Resilience Assessment of Distribution Systems Considering the Effect of Hurricanes

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***Abstract*—High wind speeds during hurricanes cause damage to power distribution lines resulting in power outages that last from days to months, depending on the severity of the storm. This highlights the need for accurate risk assessment procedures for decision making purposes. This paper presents a framework for assessing the hurricane resilience of power distribution systems considering the impact of protective devices on reconfiguration and restoration of the distribution network. The framework is applied to an actual distribution network composed of 7051 wood poles located in southeast of the US. Results indicate that for the distribution network reconfiguration is not effective as there is not enough redundancy in the system. However, by considering the repair prioritization and assigning enough number of repair crews, the system can recover quickly.**

Index Terms - Overhead power distribution systems, Wood utility poles, Hurricane resilience, Reconfiguration, Restoration

I. INTRODUCTION

Societies depend on the electric power grid to provide electric energy for households, industries and organizations. Any disruption in the constant flow of electricity results in considerable economic losses as well as societal and organizational disruptions. In the past few decades, hurricanes have been responsible for a considerable percentage of power outages in the United States. Storm related outages cost the US economy \$20-\$55 billion annually [1]. In the US, overhead distribution lines are mainly supported by wood poles. A significant percentage of existing wood poles are aged and weak. Several decades of decay in the wood poles have made them one of the most important factors causing power outages. For example, in 1989, Hurricane Hugo destroyed about 15,000 poles [2]. In 2005, Hurricane Wilma and Hurricane Katrina were responsible for the failure of about 12000 wood poles [3]. Since electrical power systems are Critical Infrastructures (CI), they must be reliable under normal operating conditions and have adequate resiliency towards anticipated contingencies such as hurricanes.

Although resilience of distribution power systems to high impact low probability (HILP) events is a concept of growing interest, it has not yet been adequately explored [13]. The existing hurricane resilience assessment frameworks for power distribution lines are not accurate enough. These frameworks are based on simplistic approaches that do not accurately estimate the resilience of power distribution lines. A hurricane resilience assessment model for power distribution lines consists of four sub-models including: (1) hurricane hazard model, (2) fragility model, (3) power system response model, and (4) restoration model [4]. In this regard, hurricane hazard models should be integrated with component fragility models to obtain the probability of failure of the system. For obtaining the performance of the system, connectivity analysis and power flow analysis can be used. In connectivity analysis, a node is considered as a failed node if it is disconnected from all sources of power. However, in power flow analysis, the capacity and the demand in the system are considered. In this regard, a node might be connected to power sources, but since the demand exceeds the available power, this node is considered as a failed node [4]. In the previous studies on resilience assessment of power distribution networks, the impact of protective devices such as switches, reclosers and breaker is neglected in the analysis. If any failure occurs in the system, one of these protective devices opens and subsequently cuts the power in the system to protect the rest of the electric network. The protective device remains open until the failed node is restored.

In this study, a framework for resilience assessment of power distribution lines is proposed. In the proposed framework, a connectivity based analysis is performed to calculate the performance of the system. In addition, the impact of protective devices such as switches, reclosers, and breakers on the performance of the system is considered. In order to assess the proposed framework, the resilience of an actual power distribution network in southeast of the US subjected to a hurricane category 1 is investigated. The assumed distribution network is composed of 7051 poles. The probability of failure of the components of the system are obtained by integrating a hurricane category 1 wind model and an age dependent fragility model for the wood poles. Utilizing the obtained probabilities of failure, 500 failure and survival events are generated for the poles in the system assuming the

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failure event of the poles is independent. According to Mohammadi-Darestani et al. [5], independent failure events are the worst-case scenario for the failure of distribution poles.

Furthermore, this study considers reconfiguration of the power network by changing the status of normally open (NO) and normally closed (NC) switches. This procedure is performed such that the radiality of the power network is not violated. In addition, a repair sequence is considered for the failed poles by considering the available repair crews and repair prioritization. In this regard, the poles that provide power for larger number of nodes are repaired first.

The outline of the paper is as follows: Section II presents the assumed distribution network. Sections III and IV explain the hurricane hazard and component fragility models, respectively. The network performance and restoration models are elaborated in sections V. Results of numerical study and conclusion are provided in sections VI and VII, respectively.

II. Power Distribution Network

This study investigates the resilience of an actual power distribution network composed of 7051 poles (Fig.1) located in southeast of the US using a dataset of inspected poles. For privacy purposes, the name of the owner and the location of the distribution network is not revealed in this study. The coordinates and age of the poles are obtained from the database. It is observed that the poles have a mean age and standard deviation of 38.6 and 16.6 years, respectively. Network information including the connectivity of the poles, 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 arbitrarily constructed. The resulting distribution system operates as a radial system.

The location of the substations is obtained by tracking the GPS coordinates of the poles (provided in the database) in Google Earth. Three substations are found for the distribution network. The location of the substations is provided in Fig.1. Based on the generated radial system and location of the substations, protective devices are assigned to the network. It is assumed that the network consists of a three-phase primary feeder and several single phase lateral feeders branching off from the main feeder. Therefore, the network is divided into three sections, each section receiving power from each of the three substations. Circuit Breakers are located next to substations, while switches are placed approximately every 1 kilometer of circuit length. The total circuit length is about 155 km; therefore, this network consists of 3 Circuit Breakers, 6 Reclosers and 175 switches for adequate protection.

The circuit breakers and reclosers are normally closed (NC). However, some of the switches are closed while some other are kept open. Normally closed sectionalizing switches are located on the system branches while normally open (NO) tie switches are located on feeders connecting substations to maintain radial structure of the network. By changing the status of switches, faults are isolated and network is reconfigured to reduce the number of outages. Further reduction of outages takes place through repair work performed by field crew.

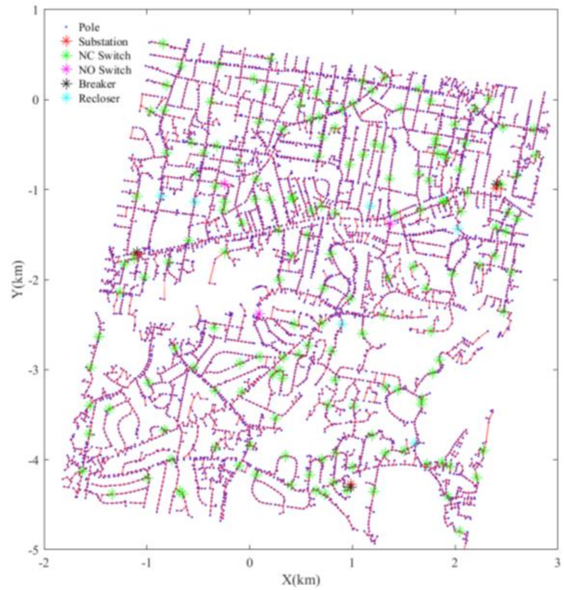

Fig. 1. The assumed distribution network

III. Hurricane Hazard Model

Hurricane is a probabilistic event. Although severe hurricanes impose a considerable probability of failure to the system, their probability of occurrence is considerably low. In this regard, two approaches can be followed for modeling hurricanes. The first approach is a probabilistic one, which considers the probability density function of wind speed. Subsequently, lower wind speeds have a higher chance of occurrence. Commonly, the probability that the wind speed does not exceed a given wind speed is a function of return period of the given wind speed as:

$$P(V < V_0) = 1 - 1/T_0 \tag{1}$$

where V denotes a wind speed, V_0 is the given wind speed and T_0 is the associated return period.

In Eq. (1), the higher the return period, it is more likely that the wind speed does not exceed the desired limit. Therefore, for high wind speeds that have a high return period, it is very unlikely that they occur. In this regard, if a probabilistic approach is considered, it is very unlikely to observe high winds and therefore, the probability of failure of the components of the system becomes comparatively small.

Second, a scenario based approach can be considered. In this approach, a specific wind speed or hurricane category is considered and the probability of failure of the system is investigated given the wind speed. In this approach, if a high wind speeds is considered, the probability of failure in the system will be much higher compared to the probabilistic approach.

IV. Component Fragility Model

In order to obtain the probability of failure in the system, the hazard model needs to be integrated with the conditional

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probability models. These conditional probability models are commonly referred as fragility models. Fragility functions define the probability of failure of a structure given a hazard with a specific intensity happening. In reliability assessment, a limit state function represented by $G(X)$ is used to obtain the probability of failure, where $G(X) < 0$ represents the failure of the structure. Incorporating the law of total probability, the probability of failure of a system with limit state $G(X)$ is defined as

$$P_f = P[G(X) < 0] = \int_y P[G(X) < 0 | IM = y]\, f_{IM}(y) dy \quad (2)$$

where IM represents the intensity measure, or a random variable that defines the intensity 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 given that $IM = y$.

The probability of failure of wood poles in overhead distribution lines under wind loadings can be obtained by using Eq. (2). The limit state function describing the failure event of utility poles is defined as

$$G(X) = R - S \quad (3)$$

where R is the moment capacity of the wood poles and S is the wind-induced moment demand on the poles. The capacity and demand models for wood poles are presented in the following subsections.

In order to obtain the fragility of distribution lines, some studies use historical data for estimating the probability of failure of individual components [4, 6]. This historical data are available for specific areas and specific hurricanes. Therefore, they cannot be used for other locations and other categories of hurricanes. However, in this study, a wind demand model presented in [5,7-9] is integrated with a age dependent capacity model of wood poles developed by Shafieezadeh et al., [8]. This model provides time-dependent mean and variance of the capacity of wood poles in terms of the initial capacity. Based on this model, the expected value and variance of the capacity of wood poles are defined as

$$\begin{aligned} E[R|T = t] = E[R_0][1 &- \min(\max(a_1 t - a_2, 0), 1) \\ &\times \min\left(\max\left(b'_1 t^{b'_2}, 0\right), 1\right)] \end{aligned} \quad (4)$$

$$\begin{aligned} Var[R|T = t] = (Var[R_0] + E[R_0]^2)\, \big(1 &- \min\left(\max\left(b'_1 t^{b'_2}, 0\right), 1\right)\big) \\ &+ \{(Var[R_0] + E[R_0]^2)[Var[L|T] \\ &+ (1 - \min(\max(a_1 t - a_2, 0), 1))^2]\} \\ &\times \left(\min\left(\max\left(b'_1 t^{b'_2}, 0\right), 1\right)\right) - E[R_0]^2 \\ &\times [1 - \min(\max(a_1 t - a_2, 0), 1) \\ &\times \min\left(\max\left(b'_1 t^{b'_2}, 0\right), 1\right)]^2 \end{aligned} \quad (5)$$

where R is the capacity of wood poles, R_0 is the capacity of the new poles, t is the age of the wood pole in terms of years, and $Var[L|T]$ is the time-dependent variance of the loss of the capacity of wood poles. Parameters a_1 and a_2 define the percentage of strength loss for wood poles and based on a regression analysis performed by Li et al. [10], they are found as 0.014418 and 0.10683, respectively. Parameters b'_1 and b'_2 account for the percentage of decayed poles and according to the regression analysis performed by Shafieezadeh et al. [8], they are found as 0.00013 and 1.846, respectively.

V. NETWORK PERFORMANCE MODEL

As mentioned previously a connectivity model is used to investigate the performance of the power system. In this regard, a node is considered as a failed node if that node is disconnected from all sources of power. Distribution networks in normal operating conditions perform as radial systems, which means that individual customers are connected to only one sub-station (source of power). However, when a fault occurs in the system, utility companies change the configuration of the distribution network by manipulating the status of switches to provide alternative power source and minimize the number of customers without power in the system. This procedure is called reconfiguration [14]. Reconfiguration is an automatic procedure that is performed instantly after a fault occurs in the system. The main steps in assessing the impact of hurricanes on distribution systems are Fault Location, Isolation and Service Restoration (FLISR).

A. Fault Location and Isolation

The first step in this analysis is determining the outaged poles in the hurricane affected network and therefore the damaged areas of the network. The hurricane model provides locations of poles that fail due to impact of the hurricane under study. Through the locations of failed poles, we identify the location of faults. The protective devices located around the fault locations are opened to isolate the faulted sections from the rest of the network and minimize damage. The devices are operated such that minimum possible network outage occurs by opening the devices. Once the appropriate devices have been opened, the outage sections of the network are determined. To determine outages from failed branches, a graph search is performed to determine connectivity of the original unaffected network. Subsequently a second graph search is performed to determine connectivity of network with failed branches. The difference between the two sets of data provides information about nodes that are not connected to any power sources. These are the outaged nodes. All customers on the isolated portion of the system lose power.

B. Restoration and Repair

Feeder reconfiguration is performed by manipulating the NC and NO status of sectionalizing and tie switches. A whole feeder, or part of a feeder, may be served from another feeder by closing a tie switch linking the two while a corresponding sectionalizing switch is opened to maintain radiality of the network [12].

For the restoration process, the recent studies consider two important factors for repairing the failed components of the system. The first factor is the mobilization of the resources and the second factor is the restoration sequence [4, 6]. The first factor pertains to the available budget, crews and resources to start the repair sequence. The second factor is the prioritization of the repair. Utility companies prioritize the restoration

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sequence based on the number of the customers that each failed pole serves. Considering these two factors is crucial to have a reliable estimation of the resilience of power distribution lines.

In the next step, tie and sectionalizing switches that should be closed and opened, respectively, to minimize power outages, are identified [12]. Each of the tie switch candidates is connected sequentially in the outaged network. After every connection, a graph search is performed to determine if outaged nodes from previous step have regained connectivity to a power source, while not violating constraints. If yes, reconfiguration successful. If outaged nodes do not regain power after all feasible switch configurations have been performed, while maintaining radiality of the network, then reconfiguration is not possible within the given network.

After reconfiguration is complete, utility companies begin to repair the failed poles. The pole repair function is dependent on two variables: the critical poles and the number of work crews. While the number of work crews is assumed to be a fixed number, the critical pole depends on the impact of the hurricane on the network in every simulated scenario. The poles which cause maximum outages are considered to be critical poles. Poles have been prioritized in the order of the number of outages their failure causes.

Repair is therefore first performed on the critical poles to reduce a larger number of outages. Once repair has been performed, the outage model is analyzed again to determine outages after reconfiguration and repair. It is expected that outages vanish when all failed poles have been repaired.

VI. NUMERICAL STUDY

To investigate the ability of the assumed distribution network to withstand and recover from wind related incidents, a study is performed to obtain the hurricane resilience of the network. The failure probabilities of poles are obtained by integrating the fragilities functions with a hurricane category 1 wind speeds. Subsequently, the failure probabilities are used to generated failure survival events for the poles assuming the independent failure events of the poles. 500 different scenarios for failure and survival of the poles in the network are generated.

After any fault occurs in the system, utility companies perform a reconfiguration procedure to isolate the faults and minimize the number of outages in the system. Fault isolation and network reconfiguration is instantaneous and automatic, controlled by a central Distribution Management System (DMS).

In the next step, utility companies send repair crews to the network to repair the failed poles. To expedite the recovery procedure, a prioritization is assumed based on the impact of the pole recovery on the number of outages in the system. Therefore, the poles whose recovery provides power for larger number of customers are repaired first. The other factor is the number of work crews; the more the number of work crews, the faster the poles are repaired. In this study, it is assumed that each work crew can repair the poles and conductors with a restoration time that follows a normal distribution. According to Ouyang and Duenas-Osorio [4], the restoration time for the poles has a mean and standard deviation of 5 hours and 2.5 hours, respectively. In addition, the restoration time for the conductors has a mean and standard deviation of 4 hours and 2 hours, respectively. Subsequently the restoration time for each node is assumed to be the maximum of the restoration time for the poles and conductors.

In this study, the metric for the performance of the system is chosen as:

$$Quality(\%) = 100(1 - \frac{N_{outaged}}{N_{tot}}) \qquad (6)$$

where $N_{outaged}$ is the number of outaged nodes in the system and N_{tot} is the total number of nodes in the system.

Using this metric, a performance curve for estimating the resilience of the power system is obtained (Fig. 2). Fig. 2 is obtained by averaging the 500 scenarios. As shown in the figure, the quality of the system drops to 5% after the hurricane impacts the system. In many scenarios, because of the presence of failed poles close to the substations, there are major outages upon fall of the hurricane (~95% of the network). Since the restoration options are restricted to the network under consideration, restoration does not cause a notable reduction in outages (about ~1%). Repairing the failed poles is the most effective course of action for the network in this study. The repair time, in terms of man hours, is calculated until outages reduce to zero. It is assumed that there are 12 work crews available with a working time of 12 hours for each crew. Therefore, 6 work crews are available at each instant of time 24 hours a day. It is shown that for Hurricane Category 1, full network power is restored in about 5 days after occurrence of hurricane (Fig. 2).

The resilience of the system can be estimated as:

$$R = \frac{\int_o^{t_{end}} Q.dt}{100\ t_{end}} \qquad (7)$$

where t_{end} is the end time for calculating the resilience. Since in the past outages had a duration of up to three weeks, in this study this parameter is taken as 4 weeks. Q is the quality of the system in terms of percent, which is shown in Fig. 2.
Using Eq. (6), the resilience of the power distribution network is obtained as 95.993%. It should be noted that this value is a function of the end time and if a different end time is considered this value will be changed.

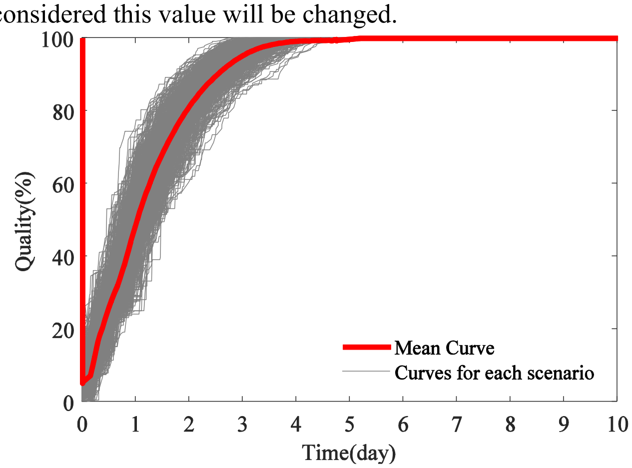

Fig 2. Quality Curve

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VII. Summary and Conclusion

In this study, the resilience of an actual power distribution network in southeast of the US under hurricane category 1 was investigated. The network consists of 7051 poles, which are powered by three substations. Since many of the poles in the system are old and the distribution network performs as a radial network with negligible redundancy, reconfiguration is not effective and therefore, the performance of the system drops significantly when a hurricane occurs. However, by prioritization of restoration poles based on the number of customer they support and assigning enough number of crews the system return to fully functional in a few days.

Due to high vulnerability of some parts of the system, it is recommended that the distribution network must be strengthened by replacing the old poles with new ones. In addition, extra distribution lines with open switches can be added to the system to increase the redundancy in the system. Therefore, reconfiguration can be effective to restore power into the system.

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