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System-level Maintenance Optimization for Power Distribution Systems Subjected to Hurricanes

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ABSTRACT: Overhead electric power distribution systems are vulnerable to extensive damage due to hurricanes. Most of the damage is caused by the failure of distribution poles, which are mostly wood poles. As a natural material, wood is susceptible to strength deterioration over time due to decay. As such, utility companies carry out preventive maintenance actions to minimize the likelihood of failure of the poles due to decay and extreme events (hurricanes). Due to the scarcity of resources for maintenance, an optimization approach to maintenance planning is necessary. Most utilities consider minimizing maintenance cost as the objective in their wood pole maintenance planning. However, due to increasing demand for higher system reliability, the consideration of cost alone in maintenance optimization is not adequate. This paper presents a maintenance optimization framework for power distribution systems under hurricane hazard considering system performance as the objective. Two maintenance strategies are explored: periodic chemical treatment and the use of fiber reinforced polymer (FRP). The distribution system of a virtual city assumed to be located in Florida is used to demonstrate the framework.

1. INTRODUCTION

Electric power systems are vulnerable to extensive damage due to natural hazards, as evident in recent hazard events such as Hurricane Michael. Overhead power distribution systems consist of conductors and other electrical equipment supported by poles. The large number of such distribution poles make them critical to overall asset management in distribution systems. In the United States (U.S.), it is estimated that there are between 160 million and 180 million wood poles supporting distribution and transmission networks (Mankowski et al. 2002). Wood poles are mostly used due to advantages such as low initial cost and natural insulation properties. Wood poles are, however, susceptible to decay over time which leads to decrease in strength. As such, utility companies carry out periodic inspections and necessary maintenance of wood poles over time. Given the scale of pole networks and their susceptibility to decay, it is reasonable to assume that a systematic risk-based or reliability-based maintenance policy would lead to considerable cost savings and failure risk mitigation

Electric power systems rely on various components that work together to deliver power to customers. Consequently, any reliable maintenance planning approach needs to take into account how the different components interact. This requires a system-level approach. However, existing research on maintenance of wood distribution has been largely focused on a component-level approach (e.g., Ryan et al. (2014), Datla and Pandey (2006), etc.).

This paper presents a framework for optimal maintenance of wood distribution poles subjected to hurricane wind hazard. The framework considers system performance using a topological-based probabilistic performance measure as an objective. In addition, both corrective and preventive maintenance of the system are considered. The optimization is constraint to account for pole residual strength requirement. The proposed framework is demonstrated using a notional power distribution system assumed to be located on the east coast of Florida in the U.S. Two preventive maintenance strategies are considered: a time-based chemical treatment and a condition-based repair using fiber reinforced polymer (FRP). The developed framework can be used for a more efficient and optimal use of resources to improve reliability considering uncertainty in both strength and applied load due to hurricane hazard.

2. COMPONENT AND NETWORK RISK ASSESSMENT

2.1. Wood pole failure risk assessment

Component risk here is defined as the annual probability of failure of poles which is given by Equation (1):

$$P_f = \int_0^\infty F_R(v,t) f_v(v,t)\,dv \tag{1}$$

where $F_R(v,t)$ is the time-dependent cumulative distribution function (CDF) of pole fragility, and $f_v(v)$ is the probability density function (PDF) of the annual maximum hurricane wind speed. The next two sections describe the evaluation of the time-dependent component fragility and hurricane wind load.

2.1.1. Wood pole vulnerability

The vulnerability of the poles is quantified using fragility analysis performed using Monte Carlo Simulation. The limit state function for the fragility analysis is given by Equation (2):

$$G(t) = R(t) - S \tag{2}$$

where $R(t)$ is the time-dependent strength of the poles; and S is the load demand (i.e. bending stress) at the ground line. Lognormal distribution has been shown to be appropriate to model fragility of wood distribution poles (Salman et al. 2015). The time-dependent cumulative distribution function (CDF) of component structural fragility, $F_R(v,t)$, in Equation (1) is therefore modeled by the lognormal distribution.

To account for decay over time, the wood decay model developed by Wang et al. (2008) is adopted. The model assumes that decay follows an idealized bilinear relation over time. The decay rate is given by Eq. (3). Further details can be found in Wang et al. (2008):

$$r = k_{wood} k_{climate} \tag{3}$$

where r is the decay rate (mm/year); k_{wood} is the wood parameter; $k_{climate}$ is the climate parameter.

2.1.2. Hurricane hazard model

Hurricane hazard is modeled through a Monte Carlo simulation. The simulation method is based on the model developed by Xu and Brown (2008) and described in Salman and Li (2016). The simulation model involves using site-specific statistics of key hurricane parameters and Monte Carlo simulation for assessing hurricane hazard level. Site-specific statistics of parameters can be derived from historical records. For the chosen location, Florida, the parameters for the hurricane simulation are obtained from Xu and Brown (2008) and Huang et al. (2001) based on historical records from the North Atlantic Hurricane Data Base (HURDAT).

200,000 hurricanes years are simulated. The Weibull distribution was found to fit the maximum annual hurricane wind speeds from the simulation (Salman and Li 2016). Hence, the probability density function (PDF) of the maximum annual hurricane wind speed, $f_v(v)$, in Equation (1) is modeled by the Weibull distribution.

3. SYSTEM PERFORMANCE

A critical part of any system-level maintenance planning is quantifying the consequences of damage to the system. For electric power systems, models of performance measure can range from purely topological-based models to complex alternating current (AC) power flow models. Topological- or connectivity-based models only consider the manner in which system components are arranged (topology) to describe the behavior of the system. Physical constraints that govern power flow within the system is ignored. Power flow-based models, on the other hand, take into account the physics of power flow, power capacity limits of components and other engineering details of the system.

Topological-based models have two main advantages: (i) they are computationally efficient especially for complex systems or in a case where system performance under various scenarios is desired, and (ii) significantly less data about a system is required to evaluate reliability. While power flow-based models provide more accurate description of system performance, they are computationally complex and often impractical (Cavalieri et al. 2014). Furthermore, detailed information about engineering properties of system components is required for such analysis. As this study focuses mainly on structural components of the power system, which define the topology, the topological-based method will be used.

In radially operated distribution systems, a line is defined as a switchable section with one or more isolator elements at its ends. Isolator elements, commonly known as sectionalizers, are usually installed at several points within a system so as to allow parts of the system to be isolated in case of any disturbance at any point along a line. The presence of isolator elements within a distribution system allows each line to be considered individually as a 'switchable section'. All components in a switchable section have the same reliability characteristics and failure of any component have the same impact regardless of the location of the failed component. Consequently, switchable sections can be reduced to single component equivalent. A failed line is assumed to be isolated from the rest of the system by activating the isolator element upstream of the line.

Due to the radial nature of most distribution systems, the accessibility of lines in the system can be modeled as a series system in which the failure of any line or component along a path can lead to failure of power delivery to lines downstream of the failed line.

Given the accessibilities of system components, a single measure of system reliability is required. A simple topological-based approach is to use the weighted reliabilities of system components (Volkanovski et al. 2009). The system reliability is thus given by Equation (4).

$$R_S = 1 - \sum_{i=1}^{N} Q_i \frac{C_i}{C} \tag{4}$$

where Q_i is the probability that power is not delivered to the ith component (lateral lines or demand substations); C_i is the load served by ith component (kVA, kW, or number of customers); C is the total load served by the system (kVA, kW, or number of customers); and N is the total number of demand components in the system. The probability of failure of a line is evaluated using Eq. (5) based on the method developed by Taras et al. (2004):

$$P_l = P_i \cdot \{2P_a - P_a^2\} \tag{5}$$

where P_i is the probability of failure of a central pole and P_a is the probability of failure of an adjacent pole conditional on the failure of the central pole. The conditional probability of failure of the adjacent poles is evaluated by increasing their applied load by 50% to account for load sharing after the failure of the central pole. The following assumptions are made in Eq. (5): (i) failure of only one pole does not constitute service failure, (ii) cascading failure due to the failure of a pole is limited to only two adjacent poles, and (iii) additional load due to the failure of a central pole is shared equally by the two adjacent poles.

4. MAINTENANCE STRATEGIES: IMPACT AND OPTIMIZATION

4.1. Time-based maintenance

Time-based preventive maintenance of utility poles is usually carried out at fixed intervals. Inspection intervals vary depending on utility company policy and can range from 3 to 6 for some companies and up to 8 years for others (Mankowski et al. 2002). The most common time-based preventive maintenance for utility poles is chemical treatment. If chemical treatment is carried out, it is assumed that decay is temporarily halted and a new time lag is added to the progress of the decay. At the end of the new time lag, decay resumes with the same rate pre-treatment. The chemical treatment considered in this research is the use of Osmoplastic which is an external diffusing chemical barrier. In a survey of 261 utility companies in the U.S., Mankowski et al. (2002) reported that a majority of the respondents, over 40%, reported using Osmoplastic for external decay control. The new lag time added by applying Osmoplastic is taken as 5 years (Wang et al. 2008).

4.2. Condition-based maintenance

The condition-based maintenance strategy considered in this research is the use of fiber-reinforced polymers (FRP) alone and in combination with chemical treatment. Saafi and Asa (2010) studied the effectiveness of using an in situ wet layup FRP in strengthening in-service wood distribution poles. The strengthening method involved installing an FRP jacket of length 3 times the diameter of the pole around the decayed area of the pole at the groundline. Field tests were carried out on 30-year-old class 4 southern pine poles and structurally intact poles were used for comparison. It was noted that in all cases, failure occurred at or near the groundline.

The results of the field tests from Saafi and Asa (2010) showed that application of FRP added between 24 MPa to 27 MPa of strength to the tested poles. Therefore, for the purpose of demonstrating the proposed framework, it is assumed that repair using FRP will add a strength of 24 MPa to the strength of the repaired pole irrespective of the time of repair. It is acknowledged that the level of improvement in strength due to repair by FRP will depend on factors such as the type of FRP used and how it is installed, among others. Hence, in this research, it is assumed that the FRP and installation method from (Saafi and Asa 2010) are used.

It is assumed that after the installation of FRP, the underlying wood continues to decay with the same rate prior to installation. It is possible that the FRP jacket will affect the rate of decay by affecting factors such as moisture content and oxygen level. However, due to lack of data, it is assumed here that the nature of the FRP-wood interface has no effect on decay rate. Little research has been carried out to investigate the deterioration of strength with time of FRP especially when used for repair of distribution poles. There is, however, some evidence, though inconclusive, that wood decay fungi can affect the strength of FRP overtime (Tascioglu et al. 2003). It is assumed in this research that the strength of the FRP will deteriorate due to fungal attack and other environmental factors with a rate that is half the deterioration rate of the wood (Saafi and Asa 2010).

Fig. 1 shows the impact of both chemical treatment and FRP repair on the service life of poles. If no action is taken against decay, it can be seen that the strength of the pole will fall below 67% of the initial strength at around 32 years at which point it is expected to be replaced according to NESC (2002) requirement. For the purpose of plotting Fig. 1, it is assumed that chemical treatment is carried out every 10 years. It is also assumed that the FRP is installed at 30 years just before the strength of the pole falls below the

NESC threshold. It can be seen that chemical treatment and FRP increased the service life of the pole from 32 years to 57 and 68 years, respectively, corresponding to about 78% and 113% increase. Fig. 1 also shows the service life when both chemical treatment and FRP repair are combined. In this case, chemical treatment is carried out for the first 50 years which is close to the time the treated pole is to be replaced and then the pole is repaired using FRP and the chemical treatment is stopped. It can be seen that combining the two methods increased the service life of the pole from 32 years to about 88 years, which implies an increase of about 175%.

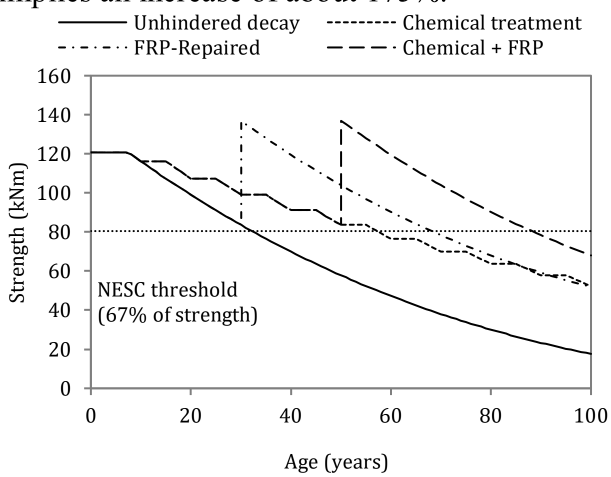

Figure 1: Service life comparison

4.3. Maintenance optimization

Deregulation, scarcity of resources, increasing demand for higher levels of reliability, and pricing concerns are forcing utility companies to come up with methodologies that will guide decision making on how resources are allocated to various projects and maintenance policies. Optimization techniques can be employed to guide decision-making concerning resource allocation and maintenance policy selection. The aim of maintenance optimization is to select a strategy from a pool of maintenance policies that satisfies prescribed objective functions such as minimizing cost and/or maximizing performance. In this research, optimization based on system performance will be carried out.

The objective here is to find the optimal FRP repair age for untreated and chemically-treated poles based on system performance considering NESC strength requirement constraint. The NESC strength constraint can be satisfied if the repair is carried out before the strength of a pole falls below 2/3 of the initial strength, R_o. As the system performance varies with time due to decay, the minimum system performance over a specified period is considered in this formulation for the optimization. Indeed, it is considered that FRP repair is implemented at the minimum system performance time. The optimization is formulated as follows:

$$\begin{cases} \underset{T_m}{\text{argmax}}\ R_{S_{min}}[F_R(t), f_v(t), P_I, C_i, C, T_m] \\ \qquad \text{Subject to: } T_m \leq T_{NESC} \end{cases} \tag{6}$$

where $R_{S_{min}}$ is the minimum system performance over a selected period; $F_R(t)$ is the fragility of the poles which is a function of time due to decay; $f_v(t)$ is the probability density function of hurricane wind speed; P_I is the probability of failure of a line in the system; and C_i and C are the loads served by the ith lateral line and the system, respectively. The optimization problem is solved numerically by evaluating the minimum system performance over a selected period for various values of T_m. Maintenance optimization with respect to system performance leads to a reliability-centered maintenance (RCM). This is an improvement over condition-based maintenance as it considers both the probability of component failure as well as the system impact should failure occur.

The optimization problem involving system performance involves a non-linear objective function that cannot be stated explicitly as a function of the decision variable (optimum preventive maintenance time, T_m). Moreover, the time-dependent nature of some of the variables involved in the optimization further complicates the solution. As such, numerical exhaustive search method is used to solve the problem. This is feasible because there is only one decision variable, and the constraint that $T_m \leq T_{NESC}$ in both cases implies the interval in which the optimum lies is finite. Additionally, T_m is an integer, which also reduces the solution space.

5. CASE STUDY

5.1. Power distribution system

The power distribution system adopted for demonstrating the proposed framework is shown in Fig. 2. It is the power distribution system of a virtual city called "Micropolis" developed at Texas A&M for use in infrastructure research. The system serves a city approximately 2 miles (3.2 km) by 1 mile (1.6 km) with about 5,000 residents and it is assumed to be located on the east coast of Florida, with the middle of the city located at 27.6ºN and 80.4ºW. The system serves 434 residential, 15 industrial, and 9 commercial/institutional customers including 3 schools and 3 churches (Brumbelow et al. 2007).

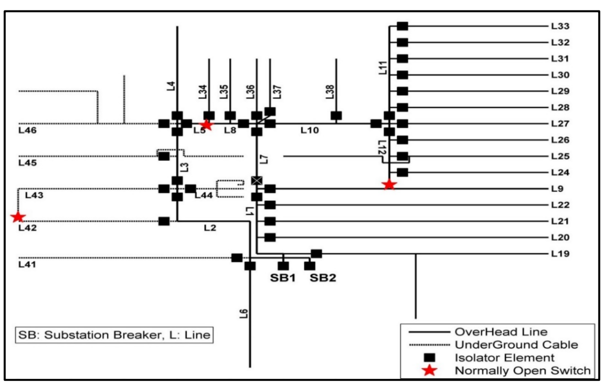

Figure 2: Micropolis power distribution system line diagram

The lines are assumed to be supported by 13.7 m high class 4 southern pine poles with a span of 46 m. There are an estimated 661 poles in the system. The three-phase main feeder poles are assumed to support three Aluminum Conductor Steel Reinforced (ACSR) conductor wires with diameters of 18.3 mm and one all-aluminum conductor (AAC) neutral wire with a diameter of 11.8 mm. The single-phase laterals are assumed to support two ACSR conductor wires and one AAC neutral wire. Based on these configurations, the required pole sizes are found to be class 4 and 5 using the reliability-based design method in ASCE-111 (2006) for the three-phase and single-phase lines, respectively. The system is assumed to be radially operated at all times. Isolator elements at the upstream of each line allow the system to be reduced to several switchable sections. For simplicity sake, customers in Micropolis are classified into 5 groups with all customers belonging to each group having a fixed average load demand throughout the year as shown in Table 1 (EIA 2013).

Table 1: Load profiles for consumers across Micropolis

Customer type	Consumption
Residential	1.5kW/h
City churches	5kW/h
City schools	10kW/h
Industrial (Feeder 1)	39.4kW/h
Central business district (Feeder 2)	10.1kW/h
Feeder 1 total	**1,334kW/h**
Feeder 2 total	**394kW/h**
System total	**1,728kW/h**

As mentioned earlier, corrective maintenance here is defined as pole replacement due to failure caused by hurricane wind. The number of failed poles in a line in a given year due to hurricane winds is calculated by multiplying the annual probability of failure of the poles with the number of poles in the line. Failed poles are replaced with poles of the same class. As the city is small compared to the size of a hurricane, it is assumed that the hurricane hazard is the same for all the poles in the city.

5.2. Optimization results

Fig. 3 shows the optimization result based on minimum system performance. As the aim here is to find the optimum time for first repair using FRP, the period over which minimum system performance is evaluated is taken as 50 years. This is because, within this period, the strength of FRP-repaired poles will not fall below 2/3 of the initial strength of the poles which will lead to the replacement of the repaired poles. From Fig. 3, the optimal repair time for FRP repair only is 27 years. The analysis stopped at 32 years because the FRP repair must be carried out before the pole strength falls below the NESC threshold. Note that the system performance at age 0 with all new poles is 88% while the minimum system performance over 50 years with neither chemical treatment nor FRP repair is 7%.

Fig. 3 also shows the optimization result for a combination of chemical treatment and FRP repair. Chemical treatment is assumed to be applied every 10 years. Therefore, the minimum time of FRP repair is 15 years which is at the end of the effect of the first chemical treatment. It is assumed that the periodic chemical treatment is stopped once the FRP is installed. The optimal FRP repair age for the chemically-treated poles is 30 years. Fig. 3 can also be used to find the optimal repair time to maximize service life for a given minimum system performance constraint. For example, in the case of FRP repair only, if it is desired that the system performance should not fall below 55% over the considered period, the repair can be carried at either around 24 years or 29 years.

The results in Fig. 3 can also be used to determine the FRP repair time if minimum system performance is constraint to a certain value. For example, if it is desired to constraint the minimum system performance to ≥ 70% over the 50-year period considered in the case of chemical treatment and FRP repair, then the FRP repair has to be carried out between approximately 20 and 32 years.

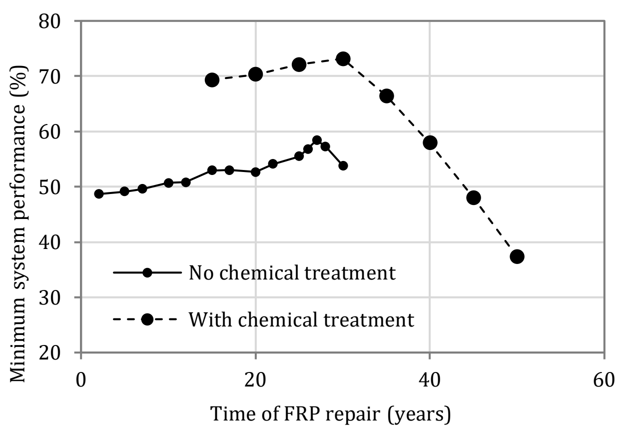

Figure 3: Optimization results based on minimum system performance

Alternatively, the optimization can be formulated based on average system performance over the considered period the result of which is shown in Fig. 4. It can be seen that the average system performance decreases slowly as the age of FRP repair increases. Consequently, an optimal repair time could be estimated by defining a threshold average system performance. Optimal repair times obtained by this formulation, however, will be very sensitive to this threshold value. In addition, the results based on average system performance do not consider the minimum system performance values that could lead to system failure, and therefore, they compromise system safety.

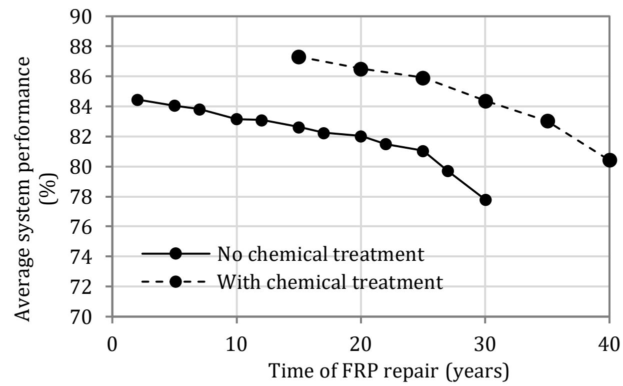

Figure 4: Optimization result based on average system performance

6. CONCLUSION

Long-term risk-based asset management of electric power distribution systems subjected to hurricane hazard requires the consideration of realistic exposure conditions such as deterioration of components. This paper presented a framework for optimal maintenance of wood poles considering system performance as the objective. The framework was demonstrated using a virtual city as a case study and considering periodic chemical treatment of the poles and repair of decayed poles using FRP. The results show that delaying maintenance will result in higher probability of failure of the poles which will reduce the system performance over time.

The Micropolis power system considered has one substation and two feeders as mentioned earlier. However, some distribution systems, especially those located in large urban areas, can have several substations with looped or networked topology comprising tens of feeders and hundreds or thousands of sectionalizing switches. This will make computing system performance using the probabilistic method described in this paper tedious. Alternatively, the optimization can be performed by taking the component performance as the constraint rather than system performance. The component performance will then be quantified in terms of annual probability of failure of the poles due to hurricane winds calculated using Eq. (1).

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