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# Failure Modes and Effects Analysis (FMEA) of a Rooftop PV System

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**Abstract:** ***The electricity requirements of the world including India are increasing at a very high rate. Only fossil fuel based generating system will not keep pace with ever increasing demand of the electrical energy of the world. Also generation by fossil fuel based power plant causes pollution. Thus new means of generation specialy based on renewable energy sources needs more attention. Utilising Solar energy source is thus becoming more popular as it has a potential of generating 750 GW in India. Rooftop PV system is one major option for generating electrical power as the urban environment provides a large amount of empty rooftop spaces and can inherently avoid the potential land use and environmental concerns. The present paper provides a comprehensive guide to ensure a trouble free & safe operation of rooftop PV system.***

**Keywords:** FMEA, Rooftop PV, Photovoltaic, Inverter, Failure Modes

## 1. Introduction

Solar PV modules converts sunlight into electricity. The electricity thus generated is Direct Current (DC). This needs to be converted into Alternating Current (AC) using an inverter. In case of rooftop PV system the panels are mounted on the rooftop using suitable mounting structures. PV systems are classified by their rated power output (the peak power they produce when exposed to solar radiation of 1,000 Watts per square meter at a module temperature of 25°C). It may be noted that the rooftop PV systems are not suitable for large scale generation. Rooftop PV systems on residential buildings typically feature a capacity of about 5 to 20 kilowatts (kW), while those mounted on commercial buildings often reach 100 kilowatts or more. The Table 1 provides an estimate of the roof area needed for several systems.

**Table 1:** Roof Area Needed in Square Feet

| *PV Module Efficiency (%)* | *PV Capacity (Watts)* | | | | |
|---|---|---|---|---|---|
| | *500* | *1000* | *2000* | *4000* | *10000* |
| 8 | 75 | 150 | 300 | 600 | 1500 |
| 12 | 50 | 100 | 200 | 400 | 1000 |
| 16 | 40 | 80 | 160 | 320 | 800 |

A typical rooftop PV system has following components
1. PV Panel - Converts sunlight to electricity. There are two kinds of modules: Thin-film, and Crystalline. Rooftop solar plants predominantly use crystalline panels because they are more efficient and therefore better suited to installations like rooftops where space is a constraint.
2. Batteries - Store electricity.
3. Charge Controller /Inverter- Manages the flow of electricity between the solar panel, battery and load. The inverter - Converts DC power from the solar panel and battery to AC power
4. Wires – For electrical connectivity among various components.

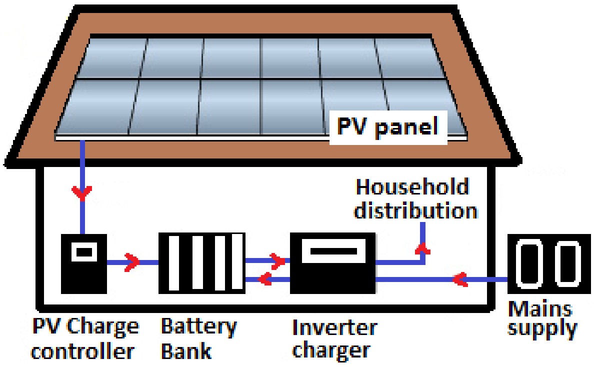


**Figure 1:** Rooftop PV system

## 2. FMEA

The Failure Modes and Effects Analysis (FMEA), also known as Failure Modes, Effects, and Criticality Analysis (FMECA), has its origin in the US military in the late 1940s.

The *failure mode* that describes the way in which a design fails to perform as intended;
The *effect* or the impact on the customer resulting from the failure mode; and
The *cause(s)* or means by which an element of the design resulted in a failure mode.

FMEA is a methodology developed to identify potential failure modes in a product or process, to determine the effect of each failure on system operation and to identify and carry out corrective actions. It may also incorporate some method to rank each failure to its severity and probability of occurrence. A successful FMEA activity helps to identify potential failure modes based on past experience with similar products or processes or based on common failure mechanism logic.

An FMEA is conducted with the following steps:
a) List all the components
b) The potential failure mode(s) for each component will be identified. Failure modes will include:

- complete failures
- intermittent failures
- partial failures
- failures over time
- incorrect operation
- premature operation
- failure to cease functioning at allotted time
- failure to function at allotted time

It is important to consider that a part may have more than one mode of failure. For each failure, the mode will be identified, the consequences or effects on system, property and people will be listed. Then the severity or criticality rating will be given with the help of statistical analysis. , which will indicate how significant of an impact the effect will have on the system.

**Table 2:** Severity ratings

| *Rating* | *Severity* | *End effect* |
|---|---|---|
| 1 | None | Effect will be undetected by customer or regarded as insignificant. |
| 2 | Very minor | A few customers may notice effect and may be annoyed |
| 3 | Minor | Average customer will notice effect. |
| 4 | Very low | Effect reconized by most customers |
| 5 | Low | Product is operable, however performance of comfort or convenience items is reduced |
| 6 | Moderate | Products operable, however comfort or convenience items are inoperable. |
| 7 | High | Product is operable at reduced level of performance. High degree of customer dissatisfaction |
| 8 | Very high | Loss of primary function renders product inoperable. Intolerable effects apparent to customer. May violate non-safety related governmental regulations. Repairs lengthy and costly. |
| 9 | Hazardous – with warning | Unsafe operation with warning before failure or non-conformance with government regulations. Risk of injury or fatality. |
| 10 | Hazardous – without warning | Unsafe operation without warning before failure or nonconformance with government regulations. Risk of injury or fatality. |

**-** For each mode of failure, the cause(s) are identified. The probability of occurrence can be determined from field data or history of previous. A subjective rating also may be made based on the experience and knowledge of the cross-functional experts.

**Table 3:** Probability of Occurrence Ratings

| *Rating* | *Occurrence* | *Failure Rate* |
|---|---|---|
| 5 | Very High: Failures must be addressed | Above 30% |
| 4 | High: Failures cause frequent downtime | 5-12.5 % |
| 3 | Moderate: Failures cause some downtime | 0.05-1.25 % |
| 2 | Low: Failures cause very little downtime | 0.001-0.01 % |
| 1 | Remote: Downtime due to failure is unlikely | Less than 0.0001 % |

**-** The controls currently in place will be identified that either prevent or detect the cause of the failure mode. The effectiveness of such control will be rated and estimated how well the cause or failure modes are prevented or detected.

**Table 4:** Control Effectiveness Ratings

| *Rating* | *Control effectiveness* |
|---|---|
| 1 | Excellent; control mechanisms are foolproof. |
| 2 | Very high; some question about effectiveness of control |
| 3 | High; unlikely cause or failure will go undetected |
| 4 | Moderately high. |
| 5 | Moderate; control effective under certain conditions |
| 6 | Low. |
| 7 | Very low. |
| 8 | Poor; control is insufficient and causes or failures extremely unlikely to be prevented or detected |
| 9 | Very poor. |
| 10 | Ineffective; causes or failures almost certainly not be prevented or detected. |

Risk Priority Number (RPN) plays an important part in the choice of an action against failure modes. After ranking the severity, occurrence and detect ability, the RPN can be easily calculated by multiplying these three numbers:

$RPN = S \times O \times D$

**-** Finally, actions will be taken to reduce risk of failure, which is the most crucial aspect of an FMEA. The FMEA should be reviewed to determine where corrective action should be taken and when. All failure modes of the system will be identified, documented and suitable actions will be recommended. Further action also may be taken in the form of design improvements, changes in component selection, the inclusion of redundancy in the design, or may incorporate change for improving safety aspects.

The results of an FMEA are usually documented in tabular format as shown in Table 5.

**Table 5:** FMEA tabular sheet

| *Part description* | *Failure modes* | *Severity* | *Results / Effects of failure* | *Cause of Failure mode* | *Occ* | *Controls* | *Det* | *RPN* |
|---|---|---|---|---|---|---|---|---|

## 3. FMEA of a Roof Top PV System

In this proposed work an effort has been made to identify all of the components to be evaluated. This will include all of the equipment / parts that constitute the Rooftop PV system. A comprehensive FMEA worksheet is shown in Table 6.

| *Part description* | *Failure modes* | *Severity* | *Results / Effects of failure* | *Cause of Failure mode* | *Occ* | *Controls* | *Det* | *RPN* |
|---|---|---|---|---|---|---|---|---|
| PV panel | Soiling or shading of panel | 9 | Reduction in energy output | Improper site selection/Installation | 5 | Proper site selection / Removal of Vegetation & obstructions | 3 | 135 |
| | | | | Accumulation of dust & soil | 5 | Regular maintenance | 2 | 90 |
| | Improper Tilt angle | 7 | Reduction in energy output | Non availability of geographical location data | 3 | Use weather data (Solar insolation level) | 2 | 42 |
| | Improper orientation | 7 | Reduction in energy output | Non availability of geographical location data | 3 | Use weather data (Solar insolation level) | 2 | 42 |
| | Fading in the heat | 9 | Reduced open circuit voltage | Weak PV modules | 2 | Selective shading test | 2 | 36 |
| | | | | Charge Controller failure | 2 | Charge Controller Field test | 2 | 36 |
| | Bypass diode short out | 8 | Reduced open circuit voltage | Lightning / Surge | 2 | Lightning / Surge protection | 2 | 32 |
| | | | | Improper material selection | 1 | Material Selection | 5 | 40 |
| | Bypass diode reverse connection | 10 | Damaged PV panel | Frequent connection and disconnection of the batteries | 2 | User Instruction | 3 | 60 |
| | | | | Lack of operating /maintenance manual | 2 | operating/maintenance manual | 4 | 80 |
| | Corroded or burnt terminals | 9 | Electric arc Shock/injury Hazard Fire | Material failure | 1 | Material Selection | 5 | 45 |
| | | | | Loose connections | 4 | Good installation practice/User training | 3 | 108 |
| | | | | Corrosion | 4 | Regular maintenance | 4 | 144 |
| | Loose or broken connections | 9 | Electric arc Shock/ injury Hazard Fire | Excessive torque or pressure | 4 | Good installation practice / user instruction | 4 | 144 |
| | Broken panel glass front | 10 | Electric shock/injury hazard Fire | Improper site selection | 1 | Proper site selection | 2 | 20 |
| | | | | Improper handling | 3 | Packaging / Handling | 2 | 60 |
| | | | | Hooliganism | 1 | No Control | n/a | - |
| | Defect in Panel mountings | 8 | Mechanical Breakage / Damage of panel Injury Hazards | Material failure | 1 | Material Selection | 5 | 40 |
| | | | | Improper installation | 3 | Installation by technician | 4 | 96 |
| | | | | Corrosion | 4 | Regular maintenance | 4 | 144 |
| Batteries | Swollen or cracked case | 9 | Injury Hazard | Overcharging | 1 | Visual Inspection | 2 | 18 |
| | Sulphation | 8 | Performance deterioration | Idle operation/ undercharging | 3 | Charge controller field test | 3 | 72 |
| | Dirt/corroded connectors | 9 | Discharge of battery | Irregular cleaning of the battery | 4 | Regular maintenance / User instruction | 4 | 144 |
| | | | | Corrosion | 4 | Regular maintenance/User instruction | 4 | 144 |
| | Not electrically connected | 9 | Open circuit | Loose / Broken connector | 2 | Packaging / Handling | 5 | 90 |
| | | | | Material failure | 1 | Material Selection | 3 | 27 |
| | Reverse connections are made | 10 | Damage to battery Damage to connection | Inadequate polarization or indexing | 1 | Manufacturing Inspection | 4 | 40 |
| | Intermittent failure & reduced battery capacity | 9 | Low energy output | Ageing | 4 | No control | n/a | - |
| | | | | End of lifespan | 5 | No control | n/a | - |
| | Low battery voltage | 9 | Low voltage | Faulty controller | 3 | Charge Controller Field test | 2 | 54 |
| | | | | Ageing | 4 | No control | n/a | - |
| | | | | End of lifespan | 5 | No control | n/a | - |
| | Completely discharge | 10 | No output | End of lifespan | 5 | No control | n/a | - |
| Charge controller / Inverter | Failure of control IC | 9 | Improper charging & discharging of the battery | Inferior design | 3 | Manufacturing Inspection/Design | 2 | 54 |
| | | | Damage to battery | Use of low quality components | 1 | Material Selection | 3 | 27 |
| | Short circuiting | 10 | Tripped protective gear | Improper connection | 1 | operating/maintenance manual | 3 | 30 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Shock/injury Hazard Fire | Fault in electrical wiring | 2 | Continuity testing | 5 | 100 |
| | Not electrically connected | 9 | Open circuit | Loose / Broken connector | 2 | Packaging / Handling | 5 | 90 |
| | | | | Material failure | 1 | Material Selection | 3 | 27 |
| | Overloading | 8 | Overheating Damage to the module | Improper selection of PV system | 1 | Electrical load calculations & study | 5 | 40 |
| | | | | Electrical Fault | 3 | Using Protective gears | 3 | 72 |
| | Low voltage output | 8 | Low voltage | Overloading | 2 | Electrical load calculations & study | 5 | 80 |
| | | | | Busting of fuse | 2 | Visual inspection | 2 | 32 |
| | | | | Abused Battery | 1 | Material Selection | 3 | 24 |
| | | | | Failure of PV system | 1 | PV system field test | 3 | 24 |
| | Overheating | 8 | Damage to PCB Fire Injury Hazard | Failure of heatsink | 1 | Material Selection / Manufacturing inspection | 3 | 24 |
| | Corroded or burnt terminals | 9 | Electric arc Shock/injury Hazard Fire | Material failure | 1 | Material Selection | 5 | 45 |
| | | | | Loose connections | 4 | Good installation practice/User training | 3 | 108 |
| | | | | Corrosion | 4 | Regular maintenance | 4 | 144 |
| Wires | Overloading | 8 | Overheating Fire | Insufficient conductor ampicity | 3 | User Instruction | 3 | 72 |
| | | | | Fault in the electrical system | 3 | Using Protective gears | 3 | 72 |
| | Insulation Failure | 10 | Short circuit – no power output, tripped protective gear Shock/ injury Hazard Fire | Pinched wire | 2 | Check for current leakage | 3 | 60 |
| | | | | Mechanical damage | 1 | Packaging / Handling | 5 | 50 |
| | Conductor failure | 8 | Open circuit – no output power | Repeated flexing of wire | 2 | Continuity testing | 4 | 64 |

The RPN is an optional step that can be used to help prioritize failure modes for action. In general, the failure modes that have the greatest RPN receive priority for corrective action. The RPN should not firmly dictate priority as some failure modes may warrant immediate action although their RPN may not rank among the highest. For using The RPN methodology The range of RPN values is divided into classes: For example

- From 1 to 50: No action necessary
- From 51 to 99: Corrective action is advisable
- For more than 99 : Immediate corrective action

This classification varies from system to system.

## 4. Conclusions

A FMEA analysis is a good help in finding better solution for a trouble free operation of the Rooftop PV systems. Using this systematic approach gives better understanding of system failures, their effects and remediation methods. Finding and preventing hidden failures is a very important task. Using the right solutions during manufacturing, packaging, installing and to end applications can reduce the risk of serious damage & failure of the system.

The analysis results as checklists and information on critical points at various levels. The FMEA report can be used to improve the system's reliability. Further research could apply this methodology to other PV systems, more components in any topology (e.g., MPPT, etc.), design of fault tolerance, and actual field failure rates. Even though FMEA models use a fixed failure rate, which might not be accurate since failure rates generally vary with time and area of installation, the proposed methodology serves the purpose of a comprehensive, straightforward, and versatile procedure for smooth operation of a Rooftop PV system.

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