Topological Analysis of the Power Grid and Mitigation Strategies Against Cascading Failures

S.Pahwa\textsuperscript{1}, A.Hodges\textsuperscript{1}, C.Scoglio\textsuperscript{1}, S.Wood\textsuperscript{2}

Abstract—This paper presents a complex systems overview of a power grid network under cascading conditions. The cascading effect has been simulated on three different networks, the IEEE 300 bus test system, the IEEE 118 bus test system, and the WSCC 179 bus equivalent model. Power Degradation is discussed here as a measure to estimate the damage to the network, in terms of load loss and node loss. A network generator has been developed to generate graphs with characteristics similar to the real networks and the generated graphs are then compared with the real networks to show the effect of topology in determining the robustness of a power grid. Four mitigation strategies, based on Homogeneous Load Reduction, Targeted Load Reduction for Neighbors, Targeted Range-Based Load Reduction, and Use of Distributed Renewable Sources in combination with Islanding, have been suggested. The Homogeneous Load Reduction is the simplest to implement but the Targeted Range-Based Load Reduction is very economical and the most effective strategy.

Index Terms—Cascading Effect, Power Degradation, Node Loss, Mitigation Strategies

I. INTRODUCTION

It is well-known that power grids are among the largest and most complex technological systems ever developed [1]. The power grid can be represented by a large graph belonging to a special family of graphs called complex networks. As is the case with most networks, the edges are not costless [2], so there is no node or group of nodes that prevail over the others, and the distribution can be fitted by an exponential function [3]. However, if we calculate the load on each node, we observe that although the network is very homogeneous in the node degree, it shows a high heterogeneity in the node load. Most of the nodes handle a small load but there are a few nodes that have to carry an extremely high load [3]. The same is true for links also. Thus, some nodes and links tend to become more important than the others and an intentional or accidental removal of these elements can lead to the collapse of the entire network. Such incidents have taken place in history, such as the one on August 10, 1996 when a 1300 MW electrical line in Southern Oregon sagged in summer heat, initiating a chain reaction that cut power to more than four million people in eleven Western States [4], [5]. Another example is the incident of August 14, 2003 when an initial disturbance in Ohio [6] led to the largest blackout in the history of the United States and millions of people throughout parts of North Eastern and Mid Western United States, and Ontario, Canada, were without power for as long as fifteen hours.

The power grid network is different from other complex networks in that the flow dynamics depend greatly on the electrical characteristics, such as the impedances of the transmission lines. Power flows along the least resistive path, and thus the amount of power flowing through the transmission lines is inversely proportional to their impedances.

In the next section, we describe the simulator that has been developed to study the cascading effect on power grid networks. In the later sections we discuss a Network Generator that was developed to generate power grid networks with characteristics similar to the original ones and compare the different metrics that determine the robustness of the network. Finally, we investigate mitigation strategies against cascading failures.

II. CASCA/DING EFFECT IN A POWER GRID

North American Electric Reliability Corporation (NERC) defines a cascading failure as “The uncontrolled loss of any system facilities or load, whether because of thermal overload, voltage collapse, or loss of synchronism, except those occurring as a result of fault isolation [7].” If a single line gets overloaded or breaks, its power is immediately shifted to a different line and the disturbance can be suspended. However, if the redistribution of power leads to the subsequent overloading of other lines, the consequence could be a cascade of overloading failures.

We developed a simulator to test the effect of cascading failures on different networks such as the IEEE 300 bus test system [8], the IEEE 118 bus test system [8], and the WSCC 179 bus equivalent system. The DC Power Flow Model [9] has been used for this analysis. The redistribution of loads and re-routing of power is dependent on the electrical characteristics such as impedances of transmission lines. The resistances of the lines have been neglected because they are very small as compared to their inductive reactances [9]. The buses in the power grid are referred to as nodes, the transmission lines as links,
and the reactances of the transmission lines as weights on the links. The systems go through multiple stages of cascade before they finally stabilize. We categorized the links into two types - vulnerable and non-vulnerable - depending upon whether they cause more or less than ten percent damage upon removal. Approximately 41.97% of the links in the 300 nodes network are vulnerable and the remaining 58.03% are non-vulnerable links. We use Power Degradation as a measure to compare the generated network with the original network, in terms of load loss. We also compare the networks in terms of the number of nodes lost by the failure of a vulnerable link. Power Degradation is the fall in the total current load of the system as compared to the total original load. The 300 node network consists of 247 nodes plus two smaller subsections of nodes which are not well connected with the main graph. These two subsections were not critical for analyzing the power grid from a topological point of view and thus were not included in the analysis. Therefore, the 300 node network will be referred to as 247 node network here onwards unless we refer to the standard test case.

III. NETWORK GENERATION AND ANALYSIS

In order to analyze the effect of topological characteristics of power grid networks on cascading effect, we used the real networks such as the IEEE 300 bus [8], IEEE 118 bus [8], and WSCC 179 bus networks as the first stage and studied cascading failures on them. Then we designed a first approximation network generator to produce networks having characteristics like number of nodes, maximum node degree, and average node degree similar to the original networks. Fig. 1, 2, and 3 show the original and generated networks for the 247 node, the 179 node, and the 118 node systems, respectively. Fig. 4 shows the node degree distributions of the 247 node original and generated networks. The figure shows that the generated network follows the node degree distribution of the original network very closely. The horizontal scale represents the degree from 1 to the maximum node degree and the vertical axis represents the number of nodes with a particular node degree. The generated graph is one of those from the family of random graphs having the node degree distribution similar to the original network. The generator takes the number of nodes, the maximum node degree, and the average node degree as inputs and gives the edge list of the network as the output. These generated networks are then used for the simulation of cascading effect. We generated the weights and loads probabilistically from measured inductance and load distributions. Fig. 5 shows the graphs for power degradation on the 247 original and generated networks. The horizontal scale represents the stages of cascade that the system goes through before it finally stabilizes and the vertical scale is the current load on the system in megawatt. Fig. 6 shows the graph for node loss in the 247 original and generated networks. The horizontal axis again represents the stages of cascade and the vertical axis represents the number of nodes remaining in the network, as a result of cascading. Table I shows the comparison between different characteristics of the original and the generated networks. The table indicates that the generated networks have a shorter characteristic path length as compared to the original. This metric causes the generated networks to be better connected and hence contribute to the robustness of the networks. However, the Clustering Coefficient of the generated networks is lower than that of the original networks due to the more random nature of the graph in the generated case.
IV. MITIGATION STRATEGIES

We propose the following mitigation strategies to limit the damage to the network by cascading failures: Homogeneous Load Reduction, Targeted Load Reduction for Neighbors, Targeted Range-Based Load Reduction, and Use of Distributed Renewable Sources. The fourth strategy can also be implemented in combination with another mitigation strategy, “Islanding”, which aims at optimally selecting clusters or islands of nodes that can be separated from the main grid and be independently powered using distributed sources such as wind turbines. Each of these strategies is discussed in detail.

A. Homogeneous Load Reduction

This mitigation strategy aims at reducing a given percentage of the load on each of the nodes in the network. This reduction in load attempts to keep the nodes and links operating below their maximum capacities and to better accommodate the redistribution of load due to failure of links or nodes. We performed a series of simulations on the original 247 node network, wherein the load on each of the nodes was reduced from hundred percent to zero percent, in steps of five. Thus, the starting load for each simulation is the initial load on the nodes. We plotted the result of each simulation for the original 247 node network to obtain the Homogeneous Load Reduction curve as shown in the Fig. 7.

B. Targeted Load Reduction for Neighbors

As the name suggests, this strategy targets at reducing the load of the neighbors of the nodes which were connected by the failed link. However, there may be some neighbors which carry negligible load or no load at all. In such cases, the strategy is not effective. Moreover, the maximum node degree of most nodes in the power grid is low. Thus, it is difficult to save the network against cascading failures by considering just the neighbors of the two nodes. As a result, this strategy does not seem to be very effective in reducing cascading failures.
C. Targeted Range-Based Load Reduction

The approach used in this strategy is to pick one of the nodes which were connected to the link that failed, and discover the tree for that node. The node being considered is the one which was sending power out to the other node through the failed link. This particular node has to re-route the outgoing power among its other neighbors. One or more of the neighbors of this root node may have their best way to the generator through it. These neighbors form a part of the tree. The same criterion is followed in every step until the entire tree is discovered. We then consider nodes in the tree which are not sources and carry some load, and reduce their load by a certain percentage. Thus, the percentage of load reduced is a function of the number of active nodes in the tree. Since we consider a smaller set of nodes as compared to the Homogeneous Load Reduction, a higher percentage of load should be removed from the tree to mitigate cascading failures. But this constitutes a very small portion of the total load of the system, less than 2%. Fig. 7 shows the comparison between the Homogeneous Load Reduction Strategy and the Targeted Range-Based Load Reduction strategy. Fig. 8 shows the load reduction only on the targeted tree.

D. Use of Distributed Renewable Sources

The aim of this strategy is to disconnect a cluster or “island” of nodes from the main grid to help reduce the load on the grid. This island will be powered by some distributed renewable sources such as wind turbines. The power output of each of the turbines is the theoretical load reduction on the transmission lines of the power grid. We are investigating some optimization techniques which could be used to disconnect the island from the main grid.

V. RESULTS

The following results were obtained from the discussions above:

- The power degradation graphs in Fig. 5 show that the worst-case cascading effect stops at an earlier stage and causes less damage in the case of generated networks. The load loss in the case of the 247 node generated network discussed above is about 42.66% less and the node loss is about 36.84% less than the original network.
- As seen from Table I, the generated graphs have a smaller characteristic path length as compared to the real networks. This property of the generated networks makes them more robust against cascading failures. However, the clustering coefficient of the generated networks is lower than that of the original networks, due to more random nature of the generated networks.
- Targeted Load Reduction for Neighbors and Targeted Range-Based Load Reduction strategies form a special case of the Homogeneous Load Reduction strategy. The Homogeneous Strategy is easier to implement, in that we simply reduce the load on all the nodes existing in the network. The Range-Based Load Reduction strategy is more economical, but requires cyber-physical system interaction to perform quick computations and reduce the load in only the desired regions. The Targeted Load Reduction for Neighbors does not seem to be an effective strategy for prevention of cascading failures.

VI. CONCLUSIONS AND FUTURE WORK

The topology of the power grid network greatly contributes to its robustness. The topology determines the connectivity of the network and hence the number of alternate paths that can be taken by the network flow. The generated graphs are better connected because of shorter characteristic path lengths and are more random in nature than the real power grid networks. As a result of randomness, they show more robustness against cascading failures. However, the feasibility of having shorter characteristic path lengths in a real power grid network, must be investigated. The distributed renewable sources can be of great assistance in reducing the ever-increasing load on the power grid. Our future work includes the following:

- Using optimization techniques to obtain feasible points for disconnection of node clusters for Islanding, and
- Weighted Analysis of the power grid network.

VII. ACKNOWLEDGMENTS

The authors would like to thank A. Pahwa, S. Starrett, I. Dobson, and P. Schumm for their valuable suggestions and comments.

REFERENCES


