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Exploration of Functional Vulnerability of the Electricity Grid

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Abstract: The complexity of modern day power grid is increasing with penetration of large-scale renewable resources at various levels of the networks. Inclusion of communication networks, to facilitate data transfer for ensuring reliability and security of the power system, with the electricity network extends the complexity to a new scale in a contemporary smart power grid. Any error in the integrated communication network can propagate through the electricity grid initiating large-scale cascading outages. Extensive precautionary measures should be taken in order to avoid such catastrophe. Complex network theory has been very useful in identifying critical components within the system as well as modelling of cascading failures. Complex network theory based percolation methods have been proved to be very useful in assessing power grid vulnerability under random and targeted attacks. In this paper, we extend our network percolation based analysis to explore the functional vulnerability of the existing electricity grid, effect on grid service efficiency, of increasing penetration of renewable energy. Vulnerable regions are identified with a fast computer simulation which helps operators to take quick preventive measures in case of emergency. Various standard IEEE test systems are simulated to test the applicability of the proposed algorithm in a real power system.

Keywords: Percolation, vulnerability, cascading failure, percolation threshold.

1. INTRODUCTION

Power grid is one of the most complex networked systems that the human race has ever made. The individual components of the grid are interconnected, operated and controlled in such a way that they behave collectively in an orderly way, but sometimes small initial failures lead to very complicated chain of events and the grid behaves destructively and finally when situations go out of control large scale blackouts occur. This chaotic behavior of the grid often costs up to billions of dollars without considering social implications and effects on other infrastructural systems (telephone, internet, computer, traffic, water, gas etc.) where the cascade may propagate Talukdar et al. (2003). The power system is intertwined with modern society in a way that the issue of cascading failure leading to infrequent but large-scale blackouts requires serious attention of researchers, system operators and policy makers to maintain grid reliability and to develop new methods to manage the risks of blackouts.

Cascading failures may be considered as sequences of dependent failures, which generally initiates from a single event of random failure within the grid and weakens the grid progressively as the cascade propagate through the grid. The definition of the power system might have a wide area. Power system components may include software, method, group, and organizations involved with the power grid planning, operating, and regulating the grid Baldick et al. (2008, 2009). Generally, the cascade initializes from a random failure of the power grid components, but there exists a connecting link with succeeding failures. The failure may also cause due to inappropriate response of human operators to control the event due to lack of necessary global information, or poor training or experience to handle transient situations. These reasons do not manifest themselves until it is very late to take action to avoid the cascading; hence these are considered hidden.

It is well established that the power grid functionality can be significantly reduced by removing a small number of components Albert et al. (2004); Crucitti et al. (2004); Fairley (2004); Andersson et al. (2005); Arianos et al. (2009); Hines et al. (2009); Wang and Rong (2009). 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 Chen et al. (2007); Nasiruzzaman and Pota (2011); Zhu et al. (2011); Xu et al. (2012); Watts (1999). The identification process takes a system level approach rather than a component based method to find a set of critical nodes or lines for cascading failure. 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.

Network percolation based analysis has been carried out in case of the power system Newman et al. (2005); Xiao and Yeh (2011). Newman et al. (2005) provided an excellent generalized framework for resiliency analysis for a networked system, but did not consider important vulnerability characteristics for the power system. The theoretical analysis of Xiao and Yeh (2011), although promising for planning operation of the power grid, but cannot be used for dynamic security assessment and monitoring systems, due to negligence of various operating parameters while modeling the power grid.

In this paper, a percolation based approach is devised to analyze the resiliency of the power grid. A fast algorithm is formulated to facilitate percolation analysis of large-scale power grids. Various standard IEEE test systems are simulated along with the Australian test system to simulate percolation in real power grids. An analysis of the effect of large-scale renewable energy penetration on the percolation threshold, which is an indicator of network robustness, is carried out at the end.

The rest of the paper is organized as follows: Section 2 deals with basics of percolation process. Section 3 provides simulation results, while Section 4 concludes the paper.

2. PERCOLATION AND NETWORK RESILIENCY

The dynamic evolution encountered in a fully connected network, where any node is connected to every other nodes within the network, by removing components from the system, either in a random fashion or following some logic, is called network percolation Newman (2005). The percolation process are divided into two subgroups, depending on the type of component being removed. In case of the power system, most cascades initiates from malfunctioning of transmission lines or links, but sometimes it is not edges in the network that fail but the vertices, i.e., substations or busbars in the grid. In order to distinguish these two types of failure involved in the percolation phenomena, we could outline them as edge percolation on one hand and vertex percolation on the other. Historically, in fact, these processes are called bond percolation and site percolation. This nomenclature has been derived from research, in the field of physics and mathematics, on percolation process. In this paper, we will consider a percolation process, which involves both edge and node removal, consistent with transmission lines tripping and out-of-service substations due to low-voltage or other reasons.

There is more than one way in which vertex or edge removal can be modeled in a power grid. In the simplest form, the components could be removed in a random fashion. We could, for example, take away some specified fraction of the vertices chosen uniformly at random from the entire power grid. This is the most commonly studied form of percolation. There, of course, are many feasible alternatives. One commonly used alternative removal scheme consists of removing vertices or edges according to a centrality measure, e.g., degree centrality or betweenness centrality. For example, components can be removed in order of betweenness from the highest to the lowest. The targeted removal of vertices according to their degree proved to be an effective vaccination strategy for the control of diseases.

By tradition, the probability involved with parameterizing the percolation process is called the occupation probability, ϕ, which is a probability that a bus or line is functional or present in the power grid. Thus, if the power grid is fully functional with all the components operating then the occupational probability $\phi = 1$, no elements are non-functional or have been removed, and $\phi = 0$ is an indication that no elements are occupied which may happen when there is a large blackout totally containing the entire grid.

An example of site percolation process is demonstrated in Fig. 1 for IEEE 30 bus test system with 30 nodes and 43 edges. In Fig. 1 (a), all vertices are present or occupied, they are connected together via transmission lines or edges into a single connected component. Now, if we concentrate on other panels in the same figure, a snapshot of the percolation process is observed. In Fig. 1 (b), 24 out of 30 vertices are functional, represented by grey color nodes, giving an occupation probability of $\phi = 0.80$. 6 non-functional nodes knocks down 12 adjacent edges, the removed transmission lines are represented by light grey colored edges. The remaining vertices still compose a single connected component through the intact edges. Fig. 1 (c) shows a situation during the percolation process, where more vertices along with associated edges have been removed, and the remaining vertices are no longer connected together. The vertices are split into two small components. In Fig. 1 (d), all vertices have been removed and the network collapses.

The process that is demonstrated in this small example is a typical percolation behavior. When ϕ is large, close to unity, the vertices tend to be connected together forming a giant connected component spanning most the grid. As the occupation probability decreases, for some reason or the other, the cohesiveness of the grid decreases, and the grid can no longer function as a single entity and collapses into various small components. The process can be understood in a reverse fashion, when the occupation probability, ϕ is low many small components exist in the network, and with the increase in the occupation probability small components are merged together to form a single large connected component, occupying the whole network.

Evolution of the power grid can be thought of as the building dynamics of the connected components in the network. In the early days of the electricity generation, generators supplied local areas only building a locally distributed small-connected components spanning various regions of a continent. As the technology flourished, with the invent of transformer, long distance power transmission was make possible. The grid began to form expand in size and number of components and finally giving rise to a massive machine running in unison with hundreds of thousands of components connected altogether.

Interconnection has many benefits such as fewer generation capacity required as a reserve for peak load and spinning reserve, economical and reliable energy generation and transmission to name a few. But the advantages comes with a great adversity of large-scale blackouts, where small

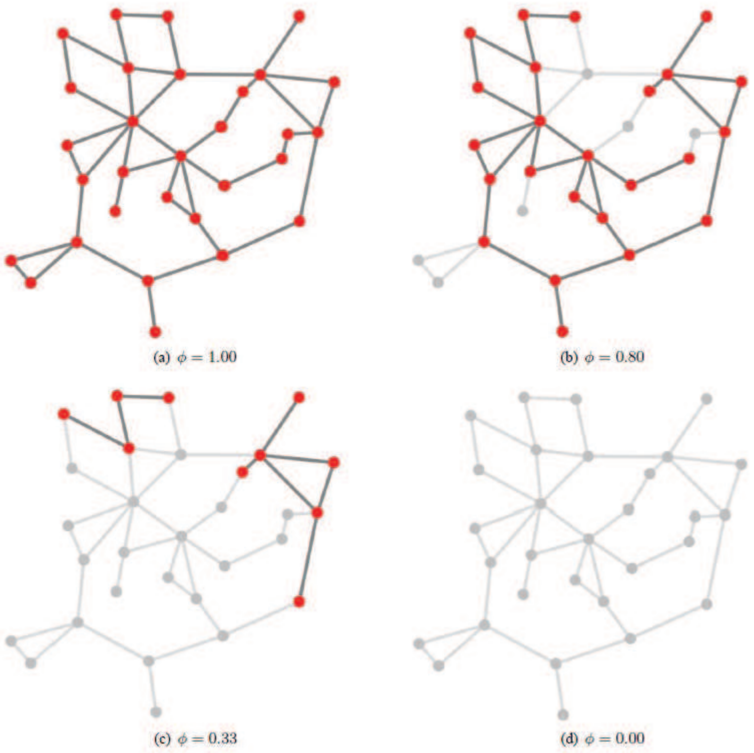


Fig. 1. An example of the site percolation process in the IEEE 30 bus test system for various values of occupation probability ϕ. Red vertices are functional nodes of the system, whereas grey vertices are non-functional. Light watermark-like color, in case of edges, denotes edges that have been removed, and dark colored edges represents those that are still present in the grid.

initial failure in amplified and large-scale cascades are propagated through the system. This process of cascading can be compared with the percolation phenomenon. Generally, the power grid runs as a single component with every substations and transmission lines fully functional, resembling the percolation process subcase as shown in Fig. 1 (a) and $\phi = 1$. Failure of a single transmission line or substation produces stress on the system because the load of the failed component is shifted upon the occupied ones. During a very stressed condition, the system operating in a heavily loaded condition, the shift of load may exceed the safe operating limit of some components and those may fail consequently, exerting even more stress on the grid. This chain of event continues and the grid in broken down with small connected components serving only local loads, similar to the percolation phenomenon with the occupation probability, $0 < \phi < 1$. In an extremely bad condition, the process of cascading proceeds even further giving birth to entire system collapse, as in the percolation process with $\phi = 0$.

The creation and demise of the of a giant component during the percolation process is known as a percolation transition. The point at which the percolation transition occurs is called the percolation threshold. The threshold value of the occupation probability suggests different aspects of grid robustness and vulnerability. Larger values of ϕ in the percolation threshold indicates the system is more vulnerable than the system with lower critical occupational probability, ϕ_{cr}. Removal of very few nodes breaks the cohesiveness of the grid and makes the system non-functional, where ϕ_{cr} is very high. Lots of components, within the grid, have to run properly in order to maintain the functionality of this type of system. On the other hand, systems with low critical occupational probability shows a great degree of robustness. In order to reduce the functionality of these types of networks, lots of components have to be taken out, making the system less vulnerable to random attacks.

In percolation studies the term ‘component’ is used to indicate the connected portion of the unaffected network, whereas ‘cluster’ refers to the components that exist in the network after and during the breakdown process. In this chapter, we will use the term ‘component’ to refer to connected group of vertices (substations, busbars, generators, and loads) on the original network before any vertices or edges have been removed and ‘cluster’ to refer to those after removal.

Delivery of electricity to the consumer end is the function of the overall power grid. Power companies and consumers are mainly concerned about providing sufficient power to the consumers, not the connectivity of the grid after failure. As it turns out, the nature in which the power grid is evolved gives the power grid sufficient robustness to deliver local power even if there is a cascade going on within the system. The total capacity of the connected generators within the disconnected area must be greater than the local load demand in order to maintain the balance of consumed and generated power.

Researchers have proposed many alternative definitions of network robustness. Here we have used grid service efficiency, GSE, as a functional measure of network robustness defined in Zio and Piccinelli (2010); Zio et al. (2012):

The loss of load for the whole system, LOL, can be calculated as follows:

$$LOL = \frac{1}{D}\sum_{i=1}^{s} \Delta L_i \tag{1}$$

where, D is the total load demand before the failure.

The grid demanded load, GDL, is the sum of the power generated from all the generators $g_i, i = 1, 2, ..., N_G$:

$$GDL = \sum_{i=1}^{N_G} g_i \tag{2}$$

The grid received load, GRL, is the sum of power received at the load nodes $l_i, i = 1, 2, ..., N_L$:

$$GRL = \sum_{i=1}^{N_L} l_i \tag{3}$$

The grid lost load, GLL, is obtained from the difference of the grid demanded load, GDL, and the grid received load, GRL:

$$GLL = GDL - GRL \tag{4}$$

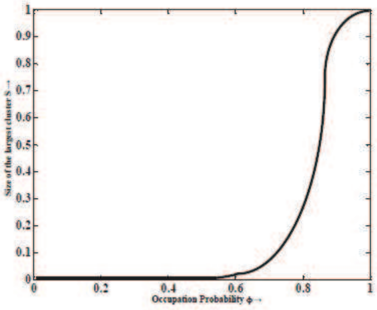
The grid service efficiency, GSE, is obtained from the ratio of two powers – the grid received load, GRL, to the grid demanded load, GDL:

$$GSE = \frac{GRL}{GDL} \tag{5}$$

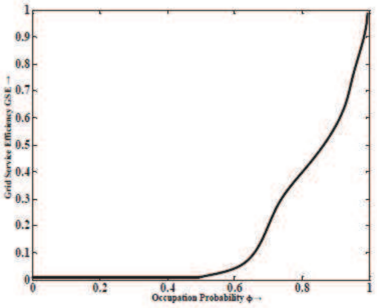
3. SIMULATION RESULTS

Network percolation can be implemented in several ways. In this paper, we have implemented a method Nasiruzzaman and Pota (2014); Akter et al. (2014) which is computationally efficient making it applicable for on line processing of information while cascade in progress. Various test systems have been incorporated to observe the effect of increased penetration of renewables in the electricity grid using complex network framework based percolation methods. The process of percolation can be implemented as follows:

(1) Consider an empty network.
(2) Initialize $c = 0$, where c represents the number of cluster in the network.
(3) Choose the order of addition of vertices in the empty network.
(4) According to the order add next vertex to the network, and increase c by one.
(5) Label the vertex with label c. This number represents the cluster of the vertex.
(6) Investigate edges attached to the vertex one after another.
(7) If the vertex at the other end of the edge has been added earlier, add the edge to the network.
(8) Examine the cluster label of the vertices at either end of the edge.
(9) If the cluster labels are the same, do nothing.
(10) If the labels are different, choose one of the clusters and relabel all its vertices to have the same label as the other cluster.
(11) Update the cluster size record to be equal to the sum of the sizes of the two parent clusters.
(12) Repeat from step 4, until all the vertices have been added.



(a) $\phi = 0.80$



(b) $\phi = 0.00$

Fig. 2. Percolation in the Australian power grid.

The test systems used for the percolation analysis are standard IEEE test systems University of Washington Electrical Engineering (2010).

Fig. 2 is the result of percolation process carried out in the Australian test system Australian Energy Market Operator (2012), with random node and line removal. The topological representation of the Australian Power Grid is shown in Fig. 3. The results shown are averaged over 1000 random simulations. It is clear from the result that GSE is a good measure of network robustness, since although the network seems to breaks down around $\phi = 0.6$ in case of largest cluster based analysis; but the network can perform well beyond that point since the percolation threshold is around $\phi = 0.5$ as shown in Fig. 2 (b).

Here we have examined the effect of increased penetration of renewable energy sources on the percolation thresholds of the network under random attack on edges, which is tabulated in Table 1. Each threshold has been calculated after 100 random edge removals from the base case. As expected, the threshold increases in all the test cases which is an indication of the vulnerability of the existing grid to withstand excess generations and loads without increasing the capacity of the network itself.

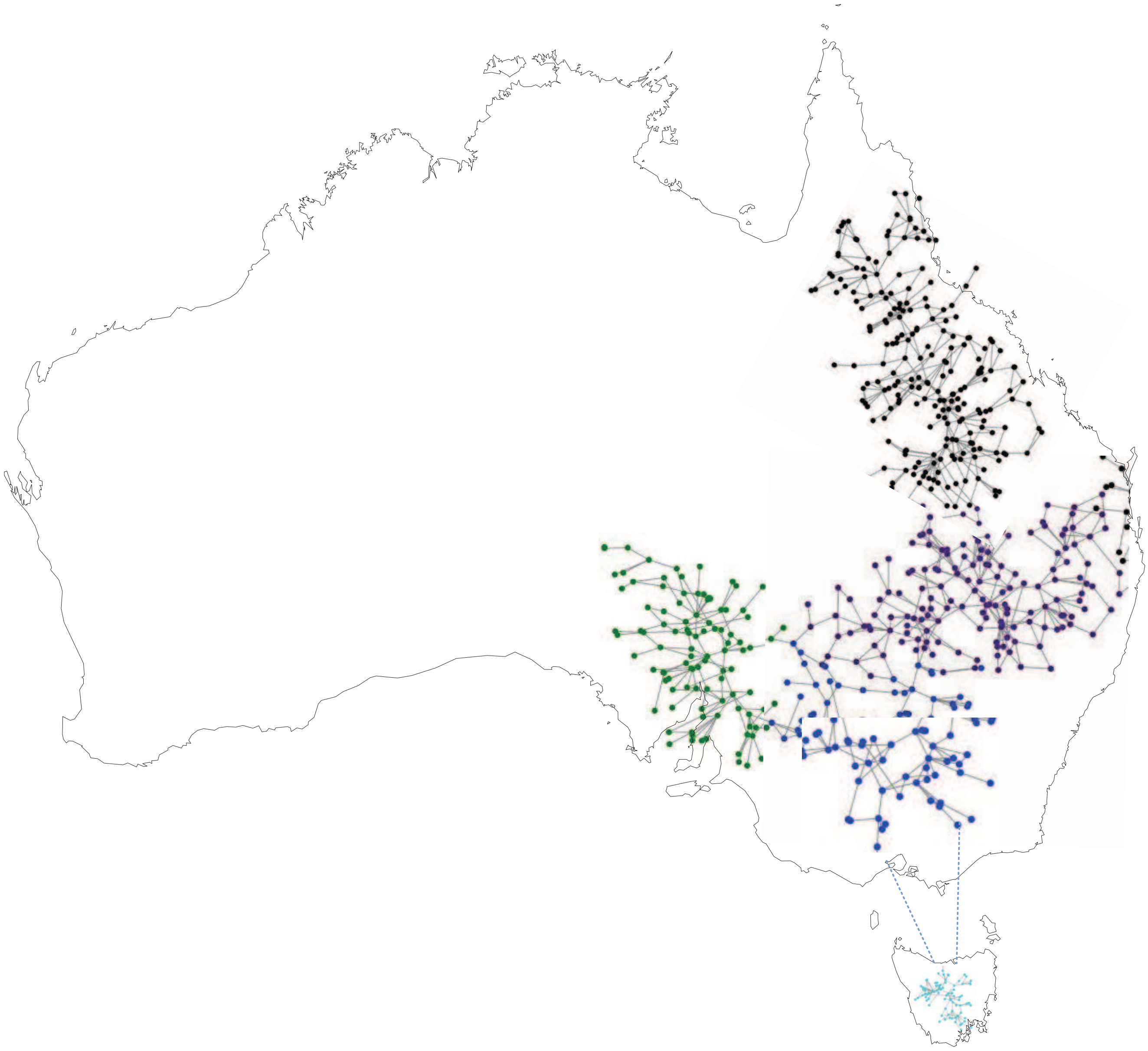


Fig. 3. Topological eastern Australian electricity grid operated by Australian Energy Market Operator (AEMO).

Table 1. Percolation Thresholds in Various Standard IEEE Test Systems with Increased Penetration of Renewable Energy

Penetration Level (%)	Percolation Thresholds		
	IEEE 57	IEEE 118	IEEE 300
0	0.50	0.55	0.57
5	0.60	0.57	0.60
10	0.69	0.60	0.61
15	0.75	0.63	0.63
20	0.80	0.65	0.64

4. CONCLUSION

This paper provides a novel approach of network resiliency analysis of the power grid, employing complex network framework based percolation method. An efficient algorithm is used to assess the vulnerability of the power grid with large scale renewable generation capacities. Our analysis finds that, although renewable energy have many advantages, and the target is to incorporate more and more renewable within the grid, but increased penetration caused vulnerability in a greater scale. Preventive measures should be taken so that critical components could be protected in order to ensure secure operation of the power grid.

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