A Probabilistic Approach to Assess Quantitative Resilience of Transmission Line During Cyclone

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***Abstract*—Power transmission system should be reliable and robust to meet the uninterrupted load demand. However, the performance of power system is affected when different system components are exposed to the extreme weather conditions. In this paper, quantitative assessment of component resilience is proposed by determining the transmission line failure under the natural disaster events like cyclone. Transmission line fragility curves are mapped with wind profile during cyclone to obtain the probability of failure of each transmission lines using Monte Carlo Simulation (MCS) method. Available Transmission Capacity (ATC) and Load Not Served (LNS) are calculated to assess the resiliency of the standard IEEE 30 bus system. The results are promising to understand the impact of such events for assessment of infrastructural and operational resiliency studies during the planning stage.**

***Keywords*—Power System Resilience, High Impact Low Probability events (HILP), Extreme Weather, Fragility Curve.**

I. INTRODUCTION

In recent years, the power system industry has suffered a lot due to critical natural hazards such as cyclones, wildfires, ice storms, floods and man-made cyber and physical attacks. This has caused a challenge to power system grid resilience [1-2]. Resiliency is the system ability to bounce back during extreme condition [3]. In [4], resilience is defined as "system persistence and the ability of the system to absorb changes and disturbances and maintain its original state".

Power system resilience is also defined by some researchers and industries based on the above definition, but no standard definition has been adopted yet. According to the IEEE PES-Technical report [5] resilience is defined as "The ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event [5]."

Extreme events have adverse impact on society [6]-[8]. Any disruption or changes in power system that affects its normal behaviour can be termed as a power system event. It may be High Impact Low Probability (HILP) event [9] or Low Impact High Probability (LIHP) event[10] as shown in Fig. 1. India has been ranked as the 7th most climate-affected country in the world by the global climate risk index. [11]. Country has seen several cyclones, floods, earthquakes, drought, heat waves, and other natural events that have impacted the power system operation [12]. A recent study by the Indian Institute of Tropical Meteorology indicated an increase of 52% in the frequency of cyclones over the Arabian Sea in last two decades [13]. In 2019, an Indian state Odisha had suffered with cyclone (Fani) that caused the state to suffer heavy financial loss of approximately Indian Rs 8000 crores only in power sector including both transmission and distribution systems [14].

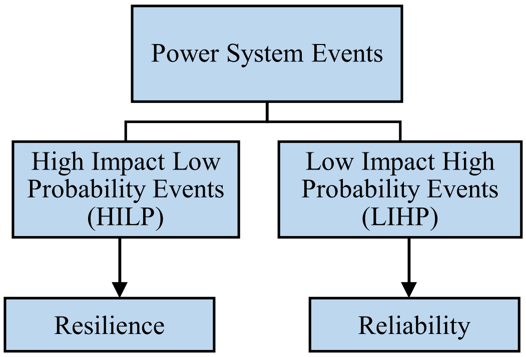

Fig. 1. Classification of Power System Events

There is strong need to focus more on power system operational and infrastructural studies during the extreme weather events to ensure the system robustness and resiliency. In the literature, different indices and matrices have been developed to measure the power system resilience. The load restoration method to measure the resilience is proposed in [15]. System performance during the disaster and ideal system performance is used in [16],[17] to calculate resilience index. A probabilistic approach is used to determine Severity Risk Index (SRI) to handle risk produced in power system during extreme weather condition [18]. Some researcher has used reliability index to measure the resilience during high impact low probability event. Loss of Load Probability (LOLP) and EENS (Expected Energy Not Supplied) is used to develop Resilience Achievement Worth (RAW) index for transmission corridor under the different wind speed. The criticality of each transmission network is identified based on criticality level ranking of each network in [19].

This paper presents probabilistic transmission line failure modelling and its fragility modelling during cyclone using Monte Carlo simulation (MCS) method. Number of transmission line outage are used as infrastructure resilience indicator. The impact of the event is used to evaluate the operational resiliency with indicators such as Available Transmission Capacity (ATC) and Load Not Served (LNS). All the quantity is measured at different wind intensity during cyclone for period of one week.

II. MODELLING OF CYCLONE IMPACTS ON TRANSMISSION LINE

A. Data Generation

The wind data during cyclone is taken from the Indian meteorological Department [20] and it is divided into three region on the basis of intensity of wind speed. Each region has different maximum wind speeds. High wind region (I) has maximum wind speed up to 65 m/s, medium wind region (II) has up to 59 m/s and low wind region (III) has up to 30 m/s as shown in Fig. 2.

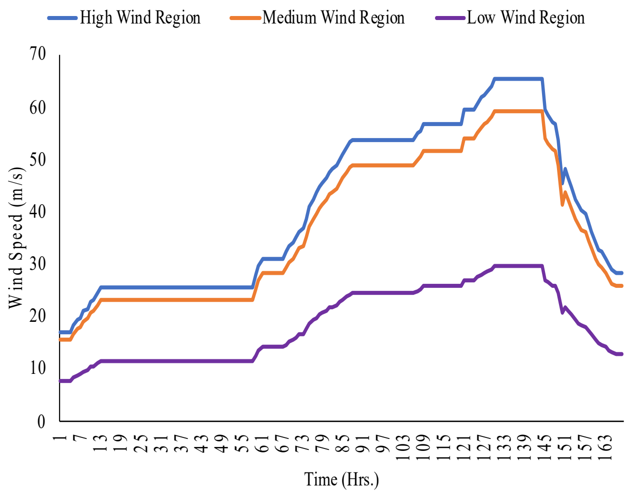

Fig. 2. Wind Profile during High , Medium and Low Wind Region

B. Transmission Lines Fragility Modelling

Transmission line resilience is affected by regional weather condition. It may be sustain or collapse depending on its resilience capability and design capability to withstand wind speed. For modelling the transmission line, different fragility curves are needed for each transmission line. Fragility curves are obtained by historical data, experimental method , analytical method, expert opinion and combination of any these methods [19]. Fragility function can be modelled using Eq.1 [21] given by lognormal function as

$$P_{(\omega)} = \phi\left[\frac{ln(\omega/\omega_m)}{\xi}\right] \quad (1)$$

where ω is wind speed , ω_m is the median value of fragility function and ξ is logarithmic standard deviation of fragility function.

Fig. 3 shows the fragility curve of transmission lines of IEEE 30 bus system considered in this paper. It represents failure probability of transmission line with respect to wind speed.

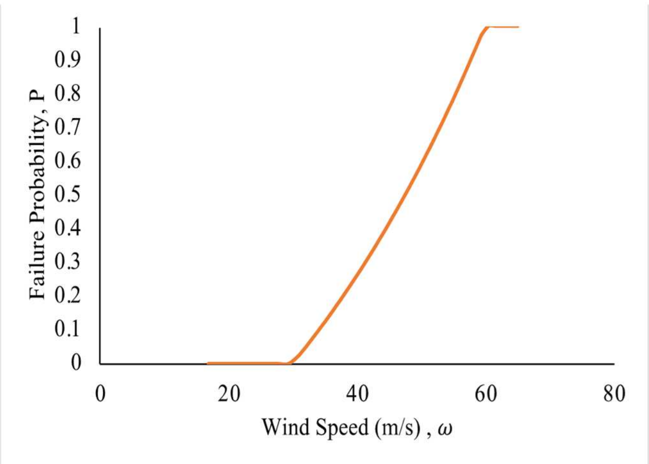

Fig. 3. Fragility Curves of Transmission Line

From Fig. 3, it is seen that as wind speed increases, the failure probability also increases. When wind speed reaches between 50 m/s to 59 m/s, the probability of failure also increases from 65% to 99 %.

C. Transmission Line Outage Modelling

Probability of transmission line failure, $P_L^{\omega_i}$ can be calculated by Eq. (2) [22] given as

$$P_L^{\omega_i} = \begin{cases} 0 & if\ \omega_i < \omega_{Cr} \\ exp\left[\frac{0.6931(\omega_i - \omega_{Cr}}{\omega_{Cr}}\right] & if\ \omega_{Cr} < \omega_i < \omega_{Col} \\ 1 & if\ \omega_i > \omega_{Col} \end{cases} \quad (2)$$

where ω_i is wind speed and i stands for the three region I, II , III indicating high, medium and low wind speed region respectively. ω_{Cr} is critical wind speed taken as 30 m/s in this study and ω_{Col} is wind speed at which transmission line will collapse taken as 60 m/s [18]. Failure probability of transmission line ($P_L^{\omega_i}$) is compared with random generated number (r~ U (0,1)) in each simulation step to obtain the transmission line failure scenario using Monte-Carlo simulation (MCS). Transmission line failure status can be obtained by Eq. (3) [19] as

$$F_{TL} = \begin{cases} 0 & if\ P_L^{\omega_i} < r \\ 1 & if\ P_L^{\omega_i} > r \end{cases} \quad (3)$$

where F_{TL} denotes the failure status of transmission line during each simulation step. If $P_L^{\omega_i} > r$ then transmission line fails to operate. If $P_L^{\omega_i} < r$ then transmission line remains in operational state.

D. Assumptions Considered

Certain assumptions are considered in the proposed methodology for reducing the complexity as follows:

- It is assumed that all the transmission line has same fragility function. Although the different transmission line may have different fragility function.
- Failure of transmission line is independent to other transmission line. It does not affect the operation of adjacent transmission line[19].
- Load is assumed to be constant during and after the event.
- In this paper, generation is assumed to be independent of weather. It may be affected if generation station are old and not designed to withstand high wind storm events like cyclone.
- As distance from centre of cyclone increases, its intensity also decreases. On this basis of cyclone intensity, the transmission network is divided into three different regions. The region nearest to the cyclone path is considered as high wind region and the region farthest from the cyclone is considered as low wind region. The region lying between these two regions is considered as medium wind region.
- During different wind storm different time may be taken to repair the faulty transmission line. It depends upon the severity of weather condition. In this study, during normal weather condition, repair time of 10 hours is assumed for faulty line [23].

III. Proposed Transmission Line Resilience Assessment

Fig. 4 shows the flowchart for resilience assessment of transmission line. Firstly, the data generation for cyclone is performed. The wind profile is mapped over the transmission line fragility curve. Using MCS, different failure scenarios are obtained in each simulation step and the failure probability of transmission line is compared with randomly generated number. Total number of seven days are considered for simulation and each day for each hour simulation has performed. Day wise failure scenario has obtained and accordingly repair time is generated for failed line. All the status is saved and it is mapped on IEEE 30 bus. AC optimal power flow is used for getting the power system status for each failure scenario for each day.

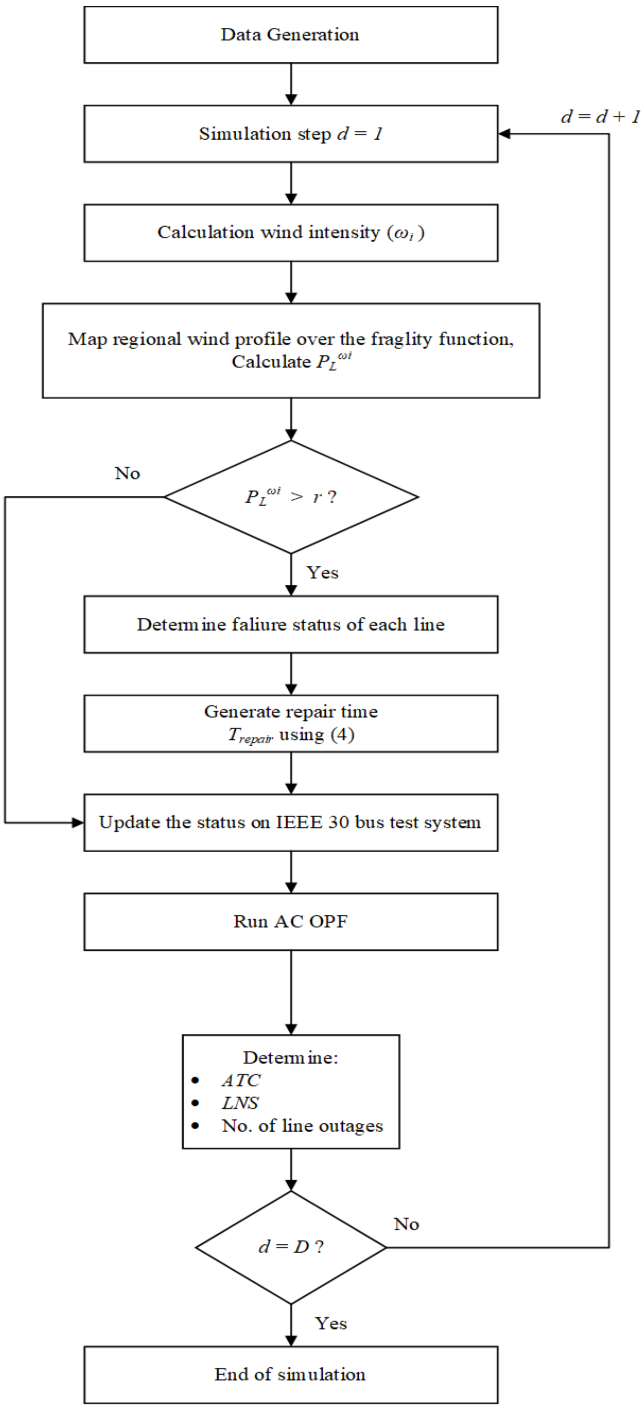

Fig. 4. Flowchart for Determining ATC and LNS

Algorithm for Determining ATC and LNS	
Step 1:	*Initialization, i=0, d=0, i=no of wind region, D= no. of days*
Step 2:	*Generate ω_i using Weibull rand function*
Step 3:	*Map ω_i over the fragility curve and calculate $P_L^{\omega_i}$*
Step 4:	*Compare $P_L^{\omega_i}$ with random number to obtained the status of transmission line failure using MCS*
Step 5:	*Generate repair time, corresponding to the faulty line*
Step 6:	*Map line failure status obtained in step 4 on IEEE 30 bus test system*
Step 7:	*Run AC OPF using to determine the operational status of power system.*
Step 8:	*Calculate ATC and LNS according to results obtained in step 7*
Step 9:	*Repeat step 2 to 8 for all the three-wind region and for all the seven days of cyclone.*

IV. Simulation and Results

In this paper, IEEE 30 bus standard transmission system is considered to investigate the proposed method. It has 41 transmission lines, 30 buses and 6 generators which are connected at bus number 1, 2 ,13, 22, 23, and 27 having total generation capacity of 335 MW. Standard 30 bus system is divided into three regions depending on wind intensity as shown in Fig. 5.

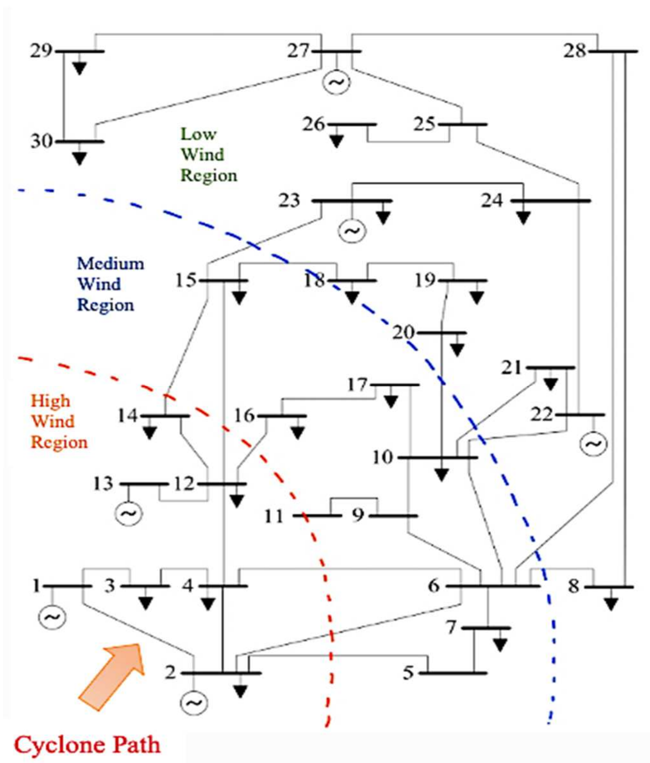

Fig. 5. IEEE 30 Bus Transmission System with Different Wind Regions

From Fig. 5, it is seen that some of the transmission lines lies in two different wind profile regions. For example, for lines 2-5, 2-6, 4-6, the failure of these transmission lines is considered according to the worst wind profile region in which these are present. Network operators generally provide repair time based on failure history and required time to repair the failed transmission line. Here, repair time is generated based on failure scenario of transmission line and it is obtained by Eq.(4) [19] as

$$T_{repair} = \begin{cases} T_{normal}, & \omega_{imax} \leq 20\, m/s \\ k_a \times T_{normal}, & 20\, m/s < \omega_{imax} \leq 45\, m/s \\ k_b \times T_{normal}, & 45\, m/s < \omega_{imax} \leq 70\, m/s \end{cases} \tag{4}$$

where T_{normal} is normal repair time of transmission line when maximum wind speed is below 20 m/s and it is considered to be10 hrs for the transmission line [23]. Repair time is divided based on the intensity of wind speed in three different regions. When wind speeds between 20 m/s to 45 m/s second then time to repair will be more as compared to T_{normal} . For considering this, a randomly generated multiplier ($k_a \sim U(2,4)$) is multiplied with T_{normal} . If wind speed fall between 45m/s to 70 m/s then time to repair will be obtained by using randomly generated multiplying factor ($k_b \sim U(5,7)$) $\times$ T_{normal} . Numbers of transmission line lying in different region are given in Table I. In high wind region (I), total number of lines are 13, in medium wind region (II) total number of lines are 15 and in low wind region (III), total number of lines are 13.

TABLE I. TRANSMISSION LINES IN DIFFERENT WIND REGIONS

Region	Transmission Line	Total No. of Transmission Line
High Wind Region (I)	(1-2),(1-3),(2-4),(3-4),(2-5),(2-6),(4-6),(4-12),(12-13),(12-14),(12-15),(12-16),(14-15)	13
Medium Wind Region (II)	(5-7),(6-7),(6-8),(6-9),(6-10),(9-11),(9-10),(16-17), (15-18),(10-20),(10-17),(10-21),(10-22),(15-23) , (6-28)	15
Low Wind Region (III)	(18-19),(19-20),(21-22),(22-24),(23-24),(24-25),(25-26),(25-27),(28-27),(27-29),(27-30),(29-30),(8-28)	13

A. Resilience Metrics

Two types of indices are used to indicate the system performance in terms of resilience, one is infrastructural and other is operational. This paper considers failure of transmission line due to the cyclone as infrastructural resilience metrics and Available Transmission Capacity (ATC) and Load Not Served (LNS) as an operational resilience metrics. ATC is evaluated by using Eq (5) [24] as

$$ATC = \sum (S_{nMax} - S_{nExt}) \tag{5}$$

where S_{nMax} is maximum power capacity of line n and S_{nExt} is the power flowing in line *n* during extreme event.

B. Identifying the Vulnerable Lines

Failure Scenarios for transmission networks are generated by MCS method. Total cyclone period is considered as one week. From the period of one week, middle 4 days are selected that are crucial for study when the cyclone builds up on the basis of wind speed intensity as shown in Fig. 2. For high impact low probability event like cyclone leads to *N-k* contingency problem with simultaneous outage of multiple transmission lines.

Infrastructure resiliency is calculated for all the three regions, as shown in Table II and Table III. Number of disconnected transmission lines are used as an infrastructure resilience indicator shown in Fig. 6. It is seen from the figure that a greater number of lines are disconnected on day four (D4) and day five (D5) as the intensity of wind is very high on these two days. There is no transmission line outage found in low wind region (III) during the simulations.

TABLE II. SAMPLE RESULTS FOR VULNERABLE LINES AND SYSTEM STATUS (HIGH WIND REGION)

DAYS	VULNERABLE LINES	NUMBER OF DISCONNECTED LINES	SYSTEM STATUS	AVAILABLE TRANSMISSION CAPACITY (MVA)
D3	(2-5),(2-6),(4-6)	3	UNSTABLE	1090.48
D4	(1-2),(3-4),(2-6) ,(12-13),(12-15),(12-16)	6	UNSTABLE	808.66
D5	(1-2),(1-3),(2-6) ,(4-12),(12-13) ,(12-14),(14-15)	7	UNSTABLE	607.82
D6	(1-3),(4-6),(4-12),(14-15)	4	UNSTABLE	607.82

TABLE III. SAMPLE RESULTS FOR VULNERABLE LINES AND SYSTEM STATUS (MEDIUM WIND REGION)

DAYS	VULNERABLE LINES	NUMBER OF DISCONNECTED LINES	SYSTEM STATUS	AVAILABLE TRANSMISSION CAPACITY (MVA)
D3	(6-8),(6-9),(10-22)	3	UNSTABLE	1260.69
D4	(6-7),(10-21) , (10-22),(15-23)	4	UNSTABLE	1098.08
D5	(6-8),(9-10),(16-17),(10-20),(10-17),(10-21),(10-22)	7	UNSTABLE	1238.97
D6	(6-8),(9-10),(10-17),(6-28)	4	UNSTABLE	1207.47

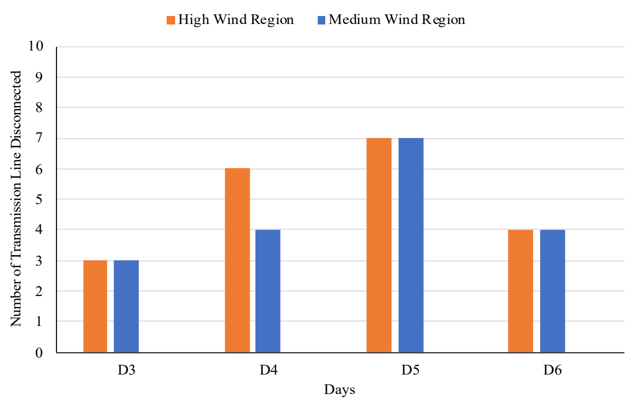

Fig. 6. Transmission line outage during the cyclone in different days

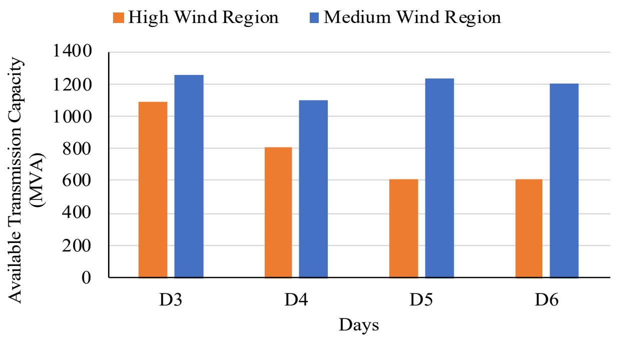

Fig. 7. Available transmission line capacity during the cyclone

For all the three regions, two operational resilience metrices are also calculated. The first operational resilience indictor is Available Transmission Capacity (ATC) during the cyclone. It is calculated by using (5). It shows the amount of power available to be transferred during the catastrophic event through the transmission line. It is shown in Table II and Table III and depicted in Fig. 7. From the above figure, it can be seen that capacity of transmission line on day four (D4) and day five (D5) has declined as compared to day three (D3) where lesser number of lines are disconnected. On day five (D5), total 14 numbers of lines are disconnected as wind intensity is highest causing maximum damage. Thus, from D3 to D6, the system becomes unstable due to catastrophic cyclone event.

The second operational resilience indicator is Load Not Served (LNS) which is calculated on basis of information available after AC optimal load flow analysis as shown in Table IV and Fig. 8. Maximum load that is not served are on day four (D4) and day five (D5) including both the regions is approximately 127 MW and 148 MW respectively.

TABLE IV. SAMPLE RESULTS OF LOAD NOT SERVED (MW)

Days	**LNS (MW)**		**Power Balance**
	High Wind Region (I)	**Medium Wind Region (II)**	
D3	29.3	35.8	Not satisfied
D4	42.9	84.3	Not satisfied
D5	49.1	99	Not satisfied
D6	49.1	99	Not satisfied

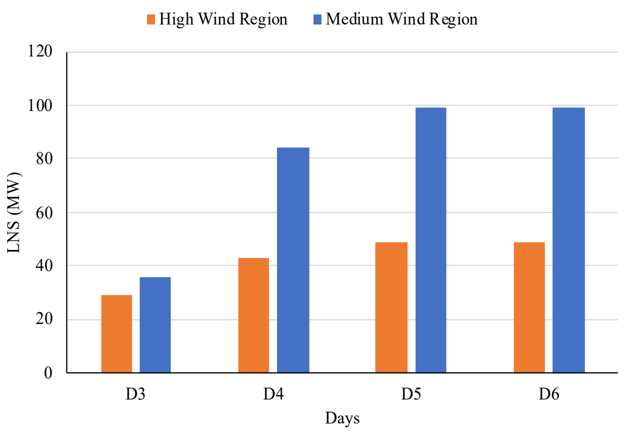

Fig. 8. Load not Served during the cyclone

V. CONCLUSIONS

In this paper, probabilistic assessment of operational and infrastructural resilience is proposed for the transmission system during cyclone. Transmission line outage is used as infrastructure resilience indicator and ATC and LNS have used as an operational resilience indicator. Based on wind intensity, three regions are divided and impact of cyclone in all the region is investigated using MCS and AC optimal power flow. Vulnerable lines and the system operational status is also determined for the test system. The proposed results are promising to understand the impact of such events for assessment of system resilience during planning studies.

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