Resilience Assessment Approach for Transmission Systems Considering Uncertainties of Ice Storms

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***Abstract*—Ice storms have a wide range of impacts on power systems ranging from long outage times to major equipment failures. The diverse spatiotemporal characteristics of ice storms create high uncertainties in the system performance and resilience level. Recent extended outages on various interdependent systems such as, power and water, due to ice storms have called for further investigation and resilience assessment approaches. In this paper, a planning-based resilience assessment framework is utilized to assess the resilience level of transmission systems. First, a spatiotemporal ice storm model is used to simulate various scenarios of ice storms. Then, a proper fragility model is implemented to evaluate the probability of failure of system components in terms of weather parameters. Finally, a quantitative resilience assessment method based on combinatorial enumeration is applied to compute a resilience index for the system. The proposed algorithm is carried out on the IEEE 30-bus system mapped on the Eastern region of the United States. Numerous ice storm scenarios are simulated based on real weather-data. The proposed algorithm is able to assess the system resilience characteristics considering uncertainties of ice storms.**

***Index Terms*—Extreme weather event, ice storms, resilience, spatiotemporal fragility.**

I. Introduction

Extreme weather events, such as ice storms, hurricanes, typhoons, have shown significant impacts on power system operations. Although the probability of occurrence of these extreme events is relatively low, their impacts on power system ranges from prolonged outages to catastrophic destruction of system components [1], [2]. In the United States, weather-related power outages are estimated to have an annual economic impact between $20 to $50 billions [3]. Between 2003 and 2012 more than 147 million customers lost power due to weather-related events in the United States [4]. Various studies have been conducted to assess the resilience level of power system against windstorms, however, ice storms have gained less interest [1]. Also, the impacts of the stochastic behavior of weather event on the overall system performance is still an undergoing research [5]. Given the recent ice storm behavior in Texas yielding power outage for a few days in some places, the importance of the severity of ice storms has increased dramatically [6]. Thus, assessing the resilience of transmission power systems and each system component against the stochastic behavior of ice storms has become more important than ever before.

Resilience assessment methods aim to quantify the impact of extreme weather events on power system operation. It is the first step toward developing proper resilience metrics as well as providing benchmark to evaluate different resilience enhancement strategies [1]. Various methods have been proposed to evaluate the overall resilience level of power systems against weather events. In [7], a planning-based framework has been developed to assess the resilience level of transmission systems against typhoons in China. The developed methods compromises of a probabilistic wind field model to simulate typhoon behavior and a spatiotemporal fragility model to determine the probability of failure of each component in the path of typhoon. Authors of [8] have proposed a dynamic resilience assessment method to evaluate the impacts of ice disasters on transmission lines. A cell partitioning algorithm is integrated with sequential Monte Carlo simulation to calculate resilience indices. The framework has been used to simulate an ice storm scenario with predefined path, wind speed, radius, central pressure, and translational speed ignoring the impacts of accompanied weather-related uncertainties. On the other hand, a resilience enhancement strategy against ice storms based on pre-positioning and routing of mobile de-icing devices has been proposed considering the interdependence between transportation and electric systems [9]. In [10], [11], a robust resilience enhancement method has been developed to create a de-icing schedule for mobile de-icing devices in distribution power systems. The proposed method has considered the congestion in transportation network as well as operational constraints of electric distribution systems. Although the aforementioned studies have provided various assessment and enhancement approaches against ice storms, the uncertainties of ice storms on overall system resilience still require further investigation.

This paper proposes a resilience assessment method to evaluate impacts of ice storms on the overall performance of transmission power systems. First, an ice storm spatiotemporal model is developed to determine the propagation behavior and severity of ice storm. A proper fragility model is implemented to evaluate the probability of failure of each component in the path of an ice storm at sequential time instants. Then, an extensive statistical analysis is conducted to determine the weather-related characteristics of the geographical location under study such as wind speed, wind direction, and ice precipitation rate. The combinatorial enumeration method is used to simulate various ice storm scenarios with diverse

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spatiotemporal behavior. During each simulated ice storm, the worst failure scenario is obtained and used to calculate the total amount of load curtailment at each time instant. The resilience level of the system is determined based on the total amount of load curtailment in each ice storm scenario and the probability of occurrence of the specified scenario. The proposed method is validated through a mapped IEEE 30-bus system in the Northeastern region of USA.

The rest of the paper is organized as follows. Section II explains the ice storm fragility model. Section III describes the resilience assessment framework based on the combinatorial enumeration method. Section IV describes the implementation procedure on the IEEE 30-bus system and discusses the results. Section V provides concluding remarks.

II. Ice Storm Fragility Model

This section provides a detailed illustration of the ice storm model. It also describes the fragility model to assess the probability of failure of system component under ice storm events.

A. Ice Storm Model

The spatiotemporal characteristics of ice storms in a certain geographical location are governed by key parameters that identify their uncertainties. Such parameters are either weather-related, i.e., wind speed, or geographically-related, i.e., landing site. During an ice storm, a component might fail as a result of accumulated ice. Various models have been proposed to model the amount of ice accumulated on overhead transmission lines and towers in freezing rain storms [12], [13]. In this paper, a freezing rain ice loads model is adopted to calculate the ice thickness on transmission components as follows,

$$\Delta H(t) = \Delta H_0 - 0.02\ [1 + sin(\phi - \delta)]t, \tag{1}$$

where $\Delta H(t)$ is the central pressure difference at time t, measured in $inHg$, ΔH_0 is the original central pressure difference before the ice storm lands, δ is the angle between the due north direction and the ice storm motion direction (the clockwise is positive), and ϕ is the angle between the coastline and the due north direction. Accordingly, the maximum radius of ice storm is evaluated [14] as follows,

$$r_{max}(t) = \exp(2.63 - 5.086 \times 10^{-5}(\Delta H(t))^2 + 0.0395 y_h(t), \tag{2}$$

where $y_h(t)$ is the latitude of the center of the ice storm.

The distance between a specific geographical location and the ice storm center at time t can be evaluated as follows,

$$d(t) = \sqrt{[x_d - x_h(t)]^2 + [y_d - y_h(t)]^2}, \tag{3}$$

where $d(t)$ is the euclidean distance between a location and the center of the hurricane at time t, measured in m, x_d and y_d are the latitude and longitude coordinates of the component location, respectively, and x_c and y_c are latitude and longitude coordinates of the center of the ice storm at time t, respectively, which can be calculated as follows,

$$x_h(t) = x_0 + V_T\ t\ sin(\delta), \tag{4}$$

$$y_h(t) = y_0 + V_T\ t\ cos(\delta), \tag{5}$$

where x_0 and y_0 are the hurricane landing coordinates, respectively, and V_T is the translational speed of ice storm, measured in m/s.

The level of ice thickness on a specific component relies on its relative position with the center of the ice storm. The amount of ice accretion can be calculated as follows,

$$R_{ice} = (N_h/\rho_i \pi)\sqrt{(P\rho_w)^2 + (3.6 V_w W)^2} \tag{6}$$

where R_{ice} is the ice thickness, N_h is the number of hours of freezing rain, P is the precipitation rate, W is the liquid water content of rain-filled air, equals $0.067P^{0.846}$, V_w is the wind speed, in m/s, and ρ_i and ρ_w are the density of ice and water, being $0.9g/cm^3$ and $1g/cm^3$, respectively.

Fig. 1 displays the spatiotemporal characteristics of ice storm across the system. It shows the relative distance between a specific element and the ice storm center. Components within the maximum radius might be impacted based on the wind speed level at their defined location, whereas components outside the maximum radius won't have much ice accumulation and can be neglected.

The main parameters that affect the severity and propagation behavior of an ice storm are original central pressure ΔH_0, precipitation rate P, translational speed V_T, wind speed v_w, motion direction δ, and landing site coordinated (x_0, y_0). By varying the values of these parameters, various ice storms can take place. Proper probability distribution function (PDF) for each parameter can be obtained via extensive statistical analysis using measured weather data at the geographical location under study.

B. Fragility Model

As an ice storm propagates through system components, various transmission corridors are impacted. A transmission corridor is defined to be the set of transmission lines and towers that connect between two terminal components. Since transmission corridors are usually very long, specifically in the transmission level, it is divided into smaller segments such as

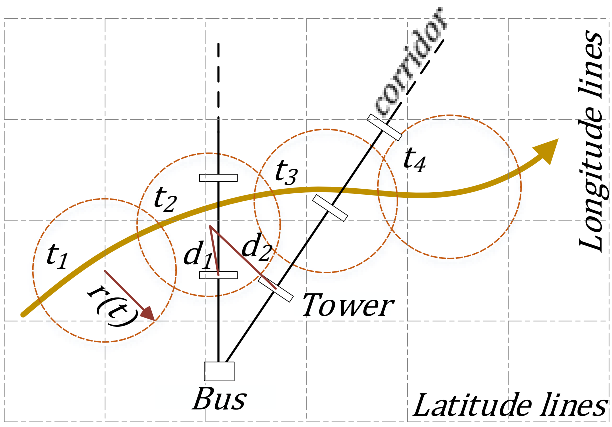

Fig. 1. Ice Storm propagation across system

one segment comprises two corresponding transmission towers and the part of transmission line connecting between them. Transmission corridors span along large geographical area and hence, wind speeds might vary from one corridor segment to another on the same transmission corridor. Also, wind speed varies for the same geographical location at different time instants. A failure of one segment will result in the failure of the whole corridor since they are connected in series. Consequently, the equivalent failure probability of a specific transmission corridor can be evaluated as a series combination of components. Fig. 1 visualizes the propagation of an ice storm across different segments.

The fragility model focuses on quantifying the failure probability of each component in terms of weather parameters from both temporal and spatial perspectives. In this work, a spatiotemporal fragility model from [7] has been integrated with ice storm model adopted from [15] to calculate the cumulative failure probability of each transmission corridor during the ice storm duration. The total ice storm duration period T can be divided into N time steps with a shorter duration period Δt, where component statuses can be evaluated easily at discrete time instants. For a transmission corridor i which is split into L line segments through M towers, the detailed model is provided as follows.

1) Failure of transmission tower

The failure rate $\lambda_{i,m}$ of the m^{th} tower of the i^{th} corridor at time t_j can be evaluated as follows,

$$\lambda_{i,m}(t_j) = \begin{cases} 0, & R_{i,m}(t_j) \leq R_{to} \\ e^{\left[\frac{0.6931(R_{i,m}(t_j)-R_{to})}{4R_{to}}\right]} - 1, & R_{to} < R_{i,m}(t_j) \leq 5R_{to} \\ 1, & R_{i,m}(t_j) > 5R_{to} \end{cases} \tag{7}$$

where $R_{i,m}(t_j)$ is the ice thickness, and R_{to} is a threshold ice thickness design of transmission tower, in this study 15 mm value is adopted. The cumulative failure probability of the m^{th} tower of the i^{th} transmission corridor during the ice storm period T can be obtained as follows,

$$P_{i,m} = 1 - \exp\left\{ -\sum_{j=0}^{N-1} \lambda_{i,m}(t_i)/(1-\lambda_{i,m}(t_i))\Delta t \right\} \tag{8}$$

2) Failure of transmission line

The failure rate $\lambda_{i,n}$ of the n^{th} line segment of the i^{th} transmission corridor at time t_j can be evaluated as follows,

$$\lambda_{i,n}(t_j) = \exp\left\{ 11 \times \frac{R_{i,n}(t_j)}{R_{li}} - 18 \right\} \Delta l, \tag{9}$$

where $R_{i,n}(t_j)$ is the ice thickness at the midpoint of the n^{th} line segment, R_{li} is a threshold design ice thickness of line segment, and Δl is the length of the line segment. The cumulative failure probability of the n^{th} line segment of the i^{th} transmission corridor during the ice storm period T can be obtained as follows,

$$P_{i,n} = 1 - \exp\left\{ -\sum_{j=0}^{N-1} \lambda_{i,n}\Delta t \right\}, \tag{10}$$

3) Failure of transmission corridor

Due to the series connection between adjacent transmission towers and line segments, the failure of one component will result in failure of whole corridor. In this study, the failure between elements on the same corridor is assumed to be independent. And hence, the cumulative failure probability of the i^{th} corridor can be evaluated by combining (10) and (8) as follows,

$$P_i = 1 - \prod_{1}^{M}(1-P_{i,m}) \prod_{1}^{L}(1-P_{i,n}), \tag{11}$$

where M and N is the total number of towers and line segments in the same corridor, respectively.

III. Resilience Assessment Methodology

This section provides a detailed formulation of the resilience assessment strategy of transmission systems against ice storms. First, it illustrates how to quantify the resilience of a power system. Then, it describes an enumeration algorithm to assess the resilience due to uncertainties of ice storms.

A. Resilience Index

A quantitative index, R, is used to quantify the resilience level of the system, specifically in the planning phase. Previous studies have used the resilience triangle and the resilience trapezoidal curves for evaluation [1], where the resilience level of system, denoted by Q, is defined to be the normalized area of the performance degradation index during the period of event [7]. As the performance of system decreases, the resilience of the system also decreases yielding higher resilience index. Such method captures the resilience of system for one event scenario, however the transmission system might be impacted by various events that have diverse behavior and severity. A modified resilience index can be evaluated as follows,

$$R = \sum_{s \in S} P_s Q_s, \tag{12}$$

where S is the set of all possible ice storms, P_s is the probability of the s^{th} ice storm, and Q_s is the worst amount of degradation in system performance. System is subjected to worst case scenario when potential failures take place. In this paper, the total amount of load curtailment during a specific time period is used as performance degradation indicator.

B. Combinatorial Enumeration Method

The combinatorial enumeration method has been widely used to quantify uncertainties of various random variables on a certain process given predefined PDF for each random variable [7]. The combinatorial enumeration method is implemented in the probabilistic ice storm model in order to be able to simulate various potential ice storms. For a given scenario, the failure probability of transmission corridors can be obtained using the proposed spatiotemporal fragility model.

Each of the parameters that affect an ice storm scenario can be governed by a well-known PDF. In the combinatorial enumeration method, each PDF is divided into several equal portions. An ice storm scenario can be generated by enumerating through a selection of specific segmented interval. For example, the original wind speed PDF is divided into C equal portions and the segmented interval C_i. For a specific ice storm scenario s, the wind speed probability can be obtained as follows,

$$P_r(V_{w,s}) = \int_{V_{w,s}-C_i/2}^{V_{w,s}+C_i/2} f(V_w)dV_w, \tag{13}$$

where $P_r()$ is the probability of each parameter, and C is the length of each portion.

By following the same convention, the probability of each parameter can be calculated. And hence, for a specific ice storm scenario s, its occurrence probability can be evaluated as follows,

$$P_s = P_r(H_{0,s})P_r(P_s)P_r(V_{T,s})P_r(V_{w,s})P_r(\delta_s)P_r(x_{0,s}, y_{0,s}), \tag{14}$$

Under a given simulated ice storm behavior, the cumulative distribution function failure probability of each corridor can be evaluated using the spatiotemporal fragility model. The determined sequential failure of system components is injected into a DC optimal power flow to determine the amount of load curtailment. The detailed algorithm to evaluate the resilience of transmission system against ice storms is provided in Algorithm 1.

IV. Implementation and Results

The resilience assessment framework is formulated using the proposed ice storm model and fragility model. The proposed approach is applied on the IEEE 30-bus system mapped on the Northeastern region of USA as shown in Fig. 2. The distance between two consecutive transmission towers is assumed to be 500 meters. The Northeastern side of USA is selected since it is one of the most impacted regions by ice storms [16].

A. Ice Storm Parameters

Since the behavior of weather parameters vary based on geographical location, statistical analysis is conducted on the Northeastern region of USA to determine the proper PDF for each parameter. Ice storm events in the Northeastern region can be found in [17]. Wind speed and direction data are extracted from [18], whereas ice precipitation rate data is extracted from [19]. On the other hand, other parameters are assumed to have predefined PDFs. Landing location is assumed to follow a Uniform distribution function, latitude, $y \in [34^0, 45^0]N$ and longitude, $x \in [90^0, 70^0]W$, central pressure difference is assumed to have a Uniform distribution function, $H_0 \in [1.5, 3]$ hPa, and translational speed is assumed to follow a Uniform distribution function, $V_T \in [0, 15]$ m/s. Although these parameters might have different distribution functions, the main scope of this work is the resilience evaluation rather than the statistical behavior of such parameters. Also, the scarcity and accessibility of data play a vital role to determine the proper PDF. A summary of PDF for wind speed, wind direction, and ice precipitation rate is summarized in Table I.

Algorithm 1: Overview of Resilience Assessment Methodology Considering Ice Storm Uncertainties

```
Input: Weather-related data for key parameters
       including, wind speed, wind direction,
       precipitation rate, central pressure difference,
       translational speed, and landing location
Compute the PDF for each key parameter
Divide the the PDFs into fixed number of segments
Determine the total number of ice storm scenarios S
for s ← 1 to S do
    Generate random value for each key parameter
      using their CDF
    Calculate probability of each parameter
    Evaluate the probability of occurrence of the ice
      storm scenario P_s
    Inject the random values into the ice storm model
      to simulate its propagation behavior
    for t ← 1 to T do
        Determine set of potential components to fail
        Use fragility model to evaluate the probability
          of failure for each component
        Determine the failed components
        Run DC optimal power flow
        Calculate amount of load curtailment
    Sum up total energy not supplied for the whole ice
      storm duration Q_s
Evaluate the system resilience index using the obtained
  P_s and Q_s for each s
Output: System resilience index
```

TABLE I
Parameters of distributions for ice storm parameters

Key parameter	PDF Type	Parameters
Ice precipitation	Lognormal	μ= 3.66 inc/hour, σ = 20.78
Wind speed	Lognormal	μ= 2.668 m/sec, σ = 0.5185
Wind direction	Binormal	μ_1= -73.3, μ_2= -7.2 σ = 22.6, σ = 70.35, α = 0.5

B. Single Scenario

A single ice storm scenario is simulated on the mapped system as shown in Fig. 3 to visualize the propagation of ice storm through system corridors. The simulated ice storm propagates from East-South to North-West where multiple transmission corridors are expected to fail. The central pressure difference is 1.5 hPa, the wind speed is 15 m/s, the translational speed is 1 m/s, the precipitation rate is 35 mm/hour, and the landing site is 37^0N/72^0W for the simulated ice storm. The ice storm duration is determined to be 48 hours.

The list of impacted corridors and their time of failure is provided in Table II. The total amount of energy not supplied during the whole ice storm is 1136 MWh with maximum load curtailment of 48.4 MW. It is noticeable that although some components start to fail earlier in time, load curtailment does not take place till the third failure. Also, ice accumulation is larger at the center of the ice storm and hence, components

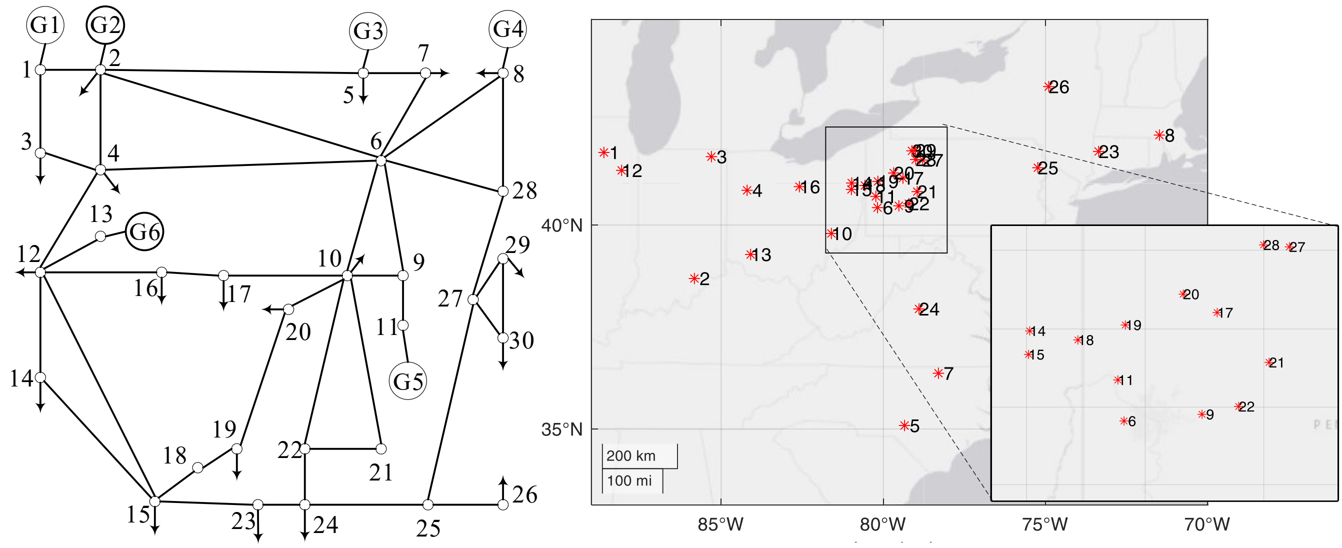

Fig. 2. The mapped IEEE 30-bus system on Northeastern region of the USA

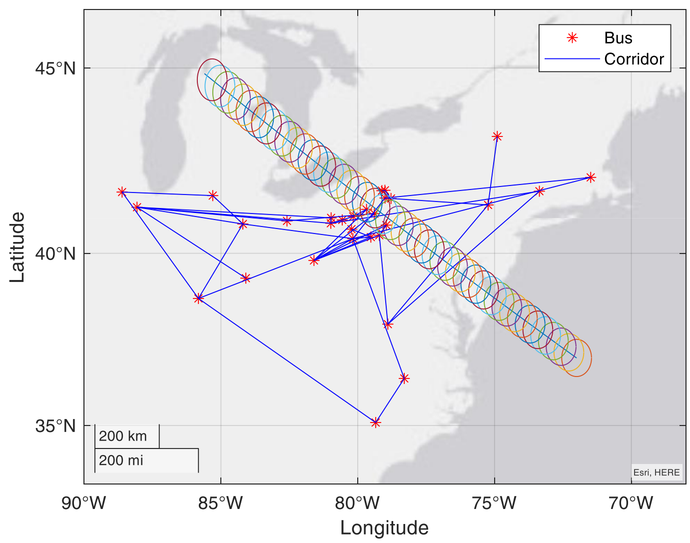

Fig. 3. Ice storm scenario on mapped IEEE 30-bus system

closer to the center are highly subjected to failure compared to farther components. Since the translational speed is very low, the duration of ice storm is longer, however higher translational velocity will yield faster ice storm propagation and shorter overall duration.

TABLE II
IMPACT OF SINGLE ICE STORM SCENARIO

Time (Hour)	17	18	23	24		25	26		27		28	
Curt. (MW)	0	0	0	16.5		19.7	37.2		46.2		48.4	
From bus	23	24	6	4	6	15	10	21	16	12	19	10
To bus	24	25	8	6	28	23	21	22	17	13	20	20

C. System Resilience Level

The obtained and predefined PDF of each key parameter in the determined geographical region is injected into the probabilistic ice storm model to calculate the probability of occurrence of each simulated scenario using the combinatorial enumeration method. The PDF of each key parameter is divided into 100 equal segments and a total number of simulation cases are set to 10000. Each ice storm scenario is assumed to last for 24 hours period. The process is repeated twice to compare different sets of ice storm scenarios for validation.

Out of all the simulated scenarios, 2021 scenarios result in load curtailment in the first case, whereas the second case has 2015 events with load curtailment. The calculated resilience indices for the two cases are 81.454 MWh/event and 81.44 MWh/event. The obtained values are relatively close assuring the effectiveness of the proposed approach to capture uncertainties of ice storms on overall system impact. For further assessment, the frequency of failure and total outage duration of each transmission corridor is obtained as shown in Table III.

The obtained results from both cases are relatively close which confirms the effectiveness of the proposed algorithm to capture the average impact of ice storms under uncertain behavior. Although the frequency of impact and duration of outage varies from one corridor to another, the overall average outage duration per outage occurrence is almost the same for many components. In other words, on average ice storms exhibit the same impact of all system components, but a unique impact for each ice storm scenario. Some corridors are impacted more than 10% of ice storms scenarios such as 6-8, 23-24, 15-23, and 8-28, yielding longer outage duration. Such corridors should have a higher priority in resilience planning enhancements.

To show the severity of ice storms over time, the average

TABLE III
OUTAGE ANALYSIS OF TRANSMISSION CORRIDORS

Corridor		Case 1			Case 2		
From	To	Freq.	Duration	Hour/occ	Freq.	Duration	Hour/occ
1	2	347	6642	19.141	349	6661	19.086
1	3	298	5742	19.268	300	5775	19.250
2	4	485	9857	20.324	488	9883	20.252
3	4	285	5757	20.200	286	5761	20.143
2	5	976	20185	20.681	979	20171	20.604
2	6	897	18862	21.028	899	18868	20.988
4	6	673	14169	21.053	679	14138	20.822
5	7	299	6116	20.455	296	6104	20.622
6	7	762	15867	20.823	764	15811	20.695
6	8	1366	28484	20.852	1366	28523	20.881
6	9	218	4558	20.908	218	4548	20.862
6	10	355	7410	20.873	355	7438	20.952
9	11	234	4775	20.406	234	4771	20.389
9	10	460	9680	21.043	461	9660	20.954
4	12	431	8533	19.798	425	8491	19.979
12	13	445	9178	20.625	444	9156	20.622
12	14	839	17195	20.495	840	17208	20.486
12	15	861	17578	20.416	859	17561	20.444
12	16	639	12967	20.293	640	12963	20.255
14	15	137	2765	20.182	137	2786	20.336
16	17	581	12192	20.985	581	12202	21.002
15	18	186	3748	20.151	186	3764	20.237
18	19	179	3624	20.246	182	3659	20.104
19	20	207	4261	20.585	208	4266	20.510
10	20	496	10234	20.633	497	10248	20.620
10	17	528	10864	20.576	526	10855	20.637
10	21	566	11765	20.786	564	11807	20.934
10	22	507	10566	20.840	509	10612	20.849
21	22	191	3894	20.387	190	3868	20.358
15	23	1226	25622	20.899	1230	25694	20.889
22	24	527	10970	20.816	531	10940	20.603
23	24	1091	22715	20.820	1090	22708	20.833
24	25	883	18377	20.812	880	18375	20.881
25	26	337	6620	19.644	328	6624	20.195
25	27	684	14299	20.905	682	14242	20.883
28	27	155	3120	20.129	155	3104	20.026
27	29	165	3395	20.576	165	3359	20.358
27	30	183	3684	20.131	180	3691	20.506
29	30	130	2640	20.308	130	2656	20.431
8	28	1145	23729	20.724	1140	23651	20.746
6	28	382	7902	20.686	384	7888	20.542

amount of load curtailed at each hour for all scenarios is calculated for both cases as shown in Fig. 4. The impacts are growing rapidly during the first few hours which highlights the importance of the restoration phase. The faster the restoration, the lower load curtailed and higher system resilience.

V. Conclusion

This paper has proposed a planning-based resilience evaluation methodology to assess the resilience of electric transmission systems against uncertainties of ice storms. The proposed method calculated the average amount of load curtailment for various ice storms. An ice storm model is used to simulate numerous scenarios based on predefined weather parameters that are governed by calculated PDF. The fragility of system component is calculated using a spatiotemporal fragility model against ice thickness. The proposed algorithm was demonstrated on the IEEE 30-bus system mapped on the Eastern region of USA. The results showed the effectiveness of the resilience assessment methodology to evaluate the

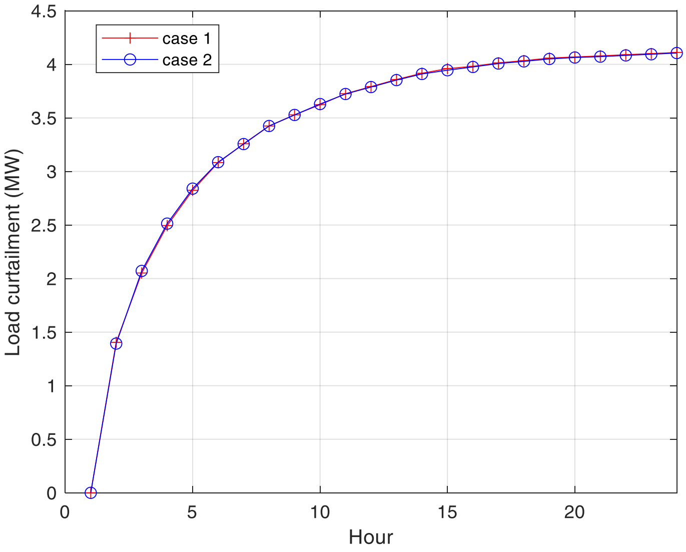

Fig. 4. Average hourly load curtailment

resilience level of power system against ice storms. In the future, the proposed algorithm will be tested on a large system to validate its scalability capabilities.

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