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

Isidoro Lillo[1], Antonio Palomo[1], Jose Guasumba[2] and Manuel Silva[1]
1 Department of Energy Engineering. University of Seville. Spain
2 Renewable Energy Laboratory. University of the Armed Forces. Quito. Ecuador
Camino de los Descubrimientos s/n, 41092 Sevilla, Spain. Phone: (+34) 954487236.
Fax: (+34) 954487233. E-mail: isidorolillo@us.es

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.

	TYPOLOGY	PV MODULES	PV MODULES: NUMBER OF PANELS	PV MODULES: PEAK POWER	INVERTER: NUMBER OF INVERTERS	INVERTER: POWER	TC
17 PARKS → 218 SYSTEMS	Ground: 11 2010-2011	SILICON	23220	5340 kWp	10	5000 kW	7
		Cadmium Telluride (CdTe)	346854	26880 kWp	90	24780 kW	27
	Covering:6 2010-2011	SILICON	25902	6000 kWp	114	5320 kW	10
		Cadmium Telluride (CdTe)	5139	400 kWp	4	400 kW	1

Total	Total	Total	Total	Total
401115	38620 kWp	218	35500 kW	45

Si	CdTe
12.20%	87.80%

Table I. - General data and system failures.

PV PARKS CHARACTERISTICS

LOCATION			TYPE	SOLAR FIELD				INVERTER		ST	PANT	
PV Park	PV Plant	Province	Ground/Roof	Nº PV Modules	Nº Strings	Material	Peak Power (Wp)	Nº Inverters	Nominal Power (kW)	Nº TSs	Peak Power (Wp)	Nominal Power (kW)
S	S-1	Valencia	Roof	3266		Si PC	230	1	630	1	751,2	630
	S-2		Roof	3266		Si PC	230	1	630	1	751,2	630
C	C1	Zamora	Ground	57888	6432	CdTe	75	4	1000	4	4341,6	4000
V	V-1	Cádiz	Ground	29106	3234	CdTe	75	21	90	3	2183,0	1890
	V-2		Ground	29106	3234	CdTe	75	21	90	3	2183,0	1890
	V-3		Ground	26334	2926	CdTe	75	19	90	3	1975,1	1710
A	A-1	Mallorca	Ground	44928	1664	CdTe	75/77,5	2 4	500 540	3	3425,8	3160
MA	MA-1	Murcia	Ground	25812	2868	CdTe	80	4	500	3	2065,0	2000
MB	MB-1	Murcia	Ground	9540	477	Si PC	235	4	500	4	2241,9	2000
MC	MC-1	Murcia	Ground	13680	684	Si PC	230	6	500	3	3146,4	3000
B	B-1	Castellón	Roof	3465	231	Si MC	238	7	100	1	824,7	700
	B-2		Roof	2590	259	Si MC	305	7	100	1	789,9	700
T	T-1	Tarragona	Roof	5374	260/270	Si PC	215-235	10	100	1	1218,6	1000
TS	TS-1	Lérida	Roof	1587		Si PC	215-235	22	15	1	354,6	330
	TS-2		Roof	1560		Si PC	235	24	15	1	366,1	360
TA	TA-1	Lérida	Roof	520	2	Si PC	220	20	5	1	114,4	100
	TA-2		Roof	520	2	Si PC	220/225	14	5	1	81,3	70
	TA-3		Roof	5139	141/148	CdTe	77,5	4	100	1	398,0	400
F	F-1	Lérida	Roof	3754	22,24,25	Si PC	235	8	100	1	880,1	800
CR	CR-1	Cremona	Ground	34080	12	CdTe	77,5	2 2	500 760	2	2641,2	2520
D	D-1	Cremona	Ground	16200	12	CdTe	77,5	2	630	1	1255,5	1260
PP	PP-1	Palazzo P.	Ground	46200	12	CdTe	77,5	2 3	800 630	3	3580,5	3490
P2	P2-1	Parmense	Ground	20520	12	CdTe	77,5	2	800	1	1590,3	1600
P3	P3-1	Parmense	Ground	16680	12	CdTe	77,5	2	630	1	1292,7	1260
TOTAL 17	24		Ground 13 Roof 11	401115		Si 12,2% CdTe 87,8%		218	MAX 1000 MIN 5	45	38452	35500

FAILURES AND INCIDENTS

	INVERTER					MONITORING SYSTEM		SOLAR FIELD								ST				ELECTRICAL GRID		
PV Park	Operation Failures	Starting and Stop Failures	Monitoring and Communication Failures	Total Incidents	%	Total Incidents	%	Replacement of PV Modules	Wiring Failures (Strings)	String Boxes Failures	Vandalism Incidents	Robbery Incidents	Wind Impacts Incidents	Total Incidents	%	Total Incidents	%	Meteorological Inclemencies	%	Total Incidents	%	Total Incidents
S	0	0	0	0	0,0%	4	66,7%	0	0	0	0	0	2	2	33,3%	0	0,0%	0	0,0%	0	0,0%	6
C	1	0	2	3	10,7%	4	14,3%	13	0	2	0	0	0	15	53,6%	4	14,3%	0	0,0%	2	7,1%	28
V	31	16	24	71	47,3%	41	27,3%	6	2	0	1	4	0	13	8,7%	2	1,3%	1	0,7%	22	14,7%	150
A	6	2	9	17	32,1%	3	5,7%	26	0	1	1	0	0	28	52,8%	3	5,7%	2	3,8%	0	0,0%	53
MA	0	1	0	1	25,0%	2	50,0%	0	0	0	0	0	0	0	0,0%	0	0,0%	0	0,0%	1	25,0%	4
MB	3	0	0	3	27,3%	4	36,4%	0	0	2	0	0	0	2	18,2%	0	0,0%	0	0,0%	2	18,2%	11
MC	0	2	0	2	28,6%	2	28,6%	0	0	3	0	0	0	3	42,9%	0	0,0%	0	0,0%	0	0,0%	7
B	2	0	0	2	5,6%	34	94,4%	0	0	0	0	0	0	0	0,0%	0	0,0%	0	0,0%	0	0,0%	36
T	2	1	0	3	10,3%	26	89,7%	0	0	0	0	0	0	0	0,0%	0	0,0%	0	0,0%	0	0,0%	29
TS	38	30	2	70	59,8%	47	40,2%	0	0	0	0	0	0	0	0,0%	0	0,0%	0	0,0%	0	0,0%	117
TA	2	17	1	20	45,5%	24	54,5%	0	0	0	0	0	0	0	0,0%	0	0,0%	0	0,0%	0	0,0%	44
F	0	2	0	2	8,3%	20	83,3%	0	0	2	0	0	0	2	8,3%	0	0,0%	0	0,0%	0	0,0%	24
CR	2	0	4	6	14,3%	15	35,7%	16	0	0	1	0	0	17	40,5%	4	9,5%	0	0,0%	0	0,0%	42
D	0	0	0	0	0,0%	11	55,0%	8	0	0	0	0	0	8	40,0%	0	0,0%	0	0,0%	1	5,0%	20
PP	1	2	0	3	5,2%	3	5,2%	45	0	0	1	0	0	46	79,3%	5	8,6%	0	0,0%	1	1,7%	58
P2	1	0	1	2	8,0%	5	20,0%	12	0	1	0	0	0	13	52,0%	2	8,0%	2	8,0%	1	4,0%	25
P3	0	0	0	0	0,0%	4	20,0%	11	0	0	0	0	0	11	55,0%	2	10,0%	3	15,0%	0	0,0%	20
TOTAL	89	73	43	205	30,4%	249	36,9%	137	2	11	4	4	2	160	23,7%	22	3,3%	8	1,2%	30	4,5%	674

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 faults and failures 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 no 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.

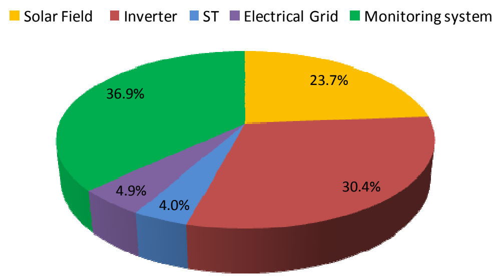

Figure 1. Distribution of equipment failures.

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

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 thay 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.

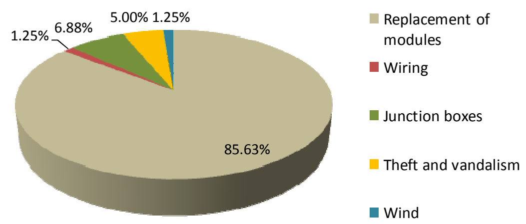

Figure 2.- Distribution of PV array failures.

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.

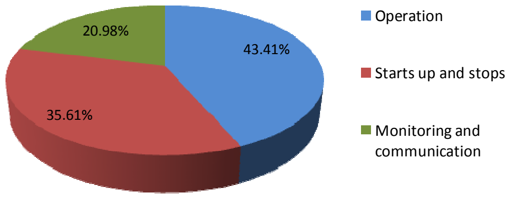

Figure 3.- Distribution of inverter failures

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.

Power (kW)	Number of inverters	Number of failed inverters	Percentage of failured inverters	Operation failures	Start-up and shutdown failures	Total failures	Total failures/Total inverters
5	34	10	29.4%	1	12	13	0.4
15	46	23	50.0%	38	30	68	1.5
90	61	22	36.1%	31	16	47	0.8
100	36	9	25.0%	5	8	13	0.4
500	19	8	42.1%	6	4	10	0.5
540	4	3	75.0%	4	2	6	1.5
630	8	1	12.5%	1	1	2	0.3
760	2	1	50.0%	1	0	1	0.5
800	4	1	25.0%	1	0	1	0.3
1000	4	1	25.0%	1	0	1	0.3
Total	218	79		89	73	162	

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.

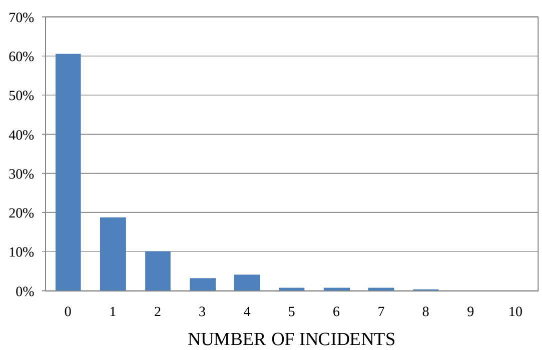

Figure 4. Distribution of the number of inverter incidents.

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.

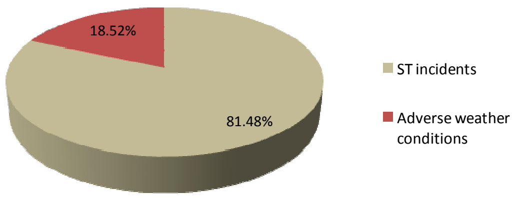

Figure 5. Distribution of transformer failures.

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

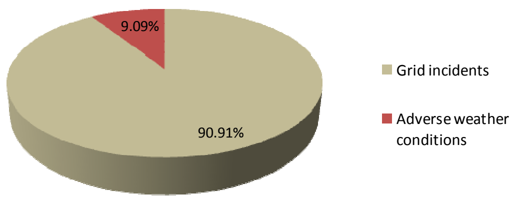

Figure 6. Distribution of failures in the power grid.

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

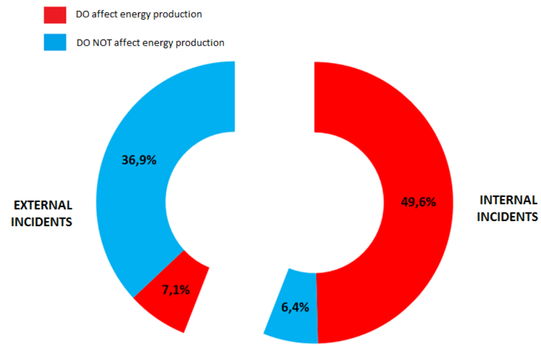

Figure 7. Distribution of failures (internal and external) and whether or not have impact on production.

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.

PV PARKS	Internal Incidents		External Incidents		A. P. Incidents		NOT A.P. Incidents	
	Number of incidents	Number of incidents/Month	Number of incidents	Number of incidents/Month	Number of incidents	Number of incidents/Month	Number of incidents	Number of incidents/Month
S	0	0.0	6	0.4	2	0.1	4	0.3
C	22	1.5	6	0.4	22	1.5	6	0.4
V	81	5.4	69	4.6	85	5.7	65	4.3
A	47	3.1	6	0.4	41	2.7	12	0.8
MA	1	0.1	3	0.2	2	0.1	2	0.1
MB	5	0.3	6	0.4	7	0.5	4	0.3
MC	5	0.3	2	0.1	5	0.3	2	0.1
B	2	0.1	34	2.3	2	0.1	34	2.3
T	3	0.2	26	1.7	3	0.2	26	1.7
TS	70	4.7	47	3.1	68	4.5	49	3.3
TA	20	1.3	24	1.6	19	1.3	25	1.7
F	4	0.3	20	1.3	4	0.3	20	1.3
CR	26	1.7	16	1.1	23	1.5	19	1.3
D	8	0.5	12	0.8	9	0.6	11	0.7
PP	53	3.5	5	0.3	55	3.7	3	0.2
P2	17	1.1	8	0.5	19	1.3	6	0.4
P3	13	0.9	7	0.5	16	1.1	4	0.3
Σ	377	1.5	297	1.2	382	1.5	292	1.1

Criterion 3: Figure 8 shows the distribution of failures depending on the technology.

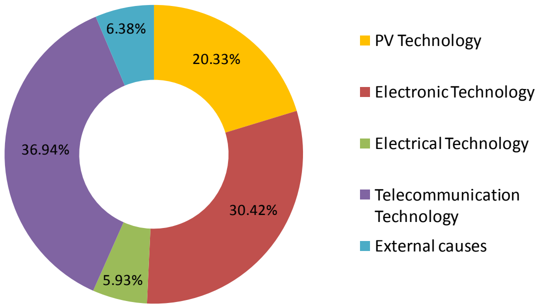

Figure 8.- Distribution of failures depending on the technology.

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.

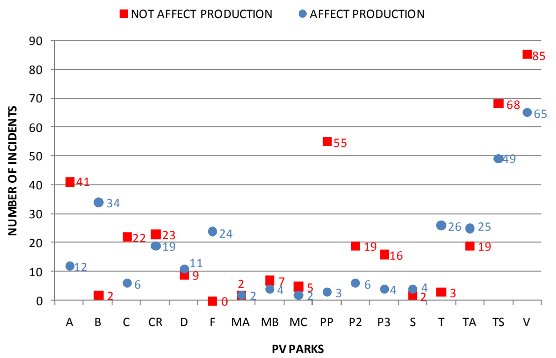

Figure 9.- Number of failures per park affecting or not to the production.

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.

$$PR(\%) = \frac{E(kWh)}{\frac{H_g(kWh/m^2)}{1000(W/m^2)} \cdot P_p(W_p) \cdot \left[1 - \alpha(\%/^{o}C) \cdot (\bar{T}_p - 25)(^{o}C)\right]} \cdot 100 \quad (1)$$

$$RE(\%) = \frac{E(kWh)}{H_g(kWh/m^2) \cdot A_{cap}(m^2)} \cdot 100 \quad (2)$$

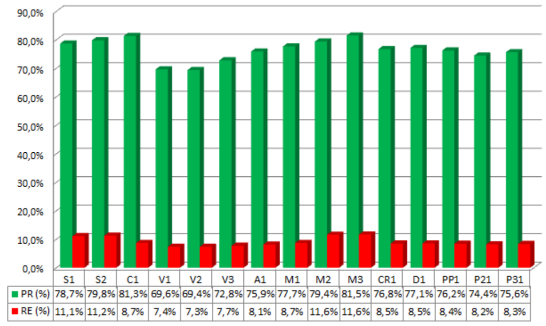

Figure 10.- PR and RE of the 15 parks on the analyzed period.

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.

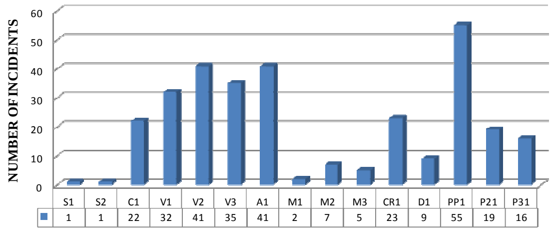

Figure 11. Failures affecting production in the different photovoltaic parks.

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

[1] GTM Research/SEIA, Q3 2015: U.S. Market insight. December 2015.

[2] Drews A., de Keizer, A.C., Beyer. H.G.., Lorenz, E. Betccke, J., Van Sark, W.G. et al., 2007. Monitoring and remote failure detection of grid-connectedPV systems base don satellite observations. Solar Energy 81, 548-564

[3] W. Chine, A Mellit, V. lugi, A. Malek, G. Sulligoi, A. Massi Pavan. 2016. A novel fault diagnosis technque for photovoltaic systems based on artificial neural networks. Renewable Energy 90. p. 501-512.

[4] W. Chine, A. Mellit, A. Massi Pavan, S.A. Kalogirou. 2014. Fault detection method for grid-connected photovoltaic plants. Renewable Energy 66, 99-100.

[5] Yihua Hu, Bin Gao, Xueguan Song, Gui Yun Tian, Kongjing Li, Xiangning He. 2013. Photovoltaic fault detection using a parameter based model. Solar Energy 96. Pp 96-102.

[6] Santiago Silvestre, Aissa Chouder, Engin Karatepe. 2013. Automatic fault detection in grid connected PV systems. Solar Energy 94. pp 119-127.

[7] Choulder, S. Silvestre. 2010. Automatic supervisión and fault detection of PV systems based on power losses analysis. Energy conversion and Management. 51. pp. 2929-1937.

[8] M. Wiwa, S. Kawamura, H. Ohno.2006. Diagnosis of a power output lowering of PV array with a (dI/dV)-V characteristic. Proceeding of IEEE 4th World Conference on Photovoltaic Energy Conversion. Waikoloa. 2442-2445.

[9] Khomfoi, S., Tolbert, L.M., 2007. Fault diagnostic system for a multilevel inverter using a neural network. Power Electron., IEEE Trans. 22 (3), 1062–1069.

[10] Kim, T.J., Lee, W.C., Hyun, D.S., 2009. Detection method for opencircuit fault in neutral-point-clamped inverter systems. Ind. Electronics, IEEE Trans. 56 (7), 2754–2763.

[11] Cameron, C.P., Goodrich, A.C., 2010. The levelized cost of energy for distributed PV: a parametric study. 2010 35th IEEE Photovoltaic Specialists Conference (PVSC). Institute of Electrical & Electronics Engineers (IEEE), pp. 529–534. http://dx.doi.org/10.1109/pvsc.2010.5616811.

[12] Darling, S.B., You, F., Veselka, T., Velosa, A., 2011. Assumptions and the levelized cost of energy for photovoltaics. Energy Environ. Sci. 4 (9), 3133. http://dx.doi.org/10.1039/c0ee00698j.

[13] IEA. P h o t o v o l t a i c p o w e r s y s t e m s p r o g r a m m e annual report. 2015. task 13.Performance and reliability of PV systems. Subtaks 3.3. Characterization of PV Module Condition in the Field - Guidelines on IR and EL in the Field. http://www.iea-pvps.org/index.php?id=164.

[14] Lukamp, H., March 2002. Reliability Study of Grid-Connected PV Systems: Field Experience and Recommended Design Practice. Technical report Task 7, IEA PVPS.