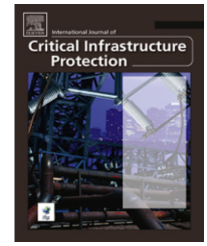
available at www.sciencedirect.com

ScienceDirect

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



Analysis of structural vulnerabilities in power transmission grids

Ettore Bompard, Roberto Napoli, Fei Xue*

Dipartimento di Ingegneria Elettrica, Politecnico di Torino, I - 10129 Torino, Italy

ARTICLE INFO

Article history:
Received 30 October 2008
Received in revised form
2 January 2009
Accepted 9 February 2009

Keywords:
Complex networks
Power system security
Power grid
Topological vulnerabilities
PTDF
Degree
Entropy

ABSTRACT

Power transmission grids play a crucial role as a critical infrastructure by assuring the proper functioning of power systems. In particular, they secure the loads supplied by power generation plants and help avoid blackouts that can have a disastrous impact on society. The power grid structure (number of nodes and lines, their connections, and their physical properties and operational constraints) is one of the key issues (along with generation availability) to assure power system security; consequently, it deserves special attention.

A promising approach for the structural analysis of transmission grids with respect to their vulnerabilities is to use metrics and approaches derived from complex network (CN) theory that are shared with other infrastructures such as the World-Wide Web, telecommunication networks, and oil and gas pipelines. These approaches, based on metrics such as global efficiency, degree and betweenness, are purely topological because they study structural vulnerabilities based on the graphical representation of a network as a set of vertices connected by a set of edges. Unfortunately, these approaches fail to capture the physical properties and operational constraints of power systems and, therefore, cannot provide meaningful analyses.

This paper proposes an extended topological approach that includes the definitions of traditional topological metrics (e.g., degrees of nodes and global efficiency) as well as the physical/operational behavior of power grids in terms of real power-flow allocation over lines and line flow limits. This approach provides two new metrics, entropic degree and net-ability, that can be used to assess structural vulnerabilities in power systems. The new metrics are applied to test systems as well as real power grids to demonstrate their performance and to contrast them with traditional, purely topological metrics.

1. Introduction

Accidental failures and intentional attacks on public infrastructure components can have disastrous social and economic consequences. Among public facilities, the electric power supply infrastructure has particular importance since it is widely distributed and is indispensable to modern society. A large-scale power system outage can have a severe impact on a country [1].

In addition to accidental and natural threats, recent events in the United States (US) and the European Union (EU) indicate that terrorist groups can potentially exploit vulnerabilities in power systems. Several researchers have begun to examine this issue [2,3]. Power systems engineers and critical infrastructure analysts are developing approaches

* *Corresponding author.* Tel.: +39 0110907154; fax: +39 0110907199.
E-mail address: ettore.bompard@polito.it (E. Bompard).

1874-5482/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.ijcip.2009.02.002

and tools for assessing power infrastructure vulnerabilities. However, current research is mostly based on classical and detailed physical models that require complete information and data regarding system operation.

Power systems and power transmission grids are characterized by a set of physical properties and operational constraints that must be taken into account when assessing the vulnerability of the infrastructure. Electricity is non-storable in large amounts, so an instantaneous balance between power production and power consumption plus transmission losses is needed. Various operational limits (voltage modules and angles, line flows, etc.) define the feasible region of a power system and must be enforced. Power flow paths depend on various physical system parameters (resistance, inductance, conductance and capacitance) that impose limits on flow when transferring power to and from different locations.

Complex networks (CNs) have received considerable attention as a result of the investigation of small-world networks [4] and the scale-free nature [5] of many real networks. Power grids are widely acknowledged as CNs because of their massive size and the complex interactions existing among individual components. The UCTE (Union for the Coordination of Transmission of Electricity) transmission network, for example, has 5910 nodes and 7970 transmission lines. The North American power grid has 14,099 nodes and 19,657 transmission lines. Furthermore, the working pattern and state of a power system continuously change as electrical loads change and generators are regulated to maintain frequency and control voltages. Therefore, both steady state and dynamic behaviors should be considered when analyzing power system operations. However, due to the network size and the associated computational complexity, it is extremely difficult to perform dynamic analysis for real-world networks within an acceptable time-frame. Furthermore, in the relatively new market context of the electric industry, there is no centralized decision-making. Rather, a multitude of decision-makers compete amongst themselves in the power transmission grid; this makes it difficult to predict grid utilization patterns. System operators, who are in charge of assuring power system feasibility, need to impose authority over the market players and loads without affecting market fairness while simultaneously assuring system security. Therefore, a complete and detailed security assessment that takes into account all of these features is almost impossible to perform within a reasonable time-frame.

Topological approaches based on CNs have been proposed as an alternative. These approaches are promising because they approach the security problem from a more general perspective.

Several researchers have applied purely topological metrics such as degree distribution and network efficiency to analyze structural vulnerabilities [6–9] and cascading failure mechanisms [10–12] in power grids. However, these metrics fail to capture specific physical and operational features of power transmission grids. This paper examines the main deficiencies of purely topological approaches and describes an extension in which conventional topological metrics are modified to account for the physical/operational behavior of power grids in terms of real power-flow allocation over the lines and line flow limits. Two new metrics, entropic degree and net-ability, for assessing structural vulnerabilities in power systems are introduced and their application to real-scale power systems is discussed.

This paper is organized as follows: Section 2 discusses the purely topological model of a power grid and the metrics used for analysis. Section 3 proposes an extended topological approach that engages the new concepts of net-ability and entropic degree to overcome the shortcomings of purely topological approaches. Section 4 presents the results of applying our extended topological approach to various test systems. Section 5 presents our conclusions.

2. Power grids as purely topological complex networks

A complex network has non-trivial topological features, i.e., features that do not occur in simple networks. For as long as complex networks have been investigated, power grids have been considered to be exemplars for verifying the existence of small-world or scale-free features [4,5]. Several researchers have analyzed structural vulnerabilities in the UCTE network and the North American power grid using topological features such as distance, degree and betweenness [6,7]. The concept of global efficiency and cascading failure models have been applied to power transmission networks such as the Italian power grid [8,11,12].

In a purely topological model, a power grid is considered to be a network composed of vertices (buses) connected by edges (transmission lines). In most cases, an unweighted and undirected network model is utilized. All the vertices and edges are considered to be identical, without differences in their quantitative features or directions. In an unweighted and undirected graph, the length of a path is the number of edges in a path connecting vertices i and j. A geodesic path (or shortest path), characterized by distance d_{ij} between vertices i and j, is the path with the minimum length [13].

The connectivity of a node is traditionally measured by its degree in an unweighted topological model or its strength in a weighted model. In an unweighted and undirected network model (according to traditional graph theory), the degree of a vertex i is the number of edges connected to it (or the number of vertices adjacent to it):

$$k_i = \sum_j l_{ij}; \quad (1)$$

where l_{ij} represents the number of lines connecting i and j.

In a weighted network model, connectivity can also be expressed by the strength measured as the sum of the weights of the corresponding edges:

$$s_i = \sum_j w_{ij}; \quad (2)$$

where w_{ij} represents the weight of the line connecting i and j.

Some researchers [8,14,15] define efficiency as the overall performance of a network and use it to locate the critical components of networked infrastructure systems, including