Assessment of Infrastructural and Operational Resilience of Transmission Lines During Dynamic Meteorological Hazard

2023 14th International Conference on Computing Communication and Networking Technologies (ICCCNT) | 979-8-3503-3509-5/23/$31.00 ©2023 IEEE | DOI: 10.1109/ICCCNT56998.2023.10306797

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***Abstract*—The occurrence of extreme meteorological dynamic hazards has endangered the operation of power system and its components in the past few decades, emphasizing the need to create efficient methods and models to assess the resilience capability of the critical system infrastructure and the impact of such hazards on the system in future. In this paper, resilience metrices based method is proposed for assessment of infrastructural and operational resilience of the transmission lines during hazardous weather events such as severe cyclonic windstorms. A sequential Monte Carlo (MC)-based time-series model is used to determine the weather effect on the transmission networks. Weather data is mapped with the fragility curve of the transmission line to obtain the failure status of the transmission line. The proposed study is investigated on the standard IEEE 30 bus system for determining the vulnerable transmission lines lying in the path of cyclonic windstorm. The findings may be helpful in planning and operation of power system by determining the impact of such hazards and establishing an early warning weather hazard system to avert substantial system component damage.**

Keywords— Meteorological Hazard, Fragility Curve, Windstorm, Power Systems Resilience.

I. Introduction

In recent years, the increasing frequency and severity of meteorological dynamic hazards have posed significant challenges to the power system infrastructure. These hazards, such as hurricanes, tornadoes, and severe storms, can cause extensive damage to the transmission lines resulting in disruption of the normal system operation. Such catastrophic event are termed as High Impact Low Probability events (HILP) [1]. Ensuring the infrastructural and operational resilience of transmission lines under such hazardous conditions is crucial for maintaining a robust and stable electrical grid [2].

Power system resilience is defined as the ability of system to anticipate, adopt effective measure, and restore the system capability before, during and after the disasters [3]-[5]. Severe wind storms can cause significant damage to the transmission lines, resulting in power outages and disruptions to the electricity supply. Therefore, it is crucial to assess the vulnerability of the transmission lines against severe wind storms to determine their resilience. Three strategies are primarily considered for determination of resilience in the literature [6]: The analytical approach [7], the statistical analysis [8],[9] and the simulation-based approach [10],[11]. The research gap lies in the lack of comprehensive studies that integrate the analytical, statistical, and simulation-based approaches for assessing the vulnerability and resilience of transmission lines against severe cyclonic windstorms. The intensity of a cyclonic windstorm along its path is a crucial factor in determining the potential impact and damage it can cause. Addressing this gap will contribute to the development of more accurate and reliable methodologies for evaluating transmission line resilience and informing decision-making processes in power system planning, maintenance, and emergency response.

Weather is highly unpredictable and challenging to quantify its effects. In order to accomplish this, a unique time-series simulation approach using sequential Monte Carlo (MC) is developed in this study to capture the inherent uncertainties and complexities of weather phenomena. Various resilience metrics are evaluated to examine how the weather can affect the resilience of power networks.

II. Proposed Methodology for Resilience Assessment

A. Modelling of Transmission Line Fragility during Meteorological Hazard

Resilience of transmission line is affected by extreme weather event (e.g. cyclone , flood etc). Assessment of transmission line resilience during such events indicates the strength of its design capability of handle them. A fragility curve is used to obtain the weather-dependent failure probability of power system components. The fragility curve can be mathematically modelled using Eq. (1) [12] as

$$P = \varphi\left[\frac{ln(w/w_m)}{\beta}\right] \tag{1}$$

In Eq.(1), β is logarithmic standard deviation of fragility function, w_m is the median value of fragility function and w is wind speed. Transmission line failure probability, $P_{TR}^{\omega s_i}$ can be evaluated using Eq. (2) [13] as

$$P_{TR}^{\omega s_i} = \begin{cases} 0 & if\ \omega s_i < \omega s_{Cr} \\ exp\left[\frac{0.6931(\omega s_i - \omega s_{Cr}}{\omega s_{Cr}}\right] & if\ \omega s_{Cr} < \omega s_i < \omega s_{Col} \\ 1 & if\ \omega s_i > \omega s_{Col} \end{cases} \tag{2}$$

In Eq. (2) ωs_i wind speed in i^{th} region. Three region-I, region-II and region-III has considered for study having different wind speed high, moderate and low. The critical wind speed, ωs_{Cr} is 30 m/s and ωs_{Col} is 60 m/s which is the wind speed at which transmission line will collapse [14]. The proposed model employs sequential Monte Carlo Simulation (MCS) to model the behaviour of a system as a sequence of events affecting each other as the event progresses in time. It utilizes weather and time dependent failure probabilities to the components of a power system. This is accomplished using time-series weather profiles and fragility curves, as shown in

Figure 1. At each simulation step, the weather-affected failure probability of the components can be derived by mapping the time-series weather profile to the fragility curve. A random generated number (r~ U (0,1)) is compared with the failure probability of transmission line, $P_{TR}^{\omega s_i}$ to obtain the failure status and it is evaluated by Eq. (3) [14] given as

$$F_{TR} = \begin{cases} 0 & if\ P_{TR}^{\omega s_i} < r \\ 1 & if\ P_{TR}^{\omega s_i} > r \end{cases} \quad (3)$$

where F_{TR} indicates the collapse status of transmission line during each simulation step. If $P_{TR}^{\omega s_i} > r$, it indicates that the failure probability is higher than the generated random number, and therefore the transmission line is in a failed state, leading to its tripping or disconnection. If $P_{TR}^{\omega s_i} < r$, it indicates that the failure probability is lower than the random number, indicating that the transmission line remains in an operational state and does not experience a failure or trip.

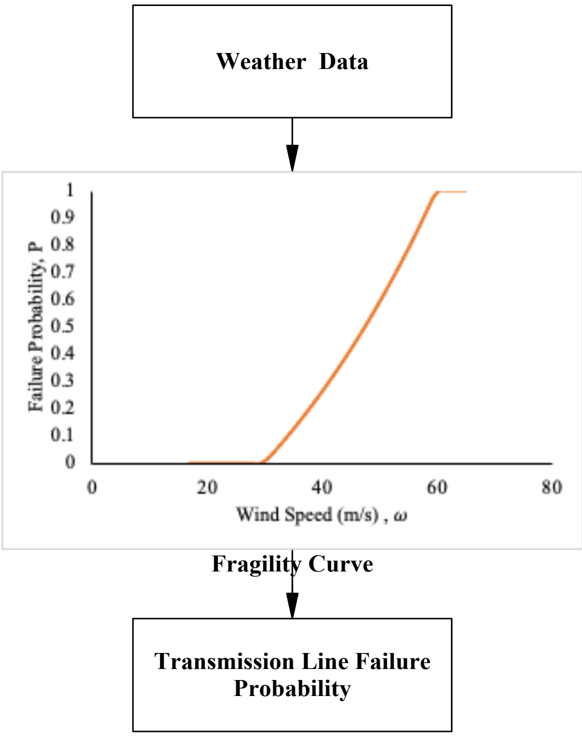

Fig. 1. Estimating the failure probabilities using fragility curves

B. Quantitative Resilience Metrics

The resilience of power systems against catastrophic meteorological events has been evaluated statistically in several research studies [3], [6], [8-10] but no standard metrics have been identified. To assess the performance of the power system, time-dependent metrics are proposed in this paper.

a) Number of Transmission Line Tripped

$$TR_{tripped} = \sum F_{TR} \quad (4)$$

In Eq. (4) $TR_{tripped}$ represents numbers of transmission line tripped per day. By summing up the individual failure status F_{TR} of all the transmission lines obtained by Eq. (3), the total count of tripped transmission lines per day can be determined, which serves as an important metric to assess the resilience of the power system in the face of transmission line failures.

b) Number of Transmission Line in Service

$$TR_{service} = IR_{pre} - \sum F_{TR} \quad (5)$$

In Eq. (5), $TR_{service}$ represents the number of transmission line that remain in service or 'on' state corresponding to each day as the cyclonic windstorm progresses for its entire duration. This gives the count of transmission lines that remain in an operational state during the events, indicating their ability to withstand the impacts and continue delivering power. The pre hazard condition known as pre disturbance infrastructure resilience, IR_{pre} is assumed to be 100% indicating that all the transmission lines are intact and in service before the dynamic hazard hits the transmission network. It serves as a baseline reference, assuming that all transmission lines are initially in an operational state. Numerically it will be equal to total operational transmission line lying in each of the regions I, II and III.

c) Infrastructural Resilience Metrics

$$RM_{inf} = \left.\frac{IR_{pre} - IR_{post}}{IR_{pre}}\right|_{Day\in[1,5]} \quad (6)$$

The RM_{inf} metric provides insight into the resilience capability of the transmission network per day during the event, indicating the proportion of transmission lines that experienced failures or disruptions. In this study, the total duration of the cyclonic windstorm occurring on the system is for a period of 5 days (T=120 Hrs) with reduced intensity along the path it follows. IR_{post} is the post disturbance infrastructure resilience metric obtained by sum of total transmission line tripped during the hazardous event in each region for each day. A higher value of RM_{inf} indicates a higher level of infrastructure resilience, as it suggests that a larger proportion of the transmission lines remained in an operational state during the event. Conversely, a lower value of RM_{inf} signifies a lower resilience level, indicating a significant impact on the transmission network and a higher number of tripped transmission lines during the event.

d) Operational Resilience Metrics

$$RM_{op} = \left.\frac{OR_{pre} - OR_{post}}{OR_{pre}}\right|_{Day\in[1,5]} \quad (7)$$

OR_{post} is the post disturbance operational resilience given by the total transmission line installed capacity in MVA available per day after the event has occurred. OR_{pre} is the pre disturbance operational resilience and is obtained by total transmission line installed capacity in MVA of the system before the event with 100% transmission lines in service. A higher value of RM_{op} indicates a higher level of operational resilience per day suggesting that a larger proportion of the transmission capacity remains available after the event. This indicates the network's ability to continue meeting the power demand despite the event's impact. Conversely, a lower value of RM_{op} signifies a lower resilience level, indicating a significant reduction in the operational capacity of the transmission network due to the event.

III. Illustrative Case Study

A. Test Network under Different Wind Profiles

The test system considered in this paper is IEEE 30 bus system. It consists of 30 buses, 41 transmission lines and 6 generators. The generators are connected at bus 1,2,13,22, and

27 with total 335 MW generation capacity. Three different wind profiles are considered here for evaluating the impact on transmission lines of the test system [15]. Wind profile have three different regions: Region-I (High), Region-II (Medium) and Region-III (Low). Probability distribution of all the region is depicted in Fig. 2. These probability distributions can be sampled to get the hourly wind profiles.

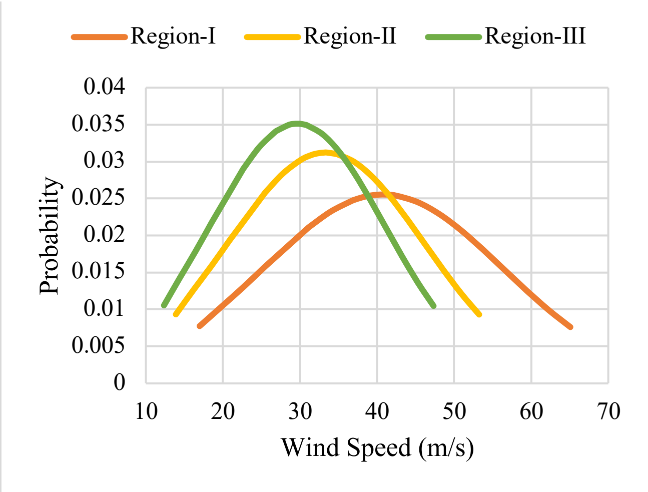

Fig. 2. Probability distribution of the wind profiles in different region

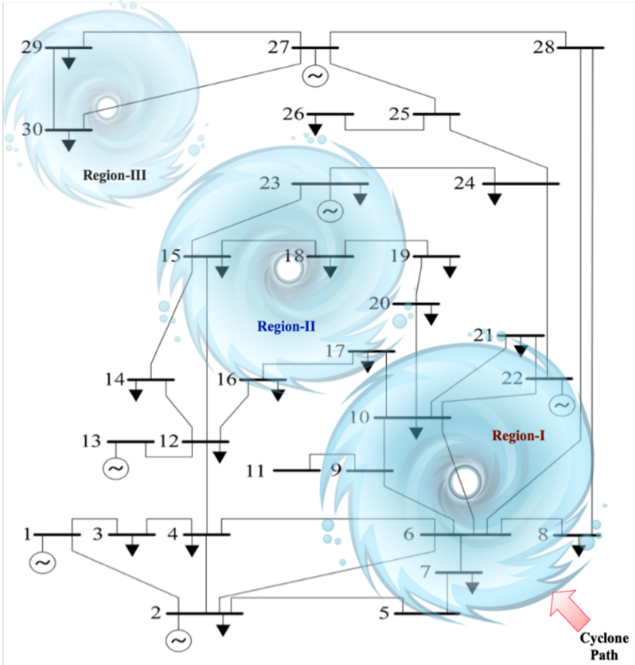

Fig. 3. IEEE 30 Bus Transmission with Different Wind Region

TABLE I. TRANSMISSION LINES IN DIFFERENT CYCLONE PATH REGIONS

Wind Region	Transmission Line	Total No. of Transmission Line
Region-I	(2-5),(2-6),(4-6), (5-7),(6-7), (6-8),(6-9),(6-10),(9-11),(9-10), (10-20), (10-17), (10-21),(10-22),(21-22), (22-24), (8-28), (6-28)	18
Region-II	(12,15),(12-16),(14-15) ,(16-17),(15-18) , (18-19),(19-20), (15-23), (23-24)	9
Region-III	(27-29),(27-30),(29-30)	3

IR_{pre} = 18+9+3=30

Based on wind intensity and path of cyclone IEEE 30 bus is divided into three region as depicted in Fig.3. In region-I lies total 18 transmission lines and one generator with 50 MW maximum capacity, in region-II total 9 transmission line lies and one generator with 30 MW capacity, in region-III total 3 transmission lines are lying as shown in Table I and Table II. The transmission tower and generators that are unaffected by the hazard are not considered in resilience quantification.

TABLE II. GENERATOR IN DIFFERENT WIND REGIONS

Wind Region	Bus No	P_G (MW)	P_G Max (MW)
Region-I	22	21.59	50
Region-II	23	19.2	30

B. Simulation Results

Input meteorological dynamic data is mapped with transmission line fragility curve to obtain the transmission line failure probability. It is compared with random generated number between 0 and 1 using Eq. (3). If failure probability of transmission line (obtained by using Eq.2) is greater than random generated number then transmission line will be failed to operate and it is denoted by '1' as mentioned in Table III and If failure probability of transmission line is less than random generated number then transmission line will be remained in service and it is denoted by '0'. Based on above simulation transmission line failure scenario is generated in all the three region which is tabulated in Table III, Table IV and Table V.

TABLE III. TRANSMISSION LINE FAILURE STATUS, F_{TR} (REGION-I)

From Bus	To Bus	D1	D2	D3	D4	D5
2	5	1	1	1	1	1
2	6	1	1	1	1	1
4	6	0	1	1	1	1
5	7	1	1	1	1	1
6	7	1	1	1	1	1
6	8	0	0	0	1	1
6	9	0	1	1	1	1
6	10	0	0	0	0	0
9	11	0	0	0	0	0
9	10	0	0	0	1	1
10	20	0	0	0	0	0
10	17	0	0	1	1	1
10	21	1	1	1	1	1
10	22	0	0	0	0	1
21	22	0	0	0	0	0
22	24	0	0	0	0	0
8	28	0	1	1	1	1
6	28	1	1	1	1	1

TABLE IV. TRANSMISSION LINE FAILURE STATUS, F_{TR} (REGION-II)

From Bus	To Bus	D1	D2	D3	D4	D5
12	15	0	0	0	0	0
12	16	1	1	1	1	1
14	15	0	0	0	0	0
16	17	0	0	1	1	1
15	18	0	1	1	1	1
18	19	0	0	0	0	1
19	20	1	1	1	1	1
15	23	0	1	1	1	1
23	24	0	0	0	0	0

TABLE V. TRANSMISSION LINE FAILURE STATUS, F_{TR} (REGION-III)

From Bus	To Bus	D1	D2	D3	D4	D5
27	29	0	0	0	0	0
27	30	0	0	0	0	0
29	30	0	1	1	1	1

TABLE VI. NUMBER OF TRANSMISSION LINE TRIPPED PER DAY, $TR_{tripped}$ DURING CYCLONE

Days	Wind Region	Vulnerable Lines	$TR_{tripped}$
D1	Region-I	(2-5), (2-6), (5-7), (6-7), (10-21), (6-28)	6
	Region-II	(12-16), (19-20)	2
	Region-III	--	0
D2	Region-I	(2-5), (2-6), (4-6),(5-7), (6-7), (6-9), (10-21), (8-28), (6-28)	9
	Region-II	(12-16), (15-18), (19-20), (15-23)	4
	Region-III	(29-30)	1
D3	Region-I	(2-5), (2-6), (4-6),(5-7), (6-7), (6-9),(10-17), (10-21), (8-28), (6-28)	10
	Region-II	(12-16), (16-17), (15-18), (19-20), (15-23)	5
	Region-III	(29-30)	1
D4	Region-I	(2-5), (2-6), (4-6),(5-7), (6-7), (6-8), (6-9), (9-10), (10-17), (10-21), (8-28), (6-28)	12
	Region-II	(12-16), (16-17),(15-18), (19-20), (15-23)	5
	Region-III	(29-30)	1
D5	Region-I	(2-5), (2-6), (4-6),(5-7), (6-7), (6-8), (6-9), (9-10), (10-17), (10-21),(10-22), (8-28) , (6-28)	13
	Region-II	(12-16), (16-17), (15-18), (18-19), (19-20), (15-23)	6
	Region-III	(29-30)	1

Based on the failure scenario, the number of transmission line tripped are calculated using Eq. (4) as shown in Table VI. Day wise analysis is performed and vulnerable line are identified for each region. It is assumed that the maintenance work starts after the extreme event is over. On day-1, in region-I, 6 transmission lines are tripped and in region-II, 2 transmission lines are tripped. Total 8 transmission lines are tripped on day-1. In region-I, wind speed is very high thus resulting in tripping/disconnection of more transmission lines as compared to the region-II and III which represents medium and low wind speeds respectively. For each day, the number of lines that sustained during extreme weather event is calculated using Eq. (5) as shown in Table VII.

Based on the above information, two types of resilience metrics are evaluated to measure the performance of the transmission lines of the test system: infrastructural resilience metric, RM_{inf} and operational resilience metric, RM_{op} . Infrastructure resilience depends on the physical strength of transmission line. It is calculated by Eq. (6) and result is mentioned in Table VIII. Day wise resilience and overall infrastructure resilience of the system is also evaluated. The overall average resilience is evaluated for entire duration of event lasting for 5 days. It is found that with each passing day as the cyclonic windstorm moves along the path indicated, the infrastructure availability is reduced as more number of transmission lines are tripped in all the regions. Thus, the transmission line infrastructure left intact is found to be 73% in day D1, when 8 transmission lines are tripped, while in day2, D2 14 transmission lines are disconnected from the system indicated by resilience metric value of 0.53 or 53% and so on for all other days. Day 5, D5 indicates the day very less available resilient infrastructure indicating highest disconnection of transmission lines. When wind speed is higher, than more number of transmission line will be tripped and resilience of the system will degrade as mentioned in Table VIII. The overall infrastructural resilience is 49% when the system is subjected to given meteorological dynamic hazard.

TABLE VII. NUMBER OF TRANSMISSION LINE REMAIN IN SERVICE PER DAY, $TR_{service}$ DURING CYCLONE

Days	Wind Region	Resilient Lines	$TR_{service}$
D1	Region-I	(4-6), (6-8), (6-9), (6-10), (9-11), (9-10), (10-20), (10-17), (10-22), (21-22), (22-24), (8-28)	12
	Region-II	(12-15), (14-15), (16-17), (15-18), (18-19), (15-23), (23-24)	7
	Region-III	(27-29), (27-30), (29-30)	3
D2	Region-I	(6-8), (6-10), (9-11), (9-10), (10-20), (10-17), (10-22), (21-22), (22-24),	9
	Region-II	(12-15), (14-15), (16-17), (18-19), (23-24)	5
	Region-III	(27-29), (27-30),	2
D3	Region-I	(6-8), (6-10), (9-11), (9-10), (10-20), (10-22), (21-22), (22-24),	8
	Region-II	(12-15), (14-15), (18-19), (23-24)	4
	Region-III	(27-29), (27-30)	2
D4	Region-I	(6-10), (9-11), (10-20), (10-22), (21-22), (22-24)	6
	Region-II	(12-15), (14-15), (18-19), (23-24)	4
	Region-III	(27-29), (27-30)	2
D5	Region-I	(6-10), (9-11), (10-20), (21-22), (22-24),	5
	Region-II	(12-15), (14-15), (23-24)	3
	Region-III	(27-29), (27-30)	2

TABLE VIII. INFRASTRUCTURAL RESILIENCE METRIC RM_{inf}

Days	Total $TR_{tripped}$ / day in each region, IR_{post}	RM_{inf} / day	*Overall Average* RM_{inf} (%)
D1	8	0.73	49%
D2	14	0.53	
D3	16	0.46	
D4	18	0.40	
D5	20	0.33	

To determine the operational resilience of the system, an AC OPF is performed and the available transmission line power transfer capacity for each day during the extreme event is calculated using Eq. (7) and day wise operational metrics are evaluated as shown in Table IX. Also, from Fig. 4, it can be observed that as event progresses, the available transmission capacity of the system is decreases because of availability of a smaller number of transmission lines to transfer power. The pre-event power transfer capacity of the

41 transmission lines is 1442.96 MVA with 100% lines in service. On day 5 (D5), only 769.20 MVA capacity is available to transfer power through the remaining operating lines in service. This shows that nearly 46.69% of transmission line capacity is lost during extreme weather event with respect to initial state. The values of RM_{op} for each day represent the percentage reduction in the transmission capacity of the lines after the event compared to the pre-event capacity. A higher value of RM_{op} indicates a higher level of operational resilience, as it suggests a smaller reduction in the available transmission capacity after the event. This indicates the network's ability to continue delivering power efficiently despite the event's impact.

TABLE IX. OPERATIONAL RESILIENCE METRIC RM_{op}

Days	**Total pre-event transmission capacity of the lines / *day*, OR_{pre} (MVA)**	**Total post event transmission capacity of the lines / *day*, OR_{post} (MVA)**	**RM_{op} / *day***	***Overall Average* RM_{op} (%)**
D1	1442.96	1169.25	0.189	11.52%
D2	1169.25	946.71	0.190	
D3	946.71	898.71	0.050	
D4	898.71	801.71	0.107	
D5	801.71	769.20	0.040	

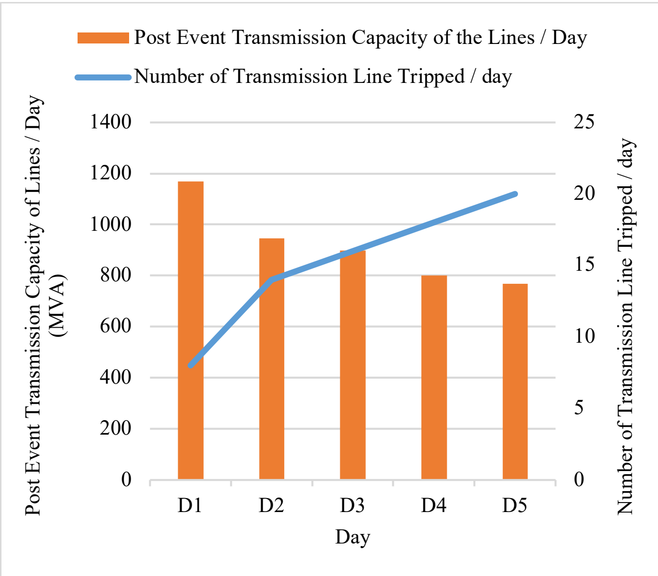

Fig. 4. Transmission line capacity of the system available for each day for the given cyclonic windstorm

IV. CONCLUSIONS

In this paper, resilience assessment has been evaluated through proposed metrics. The effect of the weather on power system components has been modelled using the fragility curve and Monte Carlo Simulation. The failure probability of the transmission line has been calculated and the number of vulnerable transmission lines has been identified. The failure scenario is mapped on the IEEE 30 bus transmission system. The infrastructure resilience metrics have been determined and AC OPF has been performed to obtain operational resilience metrics during the dynamic meteorological hazard. It is observed from the results that the power system's resilience is inadequate at higher wind speeds greater than 45 m/s. The proposed results are promising for understanding such events' impact on system resilience assessment during planning studies.

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