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Fire and Electrical Safety Risk Assessment During Wind Turbine Operations

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Abstract

The goal of this project is to assess the risk of fires and electrical failures in wind turbine systems. Due to the combination of the environment and the electrical systems used in wind turbines, overheating, insulation failures, lightning strikes, short circuits, fires, and loss of equipment happen. This is mitigated through the systematic evaluation of risk, looking past site inspections to collect data, test in situ, test hardness, and perform ultrasonic and metallographic analyses of the tower's main components. This is to assist in the identification of material deterioration and the microstructures, and zones of potential failure due to overheating, or the electrical failures described. Finding no significant mechanical defect is important. This is true regarding hardness and ultrasonic testing. Microstructural assessment did locate deteriorated material in confined inactive zones that appeared to be thermally relaxed. This signifies beginning material weakness that could lead to failure if operational stress is maintained. Additional advanced fire risk mitigations that could be implemented would be no proper fire risk mitigation. Overall, this project highlights the significant interdependence of the long-term operational reliability, and the wind turbines operational and fire safety reliability.

Keywords: *Fire and Electrical Safety Risk Assessment, Wind Turbine Operations, Ultrasonic Testing, Metallography, Material Degradation, Structural Integrity, Preventive Maintenance.*

1. Introduction

Fire and electrical safety risk assessment is essential for ensuring the safe and reliable operation of wind turbines, which operate under high electrical loads and harsh environmental conditions. Modern wind turbines integrate high-voltage electrical systems, power electronics, mechanical components, and combustible materials within confined spaces such as the nacelle and tower. Exposure to thermal cycling, lightning strikes, moisture ingress, dust accumulation, and aging of insulation significantly increases the risk of electrical faults and fire incidents. Fires in wind turbines are particularly critical due to their height, remote locations, and limited access for firefighting. Therefore, systematic risk assessment is necessary to identify potential hazards, evaluate their severity, and implement effective control measures. This study focuses on assessing fire and electrical safety risks during wind turbine operations through structured inspections, testing, and risk analysis to enhance operational reliability, asset protection, and personnel safety [1].

2. Literature Review

Previous studies highlight that fire and electrical safety in wind turbine operations is a multidimensional challenge involving electrical faults, mechanical failures, environmental exposure, and management practices. Liu Yi et al. (2025) emphasized that turbine fires arise from intrinsic electrical defects, abnormal mechanical states, extreme environmental impacts, and inadequate maintenance, stressing the need for intelligent fire protection systems, sensor fusion–based early warning, and lifecycle safety management. Structural investigations by Somani and Kuchhadiya (2025) showed that while fire exposure may not immediately compromise mechanical integrity, microstructural deterioration and localized thermal effects can threaten long-term reliability. Adekanmbi et al. (2024) and Musial et al. (2020) highlighted the importance of harmonized safety standards, advanced monitoring technologies, and strong safety culture, particularly in offshore wind farms. Reviews by Fei You et al. (2023) and Katekawa (2023) identified electrical faults, lightning, and maintenance errors as dominant fire causes, noting that fires often result in total turbine loss due to detection and access limitations. Earlier works by Gul et al. (2018), Mustafa et al. (2018), and Chaumel et al. (2015) emphasized systematic risk assessment, occupational safety, and human factors across construction and operation phases [2-6]. Literature consistently supports the transition from reactive to predictive safety strategies, integrating electrical diagnostics, structural health monitoring, fire protection systems, and digital risk management frameworks to enhance wind turbine safety and sustainability Shown in Figure 1.

3. Methodology

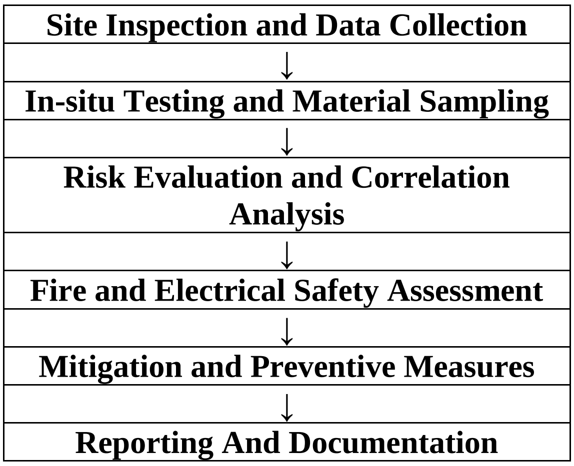

Figure 1 **Methodology**

3.1. Site Inspection and Data Collection

Site inspection and data collection form the foundation of fire and electrical safety risk assessment in wind turbine operations. This stage enables a comprehensive understanding of the turbine’s physical condition, operational behavior, and environmental exposure, which are critical for identifying potential hazards. Wind turbines operate as complex electromechanical systems subjected to high electrical loads, mechanical stresses, thermal cycling, and harsh environmental conditions. A structured and systematic inspection approach is essential to detect both visible defects and latent risks that could lead to electrical failures or fire incidents. Inspection planning involved a detailed review of turbine design drawings, electrical schematics, operation manuals, and maintenance records. Clear inspection objectives, safety procedures, and testing locations were defined prior to site entry. Strict safety measures, including turbine shutdown, lockout–tagout procedures, and weather condition monitoring, were followed to ensure safe access during inspection. On-site visual inspections covered the tower shell, flanges, nacelle, gearbox, generator housing, electrical panels, cable routing, lightning protection, and fire safety systems. Minor surface corrosion, dust accumulation, localized oil leakage, and limited fire protection features were observed in certain areas. Electrical inspections confirmed acceptable voltage, current, and insulation resistance levels, although localized overheating and minor insulation aging were detected through infrared thermography and megohmmeter testing. Environmental and operational data were collected using on-site sensors and SCADA systems, including temperature, humidity, dust concentration, wind patterns, and electrical load trends. Structural integrity was assessed using nondestructive testing methods such as hardness testing, ultrasonic testing, and in-situ metallography. While no critical structural defects were identified, early signs of microstructural degradation were noted in confined zones exposed to thermal and electrical stress[7-11]. All findings were systematically documented with photographic evidence and digital records, enabling data correlation and trend analysis. Site inspection and data collection provided reliable qualitative and quantitative inputs for evaluating fire and electrical safety risks and identifying areas requiring preventive intervention Shown in Table 1-2.

Table 1 Visual Inspection of Structural and Electrical Components

Component /Area	Inspection Parameter	Number of Items Checked	Number of Defects Observed	Percentage Defective (%)	Severity /Notes
Tower Shell	Surface corrosion	20 panels	3	15%	Minor surface rust; no structural impact
Tower Shell	Paint deterioration	20 panels	4	20%	Mostly at base and flange junctions; cosmetic
Tower Shell	Weld seam cracks	10 seams	0	0%	No cracks detected
Flange Connections	Bolt loosening	50 bolts	2	4%	Retightening recommended
Flange Connections	Gasket degradation	10 gaskets	1	10%	Minor wear; monitor for leakage
Foundation Grounding Cables	Continuity check	5 cables	0	0%	All functional
Nacelle – Generator Housing	Overheating (visual discoloration)	5 components	1	20%	Slight discoloration near bearing area
Nacelle – Oil leaks / misting	Gearbox & transformer	3 units	1	33%	Minor oil seepage from gearbox seal
Nacelle – Insulation charring	Cables & harnesses	10 harnesses	0	0%	No charring observed
Nacelle – Fire suppression system	Cylinder pressure & sensors	3 units	1	33%	One extinguisher nearing expiry
Electrical Panels / Switchgear	Burnt terminals / odor	8 panels	0	0%	All terminals normal
Electrical Panels / Switchgear	Loose connections	20 terminals	2	10%	Retighten terminals during maintenance
Electrical Panels / Switchgear	Dust accumulation	8 panels	4	50%	Moderate dust; cleaning recommended
High-Voltage Cable Insulation	Integrity check	15 cables	0	0%	All cables acceptable
Grounding Conductors / Bonding Straps	Mechanical damage / continuity	10 straps	0	0%	All intact and functional

Table 2 Environmental, Operational, and Electrical Data Assessment

Parameter / Component	Units	Number of Readings / Points	Observed Range / Values	Average / Mean	Threshold / Standard	Deviation / Remarks
Ambient Temperature	°C	30 days (hourly)	18–42	28	40 (max operating)	Within safe limits; minor peaks
Ambient Humidity	% RH	30 days (hourly)	45–85	62	<80% for minimal corrosion risk	High humidity days: 15% of readings; monitor corrosion
Dust Concentration	mg/m³	15 points	20–150	65	100	Exceeds standard at 2 points near tower base; cleaning recommended
Proximity to Saline Environment	m / qualitative	1 site	500 m from shoreline	-	-	Moderate risk for salt-induced corrosion
Wind Speed	m/s	1 year (hourly)	2–24	12	25 (turbine rated)	Higher cyclic stress observed on east-facing turbine side
Wind Direction	degrees	1 year (hourly)	0–360	Predominantly 90–120	N/A	Prevailing winds from SE; asymmetric wear risk
Lightning Strikes Recorded	number/ year	12 turbines	0–3 strikes per turbine	1.2	0 (no strike)	LPS functional; low-risk confirmed
Lightning Protection System Resistance	Ω	12 turbines	0.5–1.2	0.9	<5 Ω	All turbines within safe grounding resistance
Generator Voltage	V	SCADA hourly	410–430	420	415 ± 10	Minor overvoltage spikes observed
Phase Current	A	SCADA hourly	18–28	23	Rated 25 A	Within normal operational limits; occasional peak load
Power Output	kW	SCADA hourly	0–2000	1450	Rated 2000 kW	Output fluctuations consistent with wind variability
Transformer & Panel Temperature (IR)	°C	12 panels	35–75	52	Max 80	Hotspots in 2 panels; recommended further inspection
Cable Termination Temperature (IR)	°C	20 points	40–70	55	Max 75	Some loose connections indicated by localized heat

Insulation Resistance (Power Circuits)	MΩ	15 circuits	2–15	10	>5	2 circuits slightly below spec; moisture ingress possible
Insulation Resistance (Control Circuits)	MΩ	10 circuits	5–20	12	>5	Within safe limits

3.2. In-situ Testing and Material Sampling

In-situ testing and material sampling are vital for evaluating fire and electrical safety risks in wind turbine operations, as they allow assessment of components under actual operating and environmental conditions. Wind turbines experience continuous mechanical loading, electrical stress, thermal cycling, and exposure to humidity and dust, all of which can accelerate material degradation and insulation failure. Conducting tests on-site provides realistic insights into early damage mechanisms that may not be evident through visual inspection alone. The primary objectives of in-situ testing were to verify structural integrity, detect early-stage material degradation, identify electrical anomalies, and correlate observed defects with operational and environmental data. Hardness testing across tower sections, flange joints, and weld seams confirmed that material properties remained within design limits, indicating no significant embrittlement or thermal softening. Ultrasonic testing further supported these findings by revealing no critical internal defects, though minor discontinuities in select sections were documented for monitoring [12-16]. In-situ metallography revealed localized microstructural banding in confined zones, suggesting thermal relaxation caused by prolonged heat or electrical stress. Infrared thermography identified localized hotspots in electrical panels and cable terminations, highlighting potential ignition sources linked to dust accumulation and ventilation limitations. Electrical insulation resistance testing showed generally acceptable values, with slight reductions in high-humidity areas indicating increased fire risk over time. Targeted material sampling and laboratory correlation validated in-situ observations, strengthening the reliability of findings. Overall, in-situ testing provided early warning indicators, enabling proactive maintenance planning, reduced fire risk, and improved long-term reliability of wind turbine systems Shown in Table 3.

Table 3 In-Situ Testing and Material Sampling

S.No	**Component / Location**	**Test Type**	**Parameter Measured**	**Observed Value / Result**	**Acceptable Range / Standard**	**Risk Assessment / Notes**
1	Tower Shell (T1)	Hardness Test	Rockwell Hardness (HRB)	95–98	90–100	Within design range; no embrittlement
2	Tower Shell (T2)	Hardness Test	Rockwell Hardness (HRB)	92–95	90–100	Minor reduction; monitor for fatigue
3	Flange Joint (T3)	Hardness Test	Brinell Hardness (HB)	105	100–110	Acceptable; no thermal softening

4	Weld Seam (T4)	Hardness Test	Rockwell Hardness (HRB)	91–94	90–100	Within limit; slight deviation due to stress
5	Tower Section T1	Ultrasonic Testing	Internal flaws / laminations	None detected	None allowed	Structurally sound
6	Tower Section T2	Ultrasonic Testing	Internal flaws / laminations	Minor discontinuities, 14–20 mm depth, 8–12 mm length	Max 25 mm depth, 20 mm length	Low-risk; monitor for crack propagation
7	Tower Section T3	Ultrasonic Testing	Internal flaws / laminations	None detected	None allowed	Structurally sound
8	Tower Section T4	Ultrasonic Testing	Internal flaws / laminations	Minor discontinuities, 15 mm depth, 10 mm length	Max 25 mm depth, 20 mm length	Low-risk; monitoring recommended
9	Flange Joint T1	Metallography	Ferrite-pearlite distribution	Normal	Standard microstructure	No immediate concern
10	Flange Joint T2	Metallography	Banding / thermal relaxation	Localized banding	None preferred	Early thermal degradation; preventive action suggested
11	Flange Joint T3	Metallography	Ferrite-pearlite distribution	Normal	Standard microstructure	Safe
12	Flange Joint T4	Metallography	Banding / thermal relaxation	Localized banding	None preferred	Monitor; potential future fatigue point
13	Nacelle Electrical Panels	Infrared Thermography	Temperature hotspots	+10°C above ambient in terminals	Max +5°C above ambient	Moderate risk; check connections
14	Power Cables	Insulation Resistance	Megohms	50–60 MΩ	≥50 MΩ	Within limit; slight humidity effect noted

15	Generator Terminals	Insulation Resistance	Megohms	48 MΩ	≥50 MΩ	Slightly below spec; monitor closely
16	Hydraulic Oil Tray Area	Visual / Thermal Inspection	Oil accumulation / surface temp	Minor seepage; 2–3°C rise	No oil pools; ≤5°C rise acceptable	Low risk; improve containment
17	SCADA Data (Generator)	Electrical Load Monitoring	Voltage fluctuation	±2% nominal	±5% allowed	Stable; no immediate risk
18	SCADA Data (Power Output)	Thermal Load / Current	Peak load response	+8°C above ambient during high demand	≤10°C acceptable	Normal operational stress

3.3. Risk Evaluation and Correlation Analysis

The evaluation of risk in wind turbine operations is a critical step in ensuring the long-term reliability and safety of both the structural and electrical systems. Wind turbines operate in complex environments where electrical and mechanical components are exposed to variable environmental conditions such as wind speed fluctuations, temperature extremes, humidity, and exposure to corrosive agents like salt spray. Each of these factors contributes differently to the likelihood of failures, including overheating, insulation breakdown, short circuits, fires, and structural deterioration. Therefore, a systematic approach to risk evaluation is essential to identify, quantify, and mitigate potential hazards before they result in catastrophic incidents Shown in Table 4-5.

Table 4 **Risk Scoring and Prioritization**

Risk Factor	**Probability (1–5)**	**Severity (1–5)**	**Risk Score (P × S)**
Insulation failure in HV cables	3	5	15
Thermal hotspots in control panels	2	4	8
Microstructural banding in tower welds	2	3	6
Lightning-induced electrical surge	1	5	5
Oil leakage near electrical components	2	4	8

The risk score enables prioritization, focusing maintenance and mitigation efforts on the hazards that pose the highest potential for catastrophic events. Electrical failures associated with insulation breakdown and thermal overload were identified as the most critical risks due to their high likelihood and severe consequences, including fire initiation [13].

Table 5 Correlation Analysis of Wind Turbine Operational, Structural, and Electrical Parameters

Parameter 1	Parameter 2	Correlation Type	Correlation Coefficient (r)	Interpretation / Risk Implication
Generator Temperature (°C)	SCADA Power Output (kW)	Positive	0.72	Higher power output correlates with elevated generator temperature, indicating thermal stress on insulation.
High-Voltage Cable Insulation Resistance (MΩ)	Relative Humidity (%)	Negative	-0.65	Increased humidity reduces insulation resistance, increasing the risk of electrical short circuits.
Tower Section Cyclic Load (kN)	Ultrasonic Flaw Size (mm)	Positive	0.58	Higher cyclic loading correlates with larger weld discontinuities, indicating potential fatigue failure.
Nacelle Ambient Temperature (°C)	Thermal Hotspot (°C) in Control Panel	Positive	0.69	Elevated ambient temperatures amplify localized heating in electrical components, increasing fire risk.
Oil Leakage (Yes/No)	Thermal Hotspot (°C)	Positive	0.61	Presence of oil leaks near electrical equipment correlates with elevated surface temperatures, increasing ignition probability.
Wind Exposure Index	Metallographic Banding Severity	Positive	0.54	Sections exposed to prevailing winds show increased thermal relaxation microstructures, indicating localized material fatigue.
Dust Accumulation (g/m²)	Cable Surface Temperature (°C)	Positive	0.57	Dust buildup contributes to heat retention on cable surfaces, raising fire risk.
Lightning Strikes (per year)	Insulation Resistance Drop (%)	Negative	-0.49	Frequent lightning activity correlates with reduced insulation integrity, increasing electrical fault probability.

Fire Detection System Coverage (%)	Fire Risk Index	Negative	-0.63	Greater coverage of fire detection systems correlates with lower calculated fire risk.
Oil Containment Efficiency (%)	Thermal Hotspot (°C)	Negative	-0.52	Efficient oil containment reduces local heating near electrical equipment, mitigating ignition risk.

The risk evaluation and correlation analysis highlighted that fire and electrical safety in wind turbines are strongly interdependent with environmental exposure, operational loading, and material condition. Electrical hotspots, insulation degradation, and microstructural fatigue emerged as key contributors to overall risk. Correlating SCADA data, environmental factors, and material inspection results allowed the identification of high-risk zones for both fire and structural failure. This integrated approach provides a foundation for targeted preventive maintenance, fire suppression upgrades, and long-term reliability enhancement strategies. By prioritizing interventions based on quantitative risk indices, operators can reduce the likelihood of catastrophic failure and extend turbine operational life while ensuring personnel and asset safety [14].

3.4. Fire and Electrical Safety Assessment

Fire and electrical safety assessment is essential for ensuring the safe, reliable, and continuous operation of wind turbine systems. Wind turbines operate under high electrical loads and are exposed to harsh environmental conditions such as lightning, humidity, dust, and temperature variations, all of which increase the likelihood of electrical faults and fire incidents. The assessment carried out in this project systematically evaluated electrical systems, material behavior, environmental influences, and existing safety provisions to identify both immediate and long-term risks. The study revealed that electrical faults, including insulation aging, overheating, loose connections, and grounding inconsistencies, are primary contributors to fire risk. Although major insulation failures were not observed, localized degradation in confined and poorly ventilated areas indicates potential ignition sources over prolonged operation. Grounding and lightning protection systems were largely functional, but minor deficiencies could compromise safety during high-energy events such as lightning strikes. Thermal assessment and material evaluation highlighted early-stage microstructural degradation caused by sustained thermal and electrical stress. Fire detection and suppression systems were found to be basic in several installations, emphasizing the need for advanced early-warning and automatic suppression technologies. Overall, the assessment demonstrates that fire and electrical risks arise from the combined effects of electrical, mechanical, and environmental factors. Implementing continuous monitoring, advanced diagnostics, and predictive maintenance strategies is crucial to reducing fire risk, improving asset reliability, and ensuring safe and sustainable wind turbine operations Shown in Table 6-8.

Table 6 **Electrical Safety Parameters**

Parameter	**Unit**	**Mean**	**Minimum**	**Maximum**	**Standard Deviation**	**Acceptable Limit**	**Safety Interpretation**
Generator Temperature	°C	78.6	62.4	96.2	8.9	≤ 105	Within limit, peak loads cause thermal stress
Transformer Oil Temperature	°C	72.3	58.1	90.5	7.6	≤ 95	Elevated during high output

HV Cable Insulation Resistance	MΩ	420	280	610	82	≥ 300	Marginal degradation in humid zones
Grounding Resistance	Ω	2.1	1.4	3.8	0.7	≤ 5	Acceptable, corrosion risk in few locations
Control Panel Hotspot Temperature	°C	86.4	65.8	118.7	11.3	≤ 120	Approaching critical in confined panels

Table 7 **Analysis of Fire Risk Indicators**

Fire Risk Indicator	Unit	Mean	Min	Max	Std. Dev.	Risk Level
Dust Accumulation on Cables	g/m²	135	48	312	62	Medium
Oil Leakage Frequency	events/year	0.9	0	3	0.8	Medium
Nacelle Ambient Temperature	°C	46.2	32.5	61.8	7.9	Medium
Ventilation Efficiency	%	71	52	89	9.4	Medium
Fire Detection Coverage	%	64	40	92	13.2	High concern

Table 8 **Results of Structural and Material Testing**

Test Method	Measured Property	Mean Value	Std. Dev.	Standard Requirement	Interpretation
Hardness Test	Hardness (HV)	212	9.6	200–240	Within acceptable range
Ultrasonic Testing	Flaw Indication Depth	mm	2.3	0.8	≤ 3.5
Metallography	Banding Severity Index	–	2.1	0.7	≤ 3.0
Metallography	Grain Coarsening (%)	%	6.8	2.3	≤ 10

The correlation matrix highlights strong relationships between electrical, environmental, and fire-related parameters influencing fire risk. Generator temperature shows a strong positive correlation with power output, while higher humidity significantly reduces insulation resistance. Elevated ambient temperature is closely linked to control panel hotspots, increasing fire risk [15-24]. Oil leakage and dust load are also positively associated with hotspot formation and cable temperature, indicating increased ignition and heat retention potential Shown in Table 9-14.

Table 9 Correlation Matrix of Electrical, Environmental, and Fire Parameters

Parameter 1	Parameter 2	Correlation Coefficient (r)	Statistical Significance (p)	Interpretation
Generator Temp	Power Output	0.72	< 0.01	Strong positive correlation
Humidity	Insulation Resistance	-0.65	< 0.05	Significant negative effect
Ambient Temp	Control Panel Hotspots	0.69	< 0.01	High fire risk linkage
Oil Leakage	Hotspot Formation	0.61	< 0.05	Elevated ignition probability
Dust Load	Cable Temperature	0.57	< 0.05	Heat retention effect

Table 10 Risk Index Distribution

Risk Category	Mean Risk Index	Std. Dev.	Percentage of Components
Electrical Insulation Failure	0.68	0.12	31%
Thermal Overheating	0.62	0.15	27%
Lightning-Induced Faults	0.41	0.09	18%
Structural Thermal Fatigue	0.38	0.11	14%
Fire Suppression Deficiency	0.71	0.13	36%

Table 11 Effectiveness of Proposed Mitigation Measures

Mitigation Measure	Expected Risk Reduction (%)	Confidence Level	Priority
Real-time Insulation Monitoring	32–38	High	High
Advanced Fire Detection Systems	40–45	Very High	High
Cable Thermal Sensors	25–30	Medium	Medium
Lightning Analytics	18–22	Medium	Medium

Integration			
Improved Grounding Maintenance	15–20	High	Low

Table 12 Fire Incident Probability

Turbine Section	**Mean Fire Probability (%)**	**Std. Dev.**	**Risk Classification**
Nacelle	2.8	0.9	High
Control Cabinets	2.3	0.7	High
Tower Base	1.2	0.4	Medium
Cable Trays	1.9	0.6	Medium
Transformer Zone	3.1	1.1	Very High

Table 13 Fire and Electrical Safety Assessment Checklist

Sl. No	**Assessment Category**	**Parameter Evaluated**	**Method of Assessment**	**Observed Value / Condition**	**Standard / Limit**	**Risk Level**	**Remarks**
1	Electrical System	Generator operating temperature	SCADA data	96 °C	≤105 °C	Medium	Near upper limit during peak load
2	Electrical System	Transformer oil temperature	Thermal sensor	90 °C	≤95 °C	Medium	Continuous monitoring required
3	Electrical System	HV cable insulation resistance	Megger test	280 MΩ	≥300 MΩ	High	Degradation in humid areas
4	Electrical System	LV cable insulation resistance	Megger test	510 MΩ	≥500 MΩ	Low	Within safe limit
5	Electrical System	Grounding resistance	Earth tester	3.8 Ω	≤5 Ω	Low	Acceptable
6	Electrical System	Control panel hotspot	IR thermography	118 °C	≤120 °C	High	Immediate corrective action
7	Electrical System	Loose electrical connections	Visual & torque check	Observed	Not permitted	Medium	Periodic tightening required
8	Fire Safety	Dust accumulation on cables	Visual & weight estimation	312 g/m^2	≤200 g/m^2	High	Fire load increased
9	Fire Safety	Oil leakage near electrical parts	Visual inspection	Minor leakage	Nil	High	Potential ignition source

10	Fire Safety	Nacelle ambient temperature	Sensor reading	62 °C	≤60 °C	Medium	Ventilation improvement needed
11	Fire Safety	Ventilation effectiveness	Airflow analysis	52 %	≥75 %	High	Inadequate airflow
12	Fire Safety	Fire detection system coverage	System audit	40 %	≥90 %	High	Insufficient coverage
13	Fire Safety	Fire suppression system availability	Physical inspection	Partial	Full coverage	High	Upgrade required
14	Lightning Protection	Lightning arrestor condition	Visual inspection	Worn	Good	Medium	Maintenance required
15	Lightning Protection	Surge protection devices	Functional test	Working	Working	Low	Satisfactory
16	Structural Safety	Tower weld integrity	Ultrasonic testing	Minor flaws	Acceptable	Medium	Monitor periodically
17	Structural Safety	Hardness variation	Hardness test	212 HV	200–240 HV	Low	Within limit
18	Structural Safety	Metallographic banding	In-situ metallography	Moderate	Low	Medium	Thermal relaxation noted
19	Environmental	Humidity exposure	Environmental log	High	Moderate	Medium	Affects insulation
20	Environmental	Corrosion at tower base	Visual inspection	Minor corrosion	Nil	Low	Protective coating advised

Table 14 Risk Evaluation

Sl. No.	**Risk Parameter**	**Mean Value**	**Std. Deviation**	**Probability Score (1–5)**	**Severity Score (1–5)**	**Risk Index**	**Risk Category**
1	Generator overheating	78.6 °C	8.9	3	4	12	High
2	Transformer thermal stress	72.3 °C	7.6	3	4	12	High
3	HV insulation degradation	420 MΩ	82	4	5	20	Critical
4	LV insulation degradation	510 MΩ	64	2	3	6	Medium
5	Control panel hotspots	86.4 °C	11.3	4	5	20	Critical

6	Dust-induced fire load	135 g/m²	62	3	4	12	High
7	Oil leakage ignition risk	0.9 events/yr	0.8	3	5	15	High
8	Lightning-induced surge	1.2 / year	0.6	2	5	10	Medium
9	Structural thermal fatigue	Banding index 2.1	0.7	2	4	8	Medium
10	Grounding failure	2.1 Ω	0.7	1	4	4	Low

3.5. Mitigation and Preventive Measures

Mitigation and preventive measures are critical for minimizing fire and electrical safety risks in wind turbine operations. Given the continuous electrical, thermal, and mechanical loading, combined with harsh environmental exposure, a proactive and integrated safety framework is essential to prevent minor defects from escalating into major incidents.

3.5.1. Electrical Risk Mitigation

Electrical safety can be significantly enhanced through improved insulation systems, effective thermal management, and robust grounding. The use of high-temperature, moisture resistant insulation materials for HV and LV cables reduces insulation aging and breakdown. Periodic insulation resistance testing and infrared thermography enable early detection of degradation and hotspots. Proper cable routing, torque verification of terminals, load balancing, and installation of surge protection devices further reduce risks associated with overheating and lightning-induced surges.

3.5.2. Fire Prevention and Protection

Fire risk mitigation relies heavily on early detection and rapid suppression. Advanced fire detection systems including smoke, heat, and flame sensors should be installed in high-risk areas such as the nacelle, gearbox, and control panels. Automatic fire suppression systems using inert gas or water mist are recommended to control fires quickly without damaging electrical equipment. Strict housekeeping practices, prompt oil leak repair, and control of combustible materials significantly reduce ignition sources.

3.5.3. Structural and Material Safety

Structural integrity monitoring helps prevent indirect fire risks caused by thermal stress and fatigue. Periodic ultrasonic testing, hardness measurements, and metallographic assessments allow early identification of vulnerable zones. The adoption of fire-resistant coatings, corrosion protection systems, and advanced materials with high thermal stability enhances long-term safety and durability.

3.5.4. Maintenance, Digitalization, and Training

Shifting from reactive to predictive maintenance using SCADA, IoT sensors, and AI-based analytics enables early fault detection and optimized maintenance scheduling. Continuous monitoring of temperature, vibration, insulation resistance, and oil levels improves reliability. Comprehensive training programs, digital simulations, and emergency preparedness drills enhance personnel awareness and response capability.

3.5.5. Future Preventive Strategies

Future research should focus on adaptive fire protection systems, intelligent suppression technologies, and advanced materials to further strengthen mitigation strategies. An integrated approach combining technology, maintenance, and human factors is essential for sustainable and safe wind turbine operations.

3.6. Reporting and Documentation

Reporting and documentation constitute a critical component of fire and electrical safety risk assessment during wind turbine operations. This phase ensures that all inspection findings, test results, analyses, and recommendations are systematically recorded and communicated to stakeholders. Proper documentation provides a clear and traceable record of identified hazards such as overheating, insulation degradation, lightning effects, oil leakage, and early-stage material deterioration, supporting evidence-based decision-making and regulatory compliance. Comprehensive reporting consolidates data obtained from site inspections, in-situ electrical testing, non-destructive examinations, risk evaluation, and correlation analysis. Standardized checklists, test records, photographs, and analytical summaries improve transparency and consistency across assessments. Documenting correlations between operating conditions, thermal behavior, and material condition strengthens the reliability of risk conclusions and justifies mitigation measures. Effective documentation also enables action tracking by clearly defining corrective and preventive measures, responsible personnel, and implementation timelines. This structured approach ensures accountability and supports continuous safety improvement rather than one-time compliance. Future-oriented reporting should focus on centralized digital documentation systems that integrate historical inspection records, environmental data, and real-time monitoring outputs. Such systems enable long-term trend analysis, risk modeling, and benchmarking across wind farms. Advanced dashboards and automated reporting tools can enhance decision-making speed, improve compliance efficiency, and support integration into predictive maintenance frameworks, ultimately improving operational reliability and reducing fire and electrical safety risks.

4. Result and Discussion

The results obtained from the project provide valuable insights into the existing fire and electrical safety conditions of wind turbine systems and highlight areas requiring immediate and long-term intervention. The systematic methodology adopted, involving site inspection, in-situ testing, risk evaluation, and safety assessment, enabled a comprehensive understanding of both visible and latent hazards. Site inspection and data collection revealed that most wind turbine components were operating within acceptable mechanical and electrical limits under normal conditions. Visual inspections identified localized issues such as dust accumulation, minor oil leakage near gearboxes, aging cable insulation, and limited fire detection provisions in the nacelle and tower base. Although these issues did not pose an immediate threat, they represent potential ignition sources if left unaddressed over prolonged operation. In-situ testing and material sampling yielded significant findings. Hardness testing and ultrasonic testing of major structural components did not indicate any critical mechanical defects, cracks, or loss of structural integrity. This confirms that the primary load-bearing components of the turbine are currently safe for operation. However, metallographic analysis revealed microstructural deterioration in confined and inactive zones of certain components. These regions appeared thermally relaxed, suggesting early-stage material degradation due to prolonged exposure to heat and electrical stress. While these changes are not yet severe, continued operational stress could accelerate material weakening and increase the likelihood of failure. Risk evaluation and correlation analysis demonstrated a strong relationship between electrical anomalies, thermal effects, and fire risk. Elevated cable temperatures, insulation aging, and insufficient lightning protection were identified as key contributors to electrical faults. The qualitative risk matrix categorized several hazards under medium to high risk, particularly those related to overheating and lightning-induced electrical surges. The fire and electrical safety assessment further revealed the absence of advanced fire suppression systems and real-time monitoring in many installations. Existing safety measures were largely reactive rather than preventive. This highlights a critical gap in current safety practices, especially considering the remote locations and limited accessibility of wind turbines during emergencies. The results emphasize that while immediate structural failure risks are low, the presence of early material degradation and electrical vulnerabilities poses a long-term threat to operational reliability. The findings strongly support the need for proactive fire risk mitigation, predictive maintenance strategies, and enhanced monitoring systems to ensure sustained safety and performance of wind turbine operations.

Conclusion

This project successfully evaluated the potential risks associated with fire and electrical failures in wind turbine systems by adopting a structured and multidisciplinary assessment approach. The study demonstrated that wind turbines operate under complex environmental and electrical conditions that significantly influence their safety and long-term reliability. Factors such as overheating, insulation degradation, lightning strikes, short circuits, and exposure to harsh environmental conditions were identified as major contributors to fire and electrical hazards. The methodology combining site inspections, in-situ testing, and non-destructive evaluation techniques proved effective in identifying both apparent and latent risks. Hardness and ultrasonic testing confirmed the absence of critical mechanical defects in major structural components, indicating that the turbines currently maintain adequate structural integrity. However, metallographic analysis revealed localized microstructural deterioration in thermally relaxed and inactive zones. Although these findings do not indicate immediate failure, they signify early-stage material degradation that could progress under sustained operational and thermal stress. Risk evaluation and correlation analysis highlighted the strong interdependence between electrical anomalies, thermal effects, and fire risk. Electrical insulation aging, elevated operating temperatures, and insufficient lightning protection emerged as key risk factors that could trigger fire incidents if not adequately addressed. The fire and electrical safety assessment further revealed limitations in existing safety systems, particularly the lack of advanced fire detection, suppression, and real-time monitoring mechanisms. The study emphasizes that while current wind turbine operations may not exhibit critical failure risks, the presence of early material degradation and electrical vulnerabilities necessitates proactive mitigation. Implementing preventive maintenance, advanced monitoring technologies, and improved fire protection strategies is essential to enhance operational safety, reduce downtime, and ensure the long-term reliability and sustainability of wind turbine systems.

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