# TOPOLOGICAL ANALYSIS AND MITIGATION STRATEGIES FOR CASCADING FAILURES IN POWER GRID NETWORKS

by

SAKSHI PAHWA

B.E., Mumbai University, India, 2007

---

A THESIS

submitted in partial fulfillment of the
requirements for the degree

MASTER OF SCIENCE

Department of Electrical and Computer Engineering
College of Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas
2010

Approved by:

Major Professor
Caterina Scoglio

# Abstract

In recent times, research in the field of complex networks has advanced by leaps and bounds. Researchers have developed mathematical models for different networks such as epidemic networks, computer networks, power grid networks, and so on. In this thesis, the power grid has been modeled as a complex network.

The power grid is being used extensively in every field today. Our dependence on the power grid has exceeded to an extent that we cannot think of survival without electricity. Recently, there has been an increasing concern about the growing possibility of cascading failures, due to the fact that the power grid is works close to full utilization. Furthermore, the problem will be exacerbated by the need to transfer a large amount of power generated by renewable sources from the regions where it is produced to the regions where it is consumed. Many researchers have studied these networks to find a solution to the problem of network robustness. Topological analysis may be considered as one of the components of analysis of a system's robustness.

In the first part of this thesis, to study the cascading effect on power grid networks from a topological standpoint, we developed a simulator and used the IEEE standard networks for our analysis. The cascading effect was simulated on three standard networks, the IEEE 300 bus system, the IEEE 118 bus test system, and the WSCC 179 bus equivalent model. To extend our analysis to a larger set of networks with different topologies, we developed a first approximation network generator the creates networks with characteristics similar to the standard networks but with different topologies. The generated networks were then compared with the standard networks to show the effect of topology on the robustness of power grid networks. A comparison of the network metrics for the standard and the

generated networks indicate that the generated networks are more robust than the standard ones. However, even if the generated topologies show an increased robustness with respect to the standard topologies, the real implementation and design of power grids based on those topologies requires further study, and will be considered as future work.

In the second part of this thesis, we studied two mitigation strategies based on load reduction, Homogeneous load reduction and Targeted range-based load reduction. While the generic Homogeneous strategy will only mitigate the severity of the cascade when a non-negligible load reduction is performed, our newly proposed Targeted load reduction strategy is much more efficient, reducing the load only in a small portion of the grid. The determination of this special portion of the grid is based on an algorithm, which finds the paths supplying power from the generators to the nodes. This algorithm is described in details in the Appendix B. While the Homogeneous strategy is easier to implement, efficient results can be obtained using the Targeted strategy.

# Table of Contents

# List of Figures

# List of Tables

# Acknowledgments

I would sincerely like to thank my advisor, Dr. Caterina Scoglio, for her confidence in me. She has been instrumental in making me think independently and has always been a great support, professionally and personally. The Energy and Power Affiliates Program (EPAP), comprising of Westar Energy, Burns and McDonnell, Nebraska Public Power District, and Omaha Public Power District, have been the financial sponsors for this work, for the past two years. Special thanks to the EPAP.

I wish to express my gratitude to Dr. Anil Pahwa and Dr. Shelli Starrett for their very useful suggestions and resources, and Dr. Ian Dobson of the University of Wisconsin-Madison for providing me with additional data for analysis. Special thanks to Dr. Alessandro Vespignani of Indiana University for helping me improve with his reviews, comments, and suggestions. Thanks to Dr. Don Gruenbacher, who helped me learn about my field of research by organizing field trips and tours of power stations and utilities.

I would like to extend a word of appreciation to every member of the Sunflower Networking Group, for asking questions, giving suggestions, and all the help and support at all times.

Credit also goes to my parents, Mrs. Priti Pahwa and Mr. Sunil Pahwa, for being there with and for me, always. Lastly, I would like to thank all of my family and friends for their support.

# Chapter 1

# Introduction to Complex Networks

In recent times, the field of complex networks has made great advances. Many real world systems such as WWW, Internet, and Power Grids have been modeled as complex networks and a topological analysis of these systems has been carried out[1,2,3,4,5,6,7,8,9,10]. To understand the basic concepts of complex networks and the approach used in this thesis, some of the definitions and terminology have been listed below[3,11,12,13,14,15,16,17].

In most of the previous work in this field a purely topological approach has been used and more importance has been given to the network metrics. However, in this thesis, care has been taken to incorporate power flow dynamics of the network along with the topological aspect of the network.

## 1.1 Some definitions

1. Graph: A simple graph G(V, E) is usually a set of vertices V and edges E connecting these vertices. A multi-graph is a graph with multiple edges between the same vertices. A graph is called a digraph if the edges of the graph are directed.

2. Network: In simple words, a graph with flows is called a network.

3. Nodes: Each of the vertices in the set V are called nodes. The nodes may represent routers in the Internet or people of different nationalities in a social network.

4. Links: Each of the edges in the set E are called links. Links connect nodes, indicating the relationship between them. Links can carry weights, representing a certain characteristic of a network. For example, weights may represent the traffic conditions in the Internet or impedances in a power grid. Edges can be directed, pointing in one direction and forming a digraph. A graph may have hyperedges - edges that join more than two vertices together.

5. Adjacency matrix: It is a square matrix with the rows and columns representing all the nodes of the network. It gives a node-node relationship of a network. Whenever a link exists between two nodes, the corresponding element of the adjacency matrix is 1, else it is 0. A weighted adjacency matrix contains a non-zero weight instead of a 1, when a connection exists.

6. Node degree: It is the number of edges connected to a node. In other words, it is the number of edges that end at a node. A directed graph has an in-degree and an out-degree indicating the number of incoming and outgoing edges, respectively.

   The average node degree is the average number of edges connecting the vertices in the graph. The average node degree of a graph is given by

$$< k >= \frac{2 * m}{n} \tag{1.1}$$

   where $m$ is the number of links and $n$ is the number of nodes in the network.

7. Degree distribution: Let $n(k)$ be the number of nodes of degree $k$ ($k$-degree nodes). The node degree distribution is the probability that a randomly selected node is $k$-degree:

$$P(k) = \frac{n(k)}{n} \tag{1.2}$$

8. Clustering coefficient: This measure assesses the degree to which nodes tend to cluster together. Evidence suggests that in most real-world networks, and in particular social networks, nodes tend to create tightly knit groups characterized by a relatively high

density of ties. In real-world networks, this likelihood tends to be greater than the average probability of a tie randomly established between two nodes. Two versions of this measure exist - local and global. Local clustering of a node in a graph quantifies how close it's neighbors are to forming a clique (complete graph). If $\overline{m}_{nn}(k)$ is the average number of links between the neighbors of $k$-degree nodes, local clustering is the ratio of this number to the maximum possible such links. It is the average number of 3-cycles involving $k$-degree nodes.

$$C(k) = \frac{2 * \overline{m}_{nn}(k)/k}{k-1} \tag{1.3}$$

9. Geodesic path: A geodesic path is the shortest path through the network from one node to another. The number of edges traversed by the shortest connecting path between two vertices $i$ and $j$ or a source-destination path with the optimal sum of weights is called the shortest path length and denoted as $l_{ij}$. It is a symmetric quantity for undirected graphs but it does not coincide, in general, for the directed graphs. The shortest path may be measured in terms of hop count or distance.

10. Characteristic path length: Average distance, characteristic path length, and average shortest path, all refer to the same metric. It is the average value of $l_{ij}$ over all the possible pairs of vertices in the network.

$$< l >= \frac{\sum_{i,j} l_{ij}}{N(N-1)} \tag{1.4}$$

It is the sum of all source-destination shortest paths divided by the number of node pairs in the network.

11. Hop Count: Hop count is a measure which is defined as the number of links in the shortest path of a source-destination pair in the network. In a simple network with homogeneous weights on all links, equal to unity, the hop count would be the addition of weights in the shortest path from the source to the destination.

12. Diameter: The diameter is defined as the longest shortest path between any source-destination pair in the network.

$$d_G = max(l_{ij}) \tag{1.5}$$

When a network is disrupted, some of the links or nodes that are deleted may constitute a part of the shortest path in the network. So the shortest path after the disruptions may become longer than it was originally. Thus, disruptions reduce the global connectivity of the network by increasing the diameter. If the disruptions are severe enough to fragment the network, the diameter becomes infinite.

13. Betweenness Centrality: It is defined as the number of shortest paths between pairs of vertices that pass through a given vertex. More precisely, if $p_{hj}$ is the total number of shortest paths from $h$ to $j$ and $p_{hj}(i)$ is the number of these shortest paths that pass through the vertex $i$, the betweenness of $i$ is defined as

$$b_i = \frac{\sum_{h \neq j \neq i} p_{hj(i)}}{p_{hj}} \tag{1.6}$$

# Chapter 2

# Power grids as complex networks

## 2.1 Motivation

Commonly known as blackouts, there have been a number of incidents of power grid cascading failures, recently. The United States Northeast blackout of 2003 was one of the major blackouts within the last decade. Some of the others were the blackouts in United Kingdom, Denmark, and Italy, which took place within weeks or months of the U.S. blackout[18, 19]. There were other blackouts in Brazil in 2005, and in Switzerland in 2009, and many more in different parts of the world. Cascading outages were once thought to be rare incidents but are becoming common in recent times. Such incidents have led to an interest among researchers to understand power grid dynamics in greater depths.

Power grids are among the most complex technological systems ever developed[6]. Today, electric energy is significantly being used in every walk of life. This ever-growing demand for electricity is putting a tremendous pressure on the power grid, which transmits and distributes this electricity. When the power grids were designed initially, they were not designed to handle this amount of pressure. However, the advancement of technology and automation of devices in modern times is increasing the demand for reliable energy which calls for an increase in the efficiency of the power grids, both by better technology for transmission and distribution, as well as by redesign and restructuring.

The power grid can be thought of as having three subsections: Generation, Transmission, and Distribution. Transmission section may further have one or more sub-transmission sections. In this work, we have studied the transmission section of the grid, with generation as an integral part. While analysis of power grids as a power flow problem is important, it is also important to evaluate them from a topological standpoint because topology plays an important role in determining the robustness of a network.

The following are the important features of the power grid as a complex network:

1. Node Degree Distribution: Most of the nodes in the network have a low degree, usually close to the average node degree, defined in Chapter 1. There are very few nodes with a high degree. In other words, the node degree follows a Poisson distribution[20]. The node degree distribution for a 300 bus power grid network is shown in Fig. 2.1.

2. Load Distribution: There are very few nodes handling a very heavy load. In other words, the load follows a Power Law distribution[1]. Fig. 2.2 shows the load distribution for a 300 bus power grid network.

3. Flow Routing: The flow dynamics depend greatly on its electrical characteristics, one of them being the impedances of transmission lines. Power flows through the least resistive path, and thus the amount of power flowing through the transmission lines is inversely proportional to their impedances.

It has been mentioned in literature by many power systems researchers that usually, the power grid is robust against single component failures. This is true, in the sense that if a single line gets overloaded or breaks, its power is immediately re-routed to a different line and the disturbance can, usually, be suspended. However, in case of an overloaded system, the redistribution of power leads to the subsequent overloading of other lines, and the consequence could be a cascade of overloading failures. In this thesis, we have considered the base case of a system working close to its maximum capacity. The authors of[21] have described the presence of a hidden failure phenomenon in power grids and have presented a

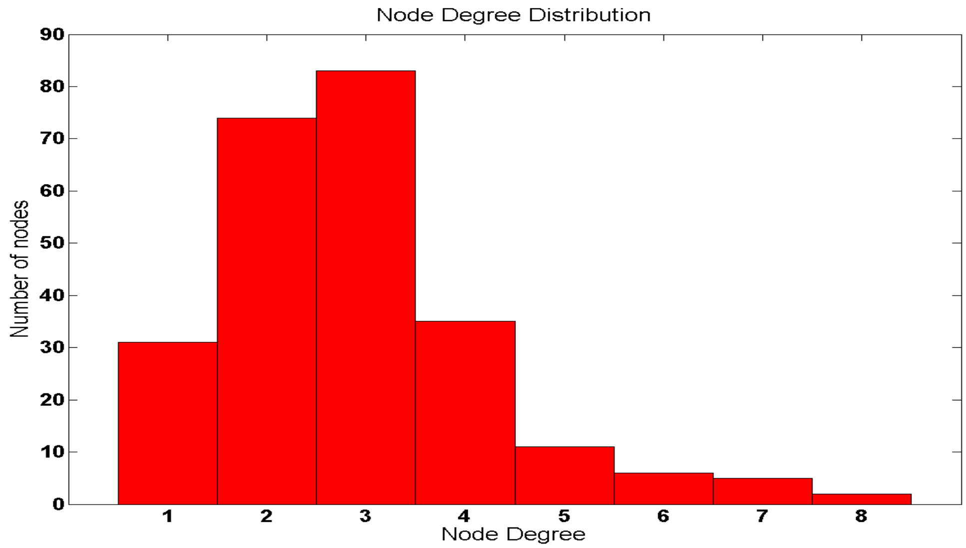


Figure 2.1: Node Degree Distribution for a power grid network

model for the same. Hidden failures in the power grid are exposed in the event of abnormal operating conditions such as overloading, and these failures lead to the spreading of an initial single component failure. Such failures may involve the incorrect or false tripping of protective relays.

One general way to define a network to be robust from a topological viewpoint is to say that its components cannot be easily disconnected[22]. In other words, a network is robust if the removal of one or few network elements does not cause it to fragment into a number of components. In this thesis, we define a network to be robust when the failure of one component and the consequent cascade of failures minimally reduces the power delivered to the loads.

In the next section, the related work in this field is discussed. Chapter III presents the simulation of the cascading failure on standard networks, followed by the generation of random networks, in Chapter IV. Chapter V discusses the mitigation strategies for the power grid network, and the results, conclusions, and future work are presented in Chapter VII, followed by Appendices A, and B

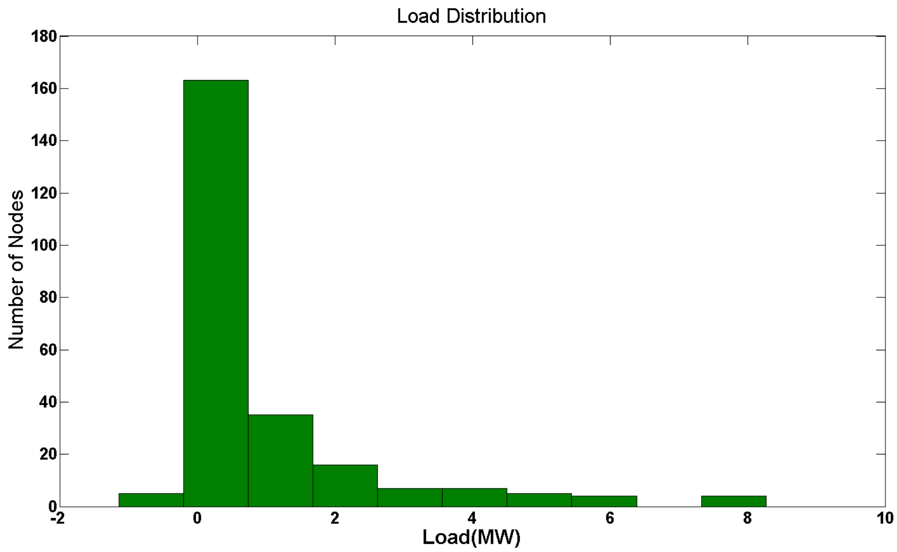


Figure 2.2: Load Distribution for a power grid network

## 2.2 Related Work

Study of the impact of topology on a network is important because it has an important role to play in the determination of robustness of a network. Most earlier research in power grid as a complex network has mainly addressed the static properties of the network[1,2,3].

In[7], the authors have considered the power transmission grid as a complex network in which the energy is exchanged between every pair of nodes and transmitted along the shortest path connecting them. They have considered the concept of a finite capacity for every node in the network, the total load on each node being the total number of shortest paths passing through that node, in agreement with[4,23,24]. This load was also called as betweenness centrality. They have tried to prove that cascading effect is more likely to take place in a network with a high heterogeneity of load. Their results show that scale-free networks experience cascading failures more easily than the homogeneous networks. However, it must be noted here that although the power grid networks show less heterogeneity in the node degree but a high heterogeneity in the node load, the load is not the betweenness but the actual consumption in MW. Some of the nodes handle a heavy load while most others handle medium or light load.

Load has been considered as betweenness or number of shortest paths passing through a node in some previous works. In[25], the efficiency model introduced in[26] has been used to evaluate the redistribution dynamics of a given system before and after removal of nodes. This model, used by several complex networks researchers states that efficiency of exchanging information between two nodes is the inverse of the shortest distance between them. The most efficient paths are thus the same as the shortest paths between any two nodes. However, it seems unsuitable to consider shortest paths for a power grid network because the flow of power between two nodes depends on the electrical characteristics of the nodes and the link carrying the power. As a result, this model was not used for our analysis.[27] uses the same model with slight variations. The authors of this work have said that the overloaded nodes are not removed from the network but the information passing through the overloaded nodes gets worse so that eventually these nodes will be avoided and the shortest paths will change. The load on each node is the number of most efficient or shortest paths passing through it. They reduce the efficiency of the node inversely proportional to the load on the node at the given time instant.

Attacks on nodes as well as on links has been considered in[8]. Like the other previous research, this work too has spoken about the robust-yet-fragile property of heterogeneous networks. The heterogeneity is considered in loads where the definition of load is still betweenness centrality. The networks are considered to be robust for random failures and fragile for intentional attacks. The cascade causing nodes are the ones with a higher betweenness/load or higher connectivity/degree. The authors of this publication have used the model proposed by them in another paper[7]. All these studies are mainly focused on scale-free networks because of the heterogeneity aspect that has been incorporated into them. Similar concepts and analysis has been addressed in some other papers such as[5,28]. The authors have explicitly mentioned in their publication[9] that they have neglected the details of the electromagnetic processes and focused only on the topological properties of the grid. However, they also agree that their model may be too simple to be used in the real world.

Another aspect of cascading dynamics has been considered in[21,29,30,31] based on a hidden failure model. The first of these references is an improved hidden failure model over the other three. The hidden failure model suggested that a hidden failure is undetectable during normal operation but will be exposed as a direct consequence of other system disturbances such as failure of a network element and consequent overloading of some lines, which might cause a relay system to incorrectly and inappropriately disconnect network elements. These analyses are totally from a power systems perspective and do not involve much topological analysis.

More attention has been given to the flow dynamics lately, and[32] has a discussion on the point that the ability of a transmission grid to perform properly depends on its topological structure, and on the impedance and flow limits of its lines. The authors have discussed the problems associated with the general definition of vulnerability based on global efficiency of power grid networks, as mentioned in[7,9,33], and others. Efficiency has been replaced by net-ability in[32] and a comparison is shown between the two metrics. The authors of this work have also considered link characteristics, adding that the capacity of a link is the maximum amount of power it can carry and this power is inversely proportional to the line impedance. The authors of[34] have explained very clearly that the power grids differ substantially from the preferential attachment model[1] as well as the small-world model[3]. They say that these abstract models do not provide much utility for modeling power grids. Power grids have high clustering coefficient but not as high as small world networks. At the same time, they show exponential degree distribution like the random graphs. They have outlined the differences between the topological and electrical structure of the power grids and proposed a graph-generating algorithm that produces random networks that are roughly similar to what is found in the real power grids, except for the negative assortativity. It has been discussed in[35] that a topological approach must be supported by a power grid model to give more accurate results than those obtained from a purely topological aspect. The authors have used three measures of vulnerability to find the impact of random failures and directed attacks on the power grid, the first two being purely topological measures.

The work in this thesis highlights this very aspect of using a power flow model and flow dynamics to measure the vulnerability of the power grid, along with using a topological approach.

# Chapter 3

# Simulation of Cascading Effect

The 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" [36]. In most real transportation/communication networks, the breakdown of a single or of a very small size group of elements can be sufficient to cause the entire system to collapse, due to the dynamics of redistribution of flows on the networks[28].

To simulate the cascading effect on power grid networks, we considered three standard networks: IEEE 300 bus test system[37], IEEE 118 bus test system[37], and WSCC 179 bus equivalent model. A simplified model, the DC Power Flow model[21,32,38] is used for this analysis. Due to some of the assumptions listed below, this model is suitable for such an analysis[39], as it removes the non-linearities of the system. This model is also known as a linearized model because it gives a solution of simultaneous linear power flow equations. The complete description of the DC Power Flow model is given later, in Appendix A. The method uses matrices for the different physical quantities such as power flow, phase angles, and impedances of the network. A full-blown AC analysis becomes very complicated for the topological study of the grid. Hence, the DC model was considered appropriate for such a study, under some assumptions[39].

## 3.1 The Model

The power grid can be modeled as a circuit with resistances, inductors, and capacitors. The model is explained in details in Appendix A. Some of the assumptions associated with the DC Power Flow model are:

1. All voltages have a magnitude of 1 per unit or 1 p.u., which means that the voltage profile is flat and all voltages are equal. Hence, we consider only the phase angle of the voltage in calculations.

2. The voltage angle difference is small, and consequently $\sin\delta \approx \delta$.

3. Resistances are very small as compared to inductive reactances, i.e. $R << L$. Hence, they are neglected.

Some additional approximations that were made are:

1. Loads are static, which means that they do not change with time

2. The problem is considered in discrete time

In spite of these approximations, the DC model takes into account the important electrical properties, such as the impedances, to find the paths from the generator to each node. The DC model also takes into account the direction of power flow which is often neglected in a topological analysis of the power grid. Overall, the DC model is quite suitable for such an analysis because it considers the most important electrical properties, while previous research in complex networks has used a model based on shortest path for power flow[9, 8, 28, 27].

The power grid can be modeled as a complex network by considering that the transmission lines are the links of the network, and the power substations (and generators) are the nodes, as shown in Fig. 3.1. The impedances of the transmission lines are the weights on the links.

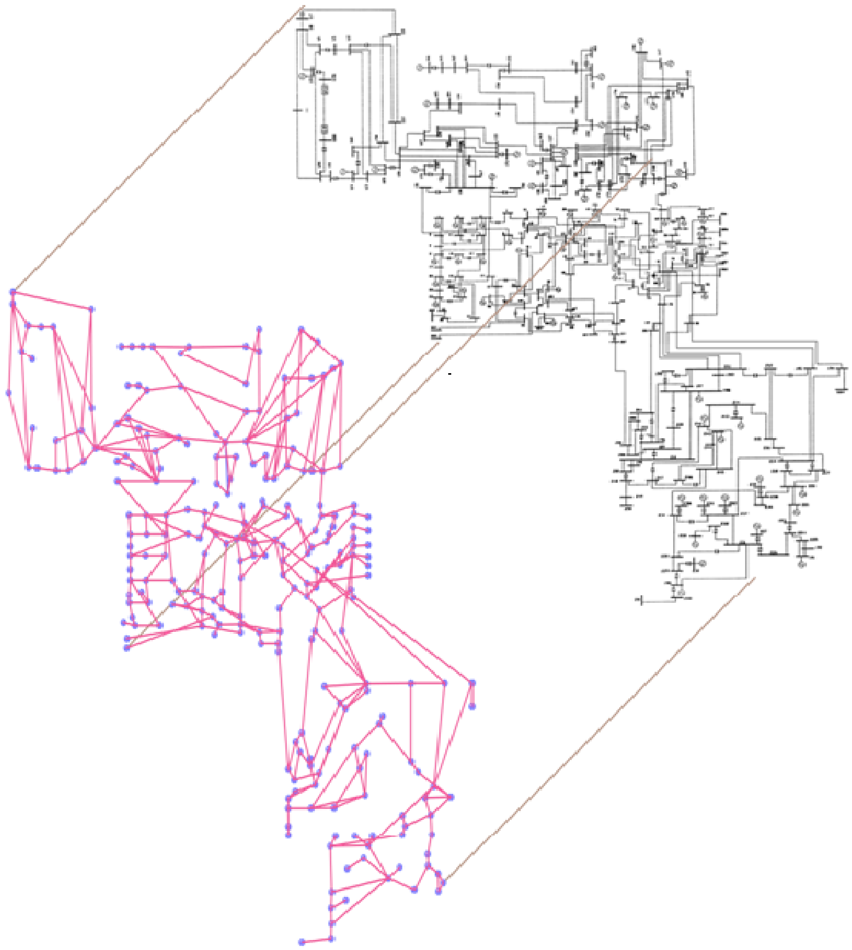

Figure 3.1: Modeling the transmission grid as a complex network

## 3.2 Data set

The IEEE 300 node network has a section of 247 nodes and two other subsections of nodes which were not very well-connected with the main section and were not important for topological analysis. These two subsections were removed, leaving 247 nodes in the network. Therefore, the 300 node system is referred to as the 247 node network here onwards, unless we refer to the standard case.

For the simulation, we take the load information and the link information from the data sheets available for these networks[37]. The load on the nodes is the consumption at each node in MW. The amount of load handled by each node is different, with some nodes handling a heavy load while others do not. In reality, the load or demand changes at every time step. The capacity of a node is the sum of the load it serves and the power it sends out on adjacent links. However, there are some nodes which handle no load at all but are present just for the purpose of transferring power from one node to another.

The link information consists of the list of the pairs of vertices that every edge connects. The link and load information suggests that power grid networks are quite homogeneous in their node degree distribution, with the average node degree between 2.5 and 3.5. The degree of a node is the number of edges that end at that node. We then populate a weighted adjacency matrix $\{x_{ij}\}$ using the link information and the corresponding weights (line impedances) of each link. These weights are the elements of the matrix. The load and link information is then used with the DC Power Flow model to calculate the phase angles, and eventually, the power flow in each link of the network. The main generator is named as the reference node and is assigned a phase angle of 0 degree. All the other phase angles are calculated with reference to this phase angle, i.e, all the other angles are smaller as compared to the reference angle. This is because electric current flows from a higher electric potential to a lower electric potential. Thus, the angles determine the direction of power flow. Any removal of system elements is capable of disturbing the balance of flows, leading to their redistribution and recalculation of all the associated physical quantities. The direction of flow might also be affected by any intentional or accidental removal of network elements. In general, the system is assumed to be operating at maximum capacity.

To simulate the cascading failure, we select one of the links and remove it from the network. The power carried by this link should be redistributed among the neighbors and so all the parameters such as the adjacency matrix, load vector, phase angles, and link powers should be resized, recalculated, and updated. This is the first stage of failure, known as the first iteration. Since all the links are operating close to their maximum capacity, the redistribution might cause some of the links to become overloaded and to fail. Now, the power carried by these newly failed links has to be redistributed, and once again recalculation and updating of quantities must be done. This is the second iteration. This procedure is repeated until there are no more overloaded links. This network condition is reached due to the fact that removing failed links also removes loads and progressively the total load is reduced to a level that can be managed by the network. At this point, the system is said to have attained the state of stability.

We individually use each link in the network as the initial failure and record the number of additional failures it causes consequently. We assume that a failure of more than 10% of the nodes is a serious outage. We classify the links into two categories: Critical and Non-Critical. Critical links are those which, if removed, will cause more than or equal to 10% damage to the network, and Non-Critical links are those which cause less than 10% damage on removal. Thus, links which cause more than or equal to 10% damage were said to cause a cascading effect on the network.

In addition to the number of nodes failed, we use power degradation as a measure to quantify the severity of the damage from cascading failures. Power degradation is defined as the loss in power as compared to the original power on the system before the failure[40]. We note the total remaining load on the system in every iteration and plot a graph of current load versus iteration number. We determine the worst-case power degradation graphs for the 247, 179, and 118 node networks. By worst-case we mean that the simulation is carried out for the most critical link which causes the maximum damage to the network in terms of links failed. In fact, power degradation for different networks is proportional to their link losses and it is appropriate to determine the worst-case using link loss.

# Chapter 4

# Network Generation: Creation of Topologies

To study the effect of topology on network robustness, topologies other than the standard IEEE topologies were required for analysis. Since the power grid is a critical infrastructure, it is very difficult to obtain information about its structure and data. To overcome this problem, we developed a "‘first approximation"’ network generator to generate more topologies.

However, to make the generated network close to the realistic network, we imposed the constraints that the average and maximum node degree of the generated networks be the same as that of the standard networks. This constraint is due to the physical limitations of the nodes (substations) that cannot have an arbitrarily high number of transmission lines originating from them.

The number of nodes, average node degree, and maximum node degree were given as inputs to the generator and the output was the edge list of the generated network. The edge list is a list of the pairs of vertices that connect all the edges in the network. These connections are made keeping in mind the constraints, and avoiding self-loops and multiple edges between pairs of nodes. We generated the loads and inductances probabilistically, using the data in the data sheets for the three standard networks. The "first approximation" generator models the generated networks based on the node degree distribution of the original networks. Thus, there will be a family of networks that can be generated with the same degree distribution. The node degree distributions of the original 247 node network and five of the family of new 247 node networks is shown in 4.4. The original and generated topologies for the 247, 179, and 118 node networks are shown in Fig. 4.1, Fig. 4.2, and Fig. 4.3, respectively.

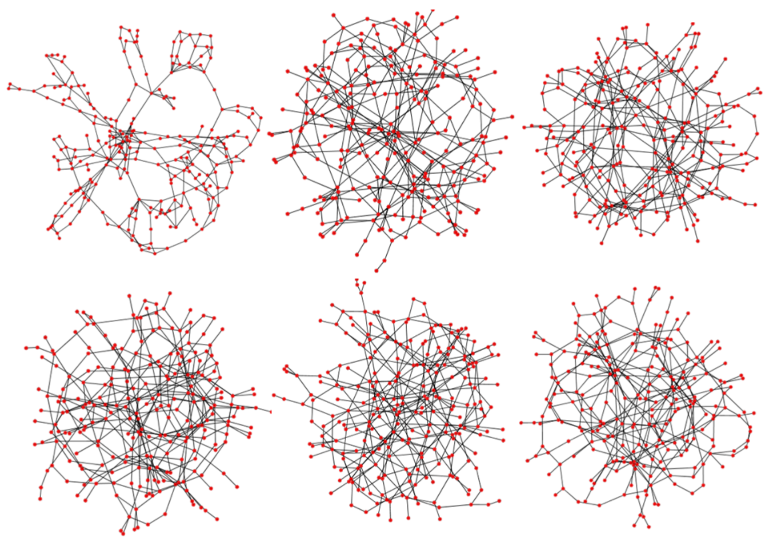

Figure 4.1: Standard(left) and Generated 247 node networks

The same procedure, as that used for the standard networks, is applied for the generated networks for simulating failures. The most critical link is removed initially and the redistribution dynamics are studied.

Interestingly, results show that the generated networks are more robust against cascading failures than the standard networks. By this it is meant that the power degradation and node loss for each of the generated networks is less than that of the standard networks. However, the generated networks themselves vary in the level of robustness with some generated networks being more robust than the others, in the same family.

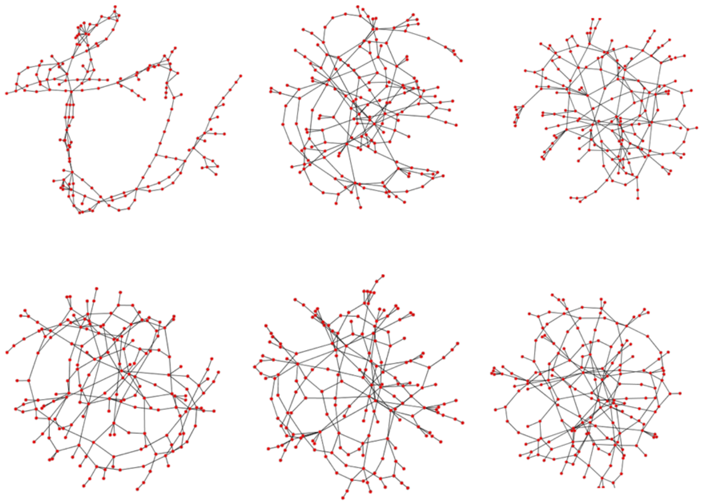

Figure 4.2: Standard(left) and Generated 179 node networks

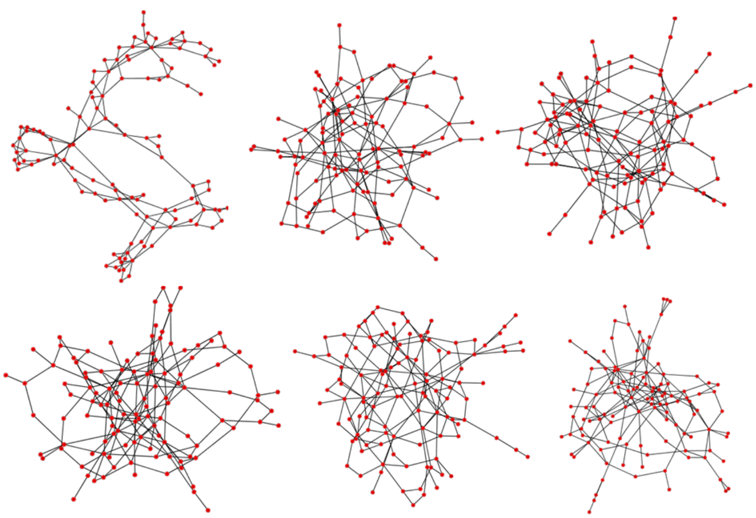

Figure 4.3: Standard(left) and Generated 118 node networks

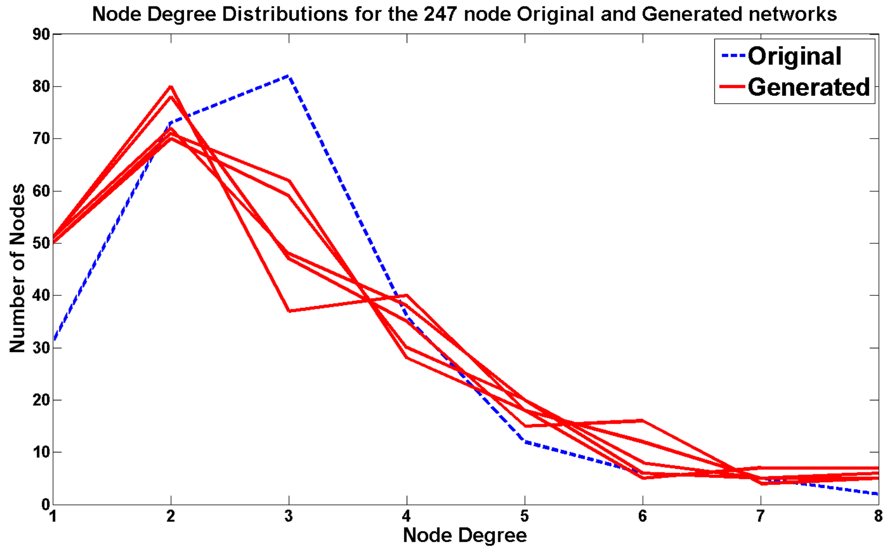


Figure 4.4: Node Degree Distributions of the Original and Generated 247 node networks

## 4.1 Robustness Evaluation

The power degradation graphs and node loss graphs for the standard and generated networks are shown in Fig. 4.5, and Fig. 4.6, respectively. The generated 247 node networks have an average of about 72.56 MW of load remaining for the worst case, but the standard 247 node network has less than 5 MW of load remaining, at stability. Similarly, the generated networks have an average of 76 nodes remaining in the network at stability, whereas the standard network has about 4 nodes remaining. However, it must be noted that there is just one or very few links which cause a worst-case damage. Fig. 4.7 and Fig. 4.8 represent the power degradation and node loss graphs for the standard and generated 179 node networks. Similarly, the power degradation and node loss graphs for the standard and generated 118 node networks are shown in Fig. 4.9 and 4.10.

These results pose an interesting consequent question: given that the generated networks are more robust than the standard networks, what are their topological characteristics, and how can we modify the standard topologies to become more robust? In the following section, we address the first part of the question, and a comparison of the topology metrics of the

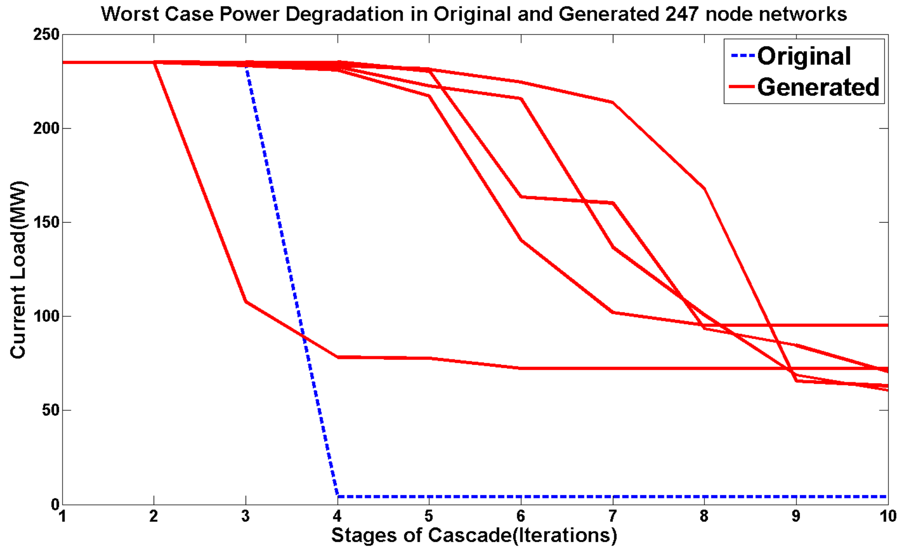


Figure 4.5: Power Degradation graph for Standard and Generated 247 node networks

standard and generated networks is done in the next section.

## 4.2 Comparison of network metrics

To characterize the generated and standard networks, we computed three metrics:

1. Characteristic path length: The average shortest distance over all the possible pairs of nodes in the network.

2. Diameter: The longest shortest path between any two nodes of the graph.

3. Clustering coefficient: Measure of the degree to which nodes in a graph tend to cluster together.

These metrics are discussed in more details in Chapter 1.

Results obtained computing these three metrics are shown in table 4.1. It is important to note that the diameter and characteristic path lengths are measured here in terms of shortest path in number of hops; real power flow routing is consequently not considered.

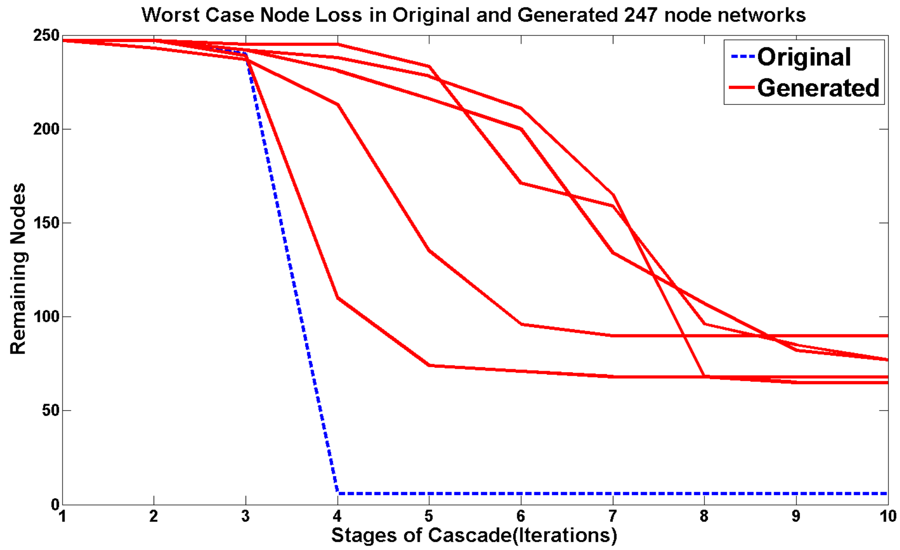


Figure 4.6: Node Loss graph for Standard and Generated 247 node networks

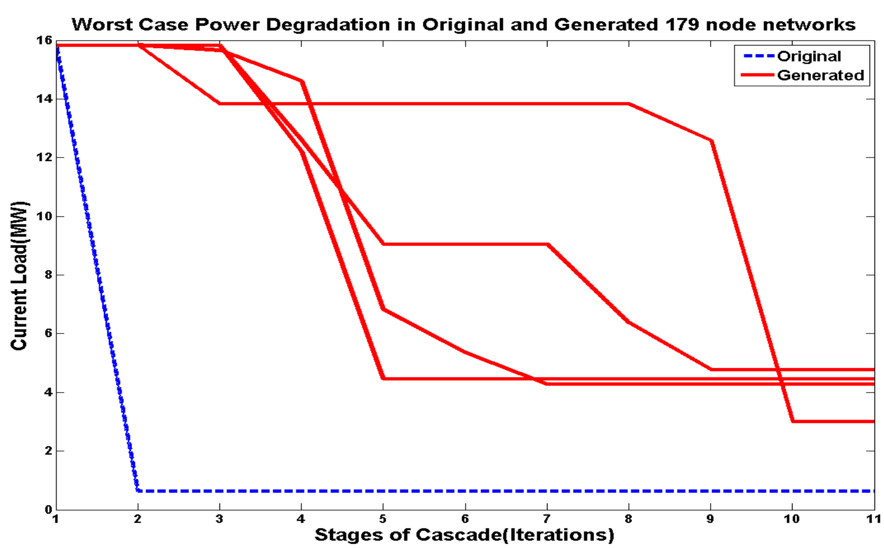


Figure 4.7: Power Degradation graph for Standard and Generated 179 node networks

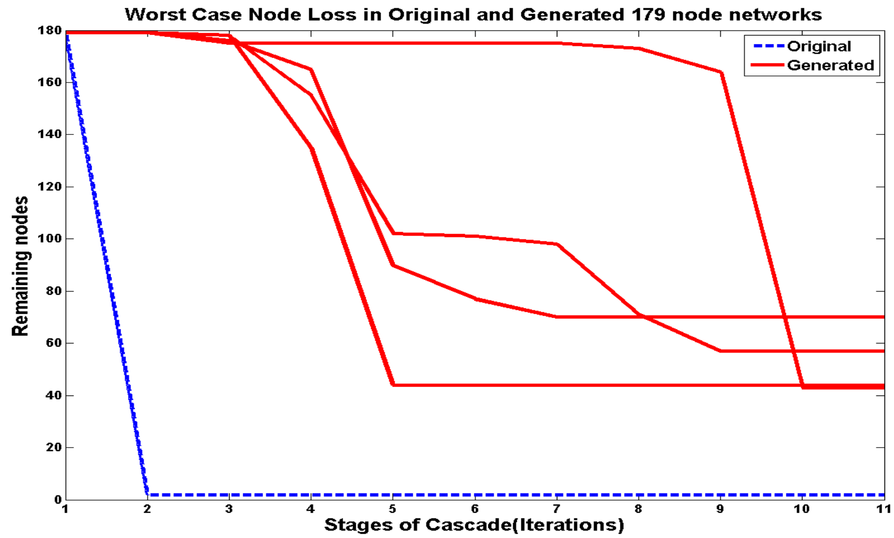


Figure 4.8: Node Loss graph for Standard and Generated 179 node networks

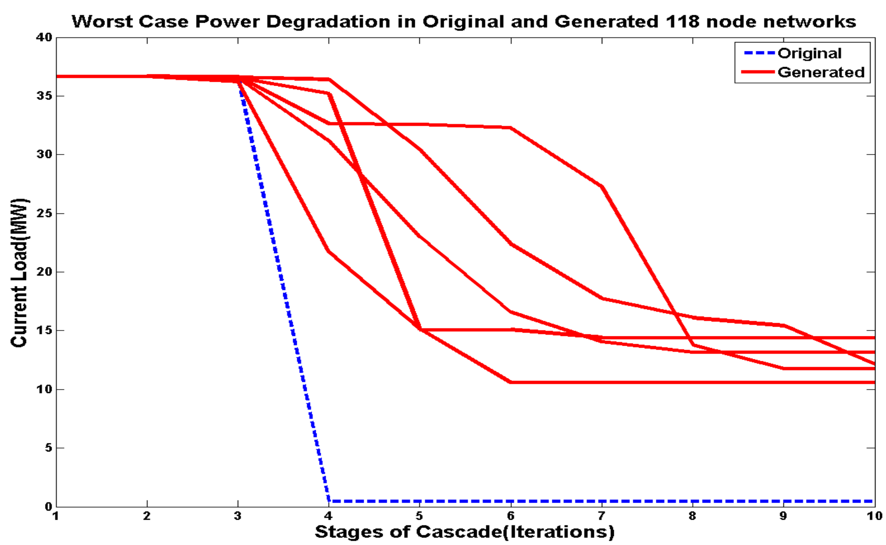


Figure 4.9: Power Degradation graph for Standard and Generated 118 node networks

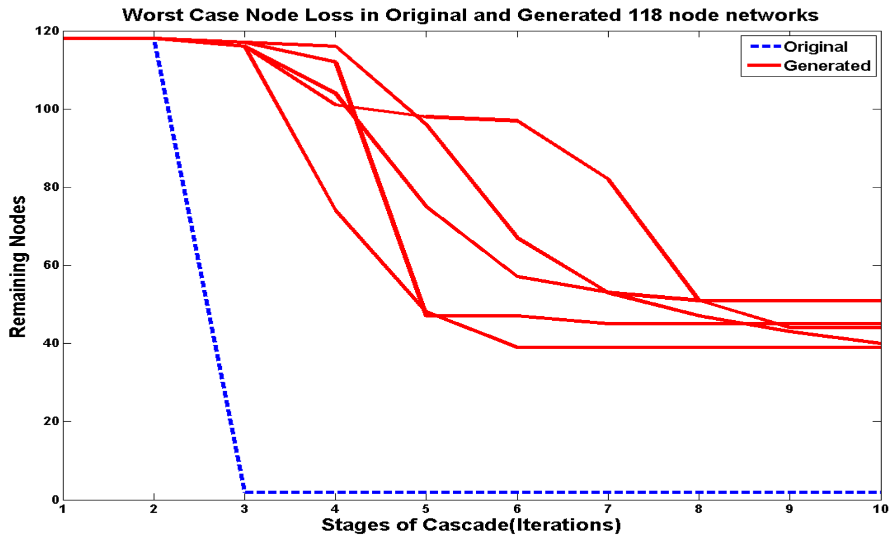


Figure 4.10: Node Loss graph for Standard and Generated 118 node networks

| Nodes | Network | Path Length | Diam | Cluster Coeff |
|---|---|---|---|---|
| 247 | *Standard* | 9.646 | 24 | 0.102 |
| | $G1$ | 5.162 | 10 | 0.0 |
| | $G2$ | 5.191 | 11 | 0.008 |
| | $G3$ | 5.263 | 13 | 0.016 |
| | $G4$ | 5.190 | 11 | 0.006 |
| | $G5$ | 5.300 | 12 | 0.001 |
| 179 | *Standard* | 12.382 | 34 | 0.089 |
| | $G1$ | 5.968 | 14 | 0.012 |
| | $G2$ | 6.058 | 15 | 0.0 |
| | $G3$ | 5.661 | 13 | 0.012 |
| | $G4$ | 5.683 | 13 | 0.004 |
| | $G5$ | 5.616 | 12 | 0.001 |
| 118 | *Standard* | 6.309 | 9 | 0.165 |
| | $G1$ | 4.223 | 9 | 0.032 |
| | $G2$ | 4.259 | 9 | 0.008 |
| | $G3$ | 4.278 | 9 | 0.004 |
| | $G4$ | 4.348 | 9 | 0.004 |
| | $G5$ | 4.258 | 9 | 0.025 |

Table 4.1: Differences in Characteristics of Standard and Generated Networks, in terms of shortest distance or hop count

As seen from the table, the characteristic path length of the generated networks is shorter as compared to the standard networks. The shorter characteristic path length ensures better global connectivity of the network. This is because the characteristic path length is the average of the shortest paths in the network. This feature of the generated networks contributes to their robustness.

Among two networks of the same size and same average node degree, the network with a shorter diameter would be more robust than the one with a longer diameter. This is again because a shorter diameter ensures better global connectivity. When nodes or links are removed from a path connecting a source and a destination, the diameter becomes longer. For a completely fragmented network, the diameter would be infinite. Hence for a network without any disruptions, a shorter diameter implies better global connectivity. As seen from the table, the 247 and 179 node generated networks have a smaller diameter as compared to the standard networks. Smaller diameters, thus, contribute to greater network robustness. Each of the generated 118 node networks have the same diameter as the standard network indicating that the increased robustness of the generated 118 node networks is not contributed to by the diameter for the 118 node networks. In this case, it is mostly due to a shorter characteristic path length.

The clustering coefficient of the generated networks is very small as compared to the standard networks because of the random nature of the generated networks. Although the clustering coefficient does not seem to show any direct effects on the robustness of the networks, we see a considerable difference between the clustering coefficients of the standard networks and each of their respective generated networks. This may be considered as an indication that the clustering coefficient might have a role to play in the robustness of the power grid networks. It would be interesting to do a robustness evaluation based on the clustering coefficient, as it is independent of any routing schemes. However, this evaluation will be considered as future work at this point.

# Chapter 5

# Mitigation Strategies for Cascading Failures

Load shedding has been a classical method to prevent the power systems from getting overloaded due to excessive demand from the consumers. In other words, whenever the demand for electric power exceeds the generation, parts of the distribution system must be disconnected to protect the system and to stop the cascade. We suggest two mitigation strategies, based on load reduction, to reduce the effect of cascading failures: Homogeneous Load Reduction and Targeted Range-Based Load Reduction.
These strategies are discussed below:

## 5.1 Homogeneous Load Reduction strategy

This strategy is very similar to what is commonly known as 'brownouts'. In this strategy, we reduce a given percentage of load for each of the nodes in the network in the event of a failure. This reduction of load helps to keep the other nodes and links operating below their maximum limit and makes room for the redistribution of the excess load due to the failure. We perform a series of simulations and reduce the load in steps of five from 0% to 100%. Each step is a separate simulation, and the final result of each simulation is plotted on the graph in Fig. 5.1. The horizontal axis represents the percentage of load reduced, while the vertical axis shows the number of nodes remaining in the system as a result of load reduction or, in other words, the number of nodes protected. About 10% reduction on all nodes allows about 89% of the nodes of the network to remain functional. In other words, about 89% nodes are protected by 10% homogeneous reduction of loads. About 99% of the nodes are protected from failure at 20% reduction. However, the complete protection of the network takes place at 80% reduction on the network. By reducing about 10% or 20%, a considerable amount of connectivity is achieved but at the cost of a few disconnected nodes. It must, however, be noted that even if total protection of the network is achieved, there will be some power degradation due to the initial failure.

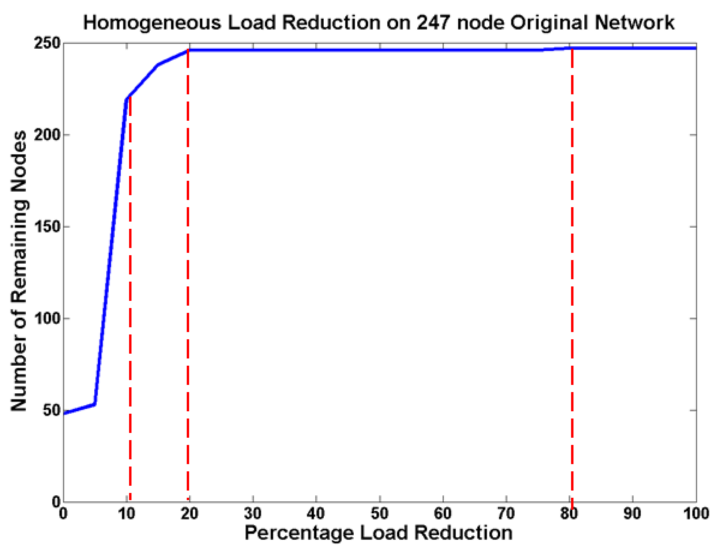


Figure 5.1: Homogeneous Load Reduction strategy on the original 247 node network

## 5.2 Targeted Range-Based Load Reduction strategy

The Homogeneous Load Reduction strategy is very simple to implement because it requires the same amount of reduction for each of the nodes in the network. But the drawback of this strategy is that load is reduced even from the nodes which may not be responsible for overloading. Thus, we propose a more efficient strategy, the Targeted Range-Based Load Reduction strategy.

The objective of this strategy is to reduce the load only in a small portion of the network that will be affected by the re-routing of power due to the initial failure.

If we select a node $i$ from the network and follow it along the adjacent nodes, considering just one direction of power flow (outgoing), we discover a tree, called the propagation tree, for node $i$. Fig. 5.2 would be helpful in understanding the approach. The approach used in this strategy is to select a node which was connected to the link that failed and discover the tree for that node. It should also be noted that out of the two nodes connected to the failed link, the one which was sending power out on that link is used for tree discovery because this is the node which has to redistribute the power to the adjacent links. Node $R$ represents the root node in Fig. 5.2. The node $R$ is connected to nodes 1, 2, and 3 referred to as the first-level nodes. The second step is to find the other neighbors of these first-level nodes. As seen in the figure, node 1 has two other neighbors, $A1$ and $B1$. Out of all the neighbors of node 1, the root node $R$ and node $B1$ provide power to node 1. If the magnitude of power supplied by the root node is higher than that supplied by node $B1$, it can be said that the root node is on the maximum power flow path from the generator for node 1. A maximum power flow path is the path which supplies the highest magnitude of power to a node from the main generator, as compared to all the other paths. This means that node 1 will be affected by the failure of the link which was connected to the root node. Hence, node 1 forms a part of the tree and would be used for load reduction so that it can handle the additional load due to redistribution. Node 1 supplies power to node $A1$. In the next step, we consider the other neighbors of node $A1$ and find out if node 1 is the best supplier of power for node $A1$ or not. If it is, then node $A1$ forms the next level of the tree and the procedure is continued for other nodes in a similar way.

There may be some nodes in the propagation tree which may not carry any load but are simply used to transfer power from one node to the other. We reduce the load from the nodes in the tree, which carry load and are not source nodes. The tree terminates when it reaches a source node or a leaf node. A leaf node is the one which is on the periphery of the network, and has a node degree of one. The discovered tree for a specific link in the network is shown in Fig. 5.3 and more clearly in Fig. 5.4. The total number of nodes in the tree is 90 but load is reduced on only 55 of these nodes. All the other nodes have no load on them. The magnified circular and diamond-shaped nodes are a part of the tree, the diamond-shaped ones being used for load reduction. The thicker links form a part of the tree and the broken link is shown dotted.

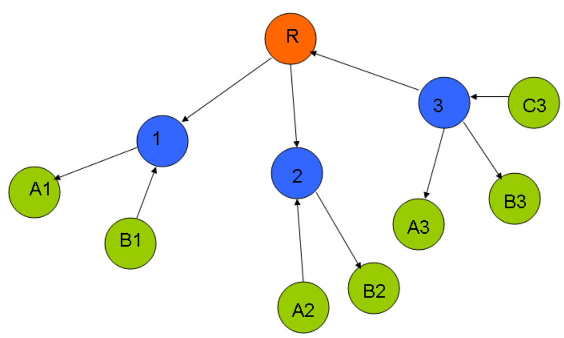


Figure 5.2: Example showing tree discovery

The Fig. 5.5 shows the load reduction on the tree for the link. The horizontal axis represents the percentage load reduction on the tree and the vertical axis represents the number of nodes remaining in the network. As seen, there is no improvement in the network until 40% reduction. However, at 45% reduction, about 99.5% connectivity is achieved or in

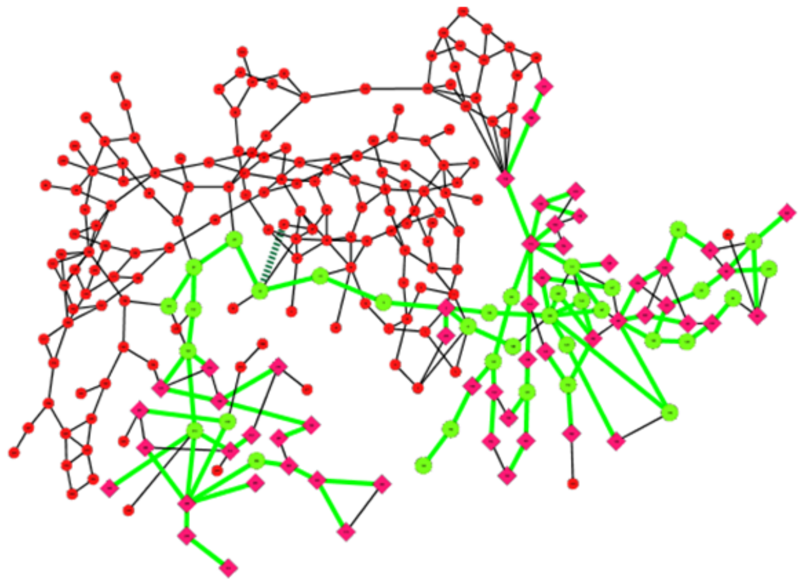

Figure 5.3: Targeted Range-Based Load Reduction strategy - Load reduction on each of the diamond-shaped nodes

other words, 99.5% of the network is protected. The behavior of the system again remains constant until 80% reduction, at which point complete protection of the system is achieved. But this reduction on the tree is equivalent to a very small reduction in the network, as a whole. For this specific link, the overall load reduction in the network is less than 0.35%, as compared to 20-80% in the homogeneous strategy. This strategy, thus, aims at reducing the load of only a small subset of the nodes in the network, those which will be affected by the failure and the redistribution dynamics.

Fig. **??** shows the comparison between the two mitigation strategies. The inset shows the targeted strategy on an expanded scale.

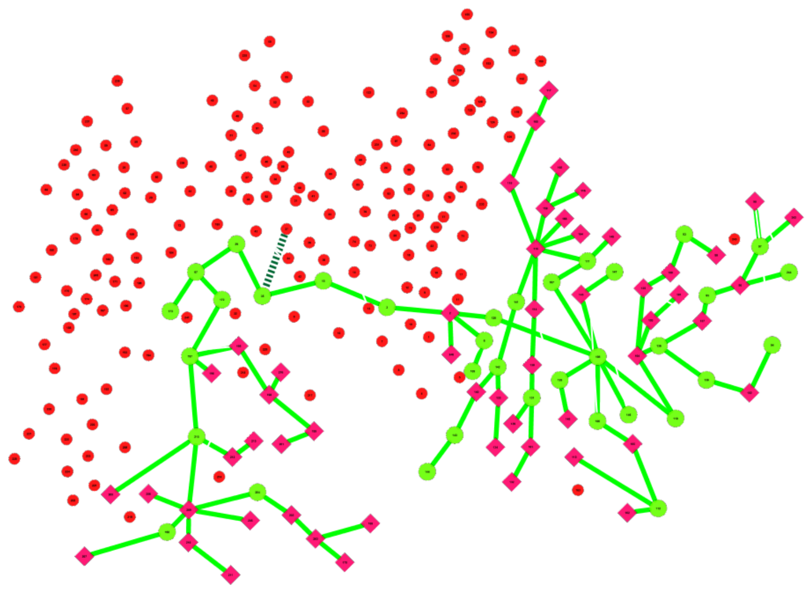

Figure 5.4: The propagation tree, of node $i$

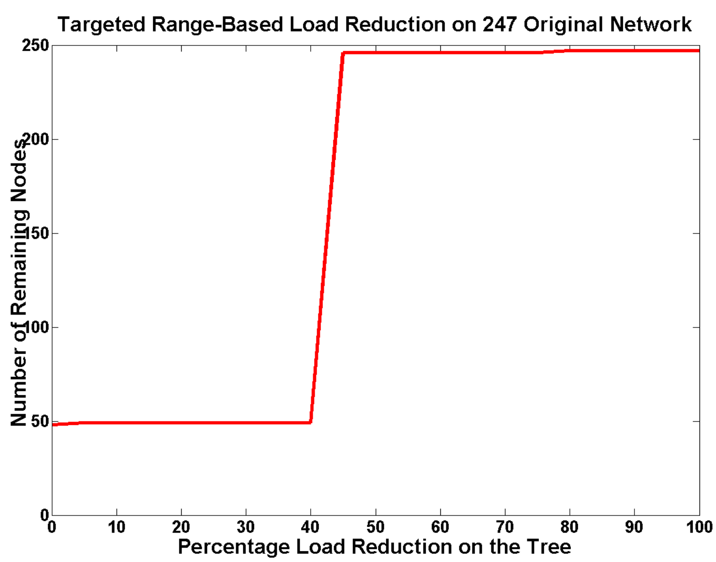


Figure 5.5: Load Reduction on the propagation tree

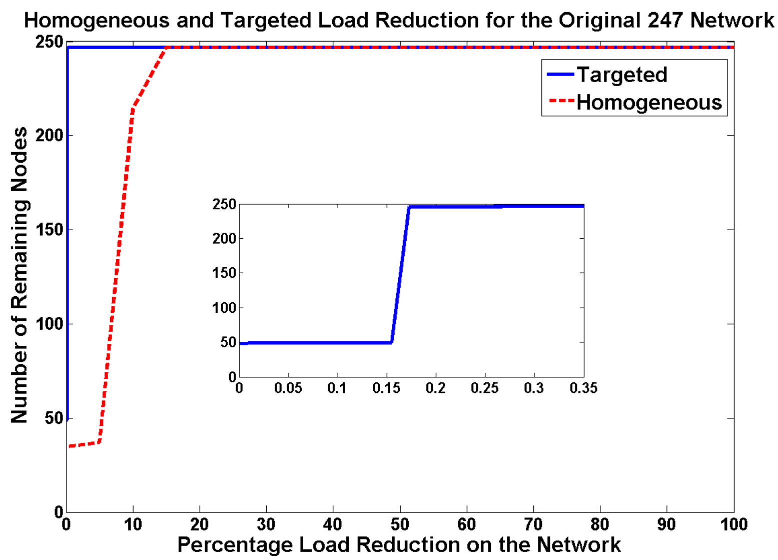


Figure 5.6: Comparison between Homogeneous and Targeted Load Reduction strategies, applied on the network. **Inset: Targeted Reduction on the network, shown on an expanded X axis. The cascading can be controlled by just 0.15% load reduction on the network using the targeted strategy. 0.35% reduction on the network corresponds to 100% reduction on the tree.**

# Chapter 6

# Results, Conclusions, and Future Work

## 6.1 Results

The analysis of the power grid networks gave us the following results:

1. Power Degradation and Node Loss: The power degradation graphs in Fig. 4.5, Fig. 4.7, and Fig. 4.9 show that the worst case cascade stops at an earlier stage and causes less damage in the case of generated networks. The node loss graphs in Fig. 4.6, 4.8, and 4.10 also indicate that stability is achieved earlier in a generated network as compared to the standard network. In this case, the topologies were generated so that the network characteristics such as number of links and nodes, along with average and maximum node degrees are the same as the original networks and only the link connections were changed and made random. This shows that a change in topology can affect the robustness of the network. However, attempts are being made to reduce the level of rewiring of links and incorporating geographical information to decrease the randomness in the networks.

2. Network metrics: As seen from Table 4.1, the characteristic path length of the generated networks is shorter than that of the standard networks. Similarly, the diameter of the generated networks is also smaller than that of the standard networks. This

is because of the random nature of the generated networks. A shorter characteristic path length and diameter contribute to better global connectivity of the network and consequently, to its robustness. The generated networks have a smaller clustering coefficient as compared to the standard networks. However, clustering coefficient is a local measure and does not affect the robustness of the network significantly.

3. Mitigation strategies: The Homogeneous Load Reduction strategy is similar to the classical load shedding techniques employed in power grids. It resembles 'brownouts', in which a certain percentage of load is reduced for each node in the network. This strategy is very easy to implement but requires higher amount of load reduction on all the nodes for the protection of the network. The Targeted Range-Based Load Reduction strategy is very efficient as compared to the Homogeneous strategy as it requires a very small amount of load reduction on a small subset of nodes, to protect the network.

## 6.2 Conclusions

The analysis of the power grid network carried out in this thesis, and the above results lead us to some interesting conclusions. The topology of the power grid network greatly contributes to its robustness. It determines the connectivity of the network and hence gives an idea about which connections may impart more strength to the network. However, the feasibility of modeling the real power grid networks according to the presented analysis must be investigated. The generated networks are better connected than the standard networks because of shorter characteristic path length and shorter diameter. They show more resistance to cascading failures because of their topology.

Among the possible strategies that can be used to reduce the severity of the cascading effects, in this thesis, we have proposed and tested two methods, the Homogeneous load reduction strategy and the Targeted load reduction strategy. The Homogeneous load reduction strategy is similar to the classical load reduction strategy, in which an equal percentage

of load is reduced for all the nodes present in the network after an initial failure. The Targeted range based load reduction strategy is a newly proposed strategy which aims at reducing a very small percentage of the load for only a subset of the nodes in the network, which will be directly affected by the re-routing of power due to the initial failure.
The Homogeneous strategy is easier to implement but the Targeted strategy is more efficient as it requires a small percentage of reduction on a small subset of nodes.

## 6.3 Future Work

There are some open problems that should be investigated in future:

Work is going on to find an expression for weights using the power flow equations so that the shortest paths coincide exactly with the maximum power flow paths. This will enable us to find the paths by a simple addition of weights. The use of power flow equations would ensure that the flow dynamics of the networks are considered while computing the topological metrics.

Efforts are being directed towards the implementation of islanding as a mitigation strategy, in conjunction with distributed renewable energy. Using optimization techniques to obtain feasible points for disconnection of node clusters and to ensure load balancing in the process will be an interesting point of research in complex networks.

We are also working towards determining a threshold value for load reduction in the Targeted range-based load reduction strategy. As seen from Fig. 5.5, there is a sudden change in the number of protected nodes at a particular percentage of load reduction. However, this is for a particular link. We intend on finding a general expression for all links in the network.

# Bibliography

[1] A.-L. Barabasi and R. Albert, Science, vol.286, no.5439, pp.509-512 (1999).

[2] R. Albert, H. Jeong, and A.-L. Barabasi, Nature, vol.406, pp.378-381 (2000).

[3] D. Watts and S. Strogatz, Nature, vol.393, pp.440-442 (1998).

[4] P. Holme and B. Kim, Physical Review E, vol.65, no.6, pp.066109 (2002).

[5] R. Albert, I. Albert, and G. Nakarado, Physical Review E, vol.69, no.2, pp.025103 (2004).

[6] M. Anghel, K. Werley, and A. Motter, Stochastic model for power grid dynamics, in *Proceedings of the 40th Annual Hawaii International Conference on System Sciences, Big Island, Hawaii*, 2007.

[7] A. Motter and Y. Lai, Physical Review E, vol.66, no.6, pp. 065102.1-065102.4 (2002).

[8] Y. Lai, A. Motter, and T. Nishikawa, Physical Review E, vol.66, pp.065102 (2002).

[9] P. Crucitti, V. Latora, and M. Marchiori, Physica A : Statistical Mechanics and its Applications, vol.338, no.1-2, pp.92-97 (2004).

[10] L. Amaral, A. Scala, M.Barthelemy, and H. Stanley, Proceedings of the National Academy of Sciences of the United States of America, vol.97, no.21, pp.11149-11152 (2000).

[11] A. V. A. Barrat, M. Barthelemy, *Dynamical processes on complex networks*, Cambridge University Press, 2008.

[12] P. Mahadevan et al., Lessons from three views of the internet topology, Technical report, Cooperative Association for Internet Data Analysis (CAIDA), 2005, http://arxiv.org/abs/cs.NI/0508033.

[13] A. Sydney, Characteristics of robust complex networks, Master's thesis, Kansas State University, Manhattan, Kansas, 2009.

[14] C. Caldwell, Graph theory glossary, http://www.utm.edu/departments/math/graph/glossary.html, 1995.

[15] M. Newman, Society for Industrial and Applied Mathematics Review, vol.45, no.2, pp.167-256 (2003).

[16] F. Zhan, Representing networks, http://www.ncgia.ucsb.edu/giscc/units/u064, 1998.

[17] P. Holland and S. Leinhardt, Small Group Research, vol.2, no.2, pp.107-124 (1971).

[18] J. Glanz and R. Perez-Pena, New York Times (2003).

[19] P. Fairley, IEEE Spectrum (2004).

[20] P. Erdos and A. Renyi, Publication of the Mathematical Institute of the Hungarian Academy of Sciences, vol.5, pp.17-61 (1960).

[21] J. Chen, J. Thorp, and I.Dobson, International Journal of Electrical Power and Energy Systems, vol.27, no.4, pp.318-326 (2005).

[22] A. Sydney, C. Scoglio, P.Schumm, and R. Kooij, Elasticity: Topological characterization of robustness in complex networks, in *Proceedings of 3rd International Conference on Bio-Inspired Models of Network, Information, and Computing Systems(BIONETICS), Hyogo, Japan*, 2008.

[23] M. Newman, Physics Review E, vol.64, no.1, pp.016132 (2001).

[24] K.-I. Goh, B. Kahng, and D. Kim, Physical Review Letters, vol.87, no.27, pp.278701 (2001).

[25] P. Crucitti, V. Latora, M. Marchiori, and A. Rapisarda, Physica A: Statistical mechanics and its applications, vol.340, no.1-3, pp.388-394 (2004).

[26] V. Latora and M. Marchiori, Physical Review Letters, vol.87, no.19, pp.198701 (2001).

[27] P. Crucitti, V. Latora, and M. Marchiori.

[28] R. Kinney, P. Crucitti, R. Albert, and V. Latora, European Physical Journal B, vol.46, no.1, pp.101-107 (2005).

[29] J. Thorp, A. Phadke, S. Horowitz, and S. Tamronglak, International Journal of Electric Power and Energy Systems, vol.20, no.2, pp.147-152 (1998).

[30] K. Bae and J. Thorp, Decision Support Systems, vol.24, no.3-4, pp.259-268 (1999).

[31] H. Wang and J. Thorp, Enhancing reliability of power protection systems economically in the post-restructuring era, in *Proceedings of the 32nd North American Power Symposium, Waterloo, Ontario, Canada*, 2000.

[32] A. Carbone, S. Arianos, E. Bompard, and F.Xue, CHAOS, vol.19, no.1, 013119 (2009).

[33] G. K. V. Goldshtein and G. Surdutovich, Vulnerability and hierarchy of complex networks, http://arxiv.org/abs/cond-mat/0409298, 2004.

[34] E. S. C. B. P. Hines, S. Blumsack, The topological and electrical structure of power grids, in *Proceedings of the 43rd Annual Hawaii International Conference on System Sciences, Hawaii*, 2010.

[35] P. Hines, E. Cotilla-Sanchez, and S. Blumsack, Do topological models provide good information about vulnerability in electric power networks?, http://arxiv.org/abs/1002.2268, 2010.

[36] N. A. E. R. Council, Evaluation of criteria, methods, and practices used for system design, planning, and analysis response to nerc blackout recommendation 13c [online], http://www.nerc.com/docs/pc/tis/, 2005.

[37] W. University, Power systems test case archive, http://www.ee.washington.edu/research/pstca/, 1999.

[38] B. Gungor, *Power Systems*, Technology Publications, 1988.

[39] K. Purchala, L. Meeus, D. Dommelen, and R. Belmans, Usefulness of dc power flow for active power flow analysis, IEEE PES General Meeting, San Fransisco, California, USA [Online]. Available: http://www.esat.kuleuven.be/electa/publications/fulltexts/pub_1456.pdf, 2005.

[40] S. Pahwa, A. Hodges, C. Scoglio, and S. Wood, Topological analysis of the power grid and mitigation strategies against cascading failures, in *Proceedings of the IEEE 4th Annual International Systems Conference, San Diego, USA*, 2010.

# Appendix A

# DC Power Flow Model

The model has mainly been used for analysis of the topological features of the power grid network. Because the resistance are smaller compared with the reactances of those lines, the resistances are neglected to simplify the solutions. The power grid network is being considered as a DC power flow model and the shunt admittances of transmission lines have also been neglected. The line inductances govern the amount of power that flows through the links. Node 1, which is the generator, has been selected as the reference node, and the synchronous condensers have been neglected.

## A.1 DC Power Flow Model

We cannot use metrics such as number of hops or shortest distance to find the best path from the generator to the destination node, in case of a power grid. This inability to use such metrics arises from the fact that the amount of power flowing through a link depends upon its impedance. In the rest of this section we use capital letters for matrices and the corresponding small letter for their respective elements.

The map of the power grid in the form of nodes and links is used to create a weighted adjacency matrix $X$ of size $N$x$N$, where $N$ is the total number of nodes in the network. When nodes $i$ and $j$ are connected, $x_{ij}$ is a positive non-zero entry representing the impedances of the transmission line between nodes (buses) $i$ and $j$, and it is zero otherwise. A matrix $B$ is created from the adjacency matrix using the following formula[38]:

$$b_{ij} = \frac{-1}{x_{ij}}, \quad i = 1, 2, ...N, \quad j = 1, 2, ...N, \quad \forall\ i\ \neq\ j \tag{A.1}$$

$$b_{ii} = \sum_{j=1}^{N} -b_{ij} \tag{A.2}$$

The system ground is usually the reference. However, in simplifying things, all the shunt admittances have been dropped. Thus, the reference is lost.This means that the $B$ matrix obtained from the above equation will be a singular matrix. In further equations, we will need to calculate the inverse of the $B$ matrix which cannot be done if it is singular. To overcome this, one of the generators is selected as the reference node and is assigned an angle of zero radians[38]. Then, all the calculated angles are referred to this reference, and the row and column corresponding to this reference node in $\{B\}$ are dropped to produce a non-singular $\{B\}$ and its inverse is calculated. The phase angle, $\delta_i$ for node $i$ is calculated using the inverted $B$ matrix and a $N$-1x1 load vector $\Lambda$. The elements of this vector $\lambda_i$ represents the load on each node.

$$\Delta = B^{-1}\Lambda \tag{A.3}$$

where

$\Delta = \{\delta_2, \delta_3, ..., \delta_N\}^T$

$\Lambda = \{\lambda_2, \lambda_3, ..., \lambda_N\}^T$

We assume a lossless transmission line. Thus, the total power going into a node is the sum of the total power coming out of it and the power consumed by the load at that node. Power $p_{ij}$ in each link $(i, j)$ must be calculated as follows:

$$p_{ij} = -b_{ij}\delta_{ij} = \frac{\delta_i - \delta_j}{x_{ij}}, \quad i = 1, ...., N, \quad j = 1, ...., N, \quad i \neq j \tag{A.4}$$

where $\delta_{ij} = \delta_i$ - $\delta_j$

The power $p_i$ on each node $i$ can be calculated as:

$$p_i = \sum_{j \in N(i)} p_{ij} = \sum_{j \in N(i)} -b_{ij}\delta_{ij}, \quad \forall\ i = 2, ..., N \tag{A.5}$$

where $N(i)$ is the set of nodes which are neighbors of $i$.

For the generator node,

$$p_1 = \sum_{j \in N(1)} p_{1j} = \sum_{j \in N(1)} -b_{1j}\delta_{1j} \tag{A.6}$$

where $N(1)$ is the set of neighbors of node 1 and $p_i$ is the total generated power.

In this thesis, we have assumed that the power generated satisfies the total demand in the network.

# Appendix B

# Back Tracing Algorithm for Optimal Paths

## B.1 Algorithm

The steps of the algorithm are described below. The algorithm back traces the path from the destination node to the generator.

1. Search for the neighbors of the selected destination node from the adjacency matrix. A given node is a neighbor if

$$b_{ij} \neq 0, \forall j \neq i \tag{B.1}$$

2. We assume outgoing power to be positive and incoming power to be negative. We select the neighboring nodes which send power into the destination node. In other words, the nodes providing power to the destination node are candidate previous nodes in the optimal path.

$$P_{ij} < 0, \forall j \neq i \Rightarrow \tag{B.2}$$

   $j$ is a possible candidate for the previous node in the path

3. We compare the magnitudes of link power between the destination node and each candidate previous node and select the one with the highest magnitude.

$$|P_{ij}| > |P_{ik}| \Rightarrow \tag{B.3}$$

previous node $= j$

Else previous node $= k$ where $j,\ k \in$ neighbors of $i$

4. Now the previous node becomes the destination node and the same back tracing procedure is applied to search for its previous node and so on till we reach the generator.