Probabilistic simulation of power transmission systems affected by hurricane events based on fragility and AC power flow analyses

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ABSTRACT: This paper presents a technique for probabilistic simulation of power transmission systems under hurricane events. The study models the power transmission system as a network of connected individual components, which are subjected to wind-induced mechanical failure and power flow constraints. The mechanical performance of the transmission conductors are evaluated using an efficient modal superpoistion method and extreme value analysis. The fragilty model is then deveoped using first order reliability theory. The asssumptions of the method are discussed, and its accuracy is thoroughly investigated. The component fragilities are used to map the damage of hurricane events to the failure probabilities. The electircal performance of the components is modeled through an AC-based power flow cascading failure model, to capture the unique phenomena affecting power systems, such as line overflow and load shedding. The methodology is demonstrated by a case study involving a hurricane moving across the IEEE 30-bus transmission network. This technique aims at helping decision makers gain fundamental insights on the modeling and quantification of power system performance during hurricane events.

1. INTRODUCTION

Power transmission is the bulk transportation of electrical energy from power plants to electrical substations. The power transmission systems are among the most critical infrastructures in modern society, since most of the other infrastructures rely on the electrical power supply to be functional. However, power transmission systems are extremely vulnerable to hurricane events. During Hurricane Harvey, hundreds of high-voltage transmission lines experienced storm-related outages and left thousands of customers without power. Power loss (i.e., unsatisfied power demand) is often initiated by failure of individual components, such as support structures and conductors, triggering cascading failures of the network.

At the component level, research has been conducted to study the fragility of poles (Shafieezadeh et al., 2014) and towers (Fu et al., 2016). However, fragility curves for transmission conductors are not available. At the system level, failures of structural components are usually considered using fragility models, and cascading failures were captured using a DC power flow model by Ouyang and Duenas-Osorio (2014). Recently, AC power flow models, which render a better estimation of the system performance, have been adopted by Li et al. (2017) to simulate power network dynamics. However, the accuracy of these system analyses is undermined by the lack of detailed structural analyses.

This paper first presents a framework for efficient fragility analysis of transmission conductors

against hurricanes. The wind induced demands on conductors are characterized probabilistically using a random wind field to capture the uncertainties of the wind fluctuation process and correlations. Random vibration theory is used to derive the closed-form distribution of extreme loading on conductors. Fragility curves are computed using first order reliability theory. With the obtained fragility models, a technique is introduced for the probabilistic simulation and objective quantification of power transmission systems performance. The proposed technique takes into account both the structural and electrical properties of the components and their network topology. The relationship between reliability of individual components and power network resilience is addressed. Finally, a case study is conducted using Monte Carlo simulation, studying the effect of Hurricane Katrina on an IEEE benchmark network.

2. FRAGILITY MODELS OF TRANSMISSION CONDUCTORS

The failure mode considered in this study is rupture of the conductor due to excessive wind load. A power network is formed by multiple transmission lines, and each transmission line consists of thousands of conductors connected in series. Although the failure of a single conductor can be considered as a rare event, the probability of failure for a transmission line is not negligible, and such failure can cause severe damage to the system. There are two difficulties in deriving the fragility model for transmission conductors: (1) predicting the load response of a conductor with accuracy and efficiency, (2) and computing the probability of failure for a conductor, a rare event, with enough accuracy. Figure 1 presents the conceptual flowchart of the methodology that has been developed to derive the fragility models of transmission conductors.

2.1. Wind field simulation

In a hurricane event, the largest component of the conductor's displacement is due to the transversal wind flow in the direction perpendicular to the conductor's plane. In this study, the wind direction is assumed to be perpendicular to the longitudinal direction of the conductor, which is the worst case
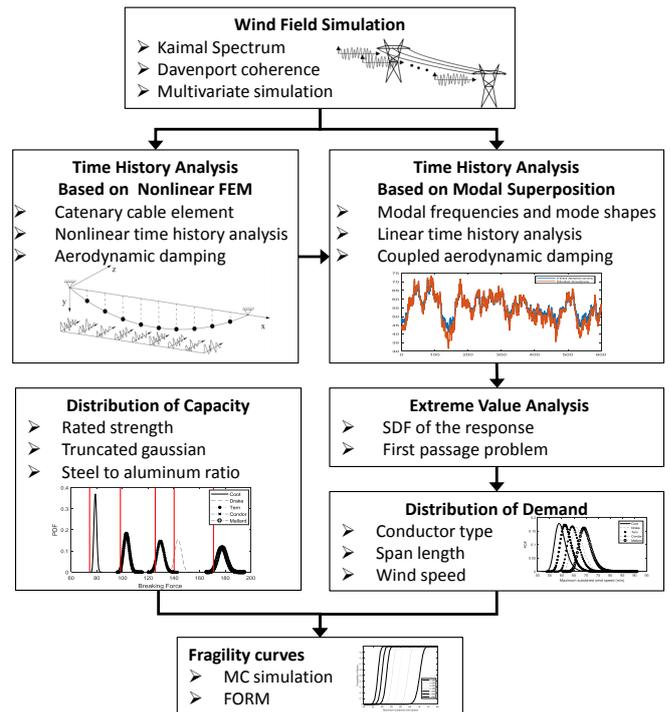

Figure 1: Flowchart of the methodology for fragility models of transmission conductors

scenario. The mean wind profile follows the famous power law (Hellman, 1916):

$$\bar{V}(z) = \bar{V}_0(z/10)^\alpha \qquad (1)$$

where $\bar{V}_0$ is mean wind speed at 10 meters high, z is the height of the conductor above the ground, and α is the an exponent that depends on the roughness of the terrain. The spectral density function of the wind turbulence is modeled by Kaimal spectrum (Kaimal et al., 1972):

$$\frac{fS_v(f)}{u_*^2} = \frac{200fz/\bar{V}}{(1+50fz/\bar{V})^{5/3}} \qquad (2)$$

where f is the frequency in Hertz, and u_* is the shear velocity of the flow. The coherence function, which is a measure of the degree to which two records of wind fluctuations at different locations are correlated is defined by Davenport's exponential function model (Davenport, 1968). The wind field is modeled by a stationary, Gaussian, one-dimension and multivariate random process. The simulation algorithm used in this study is the one developed by Deodatis (1996) based on the spectral representation method and fast Fourier transform technique. Figure 2 presents one realization
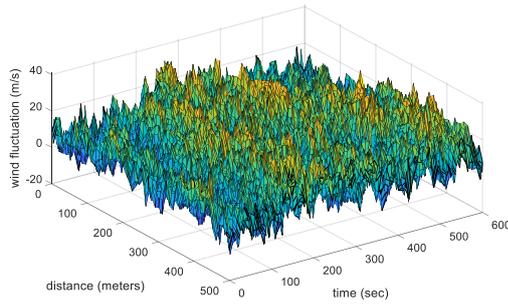
Figure 2: Realization of wind field simulation

of the wind field simulation correlated in time and space. The simulated wind field covers 500 meter distance and a time span of 10 minutes.

2.2. Time history analysis with nonlinear FEM

The FEM model is built in the OpenSees platform (McKenna et al., 2010), and catenary element is used in this study to model the conductor (Abad et al., 2013).To account for the pretension force of the conductor, the unstrained length of the cable is determined. The conductor is then divided into a number of catenary cable elements equally spaced along the x direction, as shown in Figure 3. The y coordinates for each node can be determined following the procedure described by Irvine (1981). After specifying the nodal coordinates, the gravity load are applied to the conductor and the pretension force is automatically implemented as reaction force at the supports. The nonlinear FEM time history analysis is performed by solving the equation of motion. The external force per unit length is computed as :

$$F_{t+\Delta t} = \frac{\rho}{2} C_D D \left[(\bar{V} + V_{t+\Delta t} - \dot{z}_{t+\Delta t})^2 + (\dot{y}_{t+\Delta t})^2 \right]$$
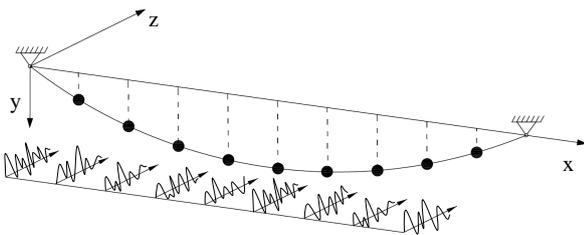(3)

Figure 3: Finite element model of the conductor subjected to dynamic wind force

where $\rho = 1.25 kg/m^3$ is the air density; $C_D = 0.9$ is the static drag coefficient; D is diameter of the conductor; $V_{t+\Delta t}$ is the turbulence at time instant $t + \Delta t$; $\dot{z}_{t+\Delta t}$ and $\dot{y}_{t+\Delta t}$ are the nodal velocities at time instance $t + \Delta t$ in z and y directions which can be extracted during the time history analysis. The nodal velocities at time $t + \Delta t$ are approximated by those at the previous time step, given that the time step Δt is small enough. Since the external force depends on the nodal velocities of the cable, the aerodynamic damping effect has been accounted for. Even though the time history analysis using nonlinear FEM is time consuming, it is considered the most accurate, as the geometrical nonlinearity of the cable is taken into consideration.

2.3. Time history analysis with modal superposition

In this section, the time history analysis is carried out using the modal superposition method (Wang et al., 2017). The first step of the method is to determine analytically the state of the conductor under static mean wind speed and calculate the natural frequencies and mode shapes based on the theoretical solutions (Irvine, 1981). The coupled modal damping ratios are derived to take into account the aerodynamic effect. Then, the conductor is modeled as a linear system characterized by those dynamic properties, and the time history analysis can be performed. To validate the linear assumption of the modal superposition, the time history response of the modal superposition method is compared to the response of nonlinear FEM, where geometric nonlinearity is considered. Multiple tests with different cables and winds have shown that the modal superposition method is always able to accurately capture the peak force, but deviates from the FEM results when the response is relatively small, as shown in Figure 4. This is probably due to the fact that the conductor dynamic properties at the mean wind situation are similar to the dynamic properties under extreme loadings, but different from the dynamic properties under relatively small loadings. At the mean wind state the conductor is already stretched tight, therefore in the high wind state the dynamic properties do not change significantly. However, under low wind loading the conductor
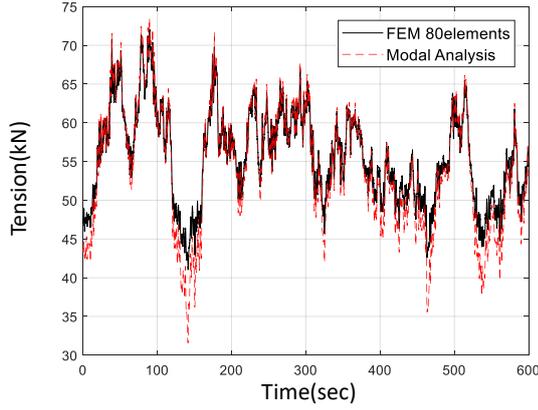
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Figure 4: Comparison of conductor tension response between FEM and modal superposition method

becomes slack and its dynamic properties deviate from the linear estimation. Since the assessment of fragility curves requires to determine only the peak response, the modal superposition method is considered sufficiently accurate to be used to evaluate the maximum response of conductors during a hurricane event. The modal superposition method not only reduces the computational time for time history analysis, but more importantly, facilitates the computations in the frequency domain, which is important for the next step.

2.4. Extreme value analysis

The spectral density matrix of the modal displacement vector is calculated as:

$$S_q(f) = H(f)S_Q(f)H(f)^* \qquad (4)$$

where $H(f)$ is the transfer matrix and $S_Q(f)$ is the spectral density matrix of the generalized force vectors. The spectrum of the total force response can be determined as:

$$S_N(f) = r_N^T S_q(f) r_N \qquad (5)$$

where r_N is the modal participation coefficient for the conductor tension response N. The variance of N is then computed by integration of $S_N(f)$ and the variance of $\dot{N}$ can be computed by integration of $S_{\dot{N}}(f)$. Then the problem falls under the category of "first-passage problems" in the theory of random vibrations. The expected number of up-crossings of level a per unit time is:

$$v_a^+ = \frac{1}{2\pi}\frac{\sigma_{\dot{N}}}{\sigma_N}exp(-\frac{a^2}{2\sigma_N^2}) \qquad (6)$$

It is well known that the probability of up-crossing level a in the interval $0 < t < T_0$ is

$$P(T_0) = 1 - exp(-v_a^+ T_0) \qquad (7)$$

For a fixed T_0, Eqs. (6)–(7) provide the distribution of v_a^+, a, and, in turn, of the peaks $\bar{N} + a$:

$$S_i = \bar{N} + \left[-2\sigma_N^2 \ln\left(\frac{2\pi(v_a^+)_i\sigma_N}{\sigma_{\dot{N}}} \right) \right]^{0.5} \qquad (8)$$

where $\bar{N}$ is the mean tension response under mean wind speed, σ_N and $\sigma_{\dot{N}}$ are functions of the properties and location of the conductor as well as the intensity measure of the hurricane. $(v_a^+)_i$ is the ith realization of the random variable v_a^+ and S_i is the ith realization of the conductor demand. Maximum sustained wind speed, which is the highest average wind over a one-minute time span, is chosen as the intensity measure in this study. The maximum sustained wind speed is then convert to the average wind speed over 1 hour. The first reason for this conversion is that the Kaimal spectrum requires the wind speed averaging period to be at least 10 minutes. The second reason lies in the concept of spectral gap. According to Van der Hoven (1957) there exists a spectral gap at around 1 hour. The presence of this spectral gap indicates that there is much less variability in the mean wind speed of 1 hour than the mean wind speed averaging over other periods. Figure 5(a) shows the demand PDFs of conductor 'Drake' subjected to different maximum sustained wind speeds with same span length. The probability distributions of the demand are sharp when the wind speed is relatively low, but under large wind speed the probability distribution becomes wide and the variability increases significantly. It is noted that most codes are developed based on the work by Davenport Davenport (1964), assuming extremely narrow probability distributions of the demand. The assumption is valid for relatively low wind intensity, but may not be valid when the intensity measure is large. Figure 5(b) presents the demand PDFs of five types of conductors with the same span length and subjected to the same maximum sustained wind speed of 50m/s.
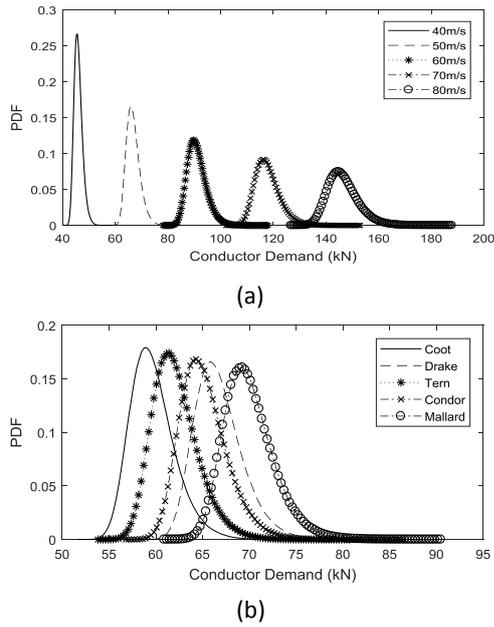
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(a)

(b)

Figure 5: (a) Conductor 'Drake' demand distribution with different intensity measure (b) Demand distribution of five types of conductor with the same intensity measure

2.5. Capacity of transmission conductors

Most of the conductor producers specify conductor strength as a single value: rated strength. The rated strength represents the lower exclusion limit of the conductor strength and is calculated in accordance with specification requirements. Therefore, rated strength cannot be directly used to represent the breaking force (capacity) of the conductor. The breaking force of the conductor in this study is modeled by Monte Carlo simulation with the ASTM rule as:

$$R_i = n_{aw}S_{(aw)}\frac{\pi d_{(aw)}^2}{4} + n_{sw}S_{(sw.1\%)}\frac{\pi d_{(sw)}^2}{4} \quad (9)$$

where R_i is the ith realization of the conductor breaking force; d_{aw} and d_{sw} represent the aluminum wire diameter and steel wire diameter respectively; $S_{(aw)}$ is the breaking stress of individual aluminum strands; $S_{(sw.1\%)}$ is the stress in steel strands at 1% extension. d_{aw}, d_{sw}, $S_{(aw)}$, $S_{(sw.1\%)}$ are all random variables with truncated normal distribution. The parameters of these distributions are taken from Farzaneh's research (Farzaneh and Savadjiev, 2007). Figure 6 shows the realizations of the Monte Carlo simulation of the conductor breaking force.
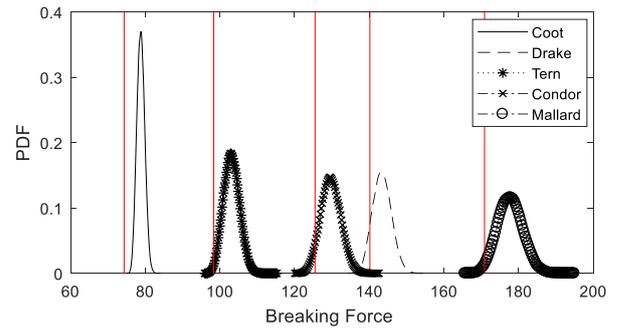

Figure 6: Distribution of the conductor capacity

Each vertical line in the figure represents the rated strength of one conductor.

Once the distribution of demand and capacity of the conductor are obtained, the probability of failure can be computed by Monte Carlo simulation. However, the failure probability of the conductor is very small (often in the order of 10^{-7}), therefore conducting Monte Carlo simulation can be very costly and the first order reliability method (FORM) is used to replace Monte Carlo simulation. The implementation of FORM is facilitated by UQlab (Marelli and Sudret, 2014). To test the validity of FORM, a large scale Monte Carlo simulation has been conducted and its results are compared against the results from FORM. FORM has very good accuracy for the computation of the failure probability. In this study, the fragility curves of conductors are computed and the uncertainties of wind load and conductor capacity are considered. The nonlinear FEM dynamic model is replaced by the modal superposition method. Figure 7 shows the fragility curves of five types of transmission conductor with span length of 300 meters. The wind direction is often unknown and therefore assumed to have uniform distribution. The fragility curves indicate that the failure of the conductors is very sensitive to the intensity measure. Once the hurricane intensity reaches the critical range, large amount of conductor damage can be expected. Span length also has significant impact on the fragilities.

3. PROBABILISTIC SIMULATION OF POWER TRANSMISSION SYSTEMS

This section presents the methodology to conduct probabilistic simulation of power transmission sys-
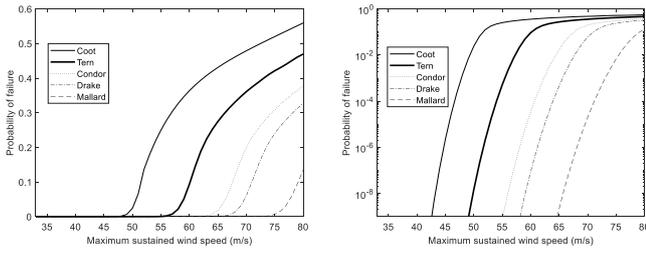
Figure 7: Fragility curves of five types of conductor with span length of 300 meters

tems incorporating the structural fragility models developed in Section 2 with a power system model and power flow models. Figure 8 presents the flowchart of the methodology. The first step is to identify the critical components in the system and extract the hurricane intensity measure from historical data. The network topology (i.e., connectivity) is also modeled. The second step is to conduct damage assessment of the structural components with the fragility model. Finally, the failure of the power supply due to disconnection of the electrical components and load balancing is simulated by an AC-based power flow model. Monte Carlo simulation is conducted to quantify the power loss and assess the probabilistic characteristics of the system performance.
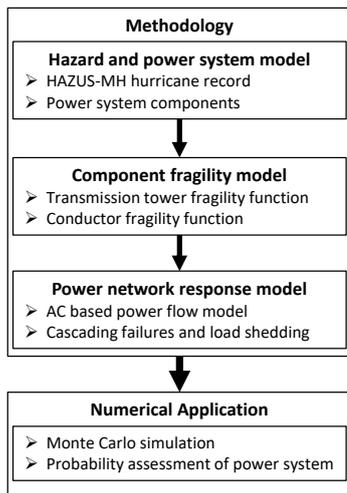

Figure 8: Flowchart of the methodology for probabilistic simulation of power transmission systems

3.1. Hazard and power system model
This methodology requires to model the regional hazard with a specific scenario, which can be a historical event, or a simulated intensity measure map. In particular, the intensity measure used for this analysis are the peak gust speed and maximum sustained wind speed. The power transmission system is modeled by power plants and transmission substations connected by high-voltage transmission lines, which include the transmission support structures and the conductors between the support structures. In the graph model, power plants are nodes generating real and reactive power with specific power generation capacity; transmission substations are nodes receiving power from power plants and then supplying the low-voltage power to distribution systems with certain load demand; transmission lines are links between power plants and transmission substations, with certain load capacity. All the electrical properties of the components in power transmission systems are modeled using MATPOWER (Zimmerman et al., 2011). Failure of a link is determined by the damage state of transmission support structures (i.e. transmission towers etc.) or conductors along the link. The conductors and support structures are considered in series, thus collapse of a single support or conductor trips the whole line.

3.2. Power network response model
An AC-based power flow model is used to capture the power system response after component failures due to a hurricane. In this study, the performance of the power system is measured under the following assumptions: (a) the vulnerability of power plants and substations is negligible; (b) the damage state of the transmission line is binary: functional or failed; (c) network operators and automated switches have enough time to interrupt power supply to certain areas to prevent further failures of the network. In this situation, this study leverages MATPOWER to solve the AC optimal power flow (ACOPF) problem, carrying out an optimization aiming to maximize the total power demand satisfaction in the system. This is achieved by changing load demand at the substations and power generation at the plants, while considering all the necessary physical constraints. The failed branches determined by the fragility model are removed, and sub-grids are formed automatically by
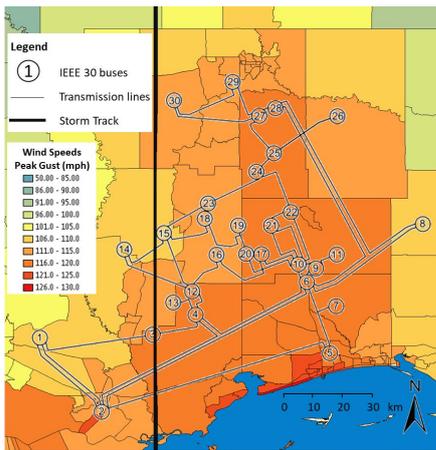
Figure 9: Hurricane Katrina wind field and georeferenced IEEE 30-buses network
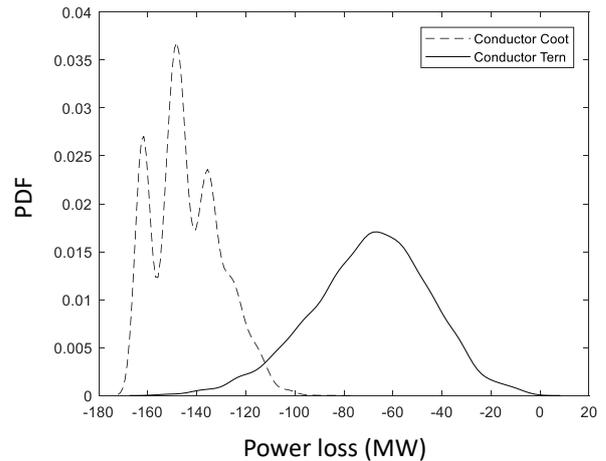

Figure 10: PDF of system power loss

appropriate codes. Power redistribution in the sub-grids is computed and load shedding is conducted when ACOPF cannot converge. The simulation stops when all the sub-grids achieve a stable power flow and the power loss for the whole network is computed and stored.

4. NUMERICAL APPLICATION

The IEEE 30-bus system with 6 generators, 20 loads and 41 transmission lines which represents a portion of the American Electric Power (AEP) network is used as a case study, in its version adapted by Zimmerman et al. (2011). The wind field data of Hurricane Katrina, which hit the Southern US in 2005 is obtained from the HAZUS database. The intensity measures are obtained at the resolution of a census tract. The IEEE 30-bus system with power demand of 189.2 MW can serve approximately a population of 700,000. The bus system is selected and projected onto costal Mississippi and Louisiana, as shown in Figure 9, where a comparable population lives. The IEEE 30-bus system is considered a good approximation of the real power network in the studied region. The power network consists of 4656 transmission support structures, whose fragility models are governed by peak gusts (Quannta-Techonology, 2009), and 4615 spans of conductors, with span length of 400 meters and fragility models built following the procedure described in Section 2. The results of the Monte Carlo simulations are presented in Figure 10. To inves-

tigate the influence of each type of structural component on the system performance, two simulations are conducted for two different types of conductors. As shown in Figure 10, the probabilistic distribution shifts to the right when the conductors type changes from 'Coot' to 'Tern', because conductor 'Tern' has lower probability of failure. In addition, changing the conductor type also changes the probabilistic distribution completely. This indicates that this power system is highly sensitive to conductor types. Therefore, detailed information and rigorous fragility models about each component in the power system are needed in order to evaluate the power system behavior accurately.

5. CONCLUSIONS

This paper introduced a method for efficient computation of transmission conductor fragility and a multi-scale, probabilistic methodology to assess the performance of a power system subjected to a hurricane event. The proposed methodology combines, in a coherent way, the electrical properties of the power system and the structural behavior of the network components. The response of transmission conductors is computed using the modal superposition method, which enables the extreme value analysis using random vibration theory. The demand and capacity of the transmission conductors are obtained and their probabilities of failure are computed by FORM. The obtained structural fragilities are used to map the hurricane intensity measure to component damage in the power network by dis-

crete event simulation. Then, an AC-based power flow analysis is performed to simulate the load redistribution process within the damaged power system. A case study using the IEEE 30-bus system with wind field data from hurricane Katrina was conducted to illustrate the methodology. This comprehensive model, can be used for various types of analyses and offers a protocol to quantify power system performance.

6. ACKNOWLEDGMENTS

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