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Topology and vulnerability of the Iranian power grid

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HIGHLIGHTS

- The Iranian high voltage power grid displays a relatively moderate clustering coefficient.
- The Iranian power grid is a small-world network.
- The power grid showed relatively poor performance against cascaded failures.

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ABSTRACT

In this paper we investigated the structural properties of the ultra high voltage power transmission network of Iran. We modeled the power grid as a network with 105 nodes and 142 connection links. We found that the Iranian power grid displays a relatively moderate clustering coefficient – much larger than that of corresponding random networks – and small characteristics path length comparable to that of corresponding random networks; i.e. the power grid is a small-world network with exponential degree distribution. Global efficiency was considered as an indicator of grid's performance and the influence of random and intentional nodal failures on the efficiency was investigated. We also studied the influence of cascaded failures on the largest connected component of the network. The power grid was vulnerable against cascaded failures, which should be considered serious in redesigning the network topology.

1. Introduction

Complex dynamical networks have a vital role in our everyday life. It has been shown that many biological, technological and social networks lie between random and regular networks, with high clustering coefficient and small characteristics path length; they are indeed small-world networks [1–3]. The idea that the dynamical behavior of complex systems could be strongly influenced by the structure of an underlying network, was suggested first by Watts and Strogatz in their seminal work on small-world networks [1]. In this context, the importance of the network structure became even more evident after a work by Barabasi and Albert on scale-free networks [4–6]. The role of network structure is further emphasized by the presence of communities, correlations, patterns of weighted connections and other nontrivial structures in many real-world networks that had not been anticipated from the classical random graph theory of Erdos and Renyi [7].

The first approach to capture the global properties of complex systems is to model them as graphs with nodes representing the dynamical units and links the interactions between them [8–10]. Power grids are among important engineering systems that can be modeled by networks with generation units and transformers as the nodes and wirings as the edges [11–15].

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Energy grids have important roles in modern societies and proper functioning of the societies is significantly dependent on these grids [16]. Many services such as the Internet, communication, media, supply chain, transportation and urban infrastructure are highly dependent on reliable energy supply systems. The global power grid is growing fast, and it is suggested that the future energy need would necessitate having a grid spanning the whole planet and connecting most of the large power plants in the world [17,18]. Proper functioning of a power grid largely depends on its topological structure. This calls for studying the topological properties of powers grids.

There have been efforts in studying the topology of power networks in various places of the world [11–15]. Chassin and Posse [19] analyzed the topological structures of the North American electric grids with the purpose of estimating their reliability. Rosato et al. [12] studied the topological properties of high-voltage electrical power transmission networks in three European countries (the Italian 380 kV, the French 400 kV and the Spanish 400 kV networks). Casals et al. [14] and Solé et al. [20] presented new analyses of the topological structure and static tolerance to errors and attacks of the UCTE (Union for the Coordination of Transport of Electricity) power grid, involving thirty-three different networks. In this manuscript, we investigate the structural properties of the 400 kV power transmission network in Iran. We first extract the structure of the network and then calculate a number of graph theoretical metrics for the network. Our findings reveal an exponential degree distribution and small-worldness for the Iranian ultra high voltage power grid.

Error and attack tolerance is the most important technique used for vulnerability and robustness analysis of real complex networks such as power grids [21–24]. It has been shown that removing network components (randomly or intentionally) changes its functionality. For example, synchronization of dynamical networks has been shown to be influenced by random errors in the nodes [25]. Link removal has also significant effects on the cooperation properties of complex networks [26,27]; where the cooperativity of the network is defined considering coevolutionary games on the network [28]. The structural vulnerability of power grids has been studied in several works. Crucitti et al. [29] analyzed the structural vulnerability of the Italian power grid by developing a novel way of modeling cascading failures. Bao et al. [13] analyzed cascading failures and the power flow entropy in the IEEE 300-bus electric grid. In this manuscript, we study the effects of cascaded failures on the structural properties. Our results show that the Iranian high voltage power grid is vulnerable against cascaded failures; this issue should be considered when redesigning the network topology.

2. The structure of complex networks

Let us introduce some notations and basic network metrics. A complex network is often represented as a directed (or undirected), weighted (or unweighted) graph $G = (N, L)$ with N as the set of nodes and L as the set of edges. A binary graph can be completely described by its adjacency (or connectivity) matrix A, an $N \times N$ square matrix whose entry a_{ij} $(i, j = 1, \dots, N)$ is equal to 1 when the link l_{ij} exists, and 0, otherwise [8].

2.1. Topological measures

There are a number of measures characterizing the topological properties of networks. To name a few, one can list measures such as degree, degree distribution, average shortest path length, and clustering coefficient. Various network measures are described in Table 1.

3. The power transmission grid

From the structural point of view, the power grid has evolved in years connecting generation sites to consumption centers within its own borders, i.e. each power grid is engineered in a sequential approach to cope with specific economic situations, population distributions, geographical morphologies and industrial requirements among other factors. The structural properties of power grids have attracted attention within the community of complex networks, e.g., see Ref. [19] for the North American power grid and Refs. [14,20] for European cases. In this paper, we provide an analysis for the structural properties of the power grid in Iran.

3.1. Data for structural analysis

We extracted data for our analysis using an official document updated in 2011 (www.igmc.ir), which contains detailed description of the Iranian power grid comprising lines from 400 kV down to 33 kV. A part of this drawing which entails the subnet of north eastern province of Khorasan is shown in Fig. 1.

According to the data extracted from this drawing and also from the official documents of Iranian power organization (www.tavanir.org.ir), the power transmission network in Iran has 419 bus-bars (or nodes), i.e. power generating stations and substations including transformers, switching stations and reactive power compensators, and 546 edges, i.e. transmission lines summing up to more than 108 960 kms. The transmission lines in the Iranian grid operate at different voltage levels including 400, 230, 132, 63, and 33 kV. Details are presented in Table 2 for three subnetworks of 400, 230, and <230 kV (i.e., 132, 63 and 33 kV) and the total network.

Next, we investigated the structural properties of the most important component of the transmission networks, i.e., the ultra high voltage network of 400 kV. The schematic graph of the network is shown in Fig. 2.