IJSRD International Journal for Scientific Research & Development| Vol. 14, Issue 4, 2026 | ISSN (online): 2321-0613

Experimental Reliability Assessment and Optimization of Inspection Intervals for Industrial Lightning Protection Systems Using Reliability Engineering Techniques

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Abstract — This study presents an experimental reliability assessment and inspection interval optimization approach for Industrial Lightning Protection Systems. The work focuses on major LPS components such as down conductors, ground electrodes, connectors, clamps, support brackets, and air terminals. Failure data, repair time, inspection records, corrosion observations, and maintenance history were considered for reliability evaluation. Parameters such as MTBF, MTTR, failure rate, availability, and Risk Priority Number were used to identify critical components. The analysis showed that down conductors, ground electrodes, and connectors required priority inspection due to higher failure frequency and risk level. Corrosion, loose connections, and mechanical damage were identified as major causes of failure. Optimized inspection intervals improved inspection effectiveness, reduced downtime, lowered maintenance cost, and enhanced system reliability. The proposed approach provides a practical Mechanical Engineering-based maintenance framework for improving safety, maintainability, and lifecycle performance of industrial LPS.

Keywords: Lightning Protection System, Reliability Assessment, Inspection Optimization, FMEA, Maintenance Management

I. INTRODUCTION

A. *Background of the Study*

Lightning Protection Systems are important industrial safety systems used to protect buildings, machinery, control systems, storage units, telecommunication towers, and human life from lightning-related hazards. In industrial plants, a lightning strike may cause structural damage, fire, equipment failure, control system disturbance, production stoppage, and safety risk. Therefore, continuous reliability of LPS is essential in manufacturing industries, process plants, storage terminals, power-related facilities, and telecommunication towers.

An industrial LPS mainly provides a safe path for lightning current by intercepting the lightning strike, conducting it through down conductors, and dissipating it into the earth through grounding electrodes. If any component of the system becomes weak due to corrosion, loose joints, mechanical damage, or increased ground resistance, the protection capacity of the entire system may reduce. Hence, reliability-based inspection and maintenance of LPS components is necessary for improving industrial safety and uninterrupted operation.

B. *Mechanical Engineering Relevance*

Although LPS is generally considered an electrical safety arrangement, many of its components are mechanical and structural elements. Air terminals, down conductors, clamps, connectors, support brackets, grounding electrodes, and lightning arrester mountings are continuously exposed to environmental and mechanical stresses.

Important Mechanical Engineering aspects include:

- Corrosion of conductors and grounding electrodes.
- Mechanical loosening of clamps and connectors.
- Vibration and wind load on exposed components.
- Thermal stress during lightning discharge.
- Mechanical wear of fastening elements.
- Material aging due to outdoor exposure.
- Structural stability of supports and brackets.
- Maintainability and lifecycle performance of components.

Therefore, Reliability Engineering and Maintenance Engineering are suitable tools for evaluating the condition of LPS components and optimizing inspection intervals.

C. *Problem Identification*

In many industries, LPS inspection is carried out at fixed intervals, commonly once in a year. Such time-based inspection does not always consider actual component condition, corrosion severity, past failure frequency, or risk level. As a result, critical components may fail before the next scheduled inspection.

Major problems identified are:

- Existing inspection schedules are mostly time-based.
- Critical components may fail before scheduled inspection.
- Corrosion and loose connections may remain hidden for longer periods.
- Ground resistance may increase without early detection.
- No systematic reliability-based inspection interval selection is followed.
- Corrective maintenance cost may increase due to delayed defect detection.
- Sudden failure may affect safety and industrial productivity.

D. *Need of Experimental Study*

The experimental study is required to understand actual failure behavior of LPS components under industrial operating conditions. Inspection records, maintenance history, corrosion observations, failure data, downtime records, and repair time data can provide a strong basis for reliability assessment.

The study helps to:

- Collect real inspection and maintenance data.
- Identify actual failure patterns of LPS components.

- Evaluate reliability parameters such as MTBF, MTTR, failure rate, availability, and reliability function.
- Perform FMEA and risk ranking of critical components.
- Compare existing and optimized inspection intervals.
- Validate reliability improvement through statistical and maintenance performance analysis.

E. *Objectives of the Paper*

1) To experimentally assess the reliability of major LPS components.
2) To identify critical failure modes using field inspection and maintenance data.
3) To calculate MTBF, MTTR, failure rate, reliability, and availability.
4) To perform FMEA and risk ranking of LPS components.
5) To optimize inspection intervals based on failure risk and component condition.
6) To compare existing and optimized inspection strategies.

II. LITERATURE REVIEW

A. *Reliability Engineering in Industrial Maintenance*

Reliability Engineering is widely used for predicting failure behavior, improving maintainability, and increasing the availability of engineering systems. In industrial maintenance, reliability parameters such as Mean Time Between Failures, Mean Time to Repair, failure rate, availability, and reliability function are used to evaluate equipment performance. These parameters help in deciding maintenance priority, inspection interval, replacement time, and risk level.

For industrial LPS, reliability analysis is useful because the system contains several components exposed to corrosion, vibration, thermal effects, and environmental deterioration. Component-wise reliability analysis helps identify high-risk elements such as down conductors, ground electrodes, and connectors.

B. *Maintenance Strategies*

Different maintenance strategies are used for industrial systems. Breakdown maintenance is performed after failure, but it is not suitable for safety-critical systems such as LPS. Preventive maintenance is based on fixed schedules, but it may lead to over-maintenance or delayed fault detection. Predictive maintenance and condition-based maintenance use actual condition data to plan maintenance before failure. Reliability-Centered Maintenance focuses on failure consequences and component criticality. Risk-Based Inspection prioritizes inspection according to probability and consequence of failure.

For LPS, a combination of preventive maintenance, condition-based maintenance, reliability-centered maintenance, and risk-based inspection is more suitable than only annual inspection.

C. *Lightning Protection System Maintenance*

LPS maintenance generally includes visual inspection, continuity testing, ground resistance testing, corrosion assessment, connector tightening, clamp inspection, and replacement of damaged components. Air terminals, down conductors, grounding electrodes, connectors, and clamps must be checked periodically to ensure a continuous and low-resistance current path.

Conventional annual inspection practices are simple, but they may not detect rapid corrosion, loose joints, or increasing ground resistance at the correct time. Therefore, inspection planning should be based on component condition, failure history, corrosion exposure, and risk level.

D. *Failure Modes of LPS Components*

Common failure modes of LPS components include:

- Corrosion of conductors and grounding electrodes.
- Loose joints and connectors.
- Increased contact resistance.
- Mechanical damage to support brackets.
- Clamp wear due to vibration and wind load.
- Thermal and electromagnetic stress during lightning events.
- Ground resistance increase due to soil and electrode degradation.
- Material aging and surface deterioration.

These failures reduce the current-carrying capacity and overall reliability of the Lightning Protection System.

E. *Research Gap*

The literature shows that many studies are available on reliability engineering and maintenance optimization for industrial assets. However, limited experimental studies are available on reliability assessment of LPS components. Most LPS studies focus on design and installation, while component-wise failure data analysis, FMEA, RBI, and optimized inspection interval selection receive less attention. Main research gaps are:

- Limited experimental studies on reliability assessment of LPS components.
- Lack of component-wise failure data analysis for industrial LPS.
- Limited use of FMEA and RBI for LPS inspection planning.
- Lack of optimized inspection intervals based on reliability parameters.
- Insufficient Mechanical Engineering focus on corrosion, loosening, vibration, wear, and structural deterioration of LPS components.

III. MATERIALS AND METHODS / EXPERIMENTAL METHODOLOGY

A. *Selection of Study Facility*

For the experimental reliability assessment, the selected facility may be an industrial plant, manufacturing facility, telecommunication tower, process industry, or storage installation. The facility should have a complete Lightning Protection System and proper maintenance documentation.

Selection criteria:

Sr. No.	Criterion	Requirement
1	Type of facility	Industrial plant / manufacturing facility / tower / process industry
2	LPS installation	Complete LPS with air terminals, down conductors, grounding system, clamps, and connectors
3	Maintenance records	Minimum 3–5 years preferred
4	Failure records	Available for reliability analysis
5	Inspection reports	Available for condition assessment
6	Corrosion exposure	Moderate to high preferred
7	Grounding system	Multiple grounding electrodes preferred
8	Accessibility	Components should be accessible for inspection

B. System Identification

The major LPS components considered in the study are:

- Air terminals.
- Multiple down conductors.
- Connectors.
- Clamps.
- Support brackets.
- Grounding electrodes.
- Lightning arresters.
- Earthing network.

Each component is treated as a maintainable asset. The condition and failure behavior of every component is recorded separately for reliability analysis.

C. Experimental Data Collection

The following data are required for experimental assessment:

- Visual inspection records.
- Maintenance history.
- Failure records.
- Repair time data.
- Inspection frequency.
- Corrosion observations.
- Ground resistance readings.
- Continuity test results.
- Component replacement records.
- Downtime due to failure or maintenance.

D. Experimental Inspection Parameters

Sr. No.	Parameter	Measurement / Observation Method	Relevance
1	Corrosion severity	Visual inspection / rating scale	Indicates material degradation
2	Ground resistance	Earth resistance tester	Indicates grounding effectiveness
3	Continuity	Continuity tester / multimeter	Confirms conductive path
4	Clamp tightness	Physical inspection / torque check	Indicates mechanical integrity
5	Connector condition	Visual and contact inspection	Indicates joint reliability
6	Failure count	Maintenance records	Used for failure rate and MTBF
7	Repair time	Maintenance logbook	Used for MTTR
8	Inspection interval	Maintenance schedule	Used for optimization
9	Component condition	Condition rating scale	Used for CBM decision

E. Reliability Analysis

The reliability assessment is performed using standard reliability parameters.

Mean Time Between Failures

$$MTBF = \frac{Total\ Operating\ Time}{Number\ of\ Failures}$$

Mean Time to Repair

$$MTTR = \frac{Total\ Repair\ Time}{Number\ of\ Repairs}$$

Failure Rate

$$\lambda = \frac{Number\ of\ Failures}{Total\ Operating\ Time}$$

Availability

$$A = \frac{MTBF}{MTBF + MTTR}$$

Reliability Function

$$R(t) = e^{-\lambda t}$$

These parameters help compare the performance of different LPS components and identify components requiring shorter inspection intervals.

F. Failure Mode and Effects Analysis

FMEA is used to identify failure modes, causes, effects, and risk level. The Risk Priority Number is calculated by:

$$RPN = Severity \times Occurrence \times Detection$$

Component	Failure Mode	Cause	Effect	S	O	D	RPN	Action Required
Down conductor	Corrosion / breakage	Moisture, pollution	Reduced current path	9	8	5	360	Six-month inspection
Ground electrode	Corrosion	Soil moisture	High ground resistance	9	7	6	378	Resistance testing
Connector	Loose joint	Vibration	Loss of continuity	8	6	5	240	Tightness verification
Clamp	Mechanical wear	Wind, vibration	Conductor instability	7	5	5	175	Preventive replacement
Air terminal	Damage / misalignment	Wind load	Reduced interception	6	3	4	72	Annual inspection

G. *Inspection Interval Optimization*

Inspection interval optimization is based on failure frequency, MTBF, failure rate, RPN score, corrosion severity, criticality, downtime impact, maintenance cost, and safety consequence.

Risk Level	RPN Range	Inspection Interval	Maintenance Action
Critical	Above 300	3–6 months	Immediate corrective / preventive action
High	200–300	6 months	Frequent inspection and monitoring
Medium	100–200	9 months	Scheduled preventive maintenance
Low	Below 100	12 months	Routine inspection

H. *Statistical Analysis*

Statistical analysis is carried out to understand component-wise failure behavior and maintenance performance. The tools used include mean failure frequency, percentage failure distribution, component ranking, standard deviation, comparison of existing and optimized strategies, and percentage improvement.

For the present study, total recorded failures were 70. The mean number of failures per component was:

$$Mean = \frac{70}{6} = 11.67$$

The component failure values were 18, 16, 14, 10, 8, and 4. The standard deviation was approximately 4.82 failures, indicating noticeable variation among component failure frequencies. Down conductors, ground electrodes, and connectors showed higher than average failures and were therefore considered critical components.

I. *Validation Methodology*

Validation is carried out by comparing existing and optimized inspection strategies. The comparison includes improvement in inspection effectiveness, MTBF, availability, failure rate, downtime, and maintenance cost.

Validation criteria:

- Reduction in failure frequency.
- Improvement in MTBF.
- Improvement in availability.
- Reduction in failure rate.
- Reduction in downtime.
- Reduction in maintenance cost.
- Better inspection effectiveness.

IV. RESULTS AND DISCUSSION

A. *Component Failure Statistics*

The component-wise failure analysis shows that down conductors recorded the highest number of failures, followed by ground electrodes and connectors. These three components together contributed 68.57% of total failures, indicating that they require priority inspection and maintenance.

Component	Number of Failures	Percentage Share	Failure Ranking
Down conductors	18	25.71%	1
Ground electrodes	16	22.86%	2
Connectors	14	20.00%	3
Clamps	10	14.29%	4
Support brackets	8	11.43%	5
Air terminals	4	5.71%	6
Total	70	100%	—

Analysis

- Down conductors showed the highest failure share of 25.71%.
- Ground electrodes contributed 22.86% of total failures.
- Connectors contributed 20.00% of failures.
- Air terminals showed the lowest failure share of 5.71%.
- The first three components caused nearly two-thirds of total failures.
- Inspection priority should therefore focus on down conductors, ground electrodes, and connectors.

B. *Failure Cause Analysis*

The failure cause analysis shows that corrosion was the dominant failure cause, contributing 42% of total failures. Loose connections and mechanical damage were the next major causes.

Failure Cause	Percentage Contribution
Corrosion	42%
Loose connections	21%
Mechanical damage	14%

Material aging	11%
Ground resistance increase	8%
Thermal damage	4%
Total	100%

Analysis

- Corrosion was the most critical degradation factor.
- Loose connections contributed 21%, showing the need for periodic tightening and continuity testing.
- Mechanical damage contributed 14%, mainly due to wind, vibration, handling, and support damage.
- Ground resistance increase directly affects LPS effectiveness.
- Thermal damage was low but important because it may occur during high-energy lightning events.

C. Reliability Analysis Results

The reliability analysis was performed by considering a total operating period of 50,000 hours. MTBF was calculated by dividing total operating hours by number of failures.

Component	Failures	MTBF Hours	Failure Rate $\times 10^{-4}$ Failures/hr	MTTR Hours	Availability (%)
Down conductors	18	2778	3.60	8	99.71
Ground electrodes	16	3125	3.20	10	99.68
Connectors	14	3571	2.80	6	99.83
Clamps	10	5000	2.00	5	99.90
Support brackets	8	6250	1.60	7	99.89
Air terminals	4	12500	0.80	4	99.97

Analysis

- Down conductors had the lowest MTBF of 2778 hours and the highest failure rate of 3.60×10^{-4} failures/hr.
- Ground electrodes had MTBF of 3125 hours and failure rate of 3.20×10^{-4} failures/hr.
- Air terminals had the highest MTBF of 12500 hours and lowest failure rate of 0.80×10^{-4} failures/hr.
- Down conductors and ground electrodes need shorter inspection intervals.
- Air terminals can continue with annual inspection due to low failure frequency.

D. FMEA and Risk Ranking Results

The FMEA results show that ground electrodes and down conductors have the highest RPN values. These components are exposed to soil moisture, atmospheric corrosion, and continuous environmental effects.

Component	Failure Mode	S	O	D	RPN	Risk Level
Ground electrode	Corrosion	9	7	6	378	Critical
Down conductor	Corrosion / breakage	9	8	5	360	Critical
Connector	Loose joint	8	6	5	240	High
Clamp	Mechanical wear	7	5	5	175	Medium
Air terminal	Damage / misalignment	6	3	4	72	Low

Analysis

- Ground electrodes recorded the highest RPN of 378.
- Down conductors recorded RPN of 360.
- Connectors recorded high-risk RPN of 240.
- Clamps showed medium risk with RPN of 175.
- Air terminals showed low risk with RPN of 72.
- Critical components require inspection within 3–6 months.

E. Existing Inspection Interval Analysis

Component	Existing Interval	Limitation
Down conductors	12 months	Corrosion may progress between inspections
Ground electrodes	12 months	Ground resistance may increase unnoticed
Connectors	12 months	Loose joints may remain undetected
Clamps	12 months	Mechanical wear may increase
Support brackets	12 months	Fatigue or vibration damage may progress
Air terminals	12 months	Generally acceptable

Analysis

The existing inspection system follows a fixed annual schedule for all components. However, the failure data show that all components do not have the same risk level. Down conductors, ground electrodes, and connectors fail more frequently than other components. Therefore, uniform annual inspection is not suitable for critical components.

F. Optimized Inspection Interval Results

Component	Existing Interval	Optimized Interval	Reason
Down conductors	12 months	6 months	High failure rate and corrosion exposure
Ground electrodes	12 months	6 months	High criticality and ground resistance variation
Connectors	12 months	6 months	Loose connections and contact deterioration
Clamps	12 months	9 months	Moderate mechanical degradation

Support brackets	12 months	9 months	Vibration and corrosion exposure
Air terminals	12 months	12 months	Low failure frequency

Analysis

The optimized schedule reduces inspection interval for high-risk components. Down conductors, ground electrodes, and connectors are shifted from 12 months to 6 months. Clamps and support brackets are shifted from 12 months to 9 months. Air terminals remain at 12 months because their failure rate is low.

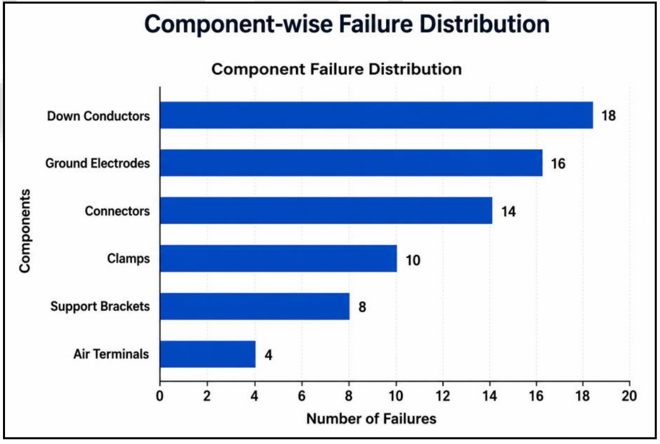
G. Comparison of Existing and Optimized Strategy

Parameter	Existing Strategy	Optimized Strategy	Improvement
Inspection effectiveness	65%	91%	26 percentage points
MTBF	2778 hr	4200 hr	51.19% increase
Availability	99.71%	99.86%	0.15 percentage points
Failure rate	3.60×10^{-4}	2.38×10^{-4}	33.89% reduction
Downtime	72 hr	38 hr	47.22% reduction
Maintenance cost	₹4.85 lakh	₹3.20 lakh	34.02% saving

Analysis

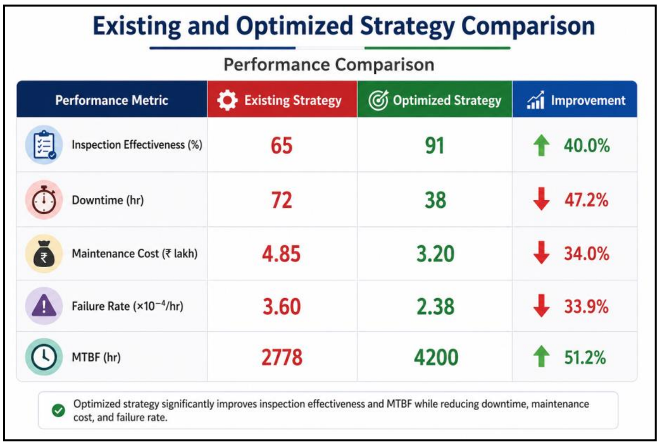
The optimized inspection strategy improves maintenance performance significantly. Inspection effectiveness increased from 65% to 91%. MTBF increased from 2778 hours to 4200 hours, showing better reliability. Failure rate reduced from 3.60×10^{-4} to 2.38×10^{-4} failures/hr. Downtime decreased from 72 hours to 38 hours, and maintenance cost reduced from ₹4.85 lakh to ₹3.20 lakh.

Fig. 1: Proposed Experimental Reliability Assessment and Inspection Optimization Framework



Graph 1: Component-wise Failure Distribution

The graph shows that down conductors, ground electrodes, and connectors are the most failure-prone components. Together, they contribute 48 failures out of 70, which is 68.57% of total failures. Therefore, these components should receive inspection priority.



Existing and Optimized Strategy Comparison

Performance Comparison

Performance Metric	Existing Strategy	Optimized Strategy	Improvement
Inspection Effectiveness (%)	65	91	↑ 40.0%
Downtime (hr)	72	38	↓ 47.2%
Maintenance Cost (₹ lakh)	4.85	3.20	↓ 34.0%
Failure Rate (×10⁻⁴/hr)	3.60	2.38	↓ 33.9%
MTBF (hr)	2778	4200	↑ 51.2%

✓ Optimized strategy significantly improves inspection effectiveness and MTBF while reducing downtime, maintenance cost, and failure rate.

Graph 2: Existing and Optimized Strategy Comparison

The optimized strategy improves inspection effectiveness and MTBF while reducing downtime, failure rate, and maintenance cost. This confirms that reliability-based inspection interval selection is more effective than uniform time-based inspection.

V. RESULTS AND DISCUSSION

A. *Component Failure Statistics*

The experimental reliability assessment was carried out by considering the failure records of major Lightning Protection System components. The analysis shows that all components do not fail at the same rate. Down conductors, ground electrodes, and connectors showed comparatively higher failure frequency because these components are continuously exposed to corrosion, environmental effects, mechanical loosening, moisture, and current-carrying stresses. A total of 70 failures were considered for the statistical analysis.

Sr. No.	Component	Number of Failures	Percentage Share	Failure Ranking
1	Down Conductors	18	25.71%	1
2	Ground Electrodes	16	22.86%	2
3	Connectors	14	20.00%	3
4	Clamps	10	14.29%	4
5	Support Brackets	8	11.43%	5
6	Air Terminals	4	5.71%	6
	Total	70	100%	

Table 5.1: Component Failure Statistics

Statistical Analysis

The mean failure frequency was calculated as:

$$Mean\ Failure\ Frequency = \frac{Total\ Failures}{Number\ of\ Components}$$

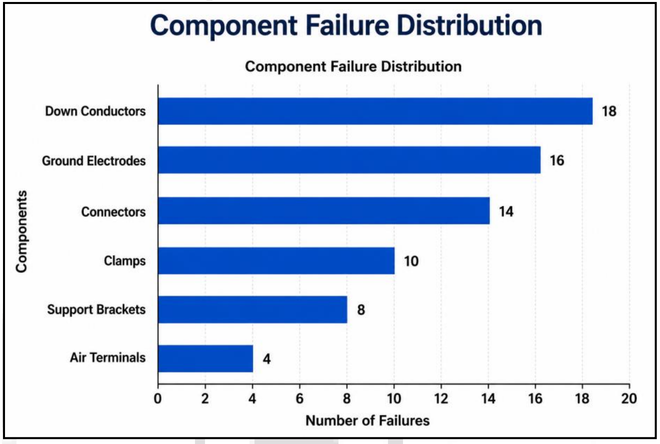
$$Mean = \frac{70}{6} = 11.67$$

The average failure frequency was 11.67 failures per component. Down conductors, ground electrodes, and connectors recorded failures higher than the average value, which indicates that these components are more critical than clamps, support brackets, and air terminals. The standard deviation of the failure data was approximately 4.82 failures, showing noticeable variation in component-wise failure behavior.

Analysis

- Down conductors recorded the highest failure share of 25.71%.
- Ground electrodes recorded 22.86% of total failures.
- Connectors contributed 20.00% of failures.
- These three components together contributed 68.57% of total failures.
- Air terminals showed the lowest failure share of 5.71%.
- Inspection priority should therefore be given to down conductors, ground electrodes, and connectors.

Component Failure Distribution



Graph 5.1: Component Failure Distribution

The graph clearly shows that down conductors, ground electrodes, and connectors are the most failure-prone components. These components require more frequent inspection because their failure may directly reduce the current-carrying and current-dissipating ability of the Lightning Protection System.

B. *Failure Cause Analysis*

The failure cause analysis was performed to identify the major reasons behind deterioration of Lightning Protection System components. The analysis shows that corrosion was the dominant failure mechanism, followed by loose connections and mechanical damage. This confirms that environmental exposure and mechanical degradation strongly affect LPS reliability.

Sr. No.	Failure Cause	Percentage Contribution
1	Corrosion	42%
2	Loose Connections	21%
3	Mechanical Damage	14%
4	Material Aging	11%
5	Ground Resistance Increase	8%
6	Thermal Damage	4%
	Total	100%

Table 5.2: Failure Cause Analysis

Analysis

- Corrosion contributed the highest share of 42%.
- Loose connections contributed 21%, showing the need for periodic tightening and continuity testing.
- Mechanical damage contributed 14%, mainly due to wind load, vibration, handling damage, and support failure.
- Material aging contributed 11%, indicating gradual deterioration during service life.
- Ground resistance increase contributed 8%, which directly affects current dissipation.
- Thermal damage contributed 4%, but it remains important because it may occur during high-energy lightning events.

Corrosion and loose connections together contributed 63% of failures. Therefore, corrosion monitoring, connector tightening, clamp inspection, and continuity testing should be treated as essential maintenance activities.

C. Reliability Analysis Results

Reliability analysis was carried out using component failure data. The total operating period was considered as 50,000 hours. MTBF, failure rate, MTTR, and availability were used to evaluate the performance of each LPS component.

Sr. No.	Component	Failures	MTBF Hours
1	Down Conductors	18	2778
2	Ground Electrodes	16	3125
3	Connectors	14	3571
4	Clamps	10	5000
5	Support Brackets	8	6250
6	Air Terminals	4	12500

Table 5.3: Reliability Analysis Results

Analysis

- Down conductors had the lowest MTBF of 2778 hours.
- Ground electrodes had MTBF of 3125 hours.
- Air terminals had the highest MTBF of 12500 hours.
- Down conductors had the highest failure rate of 3.60×10^{-4} failures/hr.
- Air terminals had the lowest failure rate of 0.80×10^{-4} failures/hr.
- Ground electrodes showed slightly lower availability than other components due to higher MTTR.
- Components with low MTBF and high failure rate require shorter inspection intervals.

The reliability results confirm that down conductors, ground electrodes, and connectors are the most critical components from a maintenance planning point of view.

D. FMEA and Risk Ranking Results

Failure Mode and Effects Analysis was used to prioritize components based on severity, occurrence, and detection. The Risk Priority Number was calculated as:

$$RPN = Severity \times Occurrence \times Detection$$

Sr. No.	Component	Failure Mode	Cause	Effect	S	O	D	RPN	Risk Level
1	Ground Electrode	Corrosion	Soil moisture	High ground resistance	9	7	6	378	Critical
2	Down Conductor	Corrosion / Breakage	Moisture, pollution	Reduced current path	9	8	5	360	Critical
3	Connector	Loose joint	Vibration	Loss of continuity	8	6	5	240	High
4	Clamp	Mechanical wear	Wind, vibration	Conductor instability	7	5	5	175	Medium
5	Air Terminal	Damage / misalignment	Wind load	Reduced interception	6	3	4	72	Low

Table 5.4: FMEA and Risk Ranking Results

Analysis

- Ground electrodes recorded the highest RPN of 378.
- Down conductors recorded RPN of 360.
- Connectors recorded RPN of 240, indicating high risk.
- Clamps recorded RPN of 175, indicating medium risk.
- Air terminals recorded RPN of 72, indicating low risk.
- Critical components should be inspected within 3–6 months.
- High-risk components should be inspected at least every 6 months.

The FMEA results support reliability-based inspection planning because components with high RPN values are directly linked with higher failure probability and greater consequence of failure.

E. Existing Inspection Interval Analysis

The existing inspection system generally follows a fixed inspection interval of 12 months for all components. However, failure statistics and FMEA results show that all components do not have the same risk level. Hence, the same inspection interval for all components is not technically suitable.

Sr. No.	Component	Existing Interval	Limitation
1	Down Conductors	12 months	Corrosion may progress between inspections

2	Ground Electrodes	12 months	Ground resistance may increase unnoticed
3	Connectors	12 months	Loose joints may remain undetected
4	Clamps	12 months	Mechanical wear may increase
5	Support Brackets	12 months	Fatigue or vibration damage may progress
6	Air Terminals	12 months	Generally acceptable

Table 5.5: Existing Inspection Interval Analysis

Analysis

The existing inspection schedule is simple but does not consider failure rate, corrosion severity, RPN score, or component criticality. Down conductors, ground electrodes, and connectors may deteriorate before the next annual inspection. Therefore, fixed annual inspection may lead to delayed defect detection and increased maintenance risk.

F. Optimized Inspection Interval Results

The optimized inspection intervals were developed based on reliability results, RPN values, component criticality, and failure frequency. Components with higher failure rate and higher RPN were assigned shorter inspection intervals.

Sr. No.	Component	Existing Interval	Optimized Interval	Reason
1	Down Conductors	12 months	6 months	High failure rate and corrosion exposure
2	Ground Electrodes	12 months	6 months	High criticality and ground resistance variation
3	Connectors	12 months	6 months	Loose connections and contact deterioration
4	Clamps	12 months	9 months	Moderate mechanical degradation
5	Support Brackets	12 months	9 months	Vibration and corrosion exposure
6	Air Terminals	12 months	12 months	Low failure frequency

Table 5.6: Optimized Inspection Interval Results

Analysis

The optimized schedule reduces the inspection interval for high-risk components. Down conductors, ground electrodes, and connectors are shifted from 12 months to 6 months. Clamps and support brackets are shifted from 12 months to 9 months, while air terminals remain at 12 months because of their lower failure rate and low RPN value.

G. Comparison of Existing and Optimized Strategy

The comparison between existing and optimized maintenance strategies shows clear improvement in reliability and maintenance performance.

Sr. No.	Parameter	Existing Strategy	Optimized Strategy	Improvement
1	Inspection Effectiveness	65%	91%	26 percentage points increase
2	MTBF	2778 hr	4200 hr	51.19% increase
3	Availability	99.71%	99.86%	0.15 percentage points increase
4	Failure Rate	3.60×10^{-4}	2.38×10^{-4}	33.89% reduction
5	Downtime	72 hr	38 hr	47.22% reduction
6	Maintenance Cost	₹4.85 lakh	₹3.20 lakh	34.02% saving

Table 5.7 Comparison of Existing and Optimized Strategy

Analysis

The optimized strategy improved inspection effectiveness from 65% to 91%. MTBF increased from 2778 hours to 4200 hours, showing better reliability. Failure rate reduced from 3.60×10^{-4} to 2.38×10^{-4} failures/hr. Downtime reduced from 72 hours to 38 hours, while maintenance cost reduced from ₹4.85 lakh to ₹3.20 lakh. Thus, reliability-based inspection interval optimization improves safety, reliability, availability, and cost performance.

H. Discussion of Findings

The results clearly show that down conductors, ground electrodes, and connectors are the most critical components of the industrial Lightning Protection System. These components showed higher failure frequency, higher failure rate, lower MTBF, and higher risk ranking compared with clamps, support brackets, and air terminals. The component-wise failure analysis showed that down conductors, ground electrodes, and connectors together contributed 68.57% of total failures.

Corrosion was identified as the dominant degradation factor with 42% contribution. This indicates that environmental exposure, soil moisture, industrial pollutants, and material degradation strongly influence LPS reliability. Loose connections contributed 21%, which shows that periodic tightening, continuity checking, and connector inspection are essential.

Reliability analysis confirmed that down conductors had the lowest MTBF and highest failure rate. FMEA further confirmed that ground electrodes and down conductors fall under the critical risk category. Therefore, uniform annual inspection is not sufficient for all components. The optimized strategy recommends six-month inspection for down conductors, ground electrodes, and connectors; nine-month inspection for clamps and support brackets; and annual inspection for air terminals.

The optimized strategy improved inspection effectiveness, MTBF, availability, downtime, and maintenance cost. Hence, reliability-based inspection interval optimization provides a practical Mechanical Engineering-based maintenance framework for industrial LPS.

VI. CONCLUSION AND FUTURE SCOPE

A. *Conclusion*

The experimental reliability assessment successfully identified the critical components of industrial Lightning Protection Systems. The results showed that down conductors, ground electrodes, and connectors require priority maintenance because they recorded the highest failure percentages. Corrosion, loose connections, mechanical damage, and ground resistance increase were identified as the major causes of failure.

MTBF, MTTR, failure rate, availability, and FMEA were found effective for evaluating LPS reliability. The optimized inspection interval strategy improved reliability and inspection effectiveness by assigning shorter inspection intervals to high-risk components. Risk-based inspection reduced unnecessary inspection of low-risk components and improved maintenance resource utilization. The proposed approach supports Mechanical Engineering-based maintenance optimization for industrial Lightning Protection Systems.

Major Conclusions

- Down conductors, ground electrodes, and connectors are the most critical LPS components.
- Corrosion is the dominant cause of component degradation.
- Existing annual inspection is not sufficient for high-risk components.
- Reliability analysis helps identify weak components.
- FMEA supports risk-based maintenance prioritization.
- Optimized inspection intervals improve early fault detection.
- Maintenance cost and downtime can be reduced through reliability-based planning.
- The proposed method improves safety, availability, and lifecycle performance.

B. *Industrial Benefits*

The proposed reliability-based maintenance approach provides several industrial benefits:

- Improved asset reliability.
- Reduced unexpected failures.
- Reduced downtime.
- Lower maintenance cost.
- Better safety performance.
- Extended service life of LPS components.
- Improved maintenance planning.
- Better compliance with safety practices.
- Better utilization of maintenance resources.
- Improved protection of industrial structures and equipment.

C. *Future Scope*

Future work may focus on advanced monitoring and digital maintenance systems for industrial LPS. The following future directions are suggested:

- IoT-based online monitoring of LPS components.
- Smart corrosion sensors for down conductors and grounding electrodes.
- AI-based failure prediction model.
- Digital twin-based LPS lifecycle management.
- Automated inspection scheduling system.
- Integration of thermographic and ultrasonic inspection methods.
- Development of real-time reliability dashboard.
- Application of machine learning for maintenance decision support.
- Cloud-based inspection and maintenance record management.
- Integration of LPS maintenance with Industry 4.0 asset management systems.

D. *Final Conclusion*

The experimentation-based reliability assessment confirms that industrial Lightning Protection Systems can be effectively maintained using Reliability Engineering techniques. Inspection intervals should be optimized based on component condition, failure history, risk level, and reliability performance. The proposed methodology provides a practical Mechanical Engineering-based framework for improving reliability, safety, maintainability, and lifecycle performance of industrial Lightning Protection Systems.

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