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Evaluating system reliability and targeted hardening strategies of power distribution systems subjected to hurricanes

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ABSTRACT

Over the years, power distribution systems have been vulnerable to extensive damage from hurricanes which can cause power outage resulting in millions of dollars of economic losses and restoration costs. Most of the outage is as a result of failure of distribution support structures. Over the years, various methods of strengthening distribution systems have been proposed and studied. Some of these methods, such as undergrounding of the system, have been shown to be unjustified from an economic point of view. A potential cost-effective strategy is targeted hardening of the system. This, however, requires a method of determining critical parts of a system that when strengthened, will have greater impact on reliability. This paper presents a framework for studying the effectiveness of targeted hardening strategies on power distribution systems subjected to hurricanes. The framework includes a methodology for evaluating system reliability that relates failure of poles and power delivery, determination of critical parts of a system, hurricane hazard analysis, and consideration of decay of distribution poles. The framework also incorporates cost analysis that considers economic losses due to power outage. A notional power distribution system is used to demonstrate the framework by evaluating and comparing the effectiveness of three hardening measures.

1. Introduction

Power systems are susceptible to damage due to weather-related events especially hurricanes. Between 2007 and 2012, the majority of power outages in the United States were caused by weather-related events [5]. In 2012 for example, hurricane Sandy caused severe damage to the power system of several coastal states causing over 8.5 million customers to lose power for weeks and even months in some areas [11]. When it comes to damage due to hurricanes, the distribution part of the power system is the most vulnerable [17]. For example, since 1998, electric utility companies in Texas have incurred about $1.8 billion in restoration costs due to hurricanes with 80% of the costs attributed to the distribution system [13].

Aging infrastructure has also been determined to be one of the main issues facing the power system [5]. Aging of components increases the vulnerability of the system in cases of natural disasters. Wood distribution poles for example are susceptible to decay as they age which causes reduction in strength. This is of particular concern as most of the distribution poles in the U.S. are wood poles [26].

Over the years, several methods of hardening the distribution system have been studied. One of the methods studied extensively is undergrounding the system [23,13,58]. However, most of these studies concluded that undergrounding is not cost effective with Brown [12] stating *"The conversion of overhead electric distribution systems to underground is expensive and, except in occasional targeted situations, cannot be fully justified based upon quantifiable benefits"*.

Another method being currently studied is targeted hardening of current overhead distribution systems. Targeted hardening involves strengthening important support structures as well as structures with very high probability of failure. Important structures include distribution poles that serve large number of customers, poles that serve critical customers (hospitals, fire stations, police stations, economic centers) and poles that are difficult to access. Brown [13] studied the hardening of 10% of distribution poles in Texas and estimated the net benefit derived from it. Bjarnadottir et al. [10] studied targeted hardening of distribution poles in Florida by replacing poles that fail with poles that are one class higher.

However, the above studies did not attempt to identify risk-critical parts of the system to be strengthen or evaluate the effect of the targeted hardening on overall system reliability. To determine the critical parts or components of a system, some form of component importance measure is required. This in turn requires evaluating the

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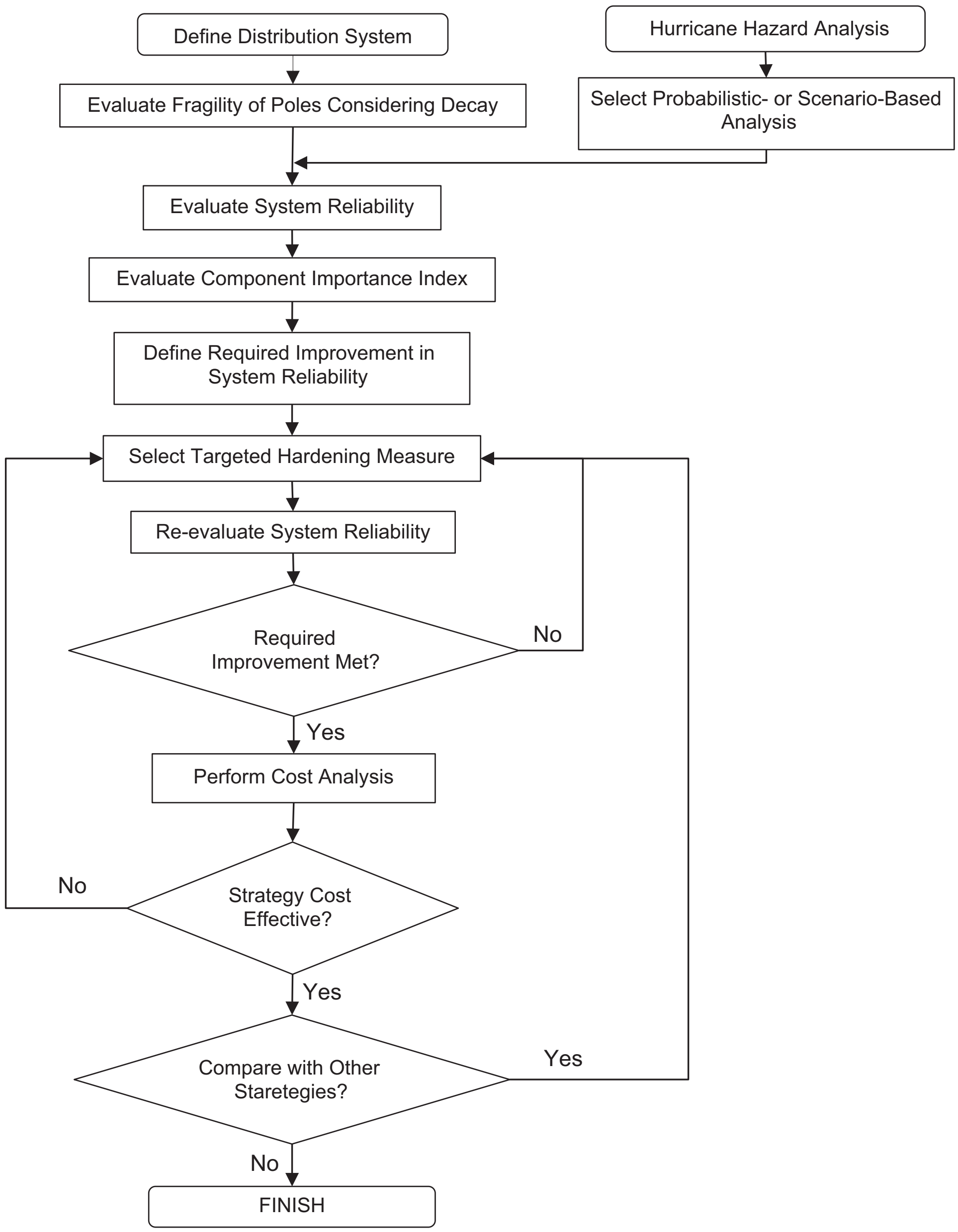

Fig. 1. Flow chart of proposed framework.

reliability of the whole system. However, previous studies (e.g. Han et al. [27], Shafieezadeh et al. [44], Bjarnadottir et al. [9], Ryan et al. [42]) conducted on the vulnerability of distribution systems to hurricane and extreme wind damage focuses on evaluating the reliabilities of individual poles rather than the whole system.

This paper presents a framework that can be used to evaluate the effectiveness of targeted hardening measures. The framework includes fragility analysis considering decay of poles, hurricane hazard analysis, a method of evaluating distribution system reliability that relates failure of support structures and power delivery, component importance measure, and cost analysis. The flow chart of the general framework is shown in Fig. 1. The framework is explained and demonstrated at the same time using a notional power distribution system.

2. Power distribution system model

The power system model adopted for demonstrating the framework is shown in Fig. 2. It is the power system of a virtual city called "Micropolis" developed at Texas A&M University for use in infrastructure risk research and planning [14,7]. The city has approximately 5000 residents in a historically rural region. The city is assumed to be located on the east coast of Florida, with the middle of the city located at 27.6°N and 80.4°W. The city has one substation supplied by a sub-transmission line (138 kV rating). Two three-phase feeders emanate from the substation to deliver power to the entire city by branching off to smaller three-phase sub-branches and single-phase laterals. Most of the left side of the city is served by an underground system. However, in this research, the underground system is transformed to an overhead system so that the entire system can be considered. The city is approximately 2 miles by 1 mile. The total circuit line is approximately 30.3 km with about 661 poles. There are an estimated 434 residential, 15 industrial, and 9 commercial/institutional customers in the city including 3 schools and 3 churches [14].

Fig. 3 shows the line diagram of the power distribution system. There are three Normally Open (NO) switches in the system that can allow rerouting. However, these switches are not considered