RELIABILITY OF PHOTOVOLTAIC SOLAR SYSTEMS THROUGH REAL O&M FOLLOW-UP DATA

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ABSTRACT: This paper provides a detailed analysis of failures and incidents that occurred in 218 PV systems, in 24 PV plants and 17 PV parks, for 15 months of performance, located in Spain and Italy. The results show that the photovoltaic technology is the cause of the 20.3% of the incidents while the 44% of failures are caused due to external causes of the PV system installation. The 56.7% of the failures affected the energy production of the PV system. The major cause of failure is given by the monitoring systems, followed by low power inverters (between 5-90 kW). Despite these failures, the efficiency of the facilities is high with a performance ratio between 69% and 83%.

Keywords: Reliability, Photovoltaic, Fault.

1 INTRODUCTION

The evolution of photovoltaic systems has been exponential for the last few years [1]. The detailed knowledge of these facilities operation under real conditions contributes to improving the design of equipment and auxiliary elements, to optimize the operation and maintenance tasks and to obtain more accurate economic evaluations.

For this reason, diagnostic methods to identify inefficiencies, failures and incidents in photovoltaic installations are being optimized. Numerous studies on diagnostic methods have been developed. A first group of studies is mainly based on the analysis of climatological and electrical data obtained through the monitoring system and the neuronal networks [2-6]. Another group proposes a method for the detection of failures based on the absolute performance ratio error (APRE) which represents the difference between measured and the simulated performance ratio [7]. Also specific methods to determine failures in equipment have been developed. Diagnostic methods based on the analysis of the dI/dV - V curve are proposed. This curve detects partial shading [8], others detect the MPP evolution or faults in a inverter [9, 10].

On the other hand, the operation and maintenance costs included in the calculate of the levelized cost of energy (LCOE) or used in the economic feasibility studies of photovoltaic installations are generally based on a fixed percentage of the total PV plant cost, between 0.8% and 1.2% per year [11,12].

The influence of the impact of uncertainties and statistics of failures in the financial and economical models of these facilities are reflected in other documents [13].

However, in contrast to the numerous studies on fault detection facilities, there are few studies of failures and incidents in real photovoltaic systems [14] that can feed back the learning process.

The current study focuses on the analysis of failures and incidents produced in grid-connected photovoltaic systems, without storage system. The reflected incidents are those that require corrective maintenance.

Some incidences that produce inefficiencies or impairments in photovoltaic systems as degradation of PV module, shading phenomena, soiling effect, mismatch effect, inverter power limitation by temperature, maximum power point tracking losses, show losses or module temperature effect are not included in this study.

The failures and incidents of this study have been obtained from real data and provided by the responsible companies for the operation and maintenance of PV systems. These failures have been mainly detected through the analysis of climatological and electrical data obtained from the monitoring system, the alarm system, the monitoring of the inverter and from the visual inspection of installations (discolouration, browning, delamination, glass and cell broken in module).

It is intended to contribute to improving the knowledge of the true reliability of photovoltaic systems through their behavior under real conditions.

2 METHODOLOGY

Operation and maintenance data for 15 months, from January 2014 to March 2015, of 218 PV systems distributed in 17 PV parks in Spain and Italy have been analyzed. Their characteristics and the incidents detected are described in Table I.

The characteristics of the analyzed facilities are summarized in Table II:

Table II. - Characteristics of the analyzed facilities.
Failures and incidents are grouped according to the following criteria for this analysis:

**Criterion 1:** Depending on the equipment or group that is affected, grouped in solar field, inverter, transformer, drainage network and monitoring system.

Within the solar field incidents have been grouped into failures that have led to the replacement of the photovoltaic module, faulty wiring, faulty junction box, theft or vandalism failures and faults by wind.

Inside the inverter incidents are grouped into operation failures, failures of starting and stopping and monitoring system failures.

Within the transformation center, incidents have been grouped in failures per share of transformer protections and failures resulting from weather.

Within the evacuation network incidents have been grouped in inherent network failures or network failures resulting from extreme weather conditions.

**Criterion 2:** Internal and external elements of the PV system distinguishing those that affect production or not. Solar field, inverter and transformation center are considered internal elements, drainage network and monitoring system are considered external elements.

Of all failures, derivatives from global monitoring installation system and monitoring inverter system are the only ones that do not affect to the electricity production. Rest of failures are included into the group that affect the electricity production installation.

**Criterion 3:** This classification is based on the technology linked to the failure, distributed on PV, electrical, electronic and telecommunications technologies. PV technology failures are associated to PV module failures.

In the case of electrical technology failures included problems related to network, faulty installation wiring and junction boxes failures. In the group associated with electronic technology failures by operation, start and stop the inverter are included. In telecommunications failures associated with the communication systems and data acquisition are included. In the group of external causes, have been included, other causes such as theft, vandalism and wind actions, of which no technology is responsible.

### 3 RESULTS AND ANALYSIS

According to Table I, we disaggregate and analyse failures according to the 3 indicated criteria.

**Criterion 1:** The 674 incidents are distributed according to Figure 1.

![Figure 1. Distribution of equipment failures.](image-url)

Note how the monitoring system is the responsible of most of the failures, but those failures do not have an impact in the production.

**Criterion 2:** Figure 2 presents the distribution of the 160 incidents of the solar field. Notice how most of them are due to the replacement of modules. This percentage would seem to be high a priori, but should not be considered that way, understanding that there are 401115 modules in all the facilities. Actually replacing modules represented 0.35 % throughout the entire period. Taking into account the impact on production, incidents by theft and vandalism are much more significant.

![Figure 2. Distribution of PV array failures.](image-url)
In the case of the inverter, according to Figure 3, approximately 21% of the incidents are caused due to the monitoring system that does not affect the production. Incidences called “operation failures” are those that have a greater impact on production.

![Figure 3.- Distribution of inverter failures](image)

In the case of the inverter it is shown in Table III a breakdown of failures in operation and start-up and shutdown depending on the inverter power. It is noteworthy that start-up and shutdown have a greater impact in inverters with lower power.

### Table III. Incidences according to the inverter power.

<table>
<thead>
<tr>
<th>Power (kW)</th>
<th>Number of inverters</th>
<th>Number of failures</th>
<th>Percentage of failures</th>
<th>Operation failures</th>
<th>Start-up and shutdown failures</th>
<th>Total failures</th>
<th>Total failures/Total inverters</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>36</td>
<td>10</td>
<td>29.4%</td>
<td>1</td>
<td>9</td>
<td>10</td>
<td>0.5</td>
</tr>
<tr>
<td>15</td>
<td>46</td>
<td>23</td>
<td>50.0%</td>
<td>18</td>
<td>10</td>
<td>48</td>
<td>1.5</td>
</tr>
<tr>
<td>90</td>
<td>61</td>
<td>22</td>
<td>34.3%</td>
<td>11</td>
<td>16</td>
<td>47</td>
<td>0.8</td>
</tr>
<tr>
<td>100</td>
<td>36</td>
<td>9</td>
<td>25.0%</td>
<td>5</td>
<td>8</td>
<td>13</td>
<td>0.6</td>
</tr>
<tr>
<td>500</td>
<td>19</td>
<td>8</td>
<td>42.1%</td>
<td>6</td>
<td>4</td>
<td>10</td>
<td>0.5</td>
</tr>
<tr>
<td>540</td>
<td>4</td>
<td>3</td>
<td>71.4%</td>
<td>4</td>
<td>2</td>
<td>6</td>
<td>0.5</td>
</tr>
<tr>
<td>630</td>
<td>8</td>
<td>1</td>
<td>12.3%</td>
<td>5</td>
<td>1</td>
<td>6</td>
<td>0.3</td>
</tr>
<tr>
<td>760</td>
<td>2</td>
<td>1</td>
<td>50.0%</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>800</td>
<td>4</td>
<td>1</td>
<td>25.0%</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>800</td>
<td>6</td>
<td>3</td>
<td>37.5%</td>
<td>5</td>
<td>0</td>
<td>6</td>
<td>0.2</td>
</tr>
<tr>
<td>Total</td>
<td>210</td>
<td>70</td>
<td>33.3%</td>
<td>56</td>
<td>28</td>
<td>84</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Complementarily presented in Figure 4 the probability density function where it is revealed that approximately 60% of the inverters have not presented any failure and that there are no inverters with more than 8 faults recorded in the period analyzed.

![Figure 4. Distribution of the number of inverter incidents.](image)

In the case of the transformer station, according to Figure 5, approximately 82% of the failures are caused due to actions of the protection system. Note that some of these actions have been derived from the own grid.

![Figure 5. Distribution of transformer failures.](image)

In the case of the grid, according to Figure 6, over the 90% of the failures are caused due to network quality.

![Figure 6. Distribution of failures in the power grid.](image)

**Criterion 2:** Figure 7 shows the distribution of the failures based on the origin of the incidence (internal and external) and whether it has impact on production or not within each of these groups.

![Figure 7. Distribution of failures (internal and external) and whether or not have impact on production.](image)

56.7% of failures affect production while 43.3% do not affect production.

A more detailed breakdown by photovoltaic park is shown in Table IV. Of note, two photovoltaic parks, V and TS, where the number of both internal and external incidents are far superior to the rest.

### Table IV. Distribution of failures (internal and external) and whether or not have impact on production in each PV park.

<table>
<thead>
<tr>
<th>PV Park</th>
<th>Number of Inverters</th>
<th>Number of Failures</th>
<th>Percentage of Failures</th>
<th>Operation Failures</th>
<th>Start-up and Shutdown Failures</th>
<th>Total Failures</th>
<th>Total Failures/Total Inverters</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>30</td>
<td>15</td>
<td>50.0%</td>
<td>9</td>
<td>6</td>
<td>15</td>
<td>0.5</td>
</tr>
<tr>
<td>TS</td>
<td>40</td>
<td>20</td>
<td>50.0%</td>
<td>12</td>
<td>8</td>
<td>20</td>
<td>0.5</td>
</tr>
<tr>
<td>M</td>
<td>10</td>
<td>7</td>
<td>70.0%</td>
<td>5</td>
<td>2</td>
<td>7</td>
<td>0.7</td>
</tr>
<tr>
<td>P</td>
<td>20</td>
<td>12</td>
<td>60.0%</td>
<td>7</td>
<td>5</td>
<td>12</td>
<td>0.6</td>
</tr>
<tr>
<td>A</td>
<td>50</td>
<td>30</td>
<td>60.0%</td>
<td>15</td>
<td>15</td>
<td>30</td>
<td>0.6</td>
</tr>
<tr>
<td>B</td>
<td>15</td>
<td>9</td>
<td>60.0%</td>
<td>6</td>
<td>3</td>
<td>9</td>
<td>0.6</td>
</tr>
<tr>
<td>C</td>
<td>25</td>
<td>15</td>
<td>60.0%</td>
<td>9</td>
<td>6</td>
<td>15</td>
<td>0.6</td>
</tr>
<tr>
<td>D</td>
<td>30</td>
<td>18</td>
<td>60.0%</td>
<td>12</td>
<td>6</td>
<td>18</td>
<td>0.6</td>
</tr>
</tbody>
</table>

In the case of the inverter, according to Figure 3, approximately 21% of the incidents are caused due to the monitoring system that does not a...
Criterion 3: Figure 8 shows the distribution of failures depending on the technology.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV Technology</td>
<td>20.33%</td>
</tr>
<tr>
<td>Electronic Technology</td>
<td>36.94%</td>
</tr>
<tr>
<td>Electrical Technology</td>
<td>30.42%</td>
</tr>
<tr>
<td>Telecommunication Technology</td>
<td>5.93%</td>
</tr>
<tr>
<td>External causes</td>
<td>6.38%</td>
</tr>
</tbody>
</table>

Figure 8.- Distribution of failures depending on the technology.

Notice how communications technology is the one presenting most failures while photovoltaic technology represents 20.33% despite the large number of existing photovoltaic units (401115).

An important aspect to note is that the distribution of the number of failures is not evenly spread across all the photovoltaic parks, as shown in Figure 9.

The average of the total failure in all facilities is 19.8 while the standard deviation is 21.5. Where failures concern energy production the average is 17.4 and the standard deviation is 17.6. In the case of failures that do not affect energetic production average is 22.2 and the standard deviation is 24.6.

Note that there are parks with no incidences or only a few and some others with more than 100.

4 INFLUENCE IN ENERGY FIELD

The calculation of the actual influence of these failures in the energy loss of the installation requires a very detailed information on the different faults. For example, to identify energy loss due to a failure in a photovoltaic module would require to know how long it has been previously failing to be identified as a failure, not only counting from the day that the failure was identified and the module was replaced.

In Figure 10 we show the Performance Ratio (PR) and the ratio efficiency (RE) defined according to expressions 1 and 2 respectively. We have determined them for 15 of the 17 parks from which we had quality information available on production and other required data. These parameters include the set of real energy losses of the system.

\[ PR(\%) = \frac{E(\text{kWh})}{H_e(\text{kWh/m}^2) \cdot P_e} \times 100 \]  
\[ RE(\%) = \frac{E(\text{kWh})}{H_e(\text{kWh/m}^2)} \times 100 \]

Figure 10.- PR and RE of the 15 parks on the analyzed period.

It is noted that the PR varies between 69% and 83% and according to Figure 11 where the failures that affect the installation are represented, it is observed that there is no direct relationship between the number of failures and the loss of energy as was expected. Thus, the park that has more failures (PP1) is not the park with greater energy losses. This is because most incidents of this park have occurred in the solar field and such losses are the least affecting energy loss compared to the impact of the inverter, transformer or power supply.

5 CONCLUSIONS

In general, the photovoltaic systems are quite reliable. The probability that an inverters fails over one year of operation is 33.2% and the probability of a photovoltaic module replacement during the 15 months was 0.39%.

The highest percentage of incidents, 36.9%, are caused due to the monitoring system. Although these failures have no influence on the energy production of the installation itself, it has important implications for ensuring compliance with the contracts between the owner of the photovoltaic installation and the maintenance company. Besides the failures in the monitoring system avoid to identify, in many cases, other failures and incidents since much of the fault detection
methods are based on the data obtained through the monitoring system itself.

There are particular circumstances that lead certain photovoltaic parks to have a significant number of failures. For example, it is remarkable the relatively high failure rate of the grid compared to the 17 grids analyzed and the importance that these failures have on the loss of energy production of the photovoltaic plant. However, almost all network failures have been caused by a single power grid, the photovoltaic park called V. Hence the importance of an optimum quality assessment of the electrical network that will be connected to the photovoltaic plant and its maintenance.

56.7% of failures affect production while 43.3% do not affect production. Of the issues affecting production, 49.6% were internal and 7.1% were external.

The probability of occurrence of at least an annual failure in a photovoltaic installation is 53.6%, meaning that this is the probability of a PV installation to fail over one year. This issue affects production in 49.6% of the cases, therefore the probability of occurring at least one fault that adversely affects the annual output is approximately 27%.

6 REFERENCES