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Risk Assessment of the Lightning Protection System for Hybrid Solar Power Generation Rooftop System on the Factory Using the FMECA Technique

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Abstract*— This paper presents a risk assessment of the lightning protection system for hybrid solar power generation rooftop system on the factory using the FMECA technique. The case study focuses on lightning strikes affecting solar power systems on hybrid roofs, leading to damage. The installation of lightning protection systems to safeguard against natural phenomena, such as direct and indirect lightning strikes, requires an assessment for preventive maintenance. This assessment considers four criteria: efficiency, environment, safety/reliability, and finance. Data collection was carried out using Microsoft Excel, and the lightning protection system was critically analyzed using the FMECA technique. The results indicate that the highest risk in financial operations is within the green, yellow, and red zones, as repair costs are still manageable. The FMECA method proves to be an effective tool for assessing lightning protection systems, enhancing maintenance efficiency, and reinforcing the reliability and stability of the protection system within a suitable budget.

***Keywords*— Lightning Protection Systems, Hybrid Solar Power Generation Rooftop System, FMECA Technique**

I. INTRODUCTION

The demand for electricity in the industrial sector is on the rise. Reducing electricity costs by installing solar power systems to supplement the power supply has become an increasingly popular option. The factory used as a case study in this work has installed a rooftop solar power system, but its lightning protection system is relatively old. To ensure effective lightning protection, regular inspection and maintenance of the lightning protection system are necessary. Thus, an analysis was conducted using the Failure Mode, Effects, and Criticality Analysis (FMECA) technique to improve and enhance the efficiency of the lightning protection system for solar power generation rooftop system to prevent damage when lightning occurs in the area. The components of the lightning protection system include air terminals, bare copper wires, grounding rods, ground wells, PVC pipes, ground test boxes, sandle clamp supports, and thermoweld. The results from the analysis allow for efficient resource management and maintenance planning.

II. ENGINEERING INSTITUTE OF THAILAND STANDARD LIGHTNING PROTECTION

A. Design of lightning protection system

Design lightning protection systems to achieve optimum results both technically and economically. It will be possible only when lightning protection system design, construction steps, design and construction steps to protect especially the design the building itself should utilize the metal parts of the building as components of the lightning protection system.

The design documentation of the lightning protection system must contain all the necessary information to ensure correct and complete installation. Lightning protection systems should be designed and installed. By designers and installers of lightning protection systems who are well trained and skilled [1]-[2].

B. Selection of external lightning protection system

In most cases, an external lightning protection system may be attached to the building to be protected. Consideration should be given to selecting an independent external lightning protection system. When an explosion occurs at the point of the lightning strike or on the conductor that carries the lightning current, it may cause damage to buildings.

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Selection of external lightning protection system, air-termination system consists of a combination of the following elements.

- Lightning rod (including free-standing poles)
- Stranded conductor
- Mesh conductor

C. The maintenance and inspection of lightning protection systems

All lightning protection systems must be inspected at the following intervals:

- During the installation of the lightning protection system, especially while installing components that will be concealed within the structure and inaccessible afterward.
- When there are significant changes or repairs to the structure, or after a known lightning strike to the lightning protection system.
- Upon completion of the installation of the lightning protection system.
- At regular intervals as specified in Table I.

TABLE I. MAXIMUM INTERVAL BETWEEN EACH INSPECTION OF THE SYSTEM OF LIGHTNING PROTECTION.

Classification of lightning protection systems	Inspection (Years)	Complete inspection (Years)	Complete inspection in specific cases (a), (b) (Years)
1 and 2	1	2	1
3 and 4	2	4	1
A For facilities that include structures at risk of explosive materials, the lightning protection system should be inspected every 6 months. Electrical testing of the installation should be done every year. An acceptable exception to the annual testing interval is testing every 14 to 15 months. It may be beneficial to test ground resistance at different times of the year to understand seasonal variations. B Specific sites refer to structures with sensitive internal systems, office buildings, commercial buildings, locations that may have a large number of occupants, or structures that have previously been struck by lightning.			

Visual inspections are performed to ensure that:

- The design complies with this standard.
- The system of lightning protection is good condition.
- No loose or accidentally disconnected conductors and connections in the system of lightning protection.
- No parts of the lightning protection system have deteriorated due to corrosion, especially at ground level.
- All visible grounding connections are intact and can still perform their intended functions.

D. Background of Lightning Protection Levels (LPL) and Classes of Lightning Protection Systems (LPS)

The lightning protection level is categorized into 4 levels based on the minimum lightning current, as shown in Table II.

TABLE II. THE MINIMUM LIGHTNING CURRENT SIZES FOR EACH LIGHTNING PROTECTION LEVEL (LPL)

Lightning protection level (LPL)	I	II	III	IV
Minimum lightning current size I_{min} (kA)	3	5	10	16

Based on the minimum lightning current sizes divided into 4 levels, the radius of the rolling sphere is calculated using the formula for the radius of the rolling sphere (r), which is equal to 10 x $(I_{min})^{0.65}$ This is used to determine the level of the lightning protection system (LPS), as shown in Table III.

TABLE III. THE PEAK VALUES OF THE MINIMUM LIGHTNING CURRENT (I_{MIN}) AND THE ROLLING SPHERE RADIUS ACCORDING TO EACH LEVEL

Lightning protection level (LPL)	I	II	III	IV
Class lightning protection system (Class of LPS)	I	II	III	IV
Minimum lightning current size (kA)	3	5	10	16
Rolling spere radios size (M)	$=10(3)^{0.65}$ = 20.423	$=10(5)^{0.65}$ = 28.466	$=10(10)^{0.65}$ = 44.668	$=10(16)^{0.65}$ = 60.628

Rolling sphere radius size (m): according to LPS standards 20, 30, 45 and 60 in sequence.

For each lightning protection level with peak lightning current values, the relationship to surge protection devices can be demonstrated with the concept that, during a direct lightning strike (10/350 μs waveform), half of the lightning current will flow into the ground, while the other half enters the building through a 3-phase, 4-wire electrical system. Therefore, surge protection devices are designed to handle only one-fourth of the total lightning current as their maximum current capacity. Additionally, if the power distribution is at a higher level, this current will be further reduced. The initial current size required for the first set of surge protection devices is shown in Table IV.

TABLE IV. THE MAXIMUM LIGHTNING CURRENT SIZE THAT THE FIRST SET OF SURGE PROTECTION DEVICES MUST HANDLE ACCORDING TO EACH LIGHTNING PROTECTION LEVEL (LPL)

Lightning protection level (LPL)	I	II	III	IV
Minimum lightning current size (kA)	200	150	100	100
Lightning current entering the building (kA)	100	75	50	50
Entering each surge protection device phase (kA)	25	18.75	12.5	12.5

III. Proposed Method

A. Risk-Based Maintenance

The method of scoring and weighting for risk in the form of improvement index (%RI) and the importance index (%ImI) for each component of the lightning protection system were calculated and plotted on a risk chart along the y-axis and x-axis, respectively. Using %RI and %ImI in the risk chart, risk management based on likelihood of damage can be inferred. %RI and %ImI are divided into three levels: the colors for %RI are green, yellow, and red, representing good, fair, and poor conditions. Meanwhile, the colors for %ImI indicate low, medium, and high importance to the system, as shown in Fig. 1. For %RI zoning, the actual ranges used are determined based on test results reflecting %RI, which requires expert experience to achieve appropriate ranges. Efficient and effective maintenance management requires these actual ranges for %ImI to be defined according to utility policies [3].

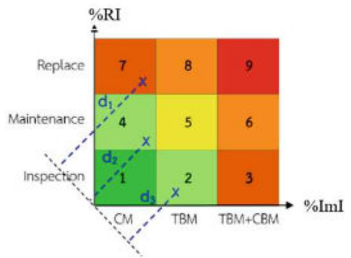

Fig. 1. Example of a Risk Matrix

B. Failure Mode, Effects, and Criticality Analysis for Lightning Protection System

This article evaluates the lightning protection system, presenting the sub-components of each part in the safety assessment using FMECA through Microsoft Excel. After analyzing with the FMECA technique, the results are compared with the criticality matrix as shown in Fig. 2. The matrix is divided into four colored bands: green, yellow, orange, and red, which represent low risk, medium risk, high risk, and very high risk, respectively. The numbers one to twenty five indicate the severity from low to high.

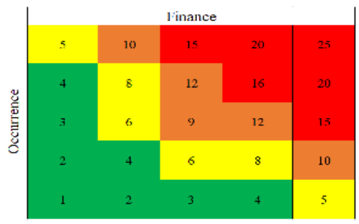

Fig. 2. Risk Matrix

FMECA analysis is used to determine the risk of the lightning protection system, identifying the importance of various criteria including performance, safety, environment, and finance of the lightning protection system. After analyzing all criteria, the maintenance methods and evaluation criteria are detailed in Table V.

TABLE V. Criticality Analysis and Its Maintenance Management

Score	Condition of the conductor clamp
22-25	Unacceptable levels need to be expedited to manage the risk to acceptable level immediately.
16-21	Unacceptable level, which manage the risk in order to be in the next acceptable level.
5-15	Acceptable level but there must be control to prevent risk moving to an unacceptable level.
1-4	Acceptable level without risk control, no additional management.

C. Severity on Environment

Assessment of environmental severity [4]-[5] has 3 criteria, such as lifespan, impact on the roof, and location, etc., which are used to score for environmental severity analysis as shown in Table VI.

TABLE VI. Sub-Criteria for Environment

Criteria	Score				
	1	2	3	4	5
Age of lightning protection	0-2	3-5	6-8	9-10	More 11 year
Impact on the roof	No impact		Loose conduct or wire		Conductor wire in contact with the roof
Location	Installed in an open area				High animal activity area

D. Severity on Safety / Reliability

Assessment of safety or reliability severity has 3 criteria such as ground resistance (Ω), voltage system (V), and protection, etc., used for scoring in the analysis of severity in environmental matters as shown in Table VII.

TABLE VII. Sub- Criteria for Safety / Reliability

Criteria	Score				
	1	2	3	4	5
Earth resistance value (Ω)	0 - 5	6 – 10	11 - 15	16 - 25	More 25
Voltage system (V)	220 - 416	11 – 33 k	69 k	115 k	More 115 k
Protection	Ground connection		Non-standard grounding		No grounding

E. Severity on Finance

The exact costs of the subcomponents of the lightning protection system must also be specified as shown in Table IX. Additionally, calculate the percentage (%) of the total costs, which can be compared with Table IV to obtain the financial severity analysis score. Score for finance as shown in Table VIII.

TABLE VIII. Score for Finance

Score	Description
1	Less than 10% of the total price
2	10 – 29% of the total price
3	30 – 49% of the total price
4	50 – 69% of the total price
5	70 – 100% of the total price

TABLE IX. FINANCE PART OF LIGHTNING PROTECTION

Part	Price (Baht)	Percentage (%)
Air Terminal Head, 0.60 meters high	49,500.00	8.714
Bare copper wire, 70 mm²	294,120.00	51.78
Grounding rod with a diameter of 5/8" x 10'	20,400.00	3.591
Grounding pit	17,200.00	3.028
PVC pipe with a diameter of 1 1/4"	7,600.00	1.338
Ground Test Box	29,200.00	5.141
Sandle Clamp Support	93,000.00	16.373
Thermoweld	42,000.00	7.394
Test Commissioning	15,000.00	2.641
Total	568,020.00	100%

F. *Severity on Efficiency Criterion*

The performance criteria consider the condition of the lightning protection system in terms of the health index (%HI). Assessing the condition of the components within each group of the lightning protection system requires various testing methods and visual inspections, as shown in Table X. The weighted scoring method (WSM) is applied, while the analytical hierarchy process (AHP) is used to determine the weights of the testing methods [6]-[7].

$$\%HI=\frac{\sum_{i=1}^{N}(S_i\times W_i)}{\sum_{i=1}^{N}(S_i\times W_i)}\times 100 \quad (1)$$

When S_i is score

S_{max} is maximum

W_i is weight of diagnostic result i_{th}

TABLE X. ASSESSMENT OF THE CONDITION OF LIGHTNING PROTECTION SYSTEM COMPONENTS

Criteria	Score 1	2	3	4	5
Visual inspection	Normal	Slightly rusty	Rusty	Starting to tear	Conductor wire in contact with the roof
Earth resistance value (Ω)	0 - 5	6 – 10	11 - 15	16 - 25	More 25
Inspect the lightning strike counter	Increase				No increase

Technical data and test results will be collected and used to calculate the %HI of the lightning protection system components. This will be converted into scores for performance severity analysis as shown in Table V.

G. *Calculation and Analysis of Critical Conditions*

Critical condition analysis must determine the probability of failure. The score for the likelihood of failure for each component can be determined as shown in Table XI. Then, the severity of various factors such as performance, environment, safety/reliability, and finance will be established. Subsequently, the overall criticality can be calculated using equation (2) [8].

$$\text{Criticality} = \text{Severity x Occurrence} \quad (2)$$

TABLE XI. CRITERIA FOR OCCURRENCE ANALYSIS

Score	Description
1	Zero failure per year
2	-
3	One - five failures/year
4	Six - ten failures/year
5	More than eleven failures/year

IV. RESULTS AND DISCUSSION

The calculation of the criticality of the lightning protection system is based on the database established from the test results in terms of performance, environment, safety, and finance, as shown in Table XII.

TABLE XII. CRITICALITY SCORE OF LIGHTNING PROTECTION

Components of a lightning protection system	Severity: Efficiency	Severity: Environment	Severity: Safety	Severity: Finance	Occurrence	Criticality: Efficiency	Criticality: Environment	Criticality: Safety	Criticality: Finance
Air Terminal Head, 0.60 meters high	4	4	4	1	4	16	16	16	4
Bare copper wire, 70 mm²	4	4	4	4	4	16	16	16	16
Grounding rod with a diameter of 5/8" x 10'	4	4	4	1	4	16	16	16	4
Grounding pit	4	4	4	1	4	16	16	16	5
PVC pipe with a diameter of 1 1/4"	4	4	4	1	4	16	16	16	4
Ground Test Box	4	4	4	1	4	16	16	16	5
Sandle Clamp Support	4	4	4	2	4	16	16	16	8
Thermoweld	4	4	4	1	4	16	16	16	4

The criticality score for all components is assigned to the matrix for efficiency as shown in Fig 3.

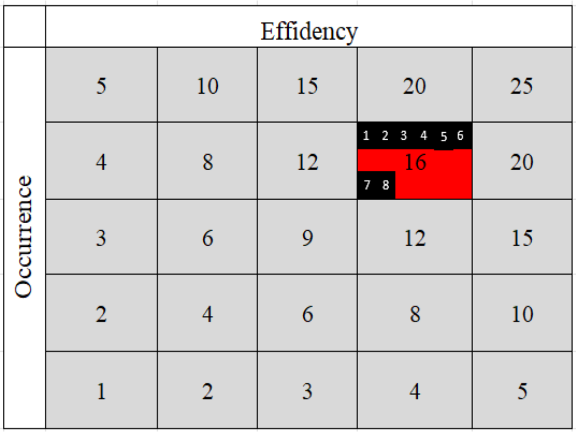

Fig. 3. Criticality matrix of the lightning protection system for efficiency.

The criticality score for all components is assigned to the matrix for the environment, as shown in Fig 4.

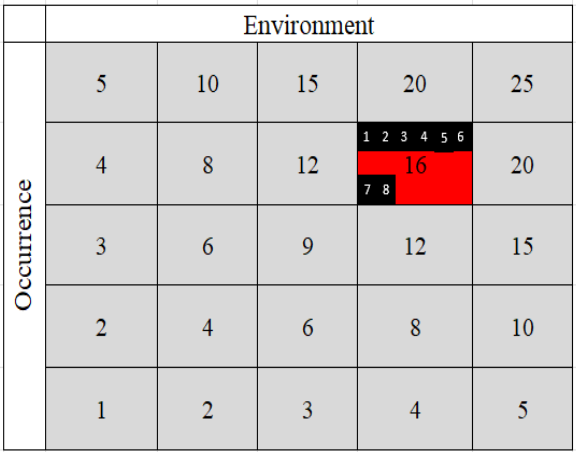

Fig. 4. Criticality matrix of the lightning protection system for the environment.

The criticality score for all components is assigned to the matrix for safety or reliability as shown in Fig 5.

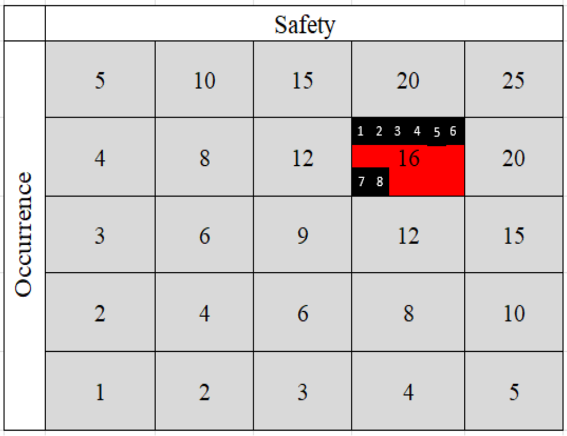

Fig. 5. Criticality Matrix of the Lightning Protection System for Safety.

The criticality score for all components is assigned to the matrix for finance, as shown in Fig 6.

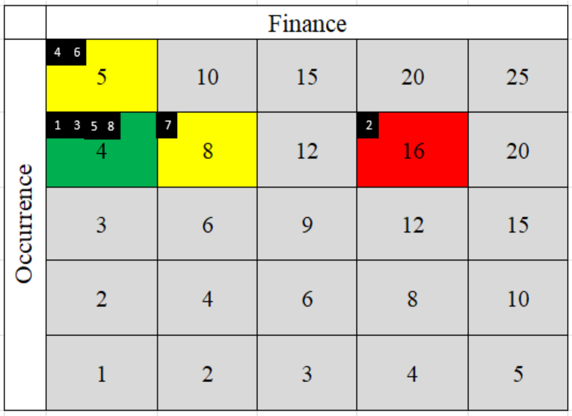

Fig. 6. Criticality matrix of the lightning protection system for finance.

From Fig 4-6, the black-bordered numerical scores assigned to the risk matrix from 1 to 8, as obtained from Table VIII, are: air terminal heads, bare copper wire, grounding rods, ground pits, PVC pipes, ground test box, sandle clamp support, and exthermo weld, in that order.

V. Conclusion

Lightning protection systems have a lifespan and deteriorate with use. The lightning protection system should be effectively improved by using evaluations to find efficient methods, considering four severity criteria: performance, environment, safety or reliability, and finance. Data is collected using Microsoft Excel, and the results of the analysis and management of the lightning protection system maintenance are presented using FMECA techniques. The results indicate that there is a high risk of operation due to the importance of performance, environment, and safety or reliability being in the red zone for all subcomponents of the system. This is because the lightning protection system has reached the end of its lifespan and is in poor condition. Additionally, it is at risk of lightning strikes based on the statistics of thunderstorms from the Engineering Institute of Thailand under the Royal Patronage, which reported an average thunderstorm occurrence rate of 67% from 2006 to 2021. In terms of finance, it is in the green, yellow, and red zones due to maintenance costs still being manageable. The FMECA method can be an effective tool for evaluating lightning protection systems, improving maintenance performance, and enhancing the reliability and stability of the system within an appropriate budget.

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