Failure rate determination and Failure Mode, Effect and Criticality Analysis (FMECA) based on historical data for photovoltaic plants

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Abstract

It is essential for photovoltaic plants investors, operators and equipment manufacturers to identify the failure modes and rates of the system in order to reduce investment risk, to focus their maintenance efforts on preventing those failures and to improve longevity and performance of the PV Plant. In this paper, it is assessed the importance of the Failure Modes within a real existing portfolio in Spain and Italy of continuous operation since 2008 and it is identified the module level failure modes, which are imperceptible in the standard monitoring systems, through the application of thermographic inspection. The experimental Mean Time Between Failures (MTBF) and the failure rates are calculated and these ratios are used to define the ranking criterion to perform the Failure Mode, Effect and Criticality Analysis (FMECA) and to focus on the module level analysis. The conclusions highlight the most critical sub-system and failure modes within a photovoltaic PV plant.

Keywords: Failure Rate, FMECA, Photovoltaic reliability, PV Module Thermography

1. Introduction

It is essential for photovoltaic (PV) plants investors, operators and equipment manufacturers to identify the failure modes and rates that the main equipment experiences in order to reduce investment risk, to focus their maintenance efforts on preventing those failures and to improve longevity and performance of the PV Plant. The reliability is defined as the capacity of a component to maintain its functionality over the years.

The Failure Mode, Effects and Criticality Analysis (FMECA) is an inductive analytical method in which the results present the failure modes and the severity of the consequences with relatively high probability. The main objective is to identify the failure modes that have a relevant combined occurrence, severity and non-detection probability in order to set the preventive actions accordingly. Equipment manufacturers try to identify all the failure modes of its products in order to increase reliability and reduce warranty cost, by researching and emulating different situations using mathematical models and experimental Highly Accelerated Life Test (HALT) (Moorthy and Tamizhmani, 2016). Resulting from the analysis, a battery of measures is implemented to reduce the key factors occurrence, severity or non-detection probability. The FMECA is a broadly used technique to assess the quality being applied on the elaboration and/or definition of, for example, safety analysis, quality control points, high standard requirements, quality procedures, working instructions, or resources distribution (Colli, 2015). The failure mode analysis also justifies the importance of maintenance activities and the associated cost on PV Plants to prevent premature failure and relevant catastrophic problems.

The greater challenge that researchers address and indicate while investigating about PV systems failures is the lack of reliable real quantitative data since most of the operators are private and do not disclose the data

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or either they do not have enough capabilities to record the data (Colli, 2012).The existing publications base their studies on the few available open-access data and subjective evaluations from experts' opinions with limited experimental and scientific base. Through the implementation of advanced PV plant monitoring systems (Cristaldi et al., 2015), the implementation of Computerized Maintenance Management Systems (CMMS) and the feedback of the field technicians, it is possible to have an experimental database to assess the failure rate and the FMECA of the PV plants (Colli, 2012).This fact is one of the greater strengths of this paper, in which the information from the historical data of fifty-eight PV plants portfolio in Italy and Spain of a well-known photovoltaic operator since 2008 has been accessible.

Monitoring of the different system components that constitute the PV plant facilitates the detection of failures and, from the reliability point of view, allows the operator to improve the plant performance (Cristaldi et al., 2015). Nevertheless, in utility scale PV plants, typically the monitoring system trails the string series current of multiple modules connected and does not track the performance of the individual PV modules, which is the key element on a photovoltaic system. Therefore, it is specially complicated the detection of failures at this level and, even more difficult, the recognition of the failure cause and mode. Because of this reason, during the last years additional tests have been required by solar PV investors at the PV module level with the aim of controlling the individual module performance, for example, IV curves tracing, electroluminescence test and thermographic test. To complete the FMECA analysis of this paper, it has been considered that other source of information is needed for the module level assessment. Aerial thermographic inspections, in which an Unmanned Aerial Vehicle (UAV) carries a thermographic sensor, are recently becoming popular because it reduces the inspection cost and it is less time consuming than manual thermographic inspections and/or IV curve tracing. Thermographic tests have been applied at a module level to a sample of the base data to complete the FMECA of the whole PV Plant.

The main objective of the paper is to assess the importance of the Failure Modes in PV plants considering the information taken within a real existing portfolio in Spain and Italy of continuous operation since 2008, and the application of thermographic inspection to identify the module level failure modes. This goal is achieved by means of calculating the experimental failure rates and the Mean Time Between Failures (MTBF) of the systems of a sample of PV plants during a relevant time using the historical database facilitated by Solarig, a worldwide PV operator. Based on the results, it will be applied the FMECA technique to the system elements. Once the different Failure Mode in the field are identified, the analysis is focused in the Module level related failures by cataloging the root cause analysis and the identification process through drone or manual thermographic inspection.

2. Method

In this section, it is summarized the different steps that have being followed to accomplish the analysis and to get the desired results.

The first step lies in identifying all the system components that can be affected and can produce a failure mode within the PV plant (Tab. 1).

In the current research, the PV system has been simplified in eight possible affected elements and for each of these elements, it has been identified the possible sub-element originating the failure. These elements are: PV generator, inverter, MV transformer station, meter, security systems, communication systems, monitoring systems and civil works.

After that, it has been analyzed all the available historical data and defined the sample that has been used for each of the calculations. These calculations are performed for different PV plants with the historical data available. With this selected data, the failure rates and the MTBF are calculated for the whole system and each sub-system. The failure rate is calculated as the number of failure per PV plant per unit year and the MTBF as the inverse of the failure rate.

These ratios are used to define the ranking criterion, to perform the FMECA analysis and to focus on the module level analysis. Finally, thermographic tests have been applied at a module level to complete the FMECA of the whole PV Plant. The results obtained throughout this analysis are presented in the results section.

Tab. 1: Affected elements and possible causes analyzed

Affected Element	Sub-element / Cause	Affected Element	Sub-element / Cause
Photovoltaic generator	Modules	Security System	Control Unit
	Cable		Cameras
	Fuse		Sensors
	Structure		Cabling
	Others		UPS
Inverter	Control Board		Others
	Communication Boards	Communications System	Router
	Protections		Satellite/LAN connect.
	Display		Others
	Power Block	Monitoring system	Control Unit
	Contactors		UPS
	Others		Fiber Optics/ Cabling
MV Transformer Station	Transformer		Others
	MV Switchgear	Civil works	Manhole
	Auxiliary System		Roads
	Others		Fence
Meter	Meter		Others
	Current /Voltage transformers		
	Others		

3. Results and discussion

The scoring system to define the ranking criterion has been defined considering the available data and the subjective evaluations of solar experts with more than a decade experience. Three different ranking criteria have been developed, for the severity, detection and occurrence respectively. Each ranking follows a scale from 1 to 5, in which 1 denotes the best situation while 5 denotes the worst. As a result, the Risk Priority Number (RPN) goes from 1 to 125, where a highest value of RPN indicates a most risky situation.

For the definition of the Severity ranking criteria, it has been considered the cost of fixing the failure (spare parts and workforce) and the Loss of Profit (LOP) that the failure generates due to the reduction of energy production (in case it is necessary to shut down the plant or part of it). The fixing price has been considered in an interval from 0 €, in case the failure does not involve a fixing cost or it is negligible, as a wire that is not well fastened, an equipment badly labelled or a communication failure due to the operator, to 60,000 € in case of an extremely high fixing cost, as the fixing cost resulting from a fire. On the other hand, the loss of profit that has been considered is the following: 0 € when the failure does not produce disconnection of the PV site, 190 € when the failure produces a disconnection of approximately 1 hour, 950 € in case of half a day disconnection, 13,300 € in case of one week disconnection and 57,000 € in case of one month disconnection. With the combination of these two factors, it is obtained the Severity ranking criteria, showed in Tab. 2 and Tab. 3.

Finally, the Occurrence ranking criteria has been calculated based on the failure rates obtained for each failure mode in the portfolio analyzed and following the subjective evaluation of this data by photovoltaic experts with more than ten years of experience in this sector. The Occurrence based on the failure rates calculated is classified following this criterion: 1 for unlikely failures, 2 for remote probability, 3 for occasional probability, 4 for moderate probability and 5 for high probability.

Tab. 2: Severity ranking intervals calculated from the fixing price and the loss of profit that a failure produces

		Loss of Profit (LOP)				
		57.000 €	**13.300 €**	**950 €**	**190 €**	**- €**
Fixing Price (Spares and Workforce)	**60.000 €**	117,000 €	73,300 €	60,950 €	60,190 €	60,000 €
	15.000 €	72,000 €	28,300 €	15,950 €	15,190 €	15,000 €
	1.000 €	58,000 €	14,300 €	1,950 €	1,190 €	1,000 €
	500 €	57,500 €	13,800 €	1,450 €	690 €	500 €
	- €	57,000 €	13,300 €	950 €	190 €	0 €

Tab. 3: Severity ranking criteria

Rank	**X (Fixing Cost + LOP)**	**Description**
1	X <690 €	Minor failure with almost no influence in the performance of the plant and insignificant parts deterioration
2	1,950 €>X>690 €	Failure with low influence in the performance of the plant and parts deterioration
3	28,300 €>X>1,950 €	Failure with quite important influence in the performance of the plant and parts deterioration
4	60,950 €>X> 28,300 €	Failure with important influence in the performance of the plant and parts deterioration
5	X >117,000 €	Major failure with extreme influence in the performance of the plant and parts deterioration

The Detection criteria has been obtained following (Colli, 2015), and it is expressed in Tab. 4.

Tab. 4: Detection ranking criteria

Rank	**Description**
1	Almost certain that the problem will be detected (chance 81–100%)
2	High probability that the problem will be detected (chance 61–80%)
3	Moderate probability that the problem will be detected (chance 41–60%)
4	Low probability that the problem will be detected (chance 21–40%)
5	None/minimal probability that the problem will be detected (chance 0–20%)

Throughout analyzing the corrective maintenance reports that the plant technicians of the analyzed portfolio have uploaded to the CMMS during the last years, it has been identified 168 failures modes that appears in the operation of PV plants. Considering the previous detailed ranking criteria, it has been attributed a Severity, non-Detection and Occurrence number to each of the failure modes detected. Multiplying these three numbers it is obtained a Risk Priority Number for each of the failures. An extract of some of the main failure modes detected in the analysis is detailed in Tab. 5.

Tab. 5: Failure mode analysis table with the Severity, Detection, Occurrence and Risk Priority Number for some of the main failure modes identified in the analyzed portfolio of PV plants

Group	Element	Description Failure	S	D	O	RPN
Security syst.	CCTV	Camera/videorecorder/barrier/Sensor failure	1	3	5	15
Security syst.	CCTV	Communications failure	1	1	5	5
Meters	Meters	Erroneous meter configuration	1	3	3	9
Meters	Meters	Meter burnt	2	2	3	12
Meters	Meters	Communications failure	1	1	4	4
Grid	Grid	Overvoltage	3	1	3	9
Grid	Grid	Overcurrent	3	1	3	9
Grid	Grid	Disconnection	4	1	3	12
Civil Work	Perimeter	Fence damaged	2	4	2	16
Civil Work	Roads	Road damaged	2	3	2	12
UPS	UPS	Damaged battery	1	4	4	16
PV modules	Modules	Junction box detached	1	3	2	6
PV modules	Modules	Module damaged: degraded, hot spot, yellowing, diode, connection.	2	5	2	20
PV modules	Structure	Galvanizing damaged	3	3	2	18
PV modules	Structure	Structure bent/rusted	3	2	2	12
PV modules	Structure	Structure not grounded	2	4	2	16
DC wiring	DC wiring	Cable damaged	2	4	2	16
DC wiring	DC wiring	Cable unfastened	1	4	4	16
Combiner box	Breakers	Circuit breaker broken	2	4	4	32
Combiner box	Cabinet	Cover damaged	1	3	4	12
Combiner box	Cabinet	Deficient ground connection	3	4	4	48
Combiner box	Communic.	Communications failure	1	1	5	5
Inverter	Inverter	High temperature	2	2	5	20
Inverter	Inverter	Display failure	2	2	3	12
Inverter	Inverter	IGBT failure	4	2	4	32
Inverter	Inverter	Communications lost	1	1	5	5
Inverter	Inverter	DC/AC fuse damaged, broken, switch off	2	4	5	40
Inverter	Inverter	Earth or insultaion fault	2	4	4	32
AC wiring	LV wiring	Cable damaged	3	4	3	36
AC wiring	LV wiring	Cable unfastened	1	4	5	20
Monitor.syst.	Monitoring	Communications card failure	1	3	4	12
Monitor.syst.	Monitoring	Power source broken	1	3	4	12
Monitor.syst.	Monitoring	Local/Remote access not allowed	1	3	4	12
Monitor.syst.	Weather Station	Weather station broken	2	3	5	30
MV	Transformer	Oil temperature alarm	3	2	4	24
MV	Transformer	Windings temperature alarm	3	2	4	24
MV	Transformer	Oil leak	4	4	2	32
MV	Transformer	Fire	5	3	2	30
MV	Transformer	Deficient transformer tank ground connection	3	4	3	36

The reported failure modes are further analyzed throughout these paragraphs, in order to identify the ones that present a higher RPN and their possible causes and effects to be considered by operators. In Fig. 1 it is shown the sum of the RPN for each of the groups of elements under study and the accumulated RPN sum.

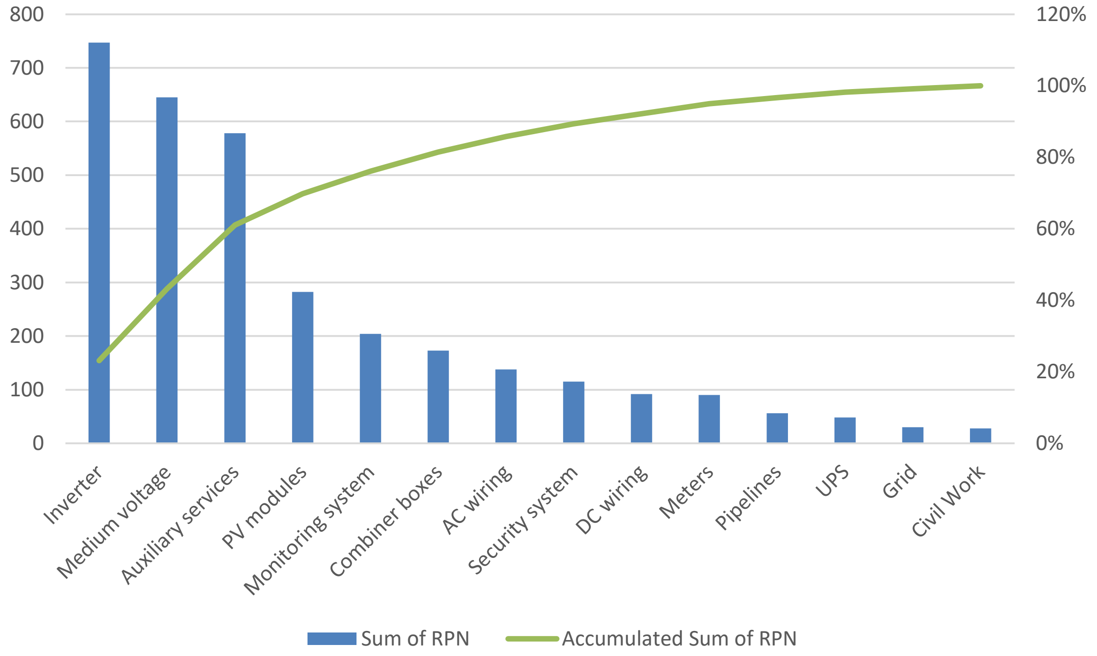


Fig. 1: Sum of RPN per group - FULL O&M

It can be seen that the inverter presents the higher RPN sum for the identified failure modes, followed by the medium voltage and the auxiliary services. Due to the fact that not all the groups present the same number of failure modes identified, it is necessary to know the average RPN in each of the groups. This analysis can be seen in Fig. 2. It can be seen that in this case, the groups that present a higher RPN in average are the medium voltage and the inverters, followed by AC wiring, combiner boxes, pipelines and PV modules.

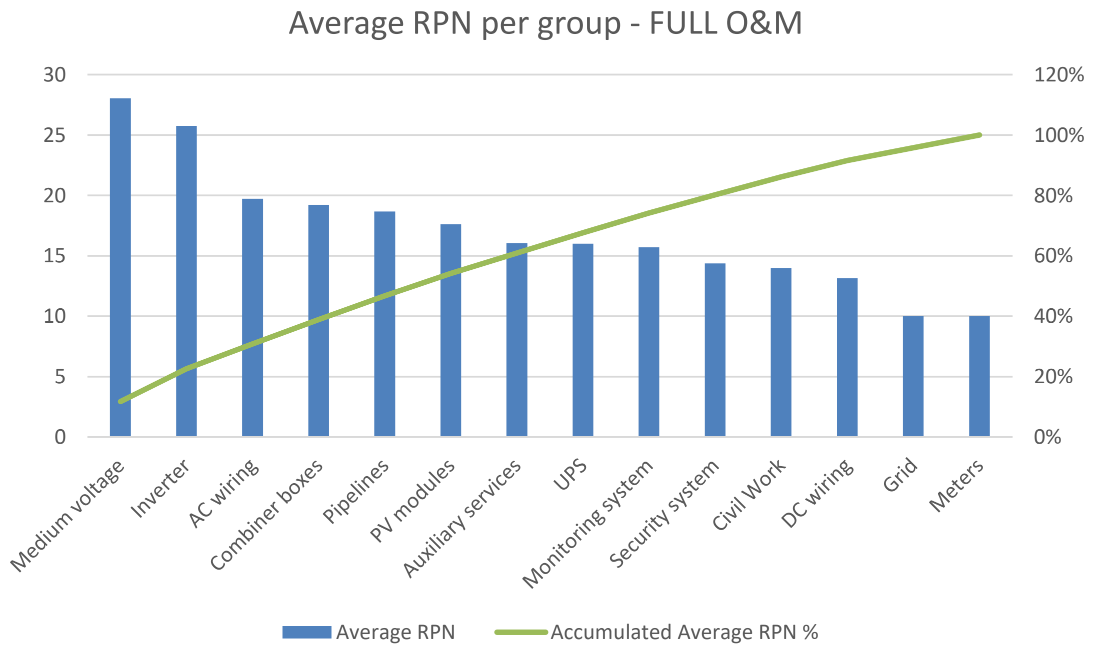


Fig. 2: Average of RPN per group - FULL O&M

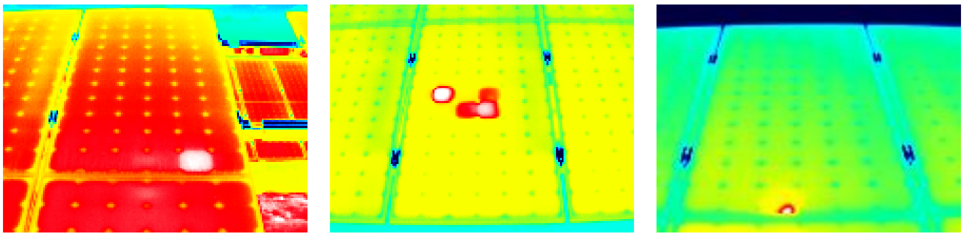
As it has been previously mentioned, monitoring the different system components that constitute the PV plant facilitates the detection of failures and from the reliability point of view allows the operator to improve the plant performance (Cristaldi et al., 2015). Nevertheless, in utility scale PV plants, typically the monitoring system trails the string series current of multiple modules connected, or even the inverter current, which is the sum of the parallel string current, and does not track the performance of the individual PV modules, which is the key element on a PV system as it converts the incident irradiance into electric power and module's cost is commonly upon 50% of the total PV installations cost (Agroui, 2012). Therefore, it is specially complicated the detection of failures at this level and even more difficult the recognition of the failure cause and mode. To complete the FMECA analysis of this paper it has been considered that other source of information is needed for the module level assessment and that is why the final point of this research is in the way of studying the current possibilities for operators to detect module failures and therefore, increasing the energy output of the PV plant

During the last years, additional tests are required by solar PV investors at the PV module level with the aim of controlling the individual module performance, for example, electrical test, electroluminescence test and thermographic test.

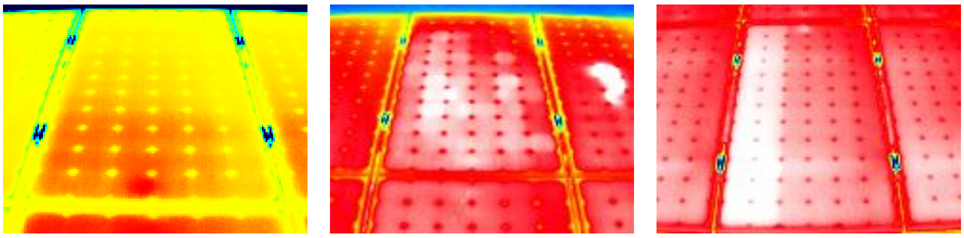
Electrical test, as IV curves tracing, allow the detection of abnormal underperforming situations but do not allow identifying the cause neither location of the defective cell. Additionally, to perform these tests it is necessary to shut down the plant during the electrical inspection, which involves an important energy output reduction. Electroluminescence (EL) imaging is a non-invasive technique developed to detect the radiative recombination of charge carriers excited under forward bias in which the resultant light intensity is proportional to the voltage. Therefore any electrically inactive parts of the module or cell are represented as dark areas, as micro-cracks that are not visible, as well as broken contact fingers, which can be identified. Although improvements in EL imaging equipment, involving InGaAs uncooled detectors and InSb cooled ones, have encompassed the first steps for reliable outdoor measurements and fault diagnosis in PV sites, electroluminescence is typically performed in indoor laboratories following strict indoor conditions.

On the other hand, thermographic inspection is fast and simple to implement and giving results in real time, not being necessary to shut down the plant during the inspection. It is non-destructive, contact-less and allows the identification of defects and their exact location with great accuracy, representing a temperature distribution of the surface of the modules which discloses the defects. Nonetheless, despite being a reliable method, manual thermography presents some relevant drawbacks. It is a costly and time-consuming technique and there are some situations in which it is hard to detect the defective cells using manual thermography, as in locations in which the inclination of modules is too low or during the middle hours of the day in PV plants with trackers. That is why aerial thermographic inspections, in which an UAV carries a thermographic sensor, is recently becoming most popular because it reduces the inspection cost and it is less time consuming than manual thermographic inspections and/or IV curve tracing.

Thermographic tests have been applied at a module level to a sample of the base data to complete the FMECA of the whole PV Plant. Some of the module failures that generate a difference in the temperature are experimentally identified by thermographic techniques and their criticality is analyze, as the overheating in multiple or one cell, connection point, module box, whole module and one row or bypass circuit. The thermographic images obtained performing on-site manual thermographic inspection are presented in Fig. 3.



(a) **(b)** **(c)**



(d) (e) (f)

Fig. 3: Thermographic image of PV modules taken on-site with a manual thermographic camera whic presents different defects (a) hot spot, (b) multiple cells hot spot, (c) connection overheated (d) module box overheated, (e) whole module overheated, (f) bypass circuit overheated.

4. Conclusions

This paper presents a failure mode analysis of PV plants based on the analyses performed to the available data of a real existing portfolio in Spain and Italy of continuous operation since 2008. Throughout the paper, it has been analyzed which are the most critical sub-system and failure modes within a photovoltaic PV plant, resulting that inverters presents the higher RPN sum for the identified failure modes, followed by the medium voltage and the auxiliary services. On the other hand, it has been proved that the groups that present a higher average RPN are the medium voltage and the inverters, followed by AC wiring, combiner boxes, pipelines and PV modules.

This information is essential for PV operators and manufacturers to focus their efforts on preventing those failures and to contribute to the improvement of the reliability in PV installations.

Additionally, it has been performed a manual thermographic inspection to a PV plant to identify the module level failure modes, as typically in utility scale PV plants the monitoring system does not track the performance of the individual PV modules, which is the key element on a PV system as it converts the incident irradiance into electric power and module's cost is commonly upon 50% of the total PV installations cost. Some of the module failures that generate a difference in the temperature have been experimentally identified, as the overheating in multiple or one cell, connection point, module box, whole module and one row or bypass circuit.

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