A Comprehensive Review of Failure Modes and Risk Prioritization in Solar Photovoltaic Systems Using FMEA and RPN

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***Abstract* - The increasing adoption of solar photovoltaic (PV) systems has necessitated the assessment of their reliability and failure mechanisms. Failure Modes and Effects Analysis (FMEA) and Risk Priority Number (RPN) are widely used methodologies to identify, assess, and prioritize potential failures in PV systems. This review provides an in-depth analysis of failure modes affecting solar PV systems, their impact on system performance, and the effectiveness of FMEA-based risk assessment. The study highlights common failure mechanisms, existing research gaps, and the potential integration of methodologies such as FMEA and RPN analysis to enhance the predictive capabilities of reliability analysis in PV modules. The findings underscore the necessity for standardized FMEA frameworks to improve the long-term sustainability of solar energy solutions.**

Keywords: FMEA, Photovoltaic System Risk Assessment, RPN.

I. INTRODUCTION

The rapid expansion of solar photovoltaic (PV) technology has led to increased focus on its long-term reliability and efficiency. Failures in PV modules can significantly impact energy output, financial investments, and maintenance costs [1,2,3,4]. Failure Modes and Effects Analysis (FMEA) is a systematic approach used to detect, classify, and mitigate potential failures in engineering systems [5,6]. The Risk Priority Number (RPN), derived from FMEA, quantifies the risk associated with failure modes based on severity, occurrence, and detection criteria [7,8]. This paper reviews existing literature on FMEA applications in PV systems, explores key failure modes, and provides recommendations for improving risk assessment methodologies.

II. METHODOLOGY FOR REVIEW

This review is based on an extensive analysis of peer-reviewed journal articles, case studies, and research reports related to FMEA in solar PV systems [9,10]. To sustain the reliability of roof top photovoltaic plant, several steps need to be taken. Firstly, it is important to study the impact of tough outdoor and climate conditions on photovoltaic modules and identify potential failure modes [11,12]. Additionally, it is crucial to assess the performance of solar plants over different periods of time, ranging from 5 to 30 years.

Once failure modes have been identified, the severity of the issues must be determined using the Risk priority number process. This will help in understanding the significance of each issue and the level of urgency required in addressing them [13,14]. Assessing the Risk Priority Number (RPN) values of various failure modes enables the determination of their influence on the overall functionality of the rooftops solar power plant [15,16].

The Adopted methodology for this review paper includes:
- Selection of literature published in reputed journals.
- Categorization of failure modes into mechanical, electrical, and environmental aspects
- Comparative analysis of traditional and advanced FMEA techniques.
- Identification of research gaps and future directions.

Finally, guidelines to design FMEA can be developed by studying the severity, occurrence and detection of failure modes, and remedies can be implemented accordingly to improve the cost-effectiveness of photovoltaic generation.

Objectives of the Study:

- Identify and classify common failure modes in PV systems.
- Assess and rank risks using FMEA and RPN techniques.
- Highlight research gaps to improve risk assessment in PV systems and suggest further improvements.

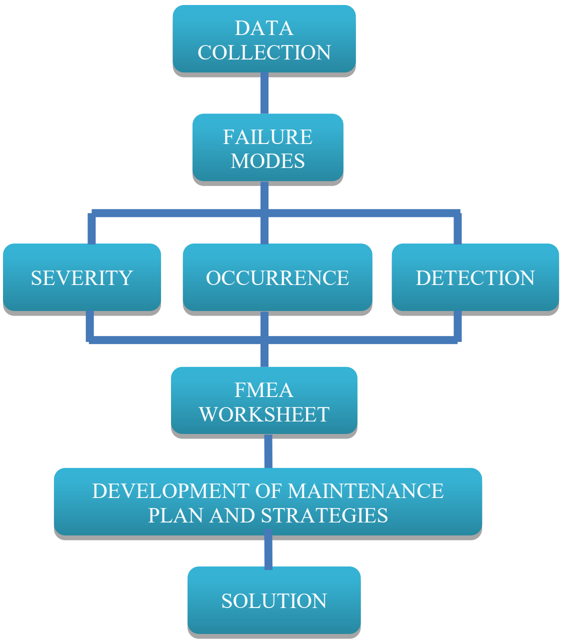

Fig 2.1: Research Methodology Model

III. COMMON FAILURE MODES IN SOLAR PV SYSTEMS

Important Failure modes in PV systems are broadly classified into:

3.1 Mechanical Failure:

Backsheet Delamination: Delamination occurs when the layers of the backsheet separate, often due to moisture ingress or adhesive failure, leading to reduced mechanical strength and potential electrical hazards.

Glass Cracking and Damage: Physical damage to the glass covering the solar cells can reduce light transmission, compromise cell integrity, and lead to moisture ingress or hotspots.

Rusting of Connecting Wire: Corrosion of connecting wires can increase electrical resistance and potentially lead to electrical faults within the PV system [15,16].

Fig 3.1: a) Backsheet Delamination b) Glass Cracking c) Rusting of connecting rod [25]

3.2 Electrical Failure:

Hotspot: Non-uniform shading or defects in cells can cause localized heating, leading to hotspots. This can reduce cell efficiency and potentially cause cell degradation or even fire hazards.

Connector Defects: Faulty connectors can lead to poor electrical connections, increased resistance, and potential safety hazards [17].

Busbar and Gridline Defects: Issues with the busbars, such as corrosion or poor soldering, can increase resistance and reduce module performance. Damage or defects in gridlines on solar cells can reduce electrical conductivity and module efficiency [18].

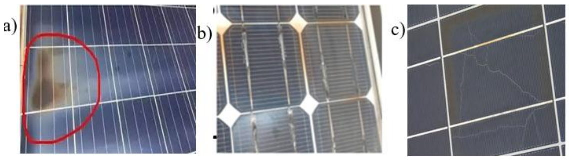

Fig 3.2: a) Hotspot formation b) Connector defects c) Busbar and gridline defects [25]

3.3 Environmental Failures:

Soiling: Accumulation of dirt, dust, or other debris on the module surface can reduce light transmission and decrease module efficiency [19,20].

Worm-like Patterns and Snail Trails: These patterns may indicate potential manufacturing defects or material degradation, which can lead to reduced module performance and reliability [21].

UV-induced degradation: It Results in the deterioration of solar panels, due to prolonged exposure to ultraviolet (UV) radiation. It leads to chemical breakdown, discoloration, brittleness, and reduced efficiency over time [22].

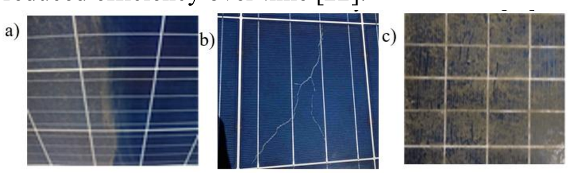

Fig 3.3: a) Soiling b) Snail trails and wormlike patterns defects c) UV- inducted degradation [26]

Fig 3.4: Solar Panel Visual Inspection for Failure identification.

IV. FMEA AND RPN ANALYSIS IN SOLAR CELLS

The application of Failure Mode and Effect Analysis in PV systems involves:

- Identification of Failure Modes: Examining defects affecting PV performance.
- Assigning Severity, Occurrence, and Detection Scores: Based on predefined criteria.
- Calculation of RPN: Severity × Occurrence × Detection [23].
- Prioritization of High-Risk Failures: Addressing critical failure modes with mitigation strategies.

Table 4.1: Assigning Severity, Occurrence and detection for calculating RPN [17].

Score	Severity (S)	Occurrence (O)	Detection (D)
	Effect	Effect	Effect
10	Hazardous Effect	Almost Certain	No known techniques are available
9	Serious	Very high	Only unproven techniques are available
8	Extreme	High number of failure	Providing durability tests
7	Major	Moderately high failures	Slight likelihood that the problem will be detected
6	Significant	Medium	Low chance of detection of the problem.
5	Moderate	Low	Medium chance of detection of the problem.
4	Minor	Slight	Moderately high chance of detection of the problem.
3	Slight	Very few failures	Moderate likelihood of the detection of problem.
2	Very Slight	Rare number of failures	Strong chance of detection of the problem.
1	No	Almost never	The problem detection is highly likely

Table 4.2: RPN calculations for common PV failures [24,25]:

Failure Mode	Causes	Effects	(S)	(O)	(D)	RPN
Mechanical Failure						
Glass Cracking and Breakage	Bad system	Results in growth of hot spot and decrease the power.	9	2	2	36
Backsheet Delamination	construction defect	Reduced energy output.	10	2	1	20
Rusting of connecting wire	corrosion, aging.	Loss of efficiency	7	5	5	175
Electrical Failure						
Hotspot Formation	Aging	improper energy output	8	2	5	80
Connector Defects	Animals, strong wind, pulled cables	No energy output	9	5	3	135
Busbar and Gridline Defects	lack of maintenance	electrical/ structural damages with reduced energy output.	5	6	5	150
Environmental Failure						
Soiling	Bad system, aging, lack of maintenance	Structural damages with reduced energy output.	6	5	5	150
UV-Induced Degradatio	Improper maintenance	Loss of efficiency.	7	2	6	84

n						
Worm-like patterns snail trails	Inadequat e protective device.	Reduced energy output.	8	1	3	24

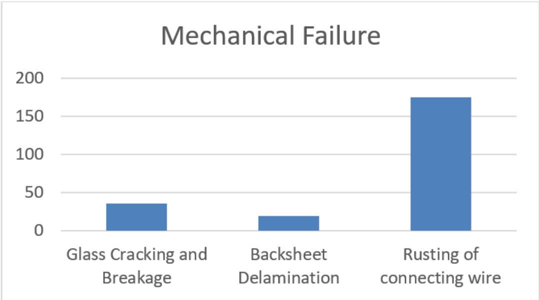

Figure 4.1: Graphical presentation of RPN value for different Mechanical Failures.

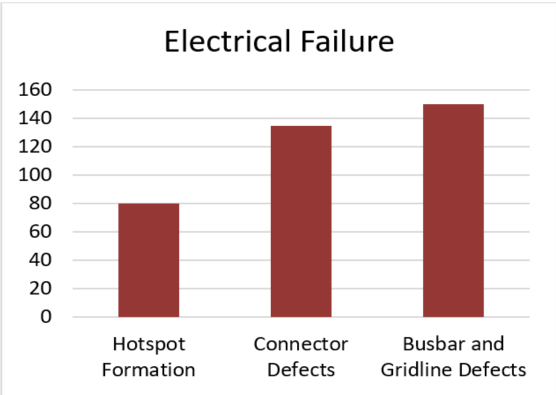

Figure 4.2: Graphical presentation of RPN value for different Electrical Failures.

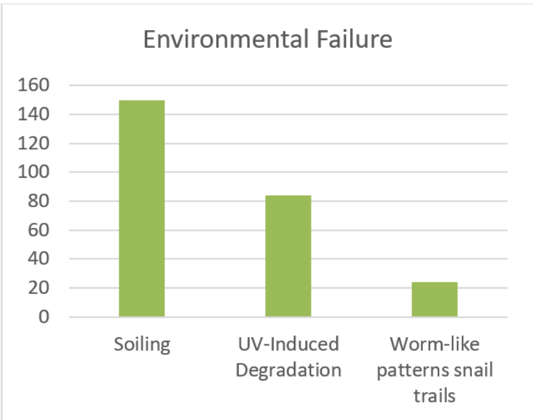

Figure 4.3: Graphical presentation of RPN value for different Environmental Failures.

The Proposed methodology framework for better results is as follows:

I. Study of rooftop solar panels based on research surveys and experimental research and identifies the existing research gaps and research opportunities.

II. Collection of degradation data by systematic sampling methods (sample size is 25) through visual inspection on rooftops solar panels and identify its defects.

III. Evaluation of risk using RPN Method to prioritize the identified failure modes and effects based on their likelihood and severity.

IV. Use Failure Modes and Effect Analysis tool to process and analyze the data and identify potential failure modes and its effects.

V. Devise an appropriate maintenance plan and strategies in order to analyse the results of FMEA and suggest maintenance actions for sustaining the overall reliability of the solar rooftop system.

VI. Experimental validation of effectiveness and feasibility of maintenance plan and strategies on solar rooftop plant and further identifying additional areas of improvement.

V. RESULTS AND DISCUSSION

The FMEA analysis revealed several critical failure modes and their associated causes and effects in rooftop solar plants. Common failure modes included:

• Solar Panel Degradation: Due to exposure to environmental factors such as UV radiation, temperature fluctuations, and moisture, solar panels may experience degradation, resulting in reduced energy output.

• Inverter Failure: Inverters are crucial components for converting DC electricity from solar panels into usable AC electricity. Inverter failures can lead to complete system shutdown.

• Electrical Connection Issues: Poor electrical connections can cause energy losses, overheating, and even fire hazards.

• Structural Integrity: Mounting structures may degrade over time, affecting the stability and safety of the solar panels.

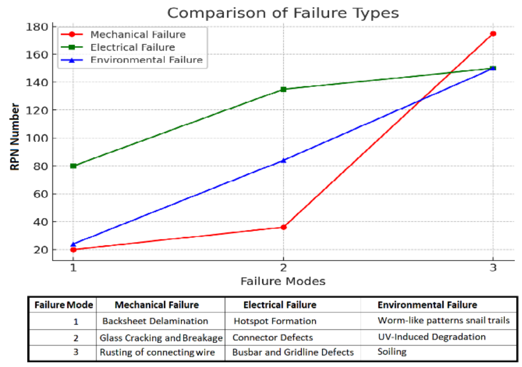

Fig 5.1: Comparison of RPN for mechanical, electrical and environmental failure

By identifying these failure modes and assessing their criticality, FMEA enables proactive maintenance and risk mitigation strategies. For example, regular inspections and preventive maintenance can address many of the identified issues before they lead to system failures.

Looking at the RPN number of different types of failure it is found that it's the electrical failure that has a high effect on photovoltaic panels and so should addressed on priority.

VI. CONCLUSION

This review highlights the significance of FMEA and RPN in assessing solar PV system reliability. By identifying critical failure modes and risk factors, manufacturers and operators can enhance preventive measures, optimize maintenance strategies, and improve overall system performance. Future research should focus on integrating advanced AI and machine learning techniques for more accurate and dynamic risk assessments.

VII. RESEARCH GAPS AND FUTURE DIRECTIONS:

Despite extensive research, gaps remain in:

- Standardizing FMEA methodologies for PV reliability assessment.
- Incorporating real-time monitoring with IoT-based FMEA frameworks.
- Evaluating economic impacts of failure mitigation strategies.
- Integrating AI-driven predictive maintenance models.

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