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Complex Network Framework Based Comparative Study of Power Grid Centrality Measures

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ABSTRACT

New closeness and betweenness based centrality measures have been evaluated in this paper. Power grid is modeled as a directed graph. The graph is analyzed in terms of complex network theory to identify influential nodes which control power flow pattern throughout the whole grid and as a result can create cascade if removed unintentionally or targetedly. Various measures of impacts have been analyzed to show that power grid has scale-free network characteristics, i.e., it is very much vulnerable to targeted node removal. Measures of impacts include characteristic path length, connectivity loss and blackout size. Rank similarity analysis have been carried out to show that nominal condition of power system gives critical nodes which remain critical with changes in system operating conditions as well.

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1. INTRODUCTION

The Cascading failures in a power system can be triggered anywhere in the system initiating various damages of several components within the grid, which can propagate to any place in the system. It is initiated as a sequence of dependent failures of various components that successively deteriorates the ability of the power grid to continue its intended functionality [3]. Technology is progressing day by day and there have been huge investments in system reliability and security. But blackout is still occurring all over the world. The latest reported large-scale blackout is found to be California blackout in the early September of 2011 [15].

Several researchers have come forward for the risk assessment of cascading outages. Various attempts have been taken by researchers in improving the understanding of cascading outages can be broadly categorized as monte-carlo simulation methods and analytical techniques [38]. Examples of these methods and techniques include several probabilistic, deterministic method as well as approximate and heuristic techniques. Pros and cons of these methods along with their limitations are addressed in [33].

ASSESS [34], CAT (Cascade Analysis Tool) [27], POM-PCM (Physical and Operational Margins - Potential Cascading Models) [4] are deterministic tools used by industries to analyze and simulate cascading events. There is a huge number of rare, unforeseeable phenomena that could trigger cascading which could lead to blackout. Some events are so complicated that cannot be analyzed deterministically. So, several researchers have taken the probabilistic approach of determining vulnerability.

Some methods are starting to emerge based on statistical analysis of cascading failure. Hidden relay failures are modeled probabilistically and some countermeasures are proposed to prevent cascading effect [10]. Short-circuit analysis together with reactive reserve calculations are used to identify vulnerable regions in a power grid [9]. Since cascading is very complicated and complete enumeration of all possibilities is impossible, there are necessarily compromises and limitations in assessing cascading risk. Since it is not feasible to include all possibilities in a model, there are significant limitations in the methods based on probabilistic approach of cascading outages.

In recent years, there have been significant involvement of researchers in analysing the power grid from the perspective of complex network theory. Power grid topology is shown to possess the characteristic of small-world network in the seminal paper [40]. The power grid is also shown to inherit the ability to cope with random attacks but it is very vulnerable to targeted attacks since the abstract network model of the grid shows scale-free distribution [35].

These preliminary results intrigued the interest of the scientific community to analyse the power grid from a holistic point of view. Debate is going on whether the purely topological approach of analysis is sufficient or does it provide useful information about the vulnerability of the power grid [22]. Several researchers have considered both topological and electrical characteristics of the network when using complex network based analysis to model the cascading effect in power system [6, 12].

It is well established that the power grid functionality can be significantly reduced by removing a small number of components. So, it is necessary to identify those critical components that can cause severe cascading effect in power system which could lead to blackout and cost billions of dollars. Identification of critical components is one of several directions of research in power system based on complex network theory. This set of nodes or lines have been named critical components, attack vectors, vulnerable components etc. in various literature. To show the effectiveness of the proposed methods, several measures of impact are adopted. These measures show the degradation of network functionality as cascading progresses.

Critical transmission line analysis is carried out to find which lines when removed from the system can have negative maximum impact on the grid [14]. Complex network theory based shortest path algorithm [32] is used find influential lines in terms of triggering cascading events in power grid. It is argued that power does not necessarily flow over the shortest path and utilizing maximal possible flow that a network can sustain under different conditions the model of cascading failure is revised and new model based on maximal flow approach [23] is proposed in [13]. This approach takes huge time to execute and the method is used to find out critical lines in standard IEEE test systems [12]. A more realistic approach based of Power Transfer Distribution Factor (PTDF) is used to simulate cascading event in an attempt to identify correlated lines [25].

Network efficiency loss and amount of load shedding due to removal of critical components are used by some researchers as a measure of impact. Bus admittance matrix is used to model the power system as a graph [7] and DC load flow is used to find flows in different lines which comes with its inherent limitation of finding real power only. A hybrid approach combining DC load flow with hidden failures in relays is considered for improving the previous method [8].

Based on network centrality measures of power grid, critical components are found from three different point of views [31] and their usefulness are discussed. Similar to the concept of bus admittance matrix [36] and bus impedance matrix [20], motivated by the gatekeeper concept of social network [16], bus dependency matrix is formulated and the characteristics of the matrix is explored in [30]. A step by step method to formulate the matrix from the system data is presented in [29]. Relationship of bus dependency matrix with closeness and betweenness centrality measures are also formulated.

This paper discusses the effect of removal of nodes found from bus dependency matrix [30]. Proposed method gives a rank of nodes based on betweenness and closeness centrality depending on centrality scores. Effect of changing nature of load and generation of power systems which varies throughout the day has been investigated on the rank of the critical components. This issue of rank similarity is of interest among computer scientists [17, 24] but has not yet been addressed in case of power system. A more detailed analysis discussion on this issue is presented in [28].

The rest of the paper is organized as follows. Power system model required for analysis based on complex network approach is described in Section 2. How to obtain the closeness and betweenness based centrality scores and ranks from the power system data is briefly highlighted in Section 3. Effect of loss of nodes with higher centrality scores is shown in Section 4. Whether the proposed rank of criticality is invariant or not with system load and generation is explored in Section 5. Section 6 concludes the paper outlining some future directions of research

2. MODELING OF POWER GRID

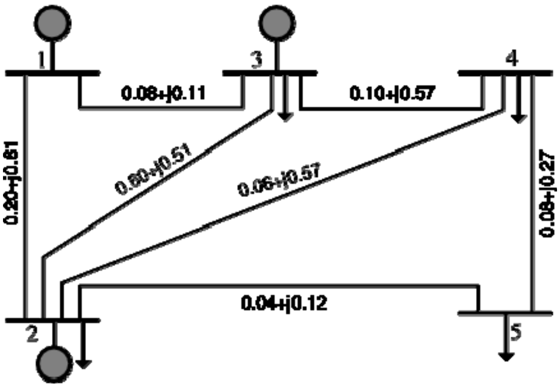

Figure 1. Simple 5 bus system

The In order to demonstrate the application of centrality measures of complex network framework in power grid, representation of the power grid as a graph is the first step [7]. 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.

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 various concepts of complex network in power system, a simple example of 5 bus system [36] is used in this paper. Fig. 1 depicts the system with 5 bus bars, and 7 links connecting them. We can model the system as a graph which contains 5 nodes/vertices which correspond to the slack, voltage-controlled, and load bus bars of the original system. The transmission lines can be represented by the 7 links/edges which connects various nodes. The system data is given in Table 1.

For the network in Figure 1, $V = \{1,2,3,4,5\}$, $E = \{(1,2),(1,3),(2,3),(2,4),(2,5),(3,4),(4,5)\}$, and $W = \{0.20 + j0.61, 0.08 + j0.11, 0.60 + j0.51, 0.06 + j0.57, 0.04 + j0.12, 0.10 + j0.57, 0.08 + j0.27\}$.

Table 1. System Data for Network in Figure 1

From	To	R	X	$\frac{1}{2}B$
Bus	Bus	in pu	in pu	in pu
1	2	0.20	0.6110	0.030
1	3	0.08	0.1123	0.025
2	3	0.60	0.5139	0.020
2	4	0.06	0.5663	0.020
2	5	0.04	0.1155	0.015
3	4	0.10	0.5727	0.010
4	5	0.08	0.2725	0.025

3. ELECTRICAL CLOSENESS AND BETWEENNESS BASED CENTRALITY MEASURES

A centrality measure for electric power grid which considers electrical topology rather than physical topology is recommended in [21]. Topological and electrical centralities are proposed to rank various substations of the power system network [37]. A method is proposed to carry out contingency analysis in power grids based on graph edge betweenness [19]. Based on admittance and impedance matrix various centrality measures to rank relative importance of nodes and edges in an electrical network are proposed in [39].

Electrical closeness and betweenness based modified centrality measure are proposed in [30, 31]. Here, the outline to find out centrality indices are presented.

Let, P_{st} be the maximum power flowing in the shortest electrical path between buses s and t, and $P_{st}(k)$ is the maximum of inflow and outflow at bus k within the shortest electrical path between buses s and t. Then, let their fraction is represented by $r_{st}(k)$ as in:

$$r_{st}(k) = \frac{P_{st}(k)}{P_{st}} \tag{1}$$

where, the ratio $r_{st}(k)$ is an index of the degree to which buses s and t needs bus k to transmit power between them along the shortest electrical path.

The pair dependency of nodes in a network is defined in [16]. The concept of pair dependency as proposed in [16] is used here in case of electrical power grid. The dependency of bus pairs can be regarded as the degree to which a bus s must depend upon another bus k to transmit its power along the shortest electrical path or geodesic to and from all other reachable buses t's in the network. For a power grid with n number of buses the dependency of bus s upon bus k to transmit power on any other buses in the network can be represented as follows:

$$d_{sk} = \sum_{\substack{t=1 \\ s \neq t \neq k \in V}}^{n} r_{st}(k) = \sum_{\substack{t=1 \\ s \neq t \neq k \in V}}^{n} \frac{P_{st}(k)}{P_{st}} \tag{2}$$

The dependency of bus pairs for the whole system can be calculated and the result can be summarized in a matrix $\mathbf{D}$ as follows:

$$\mathbf{D} = \begin{bmatrix} d_{11} & d_{12} & \cdots & \cdots & d_{1n} \\ d_{21} & d_{22} & \cdots & \cdots & d_{2n} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ d_{n1} & d_{n2} & \cdots & \cdots & d_{nn} \\ & & & & \end{bmatrix} \tag{3}$$

Each element of $\mathbf{D}$ is an index of degree to which a bus designated by row number must depend upon another bus designated by column number to transmit its power along the shortest electrical path or geodesic to and from all other reachable buses in the network. Thus, this matrix captures the information of importance of a bus as an intermediary with respect to other buses in the network. So we can call the matrix $\mathbf{D}$ as bus dependency matrix.

The procedural steps to find bus dependency matrix from the system data is as follows:

1. Modeling the system as a graph.
2. Finding a shortest path set for the graph using Johnson's algorithm.
3. Obtaining flow in various lines of the system solving load flow problem.
4. Calculating the maximum power flowing in the shortest electrical path between buses s and t, P_{st}, for the shortest path set.
5. Identifying $P_{st}(k)$, the maximum of inflow and outflow at bus k within the shortest electrical path between buses s and t.
6. Evaluating bus dependency matrix $\mathbf{D}$ from P_{st} and $P_{st}(k)$.

The sum of the elements of the k -th column of bus dependency matrix is the electrical betweenness of the k -th bus of the system. The sum of the elements of the k -th row of bus dependency matrix is the electrical closeness of the k -th bus of the system.

4. MEASURE OF IMPACT

Having found the critical nodes, it is necessary to analyze the consequence of removing nodes from the system and justify whether or not the nodes are really critical in terms of their ability to trigger cascading effects. There are a variety of measures by which one can analyze this consequence. In this paper, three measures are considered. The first two of them, characteristic path length and connectivity loss are purely topological. The third one, blackout size is found from a simple model of cascading failure. The measures are discussed below:

4.1. Characteristic Path Length

The characteristic path length is used by researchers as a measure of network connectedness. It is the average length of the shortest paths between any two nodes in the network [2]. It is found that if a node is removed from a system, it generally increases the distance between other nodes. So, the increase in network characteristic path length is considered as a measure of impact analysis of removing critical nodes from the system.

Distance between two vertices can be computed as:

$$d(u,v) = min\,|P| \tag{4}$$

where P is a path from u to v. Characteristic path length can be defined as:

$$\overline{d} = \frac{1}{k} \sum_{u \neq v \in V} d(u,v) \tag{5}$$

where $0 \leq d(u,v) \leq \infty$. k is the number of connected pairs.

4.2. Connectivity Loss

This is a purely topological measure of impact a power grid encounters when some nodes are removed from the system. In this measure we calculate how much connectivity is lost in terms of how many generators a transmission or distribution node can access due to effect of removing a node from the system. The lesser the number of generators a node is connected with the less is the redundancy and the more is the vulnerability of the node. It is given as (6) originally proposed by [1].

$$C = 1 - < \frac{N_g^i}{N_g} >_i \tag{6}$$

where the averaging is done over each intermediate nodes, i.e., substations. N_g is the total number of generators and N_g^i is the number of generators that a node i can reach.

4.3. Blackout Model

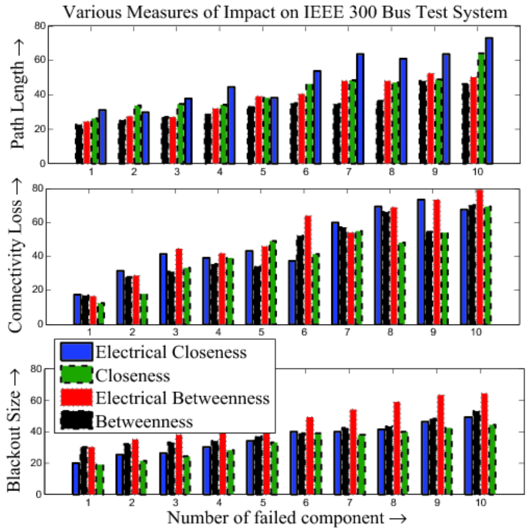

Figure 2. Impact of removing critical nodes from standard IEEE 300 bus test system in terms of increase in characteristic path length, connectivity loss and blackout size

Since it is not possible to exactly model the blackout, various approximate measures have been taken by several researchers to mimic the situation [5, 11, 22, 26].

Power system is a very much complex interconnected system whose exact modeling would require consideration of dynamics of rotating machines and devices within the system, discrete dynamics of switchgear elements, non-linear algebraic equations that govern line flows and social dynamics of governing and operating bodies.

In this paper, a fairly simple model of cascading failure of the power grid is proposed by incorporating important electrical features ignoring those which are too complicated but have little effects. The detail of the model is described here.

At first AC power flow is used to calculate the steady state condition of the network. Real and reactive power of transmission lines are found from numerical solution of line flow equations given in (7) and (8)

$$P_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}| cos(\theta_{ij} - \delta_i + \delta_j) \tag{7}$$

$$Q_i = -\sum_{j=1}^{n} |V_i||V_j||Y_{ij}| sin(\theta_{ij} - \delta_i + \delta_j) \tag{8}$$

where the symbols have their usual meanings as found in power system literature.

During the analysis, generator and load dynamics are not included. Although the limitation of not using dynamics of generators and loads are well understood but it is at least useful for modeling one mechanism of cascading failure that is cascading overload. Also, Generation Shift Factors (GSF) and Line Outage Distribution Factors (LODF) [42] are used to recalculate flows in lines after disturbance, i.e., after a new generator comes in or goes out; a new transmission line is switched on or tripped out. This helps achieving fast results without using actual load flow after each disturbance. The speed and accuracy of the result and comparison with actual load flow is out of the scope of this paper and will be addressed in another research article in future.

Also, time delayed over current relays are used in every line so if there is a lot of overload it trips fast and if there is a little bit of overload it trips slowly. Another thing that is added to the model is ramping up of generators. As the system separates into sub grids, generators are allowed to ramp up or ramp down to rebalance a little bit.

So, if a component failure disturbs the supply-demand balance, through generator set-point adjustment this balance is achieved. But if there is not enough ramping ability, then the ultimate choice is to trip lowest possible system load. The total amount of load shedded is used as the blackout size.

Two standard test systems are used to demonstrate the result of removing critical nodes from the system found from the proposed method . The test systems are standard IEEE test system [41] and Australian test system [18]. Effect on the IEEE test system of the removal of critical nodes found from proposed electrical closeness and betweenness based measures as well as classical closeness and betweenness based measures [39] are given in Fig. 2.

It is clear from the two figures that, the impact of removing critical nodes found from the proposed method is higher than removing nodes obtained from topological centrality measures. So, we can certainly conclude that topology alone cannot provide sufficient information about power grid vulnerability rather it could produce misleading information. In terms of increased characteristic path length, closeness centrality measures have greater impact than betweenness based measures. But, betweenness based measure hampers the system most when connectivity loss and blackout size indices are considered.

5. RANK SIMILARITY

In a typical power system, load varies from time to time and generation have to match the load and line loss. For this reason, various power flow profiles are found in the system during various seasons of the year. Even the scenario is different at different times in a day. To demonstrate that the proposed power flow based centrality method gives critical nodes which is insensitive to system load and generation change, an Australian test system is considered which provides six test cases from heavy to light load conditions [18].

Table II. Six Normal Steady-State Operating Conditions of Australian Power Grid

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Load Condition	Heavy	Medium Heavy	Peak	Light	Medium	Lightest
Generation (MW)	23030	21590	25430	15050	19060	14840
Load (MW)	22300	21000	24800	14810	18600	14630

Table 1 gives the six normal steady-state operating conditions for the system. Betweenness and closeness centrality of the test system is measured for various test cases.

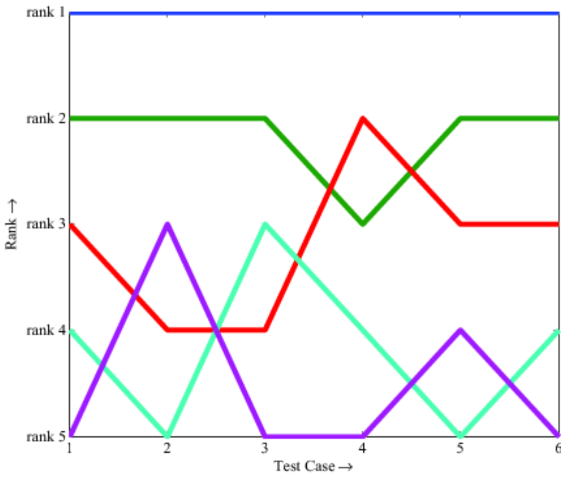

Figure 3. Variation of rank of nodes based on closeness centrality measures

Variation of ranks of the Australian test system in six test cases are shown in Fig. 3 for closeness centrality measures and for betweenness centrality measures in Fig. 4. From the figures it is clear that betweenness based measure is more rank stable than the closeness one. In case of betweenness based measure first three rank positions do not change in six different operating conditions, whereas in case of closeness centrality there are small variations in ranks two to four positions. In case of rank five there is a large variation of two ranks.

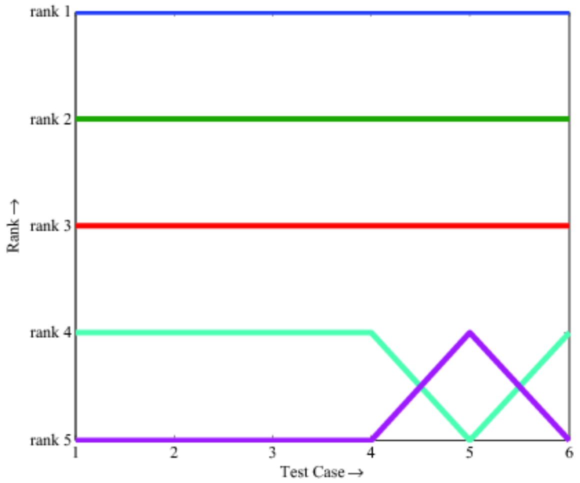

Figure 4. Betweenness centrality has better rank stability than it's closeness counterpart

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