Power System Resilience Metrics Based on Tree Failure Model

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***Abstract*—Power system resilience against high-impact, low-probability (HILP) windstorm events is crucial for utilities and operators. This study proposes a novel vegetation-based stochastic assessment framework for evaluating the resilience of distribution networks. The methodology introduces a parametric Tree Failure Model (TFM) that considers various tree characteristics, such as height, density, and crown diameter, in assessing the fragility of distribution system poles and lines. The study integrates the TFM with a mesh-view resilience assessment approach to evaluate the impact of three HILP event types: hurricane, storm, and ice freezing. The framework is tested on IEEE 33-bus radial test system via three cases based on event center. Results demonstrate that incorporating TFM shows impact of each overhead distribution component and tree on the resilience of distribution grid. This approach provides valuable insights for developing targeted strategies against disruptive HILP events on the power distribution systems. The key take away of the TFM integrated resilience modeling is the comprehensive impact assessment of damage level with respect to HILP event type, location and severity leading to a better assessment of network's energy delivery capabilities and the network restoration potential.**

***Index Terms*—HILP events, Power system, Resilience metrics, Resilience, Tree failure model.**

I. Introduction

Ensuring power system resilience against disruptive weather events, such as windstorms, has become a paramount concern for utilities, system operators and regulators [1], [2]. These high-impact, low-probability (HILP) occurrences can lead to outages in critical components like generators, lines, and poles, potentially disrupting the seamless delivery of power to customers. Some of the major weather-related power outages worldwide including date, location, event type and number of affected people are reported in [1]. In power networks, the fragility of power system component can be threatened by the presence of nearby trees, increasing the risk of failures during windstorms [3], [4]. In fact, it has been reported that tree failures account for approximately 55% of power distribution system (PDS) failures in the Northeastern United States [5]. This study proposes a novel vegetation-based stochastic assessment of power distribution resilience which we call tree failure model-based resilience assessment (TFM-RA). The study explicitly models the impact of trees on poles, line and frailties. The proposed formulation model tree fragility based on tree height, density, crown diameter, and mean height. The system fragility was assessed under three HILP events via three case of event center relative to the power grid.

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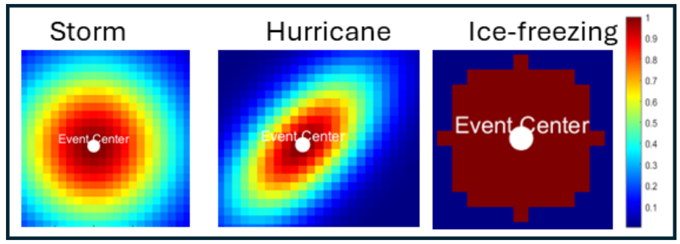

Fig. 1: Characteristics of events based on the event-type models.

The concept of vegetation impact on power grid is a recent topic that is yet to gain much attention [3], [6]. Despite the severe consequences caused by falling trees, the risk of tree failure has not been copiously incorporated in previous studies on PDS resilience modeling against extreme events. Many of the previous resilience assessment studies for PDS ignored the failures caused by collapsing trees but often considered component failures induced by some types of HILP events [7]–[11]. A geographical information of trees surrounding the overhead power distribution system (OPDS) is extracted from satellite images in [3] to develop tree failure risk models and linking it with pole failure probability to assess the vulnerability of the overhead power grid during extreme windstorm. A framework that integrates tree fragility modeling with the resilience of OPDS against extreme winds, considering the power system fragility modeling, power system component failure and resilience metrics for the enhancement system's resilience evaluation is studied in [6]. The potential impact of tree failure coupled with the occurrence of HILP events poses considerable challenges for power system operators [12]. The key dilemma faced by these operators revolves between minimizing the impact of these disasters on the power grid and a quick restoration strategies to minimize down times for the affected customers. This often include strategic deployment of mobile generating resources to specific grid locations affected by outages and system fragmentation to eliminate affected areas while restoration process is underway [11], [13], [14]. Moreover, some outages have significant implications on the power system, hindering uninterrupted and high-quality delivery of power to consumers.

The first problem in addressing HILP events is the identification of the event type, event center, and event impact on the power network. The common HILP events that have a strong damaging impact on the power network include hurricanes, super-storms, earthquakes, and ice storms (or significant line freezing), whose modeling has been studied in several works to describe the trajectories of the spread of these events from their centers [15]–[17]. Fig. 1 shows the characteristics of three of these HILP events based on the models in [15]–[17], and Fig. 2 shows a section of a power distribution network, including the primary and secondary network. The distribution grid has various power delivery components, such as overhead distribution lines, buses, poles, and other power delivery components. The figure also shows the presence of vegetation consisting of trees of different height and densities around the network.

This study aims to investigate the impact of this vegetation in the face of HILP events, which can have a damaging impact not only on the power equipment but also on the trees which in turn exacerbate the overall damage impact on the network [18]. It is a common occurrence to see trees failing on the power network, destroying power equipment and leading to serious outages, due to the HILP events whose occurrence in terms of severity or location is largely predictable from weather report assessments [19]. However, the idea of using the mesh-grid approach to locate the center of HILP events on the power grid to measure their damaging impact was first proposed by Yonesi et al. [20]. The extension of this study relating to disasters' representation, their probability of occurrences, and locations on the mesh-view cells is later investigated in [21], [22].

This study integrates a tree failure model (TFM) in the mesh-grid approach for the assessment of power system resilience metrics on the distribution network. The proposed model incorporates vegetation failure impact in addition to the impact of severe weather related (SWR) events on the power network leading to a more comprehensive impact assessment of damage level relative to the event location, event type and event's severity and consequently a better assessment of network's energy delivery capabilities and the network restoration potential. The proposed framework is tested on the IEEE 33-bus radial distribution system, considering three distinct cases based on the event center. The main contribution inthis study is the integration of the TFM with a mesh-view resilience assessment framework to evaluate the system-wide impacts of HILP events based on event type and location leading to a robust assessment of network's energy delivery capabilities and the network restoration potential.

The rest of this paper is organized as follow, Section II describe the problem formulation, Section III discusses the simulation results and Section (IV) concludes the study.

II. Problem Formulation

A. Tree Failure Modeling

According to the study in [23] which investigates TFM from storms, the most influential factors that increases the chance of trees failure in windstorm are the tree height (TH), tree density (TD), tree crown diameter (TCD) and means of trees' heights (MTH). By modeling these metrics, tree managers (such as the utility line crews) are able to predict the possibility of a tree failure. The TFM adopt in this study is an exponential function

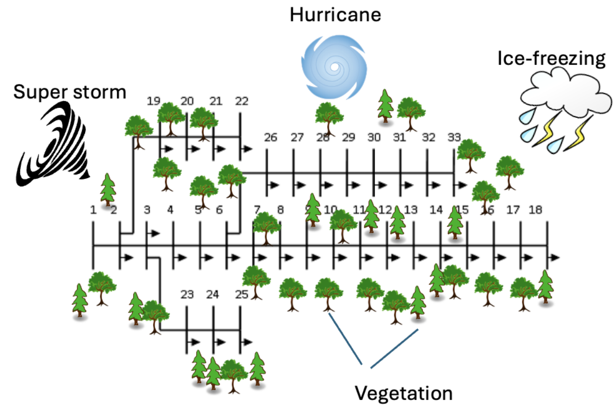

Fig. 2: Distribution network impacted by trees and weather condition.

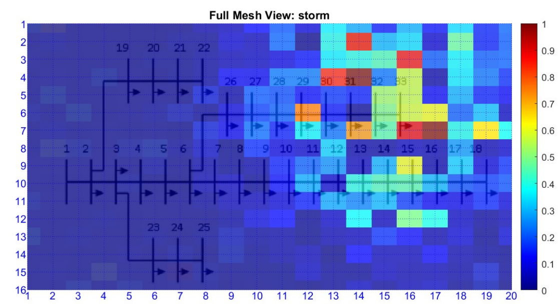

Fig. 3: Tree impact view on a 33-bus test system in storm.

that defines the probability of tree failure during storm (1). The model captures the impact of vegetation on power system resilience.

$$P_{tree} = 1 - \exp(-\alpha(h^{\beta} d^{\gamma} c^{\delta} m^{\epsilon})), \quad (1)$$

where h is tree height (in meters), d is tree density (number of trees), c is crown diameter (meter), m is mean tree height (meters), and $\alpha, \beta, \gamma, \delta, \epsilon$ are constant model parameters.

B. Failure Probability of Power System Component

Assuming direct impact of both poles and lines for a tree-related failure, the failure probability of pole is defined as a function of the base probability of a pole on the network, the type and the severity of the event as define in (2).

$$P_{pole} = k_{event} \cdot s \cdot P_{base} \quad (2)$$

where k_{event} is an event-specific constant, s is the severity level, and P_{base} is a base failure probability, i.e., the failure probability of the power system component just before the occurrence of the event which may not necessarily be its initial value when the component was new. The failure probability of a line is modeled in (3). The system failure probability is modeled in (4). This equation defines a high-level overall system failure probability in terms of the failure probability of each individual line.

$$P_{line} = P_{pole} + P_{tree} - P_{pole} \cdot P_{tree} \tag{3}$$

$$P_{system} = 1 - (1 - P_{line})^N, \tag{4}$$

The resulting failure probability, S_{line} impact of a HILP event as measured from the mesh-view and TFM is modeled as (5), where S_{line}^{mesh} is line failure probability based on the mesh view impact, $S_{line}^{tfm} = P_{line}$ from (3) is the line failure probability based on the TFM modeling. The commutative impact of the TFM on the mesh grid of power network is depicted in Fig. 3, where the entire blue overlay on the diagram shows the presence of vegetation around the network and the regions on the right with varying color density showing the area impacted by a HILP event.

$$S_{line} = S_{line}^{mesh} + S_{line}^{tfm} - S_{line}^{mesh} \cdot S_{line}^{tfm} \tag{5}$$

C. Modeling Event Types and Impact

To model the impact intensity of each event, a 2D Gaussian function has been adopted with event centered at (x_c, y_c) and radius, r. Superstorm, Hurricane, and Earthquake utilizes the Gaussian function [15]–[17] and Ice-freeze utilizes the step-function in circular region [24]. Equations (6)-(15) model the impact intensity $I(x, y)$ at point (x, y) in the grid, with values ranging from 0 to 1, indicating minimum and maximum impacts respectively.

1) Superstorm Model: The storm impact is modeled as a circular Gaussian distribution [15].

$$I(x, y) = \exp\left(-\frac{(x - x_c)^2 + (y - y_c)^2}{2r^2}\right), \tag{6}$$

where,

$$r = \frac{\min(\text{grid\_size})}{4} \tag{7}$$

2) Hurricane Model: To model the impact of the hurricane, the elliptical Gaussian distribution with rotation [16] in (8).

$$I(x, y) = \exp\left(-\frac{(x')^2}{2r^2} - \frac{(y')^2}{,}2(r/2)^2\right) \tag{8}$$

where:

$$x' = (x - x_c)\cos\theta - (y - y_c)\sin\theta \tag{9}$$

$$\tag{10}$$

$$y' = (x - x_c)\sin\theta + (y - y_c)\cos\theta \tag{11}$$

$$\theta = \frac{\pi}{4} \tag{12}$$

$$\tag{13}$$

$$r = \frac{\min(\text{grid\_size})}{4} \tag{14}$$

θ is the rotation angle, and r is radius from the center of event, x' and y' represents the directionality and elongation of the impact of the hurricane.

3) Ice Freezing Model: The ice freezing impact is represented by a step function within a circular region in (15) [24].

$$I(x, y) = \begin{cases} 1 & \text{if } (x - x_c)^2 + (y - y_c)^2 \leq r^2 \\ 0 & \text{otherwise,} \end{cases} \tag{15}$$

where,

$$r = \frac{\min(\text{grid\_size})}{6}. \tag{16}$$

D. Resilience Metrics

From the definition of resilience as the ability of the power system to withstand and recover quickly after an HILP event. The TFM-RA model considers three resilient metrics which are loss of load probability (LOLP), expected demand not served (EDNS), recovery index J_s, and expected number of lines on outages due to the HILP event.

1) Loss of Load Probability: The LOLP defined in (17) measures the likelihood of occurrence of load shedding due to the HILP event,

$$LOLP = P(L_s > 0) \tag{17}$$

where L_s is the load shedding in scenario s.

2) Expected Demand Not Served: The $EDNS$, (18) estimates the amount of unnerved demand during the event.

$$EDNS = \sum_{s=1}^{S} L_s \cdot P_s \tag{18}$$

where P_s is the probability of scenario s.

3) Recovery Index: The recovery index measures the ability of the system to recover after the event, and $P(L_s > 0)$ denotes the probability that loading shedding at scenario s is greater than zero, where L_s is defined in (19), and g_s and d_s are generation and demand, respectively, in scenario s. Then, the recovery index is defined in (20) [21] in terms of weights of coefficient denoted as w_i, recovery factors ϵ_i, and the probability of of the event characteristics, P_{char}. Some important grid recovery factors identified in [21] include severity of power infrastructure damage, severity of transportation infrastructure damage, severity of extreme event, severity of cyber-infrastructure damage and unavailability level of human material resources [25].

$$L_s = \begin{cases} 0 & \text{if } g_s - d_s \geq 0 \\ 1 & \text{if } g_s - d_s < 0 \end{cases} \tag{19}$$

$$J_s = \sum_{i=1}^{5} w_i \epsilon_i P_s P_{char} \tag{20}$$

4) Fragility Index: The fragility index is defined in (21)

$$F_i = (1 - (1 - P_{line})^N \cdot P_{char} \tag{21}$$

where P_{line} is the line failure probability. It represents the vulnerability of the entire system to the event.

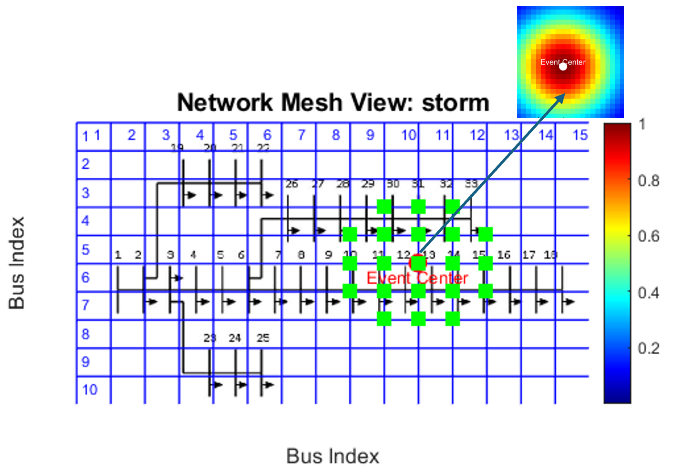

Fig. 4: Simulated TFM with wind storm on the mesh grid of the 33-bus system.

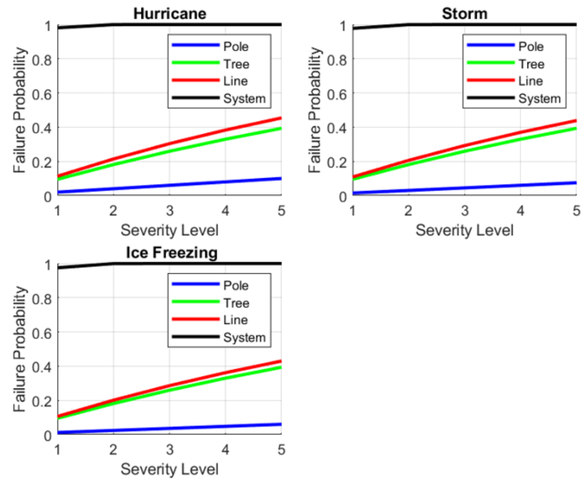

Fig. 5: Failure Probabilities for Different Components

III. Simulation Results

The TFM resilience model is tested on an IEEE-33 bus radial system. Three cases are studied: Case 1 —is event center located at cell (10,5), Case 2 — event center at (5,5), and Case 3 — event center at cell (5,10). The simulation is done over 5,000 scenarios. We first prepare the mesh-view of the distribution network, overlay the meshed-network with vegetation randomly around the network with tree characteristics as given in Table I and models explained in equations (1)–(21). When an event occurs, it impact the trees, the poles, the lines and there is an overall impact on the system resulting in a modified case on the test system based on the event type, severity level and the particular scenario. Then an optimal power flow is performed and the resilience metrics are obtained as defined in Section II-D. Simulation is carried in MATLAB using the MATPOWER libraries which allows the simulation of optimal power flow on standard test systems. Resilience metrics are evaluated for all cases and a few of the results are presented here. Table I shows the parameters of the TFM model used for the TFM simulation. Fig. 4 shows the impact of the mesh grid. The affected buses and lines due to storm in the 33-bus distribution network.

The results of the TFM simulation is given in Fig. 5. The figure shows that the impact of HILP event on component fragility increases the severity level of the disturbance increase, but the impact is quite more on the line and the tree than it is on the pole as reflected in the slope of the failure probability vs severity level in the figure.

TABLE I: Parameter for the TFM simulation [23].

Parameter	Value
Normalized TH	0.42
Normalized TD	0.46
Normalized TC	0.43
Normalized TMH	0.46
Failure probability threshold	0.3
TFM parameters α, β, γ & ϵ	0.1, 2, 1, & 1.5

Fig. 6 shows the recovery indices of the three HILP events at the severity level of 2 for three test cases. The average recovery indices in storm is higher than that of the hurricane and much higher than ice-freezing with the least recovery index. Furthermore, Case 1 has higher recovery slightly higher than the values in Case 2 and Case 3 appear to be least. This shows that relative position of the event center plays a significant factor in the values of the recovery indices across the three events. For all cases, the ice-freeze has lower average recovery indices compared to storm and hurricane. This observation is differs slightly from the findings in [21]. Thus, the impact of TFM on resilience metrics of the power grid draws some insights for further investigation.

Fig. 7 shows the resilience metrics measured with storm at severity level of 3. The figures show the histogram plots of LOLP, EDNS, number of line outages (NLO), and recovery index (RI). The NLO indicates that at this severity level, higher number of outages occurs more frequently and this mean this system will be able to recover from strong outages, however, the RI plot suggests that the system has good chance of recovery at lower recovery indices. Also the EDNS plot shows that EDNS index decreases with scenario number of simulation. Similar trend is observed in Fig. 6 in the FI, RI, LOLP and EDNS. On average, their value decreases with an increase in the number of scenarios.

Fig. 8 shows the average EDNS of the three HILP events for the three cases. The EDNS of storm are higher than those of the hurricane for all cases and the those of ice-freeze are zero. The impact event location and event also manifest here, however in all three cases the EDNS values become stabilized suggesting that the system's response becomes consistent after the initial shock of the events similar to the observation in Fig. 20. Finally, the resilience metrics of the storm, RI, FI, LOLP and EDNS for Case 1 with an event severity level of 3 are shown in Fig. 9, Fig. 10 and Fig. 11 The figures follow a similar trend as those of the previous discussed results.

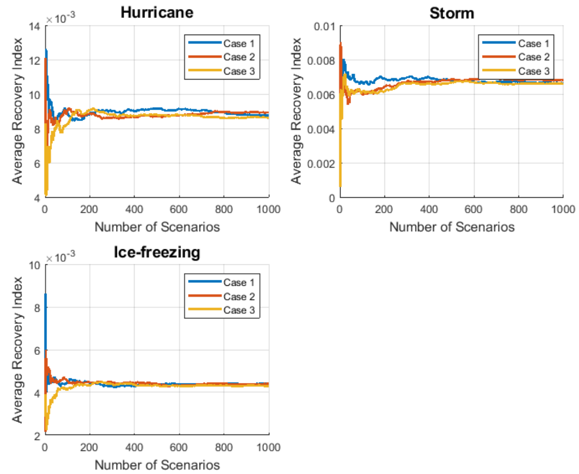

Fig. 6: Average recovery index for Case 1, Case 2 and Case 3.

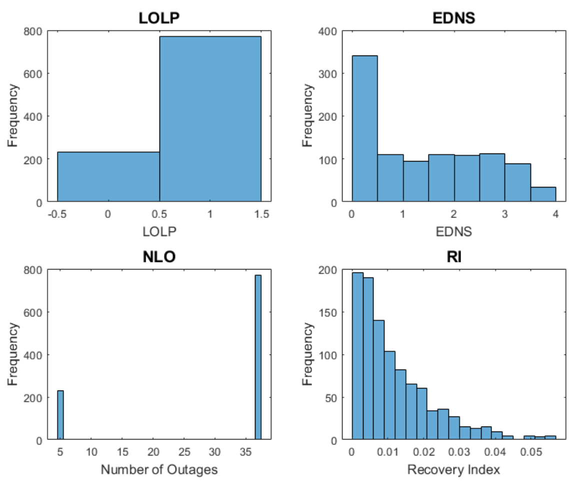

Fig. 7: Resilience metric recorded in storm of severity 3.

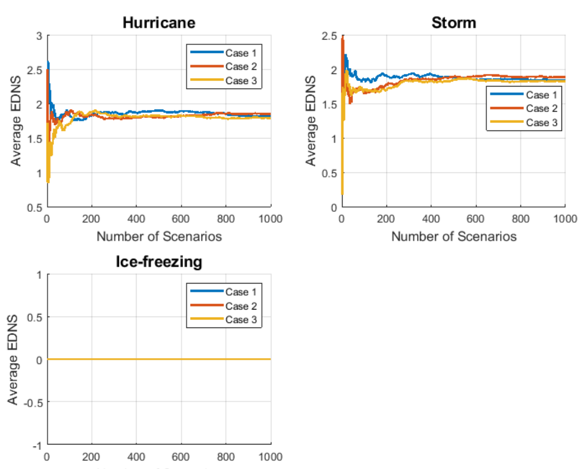

Fig. 8: Average EDNS for the three cases.

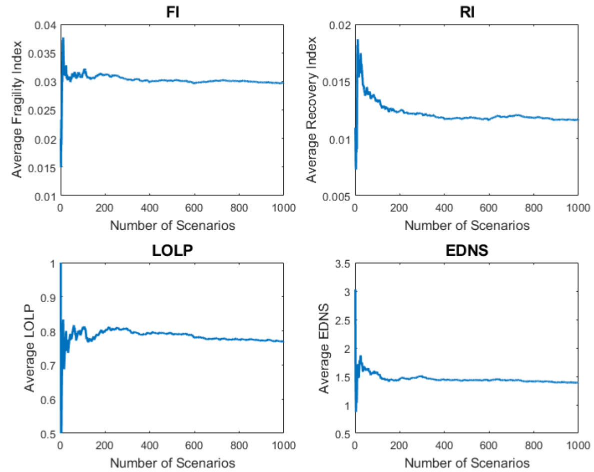

Fig. 9: Average resilience metrics recorded storm in Case1.

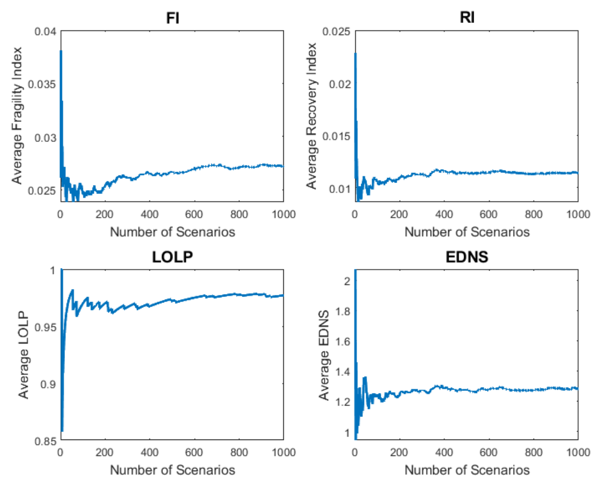

Fig. 10: Average resilience metrics recorded hurricane in Case1.

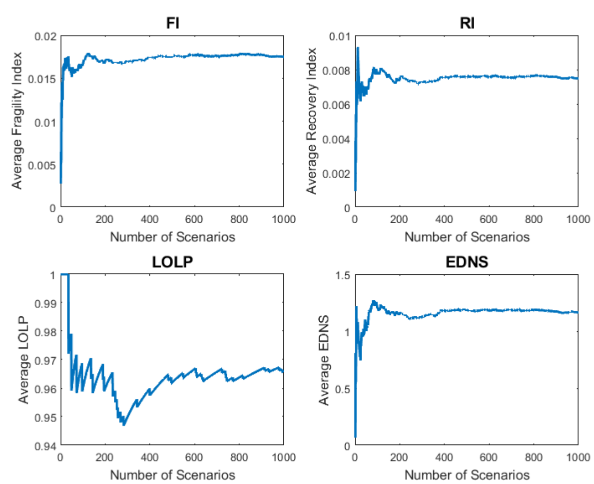

Fig. 11: Average resilience metrics recorded ice-freezing in Case1.

IV. Conclusion

In this study, a novel Tree Failure Model (TFM) that considers tree characteristics in assessing the resilience of the power network. The study incorporated TFM with mesh-view resilience assessment through three HILP event types. The framework is tested on IEEE 33-bus radial test system via three cases based on event center. The results demonstrate that incorporating the TFM provides valuable insights into the impact of individual overhead distribution components and trees on the overall resilience of the distribution grid. This approach enables the development of targeted strategies to enhance the resilience of power distribution systems against disruptive HILP events. Future work will explore the TFM-based resilience modeling HILP event occurrence probabilities, event severity and microgrid installation as well as resilience metric assessment in the pre-event, during event and post-event conditions.

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