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# A Framework for Hurricane Resilience Assessment of Power Distribution Systems

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ABSTRACT: In current resilience assessment frameworks for power distribution systems, the failure events of overhead structures e.g. utility poles are assumed independent. Since adjacent poles have similarities in wind exposure, age, rate of decay, and structural properties, among others, it is likely that a level of correlation exists between their failure events. To explore potential effects, here correlations among failure events of poles are considered in the simulation process using dichotomized Gaussian method (DGM) that generates correlated failure and survival events. A real distribution network in southeast of U.S. is chosen for the case study. The network consists of three substations with 7051 poles. Following realizations of the physical state of the infrastructure, connectivity based analyses are performed to estimate the number of customers without power considering time-dependent restoration sequences. Results indicate that correlations among failure events of poles have a noticeable impact on the resilience of the power system; neglecting this characteristic results in an error in the estimation of resilience of distribution systems. This may lead to risk management solutions such as maintenance and replacement of utility poles that are not optimal for resilience enhancement purposes.

## 1. INTRODUCTION

Overhead power distribution lines are commonly supported by wood utility poles. Due to the high rate of decay in wood material, over time, wood poles lose their strength and become vulnerable against extreme wind events. This is confirmed by the past hurricane events as failure of wood poles resulted in widespread power outages. For example, during and in the aftermath of hurricane Sandy in 2012, 8.5 million customers lost their power (Blake et al., 2013).

Considering the high vulnerability of power distribution lines supported by wood poles, there is a high demand to improve their performance. Resilience assessment procedures are helpful in this regard, as they estimate the ability of the system to absorb shocks from extreme events and the speed of recovery. According to Bruneau et al. (2003), resilience is composed of Robustness, Redundancy, Resourcefulness, and Rapidity. Robustness is the ability of the system to withstand against stresses. Redundancy is the ability of the system to substitute failed elements with redundant elements such that the system attains its functionality. Resourcefulness is the ability to apply physical and human resources to meet the functionality of the system. Rapidity is the ability of the system to avoid current and future losses in a timely manner.

There have been a handful of efforts to quantify resilience of distribution lines (Mensah and Duenas Osorio, 2015; Ouyang and Duenas-Osorio, 2014; Bhat et al., 2018). However, there are a number of areas where these analyses could be improved. For example, the resilience study by Ouyang and Duenas-Osorio (2014) uses data driven fragility models that are only function of wind speed. As the properties of poles such as class, age, height, number and diameter of conductors, and span lengths, among others are different from one pole to another one, the adopted fragility model does not estimate the performance of individual poles accurately. In addition, the network analysis is performed assuming the failure and survival events of poles are independent. From the reliability perspective, this is the worst-case scenario, as it underestimates the reliability of the system (Darestani et al., 2016a; Darestani et al. 2016b; Darestani et al. 2017; Darestani and Shafieezadeh, 2017). Moreover, Bhat et al. (2018) investigated the resilience of a real distribution network composed of 7051 poles under hurricane category 1 wind scenario. In their model, they used an age-dependent model suggested by Shafieezadeh et al. (2016) to estimate the probability of failure of wood poles. In their analysis, it was also assumed that the failure and survival events of poles are independent.

According to Mensah and Duenas-Osorio (2015), a hurricane resilience assessment framework for distribution systems is composed of: (1) wind demand model, (2) component performance model, (3) response model, and (4) restoration model. To estimate the resilience of the power distribution system, these four sub-models should be integrated. For this purpose, wind demand models are merged with component fragility models to estimate the probability of failure of wood poles. It should be noted that resilience can be analyzed in a scenario-based or fully probabilistic fashion. In the scenario-based resilience assessment, a deterministic wind scenario is used to define the wind hazard while in the probabilistic model, an uncertain wind scenario is considered.

In order to address the aforementioned limitations, a framework for resilience assessment of real power distribution networks is proposed in this study. The framework offers a scenario-based resilience assessment of a distribution network, in which correlation among the failure events of wood poles is considered. Moreover, as a large number of poles exist in a distribution network, obtaining the probability of failure of each individual pole through Monte Carlo simulation is not practically feasible. In order to address this limitation, a Kriging meta-model is used to obtain a fragility function that provides the probability of failure of wood poles with different properties. Knowing the probability of failure of wood poles, failure or survival events for wood poles are generated through a Dichotomized Gaussian Method (DGM) (Emrich, 1991). This method can efficiently generate correlated failure events. Subsequently, the failure events are used in a connectivity based network analysis to identify the parts of the system with no power. Furthermore, a restoration procedure is performed to estimate the state of the power system at several instances after the failure occurs. This procedure identifies the poles that need to be repaired and restores power outages based on the availability of repair crews, and the time that it takes to repair each pole. This procedure is repeated to obtain the resilience of power network for various levels of correlation.

## 2. WIND DEMAND MODEL

For resilience assessment, wind hazard model should be integrated with component fragility models to generate the probability of failure of wood poles in the distribution network. For this purpose, wind could be considered as a deterministic model for a specific wind scenario or it could be considered as an uncertain model. According to Ouyang and Duenas-Osorio (2014), if wind is assumed as an uncertain variable, the measured annual resilience index of the distribution line will be considerably close to 1 as the expected annual duration of power outage is insignificant. In order to more clearly observe the differences among modeling approaches, a scenario-based resilience analysis is followed in this study.

### 2.1 Wind load on distribution lines

The static equivalent wind load suggested by ASCE07 (2016) is used in this study to estimate the wind induced load on distribution lines. According to ASCE07 (2016), the wind load on non-building structures is calculated as:

$$f_w = q_z G C_f D \quad (1)$$

where $q_z$ is the velocity pressure at height z from the ground line, $G$ is the gust-effect factor set as 0.85, $C_f$ is the force coefficient, and $D$ is the width of the conductor or pole perpendicular to the wind direction. $q_z$ is calculated from:

$$q_z = 0.613 K_z K_d K_{zt} K_e V^2 \qquad (2)$$

where $K_d$ is the wind directionality factor set as 1, $K_{zt}$ is the wind topographic factor set as 1, $K_e$ is the elevation factor set as 1, and $V$ is the 3-second gust wind velocity at 10 m above the ground line. In this study, for a hurricane category III, the wind speed of 120 mph is considered. Moreover, $K_z$ is the velocity pressure exposure coefficient calculated using:

$$K_z = 2.01 \left( \frac{\max(4.75, z)}{z_g} \right)^{2/\alpha} \qquad (3)$$

where $z$ is the height from the ground line. For a distribution line located in an open terrain area, exposure category is $C$, and $\alpha$ and $z_g$ are 9.5 and 274.32 m, respectively. $C_f$ is equal to 1, for conductors (ASCE 74, 2009). For poles, $C_f$, is obtained by interpolating the values presented in Table 1. In this Table, $h$ is the height of the pole above the ground line and $D$ is the diameter of pole.

Table 1. The Force Coefficient, $C_f$ from ASCE7 (2016)

| | $h/D$ | | |
|---|---|---|---|
| | 1 | 7 | 25 |
| $D\sqrt{q_z} > 5.3$ | 0.7 | 0.8 | 0.9 |
| $D\sqrt{q_z} \leq 5.3$ | 0.7 | 0.8 | 1.2 |

## 3. COMPONENT PERFORMANCE MODEL

An actual distribution network is composed of a large number of poles. As the properties of poles such as class, height, age, number and diameter of conductors, and span length, among others are different, estimation of the probability of failure of individual poles requires a Monte Carlo simulation for each pole in the network. This process is computationally time consuming as Monte Carlo simulation requires about 20000 realizations of uncertain variables to provide an accurate estimation of probability of failure of components of the system. In order to overcome this issue, a Kriging meta-model is used to generate a fragility model that provides the conditional probability of wood poles as a function of properties of poles and the wind intensity. This meta-model was generated by applying Kriging to a set of 1000 realizations of class, height, and age of the poles, span length, diameter and number of conductors, wind speed and wind direction. Kriging is a powerful meta-modeling technique that is employed here to provide accurate estimates of probability of failure of wood poles. However, the Kriging meta-model used in this study has a complex form and therefore, it is not possible to present the generated Kriging model in this paper. The authors recently used a Generalized Linear Model (GLM) to develop a set of multi-dimensional wind fragility functions based on the CDF of lognormal distribution for wood poles (Darestani and Shafieezadeh, 2019). The generated fragility functions provide accurate estimates of probability of failure of wood poles as a function of class, height, and age of the poles, span length, diameter and number of conductors, wind speed and wind direction. Interested readers can refer to this paper for further information regarding the fragility model.

### 3.1 Capacity Model for Wood Poles

In this study, it is assumed that the failure in the poles occurs if the wind induced moment demand exceeds the moment capacity of wood at the ground line. According to Wolfe et al. (2001) the 5% exclusion limit for modulus of rupture of wood utility poles is obtained through:

$$\sigma_{R5} = K_s . K_c . K_h . K_L . A . C_{GL}^{B} \qquad (4)$$

where $C_{GL}$ is the pole circumference at the ground-line, and $A$ and $B$ are regression parameters. For Southern Yellow Pine wood utility poles, $A$ and $B$ are equal to $3.482 \times$

$10^7$ and -0.320, respectively. $K_s$ is the adjustment factor for the size effect, which is taken as 1.1. $K_c$ is the adjustment factor for conditioning; it takes a value of 1 for air drying. $K_h$ is the calibration factor, which is taken as 1. $K_L$ is the adjustment factor for the effect of load sharing, which is conservatively taken as 0.91 (Wolfe et al., 2001). In Eq. (4), $\sigma_{R5}$ is in $N/m^2$ and $C_{gl}$ is in $m$. Shafieezadeh et al. (2014) converted Eq. (4) to mean value of modulus of rupture of Southern Yellow Pine wood by:

$$E(\Sigma_R) = 1.319 \times E(\sigma_{R5}) \quad (5)$$

Subsequently, they suggested that a lognormal distribution with the mean value from Eq. (5) and a coefficient of variation of 0.169 could be considered to model uncertainty in Southern Yellow Pines.

### 3.2 Effects of In-Service Decay on the Capacity of Poles

Since the ground line is exposed to moisture from the soil, it has the highest rate of decay. In addition, wind induced moment at the ground line is maximum. Therefore, ground line is the most likely location of failure in wood poles. Shafieezadeh et al. (2014) proposed the following age-dependent models for the mean and variance of the modulus of rupture of wood poles:

$$E[R|T=t] = E[R_0][1 - \min(\max(a_1 t - a_2, 0), 1) \times \min(\max(b'_1 t^{b'_2}, 0), 1)] \quad (6)$$

$$Var[R|T=t] = (Var[R_0] + E[R_0]^2)\left(1 - \min\left(\max\left(b'_1 t^{b'_2}, 0\right), 1\right)\right) + \{(Var[R_0] + E[R_0]^2)[Var[L|T] + (1 - \min(\max(a_1 t - a_2, 0), 1))^2]\} \times \left(\min\left(\max\left(b'_1 t^{b'_2}, 0\right), 1\right)\right) - E[R_0]^2 \times [1 - \min(\max(a_1 t - a_2, 0), 1) \times \min\left(\max\left(b'_1 t^{b'_2}, 0\right), 1\right)]^2 \quad (7)$$

where $E[R]$ is the mean modulus of rupture of wood poles, $E[R_0]$ is the modulus of rupture of 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 set as 0.11. Parameters $a_1$ and $a_2$ are 0.014418 and 0.10683, respectively and parameters $b'_1$ and $b'_2$ are 0.00013 and 1.846, respectively.

## 4. NETWORK PERFORMANCE MODEL

In Sections 2 and 3, wind demand models and capacity models for wood poles were presented. These models are integrated through a Monte Carlo simulation using 20000 realizations of uncertain variables defining wind induced moment demand and moment capacity to obtain the probability of failure of wood poles in a distribution network. As noted earlier, since there are a large number of poles (7051 poles) in the system, performing a direct Monte Carlo simulation is a time consuming task. In order to overcome this issue, a Kriging meta-model was used to estimate the probability of failure of individual poles.

Knowing the probability of failure of wood poles, realizations of failure or survival are generated. As the failure event between the poles in distribution networks are statistically dependent, in this study, a Dichotomized Gaussian Method (DGM) is used to generate correlated failure or survival events. This failure and survival events are used in a connectivity based network analysis to determine the segments of the distribution network with power outages.

Distribution networks operate as radial systems such that at each instant of time each node is only connected to one source of power. This radial system is protected by a set of protective devices such as circuit breakers, reclosers, and closed switches. However, if a fault occurs in the system, these protective devices activate and cut the power in the downstream branches to prevent the upstream segments of the network from losing their power. There are a set of normally open switches in the distribution network that can reroute the power such that some customers that are without power can get their power back. This process is called “reconfiguration” and it can isolate faults and prevent power interruptions.

In the current study, a connectivity-based analysis is performed to estimate the number of power outages in the system. For this purpose, as mentioned earlier, a DGM method is used to generate failure or survival events for the wood poles in the distribution network. Subsequently, the generated failure events are used in a network connectivity analysis. To perform this analysis, the distribution network is divided into a set of groups separated by protective devices. As noted previously, if a node fails, the corresponding protective device opens up and cuts the power from downstream branches to prevent the rest of the system from power outages. In this process, all the nodes after the protective device will lose their power. In order to mimic this process in the network analysis, a graph-based analysis is performed to find the closest protective device to the failed node. Subsequently, all the poles after that protective device lose their power. This process is repeated for all the failures in the system and subsequently the number of outages is obtained as the union of power outages due to individual failures.

## 5. NETWORK RESTORATION MODEL

When power network is damaged by a hurricane, the quality of the services provided by the system decreases. In this study, the metric to measure the performance of the system is the number of customers without power. Utility companies send their repair crews to repair the damaged poles. According to Ouyang and Duenas-Osorio (2014), the time that it takes crews to repair a wood pole follows a Normal distribution with an average of 5 h and a standard deviation of 2.5 h. In addition, conductor repair follows a Normal distribution with a mean of 4 h and a standard deviation of 2 h. As a hurricane may cause multiple pole failures and the number of repair crews are limited, utility companies follow a sequence for restoring power to the system. For this purpose, poles with higher importance are repaired first. For example, the pole with the highest customers served is restored first. In this study, a similar approach is adopted. All the failed poles are ranked based on the number of customers that they serve and subsequently poles with higher ranks are restored first. Following this procedure, power is back to a higher number customers at each instance of time compared to the case that poles are repaired randomly. Moreover, the network analysis used in this study is able to update the quality of the system by identifying the nodes that their power is restored and subsequently a dynamic restoration can be performed to analyze the performance of the system at each instant of time following the occurrence of any power outages caused by hurricane scenarios.

## 6. NUMERICAL STUDY

As noted earlier, the objective of this study is to investigate effects of correlation on the resilience of power distribution networks. For this purpose, an actual power distribution line located in southeast of the United States is considered in this study. This distribution system was previously modeled by Bhat et al. (2018) to investigate the resilience of the network under a category I hurricane. This network is composed of 7051 poles and 115 protective devices shown in Fig.1. As it was mentioned in Bhat et al. (2018), the location, class, height, and age of the poles are available. However, other information regarding the connectivity of poles, number of conductors, location of protective devices are not available. In order to solve this issue, Bhat et al. (2018) suggested a radial system for the current distribution network that keeps the radiality of the network such that each node is connected to one source of power through a unique path. Three substations were also identified through Google Earth at the location of the distribution network and subsequently, used in this study. In addition, the locations of switches are modified compared to Bhat et al. (2018) such that the switches perform more efficiently.

The resilience of the current network under a 120 mph wind speed is investigated through the procedure explained in Sections 2-5. In order to measure the resilience, as it was mentioned previously, an index should be defined for the performance of the system. For the current system, the performance is defined as the percentage of customers with power as shown below:

$$Quality(\%) = 100(1 - \frac{N_{outaged}}{N_{tot}}) \qquad (8)$$

where $N_{outaged}$ is the number of outaged nodes in the system and $N_{tot}$ is the total number of nodes in the system. Subsequently, the resilience of the system is defined as:

$$R = \frac{\int_{o}^{t_{end}} Q.dt}{100\ t_{end}} \qquad (9)$$

where $t_{end}$ is the end time. In the present study, this value is taken as 15 days. To investigate the effect of correlation on the resilience of the power distribution network, various levels of correlation are considered. It is assumed that the correlation between the failure events of poles follows an exponential function as:

$$\rho_{ij} = exp\left(-\frac{|x_i - x_j|}{L_{scale}}\right) \qquad (10)$$

where $x_i$ and $x_j$ are the locations of pole $i$ and $j$, respectively. $L_{scale}$ is the length scale that is used to scale the level of correlation between poles. The level of correlation depends on various factors such as environmental conditions, structural couplings, and age and class of the poles, among others. Obtaining the actual value of the length scale requires information about the true failure of poles. However, as these data are not available, in this study, various levels of correlation are considered and the impact of correlation length on the resilience of the distribution network is investigated.

The resilience curves for the distribution line (presented in Fig. 1) with various levels of correlation are provided in Figs. 2-5. As it is seen, the resilience decreases with an increase in the length scale. Particularly, using Eq. (9), the resilience of the network is obtained as 95.1%, 93.6%, 92.2%, and 89.5% for length scales of 0, 60.96 m (200 ft) , 152.4 m (500 ft), and 1524 m (5000 ft), respectively. As mentioned earlier, length scale defines the level of correlation. The larger the length scale, the larger the correlation between the failure events of poles. In first glance, it may seem that independent failure events are the worst case scenario for the estimation of the resilience of the system. However, it should be noted that for reliability assessment purposes in which it is desired to estimate whether the system has experienced any failure or not, independent failure events are the worst case scenario. On the other hand, for any analysis that takes into account the number of failures in the system, correlation reduces the performance of the system. In the case of distribution networks, with an increase in the length scale (Eq. 10), the joint probability of failure between the poles increases. This means that the chances of multiple poles failing together increases. When multiple poles fail, the restoration time is extended as there are a limited number of crews that can repair poles and bring the power back to the system. Subsequently, the time to restore power to the system increases and the quality of the system will be lower compared to cases with smaller length scales. Therefore, an increase in the correlation results in a reduction in the estimation of the resilience of the system.

## 7. SUMMARY AND CONCLUSION

In this study, effects of correlation on the resilience of an actual distribution network in southeast of the United States under a category III hurricane were investigated. For this purpose, an age-dependent wood capacity model was integrated with a static equivalent wind load model to obtain the probabilities of failure of individual poles through Monte Carlo simulations. Fragility models are subsequently derived based on Kriging metamodeling technique for each individual pole in the distribution network. These probabilities of failure were used to generate correlated failure events via Dichotomized Gaussian method (DGM). A connectivity based network analysis was adopted to estimate the number of power outages in the system followed by a restoration of power at several instances after the hurricane. Results of resilience analysis of the network with various levels of correlation show that with an increase in the level of correlation, the resilience of the network decreases. This is partially due to the fact that with an increase in the correlation, the probability of multiple failures in the system increases. Subsequently, the time to restore power to the system increases and therefore, the resilience of the network decreases. Therefore, the common perception that independent failure events result in the worst case scenario for the performance assessment of the infrastructure systems is not true for any analysis in which the number of failures affects the performance of the system. Specifically, for resilience assessment of distribution systems, independent failure events result in an overestimation of the resilience of the system. It should be noted that the correlation level (length scale in Eq. 10) between the components of the system can be estimated using historical data for the failure of similar systems. However, such data at the resolution needed are not publicly available. Due to lack of these data, engineering judgement for the level of correlation between adjacent poles is an alternative solution. It is expected that adjacent poles have higher correlation in their failure events, therefore, a length scale in the order of a few span lengths appears to be reasonable.

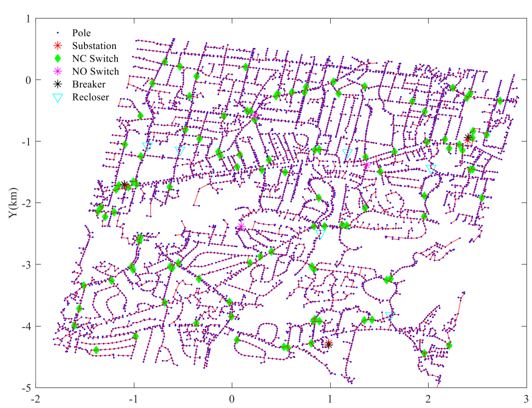


*Figure 1. The assumed distribution network*

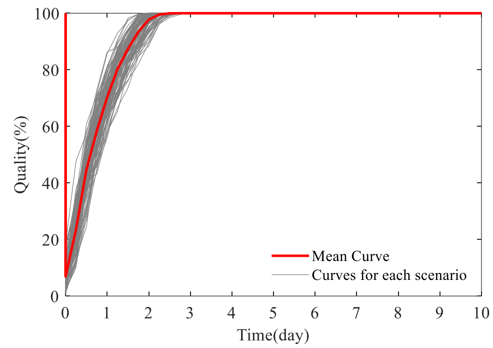


*Figure 2. Resilience curve for independent failure events (Length Scale=0)*

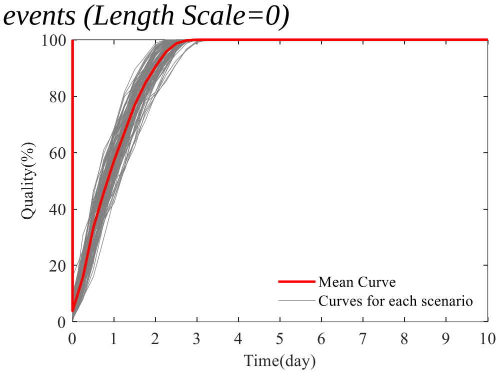


*Figure 3. Resilience curve for correlated failure events with length scale of 60.96 m (200 ft)*

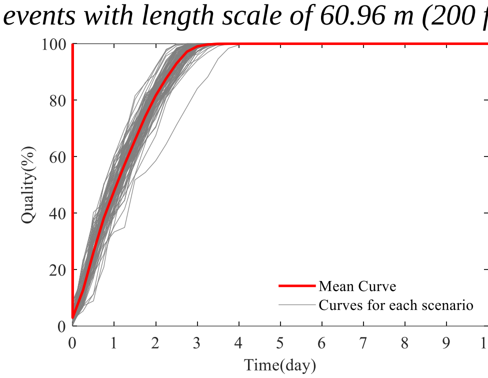


*Figure 4. Resilience curve for correlated failure events with length scale of 152.4 m (500 ft)*

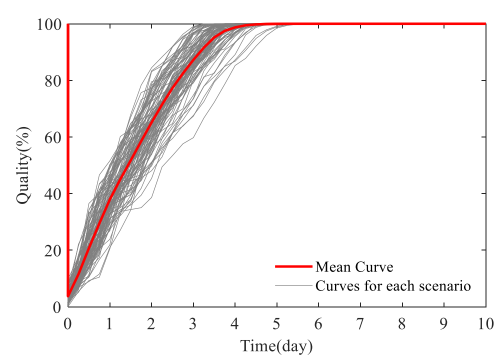


*Figure 5. Resilience curve for correlated failure events with length scale of 1524 m (5000 ft)*

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