Performance evaluation of Northern Regional Transmission System of India: Critical Analysis for Grid Resilience

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Abstract— **The resilience of electricity grids is of utmost importance to ensure uninterrupted electricity supply and sustain the functionality of critical infrastructure and essential services. This paper presents a comprehensive evaluation of the resilience of the Northern Regional Transmission Grid of India for the year 2022. The study assesses the grid's ability to withstand and recover from various challenges, including extreme weather events, equipment failures, overloading. The evaluation of northern grid resilience involves the analysis of multiple factors, including frequency of outages, response time to disruptions, impact of outages and voltage control through reactor operations and AC line opening. To conduct the assessment, historical outage records, and other related data have been utilized. The study underscores the importance of investing in robust grid infrastructure, network upgrades, proactive maintenance practices, and modernization initiatives, advanced technologies to strengthen the resilience of power grids and ensure uninterrupted transfer of power.**

Index Terms- **Interconnecting Transformer (ICT), Planned Outage, Emergency Shutdown (ESD), Tripping, Extra High Voltage AC (EHV AC) Transmission Line, High Voltage DC Transmission Line, Outage Frequency, Outage Duration, Regional Load Despatch Centre.**

I. Introduction

The reliable and efficient transmission of electricity is essential for the well-being of modern societies. Transmission lines and transformers are critical components of the power system, and their outages can have a significant impact on the reliability and stability of the grid. Therefore, it is essential to monitor and analyze the outages to identify their causes and develop strategies to minimize their occurrence.

This paper presents a comprehensive analysis of the outages of 1300 Extra High Voltage (EHV) AC transmission lines, 12 High Voltage Direct Current (HVDC) transmission lines and 645 Interconnecting Transformers (ICTs) at different voltage levels, occurred in Northern Regional Electricity Grid of India during the year 2022. The research also underscores the need for improvement in the area of maintenance of transmission system and to enhance the resilience of the grid. The data for this paper has been collected from the web portal developed in which the details of outages are being entered by various power transmission & generation utilities and State Load Despatch Centres on daily basis. This paper can serve as a useful resource for power system fraternity working towards a more reliable and resilient grid.

II. Indian transmission system

Indian transmission system consists of a vast network of 4,72,345 circuit km high-voltage transmission lines typically 800 kV, 765 kV, 500 kV, 400 kV, 220 kV etc that carry electricity over long distances. Present status of Voltage level wise transmission line length (in circuit KM) is shown in Table I [1]. The transmission grid of India is demarcated in five electrical regions and it is synchronously connected that enables the transfer of electricity between different regions. Regional Load Despatch Centres (RLDC) are established to ensure the integrated operation of the power system in each region.

TABLE I
Voltage level wise circuit KM in Indian Transmission System

Voltage	Ckt KM
800 kV HVDC	9655
500 kV HVDC	9432
320 kV HVDC	288
765 kV	52678
400 kV	197893
220 kV	202399
Total	**472345**

The transmission of power in the northern region of India presents unique challenges due to its diverse terrain and geographical features. The rugged and mountainous terrain particularly in the Himalayan regions, dense forests, and desert storms in West Rajasthan area poses significant hurdles for the installation and maintenance of transmission infrastructure. The unpredictable weather patterns, including heavy snowfall and landslides in hilly areas, further complicate the transmission of power. Also, the diversity of the northern region necessitates the transfer of power from renewable energy sources which are located in West Rajasthan to the load centers located in other parts of country. Transmitting the intermittent and distributed power generated from these sources requires effective grid management and robust transmission infrastructure.

A. Outage analysis of Transmission Elements in Northern Region

To enhance the grid resilience and maintenance of transmission system, analysis of outages of EHV-AC & HVDC transmission lines and inter-connecting transformers that occurred in Northern region in the year 2022 is done. As per the Indian Electricity Grid Code, system operator at regional level monitors the operation of inter-state transmission lines with an operating voltage of 132 kV & above, ICTs and other transmission system elements such as STATCOM/SVC/Reactor/Bus etc and the record keeping of operational data is being done through a web based portal i.e. Operation Management System.

Central Electricity Regulatory Commission (Standards of Performance of inter-State transmission licensees) Regulations, 2012 lists the following transmission elements [2] :
1. AC Transmission Line ≥ 132 kV
2. Inter Connecting Transformers
3. Reactors
4. Static VAR Compensators
5. Series Compensators
6. HVDC (Back-to-Back Stations and bi-pole links)

Outage Coordination is one of the important aspect for operational planning and reliable operation of the grid. System operators based on system conditions are coordinating the approval of planned as well as emergency outages in the transmission network in real time. Table-II shows the annual outage frequency and average duration of outage by element type for which performance analysis is done [3].

TABLE II
Element wise comparative outage frequency and duration

Element	Outage Frequency (Nos.)	Average Outage Duration (HH:MM)	Availability in %
AC lines	7	155:48	98.2%
ICTs	3	78:17	99.1%
HVDC Lines	7	457:58	94.8%
HVDC Poles	6	669:50	92.4%

All transmission assets at 400 kV and above, 132 kV and above level emanating from Inter-State Generating Stations, 132 kV and above which are inter-regional in nature and 132 kV level with one end in a State while other end in another State are treated as RLDC oversight transmission assets. Outages in the transmission network could be either planned or unplanned in nature. Unplanned Outages are divided in two category namely Emergency Shutdowns (ESD) and Forced Outage i.e. Tripping. The analysis comprises all types of outages reported by utilities and recorded in the system. Thus, availability considered for commercial purpose could be different as some of the outages are excluded such as tower collapse, failure of ICT/Reactor etc [2]. Table-III presents holistic view of AC & HVDC line outages occurred during the year 2022.

TABLE-III
Transmission line outage statistics

AC & HVDC Lines Outage	Nos.	Duration (HH:MM)
Planned Outage	4552	101402:55
Emergency Shutdown	1629	46793:16
Tripping	3358	59848:20
Total	**9539**	**208044:31**
Average Outage per line	**7**	**158:34**
Overall Availability (in %)	**98.19%**	

Planned Outage activities includes preventive/routine maintenance and shutdown for safety purpose due to construction of Highways, Railway tracks and crossing of other EHV Lines. Out of total 4552 number of planned outages, nearly 44% (1986 nos.) of outages were availed for quarterly, half yearly, yearly and routine/preventive maintenance activities as shown in Fig. 1.

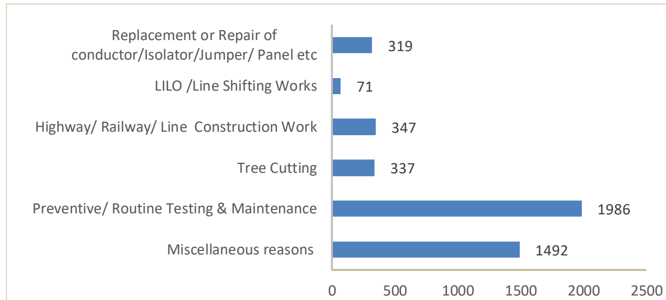

Fig. 1. Major reasons of planned outages of lines

Emergency Shutdowns are mainly availed to attend any exigency observed in real time such as sparking/hotspot on isolator/ clamps etc, snapping of jumper / earth wire, damaged insulator replacement, physical regulation for load relief and to control overloading of line, reduction of fault level, gas/oil leakage in Circuit breakers, Current Transformer etc. Thermal imaging is done to detect hot spots on transmission lines and sub-station equipments, and appropriate corrective actions are taken by availing planned or emergency shutdowns. Out of total 1629 number of emergency shutdown, about 32% (514 nos.) were availed to attend hot spot observed in any element as shown in Fig. 2.

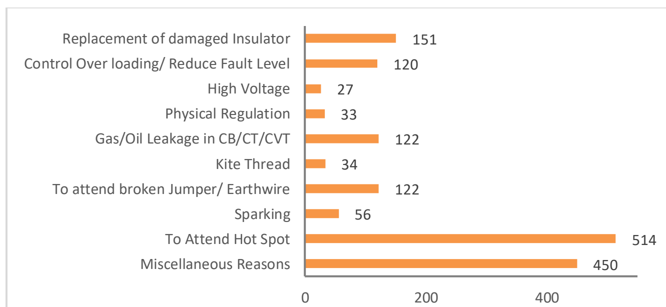

Fig. 2. Major reasons of emergency shutdown for lines

Sustained tripping of transmission lines occurs mainly due to single line to ground (L-G) fault, Line to Line (L-L) fault, bus bar protection, over current, over voltage etc. Around 60% of sustained trippings are due to single line to ground fault as shown in Fig. 3.

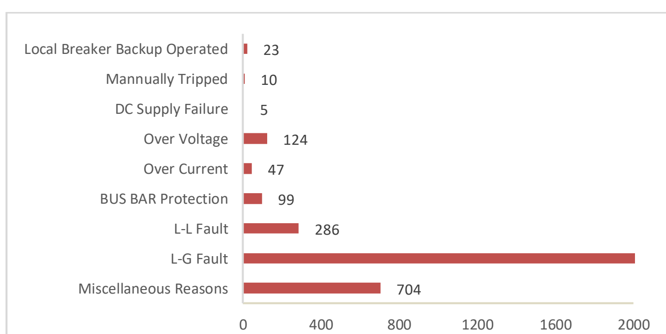

Fig. 3. Major reasons of trippings of lines

Fig. 4. shows the annual average tripping number and duration during the year 2022 at different voltage levels in terms of number and duration. It can be seen that the highest annual average number of tripping per line is for 500 kV lines (4 per line). The annual average outage duration per line is highest for 220 kV (58:30 Hrs) mainly due to tower collapse. Also, average duration of each tripping (Total duration divided by total number of trippings) is lowest at 800 kV i.e. only 1:58 Hrs per tripping.

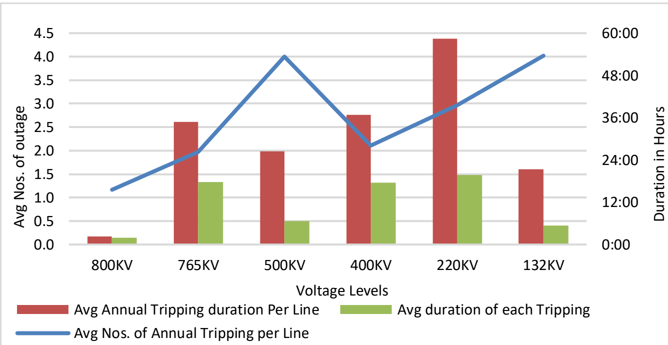

Fig. 4. Average Tripping Outages for different Voltage levels

The challenge is to achieve the fastest possible restoration of the lines following a tripping event. By examining Figure 5, it becomes evident that approximately 54% of line trippings were restored within a time span of less than 3 hours, whereas 31% of the trippings required a restoration time of 3 to 12 hours.

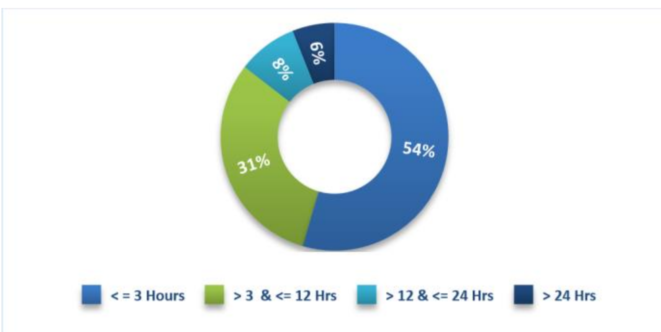

Fig. 5. Tripping Restoration Time Index

B. *Outage Analysis based on different terrain*

Power transmission in North India faces unique challenges due to the diverse terrains present in the region, including deserts and hills. In desert terrains, sand and dust accumulation on transmission lines causes insulation issues, while extreme temperatures and sandstorms pose additional risks. In hilly areas, difficult access, landslides, and unstable tower foundations present obstacles to maintenance and infrastructure stability.

TABLE IV
Terrain wise outage statistics

Terrain	Nos. of Lines	Average Outage (Planned, ESD& Tripping)		Average Tripping	
		Frequency (Nos.)	Duration (HH:MM)	Frequency (Nos.)	Duration (HH:MM)
Plain	1027	6.7	153:15	2.5	42:08
Desert	78	13.7	221:32	2.6	38:15
Hill	207	7.8	190:48	2.9	95:13
Total	**1312**	**7.3**	**163:14**	**2.6**	**50:17**

The highest numbers of lines are located in plain terrain whereas few lines are located in desert and hill terrain. The outage frequency of transmission lines located in desert terrain is on higher side due to accumulation of sand and dust on transmission lines, insulators, and conductors. Deserts often experience extreme temperature variations, including scorching heat during the day and significant drops in temperature at night. These temperature fluctuations can affect the thermal expansion and contraction of transmission line components, potentially leading to structural integrity issues. Also, desert regions are prone to sandstorms, which results in damage to the infrastructure such as collapsing of towers, further poses challenge in restoring the system on time. The same is also reflecting from the data presented in Table-IV.

The average duration of power outages caused by tripping of transmission lines in hilly areas is relatively high. Difficult access and rugged terrain in hilly regions make it difficult to access transmission line corridors for maintenance, repair, and construction activities. Landslides and soil erosion, especially during heavy rainfall causes disruption of transmission line infrastructure resulting in interruption in power supply.

Regular maintenance and effective monitoring systems is required to minimize the outage frequency & duration and to ensure reliable power transmission in these challenging environments.

C. *Seasonal Performance Assessment of Transmission Lines*

The northern region witnesses a higher incidence of outages due to Forced majeure i.e. Emergency shutdowns and Tripping during the monsoon and summer season (as derived from Fig. 6.), as the loading on transmission system remains high coupled with the high ambient temperature. Emergency shutdowns are mostly availed by the transmission utilities to attend the severe situations like Hot Spot and to control the loading of elements etc. The combination of torrential rains, gusty winds, and lightning increases the likelihood of faults and disruptions along the transmission lines.

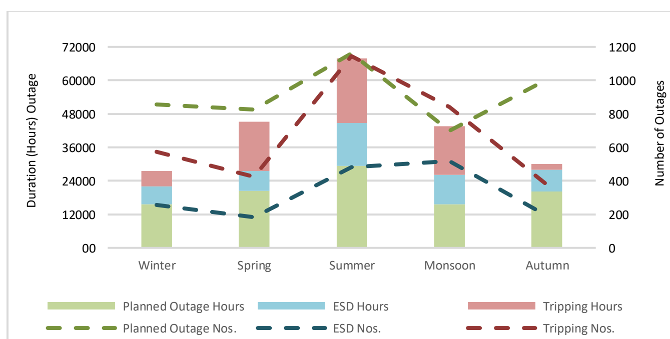

Fig. 6. Number and Duration of line outages in different seasons

Planned Outages during summer season have been taken for activities such as conductor augmentation, LILO work, substation automation, shifting of towers etc. Since it is difficult to carry out the maintenance activities in rainy season, the least number of planned outages are evident in monsoon season. During the winter season, dense fog and air pollutants compromises the insulation properties of the equipment leading to flashovers, breakdowns, leakage paths thus increasing the risk of tripping. These Trippings have been reduced to a significant number during the past few years due various measures taken such as replacement of porcelain insulators with polymer insulators, cleaning & washing of insulators etc [4]. Maintenance tasks are conducted prior to the arrival of winter to reduce the occurrence of tripping in foggy and polluted conditions. From Fig. 6, it can be inferred that the occurrence and duration of tripping during the autumn season are minimal which is mainly due to less demand at that time.

D. Analysis of Transmission Line Outages in Renewable Energy Zone

As India is witnessing towards clean and sustainable environment, Government has set an ambitious target of 500 GW renewables by 2030. As on 31.05.2023, 176 GW renewable energy sources (including large hydro) have been installed in the country [5]. With the rapid integration of more and more renewables, the expansion of transmission network also needs to be done at faster pace so that power could be transferred to the other places. As depicted in Table-V, total ~24 GW Wind and Solar based Renewable Energy Generating Stations have been commissioned in Northern Region.

TABLE V
Installed capacity of renewables in Northern region

Source	NR Installed Capacity (MW)		
	Inter-State Network	Intra-State Network	Total
Wind	866	4313	5179
Solar	12298.5	7062	19360.5
Total	**13164.5**	**11375**	**24539.5**

Any cascaded tripping in RE Zone may lead to loss of RE generation at large scale and also impacts the grid frequency. During 2022, tripping of 220 kV line led to tripping of multiple 220 kV, 400 kV and 765 kV lines, resulting in to generation loss of 5 GW and reduction of frequency from 50.16 Hz to 49.63 Hz within a minute. These high impact, low probability events may cause grid disturbance. Also, the outage of EHV lines in RE complex due to tower collapse poses evacuation constraints resulting into curtailment of RE generation. To overcome these situations, RLDC provides feedback to transmission utilities & planners to review the tower design in high wind zones and planning of single circuit lines in place of double circuit lines in critical/high loading corridors. It can be observed from Table-VI that the annual availability of transmission lines present in northern region RE zone was more than 97% during 2022.

TABLE VI
Annual availability of transmission lines in RE Zone

Voltage level	Annual Availability in Terms of %
220kV	98.72%
400kV	95.12%
765kV	98.41%
Overall	**97.47%**

It can be inferred from Table-VII that planned outage of transmission lines in RE zone are scheduled during non-solar hours. This facilitates seamless power evacuation through solar power plants as any outage during the solar generation hours can lead to degradation in transfer capability and results in curtailment of must-run solar power i.e. wastage of natural resources.

TABLE VII
Time slot wise planned outages of AC lines in RE zone

Voltage	Nos. of AC Lines in RE Zone	Total Planned Outage		Time Slot (6 Hrs) in which the Lines were Taken under Outage			
				00:00 Hrs to 06:00 Hrs	06:00 Hrs to 12:00 Hrs	12:00 Hrs to 18:00 Hrs	18:00 Hrs to 24:00 Hrs
		Nos.	Duration	Nos.	Nos.	Nos.	Nos.
765 kV	13	153	959:46	0	0	145	8
400 kV	26	115	941:34	0	10	40	65
220 kV	39	418	3461:33	8	3	5	402
	78	**686**	**5362:53**	**8**	**13**	**190**	**475**

The potential range of the Great Indian Bustard (GIB) encompasses a vast geographic area, and the key conservation areas for GIB in western Rajasthan coincide with primary renewable energy hubs of the country. Therefore, in RE pocket most of the planned outages are scheduled for installation of bird diverter as depicted in Fig. 7.

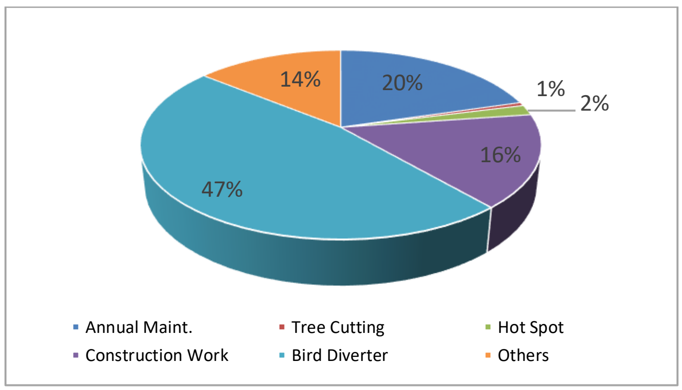

Fig. 7. Major reasons of planned outages in RE Zone

Ministry of New and Renewable Energy (MNRE) has identified 75 GW potential RE Zone in Northern Region in the state of Rajasthan, comprising of 15 GW Wind and 60 GW Solar potential [6]. Out of total identified RE potential zones of 75 GW, 45 GW RE potential zones (30 GW Solar & 15 GW Wind) lie in the GIB area in Barmer, Jaisalmer & Jodhpur Districts of Rajasthan.

E. Voltage Control through Reactors and Transmission lines

The transmission system is planned to cater the demand round the clock. A significant portion of the transmission network experiences light load conditions during off-peak or low demand period, resulting in increased net reactive power (VAr) in grid and hence exceeding the steady sate voltage above the specified limits.

The global power systems are still grappling with the complexities of reactive power management. The northern grid encounters elevated voltages during certain seasons, particularly in winter and during periods of low demand. For almost 10-20% of the time, voltages are on higher side prominently at 400 kV and above. The shunt reactors are mainly used to compensate for the effects of line capacitance, particularly to limit voltage rise on lightly loaded system. They are usually required for EHV overhead lines longer than 200 km. The shunt reactors are normally connected to the line to limit the fundamental frequency temporary over voltage and these line reactors also serve to limit the energization over voltage (switching transients). Apart from this, additional shunt reactors (i.e. Bus Reactors) are also connected with EHV bus to maintain normal voltage under low-load conditions [7].

To control the voltage in specified limits, more than 500 Reactors are installed at various locations in Northern Region. As per the reactor operation statistics shown in Table-VIII, around 220 numbers of reactors were taken out of service for 11226 times due to low voltage conditions. The average annual service outage duration of each reactor is calculated as 1065 Hours and on an average, for around 12% of time reactors have been kept out of service. Sometimes the line reactors are also used as Bus reactor by opening of line to control the persistent high voltage observed at the substation. Nearly 40 numbers of reactors were operated for more than 100 times during the year.

TABLE VIII
Reactor operation statistics

Reactor Type	Voltage Level (KV)	Total Nos. of Reactors	Reactors on which Switching Operations done	Incidents when Reactors taken out of service due to low voltage		Annual Average Reactor Outage Duration	
				Nos.	Hours	Hours	in %
		A	B	C	D	E=D/A	
Bus Reactor	**765**	53	38	2763	65572	1237	14%
	400	220	150	7861	461462	2097	24%
	220	11	4	73	13133	1193	14%
Line Reactor	**765**	87	18	512	5198	59	1%
	400	161	10	17	21512	133	2%
Total		**532**	**220**	**11226**	**566880**	**1065**	**12%**

In the event of persistent high voltage conditions when all other reactive control measures gets exhausted, the lightly loaded EHV AC lines having parallel transmission system are opened for voltage control measures [8]. In 2022, more than 7000 times the EHVAC lines were opened on account of over voltage. It is also evident from the Fig. 8 that 5360 times (73%) the operation was carried out during night hours (20:00 Hrs – 04:00 Hrs).

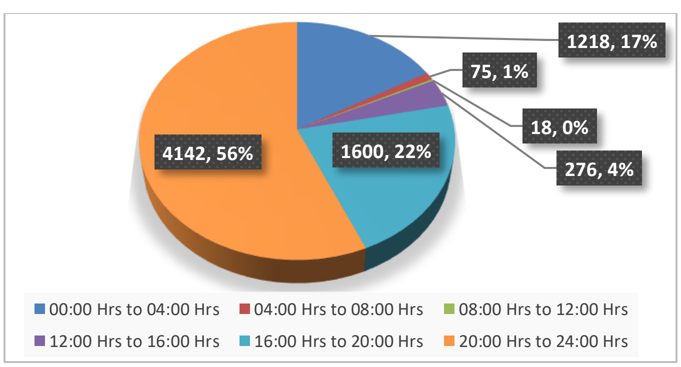

Fig. 8. Time slot wise number of times AC lines opened

F. ICT Outages in Northern Region

The importance of reliability of ICTs in a transmission system cannot be overstated and it is crucial to ensure minimum breakdowns and analyse the disruptions that can result in reduction in power transfer capability of system. Performance of Inter-connecting transformers of different voltage ratio & MVA rating has been evaluated in this section [9]. The category wise details of ICT outages are summarized below in Table-IX.

TABLE IX
Inter-connecting Transformer outage statistics

ICT Outage	Nos.	Duration (HH:MM)
Planned Outage	1000	16436:12
Emergency Shutdown	439	8223:20
Tripping	456	25840:34
Total	**1895**	**50500:06**
Average Outage per ICT	**2.9**	**78:17**
Overall Availability (in %)	**99.11%**	

Regular maintenance, testing, and monitoring of transformers are essential to identify and address potential issues proactively, ensuring their continuous and reliable operation. Implementing robust maintenance practices is vital to maintain the reliability of the transmission system and ensure the smooth functioning of the overall electrical infrastructure, which is also evident from Fig. 9(a).

There are also some incidents, which are beyond the control of transmission substation operator. In such emergency cases the shutdown of ICTs are availed in real time and the rectification is done. Some of the common issues are observance of hot spot in isolator/bushing/clamps, over fluxing, oil leakage, sparking etc as shown in Fig. 9(b).

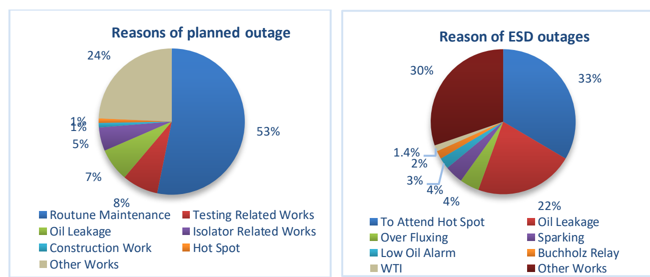

Fig. 9. Major reasons of (a) planned outage and (b) ESD of ICTs

Apart from shutdowns i.e. planned or emergency, there are many occasions when ICTs get tripped due to operation of protection relays such as Buchholz, Differential, Master (86A/86B) trip, Over Flux, Over Voltage, Over Current, Earth Fault etc. as shown in Fig. 10(a). Around 36% of total trippings were due to miscellaneous reasons such as Oil surge relay, Winding/Oil temperature indicator, Failure of CT/CVT/CB etc.

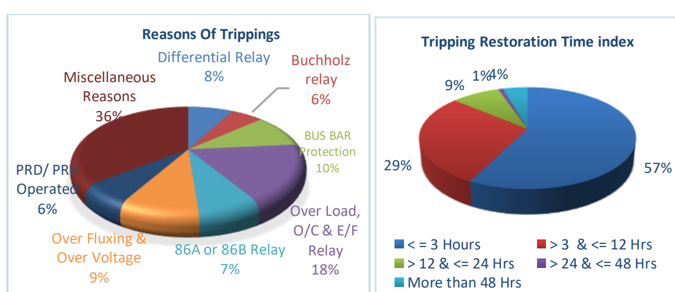

Fig. 10. (a) ICT tripping reasons and (b) Restoration time index

The challenge in such tripping is to revive the ICTs in shortest time as possible. It is evident from the Fig. 10(b) that around 57% of tripping of ICTs were restored in less than 3 Hours' time while 29% tripping took 3 to 12 hours of time in restoration. As evident from Fig. 11, ESD and Tripping events are on higher side during the Summer & Monsoon seasons. Also, in terms of duration, the tripping that occurred during monsoon & summer season took longer time in restoration due to the challenges possessed by heavy rainfall, floods particularly in hilly terrain.

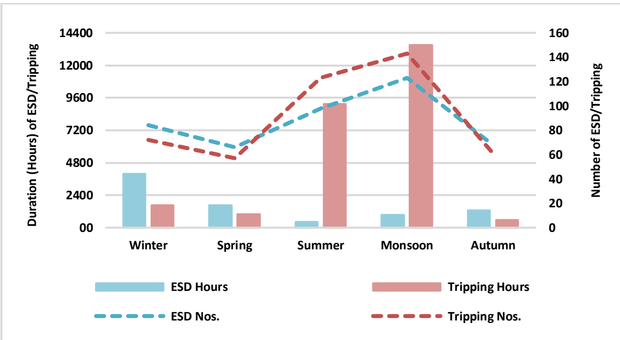

Fig. 11. Season wise statistics of unplanned ICT outages

III. Summary and Way forward

The performance evaluation has been carried out by analysing around 18000 incidents (planned/unplanned outages) of transmission lines and interconnecting transformers reported in Operation Management System of NRLDC. The analysis reflects that annual availability of Northern Grid Elements is ~98-99%, which is quite above the grid performance standards mandated by the regulator. The study also emphasizes the significance of formulating contingency & maintenance strategies aimed at reducing the repercussions of power outages on vital infrastructure and essential services. Any cascaded tripping on EHV lines may jeopardize the security and reliability of the grid. Hence, transmission utilities have to remain vigilant and take proactive measures to minimize the unplanned outages. Regular maintenance, inspection, and strengthening of infrastructure are crucial to ensure the reliability and stability of the transmission network. Additionally, the implementation of robust monitoring systems and emergency response protocols becomes essential to swiftly identify and rectify faults, ensuring a reliable power supply even in the midst of challenging monsoon conditions.

Keeping these factors in mind, the transmission utilities in India are proactively taking all the suitable measures for improvement of reliability and resiliency of grid. These measures includes GIS mapping of transmission assets, Helicopter equipped with Gimbal mounted Thermo-vision Camera & Corona Camera for Aerial patrolling of lines, advanced condition monitoring techniques viz. Frequency Response Analysis (FRA) and Frequency Domain Spectroscopy (FDS) for transformers, App Based Ground Patrolling of transmission lines, Asset health indexing, adoption of hot/live line maintenance techniques.

Central Electricity Authority (Grid Standards) regulation, 2010 mandates the availability of Emergency Restoration System (ERS) for transmission utilities in order to minimise the outage duration in case of tower collapse [10]. Therefore, most of the transmission utilities have adequate numbers of ERS in their inventory to utilize the same at the time of need.

Furthermore, India is planning to have a modern, smart and Future-ready Transmission system with more technological and digital solutions, which will allow large-scale integration of renewable sources, prudent utilization of available transmission system, reduction in forced outages through self-correcting systems etc. and resilience against cyber-attacks and natural disasters. The Artificial Intelligence & Machine Learning techniques and Robots & Drones shall be used for predictive maintenance and construction & inspection of transmission assets respectively [11]. In view of energy transition and increasing penetration of renewables, building a robust and modern transmission network is need of the hour.

IV. Acknowledgment

The authors gratefully acknowledge the support and guidance provided by the management of Grid-India. The views presented in this paper are solely those of the authors and do not reflect the perspectives of the organization.

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