RESILIENCE OF POWER DISTRIBUTION SYSTEMS UNDER EXTREME WEATHER CONDITIONS

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RESILIENCE OF POWER DISTRIBUTION SYSTEMS UNDER EXTREME WEATHER CONDITIONS

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To my dear husband, Vinda

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SUMMARY

A strong and reliable power grid is critical for the smooth functioning of society and technologies. Disruption in supply of electric power results in huge economic losses as well as inconvenience to human life. In this research, the reliability of power distribution systems under the impact of adverse weather, with an emphasis on hurricanes, is studied. Storm related outages cost the United States billions of dollars in damages per occurrence. Overhead power lines are mainly supported by wood poles, a majority of which are aged and weak. This research studies the effects of failures of utility wood poles on the reliability and resilience of electric distribution systems using historical hurricane data. The probability model of wood pole failures is used to develop an outage prediction model that serves to identify vulnerable regions of the network. Following this, the benefits of automatic network reconfiguration (a process controlled by automated Distribution Management Systems) to reduce customer outages during hurricane landfall is investigated. After hurricane occurrence, wood pole repair and restoration schemes are implemented that restore 100% of power back in the system. Network hardening strategies, including upgrading wood pole infrastructure and integrating microgrids, are analyzed. Finally, system performance metrics are calculated and discussed. The result is a holistic framework for the resiliency assessment of distribution systems in the event of hurricanes, that allows utilities to make risk-informed decisions during design and emergency planning and response, resulting in a stronger and well-prepared power grid.

CHAPTER 1. INTRODUCTION

1.1 Background and Motivation

Electric power systems are critical for the smooth functioning of society and economy since electricity is required in all facets of modern life. The power infrastructure is constantly at risk due to factors such as natural disasters, climate, and aging. Hurricane prone regions of the United States experience economic, social, and infrastructure disruptions yearly and seasonal storms cause extensive damage to power infrastructure system.

Of the different components of the power grid, the distribution system is the most susceptible to hurricane effects. At present, transmission systems are built to withstand high wind speeds, but distribution systems are very vulnerable because they have been designed to withstand less severe weather conditions[1]. Distribution structures are built according to safety standards such as the National Electrical Safety Code (NESC) [7]. NESC defines three loading grades - Grades B, C and N. According to this code, some structures must be able to withstand loading due to extreme wind speeds, based on 3 second gust speeds. However, this criterion only applies to structures that exceed 60 feet in height. Since most distribution components are less than 60 feet in height, this design criterion does not apply to distribution structures[1, 2]. While these distribution systems are structurally safe in normal operating conditions, they do not have adequate ability to withstand severe weather conditions. In the wake of recent major hurricanes across the United States and Puerto Rico, hardening the distribution systems against hurricanes is a topic of growing interest. Hardening the distribution system could potentially result in increased reliability during normal operation as well[1].

Critical Infrastructures (CI) are made up of the assets, services, and systems that support and enable economic, business, and social activities. Electric power systems are considered to be CIs and therefore they must be reliable under normal operating conditions and have adequate resiliency towards anticipated contingencies. Resilience studies must include high impact low probability (HILP) events such as hurricanes, which are a major threat to the electric infrastructure. This is a concept of growing interest in the field of power engineering [3]. Since hurricanes cause severe damage to systems, simply repairing the power lines post damage is not an efficient solution. Preventive techniques need to be developed to strengthen the electric distribution system pre-contingency such that future impacts are minimized.

The Saffir-Simpson Hurricane Wind Scale categorizes hurricanes on a severity scale of Category 1-5 based on sustained wind speeds. Hurricanes of Category 3 and higher are considered to be "Major" hurricanes because they have potential to cause extensive damage to life and infrastructure. However, all hurricane categories are dangerous. Damage rises by a factor of four for every increase in category [4].

1.2 Reliability and Resilience

The terms "reliability" and "resilience" have various definitions according to experts and scholars [3, 5-15]. This section discusses the concepts of reliability and resilience in the context of power systems. The primary goal of electricity sector is to ensure reliability of the power system. Reliability includes two concepts according to the North American Electric Reliability Corporation (NERC): adequacy, which is the ability of the bulk power system to supply the energy requirements of customers at all times; while security refers to the ability of the system to withstand sudden disturbances[15].

Table 1. Saffir-Simpson Hurricane Scale

Category	**Winds (mph)**	**Damage to Power Infrastructure**	**Example**
1	74-95	Very dangerous winds. Extensive damage to power lines and poles will likely result in power outages that could last a few to several days.	Hurricane Nate (2017) – impacts to Alabama, Florida and Mississippi. Hurricane Sandy (2012) - impacts to most of the eastern United States
2	96-110	Extremely dangerous winds will cause extensive damage. Near-total power loss is expected with outages that could last from several days to weeks	Hurricane Frances (2004) – impacts to Port St. Lucie, Florida
3	111-129	Devastating damage will occur. Electricity and water will be unavailable for several days to a few weeks after the storm passes.	Hurricane Katrina (2005) - impacts to coastal portions of Gulf Shores, Louisiana and Mississippi
4	130-156	Catastrophic damage will occur. Power outages will last for weeks to months.	Hurricane Irma (2017) -impacts to Florida Keys. Hurricane Harvey (2017)-impacts to Gulf Coast Hurricane Maria (2017)-impacts to Puerto Rico
5	>157	Catastrophic damage will occur. Power outages will last for weeks to months.	Hurricane Andrew (1992) - impacts to coastal portions of Cutler Ridge, Florida

Reliability of a system is the set of measures that are put in place to combat known threats, while resilience focuses on HILP events such as hurricanes, since these events are occurring more frequently in recent times and may no longer be low probability[3].

According to [16], resilience of power systems is “the ability to degrade gradually under increasing system stress and then to recover to its pre-disturbance secure state.” The above definition has been extended by the National Infrastructure Advisory Council (NIAC) [15], to include the ability of the system to absorb the damage and adapt/recover to prevent the impacts of similar events in the future. Resilience features according to NIAC are given below:

a) Robustness: This is the ability of the system to withstand disaster. With regards to action items, it could mean designing stronger structures, adding redundant systems, and maintaining critical infrastructures to survive high-impact, low-probability events.
b) Resourcefulness: This is the response of the system during the time of occurrence of a disaster. This involves determining options to control and mitigate damage and communicating these decisions. This feature is dependent on people rather than technology.
c) Recovery: The ability to bring the system back to normal operation as quickly as possible. This includes emergency operations and restoration procedures.
d) Adaptability: The ability to learn lessons from a disaster event. This includes modifying procedures and plans through new tools and technologies.

Edison Electric Storm report in [17] provides the following definitions for hardening and reliability – “System hardening is defined as physical changes to the utility’s infrastructure to make it less susceptible to storm damage, such as high winds, flooding, or flying debris. Hardening improves the durability and stability of transmission and distribution infrastructure allowing the system to withstand the impacts of severe weather events with minimal damage. Resiliency refers to the ability of utilities to recover quickly from damage to any of its facilities' components or to any of the external systems on which they depend. Resiliency measures do not prevent damage; rather they enable electric facilities to continue operating despite damage and/or promote a rapid return to normal operations when damages and outages do occur."

Resilience definitions show that resilience is a function of time and can be divided into short-term and long-term resilience. Short-term resilience refers to system features before, during and after a disaster, whereas long-term resilience is the adaptability of the system to new threats through risk and reliability studies [3]. M. Ouyang et al. [18] and Wang et al. [19] define the response cycle of a system by dividing the performance and resilience of the system into three zones based on time, as shown in Figure 1.1 and Figure 1.2, respectively. The disaster prevention stage is the time period when the system is under normal operating conditions. Hardening steps taken during this time are preventive, and are undertaken in anticipation of future disasters by using historical hurricane data. Performance level is expected to be at 100% during this time.

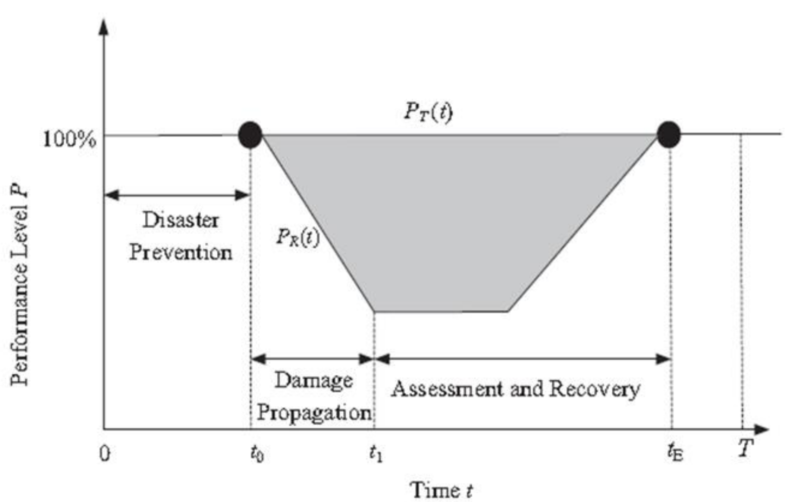


Figure 1.1 Performance curve of an infrastructure system [18]

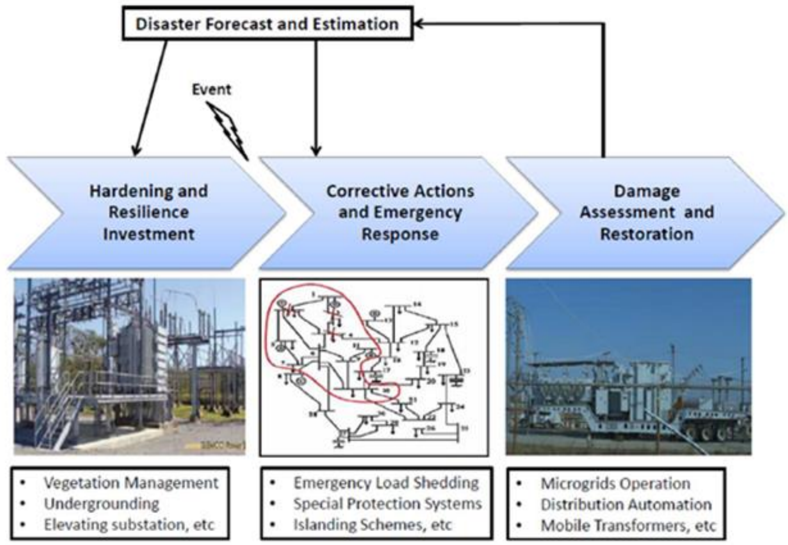


Figure 1.2 Timeline of utility response to natural disasters[19]

The second time period is called the damage propagation stage. This is in the present time scale when the disaster is occurring. This is when the hurricane hits the system and components begin to fail as a result. As can be seen in the figure, the performance of the system drops rapidly. This phase involves fault and outage analysis, and implementation of automatic network reconfiguration schemes to reduce outages. The third phase is the assessment and recovery phase. During this phase, the objective is to bring the system performance back up to 100% as quickly and safely as possible. This phase involves damage assessment by the utilities to plan for resources needed for restoration, followed by repair action taken by work crews, which can range from days to several weeks. This stage refers to future action that must be taken after the hurricane occurrence. All aspects of the response cycle are vital in developing resilience frameworks.

1.3 Hurricane History and Impacts

1.3.1 Outage and Damage Impacts

The following section discusses key components of the hearing held by the Subcommittee on Energy in November 2017 regarding the 2017 hurricane season [20].

In 2017, four hurricanes made landfall on the U.S. Gulf Coast, U.S. Virgin Islands and Puerto Rico. Hurricane Harvey made landfall as a Category 4 hurricane. More than 275,000 customers were without power across Texas, and shut down major ports across the Gulf Coast resulting in interruptions to oil and gas production and refining operations. The hurricane resulted in the evacuation and displacement of over ten thousand residents.

Hurricane Irma made landfall on the coast of Puerto Rico on September 6, 2017. This hurricane began as a Category 4 and then reduced to Category 3 and caused extensive damage and power outage through the regions. " At peak, the storm caused power outages for 870,000 Puerto Rico customers, 29,000 Virgin Islands customers, more than six million Florida customers, and more than one million customers in Georgia and South Carolina [20]."

Hurricane Maria, a Category 4 storm, made landfall along the coast of Puerto Rico in September 2017. Heavy winds caused massive damage to the island's transmission and distribution systems, knocking down almost 100% of the power distribution lines [21]. This resulted in power outages to all the 1.5 million residents of Puerto Rico and 55,000 residents of Virgin Islands. Residents have gone for months without power, and restoration efforts are ongoing.

Hurricane Nate, Category 1, made landfall over the Gulf Coast in October 2017. This hurricane caused electrical outages in Alabama, Florida and Mississippi, and resulted in the shutting down of 92% of the oil production and 78% if natural gas production.

Hurricanes Irene (Category 3) and Sandy (post-tropical cyclone) made landfall in 2011 and 2012, respectively. Both caused damage to electric transmission and distribution infrastructure in the Northeast and Mid-Atlantic and left millions of customers without power along the east coast of the United States by destroying substations, power lines and utility poles. Irene and Sandy disrupted power to 6.69 and 8.66 million customers respectively[22]. Storm winds were sustained up to 500 miles from the center.

Category 3 hurricane Wilma hit southern Florida in October 2005. Wilma caused extensive damage to the electric infrastructure of Florida Power and Light (FPL), damaging more than ten thousand distribution poles. In all, Wilma resulted in more than three million FPL customer accounts losing electrical service [1].

Table 2 provides the number of utility poles failed in the states of Virginia, Maryland and Pennsylvania as a result of Irene and Sandy [22]. It is seen that hurricanes cause significant damage to the utility poles, it is therefore important to harden the pole infrastructure and improve resiliency of distribution systems.

1.3.2 Cost Impacts

High wind speeds during hurricanes cause damage to distribution poles and conductors resulting in power outages that last anywhere from days to months, depending on the severity of the storm. Storm related outages cost the US economy between $20 billion and $55 billion annually [23].

Table 2. Utility Poles Damage Report

Utility	Number of Poles	
	Irene	**Sandy**
Dominion Virginia Power	1619	
Baltimore Gas & Electric	348	
Delmarva Power	53	
Pepco (MD)	36	
Potomac Edison	14	700
SMECO	313	
Met Ed	143	731
PECO	316	750
Penelec	30	80
PPL	900	619
UGI Utilities	39	
West Penn Power		65

Storm related costs can be categorized into operational and maintenance costs and capital costs. Operational costs include cost of labor and materials whereas capital costs include replacement of poles, wires and transformers [17]. The combined storm costs of Florida's 2004 hurricane season cost just two of the utilities, Florida Power & Light and Progress Energy more than $1 billion in restoration efforts [24].

Figure 1.3 depicts a graph from EEI (Edison Electric Institute[24]) survey which identified 81 storms between 1994 and 2004 and cost $2.7 billion in damage to electric utility systems.

The storms that require most efforts in terms of costs are hurricanes. One of the major factors affecting costs is the increase in population and customer growth, requiring utilities to expand the electric systems thereby increasing vulnerability. Utilities spend around $3 million a day on average, in system repair due to storms. However, several storms have cost more than $10 million a day [24]. This is shown in Figures Figure 1.3 and Figure 1.4. Between 1998 and 2009, Texas utilities spent more than $1.8 billion in hurricane restoration costs. 80% of these costs were due to distribution system damage[25].

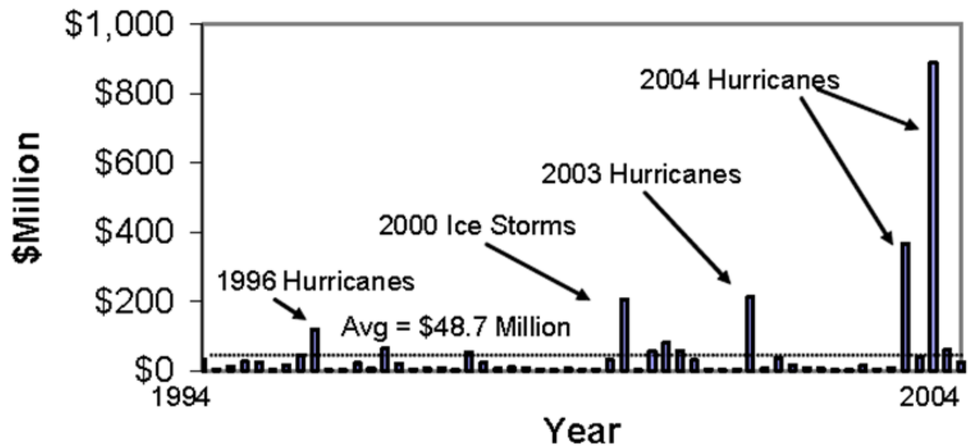


Figure 1.3 Major storm costs (1994-2004) [24]

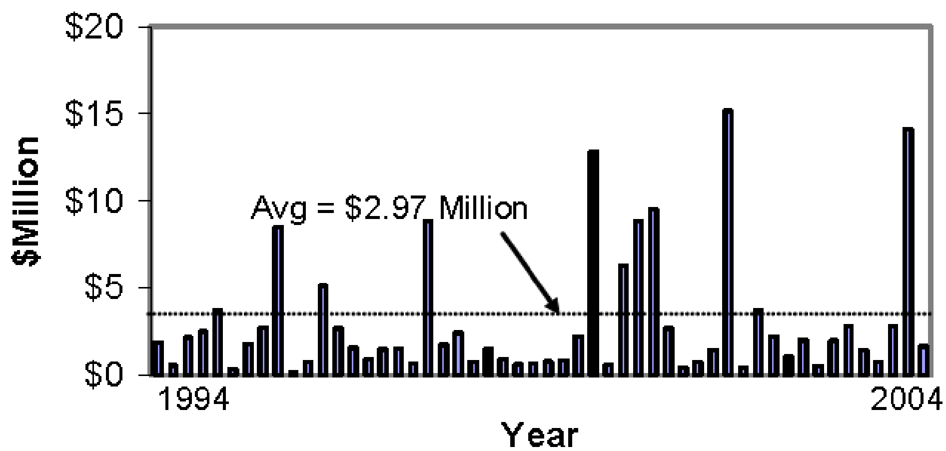


Figure 1.4 Major storm cost per day (1994-2004) [24]

For this reason, it is crucial to improve the resilience of power systems both from a customer and from a utility perspective.

1.4 Utility Poles

Overhead distribution lines are mainly supported by wood poles, and a significant portion of these poles are over 30 years old [26]. Wood poles are preferred over steel and concrete because they are relatively cheaper, available in abundance, easier to transport and have better insulation properties [27]. The durability of wood poles depends on pole species, chemical treatments and weather conditions. Falling trees and debris also impact poles and conductors, but these factors are not considered in this research because of the high degree of uncertainty involved [28]. Following hurricane occurrences, thousands of wood poles are replaced, and the number depends on storm intensity [28]. After storm occurrences, utilities gather information about the number of distribution poles exposed to strong winds as well as the total number of broken poles. This gives an idea of the failure rate of poles[1]. As can be seen in Table 3, the failure rates increase with increase in storm severity, with Andrew causing over 10% pole failure rate.

Table 3. Distribution Pole Failure Rates for Past Hurricanes [1]

Year	Name	Poles exposed to 74+ mph winds	% poles failed	Hurricane Category
1992	Andrew	203,500	10.10%	5
2004	Charley	222,666	3.10%	3-4
2004	Frances	397,134	0.90%	2
2004	Jeanne	455,302	0.50%	2-3
2005	Katrina	343,200	0.30%	1
2005	Wilma	773,700	1.50%	2-3

This information is useful in developing hardening strategies by gaining insights into the characteristics of poles that affect their failure rates. In the technical report developed by Florida Public Service Commission in the wake of Hurricane Wilma, engineering assessments led to the findings that over 95% of the poles were made of wood, with poles as old as 35 years still in service. A comprehensive assessment of pole data in the presence of hurricanes can be found in this report [29].

Newly installed wood poles are designed to withstand normal loading conditions along with additional loads of power lines, communication cables, cross arms and transformers. Installation of poles is guided by standards such as the American National Standards Institute (ANSI) and National Electric Safety Code (NESC) which provide specifications for safety and reliability of wood poles within a region and within the design lifetime of the pole. The failure of wood poles occurs when the induced moment due to lateral wind pressures exceeds the moment capacity of the pole at any location along the length of the pole[28]. The geometry of a wood pole is defined by its length and circumferences at various heights – the ground line (visible region at which the pole connects with the soil), the bottom and the pole tip. Maximum moments occur at the ground line. However, the point of maximum moment is not necessarily the point of pole failure. The diameter of a pole decreases linearly with increase in height above ground; therefore, the moment capacity also decreases correspondingly. The most vulnerable point is found to be close to the ground line of the pole. In this research, the pole species is assumed to be Southern Pine; therefore, the only variable in the calculation of the ground-line moment capacity of a pole is the ground-line circumference. ANSI O5.1 provides the minimum circumferences of wood poles as a function of the length of the poles. Pole strengths increase as the pole class decreases. The strength of wood pole is affected by its rate of decay. Wood absorbs moisture from the soil and the atmosphere which causes degradation. The strength of a wood pole should therefore be modelled as a function of time-varying decay (i.e. age of poles). In Southern Pine, decay is usually external, causing a reduction in the effective ground line circumference and consequently reducing moment capacity. Fragility curve provides the probability of failure of wood poles given the 3-sec gust wind velocity. Time dependent fragility models of wood poles are important while evaluating vulnerability of distribution networks against hurricanes [28, 30-32].

1.5 Objectives

The objective of this research is to develop a conceptual framework for the modelling and assessment of resilience of power distribution systems under consideration of hurricanes. A holistic approach is used to develop a novel and comprehensive tool (by studying resilience in all the three time-dependent phases) that can be used by utilities to make risk-informed decisions for future hurricane events. In this regard, the objectives are as follows:

1) Study the impacts of hurricanes of intensities ranging from Category 1 to Category 5 (based on the Saffir-Simpson scale) on structural components of distribution systems by assessing the vulnerability of utility wood poles against extreme wind loads. Pole failures that cause multiple network faults are dependent on the path of the storm.
2) Develop a model to assess the risk of outages and unavailability of power caused by failures of distribution poles. This provides knowledge of the breakage points of the distribution network and forms a basis for assessing system vulnerability.
3) Develop optimal network reconfiguration procedure that can be implemented automatically and rapidly during the hurricane event to reduce outages. In this

procedure, the topology of distribution network is modified through the manipulation of protective device and sectionalizer status.

4) Develop a restoration and repair scheme which takes into consideration resource mobilization and pole priority ranking.
5) Develop load flow models to capture system response during normal operation as well as during multiple fault scenarios to ensure operating constraints.
6) Develop metrics to calculate resiliency of the electric distribution system for a single hurricane event over a specified time interval.
7) Analyze and demonstrate hardening techniques to increase system resiliency and improve emergency response.

To achieve these objectives, first, a radial distribution system is synthesized using substation data from Google Earth along with utility pole data from public databases. This system is representative of a real distribution system in Southeast USA. Next, the assessment of the proposed resilience framework is performed on the test system developed above by studying the effects of hurricanes of categories 1 through 5 of the Saffir-Simpson scale. This includes determining the failure of wood poles and subsequent network outages followed by implementation of reconfiguration and repair schemes. The methods developed for the test network can be extended to larger systems currently managed by utilities.

This research will serve as a foundation for a new knowledge base in vulnerability assessment of power networks. The result will be a safer, more reliable, and better emergency prepared power system.

CHAPTER 2. LITERATURE REVIEW

Vulnerability assessment and outage management of distribution systems involves research in several areas including system hardening techniques, outage prediction, utility pole failure assessments, service restoration techniques and microgrid integration. A summary of the current literature is presented in the sub-categories below.

2.1 Hardening Techniques

The authors of [33] employ a risk sensitivity analysis method for hardening of power systems with the objective of minimum load curtailments. Preventive/corrective actions are determined based on the sensitivity of the risk of load curtailment with respect to power quality constraints such as voltage and reactive power limits. This study divides causes of catastrophic failures into physical failure of networks, software failure or operator mistakes. The physical system failures considered are voltage collapse, transient stability and accidental tripping. The study follows a heuristic approach to identify buses that are most sensitive to risk factors. This study does consider weather related failures among the physical failures. Reliability assessments that disregard weather impacts can lead to ineffective system planning and design.

The authors of [1] provide an outline of wind hardening tactics in Florida along with the hardening methods implemented by the consortium of Florida utilities. The discussion around hardening distribution systems against high winds in Florida began after the 2004-2005 hurricane season which caused extensive damage to structures. In the case of distribution systems, most utilities focus their efforts on restoration activities; however, data collection during times of disasters could provide valuable information to develop preventive actions. One such example is quantifying the characteristics of poles that increase their failure rates in times of high winds. According to [1], some hardening techniques include strengthening utility poles, upgrading the poles, reducing the span length of the lines between poles, reducing conductor diameters, and undergrounding the distribution lines. The hardening of systems also depends on the geographical area: full hardening will make the system most resilient but it is very expensive, priority hardening where only the critical poles are hardened (critical could be in terms of cost or of type of customer served), is a reasonable compromise. This study provides a good summary of various hardening possibilities, but does not demonstrate any of the techniques on a real system.

The researchers of [34] assess the reliability of distribution systems considering stresses on the system due to weather effects. The authors assess line failures by dividing weather into two categories: adverse weather and extremely adverse weather. The extreme adverse weather is modeled as a three-state weather model, whereas adverse weather is a two-state model. The reliability results are quantified in terms of reliability indices such as SAIFI, SAIDI and EENS as shown in Figure 2.1.

To improve distribution system reliability, the authors suggest increasing system redundancy through the use of parallel redundant supplies. While this study provides a good account of modeling extreme weather, it does not take into account the impacts of the weather on the structural components of the system. Redundant circuits can improve reliability provided that the supporting structures, such as wood poles, are able to withstand the weather event.

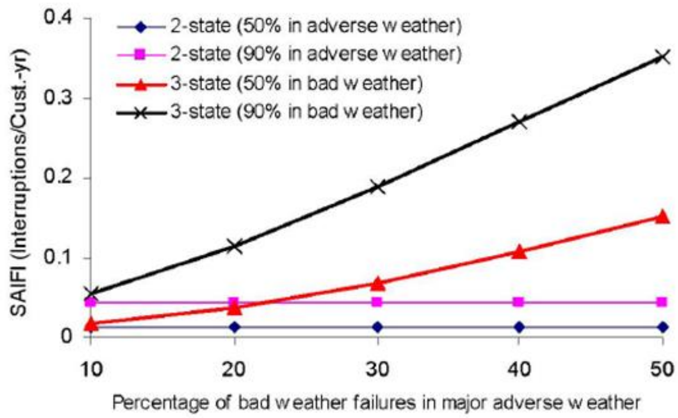


Figure 2.1 SAIFI using the two and three state weather models [34]

The authors of [3] assess the resilience of power systems against extreme weather events by using a stochastic approach to quantify their random nature, and then developing a Monte-Carlo-based time-series simulation model. This work is mainly focused on transmission systems. Failure probabilities are investigated through the fragility curves of system components. The permanent failure probabilities due to high winds are calculated for transmission lines and towers. The methodology is tested on an IEEE 6-bus reliability test system for three case studies: Normal network (winds not considered), robust network (increased robustness by using better and stronger materials for the transmission lines and towers), redundant network (addition of parallel lines) and response network (restoration procedures). However, most transmission lines and substations are designed to withstand extreme wind forces. Most customer interruptions are due to damages to the distribution system, which is much more vulnerable when compared to a transmission system. Therefore, study of distribution system resilience to High Impact Low Probability (HILP) events is crucial to strengthen the energy infrastructure.

In the research work of [35], authors developed an infrastructure hardening and maintenance scheduling model for critical power system components, using partially observable Markov processes. The authors suggest temporary as well as permanent hardening and asset management strategies. The failure of components is due to two correlated factors: natural deterioration due to age, and deterioration due to the impact of hurricanes. The actions that can be taken are classified into inspection, preventive & corrective maintenance, restoration and hardening. The component under study is a standard high voltage oil-filed transformer. As mentioned previously, transmission structures are built to withstand extreme weather, and reliability of transmission systems has been widely studied. The authors of [35] do not perform their assessment for distribution systems which are more susceptible to hurricane damages, and they do not consider structural damage of utility poles which are a significant cause of hurricane vulnerability.

In [36], the author characterized resilience as a multivariate problem and developed a multivariate inoperability model which is a combination of network topology, hurricane hazards along with the topography and climate of the geographic area, that serves as a predictive tool for assessing system resilience. The model used data from Hurricane Katrina's impact in the Central Gulf Coast region of the USA. The model produces customer outages as the result of analysis, from which resiliency studies are performed. The author indicates that tree coverage, land-cover types and soil moisture levels are the key factors affecting resilience. This study does not provide any solutions to restore power to outaged customers i.e., reconfiguring and repair strategies are not discussed. Also, this study does not take into account pole failures as one of the factors in the multivariate problem; neither does it give an idea of the vulnerable network sections from a geographic point of view, which is necessary to make future hardening decisions such as installing DGs.

The authors of [25] investigate methods to improve distribution system performance in the event of hurricanes. The authors propose a framework that involves construction of new distribution lines with normally open switches that connect feeders from multiple substations taking into account system topography, hurricane path, line length and cost considerations. The factors that affect the construction are hurricane path, number and length of lines. Longer the line, higher is the probability of failure, while also costing more in construction costs. The presence of these tie lines aids marginally (3%) in reliability due to additional paths for reconfiguration, but since hurricane tracks cannot be accurately predicted and are modeled based on historic data, investing in expensive construction of feeder lines is not practical.

The research in [19] provides a review of the progress in power system resilience and restoration under extreme weather conditions. In existing studies, the outage forecast models fall into two categories: statistical models and simulation based models. With regards to hardening, elevating substations, undergrounding lines, vegetation management and allocation of emergency generation units and black start units are the activities currently implemented by utility programs. The authors discuss the benefits of increasing generation availability by integrating distributed generation units (DGs) into the system, thereby forming microgrids. These microgrids can aid conventional restoration procedures or be a part of advanced distribution automation techniques involving decentralized restoration strategies. This study does not consider geographic analysis, while the system in this thesis specifically represents southeast USA, thereby increasing accuracy. Along the lines of [19], the authors of [37] identify the crucial pieces in the roadmap of distribution system resiliency by discussing the recommendations made by National Electrical Manufacturers Association (NEMA) for increasing resiliency . The pieces are divided into programs that alter the physical infrastructure, such as improving construction standards, reinforcement of overhead lines and undergrounding; and programs that improve maintenance and inspection procedures such as temperature monitoring, intelligent protective devices, circuit monitoring and thermal imaging. The authors do not discuss inspection programs for utility wood poles that are vital in resiliency studies. In conclusion, the reviews in [19] and [37] highlight the necessity of developing new simulation models to study distribution system resiliency that will allow utilities to make risk-informed decisions in times of disasters. Edison Electric Institute's report [17] and the CRS report for Congress [23] outline recommendations and best practices with regard to hardening the distribution infrastructure to create a more resilient system. Undergrounding is a popular choice for system hardening, however, costs can be prohibitive for total conversion, and are not always approved by regulatory bodies. Selective undergrounding is a more viable solution. Vegetation management and tree-trimming are suggested by both authors. Many of the storm related outages are due to falling trees that damage power lines. However, vegetation management by itself is not an effective hardening practice. While NERC has a vegetation management standard for transmission systems, the same rules do not apply for distribution lines. As such, there is no standard for tree management for distribution systems. The authors of [17] recommend improving design and construction standards by following a selective approach, by identifying the most critical elements or the worst preforming components. System hardening should be a part of regular maintenance schedules and not come about only in response to storm effects. Hardening should be a targeted approach, with specific hardening techniques varying from location to location, depending on storm impacts and local conditions of the facilities. The authors of [17] and [23] discuss the benefits of smart grid technologies in increasing system resilience. Some of these benefits include the ability to detect outages instantly, and reroute electricity to undamaged circuits using distribution automation technologies such as sensors, processors, communicators, and switches that can provide intelligent monitoring of distribution systems [38]. This is an area of great interest in the field of power systems, and is the focus of this research. Another hardening recommendation is the integration of distributed generation (DG) and microgrids. DGs are located close to the loads they serve, are less vulnerable to weather related service interruptions.

2.2 Outage Management

The authors of [39] developed an agent-based power outage forecasting model that considers the effect of individual behavioral responses of customers on power system reliability during hurricanes. The individual response includes customers who file complaints and customers who own their own generators that come into use during an outage. The study indicates correlation between cycle of system hardening and customer responses to changes in system. In this study, storm data is modeled in 6-hour increments, however this is inaccurate because in many cases, storm duration is less than 6 hours. Another point to be noted is that while customer behaviors may have an impact on hardening, due to the limited financial and labor resources that utilities possess, it is more critical to harden the infrastructure as a first response to hurricanes.

The authors of [40] developed a damage prediction model for distribution systems that predicts number of outages by using a Poisson regression model for spatial data in a Bayesian hierarchical framework. This statistical model uses historic hurricane data and weather observations obtained from a utility in northeastern USA. The outage results can be used by utility company in planning the power restoration process. The model takes into account uncertainties from data sources and categorizes probability of damage according to hurricane category. This study discusses only the first step in the processes of resiliency analysis. It does not provide solutions on outage management during the event of the storm and recovery and restoration options post-storm.

The authors of [41] developed a decision support tool that enables utilities to improve information for restoring distribution systems affected by large scale storms. The tool utilizes the layout of the distribution circuit, the location of protective devices and customers to determine resources needed for efficient storm management. The IT system that supports storm outage management consists of the following modules: distribution circuit configuration database, asset database (contains data about system components such as pole types and line construction), field observations and measurements (customer calls etc.), damage prediction module, crew requirements module and storm intensity data. This tool predicts the location and extent of damage, crew requirements and restoration times, and total costs. The authors of [41] discuss the capabilities of their decision support tool, and the results that the tool produces. However not much is known about modelling process and the assumptions and methodology used in developing this tool. In both [41] and [40], the authors do not evaluate the possibility of automatic network reconfiguration as a response to storm events.

In [42], the authors propose a distribution network outage pre-warning model for extreme weather conditions. The model establishes a correlation between electrical equipment failure and loading factors (based on weather information), following which failure probability models are developed for overhead lines and transformers. The objective is to minimize load shedding using a Monte Carlo approach and results are provided in the form of individual customer outage probabilities. The authors utilize a two-state weather model to develop an exponential failure model for network devices. This is not accurate because different devices have different failure models based on device characteristics. Failure of wood poles depends on a range of factors such as pole height and age, soil conditions, depth of pole installations, pole material and treatments. A simple exponential model will not adequately characterize these factors. The authors do not consider extreme weather conditions which have much higher failures than lower intensity storms.

In [43], the researchers propose a model for predicting power outages in advance of hurricane occurrence that is applicable along the U.S coastline using publicly available data. The response variable is the number of customers without power which is based on customer call-ins and utility model of the power system. A parametric wind field model is used to model the hurricane. A wind speed of 20 m/s is chosen as the cutoff for wooden poles. The statistical model uses data from the past 10 hurricanes to predict outages. The results are tested for Hurricane Sandy. This model estimates the cumulative outages as well as peak outages. Intense storms (Typhoon Haiyan is used to represent an intense storm) are assumed to cover the same distances in 6-hour intervals, and these distances are laid on top of the historic track. This model does not consider soil moisture data, which is an important factor affecting failure probability of wood poles. The model has not been tested for hurricanes with higher intensities and does not provide details about failures of system components.

In [44], the researchers developed a model based on a Bayesian Network framework to predict outages in a power system exposed to a hurricane event. The model includes a DC power flow functionality to reduce the complexity of the approach while accounting for flow within the grid. The model considers component fragilities and topology of the grid, and predicts outages at substations and distribution points. It consists of three main models: hurricane demand model that characterizes the hazard and wind field associated with a hurricane, component performance model and a substation response model. To assess component performance, the electric grid is divided into the generation system made up of generating plants, transmission system consisting of transmission lines and towers, and distribution system comprising distribution lines, conductors and poles. Pre-existing fragility curves are used for these components. Substation response is a function of the structural reliability of the network components. The framework is demonstrated on Harris County's electric power system under the effect of 2008 Hurricane Ike. The analysis showed that outage risks were higher for distribution load points, which is as expected. For accurate results however, more detailed distribution network models are required, models that would represent real systems. Also, component regression analyses must be performed based on current data.

The authors of [45] propose a methodology for assessing performance of power systems subjected to hurricanes that combines hurricane damage information with topology assessments. A joint transmission and distribution component fragility model is utilized to study the effects of topology on system reliability. The topology components include substations, generators and edges (with spatial configurations). The major cause of damage to transmission and distribution lines is wind loading. Line failure is approximated by the ratio of wind force and maximum rated line perpendicular stress resistance. The impact of flying debris is considered in distribution line fragility assessment. The authors identify meshedness, clustering, and centralization as the main topological factors influencing reliability, and find that ring-mesh configuration has highest reliability.

2.3 Utility Poles

A significant portion of overhead distribution lines are supported by wood poles. The authors of [28, 31, 32] developed a risk assessment methodology for wood poles which considers the effects of decay as well as strong winds due to hurricanes in developing failure probabilities of poles. The authors develop age-dependent fragility curves of utility wood poles that are a combination of probabilistic capacity models that depend on the age of the pole and wind force demand models. The fragility model developed in these studies is dependent on pole age, pole height above ground line, soil characteristics, pole circumference, span length, number of attached cables, additional loading (due to overhead lines, communication cables, cross-arms, and service transformers), pole class, and chemical treatments. The results indicate that the failure probability of the poles depend on the age and class of poles. This is a useful result that is implemented in this research to strengthen electric distribution systems.

2.4 Service Restoration

The authors of [46] propose a methodology that uses automatic switching operation of the protective devices in large scale distribution systems with the objective of power loss (

I^2R loss) minimization. The authors make use of simulated annealing techniques with polynomial-time cooling schedule based on statistical calculations. The study also considers power flow analysis in a radial system to ensure system constraints. The network configuration is determined by the state of the sectionalizing and ties switches. “Perturbation” of this state, i.e. modifying the open/close status of these devices, will result in a new configuration of the system. In this topology-based perturbation mechanism, solution space contains all open/close combinations of the switches. The method is tested on a 148-bus system as well as a real system in Korea Electric Power Corporation.

The authors of [47] study four heuristic algorithms for service restoration in distribution systems: reactive tabu search, tabu search, parallel simulated annealing, and genetic algorithm. The power source is taken to be a current injection source, and each section (area within switches) contains a load. Fast load flow calculations are performed through backward and forward sweep technique. The objective in this analysis is to maximize the customers restored. The heuristic algorithms require representation of state variables, initialization of these variables and generation of neighboring states. In this analysis, the state variable is represented by the configuration of the network. The analysis takes into account load priority and reliability.

In the research work of [48], service restoration in an electric distribution system is a multi-objective multi-constraint optimization problem that is solved using the non-dominated sorting genetic algorithm-II (NSGA-II). The objective is to minimize out of service areas, switch operations (manual and remote) and losses, while considering system constraints and customer priority. The network configuration is determined by a string representation of network switch statuses.

In [49], the authors use a dynamic programming approach with state reduction to solve service restoration. The study assumes a widespread blackout. Restoration is defined as an optimization problem with the objective of minimizing the unserved energy of the system, subject to the constraints of available generation, system frequency and load prioritization. State reduction reduces computational effort, while maintaining accuracy of results.

The network reconfiguration algorithms proposed by [46-49] consider power loss minimization as their objective for restoration, and do not perform any reliability assessments (both structural and electrical) under weather effects. However, in this research, the focus is on minimizing customer outages (service loss) under consideration of hurricane scenarios.

In [50], the author analyzes urban utility storm data for performance of electric distribution systems in the Seattle area. Negative binomial regression models were fitted to the storm data. The storm data includes reliability indices such as SAIFI and SAIDI that are adapted to storm scenarios (STAIFI, STAIDI). The probability of feeder damage is calculated as a fragility function, and outages are analyzed for tree-related failures. The gamma distribution is found to provide the best description of outage durations. This analysis provides information to predict system behavior for other wind events. The study limits itself to assessment of outage behavior, and does not provide any repair and restoration schemes.

The authors of [18] developed a resilience model to investigate the impact of hurricanes on electric systems, which include transmission and distribution systems. The model contains four sub-models: hazard scenario generation model, component fragility model, power system performance model, and a system restoration model. The resilience is categorized based on time scale-previous resilience which is based on historical data, current resilience which is based on current system settings such as power demand and network topology and future potential resilience that considers system improvement and hardening techniques. To test the methodology, an approximate distribution network is generated based on the assumption that distribution circuits are found along secondary roads and streets. The failures of distribution poles are modeled as exponential functions. DC power flow equations are used to monitor system constraints. The restoration process discussed in this study takes into account mobilization of restoration resources in terms of available work crews, along with the restoration sequence which is based on restoration priority.

The authors of [51] propose a resilience assessment framework of power systems (transmission and distribution) against hurricanes, which consists of five models: a hurricane demand model that generates wind intensities given a hurricane scenario, component performance model, Bayesian network (BN)–based system response model, another second system response model and a restoration model. The distribution systems are represented as minimum spanning trees (MST). In this study, the number of poles along a distribution line is determined by the line length divided by the average span length between two adjacent poles. In this research however, real utility pole data is used to model the distribution network, and is therefore more representative of a real system in current use. In [51], the number of damaged poles are determined by comparing uniformly distributed random variable realizations to their failure probabilities. This study modifies the restoration model described in [18]. The available resources for restoration are modeled as a dynamic function that increases over time. The repair sequence is based on prioritization of critical loads such as hospitals, gas compressors and water pumping plants. Among these critical loads, priority is given to the component that requires least repair time. In [52], a method is proposed to estimate restoration times to outaged customers after hurricanes and ice storms. The authors developed Accelerated Failure Time (AFT) models to calculate outage durations. AFT model was chosen because it provides a direct correlation between covariates and outage duration. The power restoration model is an application of survival analysis described by the AFT model.

Elements of the restoration methodology developed by [18] and [51] are adapted in this research. However, neither [18], [51] or [52] consider a vital smart grid application, that is, rapid and automatic network reconfiguration that utilizes automated protective devices to reroute power to adjacent substations thereby minimizing outages. Network reconfiguration under hurricane scenarios is an emerging area of interest which has significant applications with the progress in smart grid technologies.

2.5 Microgrids

The authors of [53] investigate the usefulness of autonomous microgrids in hardening power systems and increasing reliability and security. They propose that customers install utility-compatible distributed generation sources in their homes, which behave as autonomous self-supporting micro networks. This installation requires intelligent placement of protective devices such as switches and sectionalizers. The technological requirements for such a system are: optimal system configuration, dedicated communication, control & protection schemes, autonomous load management and regulatory policies. This study does not consider weather effects in the reliability discussions. The usefulness of DGs in the presence of catastrophic disasters is not an area that has been studied fully. While DGs may be effective in hardening systems in the future, there are more pressing hardening issues to be addressed at present. Existing energy infrastructure is weak and vulnerable to hurricanes, and must be strengthened first before adding additional components.

2.6 Summary of Literature Review

Reliability of distribution systems in the event of extreme weather involves research in three time phases: 1) system analysis before occurrence of hurricanes which involves development of predictive models; 2) system analysis during hurricane landfall which involves automatic Fault Location, Isolation, and Service Restoration (FLISR) models; and 3) system analysis after passage of the strong winds which involves restoration and repair models. Existing literature on the topic focuses on options to harden the distribution systems against hurricanes using methods such as integration of microgrids and increasing system redundancy. However, they do not discuss the benefits of implementing distribution automation technologies such as automatic fault isolation and reconfiguration to increase self-healing capabilities of the system. Substantial research work has been done on strengthening transmission systems, but there are fewer studies specific to distribution systems. Moreover, reliability calculations for distribution systems typically do not consider extreme weather events. However, extreme weather events which were once considered High Impact Low Probability (HILP) are now increasingly more probable and therefore reliability and resiliency studies must include weather related discussions. Research on network reconfiguration is typically performed with the objective of feeder loss minimization. However, research on reconfiguration in the event of hurricanes is lacking and is a major shortcoming of existing literature. An integrated assessment of the impact of weather on both structural as well as electrical components of distribution systems has not been performed and is the primary topic that is investigated in this research. In conclusion, there currently does not exist an integrated, holistic approach to distribution system resiliency analysis considering weather effects, and this research aims to fill the knowledge gap in this research area.

2.7 Unique Contributions of this Research

The reliability assessment of power distribution networks can be divided into three phases: the first phase is before the occurrence of the hurricane, when the system is operating under normal conditions. This includes hardening assessments, which are preventive actions performed in anticipation of the weather event. The second phase consists of actions deployed during and immediately after the occurrence of the hurricane. This is dependent on the system parameters. While many studies discuss methods to prevent outages in case of multiple contingencies, these methods cannot satisfactorily be applied to the situation in which hurricanes hit a system, and there are very few response actions that are currently being deployed by utilities during the time of extreme weather events. Therefore, research on corrective actions that can be performed during storm occurrence is of emerging interest and necessity. The third phase is after the storm occurrence, and this phase involves damage assessment and restoration strategies. [18, 19].

The research works discussed in the above sections study specific aspects of resilience with regards to distribution systems. While some researchers assess outage prediction techniques, others demonstrate restoration methods with the objective of loss minimization. The novelty of the proposed research is a holistic approach to power distribution system resiliency in the event of severe weather conditions. This research develops a comprehensive assessment framework that considers all three reliability phases discussed previously:

- Phase 1: This research investigates the resilience of a real distribution network designed with publicly available data and recommends measures to harden the network through upgrades to structural components
- Phase 2: In this stage of damage propagation, pole survival events are generated to assess failed poles and an outage prediction model is developed. Optimal network reconfiguration methodology is studied to demonstrate the benefits of instantaneous corrective actions during storm occurrence to minimize customer interruptions
- Phase 3: Restoration and repair schemes are proposed that take into account utility work crew availability as well as priority of customers.

The result is a comprehensive tool that integrates structural, topological, and electrical aspects of power distribution systems, and forms the foundation for a new knowledge base in vulnerability assessment of power networks. This analysis can be utilized to design more efficient outage prediction and management systems and will provide utilities with valuable information to make risk-informed decisions and better planning and preparedness for hurricane response. The result will be a safer, more reliable, and better emergency prepared power system.

CHAPTER 3. UTILITY WOOD POLES

3.1 Introduction

A majority of the overhead power lines in the United States are supported by wood poles. This is because wood is a relatively inexpensive material and is available in abundance. However, utility wood pole infrastructure is vulnerable to natural disasters, especially hurricanes. Utility wood poles are prone to damages caused by high winds that occur during hurricanes. Risk and reliability assessment of distribution lines require the development of utility pole models that accurately represent their behavior under such extreme wind conditions. These pole performance models integrate hurricane scenarios along with conditional probability models, also known as fragility models. The probability of pole failures depends on many factors including the size of attached conductors, size of neutral conductor, span length of distribution lines, weight of pole, type of pole equipment (for example pole mounted transformer), magnitude and direction of wind, ice accumulation, electromagnetic (EM) forces caused by fault currents, size of pole size, pole material, total pole length and height of pole above ground [54].

3.2 Hurricane Model

Most of the reliability data excludes major storm interruptions. This is because a hurricane is a low probability event, and its impact does not reflect the true performance of a distribution system. Including the effect of storms will increase reliability indices such as CAIDI and SAIDI significantly [55]. A hurricane is considered to be a High Impact Low Probability(HILP) event, and therefore, power system resilience studies must include hurricane impacts[56]. When a hurricane occurs, strong winds cause collapse of utility poles resulting in faults across the system. The North Atlantic Hurricane Database [57] provides extensive historical hurricane datasets dating back from 1851 that can be used for hurricane modeling [58]. HURDAT contains the following hurricane information: central position (to the nearest 0.1 degree latitude and longitude), direction (to the nearest 5 degree with North), translation speed (or forward speed), maximum sustained wind speed (1-minute at 10-m height), and central pressure [58].

Hurricane winds are commonly modeled using a probabilistic approach using the Homogenous Poisson probabilistic function given below [59]:

$$P[N(t) = k] = \frac{(\eta t)^k}{k!} e^{-\eta t}, k = 0,1,2 \ldots \tag{1}$$

where P is the probability that the number of hurricanes $N(t)$ is equal to k, η is the average occurrence rate and t is the time period. It has been found that the time T between successive hurricanes follows an exponential distribution [18, 59]. T is obtained by:

$$T = -\frac{1}{\eta} \ln U \tag{2}$$

Where U is a uniformly distributed random number between $[0,1]$ [59]. Damage caused by the hurricane depends on the Sustained Surface Wind Speed (SSWS) of the hurricane. The Saffir-Simpson scale categorizes hurricane intensity based on their SSWS. The probabilistic approach considers the probability density function of wind speed, which means that higher the wind speed, lower the probability of occurrence. The probability that the wind speed is smaller than a given wind speed is given by [60]:

$$P(V < V_o) = 1 - \frac{1}{T_o} \quad (3)$$

where V is the wind speed, V_o is the given wind speed and T_o is the associated return period. According to this, the probability of occurrence of high winds with high return periods is very low. If a probabilistic approach is considered, the likelihood of high wind speeds is low and therefore, the probability of failure of the components of the system becomes comparatively small and does not result in sufficient data for analysis.

For this reason, a scenario based approach is used to model hurricane hazards where probability of failure of components is considered for each wind speed based on hurricane category [60]. Hurricane scenarios can be generated using HAZUS software, which produces many hurricane scenarios with varying return periods or manually, using hurricane tracks [18]. For distribution systems, spatial variation of wind speeds is an important factor while analyzing hurricane impacts. In the HURDAT database, wind speeds are recorded at 6-hour intervals. In many cases 6 hours is longer than the duration of the storm, and therefore 6-h intervals are not small enough to model hurricanes. By interpolating 6-h data to 30-minute intervals, accuracy can be improved [25, 61]. The spatial effects of wind speed are modeled through wind field models, which give the wind speed at any distance from the eye of the hurricane. One of the most popular models is the Holland model [62, 63]. For assessing system performance, the gradient wind speed from the Holland model is converted to surface wind speed using a conversion factor ranging from 0.8 to 0.86 depending on storm category [25, 62]. The surface wind speed is then converted to a 3-s gust wind speed which is most appropriate for assessing structural damage.

The remainder of this chapter summarizes the methodology and model developed by Darestani et al.[31] and Shafieezadeh et al. [28] to obtain failure probability of wood poles. The failure model developed in the above work has been used in this research [64].

3.3 Probability of Pole Failures

The probability of failure of a structure is determined by evaluating the uncertainty in demand applied to structure and the capacity of structure to withstand the demand. A limit state function represented by $G(X)$ where $G(X) < 0$ is used in reliability analysis to define failure. Incorporating the law of total probability, the probability of failure of a system with limit state $G(X)$ is defined as

$$P_f = P[G(X) < 0] = \int_y P[G(X < 0)|IM = y] f_{IM}(y) dy \quad (4)$$

where IM is the intensity measure of the demand, $f_{IM}(y)$ is the probability density function of the intensity measure of the hazard, and $P[G(X < 0)|IM = y]$ is the fragility function that defines the conditional probability of failure with IM=y.

Equation (4) is used to calculate probability of wood pole failures in overhead distribution lines due to wind loads. The limit state function describing the failure event of utility poles is given by:

$$G(X) = R - S \quad (5)$$

where R is the moment capacity (modulus of rupture) of the wood poles and S is the maximum wind-induced bending stress in the ground-line section of the poles (wind moment demand at the ground line). The wind load on wood poles is discussed in the upcoming Section 3.4[60].

Pole failures occur when the moment demands induced by wind loads exceed the moment capacity of the poles. The moment capacity of the pole depends on the cross-sectional area of the pole, which decreases with increase in height above ground line. However, the pole is most vulnerable at the ground line because of the surrounding soil and therefore the limit state function is for the section at the ground line. The failure of the foundation of the pole is another cause of pole failure. The modulus of rupture of wood poles at the ground line decreases as the size of the pole increases. As the height of the poles increase, the location of maximum ratio of moment demand to moment capacity moves higher in the pole, and it therefore, for tall poles, the point of maximum bending stress is above the ground line. The ground line stress at the failure load called the modulus of rupture, σ_R is representative of the capacity of the poles when combined with section modulus to find the section moment capacity of the poles [28]. It has been shown in past studies that wood strength decreases as the size of the poles increases [65, 66]. Regression analyses of pole test data with respect to pole circumference at ground line (C_{gl}) in logarithmic space was performed by Wolfe et al. [67]. A power model was used as the regression function:

$$\sigma_R = AC_{gl}^B \tag{6}$$

where A and B are regression parameters. In the case of wood poles, it is common design convention to use a 5% lower exclusion limit for strength. This means that 95% of the poles exceed the minimum required strength specified by the lower exclusion limit. Parameters A and B in (6) for Southern Pine wood poles are found to be 3.482×10^7 and -0.320

respectively. This represents a 50% confidence in the lower 5% exclusion limit assuming a lognormal distribution for the strength of the poles [65, 67].

Σ_R is a random variable describing the modulus of rupture of the poles. Assuming that Σ_R follows a normal distribution, the tolerance factor, k, is derived as:

$$k_{\beta,\gamma,\eta} = \frac{1}{\sqrt{n}}\, t_{n-1}\,; 1-\gamma(z_B\sqrt{n}) \tag{7}$$

where $t_{m;1-\alpha}\,(\delta)$ denotes the $1-\alpha$ quantile of a non-central t distribution with degrees of freedom of m ; the non-centrality parameter δ and z_B denote the β quantile of a standard normal distribution.

The parameters of the lognormal distribution for Σ_R are obtained using:

$$E\,[\log(\Sigma_R)] = \log(\sigma_{RS}) + k_{0.05,0.5,\infty}\, Var\,[\log(\Sigma_R)]$$

$$Var[\log(\Sigma_R)] = \sqrt{\log(\rho_R^2 - 1)} \tag{8}$$

where $\log(\Sigma_R)$ is the random variable representing the modulus of rupture in the logarithmic space. It must be noted that Σ_R differs from σ_R discussed in Equation ((6). While σ_R is the 5% lower exclusion limit on the capacity of the poles (moment capacity or pole strength), Σ_R is a random variable that represents pole capacity and is an uncertain parameter calculated from Equation (8) [68].

The moment capacity of wood poles at the ground line can be determined as

$$M_{GL} = \frac{\Sigma_R C_{GL}^3}{32\Pi^2} \tag{9}$$

where C_{GL} is the circumference of the pole at the ground line.

Reliability assessments of wood poles are performed through Monte Carlo simulations, for which samples of ground line moment capacity of wood poles are required [31]. M_{GL} is a deterministic design value used by ANSI. Equation (9) is used for wood pole design in practice. However, for Monte Carlo simulations, the uncertain parameter R (from Equation (5)) should be considered.

$$M_{\Sigma_R} = \frac{\Sigma_R \times r}{I} \tag{10}$$

Where r is the radius of the pole, and I is the second moment of inertia. This M_{Σ_R} is used in the Monte Carlo simulations [68]. The circumference at the tip and at 6 feet from bottom for different classes and lengths of the poles can be found in ANSI O5.1 [17]. It is assumed that the ground line circumference follows a uniform distribution and samples for class n wood poles can be generated. The lower and upper bounds of the uniform distribution are the minimum ground line circumference for class n and class $n - 1$, respectively. For one run of Monte Carlo simulation, the ground-line circumference (C_{gl}) is modelled by:

$$C_{gl} U\left(\left[C_{m-gl}\middle|l, c\right], \left[C_{m-gl}\middle|l, c-1\right]\right) \tag{11}$$

Where c and l are the class length of the wood pole, respectively, $U(.)$ represents a uniform distribution, the first expression in $(.)$ is the lower bound of the uniform distribution: the minimum ground-line circumference C_{m-gl} given length l for class c from the ANSI table, and the second expression in $(.)$ is the upper bound of the uniform distribution: the minimum ground-line circumference given length l for the upper-class $c - 1$ from the ANSI table. Pole moment capacities can therefore be obtained by applying random samples of ground line circumferences in (9).

Wood poles decay over the course of their service life. It is a time dependent process that depends on environmental conditions, wood species and chemical treatments. The rate of decay is higher with rise in temperatures, moisture, and oxygen from the atmosphere [27]. The ground line has the highest rate of decay because of exposure to oxygen, and the high level of moisture transferred from soil. Shafieezadeh et al. [13] developed time-dependent fragility models of wood utility poles by accounting for the effects of decay on the poles.

The expected value and variance of the moment capacity of wood poles, is given by:

$$E[R|T=t] = E[R_o][1 - \min(\max(a_1 t - a_2, 0), 1) \times \min\left(\max\left(b_1' t^{b_2'}, 0\right), 1\right)] \tag{12}$$

$$\begin{aligned} Var[R|T=t] = {} & (Var[R_o] + E[R_o]^2)\left(1 - \min\left(\max\left(b_1' t^{b_2'}, 0\right), 1\right)\right) + \{(Var[R_o] + \\ & E[R_o]^2)[Var[L|T] + (1 - \min(\max(a_1 t - a_2, 0), 1))^2]\} \times \\ & \left(\min\left(\max\left(b_1' t^{b_2'}, 0\right), 1\right)\right) - E[R_o]^2 \times \Big[1 - \min(\max(a_1 t - \\ & a_2, 0), 1) \times \quad \min\left(\max\left(b_1' t^{b_2'}, 0\right), 1\right)\Big]^2 \end{aligned} \tag{13}$$

where R is the moment capacity of wood poles, R_o is the moment capacity of the new poles, t is the age of the wood pole in years, $Var[L|T]$ is the time-dependent variance of the loss of the capacity of wood poles (set as 0.11). The parameters a_1 and a_2 define the percentage of strength loss for wood poles found to be 0.014418 and 0.10683 based on regression analysis [69]. Parameters b_1' and b_2' account for the percentage of decayed poles found to be 0.00013 and 1.846, respectively [28]. The moment capacity model is based on experimental work performed by Wolfe et al [67].

The stiffness uncertainty of distribution line spans is due to the properties of wood poles, and the stiffness of other distribution line components is considered to be deterministic. A probabilistic model for the stiffness of poles is obtained by performing a regression analysis to derive a relationship between their modulus of elasticity and modulus of rupture. Data for this analysis was obtained from experiments conducted in [70] on thirteen class five Southern Yellow Pine wood poles.

The elastic modulus E_W is given by:

$$E_W = 206\Sigma_R \times \varepsilon \tag{14}$$

where Σ_R represents the modulus of rupture of wood poles and ε accounts for the uncertainty in the regression model. Both follow a lognormal distribution. Knowing the distribution of Σ_R and ε, samples of E_W can be generated for Monte Carlo simulations.

3.4 Wind Load on Wood Poles

The magnitude of lateral wind forces on wood poles is a function of pole and conductor geometry, including pole diameter (top and bottom), length, span, number and geometry of attached cables. Wood pole geometry is based on the ANSI O5.1 standard. Wood poles are classified from classes one though ten based on their geometry [71]. It has been observed that the wood poles used in distribution networks are most commonly classes three and five[28]. Transverse wind force is given by [71]:

$$F = q_z G C_f A_f \tag{15}$$

where G is the gust-effect factor, C_f is the force coefficient that accounts for the forces on the windward and leeward faces of the structure, A_f is the projected area normal to the wind. q_z is the dynamic velocity pressure evaluated at height z on the structure.

$$q_z = 0.613 K_z K_{zt} K_d V^2 I \tag{16}$$

where K_z is the velocity pressure exposure coefficient, K_{zt} is the topographic factor, K_d is the wind directionality factor, V is the basic wind speed which corresponds to 3-sec gust wind velocity at 10 m above ground in Exposure C, and I is the importance factor. K_{zt} and I are set as unity, while the other parameters are modelled as random variables. Table 4 presents the statistics of the parameters in Equations (13) and (16) in terms of the type of the probability distribution and the coefficient of variation which are derived from a Delphi study supported by experimental data conducted by Ellingwood and Tekie [28, 72].

Gust effect factor G accounts for the dynamic loading effects of wind on structures, approximately equal to 0.85 for rigid structures [73]. The parameter C_f depends on the shape of the cross-section, the height (h) to diameter(D) ratio, and the surface roughness of the structure. K_z (depends on elevation and exposure category) can be obtained from the following equation [71]:

$$K_z = \left(2.01 \frac{\max(4.57, z)}{z_g}\right)^{\frac{2}{\alpha}}, z \leq z_g \tag{17}$$

Exposure category is assumed to be C (open terrain with obstructions less than 9.1m in height), α as 9.5m, z_g as 274.32m, and K_d as 0.95 [71].

Table 4. Wind load statistics for ASCE07-10 [71]

Parameter	Distribution	COV
G	Normal	0.11
C_f	Normal	0.12
K_z	Normal	0.16
K_d	Normal	0.08

Knowing the distribution and mean and COV of each probabilistic parameter, Monte Carlo simulations can be performed. The moment capacity follows a lognormal distribution.

3.5 Fragility Functions

Fragility functions are developed by using the probabilistic time-dependent moment capacity model of wood utility poles and the probabilistic lateral wind load model described previously.

In order to develop the fragility curves, the geometric features of wood poles must be characterized. These features depend on the pole class and length which are specific to the geographic area under study and can be obtained from utility inspection data. Shafieezadeh et al. [28] analysed class and height data of 5792 wood poles (in a real power utility) from one year of inspections. Fragility assessment is conducted for wood pole classes three and five since they are significantly more populated than other classes. Lognormal probability distributions are fitted to the empirical cumulative distribution functions (cdf) of pole heights to generate samples for the pole geometry. The mean and standard deviation of the fitted lognormal distribution for the height of the wood poles are 13.2 m and 1.6 m for Class three, and 11.4 m and 1.0 m for Class five respectively.

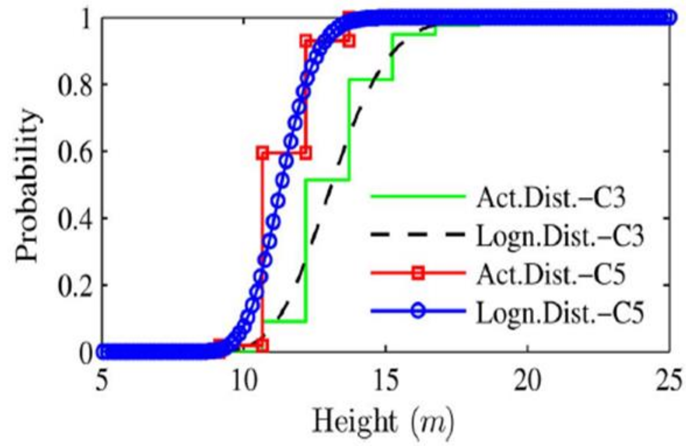


Figure 3.1 Empirical fitted distributions of Class 3 and Class 5 poles

Using the parameters of the lognormal fits, Latin Hypercube Sampling (LHS) technique is used to generate 20,000 samples of heights for each pole class. Other geometric parameters such as the circumference at top and bottom of the wood poles are generated randomly using Equation (11). Using these parameters, 20,000 samples are generated for moment capacity of wood poles for specific ages. The probabilistically generated wood pol geometric features are used in the demand model to determine the induced moments in the poles at the ground line level due to lateral wind pressures. 20,000 samples for wind induced moments are generated for each of the predefined wind velocities. These samples are paired randomly with the random samples generated for the moment capacity of the wood poles [28]. It should be noted that wind direction is assumed to be perpendicular to the conductors (worst-case). A wood pole is considered to have failed when the moment capacity is not sufficient to withstand moment demand. Fragility curve is obtained by counting the failures (where the moment demand exceeds the corresponding moment capacity), given the 3-sec gust wind velocity. It has been found that as the age of the poles increases, their probability of failure increases. Poles older than 25 are significantly vulnerable to high wind speeds [28, 31, 60]. Further details on the modelling of fragility curves can be found in [28].

The network in this study consists of 7051 poles, and each pole in the network has an associated failure probability. A random variable between 0 and 1 is generated, and this value is compared with the pole failure probability. If the randomly generated value is less than the probability of pole failure, then the pole is considered to have failed. If the random value is greater than the failure probability, then the pole is considered to have survived. Since the failure probabilities are assumed to be independent, this process is performed for each pole individually. One scenario refers to one failure or survival calculation for each of the 7051 poles. A value of 1 implies that the corresponding pole has failed, while 0 implies that the pole has survived. 1000 scenarios are considered in this study, which means that the failure assessment is performed 1000 times for each pole for each hurricane category. For each category, the wind speed parameter is considered to be the average value from the Saffir Simpson scale (in miles per hour), which are as follows: 85 mph for Hurricane Category 1, 103 mph for Hurricane Category 2, 120 mph for Hurricane Category 3, 143 mph for Hurricane Category 4, and 160 mph for Hurricane Category 5. The wind speed direction is assumed to be horizontal to the wood pole since this represents the worst-case scenario. The weight of the poles, along with that of conductors and equipment such as transformers, is taken into consideration while calculating pole failure. The effect of ice loading is not considered in this study; however, it can be included in future work.

The pole failure model is used as an input to model the electrical system response to hurricanes and assess reliability of power distribution systems. Further discussion and results are in CHAPTER 5.

3.6 Alternative Methods for Structural Analysis

3.6.1 Introduction

Another approach to structural analysis of distribution system components is through graphical modeling. It is crucial to develop a tool that can predict network vulnerability, thereby providing the base data for system hardening and improving resiliency. To demonstrate the graphical 3-D modeling method of structural analysis, several spans of the distribution system under study are developed and analyzed using the dynamic structural module of the program WinIGS, short for Windows Based Integrated Grounding System Design Program [54]. WinIGS is an analysis and design tool for multiphase power systems, based on integrated physical models[74].

3.6.2 Model Description

The single line diagram of the test system is shown below in Figure 3.2[54]. The test system is such that any pole failure will result in the disconnection of the downstream nodes, representing a radial network.

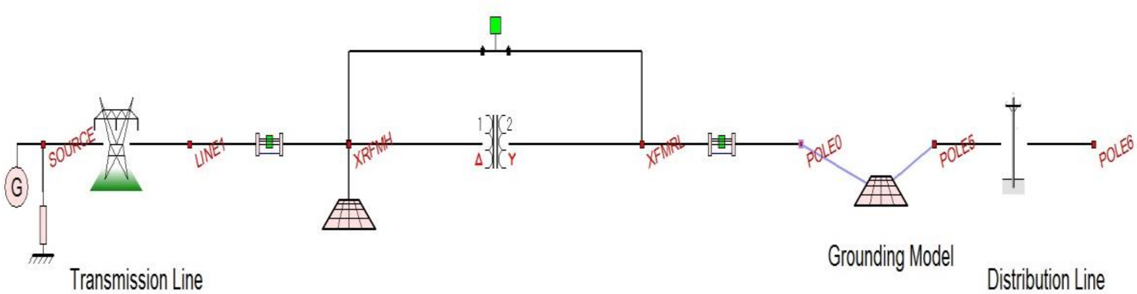


Figure 3.2 Single Line Diagram of WinIGS test network

The diagram shows the 115 kV transmission station, which connects to a 115/12.47 kV distribution substation. A 12.47 kV distribution feeder branches out from the distribution substation. This is representative of a segment of the main distribution system used in this study.

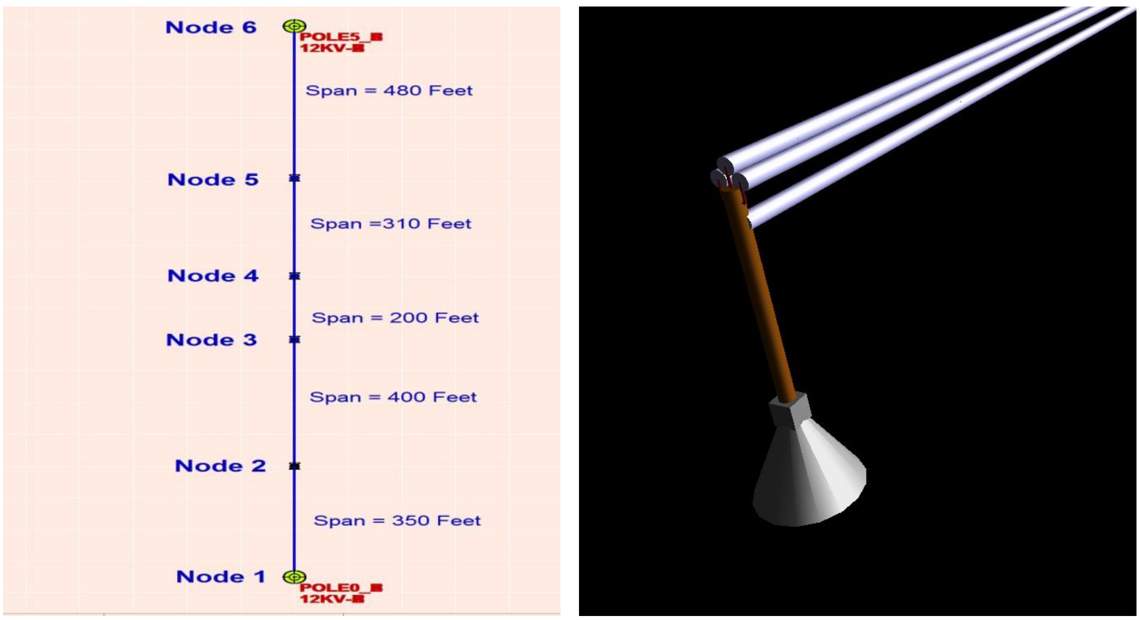


Figure 3.3 Views of grounding system (a) Top view (b) Partial 3-D view

Figure 3.3 shows the top view and partial 3D view of few spans of the structural feeder model. A 115kV, 3-phase equivalent source is connected to a transmission line, whose conductors are made of aluminum, specifically, Aluminum Conductor Steel Reinforced (ACSR) type. This is connected to a 12 kV distribution line at a distribution substation through a delta-wye connected step down transformer (115-12.47 kV). The distribution line goes on to eventually deliver power to end users, however, only a segment of the line consisting of 5 spans are modelled in this tool so as to demonstrate the analysis methodology. The modeling and analysis method can be extended to the entire distribution network.

The objective of this analysis is to perform structural dynamic analysis of distribution line components under various excitation conditions, by constructing 3-D models of required structures. Every node in Figure 3.3 (a) represents a wood pole. The pole model consists of a 40 feet long wood pole, with a wood cross-arm. The poles support conductors, insulators (made of porcelain) and other structural support elements. The type of wood used for the construction of the pole is Southern Yellow Pine. It is a Class 3 pole, of solid pipe construction. The cross-arm is also made of Southern Yellow Pine but is of a rectangular construction. Distribution line spans are connected between two poles. The line consists of 5 spans of varying lengths: 480 ft., 310 ft., 200 ft., 400 ft., and 350 ft. as shown in Figure 3.3 (a). The spans follow a series connection such that a pole failure in the circuit causes failure in downstream nodes. Interface elements allow for the structural components to be analyzed in conjunction with the electrical models. Measurements are made through the use of meters. These meters measure parameters such as maximum tensile and shear stresses acting on the structures under various excitations or loads. In this model, meters are placed at varying heights along the wood pole, since the stresses acting on the poles depend on the height of the pole above the ground line. The meters are located as follows:

Node 3: Meter 1 (10 ft.), Meter 2 (20 ft.), Meter 3 (30 ft.)
Node 4: Meter 4 (10 ft.), Meter 5 (20 ft.), Meter 6 (30 ft.)
Node 5: Meter 7 (10 ft.), Meter 8 (20 ft.), Meter 9 (30 ft.)
Node 2: Meter 10 (10 ft.), Meter 11 (20 ft.), Meter 12 (30 ft.)
The meter readings are presented in the form of time-varying plots [54].

3.6.3 Methodology

Vulnerability or "breakability" of a pole is a function of the stresses on the pole; when the stress on the pole exceeds its strength, the pole breaks. The stress depends on various factors, some related to the geometry and structure of the pole itself, while others are related to the components that are supported by the pole. The major factors affecting stress are: height of the pole above ground line, depth of pole installation below the ground, weight of the pole structure, circumference of the pole, material (wood, steel, concrete etc.) and age (time elapsed since installation, measured in years). Other factors include the size of the connected conductors (this can vary depending on the current capacity of the distribution line), size of the neutral wire, length of the span, geometry and weight of cross-arm and pole equipment (such as pole mounted transformers) and electromagnetic forces resulting from fault currents. External factors that are not related to the structural details of the pole also play a big role in determining vulnerability, the most important among these are wind forces. The effect of wind on the withstand capability of the pole depends on the speed of wind and also on the direction of wind. Winds blowing in a direction perpendicular to the axis of the pole represent the worst-case scenario and cause most damage. Other external forces include ice loads and gravity.

Structural dynamic analysis can be performed for the following excitation parameters:

3.6.3.1 Magnetics

Electric faults cause high currents to flow through the distribution circuit. These current-carrying elements generate forces (according to Biot-Savart law) that affect the structural components. The magnetics excitation parameter calculates the forces from current carrying conductors on structural components [74].

3.6.3.2 Earthquake

The effects of earthquakes are simulated through sinusoidally varying acceleration of the reference frame.

3.6.3.3 Wind and Ice

Wind force calculations are based on the IEEE standard 605 [75]. The parameters that this excitation depend on are wind speed, ice thickness, wind direction, duration and exposure class (B for urban or suburban areas, C for open terrain with scattered obstructions, and D for unobstructed areas and water surfaces)[54].

3.6.3.4 Thermal Expansion

This excitation calculates the effects on structures due to rise in ambient temperatures. It is calculated as the increase in original length due to a temperature rise that is the difference between ambient and reference temperatures. For conductors, the temperature rise is the difference between specified conductor temperature and rated temperature [74].

In this study, effects of hurricanes are modelled as wind excitations along with the effects of gravity. Other excitation parameters are not considered. It is a finite-element, non-linear analysis. The wind speed values for simulation are obtained from the Saffir-Simpson scale (Table 1). The high winds are simulated to start at 0.02 seconds and the analysis is performed for 1.5 seconds.

The gravity parameter takes into account weight of conductors, insulators, and other supporting elements. The unit weight of circular rigid bus conductors is given by:

$$F_c = \frac{\pi \omega_c}{4}(D_o^2 - D_i^2) = \pi \omega_c t_c (D_o - t_c) \tag{18}$$

Where, F_c is the conductor unit weight (N/m), w_c is the specific conductor weight (N/m^3), D_o is the outside conductor diameter (m), D_i is the inside conductor diameter (m) and t_c is the conductor thickness (m) [75]. The wind load per unit length of conductor (or pole) is given by [75]:

$$F_W = CV^2 D_o C_f K_Z G_f I \tag{19}$$

C is a design constant, V is the wind speed, D_o is the outside diameter of structure, C_f is the force coefficient, which takes into account the shape dependency, K_Z is the height and exposure factor which takes into account pole height above ground and surface irregularities, G_f is the gust response factor, 0.85 in this analysis, and I is the importance factor[75]. The system damping factor i.e., the rate at which transients die down is assumed to be 0.7. The structural wood pole model discussed in Section 3.6.2 is subject to winds with speeds ranging from 10 m/s to 100 m/s, and the tensile and shear stresses are recorded at increasing heights from the ground line of the pole through the meter readings. The wind is assumed to be moving in the horizontal direction.

3.6.4 Results

The tensile and shear stress graphs for varying wind speeds on the wood pole at Node 3 of the structural model described in Section 3.6.2 (Figure 3.3) are shown in Figure 3.4 and Figure 3.5.

Tensile and shear stress values are measured at heights of 10 ft., 20 ft. and 30 ft. from the ground using the measurement meters as described in Section 3.6.2. The wind speeds range from 10 m/s to > 100m/s to represent the hurricane severities in the Saffir Simpson scale. The direction of the wind is assumed to be horizontal i.e. perpendicular to the pole structures, which represents the worst-case scenario.

It can be seen that the stress values increase with height of the pole above ground. The stresses also increase significantly with increase in wind speed, the stresses on a pole affected by category 5 hurricane is more than double that of a Category 1 hurricane. These stresses are compared with the allowable values that are determined from the elastic limit of the material used in the design of the structural component. The component fails when the stresses exceed the allowable limits. This tool can therefore be used to assess the vulnerability of a wide range of pole structures, for different configurations of distribution lines, depending on the design parameters.

Figure 3.6 shows a time domain waveform taken from WinIGS program. It can be seen that the transients decay and the system stabilizes about halfway through the simulation [54].

In summary, the above structural dynamic model demonstrates an alternate tool for analysing the vulnerability of distribution feeders against weather conditions, specifically by studying the breakability of poles parametrically versus design parameters. Performing a detailed parametric study of a large distribution network by using the tool demonstrated in this section, will provide utilities or researchers with a range of design options that will enable them to make decisions to improve distribution resiliency. It must be noted that in the rest of this research, WinIGS is not used for structural analysis.

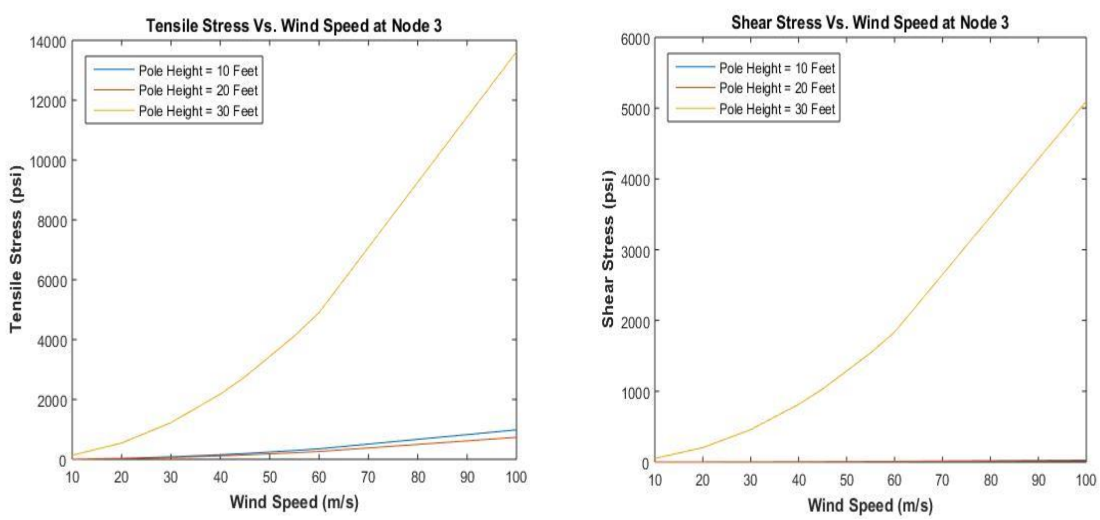


Figure 3.4 (a) Tensile stress (b) Shear stress at Node 3

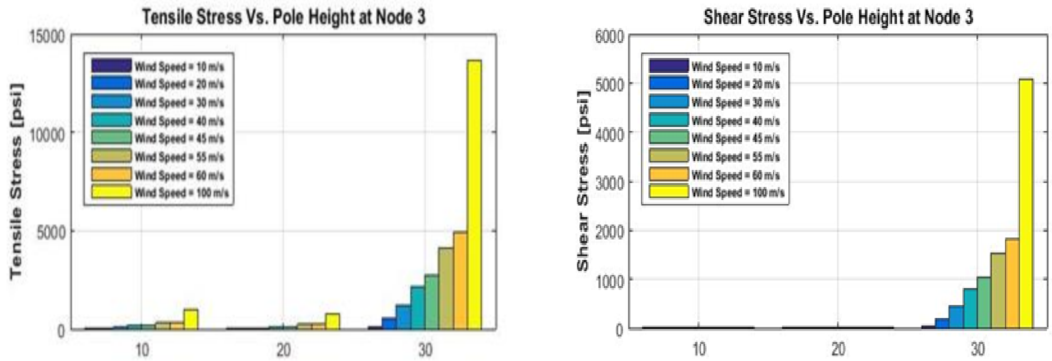


Figure 3.5 Stresses at varying heights from ground for different wind speeds (a) Tensile Stress (b) Shear stress.

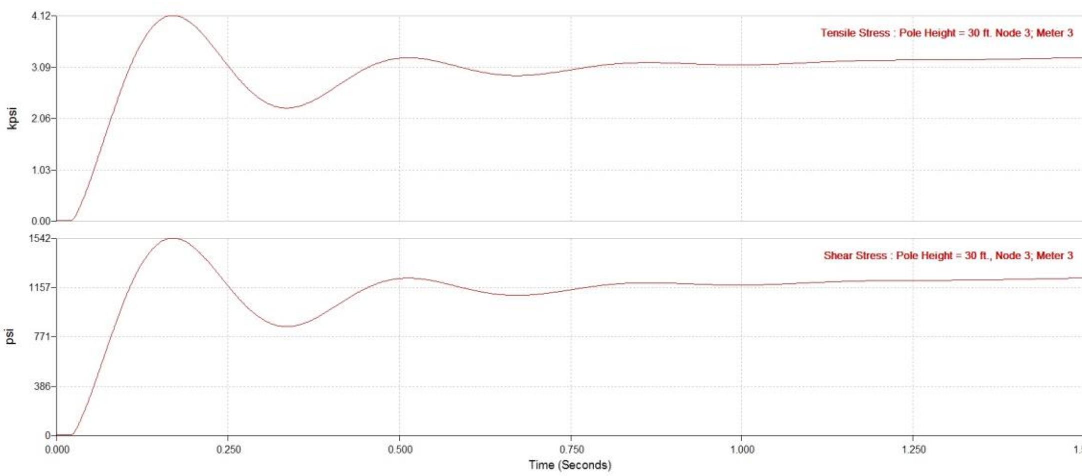


Figure 3.6 Tensile and shear stress from WinIGS over 1.5 second simulation time at wind speed = 55 m/s

CHAPTER 4. DISTRIBUTION NETWORK ANALYSIS

4.1 Power Distribution Network Model

4.1.1 Introduction

"A distribution system consists of all the facilities and equipment connecting a transmission system to the customer's equipment" [76]. Distribution systems consist of substations, feeder circuits, protective devices, transformers and customer loads. As shown in Figure 4.1, distribution systems deliver voltages in the range of 34 kV to 120V.

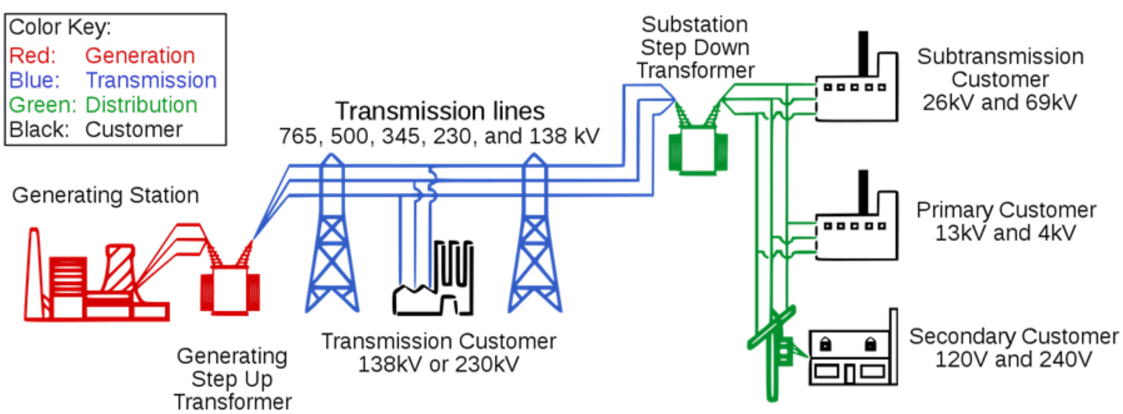


Figure 4.1 Electric power grid[77]

Data needed to develop a 100% accurate model of a real distribution system is not available for public use, security being the main reason. Therefore, to develop realistic models that will accurately represent the behaviour of a real system, some steps were taken.

The geographic area under consideration in this study is the south-east United States because it is prone to hurricanes. As a first step, Google Earth was used to obtain the GPS location coordinates of a substation in Georgia as shown in Figure 4.2.

Figure 4.2 Substation viewed on Google Earth

After obtaining the substation by means of inspection, Google Earth street view was used to identify the GPS coordinates of utility poles. Locations of 160 poles were obtained through this process as shown in Figure 4.3.

Figure 4.3 Distribution network developed using Google Earth

Although this method of inspection provides exact distribution network information and is feasible for a small network of 160 poles, following this procedure for a larger system is very time intensive and impractical. Instead, the only the locations of three substations in the south east of USA were found using Google Earth. The locations of 7051 utility wood poles were obtained through a dataset of inspected poles. In addition to the GPS coordinates of the poles, the dataset also contains age and class information. Since the connectivity data was missing for these poles, a representative radial system was synthesized using the available substation and pole location information. The feeders and laterals represent streets and secondary roads respectively. This is a good representation of the spatial pattern because according to [45], "distribution circuits are found along most secondary roads and streets to provide urban and suburban populations with electric service, allow access for construction or repair purposes, minimize the visual impact of overhead equipment by running parallel to existing roadways, and conform to the existing rectangular road grid [55, 78]." Distribution systems can be of radial or meshed configurations, however, radial configuration is most common because of the advantages of this configuration: costs are relatively low, power flow analysis is simpler and fault current analysis and protection is also easier [55]. A topology based approach is used to model the distribution network, where the connections of the poles are represented in the form of an adjacency matrix. An adjacency matrix A for a graph with n nodes is an $n \times n$ square matrix such that

$$A_{i,j} = \begin{cases} 1 & \text{if } i \text{ connected to } j \\ 0 & \text{otherwise} \end{cases} \tag{20}$$

Therefore, in this study, the adjacency matrix for the network is of size 7054×7054. This representation of the network is used for analysis.

The resulting network is as shown in Figure 4.4. This is the distribution network model that has been used to perform the resilience analyses. Detailed description of the network model will be provided in the subsequent sections.

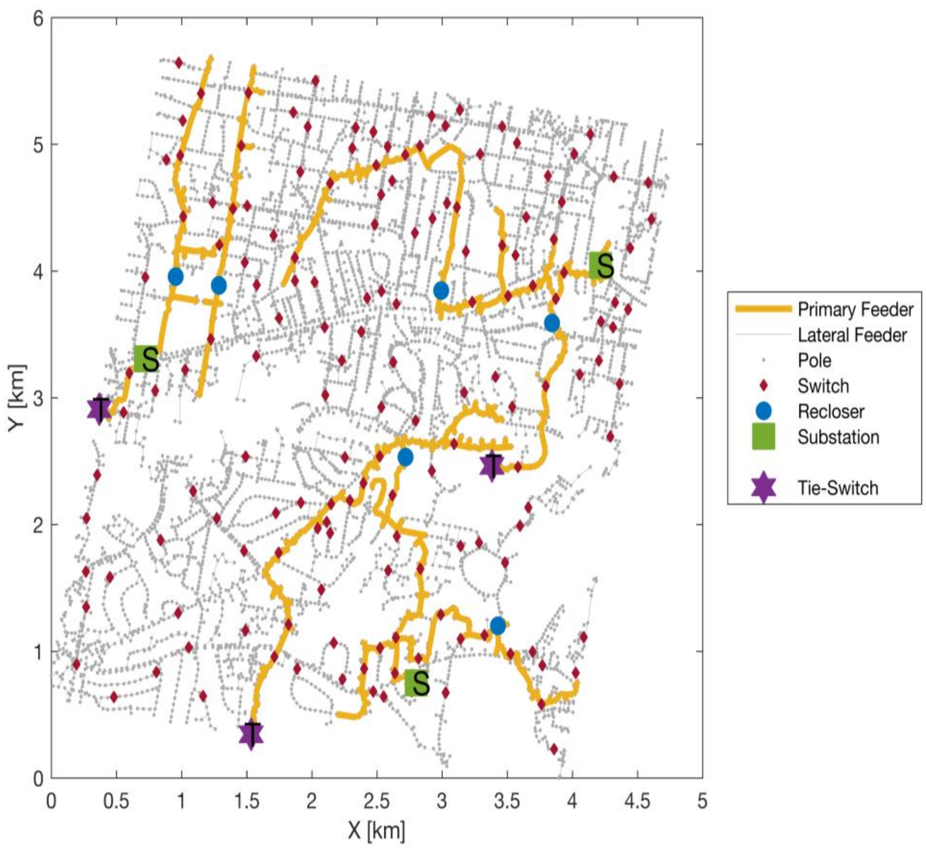


Figure 4.4 Model of test distribution network

4.1.2 Description of Network

The network used in this study consists of 7051 wood poles that are currently in use in the United States. This network spans an area of about 30 square kilometres (11.5 square miles). The grey dots in Figure 4.4 represent the wood poles. The wood poles are mainly of classes 3 and 5, and majority are over 30 years in age.

The substation in a distribution network is located at the connection point between a transmission and distribution system and steps down the voltage from 115 kV to 12 kV distribution system level. Substations are also the points of connection of the generation plants of the system. The network in Figure 4.4 consists of three substations, the locations of which were obtained from Google Earth. The substations are shown as green squares in the figure. The network consists of three sub-networks, each sub-network served by one substation. Each substation consists of 36 MVA, 115 kV generating source. These three sub-networks operate independently under normal operating conditions, and are isolated from each other through tie switches that are normally open. However, if a fault occurs on one of the sub-networks, the tie switches are operated to restore a portion of the faulted circuit quickly. Step down transformers connected to the substations reduce the voltage levels from 115 kV to 12 kV suitable for a distribution system. These transformers are connected in delta-wye configuration. This is the connection point between the substation and primary distribution circuits that branch off to serve customers. The next major component is the distribution feeders. The main feeder, also called the primary, is made up of three phase conductor circuits and delivers 12 kV voltages. The thick yellow lines in Figure 4.4 represent the primary feeder. From the main feeder, lateral feeders branch off. These are usually singe phase, 480V. This is shown by the grey lines in Figure 4.4. In a suburban layout, for example, the main feeder is located along a bigger street with laterals branching off into side streets [55]. Distribution transformers are located at these intersection points to step down voltages from 12 kV to 480V to serve residential/smaller customer loads. The main purpose of a distribution system is to deliver power to end users; therefore loads which represent customers are placed across the network. Although customer loads vary throughout the day, with peaks in the evening, in this study, loads are assumed to be constant and distributed uniformly along the feeders. The total load in this circuit is about 17 MW. The distribution feeders consist of conductors, typically made of Aluminium, because it is less expensive and has higher current carrying capability. The conductors in this network are assumed to be Aluminium conductor steel-reinforced (ACSR). ACSR conductors have high mechanical strength-to-weight ratio and can withstand higher wind loads. All distribution lines are assumed to be overhead.

4.1.3 Protective Devices

Faults that occur in a power system due to failed poles cause abnormal voltages and currents in the system. These abnormal conditions are dangerous to human life and also cause extensive damage to system components. These faults are permanent are cleared only when repaired by utility personnel. Protective devices are therefore necessary to protect customers from danger, protect equipment and minimize power interruptions.

Protective devices are placed across the model to provide adequate protection to network components from faulty conditions. Three types of protective devices are considered in this work:

4.1.3.1 <u>Circuit Breakers</u>

Circuit breakers are the most important of the power system protective devices. They have the ability to interrupt high levels of fault currents. These are typically placed very close to substations and generators. Circuit breakers are connected to protective relays which detect fault conditions and by operating a contact that is integrated with the tripping system of a breaker, causes the breaker to open thereby interrupting the currents [79]. Relays are also connected to voltage and current instrumentation transformers that generate input signals that are smaller, but proportional to the voltages and currents in the power system. In this study, an overcurrent protective relay is used for fault protection.

4.1.3.2 Reclosers

Reclosers are automatically operated breakers. Reclosers have the ability to interrupt fault currents. They consist of breakers, current sensors and control circuits that are able to automatically open and close breaker contacts. When a fault occurs, high fault currents flow through the system. The reclosers detect these abnormal currents and operate the breakers to open and close multiple times. If the fault is temporary, and clears within the recloser operating cycles, then service is restored to customers. If the fault is permanent, the recloser interrupts the fault current so that downstream sectionalizing switches can operate to isolate the fault. It must be noted that this combined action of reclosers and switches requires coordination. In this study, the design and coordination of power system protection components is implied and are assumed to operate based on standard power system protection principle.

4.1.3.3 Sectionalizing Switches

A sectionalizer interrupts a circuit when the current is below a specified design value (usually the maximum load current in the system, and are called load break switches). The sectionalizer consists of a control circuit that monitors operating conditions and has the ability to control the load break switch. It could also contain manual controls. The switches have the ability to interrupt maximum load currents, but not the fault currents. When a fault occurs in the system, sectionalizers coordinate with reclosers to provide adequate protection. Sectionalizer monitors the fault current, counts the number of recloser open and close cycles to interrupt fault current, and opens switches after count reaches a specified programmed value. By opening the switch, the circuit is interrupted, thereby minimizing the impact of the fault current [79]. Sectionalizers are used for fault isolation, load interruption, and rerouting power flow between different sources of supply [80]. In this study, the term “switch” will refer to a sectionalizer.

As mentioned previously, distribution system data is not available publicly. Therefore, the location of the protective devices is assumed within the given network.

a. Circuit breakers are placed right next to the substations and offer the most protection to the substation. In this network, there are three circuit breakers corresponding to three substations. The circuit breakers are located next to the substations in Figure 4.4.
b. Reclosers are placed in each of the three sub-networks, two per sub-network. This is sufficient to monitor and interrupt fault currents that occur during hurricane scenarios. Figure 4.4 shows the recloser locations as blue circles.
c. Switches are placed approximately every kilometer of circuit length, total circuit length is about 155 km. Switches are placed on the primary feeder, at branching points of laterals from main feeder and at branching points within the lateral feeders [25]. Figure 4.4 shows the sectionalizing switches as marron diamonds. Three tie switches are located on the tie lines between the three substations. These switches are kept open under normal operation, and are put in use only to restore power quickly to a faulted circuit.

4.2 Methodology

The reliability assessment of the distribution network in this study is comprised of two approaches: topological, graph based approach for structural assessments, and power flow approach to monitor feasibility. The topological analysis is described first, followed by the flow studies. The final reliability framework is an integration of the two approaches.

4.2.1 Topology Based Methods

4.2.1.1 Outage Prediction

In the context of this research, risk management is in terms of extent of customer outages. Damage and power outage prediction is an integrated analysis combining power system models that includes the operation of protective devices such as circuit breakers, reclosers and sectionalizers, along with weather forecast models. Distribution systems affected by extreme weather result in large-scale outages in the network. A topological connectivity approach is used to assess the performance of the power system in this study.

The first step in determining outage zones is obtaining the failure probabilities of the utility poles under consideration. Probabilities of the pole failures are obtained by integrating fragility functions with hurricane models as described in CHAPTER 3. The failure probabilities are used to generate failure survival events for the poles assuming independent pole failures. According to [81], independent failure events represent the worst-case scenario for the failure of distribution poles. A random variable between 0 and 1 is generated, and this value is compared with the pole failure probability. If the randomly generated value is less than the probability of pole failure, then the pole is considered to have failed. If the random value is greater than the failure probability, then the pole is considered to have survived. Since the failure probabilities are assumed to be independent, this process is performed for each pole individually. One scenario refers to one failure or survival calculation for each of the 7051 poles used in the test network. A value of 1 implies that the corresponding pole has failed, while 0 implies that the pole has survived. A total of 1000 scenarios are considered in this study for each hurricane category, which means that the failure assessment is performed 1000 times for each pole. Therefore, 1000 scenario events are generated for the failure and survival of poles. The failure survival matrix is a $1000\ \times 7051$ matrix, with each row corresponding to one scenario. Failure survivals are generated for hurricane categories 1, 2 and 3 on the Saffir-Simpson scale (Table 1). Matrix value of 1 implies that the corresponding pole has failed, whereas 0 implies that the pole has withstood the hurricane winds. The survival model provides locations of the failed poles in the system under study for different categories of hurricanes. From this, the location of faulted nodes is obtained, under the assumption that faults occur at the location of failed poles. Therefore, impacts of hurricanes are assessed by investigating multiple simultaneous permanent faults. When a fault occurs in the system, the nearest protective device upstream to the faulted location is operated to isolate the high fault currents. If these fault currents are allowed to flow through the network for duration longer than allowable time, catastrophic damage will occur to system components and it is extremely dangerous to human life. For this reason, switches are opened to isolate the faulted section of the network, by doing so, the area of damage along with the number of interrupted customers is reduced. It must be noted that the operation of protective device follows a coordination scheme. A simple example is shown in Figure 4.5 to explain coordination on a fundamental level:

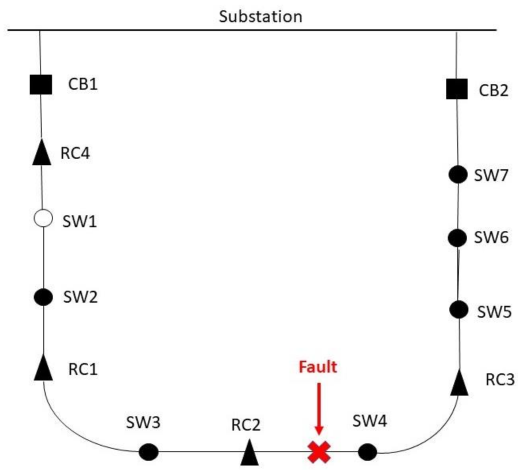


Figure 4.5 Illustrative example of protection coordination

The network shown in Figure 4.5 represents a distribution network with two generating sources protected by circuit breakers (given by CB1 and CB2). The circuit consists of four reclosers (RC1-RC4) and seven sectionalizing switches (SW1-SW7). SW1 is normally open to maintain radial structure of circuit. Consider that a permanent fault occurs as shown, between RC2 and SW4. This results in high fault currents flowing from the substation towards the point of fault. As mentioned previously, the fault must be isolated as soon as possible in order to minimize damages and outages. Among the protective devices, only the circuit breakers and reclosers have fault current interrupting abilities. RC3 senses the high currents and remains open after the pre-programmed reclosing cycles. By doing so, the section between SW1 and RC3 is isolated, and no fault current flows though this section. SW4 coordinates with RC3 and interrupts the circuit once RC3 is open in order to reduce the faulted area. Once SW4 is opened, RC3 is closed to restore service to remaining circuit components. The fault is now isolated between SW1 and SW4. To further minimize outaged areas, RC2 is opened so that fault is isolated to the small section between

RC2 and SW4. Once the fault is safely isolated, SW1 is closed to restore power to the remaining network sections. In this way, through the coordination of the protective devices, faults are safely isolated and confined within the smallest possible circuit area. Detailed discussions on power system protection coordination can be found in [55, 79, 82-85]. Protection coordination is an important consideration while developing optimal network reconfiguration algorithms.

The protection system disconnects the failed poles; since the system is radial, any fault in the network results in outages in all customers downstream. Pole failures result in the alteration of the network topology. While in normal operation, the system consists of three interconnected sub-networks, after pole failures and fault isolation, the system will be divided into multiple smaller networks, with several networks disconnected from power sources. Therefore, outage, in this context, is defined as the set of nodes not connected to any generating source. It must be noted that there is difference in terminology in this regard: failed pole refers to the pole that is directly affected by strong winds from storms, whereas outaged poles refer to all nodes that have lost connectivity to power sources as a result of faults due to the failed poles. The outaged poles therefore consist of failed poles as well as healthy poles. The method to determine the outaged nodes is based on topology and connectivity by considering the distribution network to be an undirected ‘graph’ made up of many ‘trees’. In this graph, every node is a wood pole or substation and every line section between two poles is an edge. This approach is advantageous because it is computationally efficient, and requires lesser system data to evaluate performance [25]. This is useful in the analysis of distribution systems where network data is hard to come by. A graph traversal algorithm, depth-first search, is used to traverse the graph node by node to determine paths to source nodes. This algorithm processes the graph vertices first deep, then wide. After processing a vertex, it processes all the descendants. The algorithm is as follows:

If a graph G is defined by $G = (N, E)$, where N is the set of vertices (or nodes, in this case) and E is the set of edges, the algorithm processes each node and gives it a "discovery time" when it is first processed and a finish time when all descendants are completed. The result is a collection of trees (or subgraphs) which is the set of node indices in order of discovery [86].

In the case of simultaneous pole failure, as in the event of hurricanes, multiple failed poles may be on the same feeder; however, since the network is radial, all poles downstream of the first failed pole are outaged. In this regard, computational redundancy can be reduced. An illustrative example is provided in Figure 4.6:

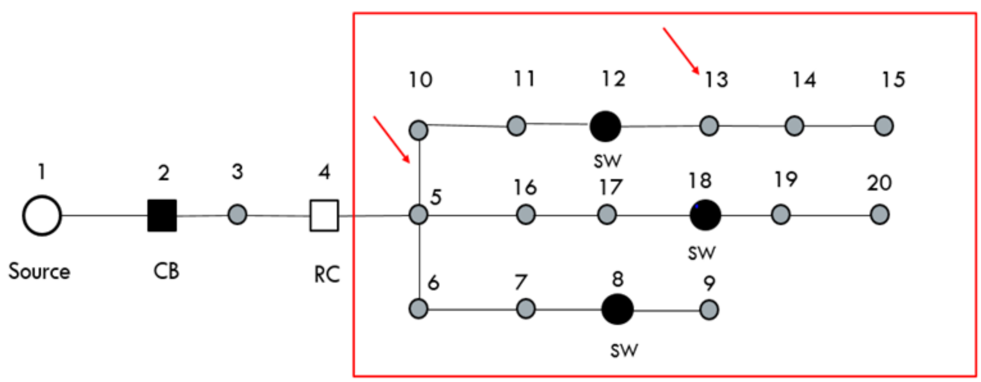


Figure 4.6 Illustrative example of fault isolation

Assume that in the above circuit, faults occur at nodes 5 and 13. To isolate the fault at 13, the switch at node 12 must open, resulting in outages at nodes 13, 14 and 15. To isolate the fault at 5, recloser at 4 must open, causing outages in nodes 5-20. Therefore, it is sufficient to perform outage analysis for node 5 since node 13 is located downstream and will be outaged anyway.

Every switch operation results in a change in the 'state' of the system, i.e. the graph of the network must be continuously updated to reflect the changes in topology due to device operation. The number of outaged nodes in the network is the sum of the outages nodes in each of the three sub-networks. The outages can be expressed in terms of number of poles, which is useful for assessing structural reliability or it can be expressed as the total power outage (in kilo-watts) for power system analysis.

4.2.1.2 Network Reconfiguration

When a hurricane hits the distribution system, large scale outages occur causing customer interruptions that can last from weeks to months. Current utility practice for power restoration involves significant manual labour, with repair crews travelling to the affected zones after the hurricane has passed and repairing the damaged poles one by one. This method takes a lot of time because the conditions in the hurricane affected zones must first be deemed safe, following which work crews perform a damage assessment and then begin repair. This process of repair of failed poles is an essential task, and cannot be eliminated from the restoration process.

However, actions can be deployed to reduce the customer outages during the storm, through an automatic, rapid reconfiguration process. This is an emerging concept in smart grid technologies. "Electric companies must respond safely, swiftly, and efficiently to restore service to large numbers of affected customers [87]." Electric companies typically form mutual assistance programs by partnering with other utility companies to unite all available resources for emergency response. Through these partnerships, utilities can request help from other utilities that are not affected by hurricanes. This is an important factor that will aid the process of automatic network reconfiguration, along with accelerating standard restoration practices. The ability of the distribution network to automatically detect failures and apply corrective actions, such as quick and flexible reconfiguration to restore loads, with little human intervention is called the self-healing capability of the system [88]. The technological changes required to support this capability are briefly described below [89]:

a) Advanced Metering Infrastructure (AMI): The installation of smart meters at customer locations. These meters will have the functionality of two-way communication, ability to monitor voltage and currents and relay this information back to the central operator. These meters will also be able to remotely disconnect services.
b) Distribution Automation: This is the most important design change that would enable automatic feeder reconfiguration as a response to hurricanes. Distribution automation (DA) involves automation of feeder protective devices that would enable them to transform into "intelligent" nodes and automatically perform the functions of Fault Location, Isolation and Service Restoration. These devices would be able to monitor feeder operating values such as currents and voltages, interrupt fault currents, and come equipped with communication systems that would enable communication with one another and the central operator. This allows for a flexible distribution network topology.

c) Distributed Generation (DG): Connecting distributed energy sources, such as renewables, to vulnerable points in the network, allows for the network to operate as multiple smaller islands or microgrids with their individual backup DG sources. More information on this topic can be found in [89].

In this study, to increase reliability of the network and to aid reconfiguration, additional lines with tie switches have been constructed in the network as shown in Figure 4.4.

These lines connect two ends of feeders from different substations, so as to provide additional paths for power rerouting. Since the tie switches are open under normal conditions, there three substation islands operate independently under normal conditions. Distribution lines served by the same substation have the same degree of vulnerability. The shortest possible line length is chosen for the tie lines, in order to reduce cost of construction. In all cases, the radial structure of the network is maintained [25]. In this study, optimization techniques to determine the location of tie-lines have not been considered. The tie switch locations have been determined based on visual inspection of the network graph.

In network reconfiguration, a whole or part of the feeder is re-routed to obtain power from another feeder section. This involves closing the tie switch in conjunction with opening a sectionalizing switch, to maintain network radiality. The feasibility of the switch combinations depends on the load flow data. The faults are first isolated by opening the protective devices upstream to fault locations. After isolating the faults, they must be contained within the smallest area possible. This is done by opening the corresponding downstream devices as well. In this way, all the protective devices surrounding the faulted locations are opened to contain the faulted regions. It must be noted that if a protective device is located on a failed pole, that device is no longer a viable candidate for reconfiguration processes. Following the isolation of faulted zones, the three tie switch candidates are connected sequentially in the outaged network. Since there are three tie switches viable for analysis, the number of switch connection combinations equals seven i.e. connect tie switches individually, then two at a time, and finally all three. If tie switch operation results in a constraint violation in the system (over-current or under-voltage), the tie-switch is opened and removed as a viable candidate. Otherwise, reconfiguration operation is successful. After each switch combination, graph traversal is performed to calculate outaged nodes. The process is repeated until all tie switches have been considered. From these, optimal tie switch connections are chosen based on two factors: the combination that results in smallest outages, and one that does not violate system limits. This analysis is performed for each of the 1000 scenarios and for each hurricane category according to the Saffir scale. The result of this analysis is discussed in CHAPTER 5. The algorithm provides as an output the outaged nodes as well as the isolating and closed tie switches (when applicable). Since hurricanes cause widespread outages, it is not possible under the existing system configuration and topographic constraints to reconfigure power to 100% of the system. In this case, partial load restoration is attempted. In fact, reconfiguration results in a marginal decrease in outages for hurricanes of lower intensity, and is not effective for stronger hurricanes. Figure 4.7 from U.S Department of Energy's Smart Grid report [90], demonstrates the operation of a Fault Location, Isolation and Service Restoration procedure. Fault isolation and network reconfiguration is automatic and controlled by a central Distribution Management System (DMS).

The distribution system in this research contains three tie switches for the three substation sub-networks; therefore, when coupled with the power flow constraints, the solution space is reduced such that optimization techniques such as non-linear and linear programming are not required [19]. However, for larger distribution systems, any of the commonly used optimization algorithms could be applied. Some studies that discuss these algorithms are [31, 73-77], which include multi-agent algorithms, simulated annealing techniques, greedy reconfiguration algorithms and other heuristic techniques such as reactive tabu search, tabu search, parallel simulated annealing, and genetic algorithm.

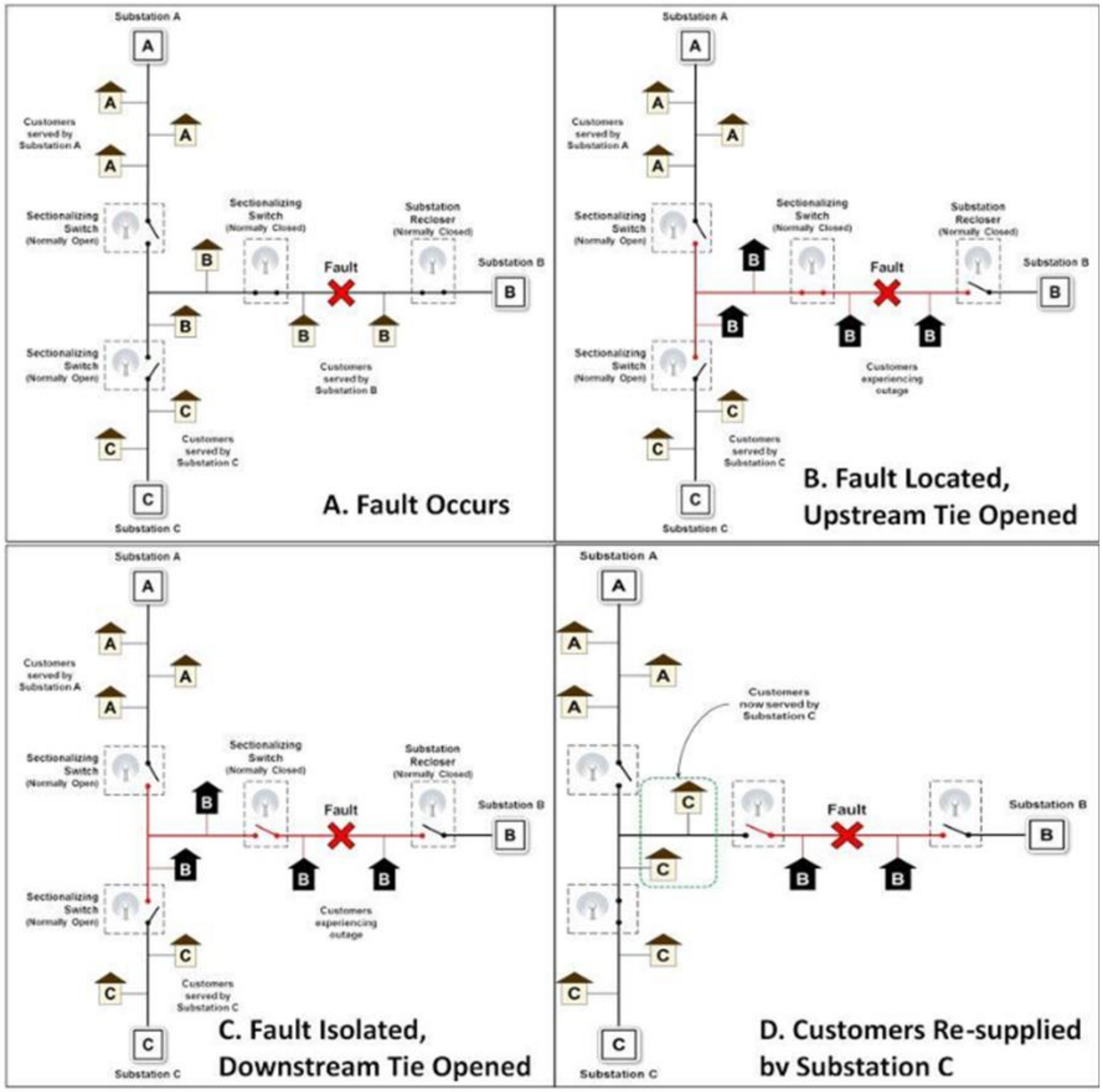


Figure 4.7 Fault Location, Isolation and Service Restoration Procedure [90]

4.2.1.3 Utility Restoration

While progress in smart grid technology will result in automation of several distribution system processes and enable faster and more effective service restoration, logical limits do exist. The smart grid does not replace the existing infrastructure completely, which means that a significant portion of system components are old and well beyond their service life.

For this reason, conventional restoration procedures cannot be completely replaced, but can be improved through more efficient emergency planning. Figure 4.8, obtained from Edison Electric Institute's report "Understanding the Electric Power Industry's Response and Restoration Process" outlines the restoration steps employed by utilities in response to storms [87]. As shown in the figure, the restoration follows a five-step sequence:

1. The primary sources of power are repaired first, as their damage would cause the largest impact on downstream systems.
2. In the second step, transmission systems are restored; this includes lines and towers.
3. Next, substations are assessed for damage and repaired
4. Steps 4, 5 and 6 involve restoring power to customers in the distribution portion of the grid. The priority ranking in descending order is: critical customers such as hospitals and fire stations followed by poles that restore power to most customers, and lastly individual homes.

After reconfiguration is performed, the restoration process begins. When a storm occurs, utilities mobilize a huge workforce, often taking assistance from partner utilities, to repair the damages as quickly and safely as possible. This is a part of phase 3 of the reliability study. The number of available crews required to meet the demands of the storm is dependent on advanced planning. The utility work crews can work on restoration only when it is safe to do so. Typically, damage assessments are conducted 24 hours after landfall. This includes extent of damage, equipment requirements for repairing downed poles and assessing accessibility. The authors of [18] discuss two critical factors that affect the post-storm restoration process, which has been adapted in this research. The first factor is the availability of resources and their mobilization.

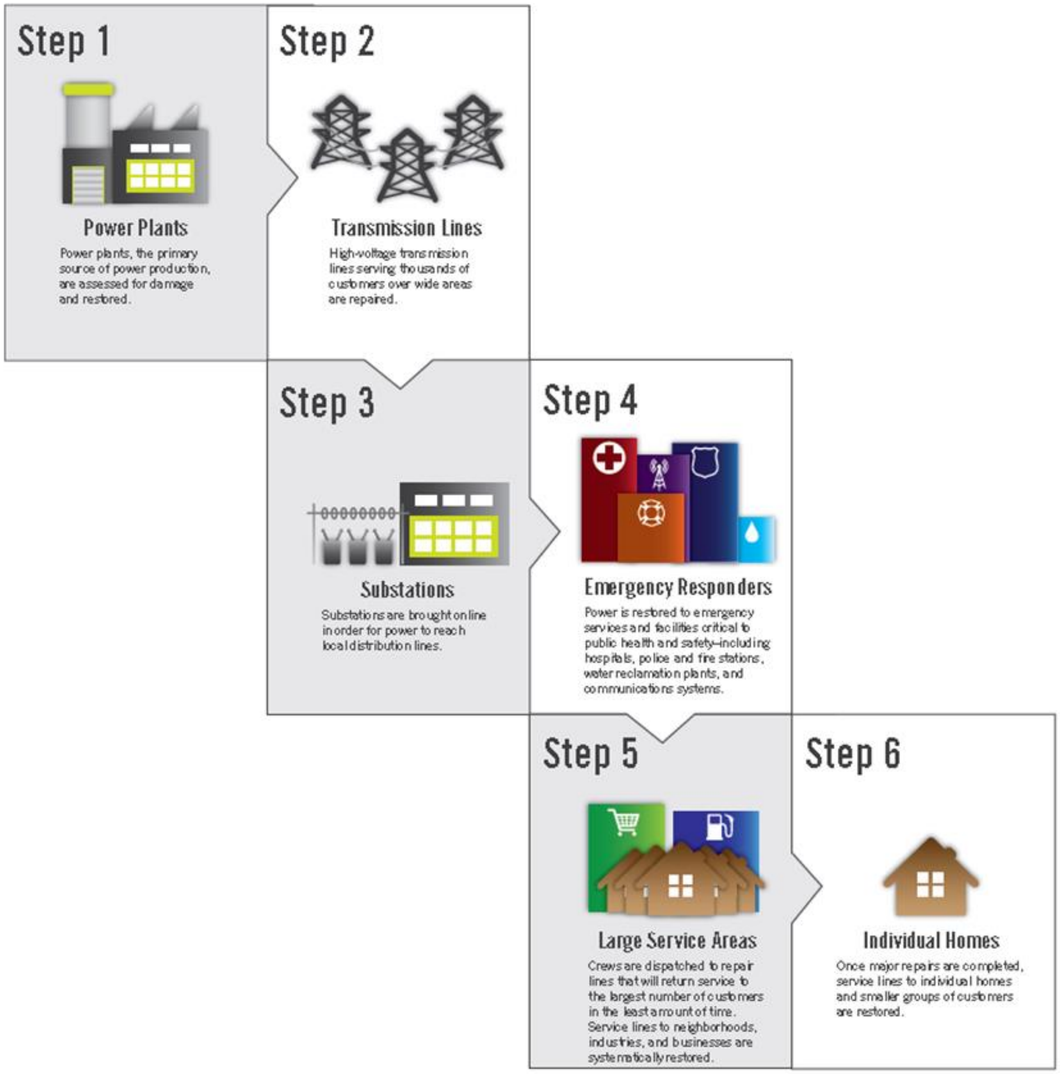


Figure 4.8 Utility storm restoration sequence

The resources required for restoration include work crews, equipment needed depending on what is being restored, transportation and communications infrastructure, etc. For example, the resources needed to repair a wood pole may be different from that needed to repair an underground line. A simplifying assumption is to consider resources as units; with all units having the same effectiveness in restoration. A 'unit' refers to one repair time consisting of work crews, equipment and vehicles [18]. Each damaged component, whether a substation, a local circuit, utility pole, or conductor, needs one unit of resource for its recovery [51]. A point to be noted is that resources could increase over time, when mutual assistance programs kick in. The second factor is the restoration sequence. As described earlier in this discussion, utilities first repair power plants and transmission structures. Following this, distribution systems are repaired with priority given to critical customers, and repairs that restore power to a larger section of the network. Usually, poles that are closer to the substation have higher priority because failure of those poles result in outages to almost the entire system. The pole repair function in this research depends on two factors: the number of available work crews, and the priority ranking of the poles. The number of work crews is assumed to be constant, i.e., dynamic resource mobilization is not considered. This research assumes 12 work crew units, with each crew working 12 hours a day. With regards to pole ranking, step 5 of the restoration sequence is considered for determining pole priority, i.e. the poles that restore power to higher number of customers are repaired first, and poles that serve smaller loads are repaired later. It must be noted that repair prioritization is also a constant, and is not updated after each repair event. While each component is assumed to require one resource 'unit' for recovery, the time required to repair and restore each component depends on the type of component. The repair times for damaged poles and conductors are assumed to be normally distributed variables, $N(5h, 2.5h)$ and $N(4h, 2h)$ respectively [51]. Repair is first performed on the critical nodes, to restore power to a majority of customers. After every repair, outage analysis is performed using the process described in Section 4.2.1.1. It is expected that outages reduce with each repair and finally reach a value of zero, in other words, 100% power restoration. This process is repeated for each of the 1000 scenarios for each hurricane category. From the 1000 hurricane scenarios generated for each hurricane category, a single hurricane event can be determined by averaging the 1000 scenarios. Finally, the resilience of the system can be calculated by measuring the normalized area under a time dependent restoration curve [51]. Resilience R, over time interval $[0, T]$ is given by [18, 51]:

$$R = \frac{\int_o^T Q_D(t)dt}{\int_o^T Q_N(t)dt} \tag{21}$$

where $Q_D(t)$ is the fraction of customers without outages in the hurricane affected network and $Q_N(t)$ is the fraction of customers without outages in the network under normal operation, at a time t. The time interval $[0, T]$ is the total time duration from the moment of hurricane landfall until power is restored back to 100%.

4.2.2 Power Flow Methods

4.2.2.1 Power Flow Analysis Model

The process of network reconfiguration is aided by a power flow analysis. A power flow analysis forms the basis for most analyses in a power system and captures the response of the system to changes in system parameters. It is essential to contingency analysis and real time monitoring systems[82].

The power flow problem is stated as:

"For a given power network, with known complex power loads and some set of specifications or restrictions on power generations and voltages, solve for any unknown bus voltages and unspecified generation and finally for the complex power flow in the network components." [82]

The first step in this analysis is the formation of the bus admittance matrix. If there are n buses (or nodes) in the system, this matrix is of size $n \times n$ and is made up of the admittances of the segments making up the system. It is represented as:

$$Y_{ij} = \begin{cases} y_i + \sum_{k=1,2,\ldots n; k \neq i} y_{ik} & \text{if } i = j \\ -y_{ij} & \text{if } i \neq j \end{cases} \tag{22}$$

where y_k is the sum of admittance of linear loads connected to bus k and the admittance-to-ground at bus k. The complex power injected into bus k of the power system is a product of voltages and currents:

$$S_k = V_k I_k^* \tag{23}$$

The current injection into a bus is given by

$$I_k = \sum_{j=1}^{N} Y_{kj} V_j \tag{24}$$

By using Equations (23) and (24) the following equations are obtained for real and reactive power [91]:

$$P_k = \sum_{j=1}^{N} |V_k||V_j| \left(G_{kj} \cos(\theta_k - \theta_j) + B_{kj} \sin(\theta_k - \theta_j)\right)$$

$$Q_k = \sum_{j=1}^{N} |V_k||V_j| \left(G_{kj}\, sin(\theta_k - \theta_j) - B_{kj}\, cos(\theta_k - \theta_j)\right) \tag{25}$$

where V_k is the voltage phasor with magnitude $|V_k|$ and angle θ_k, and G_{kj}, B_{kj} are the real and imaginary components of the admittance Y_{kj}.

These equations are known as power flow equations. For each bus in any power network, two out of the four quantities are known: $P_k, Q_k, |V_k|, \theta_k$, therefore there are two simultaneous non-linear equations available to solve two unknowns per bus[91]. These equations are solved iteratively, to arrive at the converged solution. The most commonly used algorithms to solve power flow are Newton Raphson, Gauss-Seidel, and Fast Decoupled Load Flow (FDLF). Power flow analysis is necessary to check line flow constraints so that violations do not occur during the processes of restoration.

The network used in this study has a large number of buses (>7000), which makes solving the power flow equations a challenging computing problem. For this reason, the open-source software tool OpenDSS has been used to perform the power flow simulations. OpenDSS, short for Open Source Distribution System Simulator is a simulation tool for electric utility distribution systems. OpenDSS is used to perform a distribution power flow in which the bulk power system is the main source of energy. It performs two types of power flow studies: iterative and direct. In the iterative method, loads are treated as injection sources. In the direct solution, they are included as admittances in the system admittance matrix, which is then solved directly without iterating. There are two types of iterative algorithms supported by DSS; these are "Normal" current injection mode and "Newton" mode. The Normal mode is the faster approach and has been used in this study. It is a fixed-point iterative method based on nodal admittance equations [92]. OpenDSS has been interfaced with MATLAB to perform the resiliency analysis. Further information about OpenDSS can be found in the reference guide [92]. It is assumed in this analysis that the power sources have sufficient capacity to meet the demands of this network configuration.

4.2.2.2 Faults in Distribution Systems

Faults in power distribution systems occur due to failures in insulation, physical damage or human error. When insulation failure occurs, a conductive path is formed between phase conductor and ground, or between two phases, causing excessive currents or abnormal voltages in the network. This is extremely hazardous to humans and animals, and can also cause equipment damage. Faults are caused due to lightening, trees falling on lines, breakdown of poles due to strong winds, to name a few [79].

Faults may be symmetric, involving all three phases, or asymmetrical, involving one or two phases. Symmetrical faults are analyzed through equivalent circuits, whereas asymmetrical faults require the use of symmetrical components. The four major types of faults in distribution systems are shown in Figure 4.9 shows the basic power systems fault: Clockwise - Three Phase Fault, Single Line to Ground Fault, Line to Line Fault, Double Line to Ground Fault.

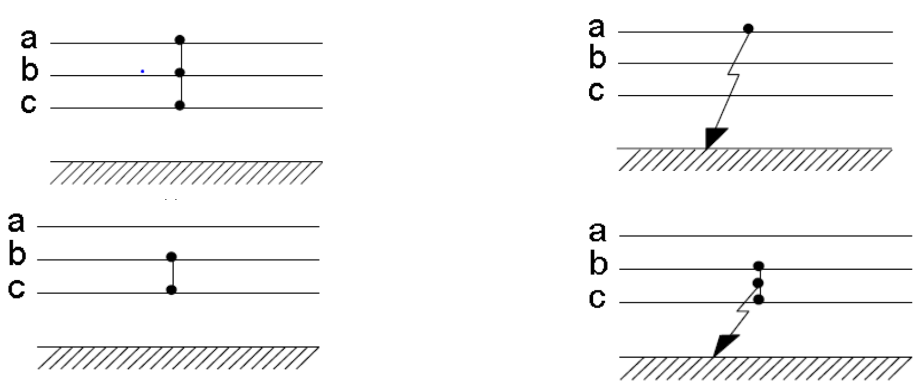


Figure 4.9 Types of power system faults [79]

In this research, faults have been modeled using OpenDSS, where the fault is a multi-phase, two-terminal resistor branch, with the second terminal connected to ground. During fault analysis, Y matrix for the network is built considering loads as admittances and generators to their Thevenin equivalents. Open circuit voltage is calculated by solving the Y matrix equations including source injections. Next, the Thevenin short circuit impedance is calculated for each bus. Using the Thevenin model, short circuit currents are calculated for each bus [92]. In this research, permanent faults are assumed to be caused due to the collapse or breakage of wood poles (that support the distribution lines) under the effect of strong winds. The test distribution system is equipped with protective devices to protect the system upon impact of multiple simultaneous faults caused by large scale pole failures.

4.3 Summary

In this chapter, the development and description of the power distribution network model used in the analysis is discussed. The network is synthesized from location data of 7051 wood poles obtained from a dataset of inspected poles in the southeast USA. The network is modelled as a graph with nodes represented by wood poles, and edges represented by line sections between the poles. Protective devices such as circuit breakers, reclosers and sectionalizing switches are placed along the feeders to provide adequate protection to the circuit in the event of fault conditions. The network described in this chapter will henceforth be referred to as 'original network' or 'weak network'. Topology and graph based methods are used to develop an outage prediction model in the event of hurricane occurrence, that provides information about vulnerable network sections. Following this, optimal network reconfiguration procedures are discussed. Network reconfiguration alters the topology of the distribution circuit by automatically changing the open/close status of network protective devices during hurricane occurrence so that the number of customer interruptions are minimized. This is a combinatorial optimization problem with multiple constraints that are monitored by using load flow techniques. Once the hurricane passes, and conditions are safe, utilities mobilize work crews to repair the damages and restore power back to 100%. The restoration scheme takes into consideration two factors: resource mobilization and pole priority.

In the next chapter, i.e., CHAPTER 5, the results of the optimal network reconfiguration procedure and utility repair and restoration scheme applied to the distribution network described in this chapter are discussed.

CHAPTER 5. SYSTEM ANALYSIS AND RESULTS

The ability of the distribution network to withstand and recover from wind related incidents is investigated through a study performed on the distribution system modeled in this research. This analysis is a combination of topology model and power flow model. Topology model considers the connectivity of the poles and treats the whole model as a graph system, whereas power flow model takes into account the system operating constraints such as generator capacity and line limits in terms of voltages and currents.

Two sets of distribution networks are considered. The first network is as described in the thesis so far, which has been constructed using pole data from a public database. This network shall be called the 'original network' or 'weak network'. Next, after assessing the results from the weak network, measures will be employed to strengthen it. The modified network will be called 'new network' or 'strong network'. The simulation results are presented below.

5.1 Original Network

The network used for the analysis in this section was described in Section 4.1. It is summarized here for reader convenience.

The network consists of 7051 wood poles whose GPS locations were obtained from a dataset of inspected poles located in the southeast USA. A majority of these poles belong to classes 3 and 5, and are older than 30 years. The locations of three substations are determined through inspection using Google Earth, in the same geographic area as the wood pole locations. A representative radial system is synthesized from the substation and pole location information, because the pole connectivity data is not available. The network is modeled as a graph with nodes represented by the poles, and edges represented by the line sections between two poles. Each substation serves its own sub-network, therefore the distribution system consists of three sub-networks. Each substation consists of a 36 MVA, 115 kV generating source. These three sub-networks operate independently under normal operating conditions, and are isolated from each other through tie switches that are normally open. Step down delta-wye transformers connected to the substations reduce the voltage levels from 115 kV to 12 kV suitable for a distribution system. The primary feeder consists of three phase conductor circuits and delivers 12 kV voltages. The thick yellow lines in Figure 4.4 represent the primary feeder. From the primary feeder, 480V lateral feeders branch off through distribution transformers that step-down voltages from 12 kV to 480V to serve residential/smaller customer loads. Loads are assumed to be constant and are distributed uniformly along the feeders. Loads are modelled as constant $P + jQ$ while lines are represented by their impedance values $R + jX$. The conductors in this network are assumed to be Aluminum Conductor Steel-Reinforced (ACSR). All distribution lines are assumed to be overhead. Protective devices are placed across the model to provide adequate protection to network components from faulty conditions. Three circuit breakers are placed next to the substations. Reclosers are placed in each of the three sub-networks, two per sub-network in order to monitor and interrupt fault currents that occur during hurricane scenarios. Sectionalizing switches are placed on the primary feeder, at branching points of laterals from main feeder and at branching points within the lateral feeders. The sectionalizing switches coordinate with the reclosers to safely isolate faulted network sections. Three tie switches are located on the tie lines between the three substations. These switches are open under normal operation, and are operated during reconfiguration procedures. The network described so far will be referred to as the 'original network' or 'weak network' since strengthening steps have not yet been discussed.

5.1.1 Pole age and class

As mentioned earlier, the data for the poles in this network is obtained from a utility inspection database in the southeast USA. The database contains pole location information, pole age, heights and class. Two major characteristics that govern the strength of wood poles are their age and their class. Table 5 provides the ANSI classification of wood poles based on class types. The ANSI 05.1 classification system is based on pole load capacity.

Table 5. ANSI classification of wood poles[93]

Pole Class	Horizontal Load (lb)	Length Range (ft.)	Minimum Tip Circumference (inch)
1	4500	35-125	27
2	3700	20-125	25
3	3000	20-90	23
4	2400	20-70	21
5	1900	20-50	19
6	1500	20-45	17
7	1200	20-35	15
9	740	20-30	15
10	370	20-25	12

The horizontal load (L_c) is applied 2 feet from the tip of the wood pole. The load includes wind forces, ice, line tension, guy tension and weight of conductors and mounted equipment such as transformers and protective devices. The bending moment (or applied bending load, in ft-lb) is given by

$$Bending\ Moment = L_C \times D \tag{26}$$

Where D is the height of the pole from ground line to two feet from the pole tip.

An illustration of this equation is provided in Figure 5.1.

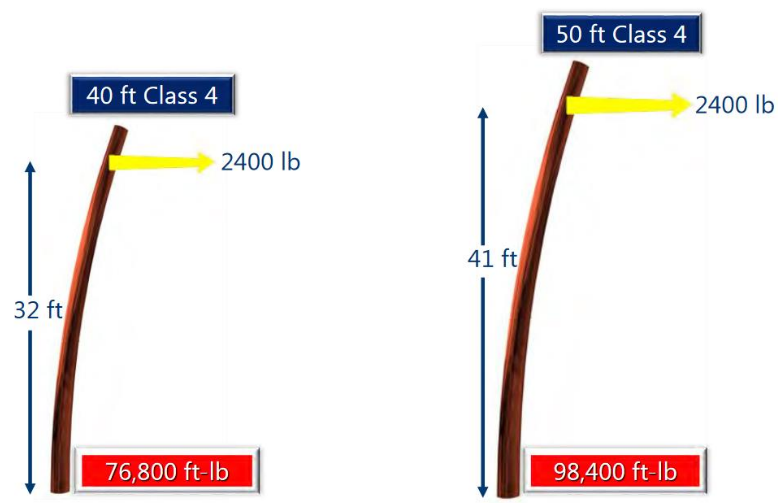


Figure 5.1 Bending Moment (ft-lb)

The bending capacity of poles (ft-lb) is given by:

$$k \times fiber\ strength \times C^3 \tag{27}$$

Where k equals 0.000264, fiber strength for Southern Yellow Pine is 8000 psi, and C is the pole circumference.

The pole survives when the bending capacity is greater than the applied bending load. An increase in pole circumference therefore increases pole strength by an order of 3. This is why poles belonging to a lower pole class have greater withstand capacity than poles of higher classes.

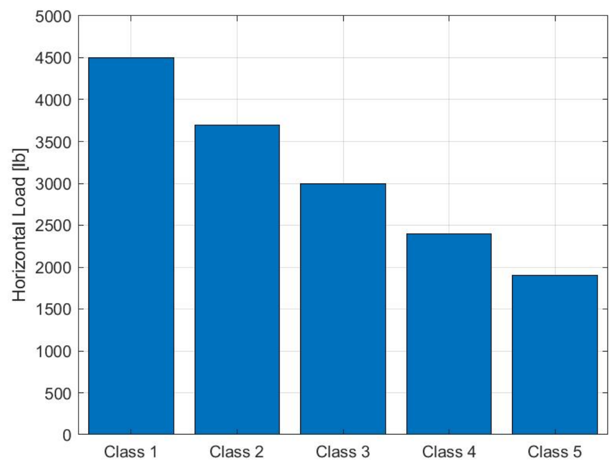


Figure 5.2 Loading of pole classes

Figure 5.3 and Figure 5.4 show the range of pole ages in the given network depicted over the network graph and as a pie-chart, respectively.

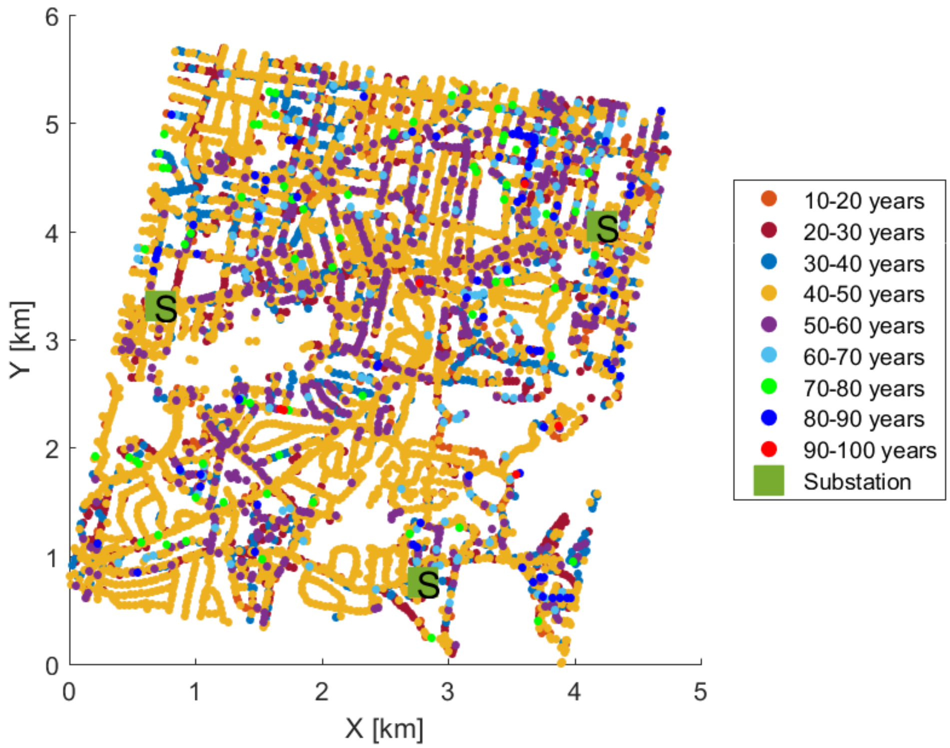


Figure 5.3 Age distribution of wood poles in original network

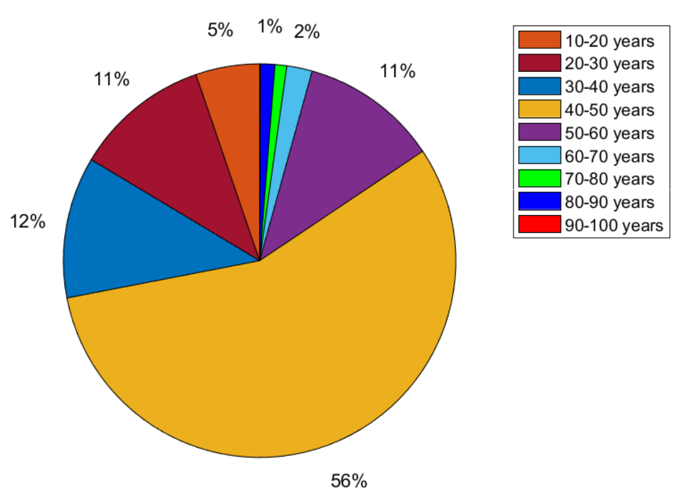


Figure 5.4 Age of wood poles in original network (in %)

It is not surprising that the majority of poles are over 30 years old. In this case, over 60% of poles are greater than 30 years old, with poles being as old as 90 still in service in some parts. An interesting finding from the network graph is that the substations are surrounded by many poles that fall in the 50-60-year age category. This is significant because most utilities estimate service life of wood poles to be 30-40 years [94]. In the report provided by Quanta Technology [95], the United States is divided into 5 wood decay hazard zones based on the level of environmental harshness towards wood poles. Zone 5 indicates harshest environments and Zone 1 indicates most benign. Southeast USA falls under Zone 5, with expected lifetime of wood poles about 41 years. This goes to show that these poles are old and extremely vulnerable to weather effects. This is important because pole failures near the substations cause larger customer interruptions than pole failures towards the ends of feeders. Therefore, weak poles near the substations have a significantly detrimental effect on the system reliability.

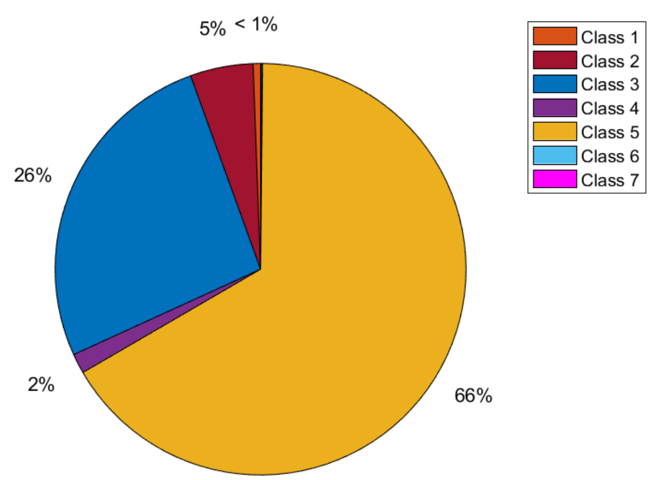


Figure 5.5 Class of wood poles in original network (%)

Figure 5.5 and Figure 5.6 present the class types of the poles in the given network. It is seen that over 50% of the poles belong to Class 5. Pole classes are defined such that the higher the pole class, the smaller is its ability to withstand strong wind forces i.e. lesser strength. Class 5 poles are weaker than Class 4, with Class 1 being the strongest.

The poles surrounding the substations are mainly of Classes 5 and 3. This combination of old poles and higher pole classes leads to substation poles being weak and easily breakable, and cause large outages even for Hurricane Category 1.

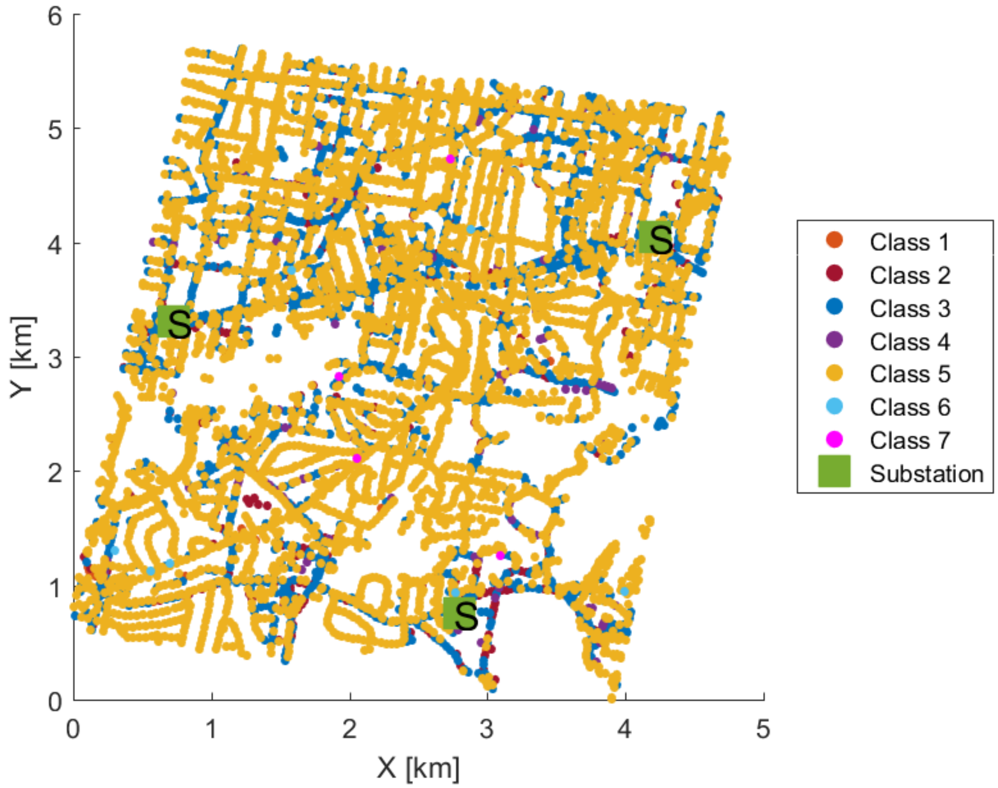


Figure 5.6 Class distribution of wood poles in original network

5.1.2 Pole Failures

The pole failure probabilities are obtained by integrating their fragility functions with hurricane hazard models which are dependent on their wind speeds. Failure survival events are generated using the probabilities of independent pole failures. These events are matrices with values of 0 or 1; 0 implies pole survival and 1 implies pole failure. 1000 scenarios for failure and survival are generated for each hurricane category. Figure 5.7 - Figure 5.10 show the failure percentages of each pole in the 1000 scenarios overlaid on the distribution network graph to provide a geographic visualization for hurricane categories one through four respectively. Poles that fail more frequently (within the 1000 scenarios) have a higher failure percentage and darker shade of red in the graph below. This implies that darker poles are those that fail more frequently and are more vulnerability to hurricanes.

These graphs reveal that the number of pole failures increases significantly with increase in hurricane severity. Observe that when a Category 4 hurricane makes landfall on this system, nearly all the poles experience failures within the set of scenarios. This finding suggests that a higher intensity hurricane would cause catastrophic damage on the system.

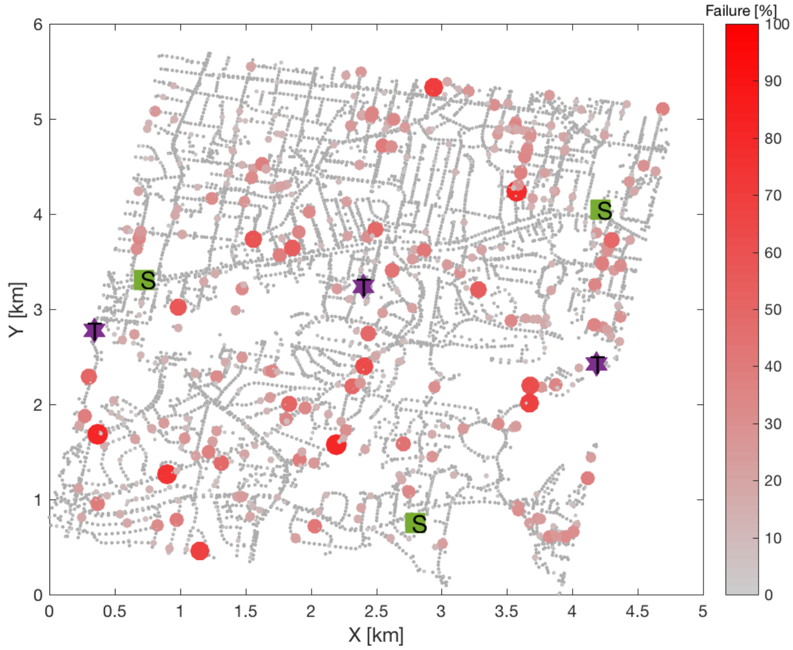


Figure 5.7 Hurricane Category 1 – failed poles (% occurrence in original network)

As discussed in the previous section, there are a considerable number of vulnerable poles surrounding the substations in this original network. Failure of poles those are closer to the substations result in larger outages when compared to poles that are farther away.

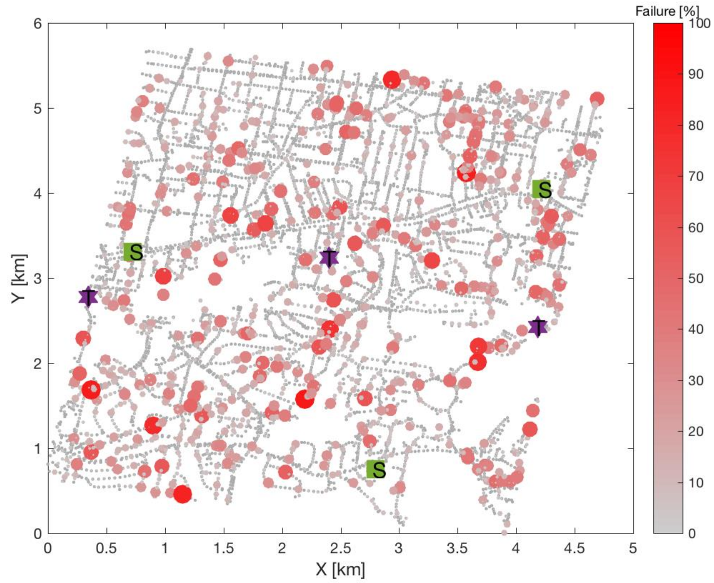


Figure 5.8 Hurricane Category 2 – failed poles (% occurrence in original network)

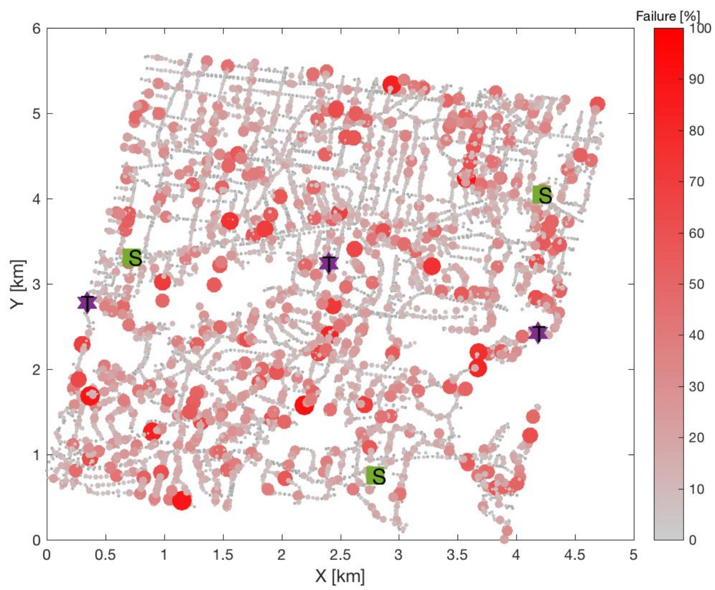


Figure 5.9 Hurricane Category 3 – failed poles (% occurrence in original network)

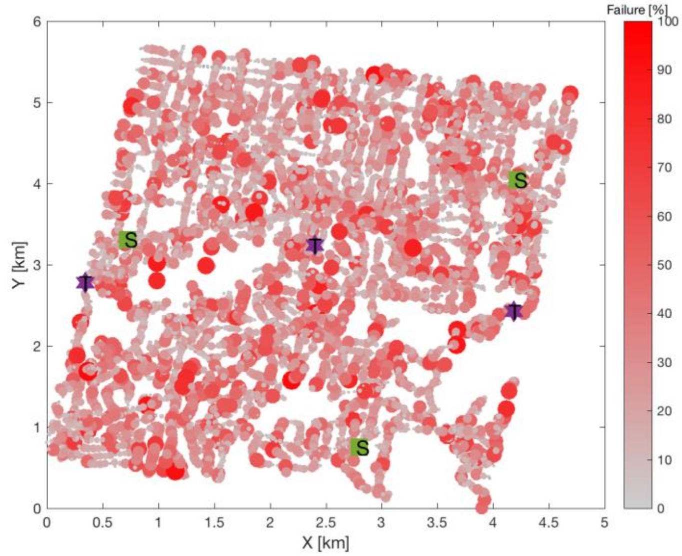


Figure 5.10 Hurricane Category 4 – failed poles (% occurrence in original network)

5.1.3 Nodes that Experience Power Outages

When a pole failure occurs, the protective devices operate to isolate the faulted sections of the network and reduce the impact of the fault by preventing it from affecting large areas of the network. The opening of fault isolating switches results in multiple nodes losing connectivity to power sources. Nodes which are not connected to any substation are considered to be outaged. Figure 5.11 presents the outage node data for 1000 scenarios of Hurricane Category 1 as a percentage outage rate, i.e., the number of times the node experienced outage in the 1000 scenario set. Poles that experience higher outage frequency are represented by darker shades of red. For example, a pole that experiences outage in each of the 1000 scenarios will be darkest, while a pole that never gets outaged in any of the scenarios is the lightest. This information is useful because the darker regions in the network are more susceptible to customer interruptions than the lighter sections.

In Figure 5.11, every node is red, which means that each node has experienced an outage once in at least one scenario out of 1000.

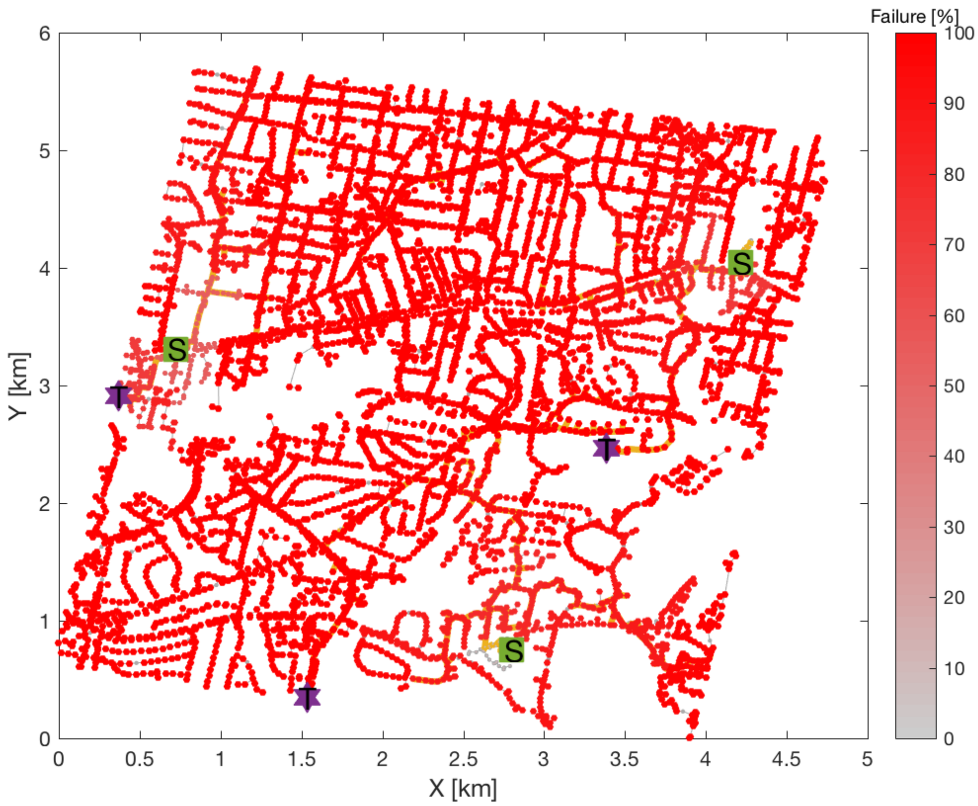


Figure 5.11 Hurricane Category 1 – Outaged Nodes (% occurrence)

The graph of outaged nodes reveals that a majority of the poles are outaged during every hurricane scenario. An average of 95% of the nodes is outaged upon impact of Category 1 hurricane as seen in Figure 5.12.

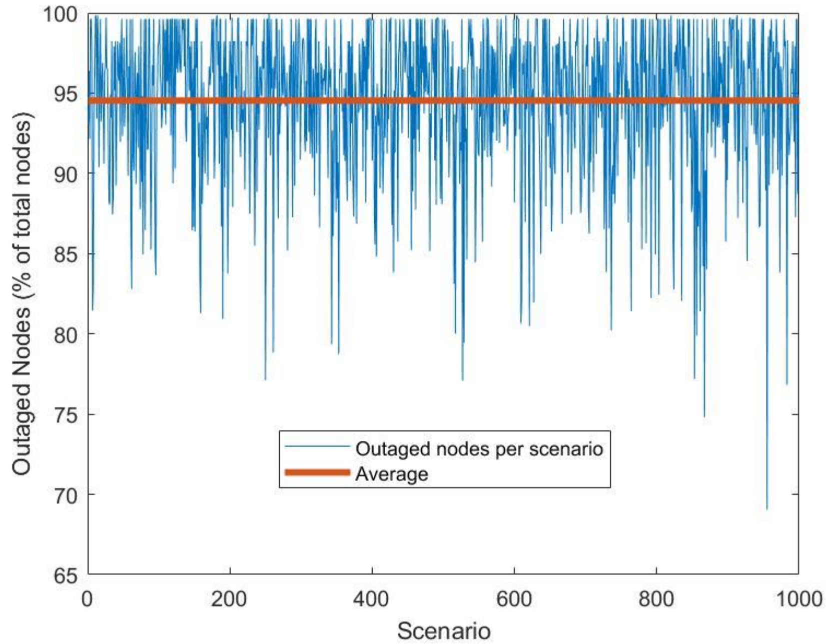


Figure 5.12 Outaged nodes for each scenario of Hurricane Category 1 as a percentage of the total number of nodes in the system

This further corroborates the finding that the wood pole infrastructure of the existing system is weak and ageing with over 60% of the poles more than 30 years old. When poles near the substations fail, the main circuit breaker protecting the substation opens to protect the system from large fault currents. The opening of the circuit breaker results in disconnection of the entire sub-network from the power source. For this reason, it is critical to ensure that poles close to the sources are strong and have high withstand capacity. Another interesting correlation is between pole class and outages. Majority of the poles belong to Class 5. The existence of class 5 poles in the immediate vicinity of the substations makes the network extremely vulnerable to high wind speeds and is a reason for large scale network outages.

To conclude, it must be noted that most structural assessments do not factor in the age of poles when performing strength studies, however, aging infrastructure is of growing concern in today's power distribution network [28]. Vulnerability models that are a combination of pole age, fragility, and weather hazard data are necessary to drive resiliency decisions [30]. Therefore, in this research, the pole fragility models take into account pole age and pole class as important factors affecting pole survival in the event of hurricanes.

5.1.4 Network Reconfiguration

Reconfiguration is an automatic process that begins when the hurricane hits the system. After faults have been isolated, large portions of the network remain without power. While it is difficult to restore 100% of the power exclusively through reconfiguration, it is possible to reduce the number of customer interruptions. The reconfiguration scheme is realized by changing the status of the protective devices in the network, thereby altering the topology as well as the operating quantities of the system. This process involves a search over feasible radial configurations. Network reconfiguration is a combinatorial, multi-constraint optimization problem described below:

5.1.4.1 Problem Formulation

The given distribution network is represented in the form a graph G with the wood poles representing the nodes/vertices of the graph, V, and the feeder line sections representing the edges of the graph E. The distribution lines are modelled as impendences $R + jX$. Every graph edge is between two nodes. Given this graph, the objectives of the optimization problem is to:

Minimize the total number of healthy customers that experience power interruptions.

$$Min\ f(X) = \sum_{i=1}^{n} C_i - \sum_{i=1}^{n_c} C_i \tag{28}$$

Where, $f(X)$ is the total number of outaged loads in the hurricane affected network which is the difference between total in-service loads in the system under normal operation and total in-service loads in system after reconfiguration (It must be noted that in-service refers to loads that are connected to a power source), X is the state of the system represented by the open/close status of the sectionalizing and tie switches, n is the number of in-service load buses in the system before occurrence of hurricane, n_c is the number of in-service load buses in system after network reconfiguration and C_i is the load on the i^{th} bus. Loads are distributed uniformly across the feeders and are modelled as constant power loads $P + jQ$.

Subject to the constraints:

a) Radial network structure must be maintained

b) Bus voltage limits must not be violated

$$V_{min} < V_i < V_{max} \tag{29}$$

Where V_{min} and V_{max} are the minimum and maximum allowable bus voltages, respectively, and V_i is the voltage at the i^{th} bus.

c) Current magnitude of each branch must lie with its permissible range

$$I_j \leq I_{max} \tag{30}$$

Where I_j is the current in the j^{th} branch, and I_{max} is the maximum allowable line current.

The operating constraints are monitored by integrating load flow analysis model (OpenDSS) with the graph/topology model (MATLAB). The theory behind load flow analysis has been discussed in Section 4.2.2.

The network consists of normally closed switches whose primary function is to isolate a fault and three normally open tie switches whose primary function is to connect two feeders or laterals. By appropriate combinations of the status of tie and sectionalizing switches, branch exchanges take place and loads are transferred between feeders. Load transfers are feasible provided the system line constraints such as voltage and current constraints are within acceptable limits. Out of the seven possible combinations of the three tie switches, the optimal configuration is one that restores most power, while maintaining the constraints.

The network reconfiguration is complemented by the power flow model developed in OpenDSS to check the line flow constraints. At every instance of change in network configuration, load flow study must be assessed to determine if the switch operations are feasible. In this procedure, the network topology changes three times: the first topology is the base case under normal operation of the system, the second topology change occurs when the hurricane hits the system, and protective devices are opened to isolate the faults, and finally the third change occurs when tie & sectionalizer switches coordinate to re-route power to reduce outages. Therefore, for every scenario within a hurricane simulation, load flow is performed thrice. One disadvantage of this process is that it can be computationally intensive. Once a feasible re-routed power network configuration has been achieved, outaged nodes are evaluated once more to determine customers without power. Unfortunately, in this weak network, the reconfiguration scheme reduces customer interruptions only by 0.55%. Since this network covers a smaller geographical area of about $3\,Miles \times 3\,Miles$, all three substations are in the vicinity of the hurricane, and are significantly strongly affected by the wind forces from Hurricane Category 1, despite it being the lowest intensity hurricane (Figure 5.11). This can be attributed to the weak infrastructure of the system, as discussed previously. This causes significant outages in all three substation islands (~95% outage). This means that sufficient rerouting capacity and/or network path is not available within this system to provide for significant outage minimization through reconfiguration while maintaining operating constraints. Therefore, optimal network reconfiguration algorithm does not result in significant reduction in customer interruptions for this network configuration. It must be noted that longer feeders are more vulnerable to outages since they have more nodes connected to them. One way to improve efficiency of reconfiguration is by strengthening the poles. This will be discussed in the upcoming sections.

5.1.5 Power Restoration

As seen in the previous section, the process of reconfiguration reduced outages only by 0.55%. To restore power to all customers such that 100% restoration is achieved, the broken poles must be repaired or replaced depending on the level of damage. After damage assessment is completed, and conditions are determined to be safe, repair crews are mobilized to begin the repair process. In this analysis, the total number of work crews is assumed to be 12. Each work crew works for 12 hours a day, i.e. one working day equals 12 hrs. Therefore, 6 work crews are available at each instant of time 24 hours a day. The work crews are assumed to repair poles and conductors with a restoration time that follows normal distribution: mean of 5 hours and standard deviation of 2.5 for poles, mean and standard deviation of 4 and 2 for conductors, respectively[18]. The restoration time for each node (which has a pole and a connected conductor) is assumed to be the maximum of the restoration time for the poles and conductors. The restoration scheme considers the fact that the system is radial, which means that failure of an upstream pole results in outage of all downstream nodes. Repair of the poles begins with the pole closest to the substation and ending with poles at the ends of the feeders. All the poles in the network are ranked according to priority. This is done by running outage scenarios for each pole failure in the given system. The pole which causes the highest customer outages has priority 1 and so on. Repair is performed in the order of descending priority. For every scenario, three data points are considered: the network outages upon hurricane landfall, network outages after reconfiguration and outages after utility repair and restoration. The outages are depicted as time varying plots.

Two metrics are chosen for assessing the system performance: the first of which is the Quality metric, given by [60]:

$$Quality(\%) = 100 - \frac{N_{out}}{N_{tot}} \tag{31}$$

Where N_{out} is the number of nodes disconnected from power sources, and N_{tot} is the total number of nodes in the system.

A performance (also known as restoration) curve is generated in which quality metric is presented as a function of repair time (days). Performance curve is simulated to relate the fraction of customers with power to the time after hurricane landfall, considering the restoration process described [51]. The graphs in Figure 5.13 and Figure 5.14 show the percentage of customer outages and percentage quality curves with respect to repair time in terms of workdays (1 workday is assumed to be 12 hours) obtained by averaging data obtained from 1000 simulation runs for Hurricane Category 1.

The procedure to compute these curves is described as follows. The time scale is in terms of number of workdays. At time $t = 0$, hurricane landfall occurs causing multiple faults due to pole failures in the network. In order to isolate these faults and minimize the impact on the healthy parts of the system, protective devices are opened to restrict the faulty sections. As a consequence of this switch operation, some of the otherwise healthy network sections lose connectivity to power source. The customers at the nodes of the network that do not have a path to any power source experience power interruptions, and the number of customers losing power is given by the term N_{out} in Equation (31). N_{tot} is the total number of nodes in the network, 7051 in this case since the loads/customers are uniformly distributed across all feeder sections. As discussed previously, for each hurricane category, 1000 scenarios are generated, with each scenario containing data about the failure and survival of the poles. Therefore, from each scenario, the number and location of poles damaged (or failed) due to hurricane winds is obtained. This allows for the determination of the appropriate devices that must be operated to protect the system in each scenario. Since the network is represented as a graph, graph algorithms such as depth first search and connected components are used to traverse the feeder lines along the graph nodes. A connected component of the network is a subgraph in which the vertices are connected to each other by paths. The connected components represent network pieces, or trees. The depth first graph traversal is used to determine the connectivity by first initializing a component number field for each node to be 0 and then search for component 1 from the initial node. As each node is visited, the field value is set to the current component number. In MATLAB, if two nodes are connected, they have the same component number. Through this algorithm, the nodes connected to power sources are determined after the isolation operation of protective devices. The difference between the total number of connected nodes and the number of nodes connected to sources after hurricane landfall gives the value N_{out} per scenario. As discussed previously (Figure 5.11), about 95% of the network is outaged upon landfall of Hurricane Category 1. Therefore, the outage is 95% at time $t = 0$. After hurricane landfall, to restore power to all customers in the original network, pole repair is the most effective course of action since automatic reconfiguration does not have a significant impact. The poles are ranked according to priority, i.e., according to the number of outages caused due to each pole failure. Since each of the 1000 scenarios consists of failed poles, repair scheme is implemented for each scenario. First, the total number of failed poles per scenario is determined by counting the number of 1s in the dataset, since 1 represents failed pole. The failed poles are then ranked according to importance; the pole that causes more failures gets higher repair priority. The repair is performed in order of this pole ranking. It is assumed that 12 work crews are available with a working time of 12 hours for each crew. The repair time for poles and conductors follows a normal distribution with a mean of 5 hours and 4 hours, and standard deviation of 2.5 hours and 2 hours, for poles and conductors respectively. The repair function provides the time taken (in hours) for each pole repair in order of priority. The next calculation is the reduction in outages per pole repair. It is assumed that the pole repairs occur sequentially, therefore, after each pole repair, connected component and graph traversal algorithms are applied to calculate the nodes without power. In other words, after each pole repair, N_{out} is determined. After the repair of the last failed pole, N_{out}=0, which means that power is restored back to 100%. Therefore, for each pole repair, two data points can be obtained: the repair time and the number of outages. The number of outaged customers are expressed as a percentage of total customer nodes (N_{out}/N_{tot}). This above process is repeated for each of the 1000 probabilistic scenarios for Hurricane Category 1 resulting in 1000 datasets. The average of the1000 curves is presented in the form of one single curve that varies with respect to repair time (in workdays) as shown in Figure 5.13. It can be seen that outage percentage is 95% at the time of landfall ($t = 0$). As time progresses with implementation of repair procedures, the outage percentage reduces until it reaches 0.

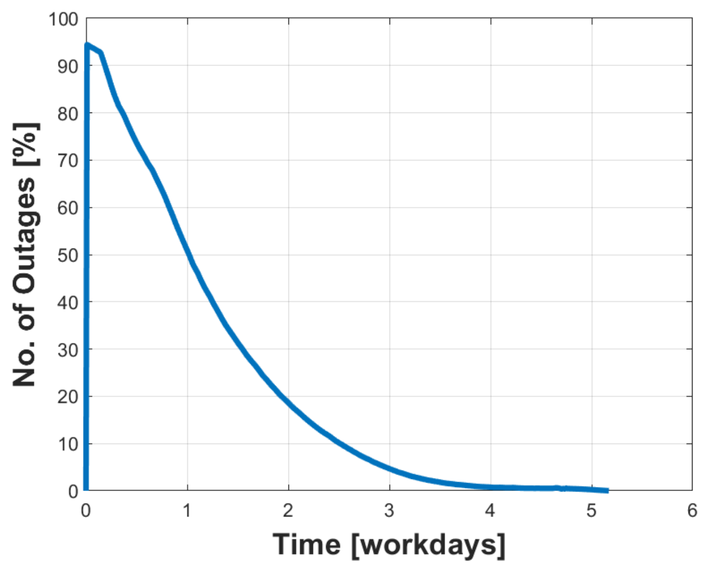


Figure 5.13 Outage Curve for Hurricane Cat 1(Original System)

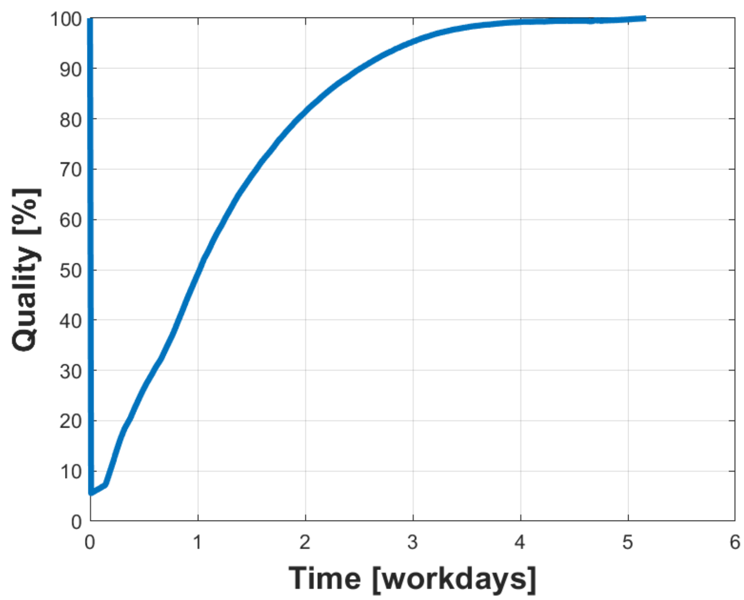


Figure 5.14 Quality Curve for Hurricane Cat 1(Original System)

Another representation of the outage and repair process is the Quality metric discussed in Equation (31). The quality metric is calculated to represent outage and restoration data in the form of a quality or performance(restoration) curve as shown in Figure 5.14. For each scenario of Category 1 hurricane, the quality metric is computed at hurricane landfall ($t = 0$) and after every pole repair in order of priority. The quality curve, just like the outage curve, is a time varying graph. 1000 quality curves are computed, one for each scenario. The average of the1000 data sets is calculated to generate one performance curve as shown in Figure 5.14. Upon hurricane landfall, the quality of the system drops to a low value of 5%. In many of the scenarios, because of the presence of failed poles close to the substations, there are major outages upon impact of the hurricane (>95%). Since the reconfiguration procedure is restricted to the network under consideration, it does not cause a notable reduction in outages (about ~0.55%). Therefore, repair is the most effective course of action. An example of large outages occurring in real distribution systems of smaller areas is the case of an electric utility in the Gulf Coast of the USA impacted by Hurricane Katrina. The service area consists of 6,681 grid cells with dimension of 12,000 × 8,000 ft. (3.66 × 2.44 km), in which more than 80% of the customers experienced outages and restoration efforts took 12 days [36].

From Figure 5.14, it can be seen that the quality of the system (average) increases from 5% to 100% in about 4.5 workdays. Therefore, it can be concluded that for Hurricane category 1, in the original system, 100% power is restored in 4.5 days.

The second metric is the resilience. As discussed in the previous chapter, this is given by:

$$R = \frac{\int_o^T Q_D(t)dt}{\int_o^T Q_N(t)dt} \tag{32}$$

Where, $Q_D(t)$ is the fraction of customers without outages in the hurricane affected network and $Q_N(t)$ is the fraction of customers without outages in the network under normal operation, at a time t. As discussed in the previous paragraph, the ratio (N_{out}/N_{tot}) provides the fraction of customers with outages in the hurricane affected network; therefore Q_D =1- N_{out}/N_{tot} is the fraction of customers without outages in the hurricane network. This has been calculated to be the quality metric from Equation (31). Therefore, the resilience metric can be expressed as:

$$R = \frac{\int_0^{t_{end}} Q.dt}{100\ T_{end}} \tag{33}$$

Where Q is the quality metric, and T_{end} is the time taken for power to be restored to 100% after hurricane occurrence. For Hurricane Category 1, as calculated in Figure 5.14, this value is ~4.5 workdays. The resiliency metric is calculated by the numeric integration of the area under the average quality curve in Figure 5.14. In other words, this value is the normalized area under the time-dependent quality curve of Figure 5.14 [51]. The value of resilience for this network is calculated to be 77%. It must be noted that the final quality curve was computed by calculating the average of 1000 quality curves, one for each scenario. Therefore, the resilience value of 77% is the mean value computed for the 1000 hurricane simulations.

5.2 Strengthened Network

5.2.1 Strengthening Steps

Most utilities have electric distribution networks that are radially connected. In radial systems, there is a unique path from the source to each node/customer. Any failure in a feeder node causes outage in all downstream nodes [25]. For this reason, radial distribution system configurations are less reliable. In the original network developed in this research, towards the goal of increasing reliability, tie lines controlled by tie switches were constructed to provide automatic and instant rerouting options from neighboring feeders in the event of hazards. These tie switches are kept open under normal operating conditions to ensure that any two substations are not connected, however, if the need arises, one or more tie switches can be closed to provide alternate paths for power rerouting from neighboring substations. As the results revealed, in the weak distribution system, reconfiguration techniques were not effective and did not result in significant reduction in outages. The primary cause of this was the presence of a large number of old and vulnerable poles throughout the system, and especially around the substations. In such situations, although the number of failed poles is small because they are located next to the substations, they can still cause massive outages.

In this regard, there are two methods for strengthening the poles and thereby improving system reliability. One method is to lower the class of poles surrounding the substations, because lower pole classes are stronger and can withstand higher wind forces. The second method is to replace the old poles with newer poles [64]. Typically, in a distribution system, this is done during an inspection program. The system is strengthened by a combination of pole class and age upgrades. In order to strengthen the system through class changes, a semi-automatic procedure is applied [68] where the impact of individual pole failures is determined in terms of number of network outages, and this impact is used to determine class and age upgrades. For example, a pole whose failure causes large network outages is a critical pole and is replaced by a new Class 1 pole. The pole class is upgraded according to the pole priority, i.e. the set of poles that cause the largest outages are replaced by the strongest poles i.e. new Class 1 poles, the set of poles that cause the next largest outages are replaced by Class 2 pole and so on [64].

5.2.2 Pole Class and Age

Figure 5.15 and Figure 5.16 show the age and classes of poles in the stronger network. It can be seen that the poles surrounding the substations have been replaced by new, Class 1 poles. These poles have a higher capacity to withstand strong hurricane winds.

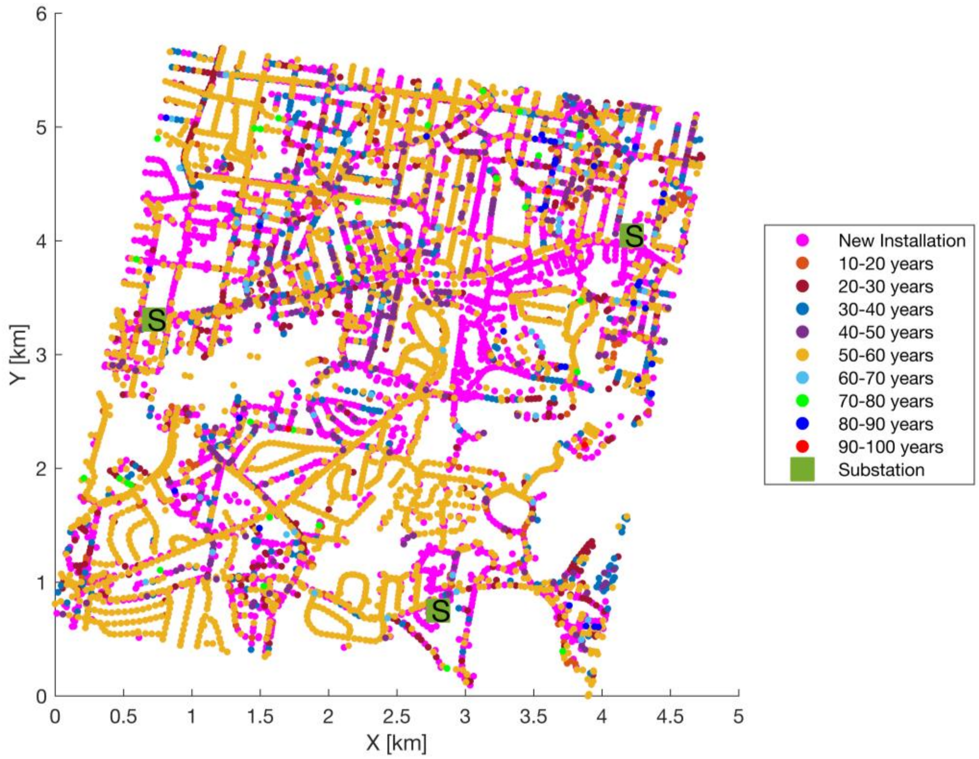


Figure 5.15 Age distribution of poles in strengthened network

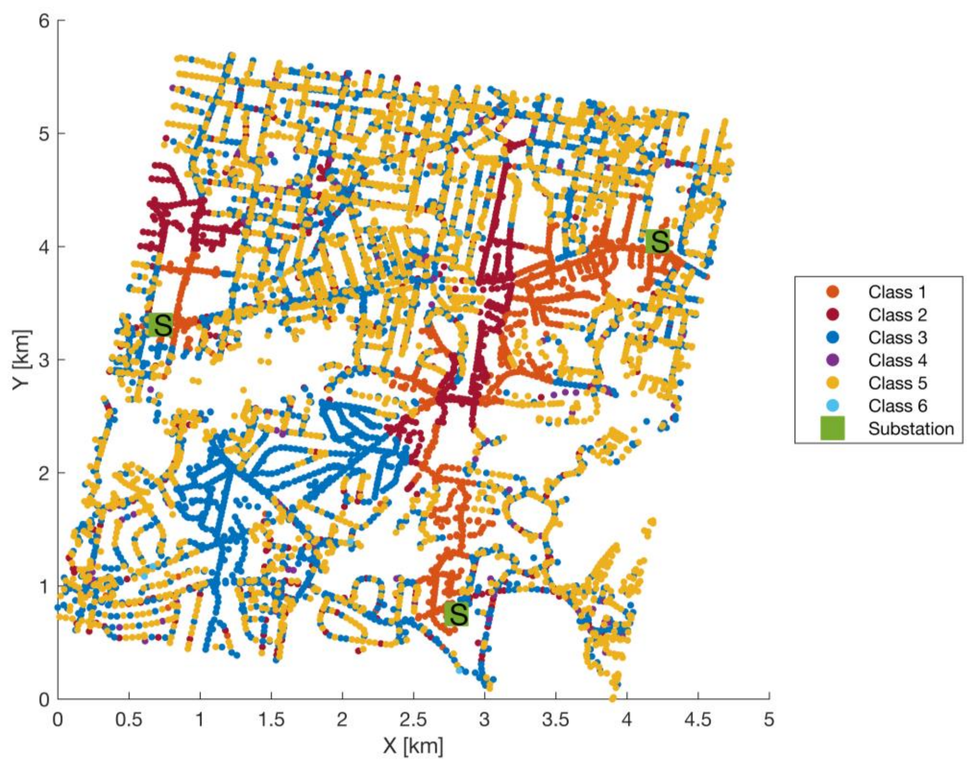


Figure 5.16 Class distribution of poles in strengthened network

Figure 5.17 and Figure 5.18 reveal that the stronger network has a larger number of Class 1 and 2 poles. Also, almost 40% of the poles have been replaced by new poles, reducing the average pole age of the network.

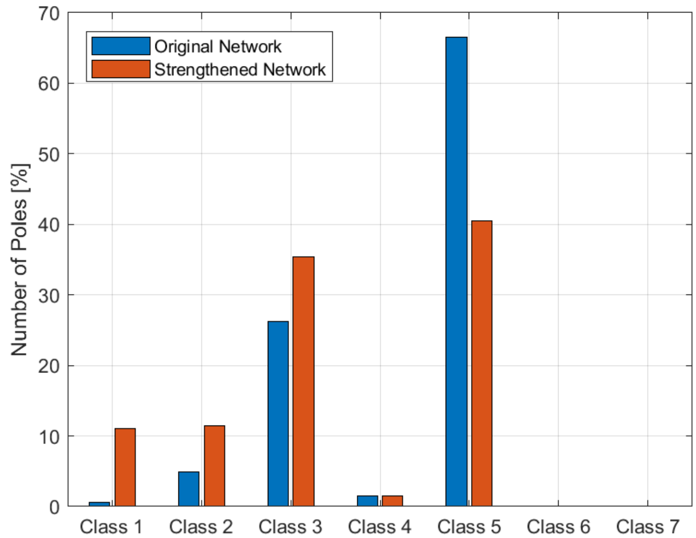


Figure 5.17 Comparison of wood pole class between original and strengthened network

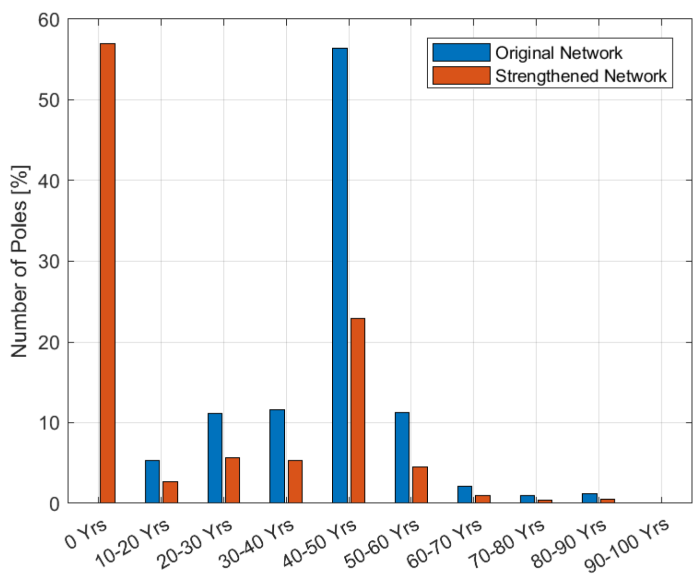


Figure 5.18 Comparison of wood pole age between original and strengthened network

5.2.3 Pole Failures

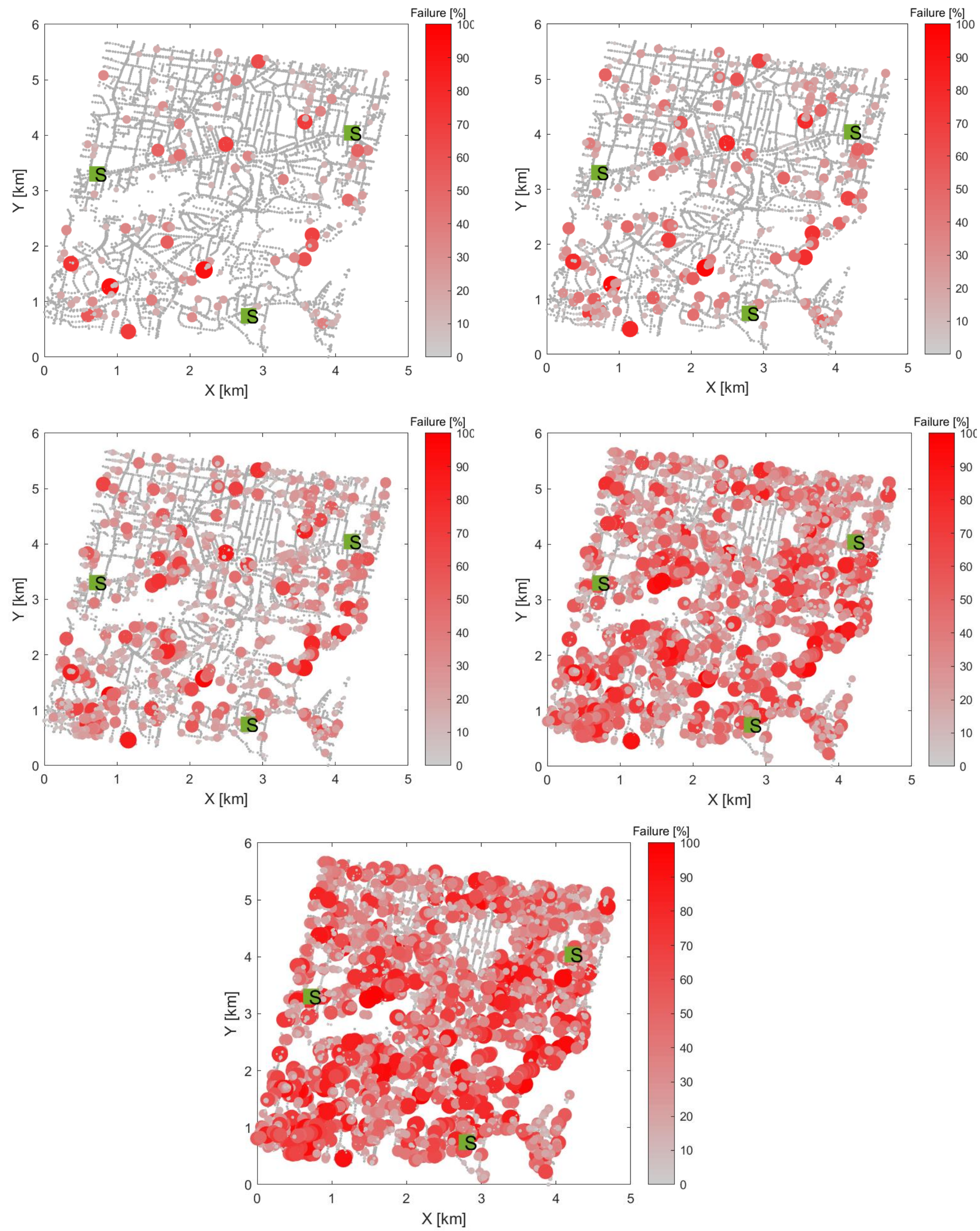


Figure 5.19 Failed poles (%) for Hurricanes Categories 1-5, L-R from Top

Figure 5.19 presents the failed pole percentages (in 1000 scenarios) for Hurricanes Categories 1-5 in the strengthened network. As expected, the number of failed poles increases with increased hurricane severity. The percentage of failed poles ranges from about 1% (out of the total number of poles) for hurricane Category 1 to about 15% for Category 5. However, the number of failed poles for every hurricane category is much lesser in the strengthened network than in the original network. The chart in Figure 5.20 shows the comparison of failed poles between the original and strong networks for Hurricanes Categories 1-4. There is a significant decrease in the number of failed poles between the weak and strong distribution networks.

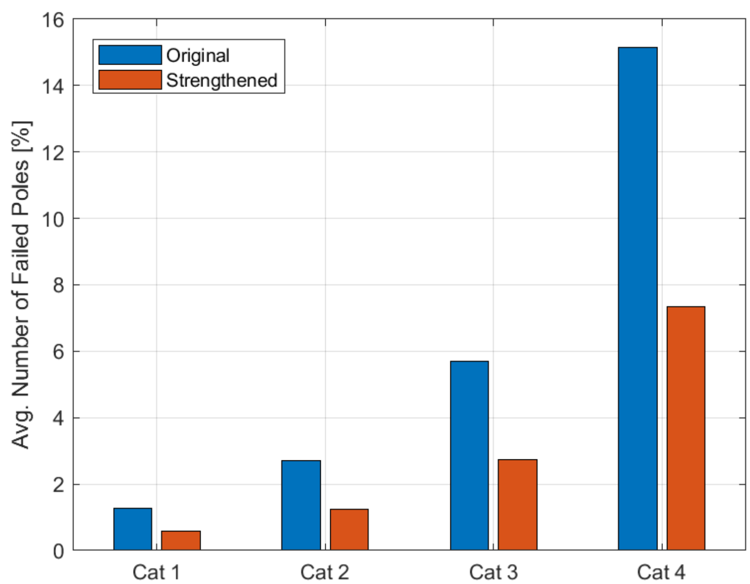
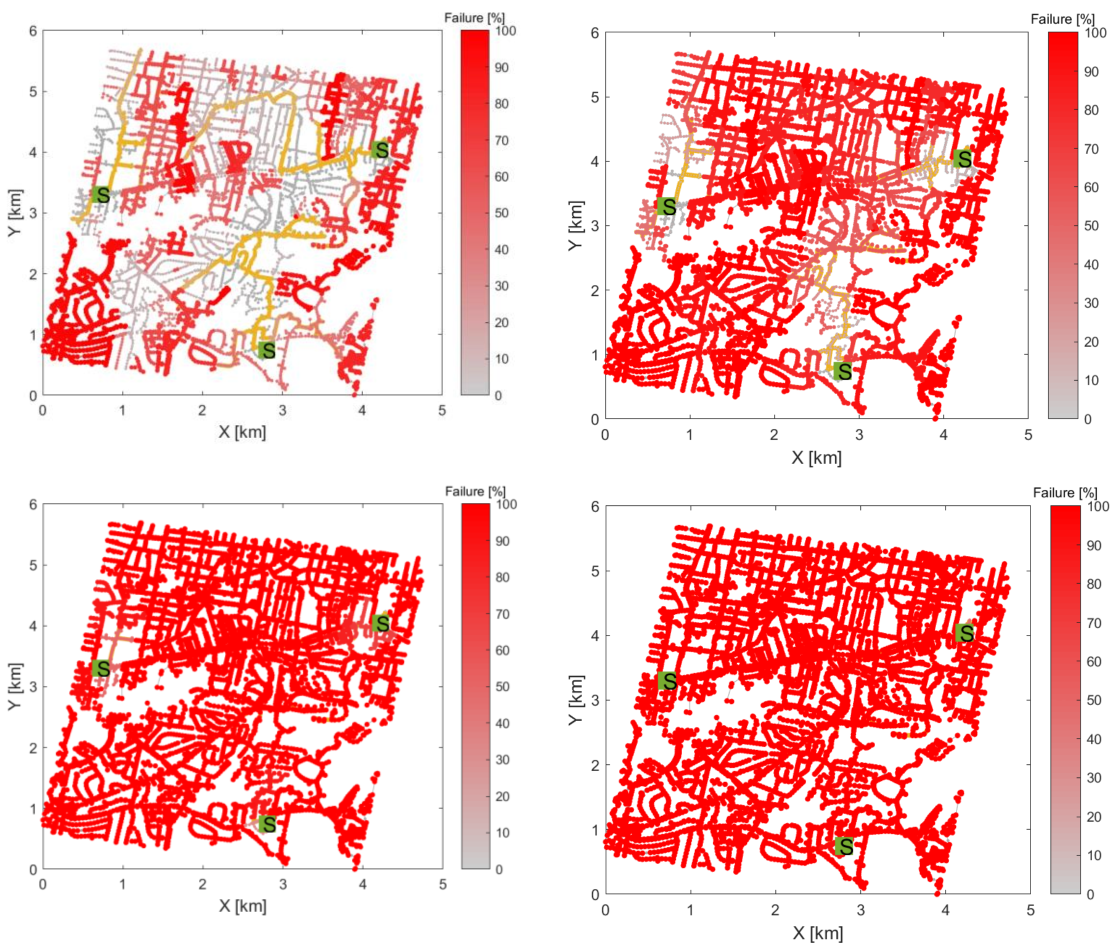


Figure 5.20. Comparison of Pole Failures for Hurricane Categories 1-4

The number of failed poles has reduced by nearly 50% in the stronger network for hurricanes 1-4. This is due to the changes made in terms of pole age and pole class, especially around the areas near the substations, which contain more number of critical poles. This result validates the structural changes made to the old network and confirms that one method of strengthening distribution systems in the event of hurricanes is by upgrading class and age of poles in the critical network area. This results in a reduction in the number of structural failures during hurricanes.

5.2.4 Nodes that Experience Power Outages

Figure 5.21 shows the outaged nodes (% outages in 1000 scenarios) for hurricane categories 1 to 5. When compared to the original network, the stronger network has fewer outages for hurricane category 1. However, for categories 3 and higher, this network experiences large outages.



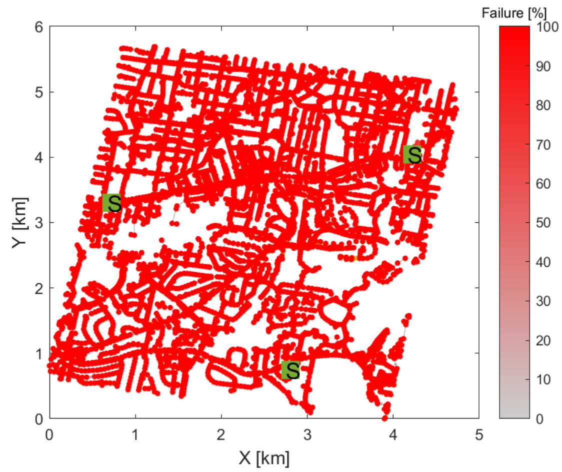


Figure 5.21 Outaged poles (%) for Hurricanes Categories 1-5, L-R from Top

This means that the new network, while more resilient than the original network, is also vulnerable to strong wind forces and causes large scale customer interruptions. It is also observed that the network is more vulnerable at the edges and stronger nearer the sources. This information is useful when making decisions on the location and sizing of Distributed Generation (DG) installations in the network. DGs installed at the network edges (within the constraints of this network) will have a significant effect on network resilience and reliability.

5.2.5 Network Reconfiguration

As discussed in Sections 4.2.1.2 and 5.1.4, network reconfiguration is an optimization problem with the objective of minimizing the number of customer outages while maintaining constraints of network radiality as well as voltage and current limits. The optimization problem is solved by integrating two models: the topology based graph model to perform connectivity analysis that is required for the objective function, and the power flow model, implemented in OpenDSS to perform load flow analysis that is required for monitoring the constraints. Load flow is performed for the base case system before hurricane occurrence. Next, 1000 scenarios are generated for each hurricane category, with each scenario consisting of pole failure and survival data in the form of 1 and 0 data entries. For each scenario, the number of 1s are counted to determine the number and location of failed poles upon hurricane landfall. It is assumed that if the failed pole contains a protective device, then that protective device is damaged as well and is no longer able to operate. After this step, two device datasets are generated: one dataset that provides the set of upstream devices that are opened to isolate the fault, and the second dataset that provides the set of downstream devices that are opened to minimize fault impact. After this step, load flow is performed again to ensure that device operation does not violate voltage and current constraints and to determine if there is sufficient feeder capacity for power rerouting. This is done so that partial reconfiguration can be attempted in case of insufficient capacity for full reconfiguration (i.e. 100% power restoration). At the end of this step, the outaged nodes in the network are determined through graph traversal algorithm discussed in 5.1.3. This is the number of customer interruptions before network reconfiguration. Once faults are isolated, the normally open tie switches are included in the dataset of available switches. This network contains three tie switches connecting three substations. Therefore, there are seven tie switch combinations are available for reconfiguration: closing one at a time (3 combinations), closing 2 at a time (3 combinations) and closing all three (1 combination). However, out of these seven configurations, the feasible configuration is chosen such that constraints are not violated and the interruptions are minimized(objective). For every tie switch that is closed, a corresponding sectionalizing switch must be opened such that radiality is maintained. This is checked using graph traversal to ensure that there is only one path between the source and each node. All the sectionalizing switches in the candidate set are sequentially opened in combination with every tie switch closure. At every instance of network topology change, load flow is monitored to ensure operating limits. The number of customer interruptions after reconfiguration is calculated by subtracting the number of customers that are connected to the power source after the tie-sectionalizer operation from the total number of healthy customers in the base case network before the hurricane event. The optimal solution is one where the number of customer interruptions are minimum while maintaining system constraints. The algorithm is programmed by integrating MATLAB's graphing tools with OpenDSS load flow. After an optimal solution is obtained for each of the 1000 scenarios for each hurricane, the average (out of 1000) number of customer interruptions before and after reconfiguration is calculated as a percentage ratio of the total number of healthy nodes in the base case system, and presented in Figure 5.22.

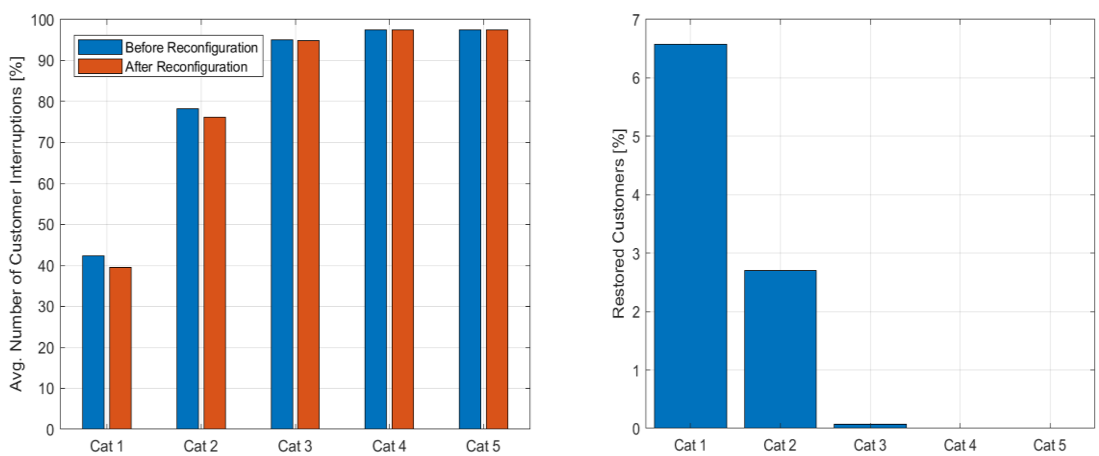


Figure 5.22 Customer outages before and after network reconfiguration

In Figure 5.22 the comparison of customer outages before and after reconfiguration for the strengthened system is shown. In the event of Category 1 hurricane, while reconfiguration is not effective in the original system, in the strengthened system, reconfiguration restores nearly 7% of the interrupted customers. This number is calculated by subtracting the average number of customer interruptions after reconfiguration from the average number of customer interruptions before reconfiguration and expressing the resulting value as a percent of average number of customer interruptions before reconfiguration. This is a drastic improvement from only 0.55% restoration in the original network. With regards to Category 2 hurricanes, approximately 3% of customers are restored through reconfiguration. However, for hurricane Category 3, the outages before and after reconfiguration is almost equal suggesting that reconfiguration is inefficient for hurricanes Category 3 and higher. This is due to the fact the hurricane 3 and higher cause large outages in each of the three substation islands reducing the solution space for reconfiguration procedure.

5.2.5.1 Power Flow Discussion

As discussed previously, reconfiguration technique is aided by a power flow model to ensure that line constraints are not violated. The distribution line conductors are of the ACSR type, and it is assumed that the conductor sizing and design for the distribution network configuration conform to standard design practices, such that the conductors can comfortably withstand base case currents. From the ACSR conductor sizing chart, conductors Martin and up have allowable ampacities >1000 amps, so it can be assumed that this conductor is used in lines closer to substations.

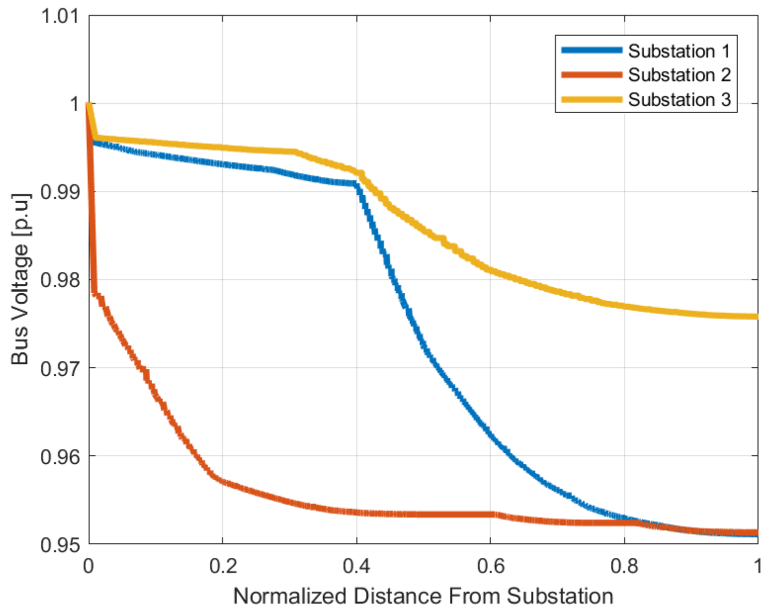


Figure 5.23 Voltage Profile for base case operation

Figure 5.23 and Figure 5.24 show the voltage and current profiles, respectively, for the three substation islands simulated using OpenDSS. The X-Axis of these plots represents distance from substation node. This is the base case results that depict normal operation before hurricane landfall. It must be noted that the three substation networks are not of equal size, Substation 1 is the smallest, with shortest feeders whereas Substation 3 has longest feeders.

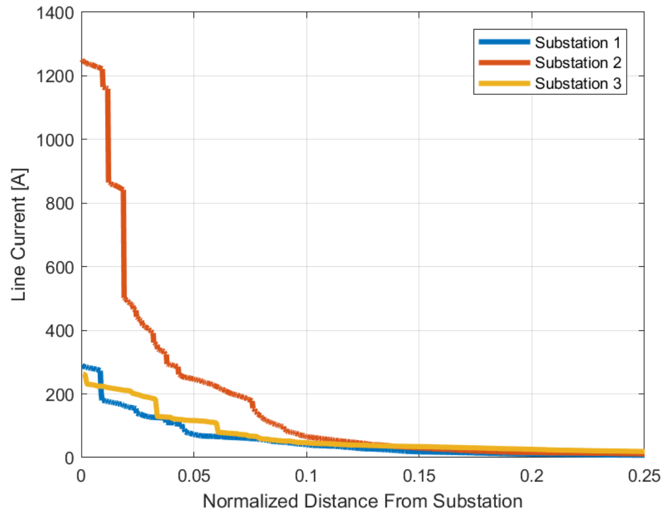


Figure 5.24 Current Profile for base case system

Figure 5.25, Figure 5.26, and Figure 5.27 show the comparison of voltages of the network buses after fault isolation, when protective devices are opened to minimize fault impact, and voltages of network after reconfiguration process.

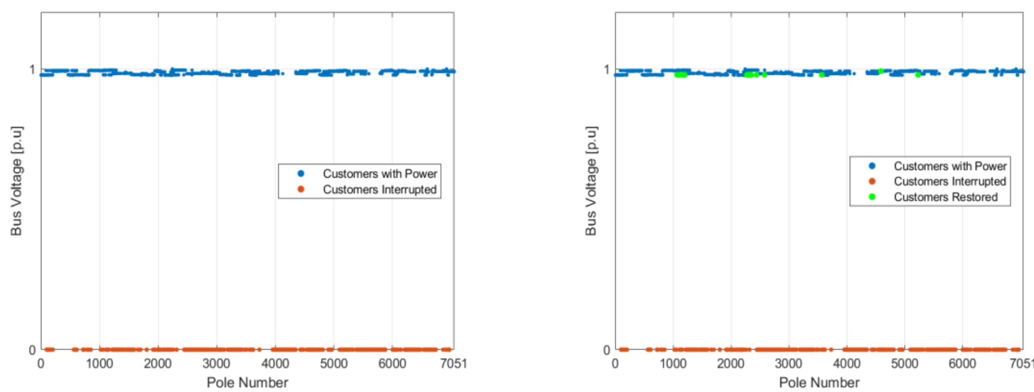


Figure 5.25 Hurricane Category 1 – Voltages before and after reconfiguration

It can be seen that a small percentage of customer are restored back to normal operation after the process of reconfiguration as indicated by the green dots. The voltage plots are shown only for Hurricane categories 1-3 because the impact of hurricanes Category 4 and stronger are so severe that most of the network is interrupted, and reconfiguration is not effective.

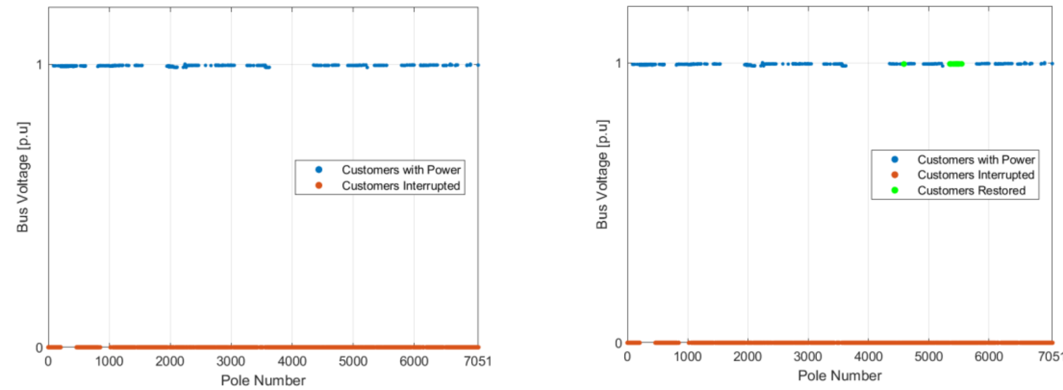


Figure 5.26 Hurricane Category 2 – Voltages before and after reconfiguration

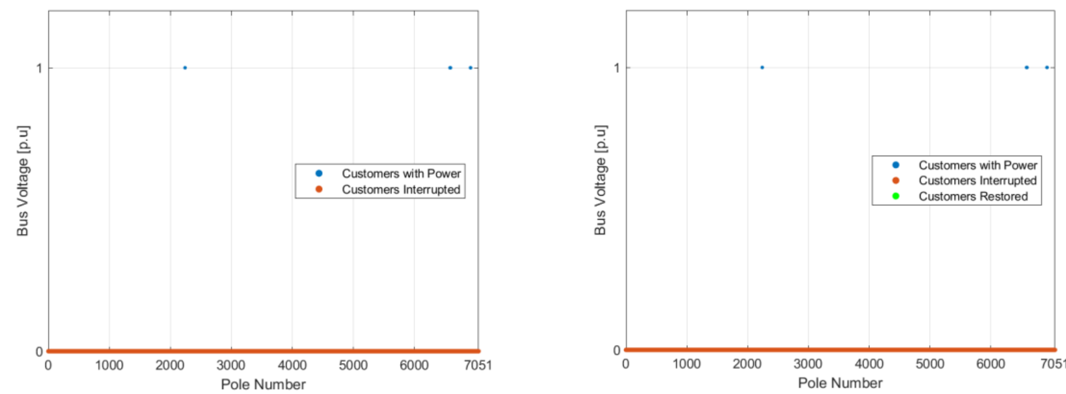


Figure 5.27 Hurricane Category 3 – Voltages before and after reconfiguration

Line current profiles are presented in a similar format in Figure 5.28, Figure 5.29, and Figure 5.30. It must be noted that the X-Axis in these plots is pole number or bus number. The buses in the network are not labelled sequentially based on distance from source i.e. pole 1 does not mean that it is the closest pole to the substation. Therefore, these plots must not be viewed as profiles with respect to distance.

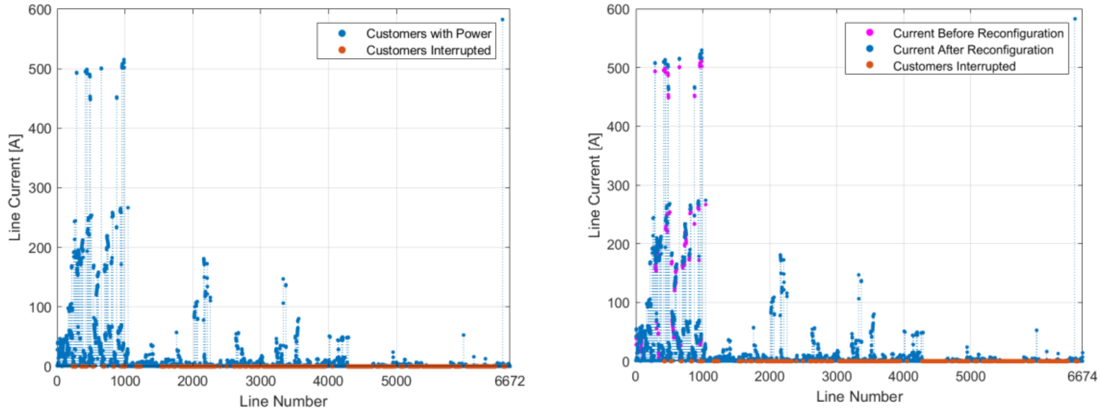


Figure 5.28 Hurricane Category 1 – Currents before and after reconfiguration

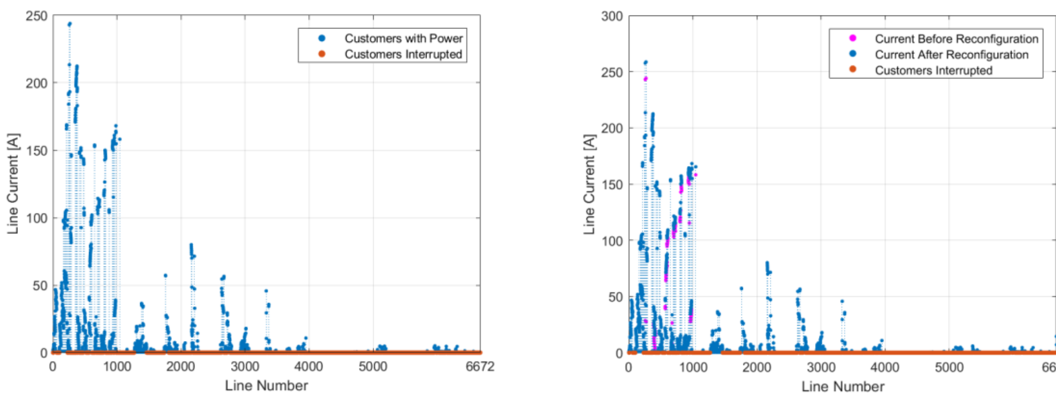


Figure 5.29 Hurricane Category 2 – Currents before and after reconfiguration

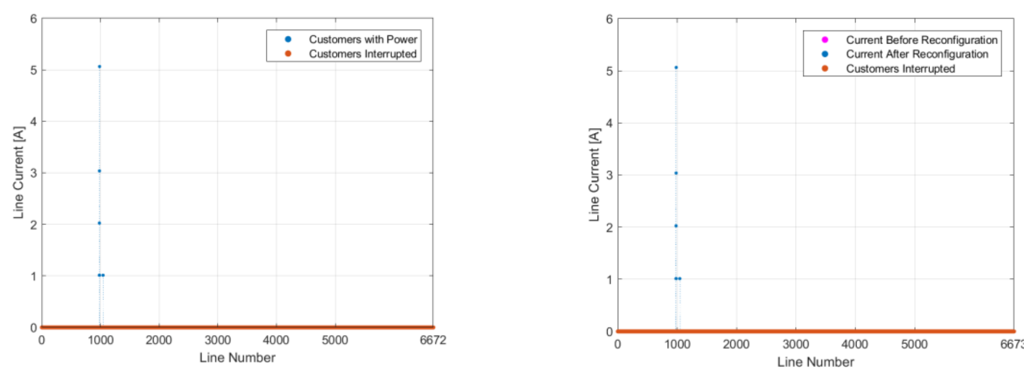


Figure 5.30 Hurricane Category 3 – Currents before and after reconfiguration

It can be seen that for Hurricane Categories 1 and 2, reconfiguration is successful, but results in an increase in line currents. The pink and blue dots represent line currents before (after fault isolation) and after reconfiguration, respectively. Although there is an increase in line currents, the increase is not large enough to exceed the conductor rated ampacities and therefore do not violate line constraints. To conclude, in this analysis, optimal reconfiguration is performed such that customer outages are minimized while at the same time distribution network lines are not overloaded and the line and voltages are within acceptable limits. The substation generators have sufficient capacities, and their limits are not violated while accommodating the extra loads resulting from feeder re-routing due to reconfiguration procedure.

Finally, Figure 5.31 presents the fault currents flowing in the network.

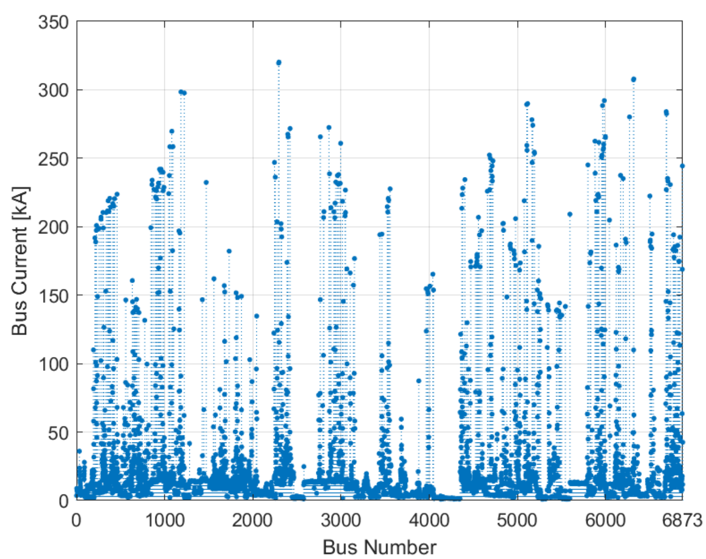


Figure 5.31 Fault currents in network

The fault current data is obtained from the “FaultStudy” mode in OpenDSS. A summary of the mode is described, but details can be found in [92]. Bus, in the context of OpenDSS, is a circuit element containing nodes. “The main electrical property of a Bus is voltage. Each node has a voltage with respect to the zero voltage reference (remote ground). There is a nodal admittance equation written for every node (i.e., the current is summed at each node) [92].” A fault is simulated by placing fault objects in the network, in this study it depends on the locations of pole failures. A fault is simulated as a multi-phase two terminal resistor branch, with the second terminal connected to ground. In the FaultStudy mode, OpenDSS builds a nodal admittance model of the system. It then solves the $I = YV$ equation for voltages to ground. Fault study is based on multiphase Thevenin equivalent at each bus. Open circuit voltage is computed for each bus, and then the short circuit impedance matric is calculated for each bus and inverted. The Norton form is used to calculate short circuit currents at each bus that corresponds to open circuit voltages. The short circuit currents that would flow from each node if all bus nodes were shorted to Node 0 (the reference node) is the fault current reported by OpenDSS.

5.2.6 Power Restoration

The final step in the resiliency analysis is the restoration of outages to bring the system back to 100% performance. In this regard, outage and quality curves are computed for hurricane Category 1 for the original system as well as the strengthened system and compared in Figure 5.32. The curves are the average values of 1000 curves generated for each scenario in hurricane 1. The procedure to compute outage and quality curves, along with the resiliency metric is described in detail in Section 5.1.5.

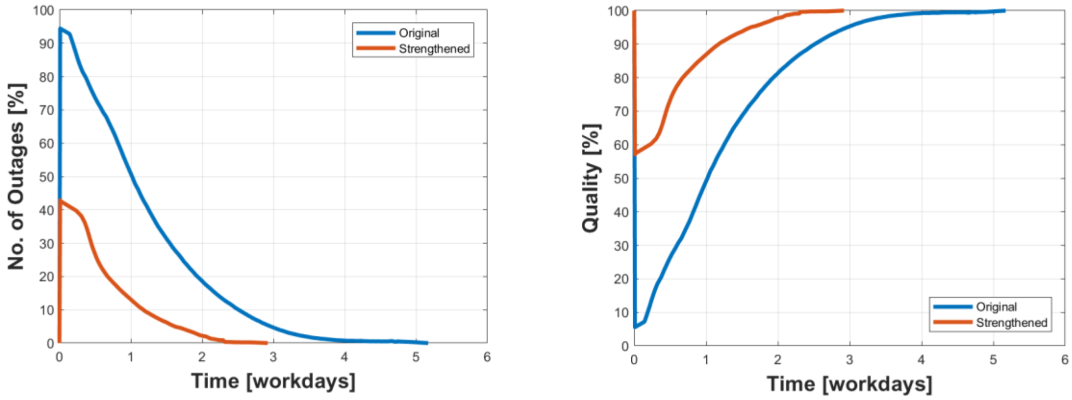


Figure 5.32 Comparison of (a) Outage curve (b) Quality curve for Hurricane Cat 1

It is seen that both the outage and quality curves of the stronger network show significant improvements over those of the weaker network. Upon hurricane landfall, the stronger network experiences ~40% customer interruptions and a reduction in quality from 100% to ~60 % when compared to ~95% and 5% respectively for the original network.

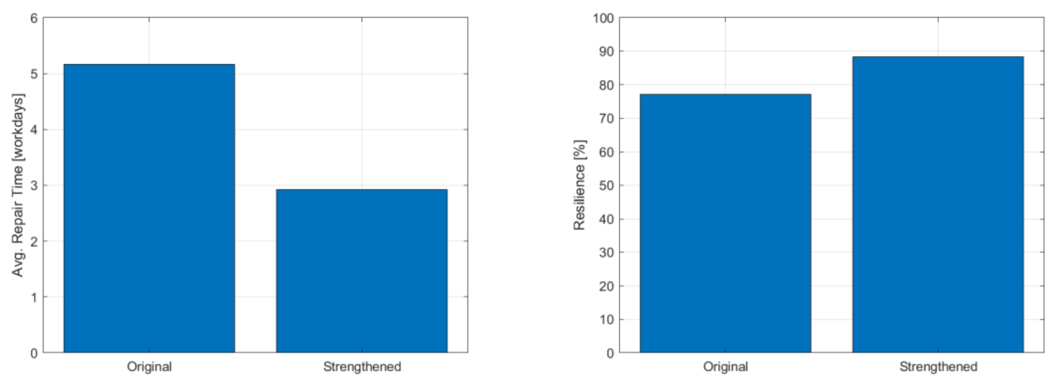


Figure 5.33 Comparison of (a) Average repair time and (b) Resilience for Hurricane Cat1

The average time for the stronger network to be completely repaired so as to achieve 100% customer power restoration is about 3 workdays when compared to 5 in the weaker network, as shown in Figure 5.33. An interesting finding is that resilience of the stronger network is almost 90% when compared to 77% for the older network. Pole strengthening resulted in a 13% increase in the system resiliency metric. These results prove that strengthening the pole infrastructure has a notable impact on improvement of restoration procedures.

Figure 5.34 and Figure 5.35 show the outage and quality curves for Hurricanes Categories 1 through 5 for the strong network. For each hurricane Category, the mean of 1000 scenarios is calculated to obtain each curve. As expected, hurricane category 5, which is the most severe, requires the longest time to reach 100% quality.

Restoration time is the time taken for the quality metric to go back up to 100%, i.e., when all pole repairs have been completed. From Figure 5.36, it can be seen that the restoration time increases with hurricane severity, with hurricane Category 5 requiring about 35 days (more than 1 month) to restore power to 100%. Finally, resilience of the system is calculated for each hurricane and presented in Figure 5.36. Resilience decreases with increase in storm intensity. The system is most resilient towards Category 1 (~90%) and least resilient towards Category 5 (~35%).

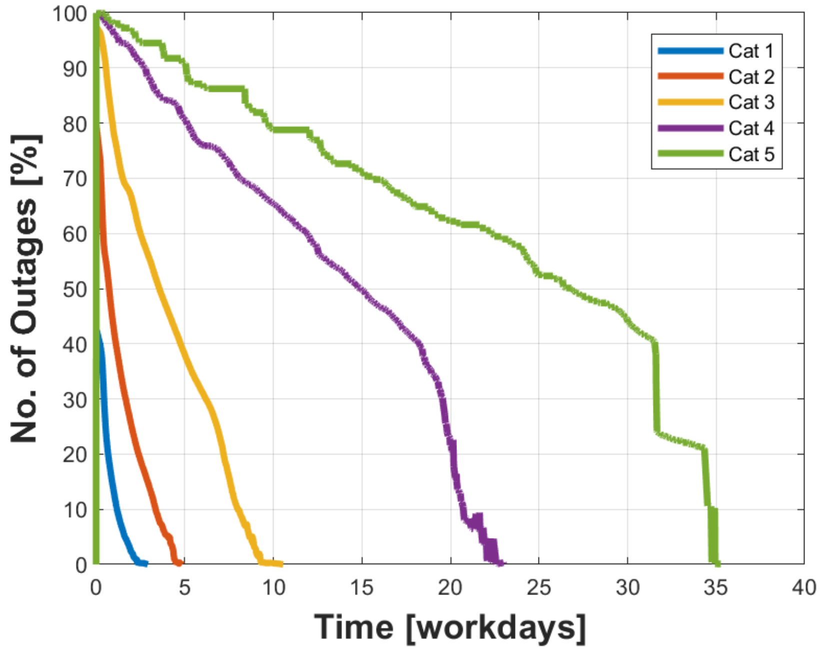


Figure 5.34 Outage Curves for Hurricanes Cat 1-5

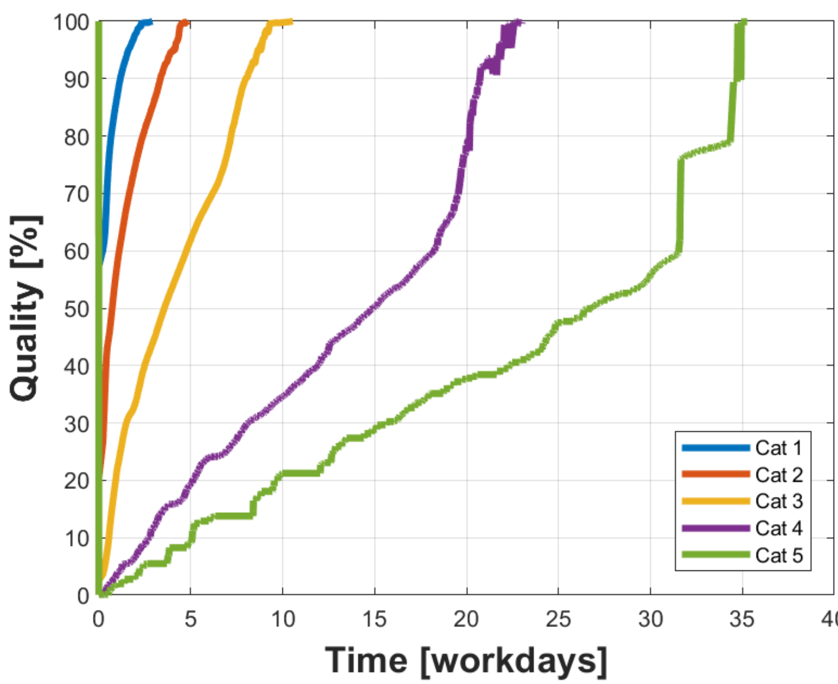


Figure 5.35 Quality Curves for Hurricanes Cat 1-5

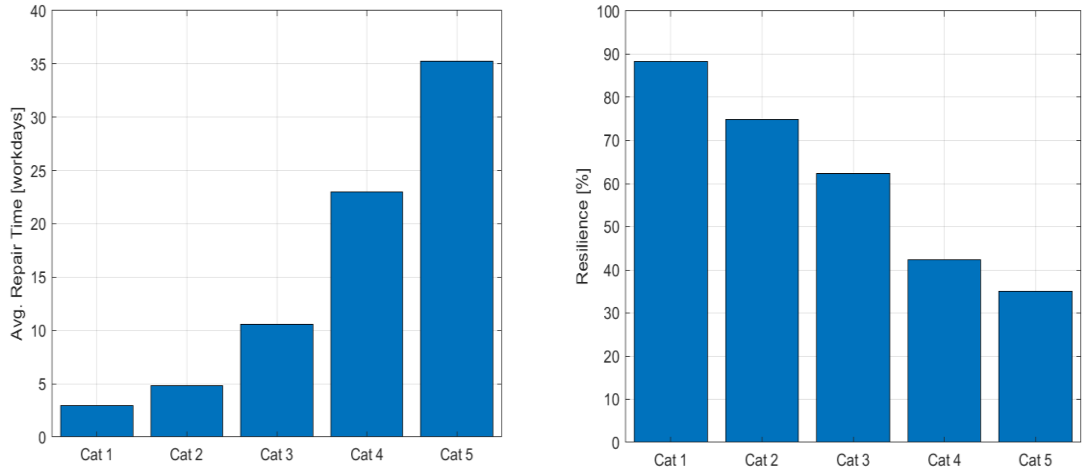


Figure 5.36 Comparison of Average Repair Time and Resilience (%) for Hurricane 1-5

5.3 Distributed Generation and Microgrids

The utility grid is constantly exposed to natural disasters and there is no method to protect the grid from 100% damage. Current methods involve step-by-step restoration schemes that depend on the regional power system characteristics, and can take months for complete power restoration[96]. To minimize the extent of de-energized healthy network sections, switching and reconfiguration processes were discussed. Another method to reduce customer outages is through the use of microgrids.

“ A microgrid is a small-scale power system typically on the medium- or low-voltage distribution feeder that includes distributed load and generation together with storage and protection devices, which are synchronized through an embedded management and control system [19].”

In this regard, when the primary power supply is not available, local distributed generation sources behave as virtual power plants and supply power to a smaller section of the network. In the case of large outages, DGs operate in island mode and supply power to the entire microgrid. The microgrid has its own DG management system to control the islanded operation [96]. Power distribution systems are designed such that the substation is the primary source of power. Therefore, when DG is integrated into the system, operation and protection problems arise [97]. For this reason, current utility practice required DG to be disconnected in the event of disturbance and connected back up once the system is healthy. However, if the microgrid survives the hurricane effects, it can be operated in island mode to supply local loads and reduce total outages. As seen in previous sections, damage on distribution networks due to hurricane events is uneven which allows for the possibility of operational microgrids even during strong winds. When these microgrids are used for load restoration in such case, system resiliency can be increased. However, microgrid implementation currently faces technical, regulatory, and financial barriers that must be resolved before microgrid use can be widespread [19].

In this section, a preliminary approach is presented to incorporate microgrids into the distribution system, with the goal of reducing customer interruptions in the event of extreme weather. The approach makes use of graph algorithms to determine outaged nodes before and after microgrid integration. The distribution network has been modeled as a graph with nodes and edges, as described earlier. Effect of microgrid integration is evaluated through graph-search algorithm. The first challenge in microgrid integration is to determine location of DG installation. Figure 5.37 shows the map of outaged nodes after hurricane category 1. The regions in red are the most vulnerable to hurricanes, and therefore, placing DGs in these areas would theoretically improve resiliency by providing local load restoration.

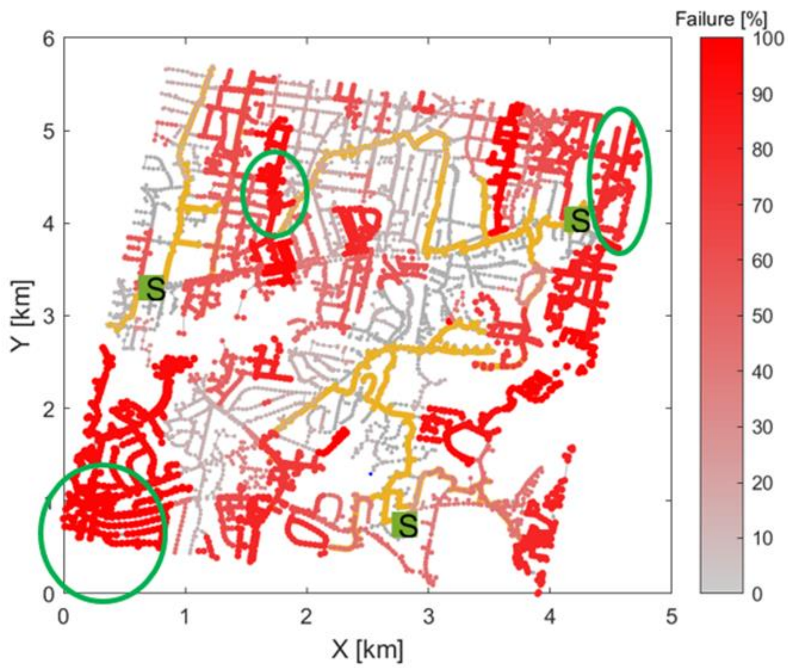


Figure 5.37 Locations of DGs

Three DGs are simulated for this network in the regions shown. The DGs are coupled to the distribution network through a virtual tie switch [98]. The microgrid is brought into operation after the hurricane landfall, when protective devices that operate to isolate faults create network sections that remain without power. The microgrid is assumed to have the ability to seamlessly connect and disconnect from the main grid[17]. A microgrid is typically connected to multiple distribution generating sources, but in this analysis, the individual sources are not explicitly modeled, but instead, a backup, virtual 'source' is assumed to be located in the areas shown and is assumed to have sufficient capacity to power the connected island. In this regard, the network consists of three substations with generators that are in use under normal operating conditions and three additional generating sources (DGs) that are connected to the three circled sections by means of virtual tie switches, and are brought into operation after hurricane landfall. The kW generation capacity of each DG is considered to be 50 kW at 480 V. When hurricane occurs, the protective devices located throughout the network operate to isolate the faulted sections. Due to the large number of failed poles in the network, many network sections become disconnected from power sources. To restore some power back to the newly formed "islands" that are no longer connected to the substations, the DGs are connected to the system by closing the tie switch. Three DGs are connected to the system at the locations shown in Figure 5.37. These DG are considered to operate as regular generating sources. Graph traversal and search algorithms are applied to this new network configuration. The nodes that are not connected to any power source, i.e. neither the substation nor DG, are calculated to be the outaged nodes. The calculation of the outaged nodes is performed for 10 scenarios of each hurricane Category from 1-5 and the average of the 10 scenarios is calculated to represent the outage for each hurricane category. A comparison between the number of outaged nodes (customer interruptions) with and without the integration of DG is shown in the bar graph of Figure 5.38. DG penetration causes a significant reduction in interrupted customers for Hurricane Categories 1 and 2, but has less benefit for higher categories of hurricanes. This is because hurricanes Category 3 and higher cause extensive damage and therefore repair is the only feasible course of action for power restoration.

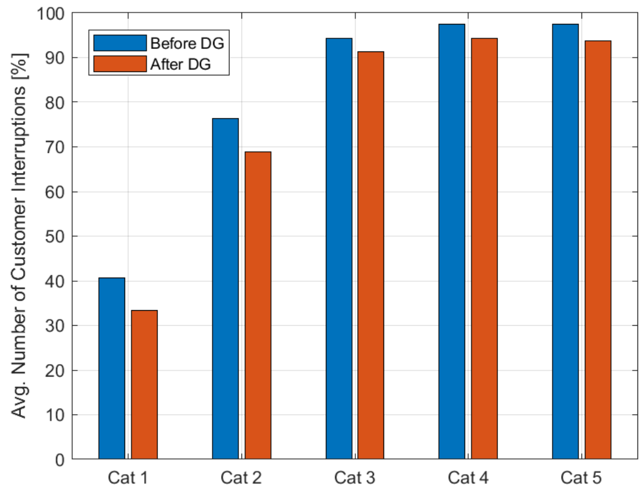


Figure 5.38 Effect of DG on customer interruptions

The location of microgrids was determined based on inspection of the outage prediction model, however, in real systems, optimal location and sizing of microgrids and DGs is an area of extensive research, and must be investigated further. DG has significant impacts on the voltages and currents in the network, and therefore this model must be aided by a power flow model. The power flow model described earlier, developed using the software tool OpenDSS, can be extended to incorporate DG penetration at desired locations. The integration of DG has significant impacts on system voltage and can cause an increase or decrease along the feeder depending on DG type and presence of distribution transformers [97]. DG causes protection issues such as fuse coordination, fault location detection and device interrupting ratings [97]. It must be noted that the purpose of this section is to introduce the concept of microgrids, and to illustrate its potential through a simple example. This work simply provides an illustration of the potential application of DGs in improving system resiliency by considering them to be backup power sources brought into operation after hurricane landfall, and does not delve into the analysis of the effects of DG on system conditions such as voltage regulation, protection coordination, etc. In reality, microgrid integration is a complex process facing multiple technological and regulatory challenges and is a worthy topic for future research.

CHAPTER 6. CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

In this research, a framework has been developed for the assessment of reliability and resilience of power distribution systems in the event of hurricanes. The contributions of this research are discussed below.

6.1.1 Model Development

To develop the framework, a realistic distribution network is synthesized using Google Earth and a wood pole dataset of inspected poles to represent the performance of a distribution network in the Southeast USA. The wood pole data includes GPS location of poles, age of poles, heights and class. The connectivity information between the poles (line data), the location of substations and protective devices (breakers, reclosers, and switches) was not available in the database. For this reason, the network of the distribution circuits is simulated such that the resulting network is radial. The network consists of 7051 wood poles, and spans an area of about 9 square miles, representing the service area of one utility. The network includes 3 substations representing power sources and protective devices are placed across the system. Loads (representing customers) are distributed uniformly across the feeders.

6.1.2 Pole Failure and Customer Outage Assessments

The impact of hurricanes (categories 1-5 from the Saffir-Simpson scale) on the structural components of the system is studied by evaluating wood pole characteristics that increases their vulnerability to strong winds. Pole survival events, based on independent pole failures, are used to identify poles that fail and survive during hurricane occurrence. Pole failure and customer outage assessments are performed by running simulations of 1000 survival events for each hurricane category. It is found that pole failures increase drastically with increase in hurricane category. Another observation is that the pole failures result in large scale outages for Hurricane Category 1 in the original system. The reason for this is that the poles surrounding the substations are aged and weak, and extremely vulnerable to wind forces. When these poles fail, large scale outages occur in the system. The solution is to upgrade the poles with regards to class and age. In this regard, an upgraded network is developed which consists of new Class 1 poles specifically surrounding the substations and also newer and stronger poles throughout the network. This results in a 50% reduction in pole failures and therefore fewer customer interruptions.

6.1.3 Network Reconfiguration

Network reconfiguration is ineffective in the original network, even for a Category 1 hurricane. This is because of the small solution space of the network, with three sources and three tie lines. The network experiences large outages, with poles failing in nearly every feeder. Since the network is radial, nodes downstream of failed nodes in a feeder experience outage. This does not allow for sufficient alternate paths for power rerouting. In the weak network, for Category 1, reconfiguration marginally reduced customer outages - by only 0.55%. In contrast, reconfiguration reduced outages by 7% in the stronger network. However, reconfiguration is ineffective in the stronger network from Hurricane Cat 3 onwards due to large scale feeder outages. Some discussions are outlined below:

a) An important factor affecting the reconfiguration procedure is the location of tie lines that connect feeder ends. For n feeders, this combinatorial problem is given by [25]:

$$Num\ of\ combinations = \frac{n!}{(n-2)!\,2!} \tag{34}$$

In this research, the location of tie lines is determined through inspection, and is fixed. However, an optimization analysis could be formed to identify tie line locations that would allow for most efficient restoration under strong winds. This would provide insights during construction of tie lines in actual systems.

b) Fault Location, Isolation and Service Restoration (FLISR) schemes are greatly affected by the nature of protective devices. Remotely controls switches with manual switching operations are less effective than fully automated switches.

c) Purely radial systems are the least reliable. System resilience can be improved by increasing the redundancy of the system. This is done through construction of multiple parallel paths between two nodes such that failure of one path will allow for re-routing through the alternate parallel paths. This structure can be implemented for lines supplying critical facilities such as hospitals and police stations.

6.1.4 Power Restoration

Two factors have been considered for power restoration, which follows the reconfiguration process: resource mobilization and restoration sequence. Restoration sequence is based on the order of pole priority; poles that serve larger number of customers have higher priority. It is found that restoration and repair is the most effective course of action in this system.

The restoration process takes about 1 month for a Category 5 hurricane and 3 days for Category 1. This is a significant improvement over the original network in which 5 days were needed for 100% power restoration for hurricane level 1. Resilience calculations determined that the resilience of the power system for a category 1 hurricane is ~90%. This research presents a holistic framework that is used to develop a novel and comprehensive tool (by studying resilience in all the three time-dependent phases). This assessment can be used by utilities to make risk-informed decisions for future hurricane events.

6.1.4.1 Note about Resilience Metric

It must be noted that the term resilience in this research refers to the system performance relative to expected performance, and differs from conventional reliability measures such as SAIFI (System Average Interruption Frequency Index) and SAIDI (System Average Interruption Duration Index). In this regard, the resilience is expressed as a percentage relative to expected performance and not in terms of duration of customer outages (in minutes) or amount of customer outages (in Mwh). The aspect of 'time' is factored in while calculating the metric, but is not part of the end result.

6.1.5 Summary of Contributions

a) Assessment of the impacts of hurricanes of severities 1-5 from the Saffir Simpson scale on the major structural component of utility distribution networks by studying wood pole vulnerability and failure probability as a function of hurricane winds.

b) Development of an outage prediction model that identifies the vulnerable sections of a given distribution network, that can be used by utilities for planning storm hardening responses.

c) Development of optimal network reconfiguration procedure with the objective of customer outage reduction during hurricane occurrence.

d) Development of pole repair and power restoration scheme that takes into account pole priority and available resources with the objective of restoring power to 100%.

e) Development of detailed load flow model to monitor electrical network constraints during normal operation as well as during hurricane conditions to ensure feasibility of proposed restoration methods.

f) Calculation of network quality and resiliency metrics and demonstration of the effects of network strengthening on these metrics.

g) Preliminary investigation on the benefits of microgrids in improving system resiliency.

6.2 Future Topics for Research

This research forms the foundation for a knowledge base in risk-based resilience assessment of power distribution system subject to seasonal storms. The topic of resiliency is of growing concern for utilities today, and as such, there are many areas of research that need to be addressed.

6.2.1 Pole Failure Analysis

6.2.1.1 <u>Boundary Conditions</u>

In this analysis, pole failures are assumed to be independent. The effect of adjacent spans and poles are not considered while analyzing a specific pole failure scenario. In a distribution system, wood poles are connected to each other through distribution lines made up of conductors. The performance of any pole is therefore dependent on the performance of the neighboring components. Equivalent boundary conditions are used to determine the impact of adjacent spans on the wind response of a single pole. When assessing the failure survival events of wood poles, boundary conditions must be taken into account to improve accuracy.

6.2.1.2 Pole Material

This research studied the effects of failures of wood poles on the power distribution system, by assuming that all the poles in the test network were made of wood. However, utility distribution poles are also made of steel, concrete, fiber reinforced polymers, or laminated wood [99]. The strength of the pole depends on the material of the pole. Therefore, the structural assessments must be extended to include poles made of other commonly used materials.

6.2.1.3 Cascading Failures

As mentioned previously, in this analysis, independent pole failures are assumed, i.e., the failure of one pole does not affect the failure of another pole. However, in an actual system, failures are cascading and dynamic. When one pole falls, surrounding poles will be dragged down as well, and those poles in turn collapse other poles in a domino effect. The research must therefore be extended to account for cascading pole failures.

6.2.1.4 Cost Evaluations

Cost is a major consideration when making decisions about strengthening pole infrastructure. Repairing a failed distribution pole is estimated to cost about $2500 [18].

An interesting extension of this work would be to develop cost models that would compare the cost of pole replacement and repair with regards to age, class and material with the cost savings from reduction in network damages and customer interruptions. Evaluating the costs associated with hardening recommendations would provide interesting insights into the feasibility of hardening strategies.

6.2.2 Effect of Vegetation

Trees and heavy branches fall on power lines and tear down poles, causing major power outages. The existence of old and decaying trees near power lines has a significant effect on the failures of poles and resilience of systems. In this analysis, pole failures are considered as direct functions of wind forces. Future work can expand this analysis to account for tree, debris and vegetation related failures.

6.2.3 Utility Restoration Procedures

Utility restoration schemes are dependent on the resources and restoration sequence. In this study, resources were assumed to have the same effectiveness i.e. the power system components whether a pole or a conductor, each required the same set of resources for restoration broadly referred to as a 'work crew'. However, the time and resources needed to repair damaged components depend on the type of component. Another aspect is that the amount of resources available for restoration, following a disaster, is a function that increases with time. Most utilities belong to mutual assistance programs with other utilities, and these neighboring utilities send in their crews to assist restoration effects in the damaged region. Therefore, resource mobilization is a dynamic process. With regards to repair priority, critical facilities are repaired first. This includes hospitals, fire and police departments, schools and so on. This research does not specifically model critical facilities, but instead determines pole priority with respect to number of customers served. The restoration model can be extended to account for resource dynamics and priority of critical facilities.

6.2.4 Communication Systems

One of the key components for successful reconfiguration schemes is the communication infrastructure between network devices and distribution management systems to control automated switches. One of the main challenges in automatic feeder reconfiguration in times of hurricanes is the collapse of essential communication systems that are required to program the automatic functions. One of the lessons learned is that communication systems are required to be more resilient to hurricane effects than the power delivery systems because they control the automated switches under conditions where the grid system is damaged due to hurricane disturbances [90]. Therefore, extensive planning and advancement of communication infrastructure is necessary for the feasibility of automatic reconfiguration [90].

Utility repair teams sent out after hurricane events typically carry communication systems including cell and radio systems among the equipment needed for restoration. Therefore, even if the existing communications systems are damaged due to high winds, these backup systems can be used to communicate critical information from the damaged network areas to the central distribution management system. Utilities would benefit from more frequent field tests and inspection programs to ensure robust communication infrastructure.

6.2.5 Additional Topics

As discussed previously, the improvement of network reconfiguration process is dependent on multiple factors. This research did not implement optimization algorithms due to limited solution space of the given system. However, future work can include optimization algorithms that complement load flow models to produce optimal topology configurations for minimum outage in real time operation. It must be noted that the location of failed poles was assumed to be known and from that information, fault location was assumed. The framework must be expanded to include fault location algorithms through the monitoring of system voltages and constraints to identify specific location of faults. For accurate analysis, it is critical to develop detailed models of distribution networks using data from real systems. Future work can be collaborative, with utility partnerships, to gain access to distribution system designs. Future research should consider integrating interdependencies of utility systems and other infrastructure components into the resiliency assessments[18, 51]. The research topic of microgrids has been of great interest in the context of resiliency. As discussed previously, microgrid and DG integration is an extremely complex task facing multiple challenges with respect to infrastructure improvements and changes in regulatory policies. This research area is quite new, but extremely relevant, and therefore provides excellent opportunities for future research.

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