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Analysis of Failure Modes Effect and Criticality Analysis (FMECA): A Stand-Alone Photovoltaic System

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Abstract: This study deals with the implementation of a methodological guide for the maintenance of photovoltaic systems in Senegal. Typical PV systems components are photovoltaic panels, and inverter, a regulator, connecting cables and the battery; so Failure Modes Effect and Criticality Analysis (FMECA) is performed on the PV system in order to increase the reliability and reduce system failures. To do that, a functional analysis of the system through an octopus diagram and a dysfunctional analysis through a fault tree, are used as a decision support for the choice of the coefficients to obtain the full system FMEA. The obtained results allowed us to detect about 40% of the types of failure that cause over 60% of system malfunction. Anticipating these types of failure through preventive maintenance would make the PV system more reliable.

Keywords: FMECA, Photovoltaic Systems, Maintenance

1. Introduction

In the actual context of sustainable development. Renewable energies are undoubtedly an ideal solution from their availability and their perennity. That explains surely all works carried out in renewable energies and particularly photovoltaic. Photovoltaic solar energy represents a factor impossible to circumvent in the race with energies in Africa and particularly in Senegal; however, there is a lack of about maintenance on PV systems. It is then of prior importance to fill this gap. For example, practically 80% of the photovoltaic street lamps does not function practically more than two to three months. It remains obvious that it is not the solar illumination, which is lacking, but rather a bad installation or a poor maintenance. Moreover this remains also valid for photovoltaic power plant. It is then a great interest to set a system for the maintenance of photovoltaic power plants in Senegal. The main objectives of this work is then to analyze the failure mode in PV systems and then apply FMECA method to set up or improve the maintenance of those systems.

2. Analysis of the Modes of Failure

2.1. The Reliability of a System

- Reliability

The reliability is the ability of an entity to perform the required functions under stated conditions for a specified time [5]. It is characterized by the probability R (t) the entity E accomplish these functions under the conditions given for the time interval [0, t], given that the entity is not broken at the time t=0, see figure 1.

R (t) = P [E not defaulting on [0, t]]

Reliability is often modeled by:

$$R(t) = \exp(-\lambda t) \tag{1}$$

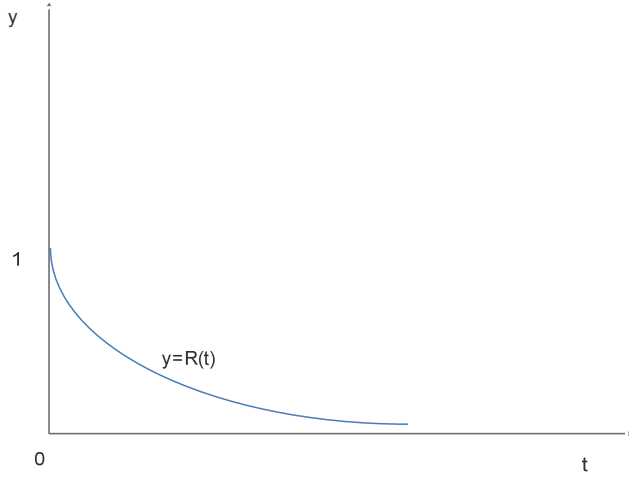Where λ is the failure rate expressed as the percentage of defects

Figure 1. Reliability.

- Availability of a system

Availability is the ability of an entity to be able to accomplish the functions required under the given conditions and at a given time [1]. It is characterized by the probability A (t) of the entity E at time t, to perform the duties required under given conditions.

A (t) = P [E non-defaulting at time t]

- Maintainability of a system

Maintainability is the ability of an entity to be maintained or restored to a state in which it can perform a required function, when maintenance is performed under given conditions with prescribed procedures and resources. It is characterized by the probability M (t) the entity E is in state at time t, to perform his duties, knowing that the entity was not working at time t = 0 [1].

M (t) = P [E is repaired on [0, t]]

- Safety

Safety is the ability of an entity to avoid, under given conditions, critical or catastrophic events. It is characterized by the probability S (t) that the entity E does not let appear in given conditions, critical or catastrophic events.

S (t) = P [E avoids critical or catastrophic events on [0, t]]

- Means reliability time

Figure 2 shows schematically the successive states possible for a repairable system [1].
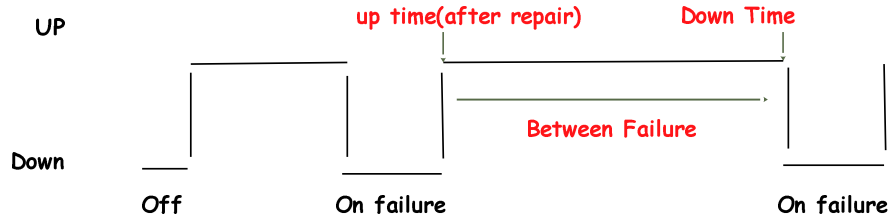

Figure 2. Means reliability time.

In fact, the magnitudes carried by the graph are the durations (TBF) to which there corresponds the means (MTBF) obtained by static operation m (t) or probabilistic E (t) of the n periods recorded and saved. The acronyms used correspond to the following concepts:

- MTTF (Mean Time To Failure)

$$MTTF = \int_0^\infty R(t)dt \tag{2}$$

- MTTR (Mean Time To Repair)

$$MTTR = \int_0^\infty [1 - M(t)]dt \tag{3}$$

- MTBF (Mean Time Between Failures)

$$MTBF = MDT + MUT \tag{4}$$

- MUT (Mean Up Time)
- MDT (Mean Down Time)

2.2. Failure Rate

The instantaneous failure rate, λ (t) is a feature of reliability. The λ value (t) dt is the conditional probability of a failure in the time interval [t, t + dt], knowing that there is no failure in the time interval [0, t]. Thus, applying the theorem of conditional probabilities, then λ (t) is so that:
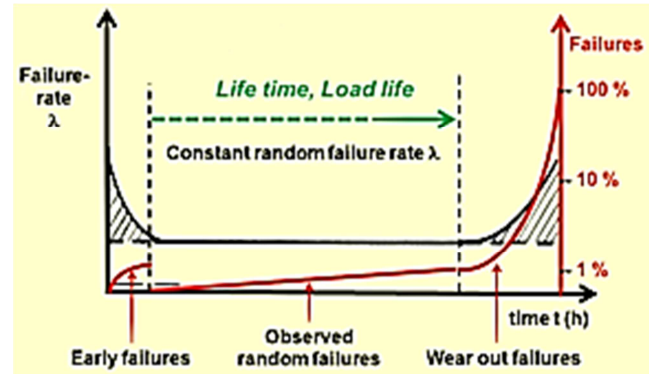

Figure 3. Failure rate.

2.3. Exponential Distribution

The exponential distribution is most commonly used in electronics to describe the reliability period during which the equipment failure rate is considered constant (random failure). It describes the elapsed time to failure, or the time interval between two failures. It is defined by a single parameter, the failure rate, λ. It is characterized by:

- The Reliability:

$$f(t) = \lambda e^{-\lambda t} \tag{5}$$

- The probability density:

$$R(t) = e^{-\lambda t} \qquad (6)$$

- The failure rate:

$$\lambda(t) = \lambda \qquad (7)$$

- MTBF (Mean Time Between Failure):

$$MTTF = \frac{1}{\lambda} \qquad (8)$$

The system

The studied system consists of a solar array connected to a controller, a battery bank and inverter (figure 4)
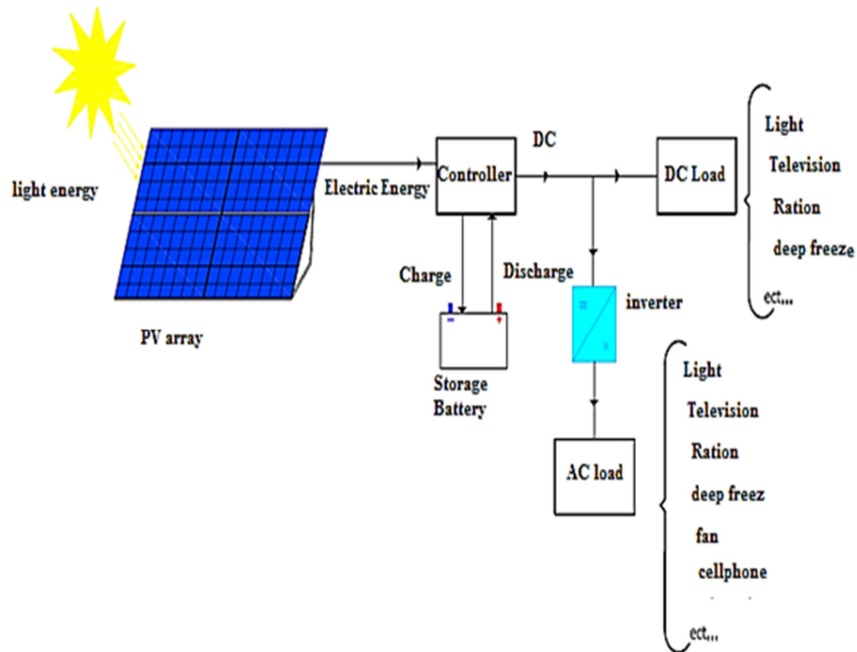

Figure 4. *The system.*

2.4. Functional Analysis Through an Octopus Diagram

The system whose failures are studied must first be "shelled".

What is it used for? What functions does it fulfill? How does it work? Functional analysis must answer these questions rigorously. The system is analyzed under two aspects:

- External: relationships with the external environment.
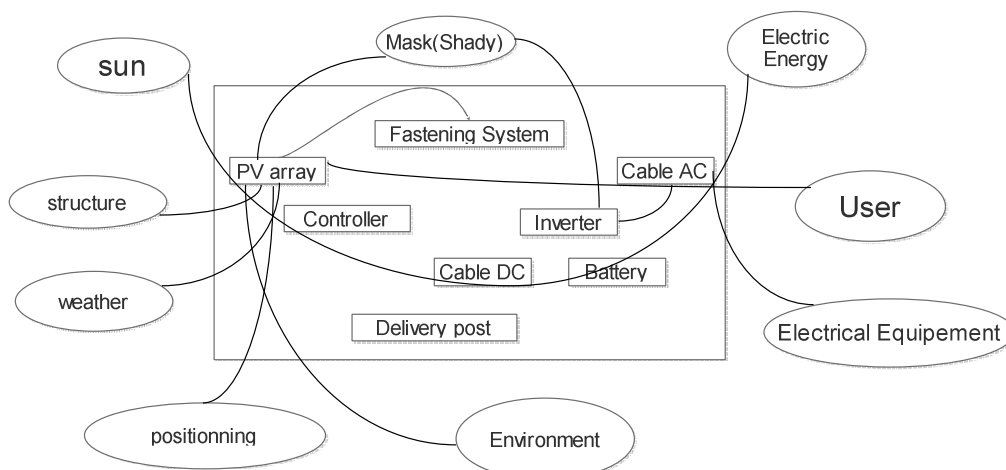- Internal: analysis of flows and activities within the process.

Figure 5. *The octopus diagram.*

2.5. Fault Tree Analysis

The fault tree comprises a plurality of branching describes the probable causes of an event may occur. These events are the result of a number of other events connected by logic "AND" and "Or" gates.
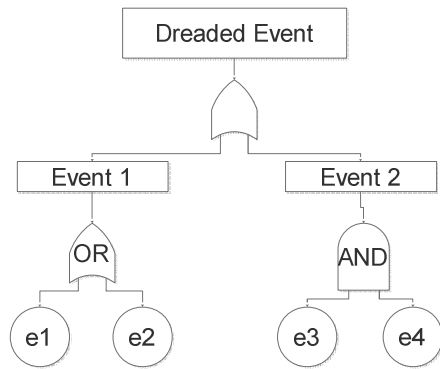
Figure 6. *Fault tree connection.*

In figure 6 the event E1 resulting from the connection of events e1 and e2 through an OR gate, can only happen if one of e1 and e2 occurs well or both events occur simultaneously. Contrary, event E2 will happen only if e3 and e4.

In our system, the feared event is that the PV system does not supply power. There are three major events and their possible causes, which are described by the fault tree. These events include lack of energy output of the AC cable following a minor failure, or following a major failure and lack of energy output of the inverter. These events result from the causes described in the following tree.
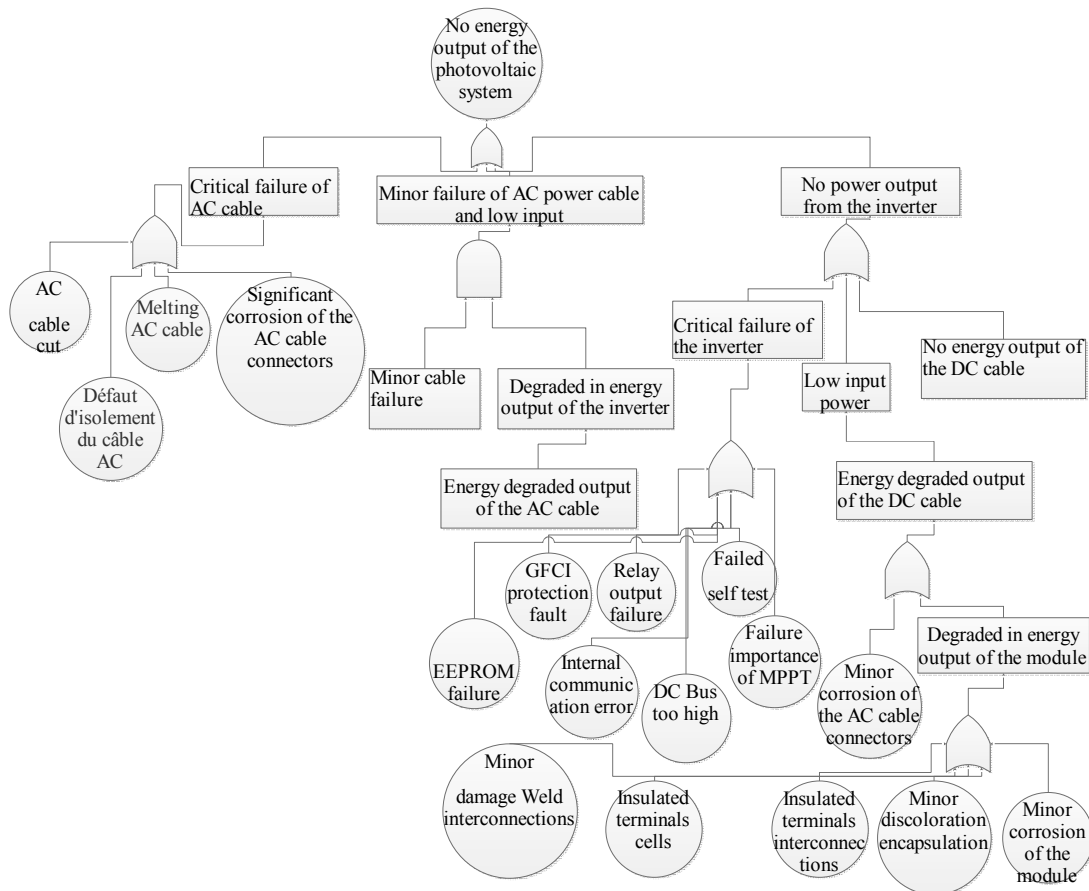

Figure 7. *System failure tree.*

2.6. Failure Modes, Effects and Criticality Analysis (FMECA)

The purpose of the FMECA is to highlight the most critical failures in order to control them. This is an estimation of the criticality index because the trio-mode-effect of potential failure studied according to certain criteria. Several criteria can be used to determine this index. A failure is even more important if:

- The consequences are serious;
- It is quite common;
- If that detection is uncertain

Criticality is the product of the rating assigned to each of the criteria. In this study the notes range from 1 to 10 for each

criterion. The allocation of these points is described by the following tables.

- Occurrence

The occurrence is the probability of the failure mode, estimated by answering the question: «What is the relative probability of occurrence of this failure mode?».

Table 1. *Occurrence listing.*

Occurrence	occurrence listing
Never or rarely appeared	1-2
Rarely appeared	3-4
That may appear or have appeared	5-6
already seen regularly appearance	7-8
Almost certain probability of occurrence	9-10

• Severity

This is to seek the prioritization of the severity of effects, by answering the question: «What is the relative severity of that effect?».

Table 2. Severity rating.

customer complaints	Severity rating
Ineffective or not perceptible effect by the customer	1
Small inconvenience for the customer	2
Noticeable discomfort to the client without much too much inconvenience, the solution can be found quickly	3-4
Significant inconvenience perceived by the customer	5-6
Total loss of function	7-8
Non- compliance	9
Security problem for the end user customer	10

• Undetected:

Failure detection is the probability of not detecting the failure mode, by answering the question: «If the failure mode occurs, what is the relative efficiency of detection means in the current or proposed surveillance plan?» We must quoting here the effectiveness of the monitoring plan or control plan, whether actual or proposed.

Table 3. Undetected listing.

Undetected	Undetected listing
Tests and planned trials will some detection	1-2
The detection by tests and planned trials is uncertain	3-4
Testing and planned tests do not guarantee detection	5-6
Detection is difficult	7-8
No tests or assays for detection	9-10

Calculation of criticality

Simply multiply the three quotations previously allocated for determining priority C:

$$C = S \times O \times U$$

C: criticality

S: Severity

U: undetected

The following table (table 4) shows the calculation of criticality coefficients for each failure mode. The choice is based on the previous tables. In the table, each element of the system is listed, cited his failure mode and the detection mode presented. Criticality is the product of the occurrence, severity and non- detection.

Table 4. Criticality coefficients.

Element	Function	methods failures	Causes	Effects	Detection	Criticality O	S	U	C
PV Module	Convert solar energy into electrical energy	The PV module does not supply electric power	hotspots	The system does not produce electric energy	Open circuit voltage measurement	6	9	3	162
			Failure of the junction box			7	9	7	441
			broken Glass			4	8	4	128
			Failure of the bypass diode module			3	7	5	105
		Notorious decrease in delivered power (less than the maximum power)	delamination	The system produces less or no electrical energy	Visual	4	7	6	168
			Broken cells / micro cracks			8	5	7	280
			Failure of the weld ribbons			6	7	8	336
			broken interconnections			6	6	7	252
			Discoloration of encapsulation			8	7	7	392
			Corrosion			8	9	5	360
Inverter	Transforming electric power to AC power	The inverter does not deliver an alternative electric energy	Failure of Microcontroller	The system does not produce electric energy	visual indicator	5	5	8	200
			Failure GFCI protection			4	7	9	252
			Internal communication malfunctioning			4	7	5	140
			Internal communication error			7	6	7	294
			Failure of the output relays			4	6	8	192
			DC BUS voltage too high			4	7	8	224
			Failed Self-Test			6	6	8	288
Cable	Ensure the flow of electricity	The electrical energy is not transmitted	cable cut	The system does not produce electric energy	Visual	5	7	2	70
		The transmitted power is low	melting cable (UV, heat,...)			4	9	6	216
			Corrosion of connectors			6	7	2	84
Battery	Store energy for a return to the system	sulfation	repetitive discharge	The battery does not restore energy	Visual	8	9	4	288
			Hardening of lead sulfate crystals of electrodes			6	7	4	168
		Drying of the electrolyte	Evaporation or leakage of electrolyte	The battery does not restore energy	Visual	7	8	3	168
Regulator	Regulate the charging and discharging of the battery for protection of both battery and loads	The controller does not control the charging and discharging	Faulty control unit	the battery is not loaded properly	indicator light	4	7	5	140
			The transistor does not work		Global measurement parameters	4	4	8	128
			Blown fusible		Visual	3	3	2	18
			Failure of MPPT		voltage measurement	3	5	7	105

For a more detailed overview of the calculation, each element will be studied separately and Pareto study will locate types of failure on which the priorities will be.

3. Analysis of Results of the FMECA Study of the System

Calculating coefficients allowed to find for each item different types of failure and their values in terms of criticality.

3.1. Criticality of Cable
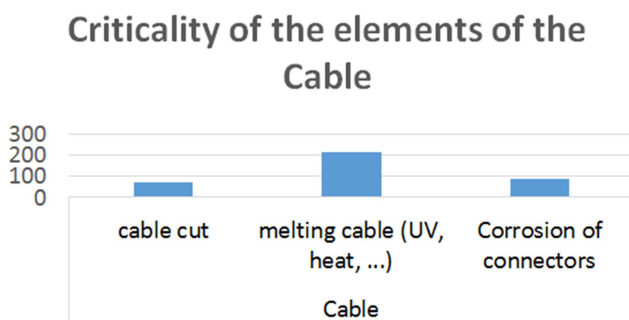
The figure 8 shows the mapped criticality for the Cable.

Figure 8. *Criticality of the cable elements.*

For the cables, the listed potential failure are breaking, melting or corrosion of connectors. Greater relative criticality is noted to melting cables that combines a total of 216 points.

3.2. Criticality of the Elements of the Inverter

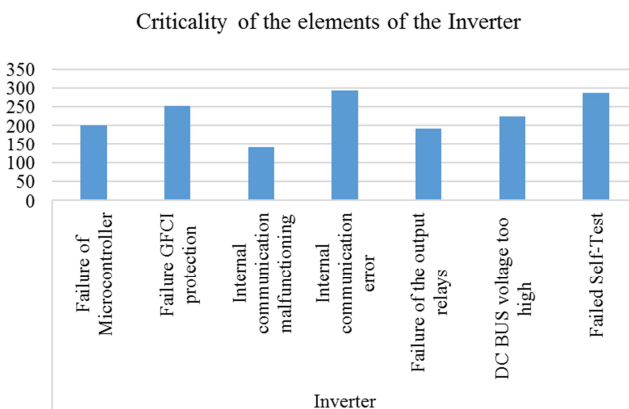The figure 9 shows the criticality traced for the inverter.

Figure 9. *Criticality of the elements of the Inverter.*

The inverter includes alone about seven opportunities failures. The internal communication error, the failure of GFCI protection and the failed self-test total respectively 294, 252 and 288 points on the criticality level.

3.3. Criticality of the Elements of the Battery

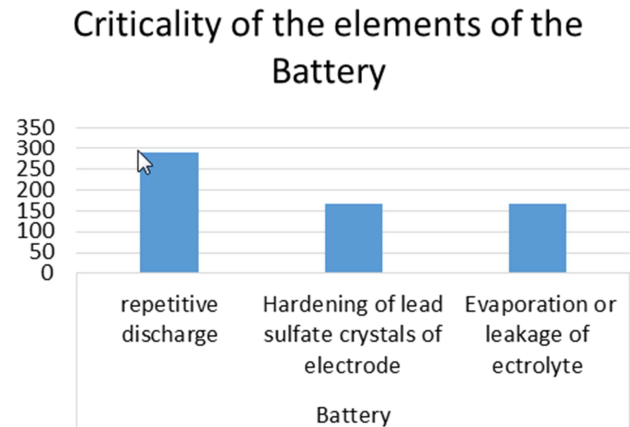The figure 10 is a graphical representation of criticality for the battery.

Figure 10. *Criticality of the Battery elements.*

The three failure modes chosen for the battery are repetitive discharges, sulfating and evaporation or leakage of the electrolyte. Their critical points exceed 150 points.
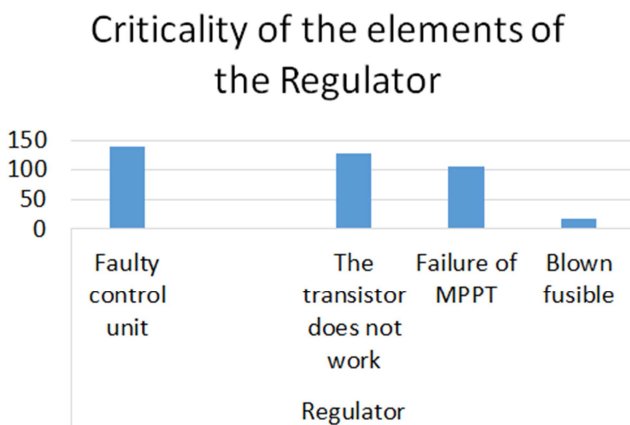
3.4. Criticality of the Elements of the Regulator

Figure 11. *Criticality of the elements of the Regulator.*

The figure 11 shows the criticality map of the regulator

For the regulator, the faulty control unit has the highest criticality with 140 followed by the transistor which combines a total of 128 each.

4. Discussion

The figure 12 shows the criticality diagram for the system by highlighting the criticality threshold giving priority to certain failure modes.
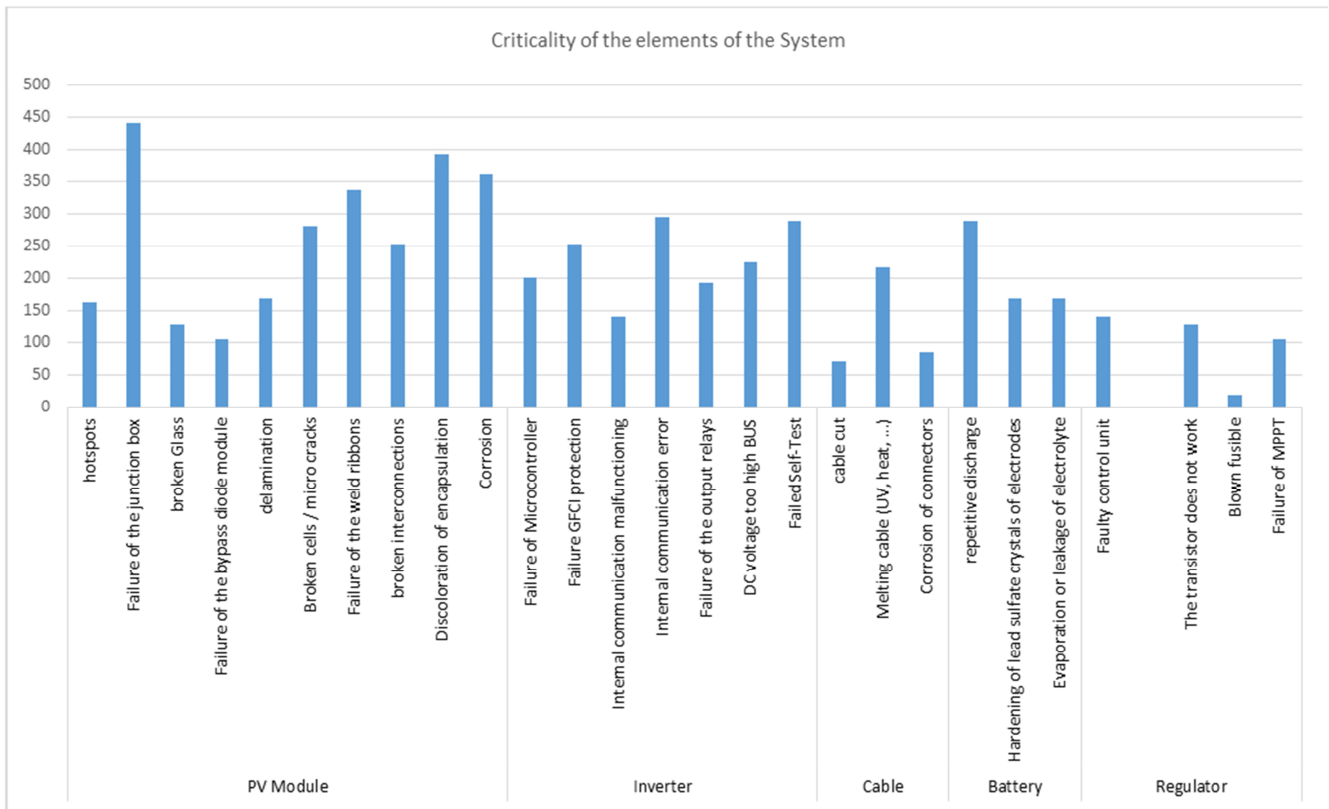
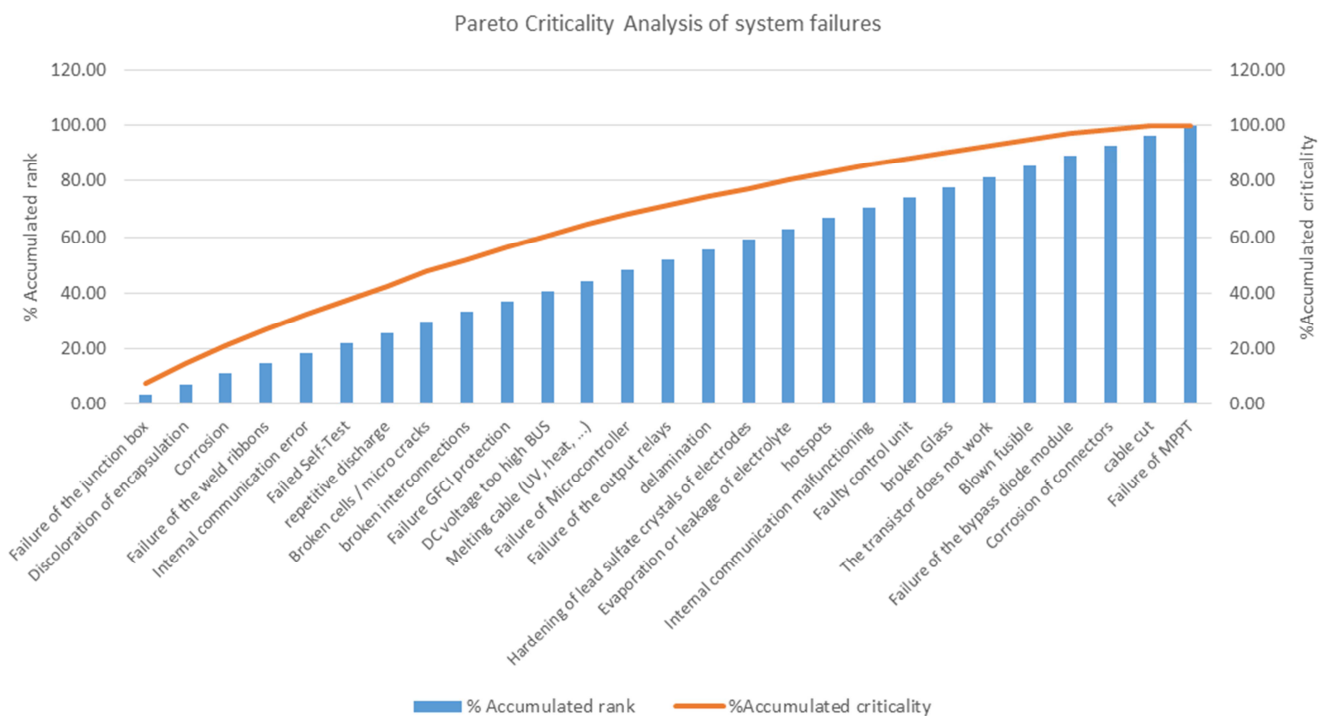*Figure 12. Criticality of the elements of the System.*

Figure 13. The Pareto curve.

Analysis of system failures shows a shared distribution of the criticality of the system elements. A threshold of two hundred (200) has been set. Failures whose criticality is less than 200 do not create any particular problem in that. They are easily identifiable, are infrequent or not too bad for the system.

Criticality includes a product consisting of case, the probability of non-detection and severity of a type of failure. Failures whose criticality exceeds the threshold (200) deserve special attention. This attention will result in preventive maintenance to deal with any eventuality on.

For better visibility, a Pareto analysis was performed.

Pareto analysis

The Pareto analysis allows to see the minimum of causes that leads to maximum effect on the system. Figure 13 represents the Pareto curve. For the draw, a ranking of failure modes has been achieved in decreasing order, and a percentage was calculated through the combination of criticality.

The Pareto analysis shows that 40% of failures makes over 60% of the criticality cumulating. In this 40% we find for the battery failures, the repetitive discharge and for photovoltaic panels, among other failures we have the broken interconnections. And finally to the failure modes of an inverter may be mentioned the failure of microcontroller and the overvoltage of the BUS.

A mastering of these failure modes (40% of the total) could reduce by 60% the system crashes and contribute strongly to the reliability of autonomous photovoltaic systems.

5. Conclusion

The study focused on maintenance of autonomous photovoltaic systems. After a reminder of the exponential law, a functional analysis of the system was made through an octopus diagram and a fault tree. This was done in order to help us choose the criticality coefficients through the Failure Modes Effects and criticality Analysis (FMECA). A Pareto study applied to the system showed that 40% of possible failures themselves include nearly 60% of the criticality of the system. Mastering these failures will increase the reliability of the entire autonomous photovoltaic system.

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