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Bus dependency matrix of electrical power systems

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ABSTRACT

Power grid vulnerability to targeted attack has been a focus of research after the robust yet fragile nature of complex systems was discovered. Various measures has been proposed to analyze the topological fragility since then. This paper focuses on providing a matrix which is able to find out critical elements within the system. A step by step method for building the matrix is shown. Various vulnerability measures has been discussed with examples.

1. Introduction

Typically a system like the power grid consists of power plants, transformers, transmission lines, distribution lines and loads. The trouble with systems like this is that individual behavior of its components is reasonably well understood. It is designed to behave collectively in an orderly fashion but sometimes it shows chaotic, confusing attitude and sometimes behave destructively like when blackout occurs.

The power grid is one of the most complex man made infrastructures of modern day. For example, the Australian power grid operated under the National Electricity Market (NEM) is the world's longest interconnected power system that runs for more than 5000 km from Port Douglas in Queensland to Port Lincoln in South Australia and supplies more than 10 billion electricity annually to meet the demand of more than 8 million end users [1]. NEM interconnects five regional market jurisdictions including Queensland, New South Wales, Victoria, South Australia and Tasmania.

Power systems play an indispensable role in modern society. However, in recent years there have been several large scale blackouts, in spite of technological progress and huge investments in system reliability and security. For instance, in August 1996, more than 4 million people in several western states of the USA were out of the power service [2].

In August 2003, a historic blackout was triggered in the power grid of the United States and Canada, which disconnected 61,800 MW of power to an area spanning most of the north-eastern states of USA and two provinces of Canada, totally containing more than 50 million people [3]. Besides, in the summer and autumn of the year 2003, several large-scale blackouts in the world happened, such as London blackout in UK, Sweden–Denmark blackout and Italy blackout [3].

Prevention of large scale outage is attributed to security assessment and monitoring system. Recent series of blackouts occurring all over the world shows that the system designated for prevention of blackouts is not working well, which stimulates researchers to seek solutions from alternative means. Recently advances of research in complex network field have attracted the interest of researchers of the power grid to model and analyze the century old power grid under complex network framework.

In case of a power system the number of possibilities to be analyzed is huge. Suppose we want to analyze the consequence of every line getting tripped with fault in several locations in the Australian power grid. It is just too complicated, time consuming and does not make any sense. So, first of all, from some the topological characteristics of the network we have to find few cases which we should study in depth. The number of contingency is too large, somehow we have to decide which contingencies are important and which are not. Complex network framework could be used for this purpose.

If the network structure is known several measures or matrices could be developed which can identify particular features of the network. Social scientists have used several centrality measures [4–7] to explain a person's influence within a network. Among these centralities most widely used measures are degree centrality, betweenness centrality, and closeness centrality. To analyze the vulnerability of the power grid or to measure which nodes are

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more important within a power network these centrality approaches were used by researchers [8–11]. Some considered the power grid as an abstract network and neglected concrete engineering features of the grid, whereas some considered various features like impedance or admittance of various lines within a network.

Three distinct centrality concepts were redefined and three measures were adopted for each concept to clarify the concept of centrality in social networks [4]. Centrality indices were used to detect community boundaries [5]. A new betweenness centrality measure was proposed to find out nodes with high centrality that do not fall in the shortest path set of the network between various node sets or could not be found using maximum flow minimum cut set [6]. A fast algorithm to calculate betweenness centrality in large-scale networks was proposed [7].

A centrality measure for electric power grid was proposed which considers electrical topology rather than physical topology [8]. Topological and electrical centralities to rank various substations of the power grid were proposed [9]. Based on graph edge betweenness a method was proposed to carry out contingency analysis in power grids [10]. Based on admittance and impedance matrix various centrality measures were proposed to rank relative importance of nodes and edges in an electrical network [11].

But the static bus admittance and impedance matrix of the power grid cannot always capture the true scenario in large interconnected dynamical power grid. In this paper various centrality measures are proposed based on power flow in the network found by solving non-linear algebraic equations of the network [12–14]. IEEE 30 bus, 57 bus and 118 bus [15] systems are simulated to find out various important nodes in these systems based on degree, closeness, and betweenness centralities.

Also, a new matrix is proposed which captures the information of pair dependency of various buses. This matrix, known as bus dependency matrix, can be used to find two centrality measures (betweenness and closeness) of buses of the grid. A generalized methodology is developed to find out bus dependency matrix for an n-bus system.

The rest of the paper is organized as follows. Section 2 describes a model for analyzing the power system within the context of complex networks. Section 3 gives various centrality measures as applied to the power system. Section 4 introduces the bus dependency matrix and gives an example to construct it from the system data and it relates two previously defined centrality measures with bus dependency matrix. Some concluding remarks are given in Section 5.

2. System model

In order to demonstrate the application of centrality measures of complex network framework in the power grid, representation of the power grid as a graph is the first step [16]. From the perspective of network theory, a graph is an abstract representation of a set of objects, called nodes or vertices, where some pairs of the objects are connected via links or edges.

To portray the assemblage of various components of the power system, engineers use single-line or one-line diagram which provides significant information about the system in a concise form [14]. Power is supplied form the generator nodes to the load nodes via transmission and/or distribution lines. The principle of mapping is described as follows [17]:

(a) all impedances between any bus and neutral are neglected,
(b) all transmission and/or distribution lines are modeled except for the local lines in the plants and substations,
(c) all transmission lines and transformers are modeled as weighted lines, the weight is equal to the admittance between the buses, and

Any power system network can be represented by a graph $G = (V, E, W)$ comprising of a set V, whose elements are called vertices or nodes, a set E of ordered pairs of vertices, called edges or lines. An element $e = (x, y)$ of the edge set E, is considered to be directed from x to y. y is called the head and x is called the tail of the edge. A set W, whose elements are weights of edge set elements. There exists a one-to-one correspondence between set E and set W.

To illustrate mapping of a single-line diagram to a directed graph, a simple example of 5 bus system [12] is used here. Fig. 1 depicts the system with 5 bus bars, and 7 links connecting them. It contains 5 nodes/vertices which correspond to the slack, voltage-controlled, and load bus bars of the original system. The transmission lines are represented by the 7 links/edges which connects various nodes. The system data is given in Table 1.

3. Application of centrality measures of complex network framework in the power grid

3.1. Measure of connectivity-degree centrality

Degree centrality is the simplest form of centrality measures for networks. Although it is very simple, it has a great significance. It represents the connectivity of a node to the network [18]. Individuals who have more links with other persons are more connected to the network in the sense that they have more resource, access of information than others. A non-social network example is the use of citation counts in the evaluation of scientific papers. The number of citations of a paper can be regarded as its impact on research [19].

For example, node 2 in Fig. 1 is adjacent to four other nodes, it's degree is four. In a 5 node graph any node can be adjacent to only remaining four nodes. So, this node has got highest connectivity. In literature degree centrality is defined as:

$$C_D(k) = \frac{deg(k)}{n-1} \tag{1}$$

where $deg(k)$ is the degree of node k.

In case of electrical network, the power flowing in the adjacent links of the node in concern can be regarded as a degree of the node and the definition of the electrical degree centrality can be given as:

$$C_D^E(k) = \frac{\sum_{k\sim t} P_{kt}}{n-1} \tag{2}$$

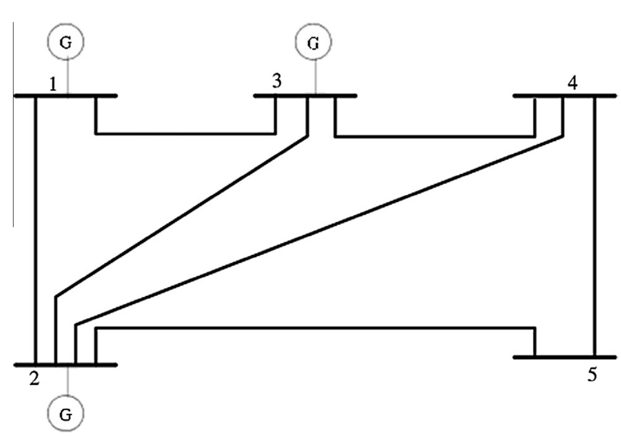

Fig. 1. Simple 5 bus system.