Development of an integrated FTA and FMEA approach for failure analysis of solar photovoltaic systems

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Submitted by:

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CANDIDATE'S DECLARATION

I, Rupender, hereby certify that the work which is being presented in this thesis entitled "**Development of an integrated FTA and FMEA approach for failure analysis of solar photovoltaic systems**" being submitted by me is an authentic record of my own work carried out under the supervision of **Dr. Girish kumar, Associate Professor, Department of Mechanical Engineering, Delhi Technological University, Delhi.**

The matter presented in this thesis has not been submitted in any other University/Institute for the award of M.Tech Degree.

Rupender

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(2K19/PIE/12)

CERTIFICATE

I, Rupender, hereby certify that the work which is being presented in this thesis entitled "**Development of an integrated FTA and FMEA approach for failure analysis of solar photovoltaic systems**" in the partial fulfillment of requirement for the award of degree of **Masters of Technology in Production Engineering** submitted in the **Department of Mechanical Engineering** at **Delhi Technological University, Delhi**, is an authentic record of my own work carried out during a period from July 2020 to July 2021, under the supervision of **Dr. Girish Kumar, Associate Professor, Department of Mechanical Engineering, Delhi Technological University, Delhi.**

The matter presented in this thesis has not been submitted in any other University/Institute for the award of M.Tech Degree.

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ABSTRACT

There is a need of an alternate source of energy that is both reliable and affordable. Solar PV system is one of the source which is reliable but it has higher cost. As technology advances, the cost of harvesting energy decreases, but their lifespan is determined by several process fault/factors and their mitigation which is true in case of solar photovoltaic systems. To mitigate the faults, industries use various fault analysis techniques such as FTA, FMEA, RBD, etc. FMEA is the most commonly used tools. The results of FMEA are dependent on the knowledge and experience of the team carrying out the process, which can change the ranking of the faults due to the vagueness of the ideas of a different team member. In the proposed methodology, fuzzy logic is used to counter the vagueness of the ideas of a different team member. The suggested methodology combines the FTA and FMEA approaches as these are both time-consuming and inefficient when used individually. An integrated FTA and fuzzy FMEA strategy uses the FTA data as input to the FMEA process, then applies fuzzy logic to generate the fuzzy RPN value to prioritize the sequence of failure modes to mitigate first. Twelve failure modes are considered in this work. The results produced utilizing the integrated technique differed significantly from the standard method for intermediate failure modes. The proposed methodology can be applied to any industry, including manufacturing, automobiles, and pharmaceuticals.

Keywords: FTA, FMEA, Fuzzy FMEA, RPN, Fuzzy RPN

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Date: 12/09/2021

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CONTENT

LIST OF TABLES

LIST OF FIGURES

Chapter 1 Introduction

In today's world, one cannot imagine life without the use of energy. Electricity is the main form of energy used on daily basis in various domestic as well as industrial applications. The conventional source of energy like coal and petroleum products is being used for a long time for producing electricity. However, this is causing the depletion of natural resources and damaging the earth as these sources produce harmful products which degrade the environment. Global warming is one of the major problems mankind is facing which is caused by the excessive emission of carbon from the burning of coal and petroleum product. To tackle this problem the renewable source of energy are being increasingly used. Renewable energy consists of solar energy, wind energy, tidal energy, hydro energy, geothermal energy, etc.

The pace of investment is largely increased in renewable energy sector because of cost reduction and increased efficiency (Cepisca & Florin, 2014). There is a decreasing trend in prices of renewable energy in general and this is more visible in case of solar energy. This has prompted more investment in the solar energy sector. Global annual solar installation grew more than sixfold in the past decade, from 16 gigawatts in 2010 to 105 gigawatts in 2019(Wood Mackenzie, 2019). Renewable sources provide the long term certainty of the energy as compared to the conventional sources. There is a rapid growth in the Photovoltaic (PV) based solar power plant. In India, the installed capacity reached 35.12GW in june, 2020 (ministry of new and renewable energy, 2019). In 2015 Indian govt raised its target to 100GW solar capacity by 2022 with an investment of 100billion US dollars. In last decade, India expanded its solar capacity from 161MW to 37,627MW. A solar power plant with a capacity of more than 20 MW requires 7.9 acres per MW of total land area. Solar power plants at utility scale can be installed and developed effectively on the Indian subcontinent's wastelands. Because wasteland is unsuited for either residential or agricultural use, constructing utility-scale solar power facilities on it has no negative impact on agricultural systems (Rathore et al, 2017).

Despite, there are a lot of challenges faced by the PV solar industry in their installation. There are several factors which affect the performance of the PV module such as irradiance, temperature, orientation and tilt angle of the module, dust, shading of PV module, and many more environmental factors such as hailstorm and snow storm etc.(Kumar and Kaur, 2014).

Most of the researchers focused on finding ways to identify the failures and failure modes in PV systems according to the working environment of the PV system. But none of those suggest the ways to eliminate or reduce these failure modes or their causes. So, the author tries to find the failure modes and suggest the ways to eliminate or reduce them in context with India as India growing its solar capacity rapidly. Because of the above discussion, the study of failure analysis of the photovoltaic system is important that will help in devising PV systems with higher efficiency and low cost.

There are numerous problems encountered in PV systems which reduce the efficiency of the PV systems by 20% approximately (Tur et al, 2019) like temperature, shading, soiling, mismatch, inverter efficiency etc. Many researchers investigated the failure in PV systems. Some of the common occurring defects in PV systems are: Encapsulate and back sheet yellowing/browning with and without power loss, encapsulate and back sheet delamination, bubble formation, oxidation of busbars, discoloration of busbars, corrosion of connections, back sheet cracking, hot spots, cell breakage (cickaric et al, 2018), micro cracks, diode failure, PV module failure (Mellit et al, 2018), Adhesion degradation, interconnect degradation, moisture intrusion (Quintana et al, 2002).

Industry is striving for better quality for PV systems. There are various ways suggested for the timely fault detection in PV systems so that appropriate measures are adopted to avoid the system failures. Some commonly used techniques to detect faults in the system are (Yang and Yeh, 2015): The statistical and signal processing approach, current-voltage measurements, I-V characteristics analysis, power loss analysis, electroluminescence, infrared imaging, visual inspection. These are required for the optimum performance and secure functioning of final product.

In this work, an integrated FTA &fuzzy FMEA approach is proposed to investigate the possible failure mode of the PV system which needs to mitigate first.

Chapter 2 Literature Review

Photovoltaic module dependability has always been one of the most essential topics, as long-term dependability and longevity is the key to entire system performance and warranty. The photovoltaic’s (PV) business has risen significantly, and as a result, the number of module manufacturers has increased as well. Defect or failure management is critical for maximum performance, and their detection is necessary to ensure the end product's secure functioning and functionality.

This chapter deals with the literature of the photovoltaic systems, their failures, fault detection techniques and failure analysis methods.

A photovoltaic system, often known as a PV system or a solar power system, is a power system that uses photovoltaics to provide usable solar energy. It is made up of several components, including solar panels for absorbing and converting sunlight into power, a solar inverter for converting the output from dc to ac, as well as mounting, wiring, and other accessories for putting the system together. PV systems are not to be confused with other solar technologies like concentrated solar power or solar thermal, which are used for heating and cooling, because PV systems transform light directly into energy.

The size of PV systems varies from small rooftop systems to large utility-scale power plants with hundreds of MW of capacity, from small to large, from rooftop to building integration. The majority of PV systems are now grid-connected, with off-grid or stand-alone systems accounting for only a small percentage of the market.

2.1 Failures in PV systems

Various types of failure scenarios can occur during the functioning of a PV system. The failure mechanisms are determined by the design of the components, the manufacturing process, type of installation, the electrical setup, and the weather conditions (Colli-2015).

Onshore and offshore, PV systems can be found all around the world. They are exposed to all or any of the world's climate zones. Overall performance losses are caused by environmental stresses, which have an impact on the system's electrical performance. They would encounter the accompanying climate stress elements if they rely on the installation like solar irradiation including UV irradiation, humidity, wind, snow, rain, hail, high / low temperatures, temperature variations, salt, sand, dust, gases, orientation and angle (Kumar and Kaur-2014), Encapsulate and back sheet yellowing/browning with and without facility loss, encapsulate and back sheet delamination, bubble formation, oxidation of busbars, discoloration of busbars, corrosion of connections, back sheet cracking, hot spots, cell breakage (Cickaric et al-2018), shading losses, dc/ac inverter efficiency losses, loss of reflection, spectrum loss, dc/ac cable and diode losses, radiation losses, disagreement losses, degradation thanks to potential (Tur et al-2018).

Future stability issues such as lamination disintegration of backing material, bubbling at solder spots, fissures in backing material, module delamination, solder-joint degradation, hot spots, encapsulant discoloration, mechanical damage, and cell degradation will continue to exist despite the continuous evolution of manufacturing practices (Quintana et al-2002, Yang-2014).

2.2 Fault Detection Techniques

The increasing demands on technical plant dependability and safety necessitate early defect diagnosis. Methods are being developed that allow for earlier fault detection than the traditional limit and trend checks using a single process variable. In high-cost and safety-sensitive processes, fault detection is vital. Early diagnoses of process flaws can assist prevent the occurrence of abnormal events. Defect detection, isolation, and recovery (FDIR) is a subfield of control engineering that deals with monitoring a system, detecting when an issue occurs, and determining the nature and location of the fault. D. Miljković(2016) defines the fault, failure and malfunction to know the difference between them. A fault is an unallowable departure from the suitable, typical, standard condition of at least one system characteristic property. Whereas a failure can also be defined as a long-term loss of a system's capacity to execute a required function under specified operating conditions. A malfunction is an irregularity in the performance of a system's desired function that occurs regularly.

Model-based, hardware-based, and history-based fault detection approaches are the three most common types. The following sections go over each of the categories. (A.Mouzakitis-2013):

A. Model-Based Fault Diagnosis: This type of diagnostic usually employs a model based on a basic grasp of the physics of the plant or process. Model-based defect diagnosis approaches are often divided into two categories: qualitative and quantitative.

    (a) Qualitative methods: A qualitative model-based fault detection technique is used to characterize the input-output relationship between a plant's various process units. Examples include fault trees, diagraphs, abstraction hierarchy, and fuzzy systems.

    (b) Quantitative Methods: Rather than using traditional formulas, quantitative models-based fault diagnosis approaches are based on mathematical functions defining a plant's input-output relationship, including analytical redundancy, parity space, Kalman filter (KF), parameter estimation, and diagnostic observers.

B. Hardware-Based Fault Diagnosis: In order to perform this method, the fundamental physics of the plant or process must not be quantified mathematically. Examples of hardware-based fault detection techniques are hardware redundancy, voting mechanisms, specific hardware testing, and frequency analysis.

C. History-Based Fault Diagnosis: There is a lot of overlap between model-based fault diagnosis and history-based fault diagnosis in the fault diagnosis literature. A model-based fault diagnosis approach, as previously described, is typically based on an understanding of how plants and processes work. A mathematical model of the physics of a plant or process is not used in this method; instead it uses input and output data that are known and observed. To determine residual errors, a model is created to mathematically link inputs to outputs to form a history-based fault detection technique. This method is applied to the critical process to determine residual errors. FL, neural networks, clustering, self-organizing maps (SOM), statistical approaches, expert systems, and pattern recognition are all examples of history-based defect diagnostic approaches.

2.3 Failure analysis methods

The process of collecting and evaluating data to establish the reason for a failure is known as failure analysis. Machinery failures, according to Bloch and Geitner(1994), disclose a chain reaction of cause and effect, generally a weakness typically referred to as the symptom. Failure analysis, if done correctly and acted upon, can save money, lives, and resources.

Every product or process has failure modes. Designers can focus on and comprehend the implications of potential process or product risks and failures by analyzing prospective failures. To quantify the repercussions and implications of failures, several systematic approaches have been established like Checklist, FMEA/Failure Modes, Effects, and Criticality Analysis (FMECA), Fault Tree Analysis (FTA), Event Tree Analysis (ETA), Hazard & Operability Analysis (HAZOP), What-If Technique, these are described below (V. Fthenakis et al.-2003):

- **Checklist -** A checklist is a series of instructions in the form of bullets or questions that are designed to facilitate a methodical EHS assessment of a process while also encouraging analysis and discussion. To construct checklists, professionals who have performed many hazard investigations interact with experts in the process being evaluated. Safety items prescribed by rules, regulations, and industry safety standards will be included on a checklist. Checklists are extremely useful when doing a safety self-assessment or audit of a process or facility.

- **What if Techniques -** The "What if" analysis is a brainstorming technique in which experts pose hypothetical questions about what could happen if something horrible happens. Experienced personnel can recognize accident circumstances and their repercussions through questioning, analyze current precautions, and suggest risk reduction strategies. The team composition determines the degree of completeness with which this plan is implemented. It can be quite effective when the team is well-versed in the technique. It is, however, a straightforward strategy that might yield results in just a few hours of meetings.

- **HazOp Analysis -** A Hazardous Operations Analysis (HazOp) is a systematic review of a system, process unit, or operation to identify accident-initiating scenarios. The HazOp team investigates the design and aim of a system or operation one step at a time. The system under examination is divided into nodes, which give a logical separation of the main subsystems to be investigated. Examining documentation documents such as drawings (PIDs and PFDs), component specifications, and logical control programmes is required as part of the procedure. HazOp searches for physically conceivable deviations from the design purpose using a collection of guidewords and system parameters. The team focuses on variations that could result in potential EHS hazards. The analyses' purpose is to be both scientific and rigorous, as well as open and innovative. When the causes of a deviation are determined, the team assesses the probable repercussions based on prior experience; for potentially damaging effects, consequence analysis techniques (atmospheric dispersion models, blast analysis models) are utilized to calculate the level of risk.

- **Event Tree Analysis (ETA) -** The term "event tree" refers to a graphical representation of the likely outcomes of an accident-causing event (e.g., a failure of specific equipment or procedure). Event tree analysis can be used to identify potential accidents in a complex system. A single analyst with a good understanding of the system may construct an event tree, but a collaborative method is ideal since it fosters brainstorming, which leads to a more thorough study. Fault tree analysis can be utilized once an ETA has identified the individual accident sequences to determine the particular combinations that could result in an accident.

- **Fault Tree Analysis (FTA) -** It can be used to calculate the failure sequences and probabilities of complex and unpleasant occurrences like catastrophic fires and automatic fire prevention system failures, as well as to comprehend their likely causes in terms of more basic events.

  The logical links between the main, intermediate, and top events are depicted in a fault tree. When creating a fault tree, the failure of interest is included as a top event. Working backward, all failures that could lead to the top event are determined. This cycle is repeated until failures occur that can no longer be mitigated or measured. This collection of logical relationships can be joined with Boolean algebra to form a logical expression that relates the top event to a group of primary events. A minimal cut set of primary events is a collection of events that is adequate to produce the top event in one variant of this statement.

- **Failure Mode and Effects Analysis -** A Failure Modes and Effects Analysis (FMEA) is a technique for analyzing equipment made up of components with well-defined failure modes. An FMEA will list the failure modes of the equipment and their implications on the system that the equipment is a part of or interacts with. A piece of equipment's failure mode describes how it fails. The failure mode's outcome is determined by the system's response to the equipment breakdown. An FMEA's purpose is to find single failure modes that may cause or contribute to an accident. Human factors are rarely considered in an FMEA, yet an equipment failure mode is the result of an operating error.

The vehicle industry prefers the FEMA method. Ford Motor Company, for example, mandates that all of its suppliers conduct thorough FMEAs on all of the designs and procedures they offer. Furthermore, the PV manufacturing industry should demand that their suppliers conduct FMEAs at the functional level of new equipment at the very least. FMEA is a hazard analysis method that additionally evaluates equipment reliability to ensure that it meets client specifications. An FMEA is intended to identify specific equipment and system failure scenarios rather than a comprehensive list of potential equipment failures that could result in an accident.

FMEA is employed with proprietary software to match the results for turbine design to spot the weak points of turbine , in order that it are often more cost effective (Hoseynabadi et al-2010). FMECA is performed to seek out the failure modes then Fuzzy TOPSIS is applied to prioritize the identified failure modes (Carpitella et al-2017). In shipping industry to scale back the collision and grounding of ships FTA is employed (Ö. Uğurlu et al-2013). HAZOP is employed with Analytic Hierarchy Process (AHP) and TOPSIS with fuzz and TOPSIS with fuzzy member to prioritize the hazards (Cheraghi et al-2019). Truss structure damaged is detected by using structured what if technique (SWIFT) in two stages (Naderi et al-2020).

Chapter 3 PV Solar system

A system is made up of interconnected or interacting parts that follow a set of rules to produce a logical whole. A system's constraints, structure, and purpose are specified and reflected in its functioning, which is surrounded and influenced by its surroundings. The conversion of light into electricity using photovoltaic materials (semiconducting materials that exhibit the photovoltaic effect) is known as photovoltaics. Therefore, a photovoltaic system, often known as a PV system or a solar power system, is a power system that uses photovoltaics to provide usable solar energy. A solar PV system's photovoltaic cells and panels are vital and interconnected components. Photovoltaic cells make up the majority of solar panels, and they are a crucial component of a solar system. The issues related to solar PV systems are discussed as follows:

- Cost - Initially, the cost of purchasing a solar system is quite high. This price includes solar panels, inverters, batteries, wiring, and installation. Nonetheless, because solar technology is developing all the time, it's reasonable to expect prices to continue to drop in the future.
- Weather-Dependent - Solar energy can be collected on overcast and rainy days, however the effectiveness of the solar system is diminished.
- Expensive - Solar energy can either be used immediately or stored in big batteries. These solar batteries are utilised in off-grid solar systems and can be charged during the day and used at night. This is an excellent way to utilise solar energy throughout the day, but it is also rather costly.

- Large space required - Solar PV panels require a large amount of area in order to absorb as much sunlight as possible, so the more power you wish to generate, the more solar panels you'll need.
- Pollution - Solar energy can be associated with pollution, despite the fact that pollution from solar energy systems is significantly lower than pollution from other sources of electricity. Greenhouse gas emissions have been connected to solar system transportation and installation. In the manufacture of solar pv systems, certain hazardous compounds and dangerous materials are employed, which may have an indirect impact on the environment.

3.1 Common challenges with solar system:

Over the last few decades, many people have discovered that solar panels are a great investment. In a number of ways, they help both commercial and residential structures. They also help to protect natural resources and the environment as they relying on the sun rather than the grid.

Solar panels are low-maintenance, so you should be able to reap the benefits with minimal work if you opt for a solar power system. However, nothing is absolutely risk-free. Problems do occur, so if you detect anything wrong with the way your system is operating, you should solve it as soon as possible before it worsens.

The following are the most typical issues with solar panels:

- Internal corrosion and delamination - Internal corrosion could occur if water seeps inside the panel. Make sure the panels are air and waterproof, and that all of the solar panel's components are laminated under vacuum pressure to avoid this problem.

- Electrical issues - Solar panels will not function correctly if the wiring is damaged. It is possible for loose connections, corrosion, and oxidation to decrease electricity output.
- Micro-cracks – Microcracks are a typical problem with solar panels, and they can reduce the system's efficiency. Microscopic cracks in the panel are difficult to perceive with the naked eye. The cracks may also grow over time and in response to substantial weather changes. The main sources of cracks include PV module production, as well as temperature and seasonal factors. They can also occur as a result of inefficient freight handling.
- Hot spots - One of the most common problems with solar or PV systems is hot spots. They have the ability to decrease solar panel performance and render them unfixable. When panels become overheated and overworked, hot spots emerge. A variety of factors contribute to them, including the accumulation of dirt on the panels. They can also be caused by poor soldering, which results in low resistance in the panel's power-generating area. The performance and lifespan of solar panels may be harmed as a result of this issue.
- Effect of PID - Degradation induced by potential is called PID. This can be caused by a voltage imbalance between the solar panel and the earth. In the primary power circuit, there is a partial voltage discharge. As a result of this, the PID effect can reduce the efficiency and performance of panels while also shortening their lifespan.

- Birds - Solar systems are at risk from those beautiful little birds. Consequently, the panels might malfunction if their nests form beneath the panels.
- Snail trails - Solar panels are also prone to contamination from "snail trails." This term is derived from the brown lines that appear on your panels and look like snails are walking across them. Snail tracks form after several years. The tracks are caused by a variety of factors, such as the use of poor silver paste (in the production of the panels). Encapsulating material and silver paste oxidize when moisture is present in the system. The pollution of snail trails could also be caused by minor defects in the PV system. Solar systems suffer from this problem which results in premature failure.
- Inverter problems - Solar panels use an inverter to convert the direct current from the sun to an alternating current. An inverter is a box that is usually found on the second or third level of a building. Inverters are not as long-lasting as solar panels, which can last up to 20 years. Inverters are replaced every 10 to 15 years on average, according to solar customers.

Chapter 4 Methodology

Due to the broader application of technologies in today’s world, various engineering fields are vulnerable to a spread of risks in engineering projects (Millerand Lessard-2001). In rail engineering field, there are risks related to production that require to be analyzed to make sure safety (Wilson et al-2009). There are different issues are found in field observations of PV systems like system cost, premature failure, site access logistics, poor or unavailable maintainence etc (Valer et al-2017). because the energy demand is growing everyday, need of more efficient system is additionally increasing. The methodology of applying symbolic logic to FMEA is usually recommended within the literature (Hayati and Abroshan-2017). Fuzzy FMEA improves the result of conventional FMEA technique (Xu et al-2002). Hence, fuzzy assessment of the traditional FMEA methodology has been administered to enhance the results. Before applying Fuzzy FMEA technique, Fault Tree Analysis (FTA) is typically employed to acknowledge the basis causes of the failure modes (Shafiee et al-2019). FTA helps find the basis causes of the failure modes and prioritizing the preventive actions on derived causes (Peeters et al-2018). A combined methodology of FTA and FMEA has been implemented before, but symbolic logic has been rarely incorporated (Bluvband et al-2005). Therefore, integrating FTA before Fuzzy FMEA is the main objective of this research.

4.1 Fault Tree Analysis

Fault Tree Analysis (FTA) is predicated on the principle of placing a system failure at the highest and determining the causes by working downwards with a logical tree.

FTA may be a top-down failure path technique which is predicated on Boolean logic. It establishes a relationship between two events by using logic gates. These relationships are arranged within the sort of a tree by using logic symbols. this permits the expert to assess the basis causes of a specific system failure. When a failure mode is to be studied, the first failure is placed at the highest whereas its causes are placed at the bottom level (Vesely-2002). A probability is assigned to every path of the fault tree and paths with the very best probability combination are selected for risk mitigation. It is often applied to a good range of applications. FTA has been used for managing fire safety of hotels (Hu-2016). In biology, FTA has been applied to cell diagnosis (YousfiSteiner et al-2012). Further, FTA has been wont to diagnose faults in robots (Jia et al-2008). FTA also can be applied in accordance with FMEA for risk analysis and mitigation (Peeterset al-2018). This integrated FTA and FMEA methodology has been applied in ergonomics and quality management (Miszta-2010l). It’s also seen its application in various mechanical plants and their operations like hydraulic turbines (de Queiroz Souza and Álvares-2008).

FTA consists of 5 major steps which are to be performed sequentially so as to spot the risks related to a specific system. These steps are as follows.

Step 1: Identification of the hazards

It is important to spot the top-level event of the fault tree or the essential failure mode. Various factors like time to failure, safety impact, functioning impact, environmental impact etc. are taken under consideration.

Step 2: Detailed system study

The required system information is collected by the experts. this will be done supported past experience, various systems literature, documents, customer feedback, etc. The potential hazards and their causes are listed. A probability of failure is assigned to every event, which is significant for risk prioritization.

Step 3: Creating the fault tree

The events listed in step 2 are arranged within the sort of a logical fault tree and therefore the top events are logically expanded till the bottom level or the first causes, where the team can actually affect these causes. The risks are classified as critical, high, minor and acceptable/low risks.

Step 4: Classifying the risks

Risk related to each failure is estimated. this is often done by evaluating the failure probability of varied path combinations which initiate to a specific failure mode. Greater the probability of failure, higher is that the priority assigned thereto failure mode. Critical and high risks involve immediate action to mitigate these risks.

Step 5: Mitigating the risks

Risk mitigation could also be of varied types, counting on the criticality of failure encountered and also, the sort of industry under analysis. For follow up, various logs and records are kept for the last word mitigation of every undesirable risk. Risks which are critical to the functioning of the system are chosen to be mitigated with a better (Sherwin et al-2016).

4.2 Failure Modes and Effects Analysis

Failure Modes and Effects Analysis (FMEA) may be a method that permits different organizations to anticipate failure during the planning phase of the merchandise by identifying all of the possible failures during a design or manufacturing process (Cassanelliet al-2006). Failure modes are defined because the modes, or ways, during which something could also be sure to fail. Further, failures are defined because the errors or defects which may be potential or actual, especially those that affect the customer. Effects analysis refers to studying the results of these failures. Therefore, FMEA may be a step-by-step approach which is implemented to spot all possible failures during a manufacturing, design or assembly process, prioritize them and take actions to lower the failure modes.

Failures are prioritized consistent with the seriousness of their consequences, frequency of their occurrence, and easiness of their detection (Stamatis-2003). the first purpose of FMEA is to require appropriate measures to eliminate or limit failures, starting with the risks with the very best priority. FMEA keeps a record of the present knowledge and actions taken against failures to be used in continuous improvement (Lolli et al-2016). Another modification of this system, referred to as FMECA model for reliability analysis, has also been implemented in aircraft equipments industry (Jun and Huibin-2012).

FMEA generally comprises six steps, with following activities at each step. The steps are separated to make sure that only the specified members of the team are present for every step. This enables for activity prioritization and efficient usage of team time (Song et al-2007).

Step 1: FMEA team formation

This comprises constituting a cross-functional team of individuals from different departments having adequate knowledge about the method, product, design and wishes of the customer. Departments generally included are: design, manufacturing, internal control, inspection, reliability, testing, maintenance, purchasing, sales, marketing, and customer service.

Step 2: Severity ranking

This step involves determining the seriousness or severity of every effect. this is often called rating of severity, or S. Severity is assessed and marked on a scale of 0 to 1, where 0 is that the least significant and 1 is that the most vital risk.

Step 3: Occurrence ranking

In this step, the occurrence is decided for every cause. this is often called rating of occurrence, or O. This rating provides the failure probability occurrence thanks to a specific cause during the lifecycle of the merchandise. Occurrence is additionally assessed and marked on a scale of 0 to 1, where 0 is remote or highly unlikely and 1 is extremely persistent.

Step 4: Detection ranking

For controlling each cause or failure mode, we determine its rating of detection, or D. This rating depends on how likely is that the detection of the cause or its failure mode before it affects the customer. Detection is additionally assessed and marked on a scale of 0 to 1, where 0 means the detection is nearly certain and 1 means the detection is completely uncertain.

Step 5: RPN calculation and task assignment

Based on the values of S, O and D, the RPN (Risk Priority Number) is calculated, which equals S × O × D. These numbers help in ranking or prioritizing potential failures within the sequence and tell us the risks on which corrective actions got to be taken so as to mitigate their criticality. These are identified and tasks are accordingly assigned to the responsible team members.

Step 6: Results and review

As actions are completed order wise, the results of the method are noted and therefore the design is reviewed to spot new failure modes alongside their RPN for continuous improvement.

Fuzzy RPN is calculated to remove the restrictions of traditional FMEA (Gargama and Chaturvedi-2011).

4.3 FUZZY Logic

While executing FMEA, various difficulties like vague information, relative importance ratings, decisions on same ratings, and opinion difference among experts arise. These problems often tend to scale back the validity of the results. Assigning a value from 0 to 1 to each aspect that determines danger can be a difficult undertaking for a multi-disciplinary team, and it can lead to significant discrepancy in the study (Yeh and Hsieh-2007). Hence, Fuzzy FMEA technique is employed to attenuate this ambiguity in RPN calculation (Kumru and Kumru-2013). "A fuzzy set takes values from the interval [0, 1] and is characterized by a membership function m(x), which represents the connection among different elements. Fuzzy sets are defined for specific linguistic variables, which may be calculated by triangular fuzzy numbers (TFNs) or trapezoidal fuzzy numbers (ZFNs)."Instead of complete inclusion or exclusion, symbolic logic with FMEA measures the degree of membership during a particular class. Failure ratings can then be calculated by the fuzzy values of severity, occurrence and detection and therefore the overall fuzzy RPN. Therefore, Fuzzy FMEA technique has been utilized in risk analysis in many fields. This system has seen its use within the risk assessment and management housing industry (Abdelgawad and Fayek-2010). Further, various mechanical systems like welding robots have also implemented Fuzzy FMEA technique (Luan-2016). Healthcare industry is one among the riskiest industries which makes it indispensable to research the associated risks accurately (Chanamool and Naenna-2016).

Fuzzy logic is employed for the calculation of fuzzy RPNs. It comprises of three steps which are as follows.

Step 1: Choosing a fuzzy membership function

Membership function is one which specifies the degree of belongingness of a given input to a group. This is often called degree of membership. Degree of membership is that the output of a membership function whose value always lies between 0 and 1, where 0 means complete exclusion and 1 means complete inclusion. Membership functions are vital within the process involving fuzzification and defuzzification of a FLS (Fuzzy Logic System), to convert crisp values to fuzzy values and the other way around.

There are different sorts of membership functions (as shown in Figure 1) such as: Triangular, Trapezoidal, Piecewise linear, Gaussian and Singleton.

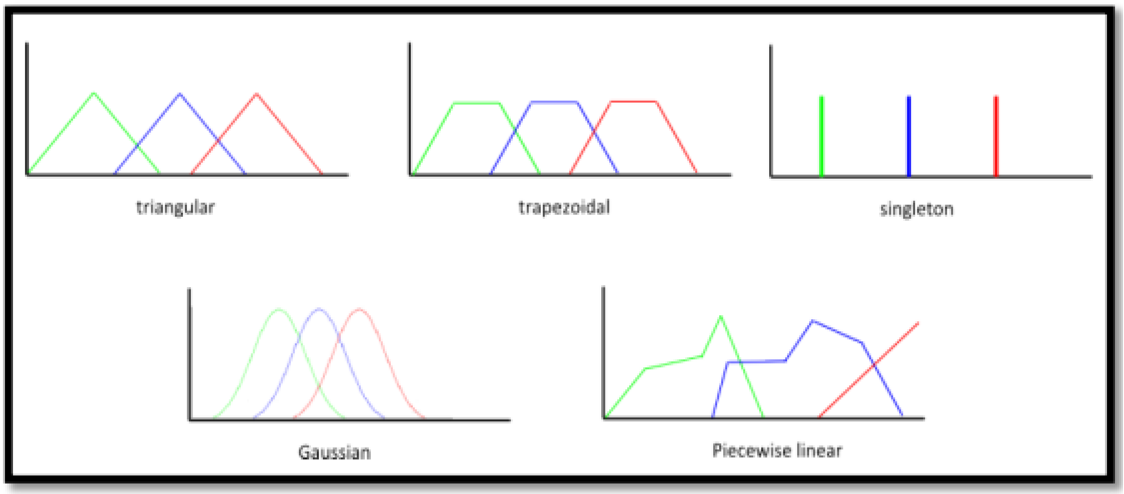

Figure.4.1 Different forms of membership functions

There is no straightforward rule of selecting a fuzzy membership function. An appropriate membership function is chosen supported the configuration of the matter (Chopra et al-2005).

Step 2: Fuzzification

Fuzzification is that the process of adjusting crisp values into a fuzzy value. this is often achieved with the various sorts of fuzzifiers (membership functions). during this study, a triangular fuzzy membership function has been used (Liang et al-2013). It are often defined by three values and its degree of membership changes linearly with change in input values (Pedrycz-1994). Since the values of severity, occurrence and detection vary linearly, this linearity is additionally observed within the calculated RPNs. Further, as these values don't occupy the height , we elect a triangular fuzzy membership function because it is linear and features a single peak (Xia-2010).Consider the triangular fuzzy number T = (l, m, u) where u and l are upper and lower limits respectively and m is that the vertex of Triangular formed. Membership function of the triangular fuzzy number is defined as follows:

$$\mu_x = \begin{cases} 0, \ x \leq l \\ \frac{x-l}{m-l}, l \leq x \leq m \\ \frac{x-m}{u-m}, m \leq x \leq u \\ 0, \ x \geq u \end{cases} \qquad (1)$$

Step 3: Defuzzification.

Defuzzification is that the process of converting a fuzzy number to a crisp value. There are several methods of defuzzification like centre of gravity (COG), mean of maximum (MOM), etc. (Van and Kerre-1999). During this study, the COG method returns the worth of the centre of area under the curve (Voskoglou-2016). The COG method is that the best defuzzification method when fuzzification of parameters is completed employing a triangular fuzzy membership function (Runkler-1996). For discrete triangular linear functions, the COG method is obtained by moments of area as defined by:

$$c = \frac{\sum_{c_i} c_i u_c(c_i)}{\sum_{c_i} u_c(c_i)} \qquad (2)$$

The first step during this methodology is system identification; an entire knowledge of the system is obtained using various system logs, records and human experiences. The system is then weakened into its various smaller constituents to form its analysis easier and more efficient (Layzell and Ledbetter-1998). On analyzing the system, the failure modes related to it are listed and various causes resulting in these failures are identified. Further, these failure modes and their causes are arranged within the sort of a fault tree. The basis causes to be placed at the bottom level of the fault tree are identified. These form the idea of FMEA. Severity, occurrence and detection of those failures are rated and RPN is obtained by multiplying these factors. These risks are then ranked consistent with their RPN values. Now, the ratings of severity, occurrence and detection are calculated using symbolic logic. Fuzzy FMEA approach helps to eliminate the vagueness or uncertainty during a given class. The new fuzzy RPN is obtained by multiplying these ratings. These risks are then ranked consistent with their fuzzy RPN values. The risks to be mitigated are selected consistent with their RPN values. Higher RPN value means the danger has got to be mitigated with a better priority. The flow chart depicting these steps is given in Figure 2.

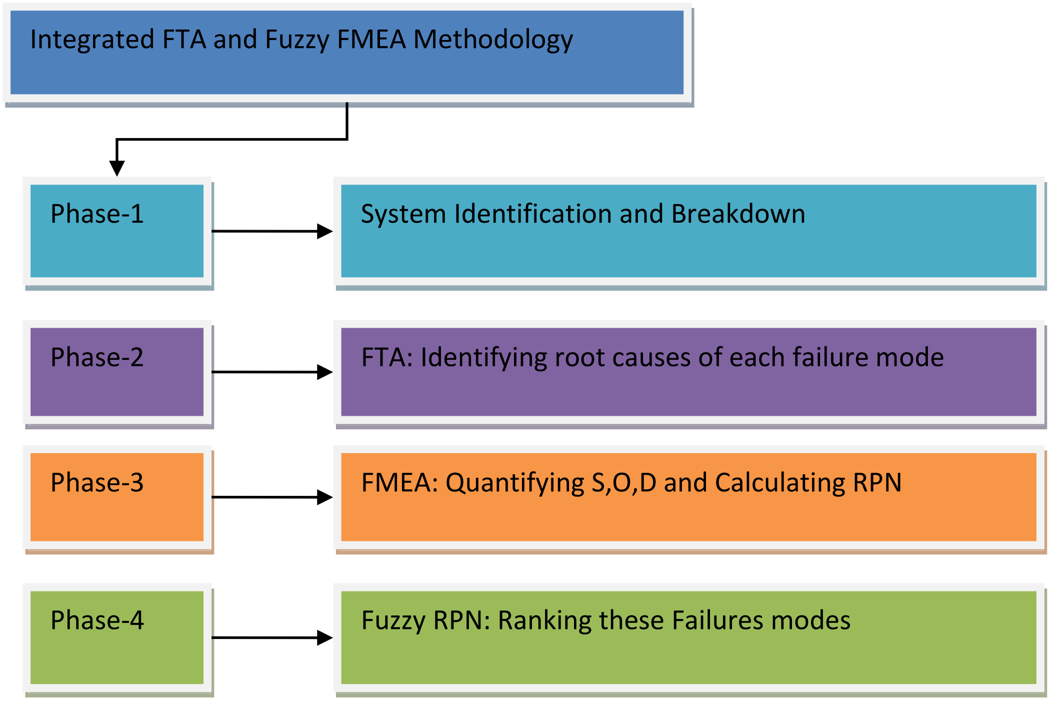

Figure.4.2 Methodology Flowchart

Chapter 5 Illustration

In contrast of conventional energy generation methods to produce electrical energy from coal, oil, natural gas; non conventional methods can produce electrical energy for longer life span without much compromise to the nature and natural resources. Solar energy attracts the researchers more as it is much more clean and abundant energy than any other form of non conventional energy source and harnessing it doesn’t produce bad effect on the earth’s environment. Solar energy is fully pollution-free, producing no air pollution, water pollution, or greenhouse gas emissions. It is also carbon-free; when power is generated by solar panels, no harmful emissions are discharged. It also cuts down on the use of precious resources. Therefore, governments also investing in setup of more and more solar power plants than any other non conventional plant for energy generation. There are more than 40 solar power plants in India producing atleast 10MW of energy along with two plants producing more than 2000MW of energy in Rajasthan and Karnataka.

However, there is no such thing as perfect so there are many risks or factors that affects the life and energy generation capacity of the solar systems. Therefore, expert’s discussion was held between power plant engineers, researchers, senior professors of reputed institutes and people from solar industries. Based on this, the major risks and failure modes were noted down. A questionnaire was provided to a cross-functional team comprising these members and they were requested to rate the severity(S), occurrence (O) and detection (D) of these failure modes. The ratings obtained were used for this study.

5.1 FTA applied to a Solar system

While applying the FTA to solar systems, failure modes are put on the top of the tree. Next, various direct causes logically enlisted are placed below the failure mode. This way tree is expanding logically till every cause is not placed below its consequence. These cause and consequences are connected with logic gates. Fault tree expanded till the time root cause is placed at the end of tree and no further expansion is possible. Now this root cause will make the basis of FMEA. PV solar system can fail through various modes which are enlisted in the figure 5.1.

Figure.5.1 Failure modes of solar system

5.2 FMEA applied to solar system

A cross functional team is made from various departments to identify the potential failure modes. These failure modes are ranked by the experts from the industry in terms of severity, occurrence and detection on a scale of 0-1 and listed in table 5.1. Then based on these ratings RPN value is calculated by multiplying the ratings of severity, occurrence and detection.

After calculating the RPN value, these risks are arranged in descending order of their RPN value as in table 5.2. Graphical representation of S, O and D is also presented between different risks in figure 5.2 and RPN vs Risk numbers in figure 5.3.

Table 5.1: Rating of Severity, Occurrence and Detection by industrial Experts

Failure mode	Severity	Occurrence	Detection	Risk Number
Encapsulant Discoloration	0.3	0.3	0.9	Risk 1
Delamination	0.4	0.4	0.6	Risk 2
Backsheet Insulation Compromise	0.4	0.3	0.6	Risk 3
Circuit Discoloration	0.5	0.5	0.7	Risk 4
Circuit Failure/Solder bond Failure	0.6	0.5	0.7	Risk 5
Hot spots	0.7	0.4	0.7	Risk 6
Cell Fracture	0.6	0.4	0.7	Risk 7

Diode failure	0.7	0.5	0.7	Risk 8
Glass breakage	0.6	0.4	0.9	Risk 9
Frame deformation	0.6	0.1	0.9	Risk 10
Potential induced degradation	0.7	0.3	0.6	Risk 11
Permanent Soiling	0.7	0.8	0.9	Risk 12

Table 5.2: Descending order of failure modes

Sr. No.	**Risk No.**	**RPN value**	**Sr. No.**	**Risk No.**	**RPN value**
1	Risk 12	0.504	7	Risk 7	0.168
2	Risk 8	0.245	8	Risk 11	0.126
3	Risk 9	0.216	9	Risk 2	0.096
4	Risk 5	0.210	10	Risk 1	0.081
5	Risk 6	0.196	11	Risk 3	0.072
6	Risk 4	0.175	12	Risk 10	0.054

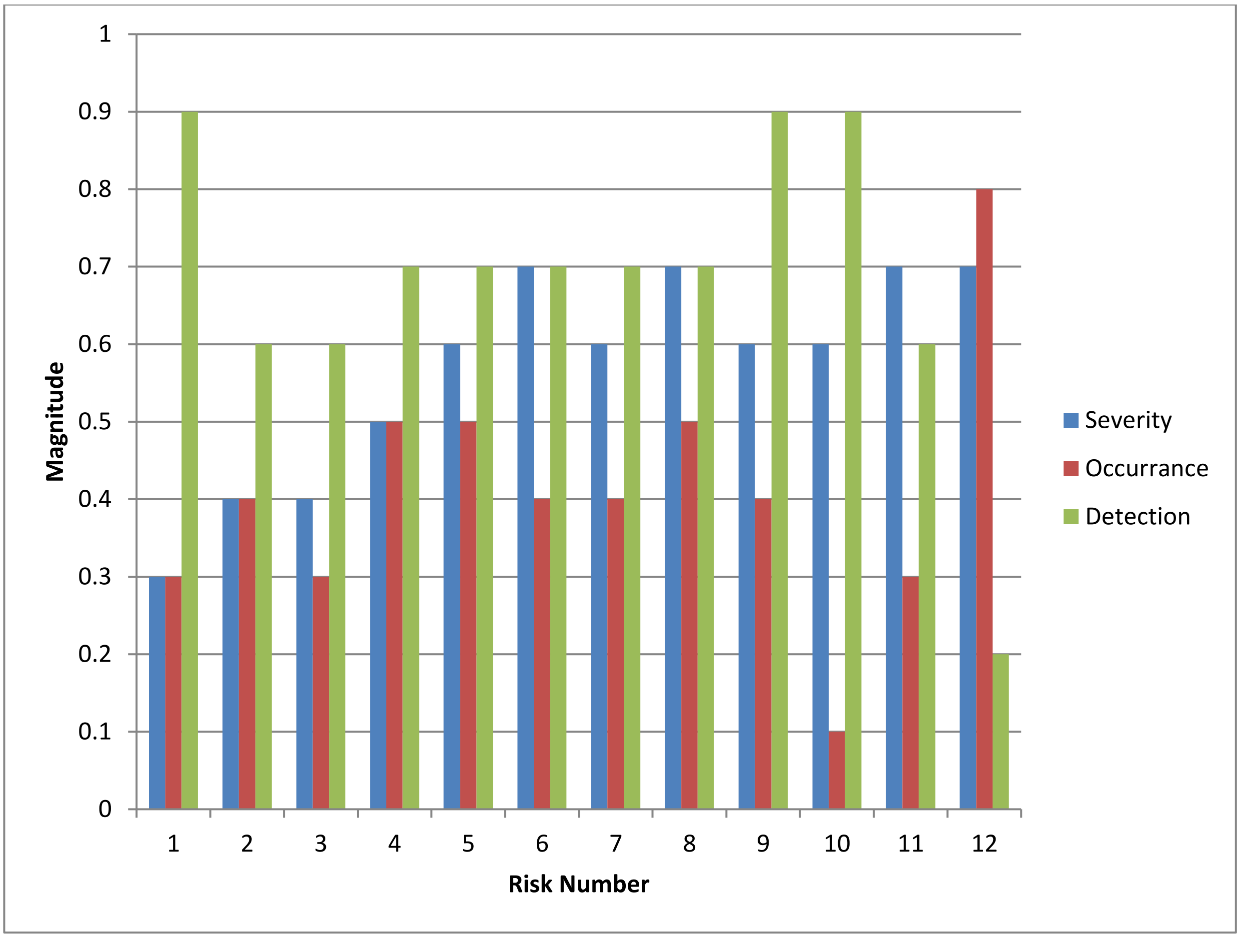

Figure.5.2 Severity, occurrence and detection of risks

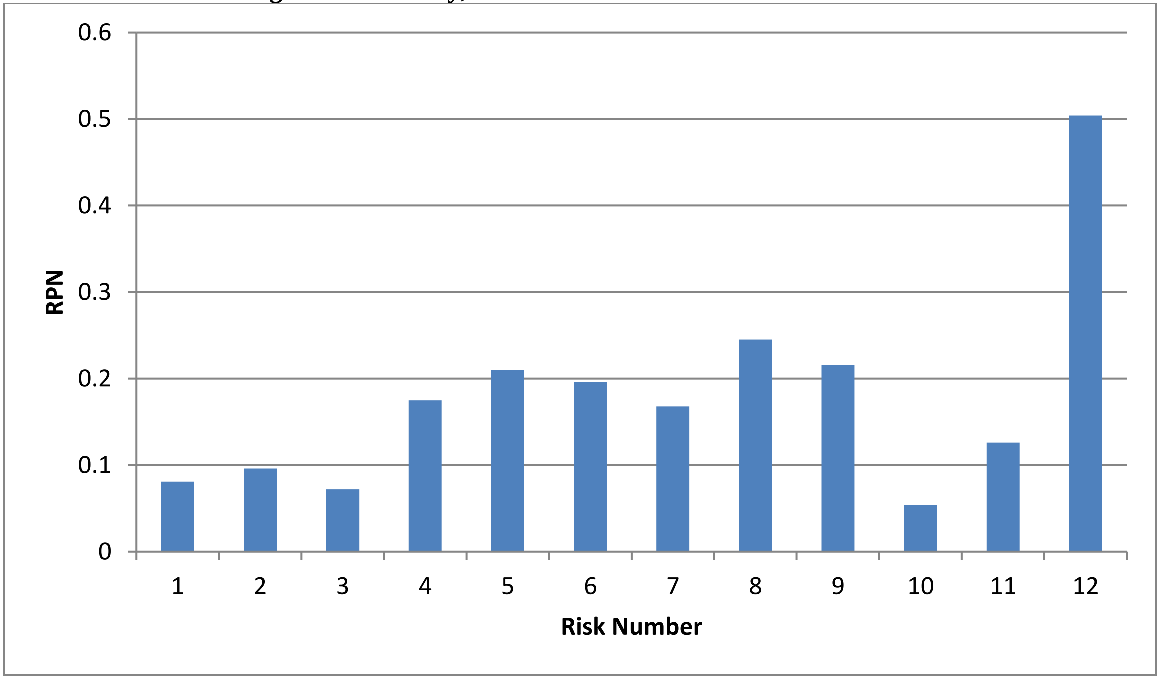

Figure.5.3 RPN vs Risk Number

5.3 Fuzzy FMEA applied to Solar PV system

To calculate fuzzy RPN, the severity, occurrence and detection provided by the industry person, are converted into fuzzy values using linguistic variables in Table 6.1. These linguistic variables are converted by using a scale defined by bastian (Bastian, 1994). There is only five linguistic terms are defined in the fuzzy range. Table 6.2 is constructed by replacing the values obtained with the linguistic variables. Now, the fuzzy values corresponding to each linguistic variable is evaluated and presented in table 6.3. Using the following relation between fuzzy numbers, fuzzy RPN value is calculated,

$$(L_1,M_1,U_1)\times(L_2,M_2,U_2)\times(L_3,M_3,U_3) = \{(L_1\times L_2\times L_3),(M_1\times M_2\times M_3),(U_1\times U_2\times U_3)\}$$

These fuzzy values are then defuzzified using the centroid method. For the defuzzication, following formula is used,

$$(L, M, U) = \frac{L + M + U}{3}$$

After defuzzification, all the obtained values are added to check that their summation is equal to 1 or not, if not then normalization of values is needed. All the respected values divided by the sum of the defuzzified values. After normalizing defuzzified values of fuzzy RPN is recorded in table 6.4. Comparison between the results of conventional FMEA and fuzzy FMEA is presented in table 6.5.

Chapter 6 Result and discussion

In table 6.5, it can be observed that both methods gives the highest priority to the same failure mode i.e. permanent soiling (Risk 12) and Diode failure (Risk 8). Despite there is no change in the highest ranking of failure modes, all other intermediate rankings are changed (for example risk 1 ranking changes from 10 to 7, risk 11 ranking changes from 8 to 5 and risk 5 ranking changes from 4 to 11) which will impact the performance of the system considerably. This shows that due to vagueness in the conventional method some of the less priority failure modes have the higher priority than the actual failure modes which needs to be place up in the order.

Table 6.1: Linguistic Terms corresponding to fuzzy number

Linguistic Term	**Fuzzy number**
No Influence **(NI)**	(0.0,0.1,0.3)
Very Less Influence **(VLI)**	(0.1,0.3,0.5)
Less Influence **(LI)**	(0.3,0.5,0.7)
Moderate Influence **(MI)**	(0.5,0.7,0.9)
High Influence **(HI)**	(0.7,0.9,1.0)

Table 6.2: Linguistic variables for each risk

Risk Number	**Severity**	**Occurrence**	**Detection**
Risk 1	VLI	VLI	HI
Risk 2	VLI	VLI	LI

Risk 3	VLI	VLI	LI
Risk 4	LI	LI	MI
Risk 5	LI	LI	MI
Risk 6	MI	VLI	MI
Risk 7	LI	VLI	MI
Risk 8	MI	LI	MI
Risk 9	LI	VLI	HI
Risk 10	LI	NI	HI
Risk 11	MI	VLI	LI
Risk 12	MI	MI	HI

Table 6.3: Fuzzy values for Severity, Occurrence and Detection of each risk

Risk Number	**Severity**	**Occurrence**	**Detection**
Risk 1	(0.1,0.3,0.5)	(0.1,0.3,0.5)	(0.7,0.9,1.0)
Risk 2	(0.1,0.3,0.5)	(0.1,0.3,0.5)	(0.3,0.5,0.7)
Risk 3	(0.1,0.3,0.5)	(0.1,0.3,0.5)	(0.3,0.5,0.7)
Risk 4	(0.3,0.5,0.7)	(0.3,0.5,0.7)	(0.5,0.7,0.9)
Risk 5	(0.3,0.5,0.7)	(0.3,0.5,0.7)	(0.5,0.7,0.9)
Risk 6	(0.5,0.7,0.9)	(0.1,0.3,0.5)	(0.5,0.7,0.9)
Risk 7	(0.3,0.5,0.7)	(0.1,0.3,0.5)	(0.5,0.7,0.9)
Risk 8	(0.5,0.7,0.9)	(0.3,0.5,0.7)	(0.5,0.7,0.9)
Risk 9	(0.3,0.5,0.7)	(0.1,0.3,0.5)	(0.7,0.9,1.0)
Risk 10	(0.3,0.5,0.7)	(0.0,0.1,0.3)	(0.7,0.9,1.0)

Risk 11	(0.5,0.7,0.9)	(0.1,0.3,0.5)	(0.3,0.5,0.7)
Risk 12	(0.5,0.7,0.9)	(0.5,0.7,0.9)	(0.7,0.9,1.0)

Table 6.4: Fuzzy RPN of each risk

Risk Number	**Severity**	**Occurrence**	**Detection**	**Fuzzy RPN**	**Defuzzified RPN**
Risk 1	(0.1,0.3,0.5)	(0.1,0.3,0.5)	(0.7,0.9,1.0)	(0.007,0.081,0.250)	0.062
Risk 2	(0.1,0.3,0.5)	(0.1,0.3,0.5)	(0.3,0.5,0.7)	(0.003,0.045,0.175)	0.040
Risk 3	(0.1,0.3,0.5)	(0.1,0.3,0.5)	(0.3,0.5,0.7)	(0.003,0.045,0.175)	0.040
Risk 4	(0.3,0.5,0.7)	(0.3,0.5,0.7)	(0.5,0.7,0.9)	(0.045,0.175,0.441)	0.012
Risk 5	(0.3,0.5,0.7)	(0.3,0.5,0.7)	(0.5,0.7,0.9)	(0.045,0.175,0.441)	0.012
Risk 6	(0.5,0.7,0.9)	(0.1,0.3,0.5)	(0.5,0.7,0.9)	(0.025.0.147,0.405)	0.106
Risk 7	(0.3,0.5,0.7)	(0.1,0.3,0.5)	(0.5,0.7,0.9)	(0.015,0.105,0.315)	0.081
Risk 8	(0.5,0.7,0.9)	(0.3,0.5,0.7)	(0.5,0.7,0.9)	(0.075,0.245,0.567)	0.164
Risk 9	(0.3,0.5,0.7)	(0.1,0.3,0.5)	(0.7,0.9,1.0)	(0.021,0.135,0.350)	0.093
Risk 10	(0.3,0.5,0.7)	(0.0,0.1,0.3)	(0.7,0.9,1.0)	(0.000,0.045,0.210)	0.046
Risk 11	(0.5,0.7,0.9)	(0.1,0.3,0.5)	(0.3,0.5,0.7)	(0.015,0.105,0.315)	0.081
Risk 12	(0.5,0.7,0.9)	(0.5,0.7,0.9)	(0.7,0.9,1.0)	(0.175,0.441,0.810)	0.263

Table 6.5: Comparison between RPN and Ranking by Conventional FMEA and Fuzzy FMEA

Risk Number	RPN by conventional FMEA	Ranking	RPN by fuzzy FMEA	Ranking
Risk 1	0.081	10	0.062	7
Risk 2	0.096	9	0.040	9
Risk 3	0.072	11	0.040	10
Risk 4	0.175	6	0.012	12
Risk 5	0.210	4	0.012	11
Risk 6	0.196	5	0.106	3
Risk 7	0.168	7	0.081	6
Risk 8	0.245	2	0.164	2
Risk 9	0.216	3	0.093	4
Risk 10	0.054	12	0.046	8
Risk 11	0.126	8	0.081	5
Risk 12	0.504	1	0.263	1

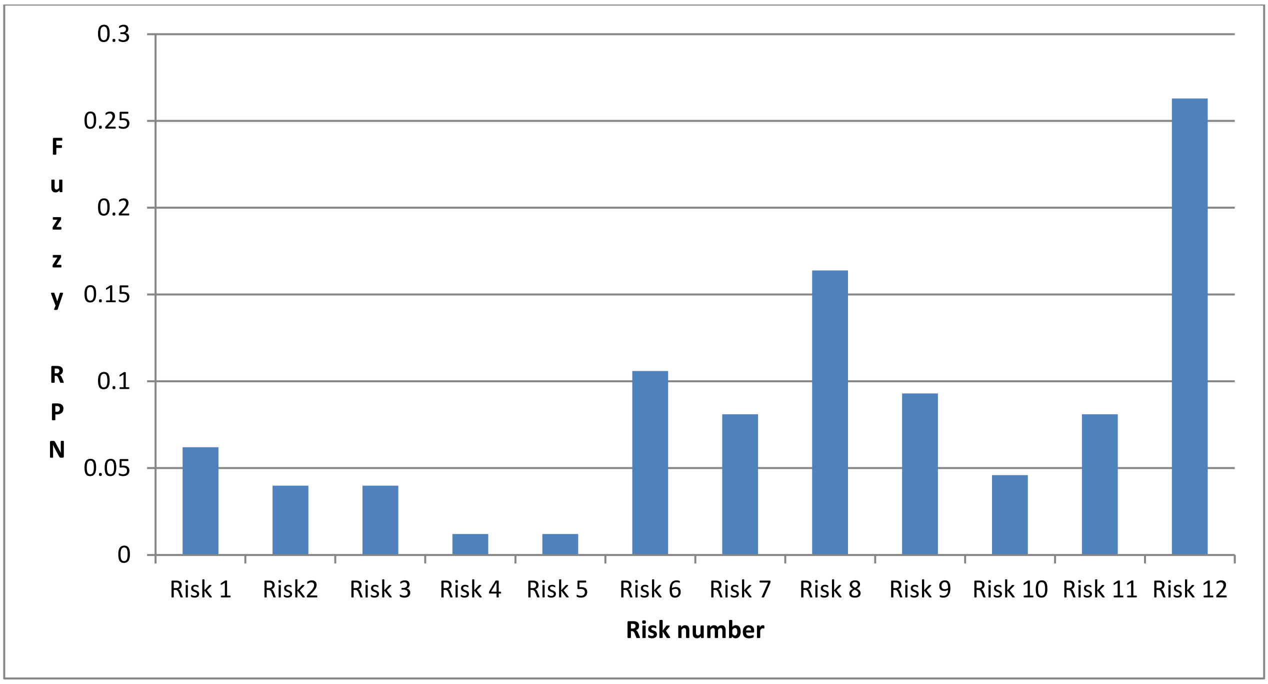

Figure.6.1 Fuzzy RPN vs Risk Number

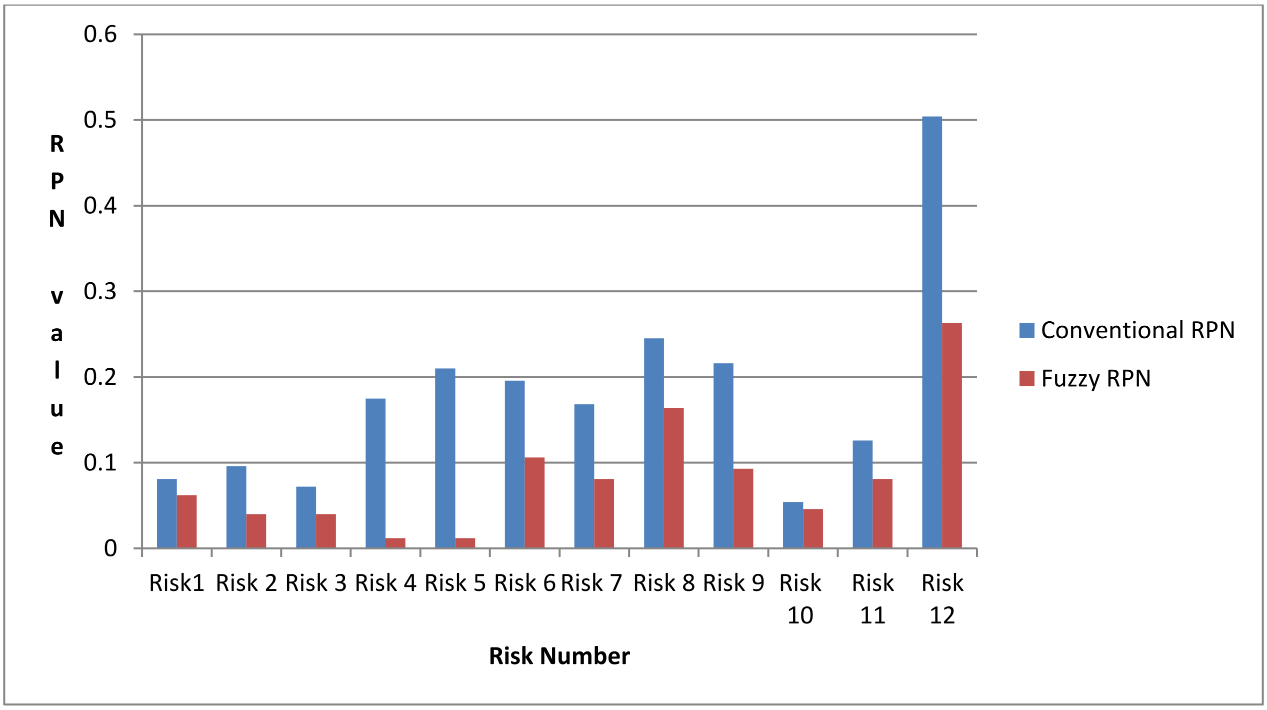

Figure.6.2 Comparison of Conventional RPN and Fuzzy RPN

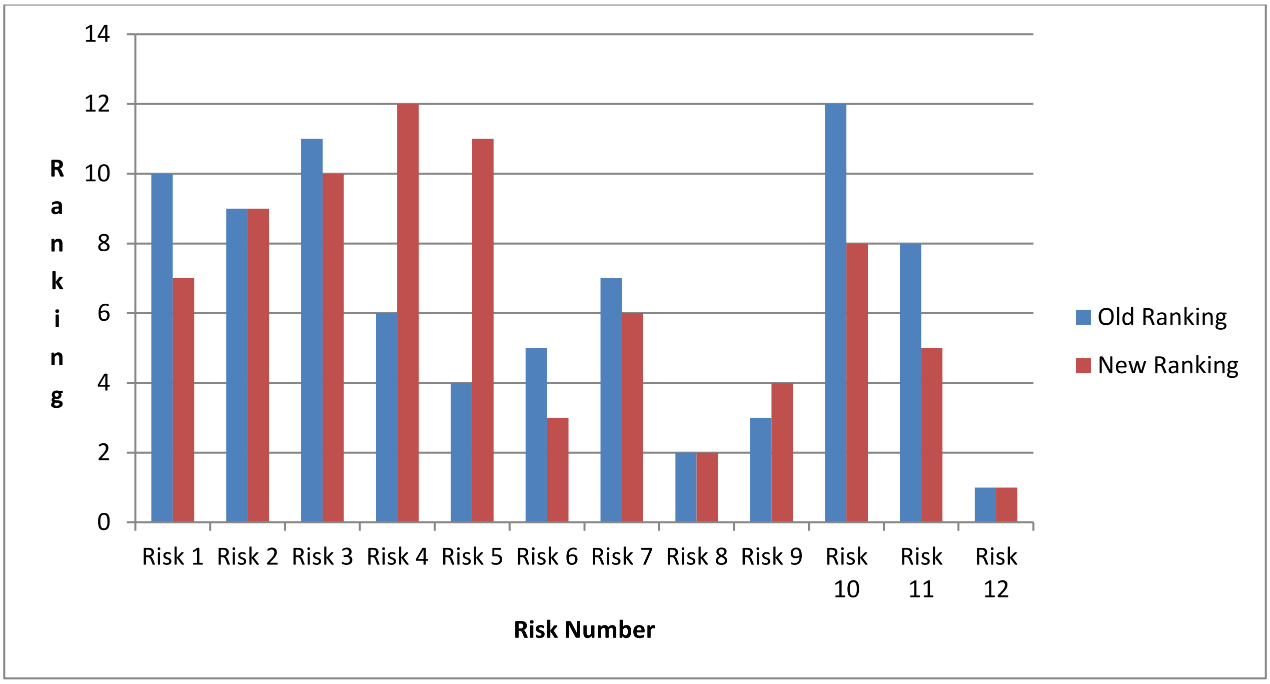

Figure.6.3 OLD vs NEW Ranking of risks

Chapter 7 Conclusion and Future Scope

Solar PV systems are the advanced technology in the category of renewable energy systems. To gain the most out of this technology the system's efficiency, reliability, and life should be maximized. In order to do so, the system failure prediction should be with much greater accuracy and precision. For the failure analysis of solar PV systems, an integrated strategy is proposed in this work, as the traditional single technique has certain limitations. This proposed methodology allows for quicker results and the benefit of more than one conventional approach.

The application of any risk priority technique requires a cross-functional/ cross departmental team. Every person prioritizes the failure modes based on own perception and knowledge which leads in the vagueness in the results. Due to this some of the high ranking failure modes will be placed lower in the table which results in poor performance of the system. Therefore to eliminate the vagueness in the results fuzzy logic is integrated with the FMEA method to obtain the more accurate results.

In the proposed method FTA is integrated with the fuzzy FMEA. FTA is used to find the root cause of the particular failure mode. However, the proposed method is efficient and less time consuming than the single conventional technique as it uses the FTA results for the fuzzy methods input. The results show that the top two positions of risks are same in the proposed method as well as in conventional method. Subsequent ranking differ in both methods. This is due to difference in opinions of respondents. The highest ranking of risks in decreasing order was risk number 12 and risk number 8 which are permanent soiling and diode failure respectively. These affect the efficiency the most among the risks under consideration. Ranking of these risks was same when obtained through conventional method. From risk 3 onwards, changes in ranking of risks were observed. In conventional results, risk 11 was ranked 8 and with fuzzy FMEA ranked 5 and risk 6 ranked 3 against its ranking 5. This difference in results is due to the difference in perception of experts. Risks that require immediate attention for mitigation fall lower on the priority list as a result of this poor prioritizing, and the system does not perform to its full capacity. As a result, the integrated FTA-Fuzzy FMEA method is far more efficient than the standard method in analyzing and prioritizing risks and determining which hazardous risk required to mitigate first.

In this study, most of the failure modes are related to the circuit, and aesthetics of the solar system. Failure modes related to the material parameters which are characteristics for specific type, hardware, electronic components, geometrical shape and size, environmental effects and any other types of failure which are not taken into account due to the limited scope of this work. Therefore, the failure modes related to the materials and more can be explored using the proposed methodology. This integrated strategy can be applied to any industry, including manufacturing, automobiles, and pharmaceuticals where the failure modes have the huge impact on the final product and their shelf life in the real time condition.

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