyses, the topological characteristics of the ensemble of networks are first quantified, including degree, shortest path length, clustering coefficient, meshedness and betweenness centrality, as well as the uncertainty associated with these and related properties. Then, the paper focuses on the controllability features of complex networks so as to detect the minimal sets of driver nodes to possibly control the networks given system linearity assumptions. Accordingly, a node is critical, intermittent or redundant if it acts as a driver node in all, some, or none of the potentially controllable system configurations. Moreover, this paper constructs a new methodology to quantify the probability of being a driver node among the intermittent nodes, and reveals the controllability importance of system components. Results show that a small proportion of driver nodes can provide the conditions for controlling the slow dynamics of entire power transmission networks from a topological perspective, despite variations in network sizes and configurations. This paper also reveals that the driver nodes tend to avoid high degree nodes and high triangulation sub-graph nodes as well as high betweenness centrality nodes. The identification of topological differences for different categories of nodes (critical, intermittent or redundant) could help researchers and utilities understand the conditions for future functional controllability of power

* Corresponding author at: Institute of Disaster Prevention Science and Safety Technology, Central South University, Changsha, Hunan 410075, China.
E-mail address: lijianethan@gmail.com (J. Li).

http://dx.doi.org/10.1016/j.physa.2016.01.087

networks while improving their reliability and resilience as well as facilitating their transition into smart grid systems.

1. Introduction

Network controllability is one of the central notions of modern control theory. It was through the work of R.E. Kalman that the notion of controllability of a linear system was shown to be of interest [1]. The controllability of linear system has a simple and appealing formulation in that the system is said to be controllable if it can be driven from any initial state to any desired final state within finite time with a suitable choice of inputs—note that by extension, this notion includes maintaining a system within a certain state despite disruptions. Since the early 1970s, research has also been directed towards nonlinear system controllability [2]. For nonlinear systems, the notion of controllability refers to the case where the control can act on the system state, but may be insufficient to transfer it to a specified terminal state. Often, nonlinear system controllability is defined in terms of system state equations and tested by means of Lie distributions or their dual form [3]—typically for fast dynamics systems. Although both linear and nonlinear system controllability have been well studied to date, they are only starting to be examined for networked systems; thus, understanding the effects of systems' internal topological connectivity and directionality is critical to support future controllability studies [4].

Structural controllability[1] of complex networks has garnered traction by integrating classical control theory and network science [5–11]. Lombardi and Hörnquist [12] first showed how linear controllability theory could be applied to networks. Later, Liu et al. [13] developed analytical tools to study the controllability of an arbitrary complex directed network, and identified the set of driver nodes (by finding a maximum matching of an associated bipartite graph), which can in principle guide the system's entire linear dynamics. They found that the number of driver nodes is mainly determined by the network's degree distribution owing to linearity assumptions. Based on Liu et al.'s method, Wang et al. [14] proposed a general approach to optimize the controllability of complex networks by perturbing the network structure, while the optimal control is referred to as the situation where such a network can be fully controlled using only one driving signal. However, Cowan et al. [15] proposed that it is nodal dynamics, not degree distributions, which determines the structural controllability of complex networks. Also, according to the role that an individual node plays in controlling a network, namely, the likelihood of being included in minimum driver node sets, nodes are classified into three categories by Jia et al. [16]: critical, intermittent and redundant. Jia et al. also developed an analytical framework to identify the category of each node, finding two distinct control modes in complex networks related to centralized and distributed control.

Clearly, the research on network controllability is far from settled. Also, most of the reviewed work has dealt with ideal networks (e.g., E–R random networks [17], Scale-Free networks [18], Small World networks [19]), or combinations of different kinds of practical networks (e.g., food web networks, social communication networks). Some research involves power networks [14], which are one of the most important networked infrastructure systems. However, as an spatial networked system, power networks have to meet engineering design principles and custom demand patterns. There are many restrictions on the topology of power networks. For example, there is a cost associated with the length of edges and the location of demand centers, which in turn have tangible effects on the topological structure of these networks. As a result, the controllability features of the class of power networks may differ from other ideal or practical networks, in part due to their topological differences. Hence, a structural controllability exploration is presented in this paper, in which we determine how the topological properties of an ensemble of power systems affect their linear controllability features, including the topological differences between critical nodes, intermittent nodes and redundant nodes [16]—the topological metrics that affect the likelihood to be a driver node. Note that linear dynamics could be associated with slow dynamics, such as those related to commodity supply/demand balance, and not to fast dynamics related to network stability.

Before performing structural controllability analyses, it is necessary to quantify the topological characteristics of the power networks, as well as to reveal topological commonalities, differences and trends across different systems in the ensemble. Previous investigations provide a foundation to assess the topological features of power networks, such as Barabási and Albert [18], Albert et al. [20], Amaral et al. [21] and Newman et al. [22]; however, these studies may be insufficient to evaluate system controllability conditions as they focus on the evaluation of network topology by using only one or a small number of cases. To this end, a unique ensemble-based topological characterization of power transmission networks and controllability conditions of different sizes and topological specifications is carried out in this paper by exploring 58 city-level power transmission networks across seven U.S. states. Through detailed measurements at both local (nodes and links) and global (network) levels, this paper identifies topological properties of the ensemble of real power networks, particularly properties that possibly relate to controllability features, including the characteristics of driver nodes.

[1] In engineering disciplines (particularly structural and infrastructure engineering), "topological controllability" would be preferable as "structural" typically refers to buildings and physical components of networks.