Analysis of critical failures and its monitorization in PV solar systems: A proposal of a new methodology "Cost of Detection"

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ABSTRACT: This thesis studies the photovoltaic (PV) system failures in several PV applications and the monitorization which alerts the presence of a failure in a PV system. Failure alerts are studied according to the monitoring system of the various types of existing inverters from 15 manufacturers. Failure Mode and Effects Analysis (FMEA) methodology was applied, which allowed the ordering of failure modes due to their criticality in three different scenarios. Taking into account the alert differences found in the various monitoring solutions analysed, this thesis proposes a new methodology named "Cost of Detection" which allows to calculate the economic impact of each failure, using a particular monitoring solution. The concepts of *Base* and *Additional Monitoring* are defined for each type of solution, which represents the worst and best case on the detection of failures respectively. Following the set of tests and previous analysis, it was verified for all the analysed scenarios that the inverter is the most critical component in the energy performance of a PV system, and the rack system of the PV panel is the most critical in the safety. When comparing the economic performance of the monitoring systems, it was found that the economic results differs with the monitorization system used and thus the failures that aren't detected have a relevant economic impact. The new proposed methodology cannot be seen as a complete tool for choosing an inverter as not include repair costs, but rather, to provide the user the knowledge of the comprehensiveness of a particular monitoring solution on the detection of failure modes.

1. INTRODUCTION

1.1. Problem

A significant number of photovoltaic (PV) systems are already installed around the world and keep expanding. Their competitiveness in the economic factors is one of the determining factors for its success and new investments in this technology. With the trend of stabilization of installation costs over the years and incentives being reduced, the PV industry is investing heavily in new Operation and Manutention (O&M) strategies to increase competitiveness and reduce variable costs. Because PV projects have a long lifespan, failures will occur due to extreme weather, poor maintenance or even random events, which will have an economic impact if not detected and corrected. A monitoring system that detects and alerts the failure as early as possible is one that will allow higher financial gains to the investor, as well as prevent the failure from affecting other components.

1.2. Research focus and methodology

This thesis has the main focus studying the impact failures in PV systems and the monitoring system that detect and alert that failures. For the analysis of the inverters alerts and there monitoring system, websites and operation manuals of the respective inverters and monitoring system were studied. In order to identify the critical failures, the methodology Failure Mode and Effects Analysis (FMEA) were studied and then applied to three scenarios: residential, industrial/commercial, and PV power plant. In addition to the FMEA, an analysis was made of the Cost Priority Number (CPN) methodology created by the European project Solar Bankability [1], which calculates the economic cost of the failure. The study of the alerts from the inverter monitoring system and the existing failure modes in PV systems, using the FMEA methodology, as well as the analysis of the CPN methodology allowed the development and application of a new methodology named as "Cost of Detection" that calculate the economic impact of the failures using a certain monitoring system. To compare the economic performance in the detection of failures by the various monitoring systems, the project evaluation indicator Net Present Value (NPV) was used. For the calculation of the NPV, it was necessary to look for inverter prices which were obtained from websites that sells PV material.

2. SOLAR PHOTOVOLTAIC SYSTEM

2.1. Principle of operation of PV system

A generic PV system is essentially composed by PV panels, inverters, DC and AC cables, protection devices and others circuit elements (meters, data-loggers…). PV panels are comprised of individual PV cells that will convert the solar radiation (photons) in electrons. That process generates direct current (DC) power and needs to be converted to AC (alternating current) power to be used by the local installation or alternatively inject it on grid. The conversion of DC power to AC power is made by the inverter.

2.2. Type of inverters

The inverter is considered the hearth of a PV system. Besides the main function of converting DC power to AC power it comprises more functions and technologies including, monitoring the PV system status and failures alerts, protection devices and Maximum Power Point Tracking (MPPT) technology. Inverters can be divided in three main categories: Central inverter if many arrays connect to an only one MPPT and usually with an output power more than 250 kW; String inverter if receive one or more strings connected to one or more MPPT and usually with an output power from 1 kW to 100 kW; Micro-inverter if it's connected, usually, to an one or two PV panels. There are devices like the power optimizer that can be used combined with string inverters that allows the PV panels be independent from each other, which reduce mismatch problems and enable module-level monitorization.

3. PHOTOVOLTAIC APPLICATIONS

Increasing efficiency, lower investment costs and minimal pollution are the advantages of photovoltaic systems that have led to a wide range of applications. In general, all photovoltaic installations can be distinguished according to their installed capacity and their connection to the grid.

3.1. Off-grid applications

These systems are disconnected from the grid and are connected directly to the load. Thus, these systems are sized to ensure that there is available energy whenever there is demand. For this, batteries are used to store the excess energy in periods where the consumption is less than the available power, and thus, to allow the use of this energy to supplement the supply when it is lower than the demand. The use of PV systems in these cases is an alternative to the conventional mode of power supply, eliminating costs with installation and use of cabling and generators at remote sites. Examples of applications are lighting poles, luminous signs, communication towers, satellites, water pumping and houses.

3.2. On-grid applications

Photovoltaic systems can also be connected to the grid, with or without batteries in the system. These systems are connected to the power grid and depending on the type of contract, can either sell the excess energy generated or consume power from the grid in situations in which the PV system cannot meet the needs. The on-grid applications can be divided in three main scenarios: residential scenario usually with PV systems up to 10 kWp; industrial/commercial scenario usually from 10 kWp to 1 MWp; PV power plant usually from 1 MWp to many Gigawatts.

3.3. Financial factors: CAPEX and OPEX

In a PV project, from the beginning of the project to the end of its operation, costs can be divided into two groups: CAPEX and OPEX. CAPEX refers to the amount of money spent on the acquisition and installation of equipment and capital goods. OPEX is related to the maintenance of the equipment and all the operational expenses necessary for the operation of the system. An inquiry to 18 PV projects located in Europe [2] shows that in the financial models used in the projects, CAPEX accounts for 70% to 90% of all project life expenses. Within OPEX, O&M is highly representative in financial terms in OPEX, ranging from 30% to 70% [2]. There has been a gradual decline in the cost of O&M over the years, with O&M falling from 50% in 2008 to 2015 [3]. Within O&M's costs, the preventive maintenance component is usually the one that has the most weight [3] [4]. It is estimated that in 2014 OPEX costs in Europe were back from 20 €/kWh/year for residential, commercial and plant systems of 1 MWp and 15 €/kWh/year for 50 MWp plants [4]. For the year 2030 it is estimated that these values will suffer a reduction of 30% due to the constant improvements in the optimization of maintenance processes and competitiveness.

4. RESEARCH ON MONITORING SYSTEMS

With the scope of knowing what monitorization solutions exists and make a systemization of the failures alerts that these solutions report, was made an extensive research on a wide range of inverters models and there monitoring system as the inverter is the main element in a monitoring system. This research includes 15 inverters manufacturers including market leaders like SMA, Huawei, Sungrow and SolarEdge. Other manufacturers were taking account like Delta, ABB, Fronius, Zeversolar, SolaX, Solis, KACO and GWL. SolarEdge inverters has the special difference of only working with optimizers. The micro-inverters studied are from Enphase, APSystem, AEconversion and SMA and the central inverters studied are from SMA, ABB and KACO. To study the failure alerts was study:

- Micro-inverters with output power between 250-500 W (4 inverters studied);
- Single-phase string inverters with output power of 2 kW and 5 kW (16 inverters studied)
- Three-phase string inverters with output power of 10 kW, 25 kW and 50 kW (27 inverters studied);
- Central inverters with output power of 1 MW (3 inverters studied);

It only was taking account inverter models available in the European market.

4.1. Failure alerts found

In this section is visualized the failure alerts that can be seen without extra or optional devices or monitoring software. The most relevant failure alert taken account in the AC electric circuit is:

1. High or low grid voltage / frequency / impedance;
2. No grid voltage;
3. Relay failure.

Figure 1 shows that alert (1) and (2) are reported in all types of inverters. About alert (3) there isn't enough available data for micro-inverters.

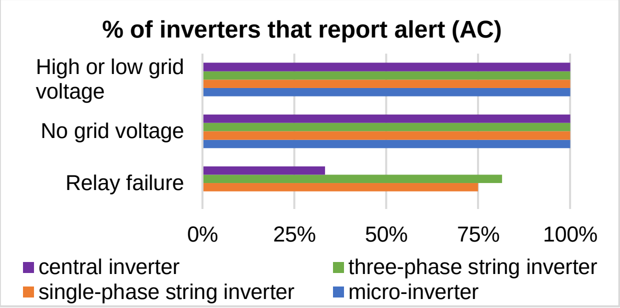

Figure 1 : Percentage of inverters that report AC failure alerts.

The most relevant alerts of failures that can occur inside the inverter are:

1. Inverter overheated;
2. *Derating* because of high ambient temperature;
3. Fan failure (when exist);
4. Internal failure (hardware failure and/or short circuit);
5. Software failure (wrong configuration and/or software update failure)

Figure 2 shows that the central inverter report all of kind of failure alerts and all inverter's types can alert when the inverter is not working.

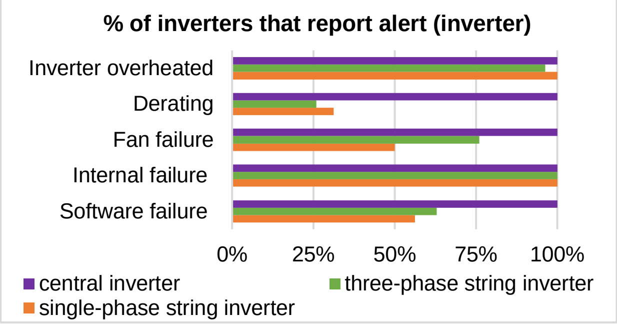

Figure 2 : Percentage of inverters that report inverter failure alerts.

The failure alerts considered about the CC electric circuit are:

1. Low energy production (low voltage);
2. Overvoltage;
3. Isolation failure;
4. Overcurrent;
5. Fuse failure;
6. High leakage current;
7. Electric arc in DC circuit.

Figure 3 shows that alert (1) and (2) are reported for in all inverter's types. Only few inverters alert presence of electric arcs in the circuit mostly because in Europe it's not mandatory protection against electric arcs.

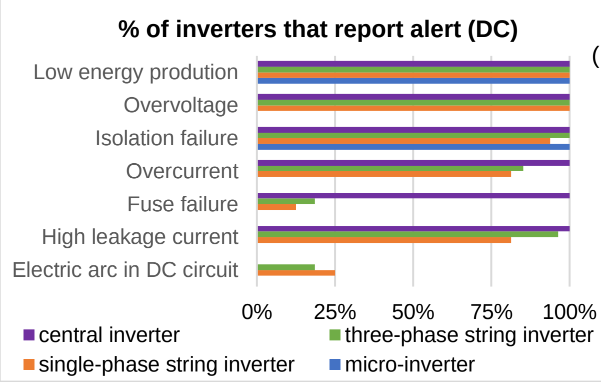

Figure 3 : Percentage of inverters that report DC failure alerts.

Summing up, that was found that central inverters report, single-phase and three-phase string inverter, report, on average, 89%, 74% and 75% of all alerts considered, respectively.

4.2. Monitorization Level

The monitorization system can be specific or not about where occurs the failure. Dependently of the monitoring system and the model of the inverter used, it can specify if there is a failure somewhere in the system or can locate more precisely, like in a string or in a panel. In the research was found 4 monitorization levels:

- Inverter-level monitoring: it does not distinguish in which MPPT or string a fault exists;
- MPPT level monitoring: refers to which MPPT exists a fault, but does not distinguish strings (if more than two strings per MPPT);
- String level monitoring: refers to which string there is a fault;
- Panel level monitoring: refers to which panel there is a fault.

Only with micro-inverters and Tigo and SolarEdge optimizers panel level monitoring can be achieved. All these three solutions require the appropriate use of manufacturers software to gain access to the monitoring system, and except for SolarEdge, data-loggers are required to access failure alerts. However, when using SolarEdge optimizers with other brand inverters, it is also necessary to use a SolarEdge data-logger.

5. FMEA METHODOLOGY AND APPLICATION

5.1. FMEA Methodology

One of the methods of reliability analysis widely used in engineering and in the field of PV systems is Failure Mode and Effects Analysis. It is a semi-qualitative systematic method which the failure modes of a system, process, product or component are identified, analysed and described, and through the identification of its causes and effects, have the objective to mitigate / eliminate any unexpected or undesired situation. The FMEA methodology, whose main objective is to improve the system design [5], has other objectives such as: identify and prevent hazards to system and human safety; develop preventive maintenance plans for equipment; improve manufacturing, testing, verification or control processes; minimize component loss of performance or degradation. For each failure mode a Severity, Occurrence and Detection ranking is established according to subjective scales that are based on the available information and by the experience and evaluation of professionals. The three together are used to define a Risk Priority Number (RPN) which (by using a numerical scale usually from 1 to 10) sort the negative impact of failure modes. The RPN is calculated by multiplying the degree of Severity (S), degree of Occurrence (O) and by degree of Detection (D), with the following equation (1):

$$RPN = S \cdot O \cdot D \tag{1}$$

After ranking the failure modes of the system under analysis, there will be a greater focus on failures with a higher value, since these represent a higher risk, in which later measures will be taken to eliminate or mitigate the problems caused by failure modes.

5.2. Application of FMEA

In this thesis, a FMEA analysis will be applied to a residential scenario, industrial / commercial scenario and power plant scenario, to analyse which critical failures cause greater energy losses to the system, and which failures represent more danger to the safety of the system and people. For each scenario it was chosen the type of inverter that is representative of scenario mentioned before. Table 1 presents, for each scenario, a typical photovoltaic system to be used in this study: PV power plant of 1 MWp, industrial / commercial of 100 kWp and, finally, a 5 kWp residential PV system.

Table 1: Solar photovoltaics systems analysed in the FMEA

	PV Power Plant	Industrial/ Commercial	Residential
Peak Power	1 MWp	100 kWp	5 kWp
Inverter	Central inv. of 1 MW	String inv. of 25 kW	String inv. of 5 kW
Nº of inverters	1	4	1
Nº of panels (300 W)	3350	336	16
Nº of panels per string	25	21	8
Nº of strings	134	16	2
Nº of strings per inverter	134	4 (2 strings per MPPT)	2
DC protection	5 combiner boxes with breaker and 28 fuses each	4 combiner boxes with 1 breaker and 4 fuses each	1 breaker
AC protection	Protection box with breaker and relay	4 Protection boxes with breaker and relay	Protection box with breaker and relay
Transformer	Yes	Yes	No

5.2.1. Failure modes and data available

The qualitative aspects of the FMEA analysis, including the identification of failure modes, their causes and their effects, are available in literature related to the reliability of photovoltaic systems and degradation studies. Thus, to gather these failure modes, causes and effects, a failure mode study was carried out on each component of the photovoltaic system in the studies [6] [7] [8] [9]. Table 2 show all the PV components, the failures mode, the performance loss in the component provoked by the failure mode and the failure rate per unit hour associated. To find out the impact of a failure on the subcomponents of the PV panel, except bypass diode, it was used the values found in [7]. For the impact of the "Malfunction" of a bypass diode, an impact of 33% was assumed, which is equivalent to the failure of the diode to disconnect a string of cells from the panel. For both failure modes of the DC cables/connectors it was assumed that a string would stop supplying power. For the AC failure modes, an impact of 100% was also assumed. For the failure mode "Broken structure" referring to the rack structure of the PV panel it was also assumed that a string would no longer supply power. For the "Malfunction" failure mode of the three-phase and central string inverter a reduction in its performance by 50% was assumed [10] [11] [12] [13]. For the single-phase string inverter it was assumed a reduction in its performance of 20% [10] [12]. For the "Malfunction" mode of the transformer it was assumed that it would reduce its performance by 50%. There are very few free literatures about failure rate of specific components or electronic subcomponents. In the study [14] was applied the methodology FMEA in a PV system and gathered information about failure rate in the PV components. Nevertheless, it was not specified if the inverter failure rate is about inverters in general or central or string inverter. So, the same failure rate was assumed in this thesis. In addition, to obtain the occurrence value (*O*) of each failure mode, the failure rate of each subcomponent must be distributed by the failure modes considered where the subcomponent participates. In [9] a survey of failures in PV system projects was carried out through questionnaires and thus a statistical distribution was obtained. It was used that statistic to distribute the PV panel failure rate obtained in [14] by the failures modes using the data from [9]. All other failures mode associated to other components was distributed equally.

Table 2 : PV Components with the failures mode associated and failure rate used in the FMEA. The performance loss is the power loss in the component.

Component	Sub-component	Failure Mode	Perf. loss in component	Failures per unit-hour)
PV panel	**PV cells**	Hot spots	4%	$6,4 \times 10^{-8}$
		Snail-track	0,3%	$1,4 \times 10^{-7}$
		Cell crack	3%	$4,5 \times 10^{-9}$
		PID	9%	$1,6 \times 10^{-7}$
	Encapsulation	EVA descoloration	0,3%	$3,4 \times 10^{-6}$
		Delamination	7%	$6,9 \times 10^{-7}$
	Front glass	Soiling	5%	$7,7 \times 10^{-7}$
		Fissures	2%	$2,1 \times 10^{-7}$
	Bypass diode	Malfunction (short or open)	33%	$1,7 \times 10^{-7}$
	Junction box	Overheated	10%	$3,4 \times 10^{-7}$
		Broken	10%	$1,7 \times 10^{-7}$
	Backsheet	Delamination	3%	$6,9 \times 10^{-7}$
Rack system	**Rack structure**	Broken structure	100% (string)	$1,22 \times 10^{-5}$
		Brackets detachment	-	$1,22 \times 10^{-5}$
	Ground/ lightning protection	Non-functional	-	$1,62 \times 10^{-5}$
Inverter	-	Non-functional	100%	$8,75 \times 10^{-5}$
		Malfunction	50% (central /three-phase string inv.)	$8,75 \times 10^{-5}$
			20% (single-phase string inv.)	$8,75 \times 10^{-5}$
Cables/ conectors	**DC cables**	Open circuit	100%	$1,10 \times 10^{-6}$
		Short circuit	100%	$1,10 \times 10^{-6}$
	AC cables	Open circuit	100%	$8,75 \times 10^{-7}$
		Short circuit	100%	$8,75 \times 10^{-7}$
Fuses	-	Slow or fail to open	5%	$1,09 \times 10^{-7}$
		Open prematurely	100%	$1,09 \times 10^{-7}$
Breaker DC/AC	-	Open prematurely or fail to close	100%	$2,00 \times 10^{-7}$
		Fail to open	-	$2,00 \times 10^{-7}$
Protective relay	-	Fail to open	-	$1,14 \times 10^{-7}$
		Open prematurely	100%	$1,14 \times 10^{-7}$
Transformer	-	Open circuit	100%	$1,41 \times 10^{-7}$
		Short circuit	100%	$1,41 \times 10^{-7}$
		Malfunction	50%	$1,41 \times 10^{-7}$

5.3. The scoring system

For the ranking Detection (Table 3) and Occurrence (Table 4) the criterion was developed and adapted from references [14] [15] and IEC 601812:2006 standard [5]. Knowing the quantitative impact of a failure on a given component, it is possible to quantify this impact in the system and thus assign a ranking value to the degree of Severity relative to the loss of power (performance) of the PV system (Table 5). In this thesis, the severity of failure in system and personal safety was separated from the severity of failure in the performance of the PV system. The safety criterion developed was based on the IEA study [6], which exhaustively addresses the effects of some safety flaws in PV panels (Table 6). In the attribution of the detection (*D*) score, the typology of the PV system was considered, that is, if a central or string inverter was installed. With the study carried out on maintenance and monitoring it was possible to subjectively classify the degree of detection for each mode of failure.

Table 3: Detection (D) ranking criteria.

Rank *D*	Description
1	The failure is immediately detected by the monitoring system
2	High probability that the failure will be detected
3	Moderate probability that the failure will be detected
4	Low probability that the failure will be detected
5	Minimal probability that the failure will be detected

Table 4: Occurrence (O) ranking criteria.

Rank *O*	Description
1	Unlikely – failure rate per unit-hour up to 5 x 10^{-7}.
2	Remote probability – failure rate per unit-hour up to 5 x 10^{-6}
3	Low probability – failure rate per unit-hour up to 5 x 10^{-5}
4	Moderate probability – failure rate per unit-hour up to 5 x 10^{-4}
5	High probability – failure rate per unit-hour up to 5 x 10^{-3} or more

Table 5: Severity in performance (Sp) ranking criteria.

Rank *Sp*	Description	Severity
1	<= 1% loss in performance	Low
2	<= 5% loss in performance	
3	<= 15% loss in performance	Moderate
4	<= 25% loss in performance	
5	>25% or more loss in performance	High

Table 6: Severity in safety (Ss) ranking criteria.

Rank *Ss*	Description
1	Failure has no effect on safety.
2	Failure may have an effect in safety on long-term.
3	Failure may cause fire (f), electrical shock (e), physical damage (m), if a follow-up failure and/or a second failure occurs.
4	High probability of a failure cause fire (f), electrical shock (e), physical damage (m), if a follow-up failure occurs.
5	Failure causes safety problem.

In the study [6], the impacts of photovoltaic panel faults on the safety (*Ss*) were classified. It was used that classification for the PV panel failures mode and for all other components it was subjectively proposed its score considering the effects caused by failure modes. Knowing the loss of performance that each mode of failure causes in the sub-component, it was possible to calculate the impact in the considered scenario and thus, a classification in the severity (*Sp*) index was obtained. The occurrence score (*O*) was explained in the section 5.2.1.

5.4. FMEA tables

In the FMEA (performance) and FMEA (safety) the failures with an RPN value more than 10 and 20 respectively, will be considered more critical.

5.4.1. FMEA PV power plant

Table 7: PV Power plant FMEA (performance).

Component	Sub-comp.	Failure mode	*O*	*D*	*Sp*	RPN
Inverter	-	Malfunction	4	2	5	40
		Non functional	4	1	5	20

Table 8: PV Power plant FMEA (safety).

Comp.	Sub-comp.	Failure mode	*O*	*D*	*Ss*	RPN
Rack	Rack structure	Broken structure	3	3	5	45
Cables / connectors	DC cable	Short circuit	2	4	5	40
Rack	Ground/ lightning protection	Non functional	3	2	4	24
Rack	Rack structure	Brackets detachment	3	4	2	24
Cables/ conectors	DC cable	Open circuit	2	4	3	24
PV panel	PV Backsheet panel	Delamination	2	4	3	24

5.4.2. FMEA industry/commercial

Table 9: Industrial/Commercial FMEA (performance)

Comp.	Sub-comp.	Failure mode	*O*	*D*	*Sp*	RPN
Inverter	-	Non functional	4	1	4	16
	-	Malfunction	4	2	2	16
Cables/ connectors	DC cable	Short circuit	2	3	2	12
		Open circuit	2	3	2	12
Rack	Rack structure	Broken structure	3	2	2	12

Table 10: Industrial/Commercial FMEA (safety)

Comp.	Sub-comp.	Failure mode	*O*	*D*	*Ss*	RPN
Cables/ connectors	DC cable	Short circuit	2	3	5	30
Rack	Rack structure	Broken structure	3	2	5	30
	Ground/lightning protection	Non functional	3	2	4	24
PV panel	Backsheet panel	Delamination	2	4	3	24

5.4.3.FMEA residential

Table 11: Residential FMEA (performance)

Comp.	Sub-comp.	Failure mode	*O*	*D*	*Sp*	RPN
Inverter	-	Malfunction	4	2	4	32
Rack	Rack structure	Broken structure	3	2	5	30
Inverter	-	Non functional	4	1	5	20
Cables/ connectors	DC cable	Open circuit	2	2	5	20

Table 12: Residential FMEA (safety)

Comp.	Sub-comp.	Failure mode	O	D	Ss	RPN
Rack	Rack structure	Brackets detachment	3	5	2	30
PV panel	Backsheet panel	Delamination	2	5	3	30
Rack	Ground/ lightning protection	Non functional	3	2	4	24

5.5. FMEA Analysis

In a general analysis of all FMEA (performance) tables, it is verified that the inverter is the most critical component due to the failure modes of this one having the highest RPN value in the three scenarios studied (except a failure mode in residential scenario). This is because the inverter receives all energy produced by the panels, which a failure in the inverter causes a great impact on the performance of the system. This coupled with a high failure rate, results in a high RPN value. Failure mode "Malfunction" of the inverter covers faults that cause the nominal power to decrease as derating due to a high ambient temperature. The high occurrence value (level 4) is supported by the "Overheat and fan failure" fault in inverters being the third largest found in inverters in [9]. In the PV power plant scenario, the "Malfunction" and "Non-functional" failure modes of the inverter obtained an RPN value of 40 and 20 respectively, while RPN values of failure modes of other components was equal to or lower than 10. In this scenario, to minimize the RPN value it's suggested the use of string inverters so that a fault in the inverter has less impact on system performance. In the industrial / commercial scenario, a decrease in the RPN value was observed to value 16 of both inverter failure modes since four string inverters were used which a failure on those will have a smaller impact on the PV system. However, it remains the most critical component in this scenario. In the residential scenario, there was a rise in RPN values in the inverter failure mode "Malfunction" to value 32 and "Non-functional" to value 20. In this scenario also appears the failure mode "Broken structure " of the rack system with one of the most (RPN = 30) due to the severity value (level 5), since it was assumed that this failure mode causes total loss in string power and in this scenario it's common to have only one or two strings. Then appears with RPN equal to 20 both DC cables/connectors failure modes due to the same reason previously considered in rack system failure mode. In this scenario, since only one string inverter is normally used, it is recommended to use inverters that provide reliability guarantees as well as inverters that guarantee the monitoring and alerting of each string (in case of two or more strings).

Analysing the FMEA (safety) tables it was found that the rack system is the most critical component due to having several failure modes with the highest RPN value in all scenarios. The RPN value of 45 and 30 of the "Broken structure" of rack structure for PV power plant scenario and industrial / commercial scenario respectively, can be supported with the data obtained on panel faults in [9]. The "Improperly Installation" fault is the second largest fault found in PV panels in [9] which it includes faults due poor handling in the PV panel and rack system installation (for example broken support). The DC cables / connectors also represent a high safety hazard in all scenarios. In the PV power plant and industrial / commercial scenarios it has a high RPN value of 40 and 30, respectively, due to the danger it presents to systems and people, such as electric arcs, and the difficulty of detecting (mainly in the PV power plant). In the residential scenario the "Delamination" of PV backsheet panel and the failure mode "Brackets detachment" both have an RPN value equal to 30, due to the high difficulty to detect it. This is explained by the panels usually being on the roof in a residential setting, making it difficult the visual inspection as well as less frequent maintenance in this scenario.

6. CPN AND PROPOSAL OF A NEW METHODOLOGY "COST OF DETECTION"

6.1. CPN reviewed

In order to understand the economic impact of the main faults in a PV system, the FMEA methodology is limited because it is based on a more technical analysis without providing the necessary tools for an economic calculation. Solar Bankability is a project funded by the European Commission's horizon 2020 program. In this context, in order to use an index similar to the RPN, it has recently developed a method of calculating the economic cost of failures by using a Cost Priority Number (CPN) [9]. This index prioritizes the failures in the economic impact on the project, corresponding to the RPN used in the FMEA. The CPN coefficient will translate into €/kWp or €/kWp/year, resulting in an estimate of the economic impact of a given failure. In the study made by Solar Bankability [9], about 1 million faults were analysed from 772 PV plants (from residential to large parks), totalling 450 MWp with an average of 3 years. With all the information about the occurrences of faults in each component of the PV system analysed, two scenarios were used in [9]: one scenario would be that the fault would never be detected after one year of operation, and the second would be the failure to be detected but with a one-month interval between detection and intervention and with a repair time of up to 2 hours. Both scenarios are based on the considerations of no monitoring system installed, there is no O&M contract or inspection and there are no spare parts in stock. In the PV panels, was found a large difference in the order of the units to tens of euros/kW/year between the highest monetary cost in repairing/replacing the failed components with the scenario of the failure not being detected and repaired. In the inverter, there is a higher cost, on average 400%, of not detected and repairing for a year compared to fix it. In cabling, the two most costly faults, if not detected, are related to the connectors and connections. The most costly repair failures are cable related.

6.2. Proposal of a new methodology “Cost of Detection”

The CPN methodology take into account the repair costs but does not account the installed monitoring. It was verified that each type of inverter has its differences in detecting and alerting faults. Considering that, it was proposed a new methodology that aims to calculating the economic impact of failures until their detection for a period of one year using a certain monitoring system and thus, to compare the economic performance in the detection of failures between the various types of inverters. All aspects related to post-detection costs, such as repair or replacement, will not be considered in the proposed methodology, focusing mainly on costs until failure detection from the inverter monitoring system. The methodology also does not take into account preventive maintenance (such as visual inspection). The following steps are required to calculate the cost of detecting failures:

1) Define the power of the PV system to be analysed and the quantity of each component that constitutes that system, i.e.: number of inverters and the power of each one, number of panels ($Npanels$) and respective unit power ($P_{DC,STC}$), number of strings, power of each string per inverter, as well as the number of circuit breakers, fuses and relays used.
2) Define the location of the PV system and the annual energy (equation (2)). A simplification will be used by using the daily peak hours of sun ($h_{peak\ sun/day}$) for a year for inclined planes (which is equivalent to the inclination of the panel). The peak hours indicate the number of hours equivalent to an irradiance of 1 kW/m^2 [16]. Knowing the number of peak hours for inclined planes of the selected location and multiplying by the installation power of the system, we obtain the expected annual energy ($E_{annual\ system}$) in kWh. The inverter efficiency ($\eta_{inverter}$) (according to CENELEC - EN 50530 [17]) is considered, neglecting cable losses. Losses due to mismatch are not considered.

$$E_{annual\ system} = P_{DC,STC} \cdot Npanels \cdot h_{peak\ sun/day} \cdot 365\ days \cdot \eta_{inverter} \qquad (2)$$

3) Calculation of the annual energy of a component ($E_{annual\ component}$) in kWh (equation (3)). To calculate the failure mode cost of a component of the PV system it is necessary to know what energy is produced or “traveled” in that component. The annual energy of the component will be equal to the annual energy of the system divided by the number of components ($Ncomponentes$) in the PV system.

$$E_{annual\ component} = E_{annual\ system}\ /\ Ncomponents \qquad (3)$$

4) Calculation of the energy lost (E_{lost}), in kWh, due to the occurrence of failure mode in a component (equation (4)). By multiplying the performance loss (PL) of the component that the failure mode causes with the annual energy that is produced or “traveled” in that component, the annual energy loss in a component caused by the failure, it’s obtained.

$$E_{lost} = E_{annual\ component} \cdot PL \qquad (4)$$

5) Calculation of the number of failures in a year in a component ($Annual\ Failures_{component}$) (equation (5)). Assuming failure rate per unit hour ($\lambda_{per\ hour}$) constant throughout the year and knowing the number of annual hours ($Hsun$) of system operation, which are equivalent to the number of hours of solar radiation in a year, the annual failure rate of a component is calculated.

$$Annual\ Failures_{component} = \lambda_{per\ hour} \cdot Hsun \qquad (5)$$

6) Calculation of the failure mode cost ($C_{failure}$), in a given component (equation (6)). The failure mode cost will equal to the "lost money" for not producing this energy. Multiplying the step 3) and 4) with the price of the renumeration (Ren) and with the total number of annual failures determined component is thus obtained the annual cost of failure mode.

$$C_{failure} = E_{lost} \cdot Annual\ Failures_{component} \cdot Ren \cdot Ncomponents \qquad (6)$$

7) Calculation of the total cost in the detection of the failures. In the study of the monitoring systems it was possible to verify that, depending on the type of inverter, the occurrence of a certain failure it triggers an alert and in others not. In the case of string inverters, there are inverters that can emit alerts for each string, others only for each MPPT or even only at the inverter level (i.e., does not differentiate between strings and MPPT). Considering this, for each type of monitoring system, *Base Monitoring* and *Additional Monitoring* concepts are defined.

   “Base Monitoring” definition: They are part of the *Base Monitoring*, faults that are guaranteed that the monitoring solution detects and alerts regardless of the inverter brand / monitoring solution.

   "Additional Monitoring" definition: Additional monitoring includes faults that are detected and alerted only by some inverters / monitoring systems.

   Thus, if the failure is detected by the monitoring system immediately, it is considered that this failure does not entail costs. The total cost of detection ($C_{total\_detection}$) will be the sum of all costs of failure modes that are not detected by monitoring each type of inverter with its *Base* or *Additional Monitoring* (equation (7)).

$$C_{total\_detection} = \sum C_{failure} \qquad (7)$$

Knowing the total cost of detecting failure modes, it is possible to calculate the impact of that cost on the annual renumeration of a PV system. The annual discounted renumeration (DR), i.e, discounting the detection cost of the failures, can be calculated by the following equation (8):

$$DR = \left(E_{annual\,system} \cdot Ren \right) - C_{total\,detection} \qquad (8)$$

6.3. Application and considerations

To illustrate the economic impact of failures using an inverter with Base or Additional Monitoring, which is equivalent to the worst case scenario and best scenario, and which inverter solution allows a higher return on investment in the detection of failures, the three scenarios were analysed: 5 kW, 100 kW and 1 MW, which correspond to a residential, industrial / commercial and PV power plant. For each scenario the following inverter solutions were considered: residential (single-phase string inverter without and with optimizer per PV panel and micro-inverters; industrial/commercial (three-phase string inverter without and with optimizer per PV panel and per two PV panels, and micro-inverters); PV power plant (three-phase string inverter without and with optimizer per PV panel and per two PV panels, central inverter without and with combiner box with string monitoring). For each scenario were studied three cities of Europe where the system is located: Lisbon, Rome and Berlin. As each country has its renumeration policy, the following considerations were made:

- Residential (5 kW): Self-consumption system with connection to the network, but without network injection for Portugal and Berlin and a net-metering system for Italy;
- Industrial / Commercial (100 kW): For Lisbon everything is sold with the price equal to the reference tariff decided by the Portuguese government in a PPA agreement; For Berlin, everything that is produced is injected into the electricity grid under a Feed-in-tariff; In Italy, everything that is produced is sold to the grid at energy market prices;
- PV power plant (1 MW): For Italy, it is the same situation described for the industrial / commercial scenario; For Berlin energy is injected into the grid under an auction price; In Portugal, the system of small production units is only available up to 250 kW systems. Thus, it was considered that it would be a production unit for self-consumption in which 50% of the production was consumed by an installation coupled to the PV power plant. From FMEA application and analysis, was obtained the failure modes, failure rates, and performance losses caused by each failure mode. The following considerations were also been made:
- A simplification was made for the failure rate of the micro-inverter due to lack of data. The failure rate would be one fifth of the failure rate of the central/string inverter, because the micro-inverter typically has 25 years of warranty and the central and string inverters 5 years;
- For the "Malfunction" failure mode of the micro-inverter, a power loss of 50% was considered [18];
- Failures were not considered in the optimizers, due to the lack of fault data in the optimizers.

For each type of monitoring solution, it has been designated which faults are detected and alerted by *Base* and *Additional Monitoring* (defined in step 7 of section 6.2). This was possible with the results obtained in the study of the monitoring system. As it turns out that the central inverters detect all faults equally, no additional monitoring was designated in this case.

Other considerations were made in both the *Base Monitoring* and *Additional Monitoring*, such as:

Base Monitoring considerations:

- If the inverter has a MPPT and a string (in the case of single-phase inverters), the failure modes of the DC cables/connectors, as well as the "Broken structure" failure mode of the rack structure, are all considered to be detected by Base Monitoring;
- In solutions with an optimizer per panel and micro-inverter, only faults that cause a loss of performance (power) greater than 5% are assumed that the system detects, that is, it is considered part of the *Base Monitoring*. In the cases of an optimizer for every two panels is considered if the loss is greater than 10%.

Additional Monitoring Considerations*:*

- For solutions with an optimizer per panel or micro-inverter solutions, with little information on which alerts these report failures in PV panels, it is assumed that there may be some micro-inverters on the market that detect and alert faults on the PV panel. For the solution of an optimizer for each two panels it is assumed again that only faults are detected in the panel with loss of energy greater than 10%;
- For a solution with micro-inverters it is assumed that there may be in the market some device that detects when the inverter is malfunctioning and report the derating alarm due to a high operating temperature or that there are micro-inverters without the failure mode inverter “Malfunction”.

6.4. Results

It was found that the failure modes with the highest economic impact if they aren’t detected are: inverter "Non-functional" and "Malfunction", as well as the "Broken structure" failure mode of the rack structure. Since the failure mode “Non-functional” of inverter is detected immediately by the monitoring system of all the inverters, it has no cost in detecting it. In *Base Monitoring* of the string inverters, "Malfunction" of the inverter and "Broken Structure" of the rack represent about 94% of the cost of detection in all PV systems analysed. In solutions that can distinguish failures in each string, such as string inverters with optimizers, micro-inverters and central inverters with string monitoring, the "Broken structure" failure mode is mitigated, resulting the “Malfunction” of inverter the failure with higher cost in the Base Monitoring. Only in the central inverter solutions the "Malfunction" failure mode of the inverter is detected by all central inverters meaning no cost of detecting it, leaving the "Broken structure" failure mode as the failure with more economic impact. Comparing the economic gain obtained by the solutions from a *Base Monitoring* to an *Additional Monitoring*, the solution with the string inverter was the one with the highest gain in the annual renumeration (discounting the cost of failures not being detected), on average 8%, 11% and 16% for residential (5 kW), industrial / commercial (100 kW) and PV power plant (1 MW), respectively.

6.5. Economic analysis using Net Present Value

It was verified the economic impact of failures on an annual basis for each system capacity and city. Considering each type of solution presented has a different price and each one provides a different annual renumeration, it is relevant to compare the economic performance of the different types of solutions for a given period. The economic performance of each solution in each city will be compared using a project/investment indicator, named Net Present Value (NPV). The NPV aims to evaluate the viability of an investment project by calculating the current value of all cash flows [19].

6.6. NPV considerations

In order to use the NPV to compare the economic performance of the inverters in the detection of failures, costs related to O&M, licenses, fees, are not considered. In the parcel of the investment, only the inverters cost and optimizers are considered. It was considered a period of analysis of 5 years. A short analysis period allows to verify which solution can result in a faster return on investment. In calculating the annual cash flow, it was considered electricity annual price inflation for residential and non-residential installations at 2.8% for all cities [20]. The market price of energy (from 2017) was considered constant over the years for Italy and Portugal. For Berlin the auction price (from 2017) was considered constant over the years; The prices of the 2017 feed-in tariffs for Lisbon and Berlin (industrial/commercial scenario) were considered. It was also considered an annual degradation of the PV panels of 1% as statistics point to a mean degradation of 0.8%/year [21]. Considering as a reference, for a 1 MW PV system the discount rate calculated in [22] was 4.6% in Italy. In this thesis for the 1 MW scenario a discount rate of 4.6% was used. For simplicity and considering that the risk decreases for smaller investments, for the industrial/commercial and residential scenario, a rate of 3.6% and 2.6% was used respectively.

6.6.1. NPV results

Taking into account the considerations made for the NPV calculation, it's not possible to make conclusions about the viability of a project using one or another type of monitoring solution, but rather to compare the NPV between them, in which a higher NPV will mean that the solution will bring a higher financial return for the same period of analysis. In the residential scenario the string inverter is the one with the highest NPV and the micro-inverter with the lowest NPV. The option of the string inverter with optimizers is the most advantageous for those who wish to monitor at the panel level and in the worst cases (string inverter with *Additional Monitoring* and string inverter with optimizers with *Base Monitoring*), on average. Will have 17% less financial return comparing the option of string inverters without optimizers. In the industrial/ commercial scenario the same conclusions were made from the residential scenario on the string inverter and micro-inverter. It has been found that the monitoring solution with string inverter with one optimizer for each two panels is the best solution with panel-level monitoring, presenting in the worst case for Lisbon, Rome and Berlin a lower NPV value of 28%, 50%, 33% respectively, compared to string inverters without optimizers. In the PV power plant scenario, it was be seen that for the three cities the best options are the central inverter and the three-phase string inverter with *Additional Monitoring*.

7. CONCLUSIONS

The FMEA showed that the inverter is the most critical component in the energy performance of a PV system, and the rack system of PV panel is the most critical in the safety. With the application of the new proposed methodology we could conclude that the three failure modes with higher economic impact, if not detected are: inverter "Non-functional" and inverter with "Malfunction", which means it operates under its rated power, and "Broken structure" of the rack structure of the PV panel. String-level monitoring ensures that failure modes in the DC circuit, related to a large loss of power and safety, such as failure mode "Broken Structure" of rack system, are immediately detected, as well as failures in the DC cables/connectors. To avoid “Malfunction” failure mode of the inverter it is recommended to install the inverter in locations that are protected from the sun or other sources of heat as well as follow the scheduled maintenance of the inverter manufacturer. Inverters that have the derating alert, will alert immediately this failure mode and then give the possibility to act immediately. Although the failure mode “Non-functional” of inverter is detected and alerted immediately by all inverters, it is essential to be aware of the alert as quickly as possible. Thus, remote access to the alerts system is crucial to act immediately. When comparing the economic performance of the monitoring systems, it was concluded that a system with only string inverters allows to obtain the highest NPV in all the scenarios and cities. The new proposed methodology has a limitation in not considering the repair costs of the components affected by a failure. Thus, it cannot be seen as a complete tool for choosing an inverter/monitoring system, but rather, to provide the user the knowledge of the comprehensiveness of a particular monitoring solution on the detection of failure modes.

References

[1] Solar Bankability, [Online]. Available: http://www.solarbankability.org/home.html. [Accessed: 22-Sept-2018].

[2] C. Tjengdrawira and M. Richter, "Review and Gap Analyses of Technical Assumptions in PV Electricity Cost," Public report Solar Bankability WP3 Deliverable D3.1, July, 2016.

[3] D. Moser *et al.*, "Proceedings of the First Public Workshop Solar Bankability: Technical and Financial Risk Quantification and Assessment," Solar Bankability Deliverable D5.4, 2016.

[4] E. Vartianinen *et al.*, "PV LCOE In Europe 2014-30," European PV Technology Platform Steering Committee PV LCOE Working Group, final report, 2015.

[5] International Electrotechnical Comission, "IEC 60812:2006 Analysis Techniques for System Reliability, Procedure for failure mode and effects analysis (FMEA)," International Electrotechnical Comission, 2006.

[6] M. Köntges *et al.,* "Performance and Reliability of Photovoltaic Systems - Subtask 3.2: Review of Failures of Photovoltaic Modules," IEA PVPS Task 13, 2014.

[7] A. Welschof, "Maintenance management for mitigation of fault and degradation effects in photovoltaic panels – a systematization," Project in Engineering and Energy Management 2, Instituto Superior Técnico, Lisbon, 2017.

[8] M. Rycroft, "Solar PV module faults and failings," *EE Publishers,* 7 September, 2016.

[9] D. Moser *et al.*, "Technical Risks in PV Projects - Report on Technical Risks in PV Project Development and PV Plant Operation," Solar Bankability WP1 Deliverable D1.1 and WP2 Deliverable D2.1, March, 2016.

[10] SMA, "Technical Information - Efficiency and Derating," SMA, [Online]. Available: http://as-iberica.com/wp-content/uploads/download-manager-files/Web/01-INVERSORES/1.%20SMA/2.%20SMA%20SUNNY%20TRIPOWER%20HIGHPOWER/5.%20INFORMACION%20TECNICA%20ADICIONAL/WirkungDerat-TI-en-44.pdf. [Accessed: 24-Apr-2019].

[11] C. Pariya, "Grid-connected photovoltaic system together with sma inverters," SMA, October, 2014.

[12] SolarEdge, "Temperature De-rating - Technical Note (Europe & APAC)," [Online]. Available: https://www.solaredge.com/sites/default/files/se-temperature-derating-note.pdf. [Accessed: 7-Dec-2018].

[13] SMA, "Sunny Central 2200," [Online]. Available: https://www.gemenergy.com.au/wp-content/uploads/2017/01/SMA_Central_SC2200-DEN1651-V29web.pdf. [Accessed: 13-Oct-2014].

[14] A. Colli, "Failure mode and effect analysis for photovoltaic systems," *Renewable and Sustainable Energy Reviews,* vol. 50, pp. 804-809, 2015.

[15] M. Lazzaroni, Reliability engineering: basic concepts and applications in ICT, Springer Science & Business Media, 2011.

[16] Aurora Energy, [Online]. Available: http://www.aurorasolarenergy.com/average-daily-sun-hours/. [Accessed: 18-Mar- 2019].

[17] CENELEC-EN 50530, "Overall efficiency of grid connected photovoltaic inverters," European Committee for Electrotechnical Standardization, 2010.

[18] "Installation and Operation Manual," AEConversion micro-inverters, [Online]. Available: https://www.ifix-solar.info/wp-content/uploads/AEcon/Manual-AEC-INV-EU_EN.pdf. [Accessed: 24-Apr-2019].

[19] R. Castro, "Uma introdução às energias renováveis: eólica, fotovoltaica e mini-hídrica," 2º Edition, IST Press, 2012.

[20] K. Rademaekers *et al.*, "Study on Energy Prices, Costs and Subsidies and their Impact on Industry and Households - Final report," Trinomics, 2018.

[21] D. C. Jordan, "Photovoltaic Degradation Rates - an Analytical Review," *Progress in Photovoltaics: Research and Applications,* nº 21, pp. 12-29, 2013.

[22] F. Salvo, M. Ciuna, M. D. Ruggiero and S. Marchiano, "Economic Valuation of Ground Mounted Photovoltaic Systems," *Buildings,* vol. 7, nº issue 2, p. 54, 2017.