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Maintenance optimization for power distribution systems subjected to hurricane hazard, timber decay and climate change

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ABSTRACT

Electric power systems are vulnerable to extensive damage due to hurricanes with most of the damage concentrated on overhead distribution systems. There is evidence that climate change will affect future hurricane patterns. Additionally, wood poles, which are most commonly used in distribution systems, are susceptible to decay. The scarcity of resources and increasing demand for higher reliability warrant the use of optimization techniques for wood pole maintenance planning. This paper presents a framework for optimal maintenance of wood poles subjected to non-stationary hurricane hazard and decay. Maintenance cost, service life, and system performance are considered separately and simultaneously in the optimization. Periodic chemical treatment and repair of decayed poles using fiber-reinforced polymer are considered. The distribution system of a virtual city assumed to be in Florida is used to demonstrate the framework. The results of the single-objective optimization indicate that the objective that maximizes service life resulted in higher optimal maintenance time. However, delaying maintenance will lead to a larger probability of pole failure, higher corrective maintenance cost, and lower system performance. The result of the multi-objective optimization is closer to the result of the cost-based optimization because the cost function is more sensitive to the variation of maintenance time.

1. Introduction

Asset management is one of the crucial aspects of concern to decision makers such as power distribution companies and involves several actions such as component acquisition, maintenance, replacement, and disposition. One of the most important aspects of asset management is preventive or corrective maintenance. The purpose of such maintenance measures is to extend the service life of components and/or reduce their probability of failure. Utility companies are constantly exploring ways to optimize the use of available resources for maintenance while ensuring an acceptable level of reliability.

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 not only because of their impact on reliability but also in terms of cost. For example, there are an estimated 5 million wood poles in Australia, with a net worth of over $10 billion [1,2]. 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 [3]. Wood poles are mostly used due to advantages such as low initial cost and natural insulation properties [4]. Wood poles are, however, susceptible to decay over time which leads to decrease in strength [5]. 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.

Power distribution systems, especially the distribution poles and lines, are susceptible to extensive damage due to hurricanes. For example, in 1992, Hurricane Andrew caused the failure of about 10% of distribution poles which resulted in a power outage to 44% of customers of Florida Power & Light [6,7]. In 2004, four major hurricanes struck Florida causing a combined economic loss of over $20 billion and damaging every segment of Florida's electricity infrastructure which resulted in a power outage to over 9.6 million

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customers combined [8]. The impact of hurricanes on distribution systems is compounded when the potential impact of climate change is considered. The *Fifth Assessment Report* of the Intergovernmental Panel on Climate Change (IPCC) noted a variation in weather patterns and projected an increase in the intensity of storms [9,10]. Gutowski et al. [11] projected that a 1.6°C rise in sea surface temperature could increase tropical wind speeds by as much as 13%, with 10–31% more precipitation. This implies that both the strength of poles and hazard intensity are time-dependent and a comprehensive long-term maintenance policy should take these new climate conditions into account.

In the face of limited resources available for preventive maintenance, an optimization approach is necessary. While maintenance optimization for electrical components of distribution systems considering common cause failures has been studied (e.g. Hilber et al. [12], Lehtonen [13], Abbasi et al. [14], Sittithumwat et al. [15], Arab et al. [16]), research on maintenance optimization for distribution poles subjected to hurricane hazard considering the potential impact of climate change is scarce. Ryan et al. [2] presented a framework for the reliability assessment of treated and untreated distribution poles subjected to wind load incorporating deterioration and network maintenance using an event-based Monte Carlo simulation. While the framework advances the state-of-the-art by incorporating network maintenance, it did not attempt to optimize maintenance strategies nor consider system performance. Winkler et al. [17] present a methodology for combining hurricane damage predictions and topological properties to investigate the impact of hurricanes on system reliability. Substations, transmission lines, and distribution lines were considered in the study. System reliability was found to correlate with topological features such as meshedness, centrality, and clustering.

Other research on distribution poles subjected to hurricane hazard includes Bjarnadottir et al. [18], Gustavsen and Rolfseng [19], and Francis et al. [20]. These papers, however, did not consider preventive maintenance of the poles, system performance, and optimization. Datla and Pandey [21] developed a probabilistic model for estimating the life expectancy of wood poles as well as determining the optimal replacement age based on cost. Pierson and Blanc [22] studied the impact of various factors such as specie, pole size, nature of attachments, location, and material imperfection on the optimal replacement time of wood poles based on cost. Preventive maintenance and system performance was, however, not considered.

This paper presents a framework for optimal maintenance of distribution poles subjected to non-stationary hurricane wind hazard. The framework considers system performance using a topological-based probabilistic performance measure, cost constraints, climate change impact, and decay. In addition, both corrective and preventive maintenance of the system are considered. Three objectives are considered separately and simultaneously in the optimization: cost, service life of poles, and system performance. The optimization based on cost is constraint to the total lifetime length while the optimization based on service life and system performance are constraint to account for pole residual strength requirement. Fig. 1 shows a general flow chart of the proposed framework. 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 and prolong the service life of distribution support structures considering uncertainty in both strength and applied load due to hurricane hazard.

The paper is organized as follows: Section 2 presents the methodology used for component and network risk assessment. Section 3 describes the considered maintenance strategies as well as the framework for maintenance optimization. Section 4 illustrates the proposed methodology with a case study focusing on the maintenance optimization of a power distribution system of a 5000-resident virtual city.

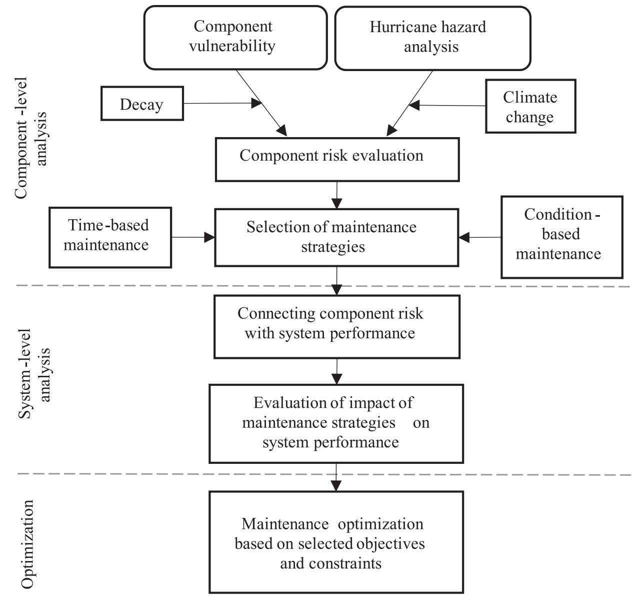

Fig. 1. General flowchart of proposed framework.

2. Component and network risk assessment

2.1. Component risk assessment

As mentioned earlier, the vulnerable components considered in this research are the wood distribution poles supporting overhead lines. Component risk here is defined as the annual probability of failure of poles which is given by Eq. (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 component structural fragility, and $f_v(v, t)$ is the time-dependent 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. Time-dependent component 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 Eq. (2):

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

where $R(t)$ is the time-dependent strength of the poles; $S(t)$ is the load demand (i.e. bending stress) at the ground line. Note that only flexural failure is considered in this research as it is the most common failure model for wood poles [17]. If data is available, other failure modes such as foundation failure and failure due to flying debris and falling trees can be easily incorporated into the framework. The steps of the fragility analysis are summarized in Fig. 2.

Lognormal distribution has been shown to be appropriate to model fragility of wood distribution poles [18,23]. The time-dependent cumulative distribution function (CDF) of component structural fragility, $F_R(v, t)$, in Eq. (1) is therefore modeled by the lognormal distribution given by Eq. (3):

$$F_R(v, t) = \Phi\left[\frac{ln(v/m)}{\zeta}\right] \tag{3}$$

where m is the median of the fragility function; ζ is the logarithmic standard deviation of intensity measure; and v is wind speed.

As a natural material, wood is susceptible to decay over time due