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Reliability of large-scale grid-connected photovoltaic systems

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ABSTRACT

This paper presents a method for assessing the reliability of large-scale grid-connected photovoltaic systems. Fault tree and probability analysis are used to compute the reliability equation and the developed model is applied on military-standard data and on data taken from scientific literature.

The method provides a tool useful to single out the different impacts that the large number of components belonging to the photovoltaic field and the BOS (Balance of System) chain have on system overall reliability, hence granting the possibility to design and implement more effective monitoring/diagnostic strategies and maintenance plans.

1. Introduction

Reliability is an important issue in large-scale grid-connected photovoltaic (PV) systems as their operations rely on business plans developed over periods of time of at least twenty years which often assume fault-free functioning. Only rarely are faults factored in cash flow budgeting, and maintenance plans represent a cost that should be kept the lowest possible to improve economic appeal of such large-scale plants.

Not many papers discussing PV systems reliability are available in literature. For instance, [1] analyzes simple stand-alone PV systems using failure mode effect analysis (FMEA) and fault tree analysis (FTA). Failure rates estimates are also given assuming that time to failure is exponentially distributed. The failure rate for a PV array is hypothesized as being $33.3 \bullet 10^{-6}$ failures/month, while inverter failure rate is assumed to be $342.5 \cdot 10^{-6}$ failures/month. [2] derives reliability equations from the application of FTA on stand-alone, grid-connected and utility-interactive simple block-diagrammed PV systems. No statistical analysis is implemented, and no estimates of reliability probability functions are computed. [3,4] study the optimal interconnection of PV modules and use of bypass diodes to maximize reliability of PV arrays. Architecture, failure modes and failure probability are the three parameters found to impact on array reliability. [5] presents a reliability evaluation method of an electric power generation system including PV sub-systems, but reliability is considered here as the capability of the PV system to provide power to the load depending on the variability of meteo conditions, given all system components never fail. The authors calculate a *Loss of Load Expectation index* as the probability of the generation system not being able of meeting the load demand. [6] studies the reliability of battery voltage regulators (BVRs) used in PV systems; it considers a constant failure rate and calculates the reliability of the overall system as the joint probability of the reliabilities for a series of system components, whose failure behavior is independent from one another. The BVRs are used in small-scale systems, and this contribution does not consider a complete PV system. [7] models the reliability in a way similar to the approach followed in this paper but with no FTA, using an exponential distribution and estimating the single solar cell as being equal to 0.0042 failures/(25 years). The focus is on verifying the reliability of several different connection modes of PV modules (series, parallel, series-parallel, total-cross-tied, bridge-linked, and their different combinations), not on the complete PV system. [8] employs highly accelerated life tests (HALTs) to determine potential failure modes for PV inverters. All results are obtained experimentally by means of laboratory measures. The paper constitutes a very interesting and complete essay of tests on the main component of the BOS chain, but does not provide fault probability density functions for inverters. HALTs are indeed not intended to supply information on component life expectancies, but rather to find failure modes which can be useful to engineers to understand possible design or manufacturing issues in very hard or even extreme testing conditions. [9] reports data from a field study in Japan, outlining failure and maintenance data in mean time between failure (MTBF) and mean time to repair (MTTR), with failure rates computed as the inverse of the MTBFs and expressed in failures/year. From the field study, it's evident that none of the monitored PV systems has reached the end of its intended life time without failures, achieving a failure rate under 0.0032 failures/year, with data taken for 1242 plants (with an average PV system power

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of 29 kW_p) over 7 years of operations. In this paper, 52 faults relative to PV modules are reported. [10] analyzes the reliability of stand-alone small-scale systems, suggesting that higher system reliability is achieved by using module-integrated inverters. Some estimates of module and inverter failure rates are also given (0.04 failures/year for PV modules, 0.1 failures/year for inverters). [11] describes several problems arising in a grid-connected PV system, quickly touching some inverter reliability issues from a qualitative point of view.

None of the papers hereby briefly reviewed though analyze the specificities and actual electrical architecture of modern large-scale grid-connected PV systems.

This paper presents a method to analyze and quantify the reliability of large-scale grid-connected PV systems. This methodology is based on FTA [12–14] using an *exponential distribution* to model the fault probability density function.

It must be pointed out that using an exponential distribution is not necessarily the correct *ex-ante* choice: the real probability density function should be derived from experiments like accelerated life tests (ALTs), with *Log-normal*, *Weibull* or *mixed-Weibull* distributions being the likeliest outputs. Changing the function from exponential to a different one is not a big issue, the application of the method staying the same, but running ALTs to correctly estimate *pdfs* should be considered as a fundamental step to be taken in order to obtain realistic reliability estimates.

The paper relies on assumptions that need to be refined in further development: failures are non repairable and components sustain no degradation during operation. Furthermore, as soon as a component fails, the overall system is considered to be in a failure state. Consequently, also the evaluation of energy and economic losses, tied to component degradation and the time needed to restore full plant functioning, needs to be refined in following contributions.

However, results are drawn and discussed to provide the reader with a possible interpretation and use of the developed methodology. Reliability data are taken from military standard manuals [15] and scientific literature (other reliability databases are available in literature [16]). The military standard we employ [15] tends to estimate higher failure rates than real ones, positioning this study towards a more conservative evaluation of real failure rates. But as already pointed out, ALTs would provide reliability data that can be readily changed in the model in order to get more precise results useful when designing real-life installations.

2. Large-scale grid-connected PV systems

The electrical architecture of a generic PV system is shown in Fig. 1.

The PV module strings are connected to the inverter by means of a protection to assure that no inverse current is running in a string as a result of i.e. partial shading. In general, the protection can be: a blocking diode (as represented in Fig. 1), a fuse or a circuit breaker. It is fair to note that such protection could also be omitted (and in some real world installations is *omitted*) when the value of the maximum inverse current resulting from the $N-1$ number of irradiated strings, being N the total number of strings connected in parallel, is considered not to be dangerous for the string which is not, at that time, operational and hence becomes a load for the other strings which inject their current in it. Furthermore, blocking diodes tend not to be used since they introduce a power loss due to their inherent voltage drop.

After the string protections, DC circuit breakers give the user the possibility to disconnect the PV field even under solar irradiation, for maintenance or safety purposes.

The inverter is then added to perform the conversion from DC to AC. Surge protection devices (SPDs) protect each inverter from inlet and outlet surges resulting i.e. from lightings hitting the installation directly or indirectly.

Downstream the inverter, on the AC side, a series of circuit breakers protect the AC lines as per normal electrical design practice.

The PV system reliability analysis ends at the point where the system is connected to the transformer, not considered in this study.

Seven large-scale PV systems, with nominal power ranging from 100 kW_p to 2500 kW_p , are designed in order to evaluate their overall reliability. To compute the total number of components needed for each system, the PV module and inverter with the characteristics shown in Table 1 are used in all systems. The resulting number of components per each PV system is shown in Table 2. It is possible to note that the number of components increases with the PV system intended nominal power output. Of course, using inverters or PV modules with different nominal power can change significantly the number of components in each system.

The total number of components is computed by considering only one main field electrical cabinet (or distribution board) in the DC side. No sub-field cabinets have been added in order to keep the installation free from site specificities and maintain the lowest possible number of components. This way, only one level of distribution boards is considered. For instance, a 1 MW_p installation

Table 1
Characteristics of the PV module and inverter used in the design of the large-scale PV systems.

PV Module (230 W_p)	$I_{sc} = 8.24$ A	$V_{oc} = 37.2$ V	$I_{mpp} = 7.60$ A
	$V_{mpp} = 30.2$ V	$\mu_I = 3.3$ mA/°C	$\mu_V = -120$ mV/°C
Inverter (100 kW)	$V_{mpp,min} = 450$ V	$V_{mpp,max} = 820$ V	$V_{max} = 1000$ V
	$I_{DC,max} = 235$ A		

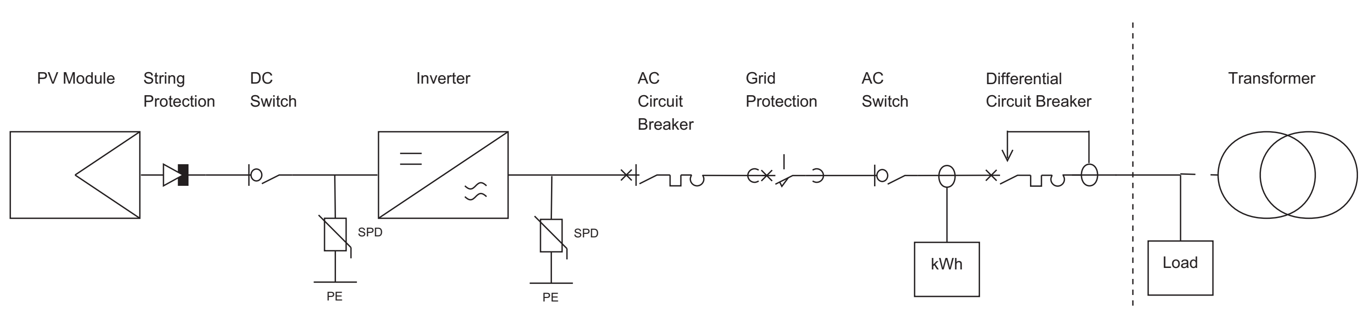

Fig. 1. Electrical architecture for the PV system.

Table 2
Number of components for each PV system.

Power (kW_p)	100	200	500	1000	1500	2000	2500
PV modules	437	874	2166	4351	6517	8702	10868
String Protection	23	46	114	229	343	458	572
DC switch	3	6	15	27	42	57	72
Inverter	1	2	5	9	14	19	24
AC circuit breaker	1	2	5	9	14	19	24
Grid protection	1	1	1	1	1	1	1
AC switch	1	1	1	1	1	1	1
Differential circuit breaker	1	1	1	1	1	1	1
Connector (couple)	874	1748	4332	8702	13,034	17,404	21,736

must resort to 229 string protections (whether diodes, fuses or MT switches) which are placed in only one field cabinet per inverter. Each inverter is equipped with 3 DC switches with DC fuses to connect strings to the inverter. In case a 2-level distribution were to be introduced in the PV field design, the number of DC switches would increase by the number of sub-fields that connect the strings together and relay them to their relevant inverter.

The analysis assumes that cables do not introduce failure modes and that system design and installation are flawless, this way granting the possibility to focus only on electrical/electronic components failures. It is also assumed that the SPDs never fail in short-circuit mode and that the measuring equipment is not opening the circuit in case of failure.

The study analyzes the reliability of seven PV systems over a period of time of twenty years, with an average of 8.5 h operations a day. The failure rate unit is hence failures/hour.

3. Quantitative reliability analysis

3.1. Probability functions and fault distributions

The following concepts are needed to describe the basics of the probability analysis of PV systems reliability. More details are available in [14].

The *probability density function (pdf)* $f(t)$ represents the failure distribution of the component population over the entire time range; the larger its value in t, the more failures will take place in a infinitesimal interval around t.

The *failure probability function* $f(t)$ is the probability that a component will fail by a specified time t; it is defined as the *cumulative distribution function* (*cdf*) of the *pdf*:

$$F(t) = \Pr(T \leq t) = \int_{-\infty}^{t} f(t)dt \quad (1)$$

and can be also interpreted as the population fraction failing before or at time t.

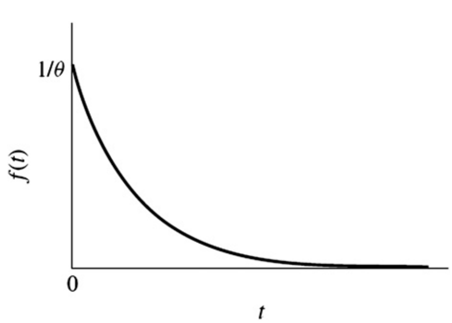

Fig. 2. Probability density function for the exponential distribution (where $\theta = \lambda$) [14].

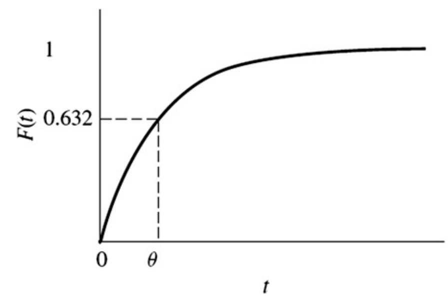

Fig. 3. Failure probability for the exponential distribution (where $\theta = \lambda$). When $t = \theta, F(t) = 0.632$ [14].

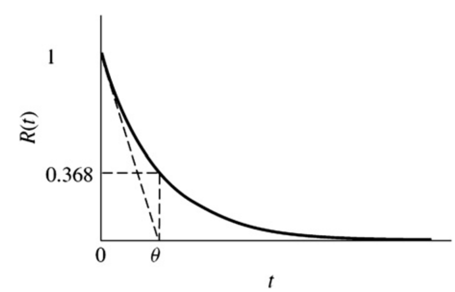

Fig. 4. Reliability probability for the exponential distribution (where $\theta = \lambda$). When $t = \theta, R(t) = 0.368$ [14].

The *reliability probability function R(t)* indicates the population fraction surviving time t, and is derived from Equation (1) knowing that it is the complement to 1 of the *F(t)* (the probability of success being one minus the probability of failing):

$$R(t) = 1 - F(t) = \Pr(T \geq t) = \int_{t}^{\infty} f(t)dt \quad (2)$$

The *failure rate h(t)* (also called *hazard rate*) is the rate of change in the probability that a surviving product will fail in the next small interval of time, given by:

$$h(t) = \frac{f(t)}{R(t)} \quad (3)$$

The *mean time to failure* (MTTF), measured in the chosen units of time, is:

$$\text{MTTF} = \int_{0}^{\infty} R(t)dt \quad (4)$$

Table 3
Component adopted failure rates and bibliographic reference.

Component	Failure Rate (10^{-6} failures/hour)	Reference
PV modules	0.0152	[9]
String Protection (Diode)	0.313	[15] Sect. 6–2
DC switch	0.2	[15] Sect. 22–1
Inverter	40.29	–
AC circuit breaker	5.712	[15] Sect. 14–5
Grid protection	5.712	[15] Sect. 14–5
AC switch	0.034	[15] Sect. 14–1
Differential circuit breaker	5.712	[15] Sect. 14–5
Connector (couple)	0.00024	[15] Sect. 17–1

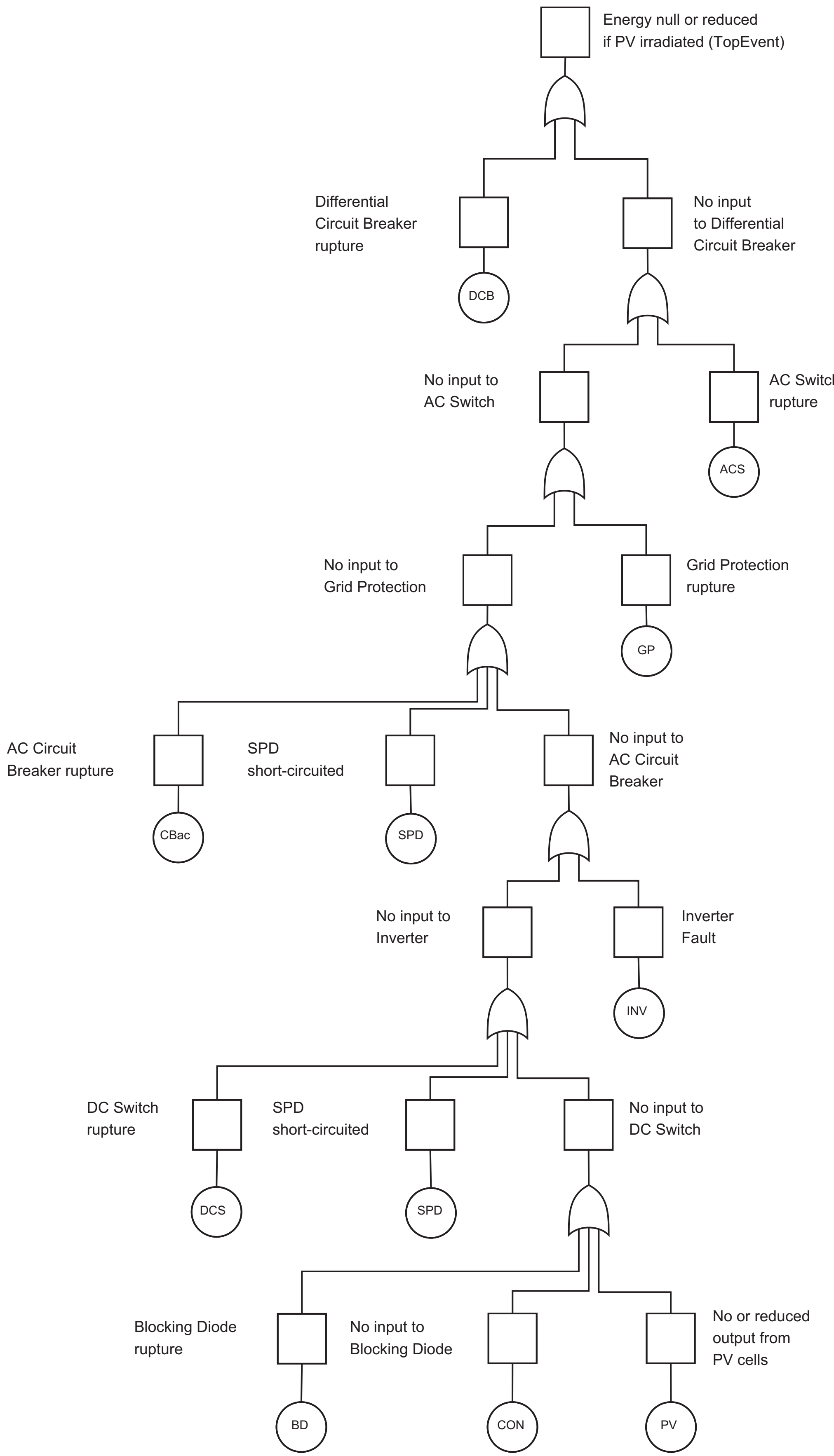

Fig. 5. Fault tree for the PV system in Fig. 1.

Table 4
Fault tree basic event codes.

DCB: differential circuit breaker	ACS, DCS: AC or DC switch	GP: grid protection
CB: AC circuit breaker	SPD: surge protection device	INV: inverter
BD: blocking diode	CON: connector	PV: photovoltaic cell

The time distribution of faults is assumed to be exponentially distributed. The *pdf* for the exponential distribution is (see Fig. 2):

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

and from Equations (1), (2), (3) and (4) (see Figs. 3 and 4):

$$F(t) = 1 - \exp(-\lambda t) \tag{6}$$

$$R(t) = 1 - F(t) = \exp(-\lambda t) \tag{7}$$

$$h(t) = \lambda \tag{8}$$

$$\text{MTTF} = 1/\lambda \tag{9}$$

To obtain systems reliability estimates, Equations (6), (7), (8) and (9) will be used.

As already mentioned, the exponential distribution is not necessarily the correct distribution for faults occurring in electrical or electronic components, as is the case for PV technology. The analysis makes use of this distribution since in most reliability databases only the failure rate λ is reported or estimated, while finding other distribution characteristic parameters (like *Weibull's* shape and scale factors) is not at all common. The real probability density function for each PV component should be estimated by means of long and relatively expensive ALTs.

Furthermore, from Equation (8) the exponential distribution failure rate is independent of time, the exponential being also indicated as the *memoryless* distribution. This confirms, again, that the exponential distribution is not realistic if applied to the description of life-long behavior of PV systems due to last many years.

This choice does not undermine the validity of the proposed methodology, but at the same time poses serious questions over the correctness of the results that occur by applying the methodology to exponential distributions. This path is followed knowing that, as soon as real distribution characteristic parameters will be made available, adapting the methodology to the correct distribution will be fairly straightforward.

The failure rate for the PV modules is obtained from [9]. The inverter failure rate is obtained by considering a change-over time of 1 in 8 years; we consider this as implying 1 failure in 8 years, hence the failure rate becomes $\lambda = 1/8/365/8.5 = 40.29 \cdot 10^{-6}$ failures/hour. All other failure rates are taken from [15]. All rates are reported in Table 3.

Table 5
Total component reliability [in %] for PV systems after one year of operations.

Power (kW_p)	100	200	500	1000	1500	2000	2500
PV modules	97.95	95.94	90.24	81.35	73.41	66.18	59.72
String Protection	97.79	95.63	89.51	80.05	71.66	64.08	57.36
DC switch	99.81	99.63	99.07	98.34	97.43	96.52	95.63
Inverter	88.25	77.88	53.53	32.47	17.38	9.30	4.98
AC circuit breaker	98.24	96.52	91.52	85.26	78.03	71.41	65.36
Grid protection	98.24	98.24	98.24	98.24	98.24	98.24	98.24
AC switch	99.99	99.99	99.99	99.99	99.99	99.99	99.99
Differential circuit breaker	98.24	98.24	98.24	98.24	98.24	98.24	98.24
Connector (couple)	99.93	99.87	99.68	99.35	99.03	98.71	98.39

Table 6
Total component reliability [in %] for PV systems after twenty years of operations (Note that a reliability of 0% means that there will be at least one component with a failure; it does not necessarily mean that the overall PV system will completely stop its energy conversion).

Power (kW_p)	100	200	500	1000	1500	2000	2500
PV modules	66.06	43.64	12.81	1.61	0.21	0.03	0.00
String Protection	63.96	40.90	10.91	1.17	0.13	0.01	0.00
DC switch	96.35	92.82	83.01	71.53	59.38	49.29	40.92
Inverter	8.21	0.67	0.00	0.00	0.00	0.00	0.00
AC circuit breaker	70.16	49.22	17.00	4.12	0.70	0.12	0.02
Grid protection	70.16	70.16	70.16	70.16	70.16	70.16	70.16
AC switch	99.79	99.79	99.79	99.79	99.79	99.79	99.79
Differential circuit breaker	70.16	70.16	70.16	70.16	70.16	70.16	70.16
Connector (couple)	98.71	97.43	93.75	87.85	82.36	77.17	72.35

3.2. Fault tree analysis

The techniques pertaining to FTA are used to understand the interdependencies between all the components belonging to the overall PV system. A fault tree is indeed very useful to comprehend the behavior of a complex system by analyzing the relationships between the single components that, together, make up the whole system.

All components in the PV system are connected in series, meaning that if a single component fails, the overall system fails as a consequence. A series connection, as far as reliability is concerned, is not necessarily a series connection in the physical world; it is a representation of the direct effect that a component has along the chain of all other components constituting the overall system. For comparison, a system with two components operating in parallel might be more reliable than a two-component series system since, if one component fails, the other paralleled component might operate as a back-up (the well known concept of *redundancy*).

In this study, system failure is intended not only as a complete shut-down, but even as a small power loss due to a single cell in a single module being damaged. This consists in a very strong constraint, since a small power loss due to a single module can not even be spotted in a large-scale PV system.

Other assumptions for the FTA quantitative analysis of large-scale grid-connected PV systems are:

- top event binary state;
- hard failure (on-off, degradation of components not considered);
- non repairable failures;
- independent events;
- non mutually exclusive events;
- good design (components are adequate and correctly installed);
- always on mode;
- constant failure rate (exponential distribution).

For the assumptions taken, the system has only two modes of functioning: ON or OFF (*top event binary state*); it is constituted by

Table 7
System failure rates and reliabilities after one and twenty years of operations (Note that a reliability of 0% means that there will be at least one component with a failure; it does not necessarily mean that the overall PV system will completely stop its energy conversion).

Power (kW_p)	100	200	500	1000	1500	2000	2500
System failure rate ($\cdot 10^{-4}$)	$0.72 \cdot 10^{-2}$	1.32	3.14	5.71	8.74	11.77	14.80
Reliability (in %, 1 year)	79.94	66.22	37.71	17.0	6.64	2.59	1.01
Reliability (in %, 20 years)	1.14	0.03	0.00	0.00	0.00	0.00	0.00

Table 8
Fussel–Vesely relative importance measures for a period of twenty years of operations.

Power (kW_p)	100	200	500	1000	1500	2000	2500
PV modules	34.3	56.4	87.2	98.4	99.8	100	100
String Protection	36.5	59.1	89.1	98.8	99.9	100	100
DC switch	3.7	7.2	17.0	28.5	40.6	50.7	59.1
Inverter	92.8	99.4	100	100	100	100	100
AC circuit breaker	30.2	50.8	83.0	95.9	99.3	99.9	100
Grid protection	30.2	29.9	29.8	29.8	29.8	29.8	29.8
AC switch	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Differential circuit breaker	30.2	29.9	29.8	29.8	29.8	29.8	29.8
Connector (couple)	1.3	2.6	6.2	12.2	17.6	22.8	27.7

non degradable components but can break (*hard failure*) without being repairable (*non repairable failures*); the events that happen during system functioning are statistically independent events and events are not preventing one another to happen (*non mutually exclusive events*). The assumption that the components are not degradable can be viewed as not realistic, but if we consider the idea that a decrease in productivity due to PV modules degradation is already considered in all large-scale PV systems business plans, only a sharp performance decrease or malfunctioning will be considered as a system failure. These hypothesis pair with the two already introduced assumptions of *good design* and *constant failure rate*.

The techniques used to draw the fault tree for large-scale grid-connected PV systems can be found in [12–14], a discussion of such techniques being outside the scope of this paper. The fault tree for the architecture shown in Fig. 1 is depicted in Fig. 5.

To help interpreting the symbols in Fig. 5, it is useful to know that the connections between the events are visualized in the form of a bi-dimensional diagram where:

- a *Circle symbol* represents a basic event, with no downstream fault analysis development. For a basic event, we need to know its *pdf* to perform a reliability analysis on the overall system;
- a *Square/Rectangle symbol* represents an intermediate event that can be developed into a combination of other intermediate or basic events;
- an *OR gate* represents a logic gate whose output occurs in case any of the inputs occur.

Of course, many other symbols and gates are used in general FTA theory. The codes used in the basic event circles in Fig. 1 are clarified in Table 4.

The fault tree in Fig. 5 shows that all the components that are outlined in the schematic in Fig. 1 constitute a series system (both logical and electrical) which creates many issues from the point of you of the overall system reliability: all basic and intermediate events are indeed connected by means of OR gates, hence every fault that is generated within the tree is propagated to the top event "Energy null or reduced if PV irradiated" causing the top event to occur in case any basic event occurs.

Table 9
Rank of relative importance and tentative solutions.

Rank	Component	Solution	Effort
1)	Inverter	Preventive maintenance, monitoring	Normal
2)	String Protection (Diode)	Preventive maintenance, monitoring	High
3)	PV module	Preventive maintenance, monitoring	High
4)	AC Circuit Breaker	Monitoring	Normal
5)	Grid Protection	Monitoring	Normal
5)	Differential Circuit Breaker	Monitoring	Normal
7)	DC Switch	Monitoring	Normal
8)	Connector	Monitoring	Normal
9)	AC Switch	Monitoring	Normal

3.3. Minimal cut set calculation

To achieve a quantitative evaluation, the fault tree must be converted into a boolean expression and then into a probabilistic equation. Since basic events are connected by OR gates, it is quite straightforward to build the boolean equation of the basic events:

$$TopEvent = (((((((PV+CON+BD)+(SPD+DCS))+INV) ++(CB+SPD))+GP)+ACS)+\mathrm{DCB}) \quad (10)$$

Equation (10) is the logical equivalent of the fault tree in Fig. 5. Since the assumption that the SPDs never fail in short-circuit mode, $SPD = 0$(no effects whatsoever on the *TopEvent)* and Equation (10) is reduced to:

$$TopEvent = PV+CON+BD+DCS+INV+CB+GP+ACS+DCB \quad (11)$$

A cut set is defined as a collection of basic events whose occurrence will cause the top event to occur. A minimal cut set is defined as the smallest combination of basic events which, if they all occur, will cause the top event to occur [14]. Equation (10) shows that the fault tree can be expressed as the union of the nine minimal cut sets; each cut set is equivalent to each basic event.

From probability theory, the probability of failure of the top event, in case of union of the minimal cut sets, is given by the total probability of the minimal cut set:

$$\Pr(TopEvent) = \Pr(E_1+E_2+\ldots+E_n) \quad (12)$$

Since the events are assumed to be independent and non mutually exclusive, using the inclusion-exclusion rule, Equation (12) can be demonstrated to be equivalent to:

$$1-\Pr(TopEvent) = [1-\Pr(E_1)]\cdot[1-\Pr(1-E_2)]\ldots[1-\Pr(1-E_n)] \quad (13)$$

Since the event probability *Pr(E)* is the failure probability, 1-*Pr(E)* is the reliability probability. The total system reliability is hence given by the product of the reliability of each event E_i where $i = 1,\ldots,n$ being n the total number of events in the fault tree cut set:

$$R_{Tot} = \prod_{i=1}^{n} R(E_i) \quad (14)$$

This product relationship entails that the more the components in the series system, the less the total system reliability. In this analysis, the total system reliability probability R_{Tot} is given by the product of the components reliabilities:

$$R_{Tot} = R(PV)\cdot R(CON)\cdot R(BD)\cdot R(DCS)\cdot R(INV)\cdot R(CB)\cdot R(GP)\cdot R(ACS)\cdot R(DCB) \quad (15)$$

Since an exponential distribution has been chosen, the total system reliability becomes, using Equation (7):

$$R_{Tot} = \exp\left(-\sum_{i=1}^{n} m_i\lambda_i t\right) \quad (16)$$

where m_i is the total number of the same kind of component i (i.e. 24 inverters in the 2.5 MW_p configuration), λ_i are the failure rates of each kind of component i, n is the total number of different components, and t is the time frame chosen for the reliability analysis.

For example, the total reliability of the set of 24 inverters over one year (3102.5 h) is given by (see Table 5):

$$R_{Inv,Tot} = -\exp\left(24\cdot 40.29\cdot 10^{-6}\cdot 3102.5\right) = 0.0498 \quad (17)$$

The system total reliability is then the product of all component reliabilities computed as in Equation (17) by changing relevant component numbers and failure rates.

4. Results and discussion

Applying the failure rates in Table 3 to Equation (16) yields the results summarized in Table 5 and Table 6 for one and twenty years of operations.

It is straightforward to notice how reliabilities decrease with system power. After one year, for a 100 kW_p system the 23 string protections (considered as a single sub-system) have 97.79% probabilities of functioning without failures, while the inverter only 88.25%; for a 2.5 MW_p system, the 572 string protections (again considered as a single sub-system) have 57.36% probabilities of functioning without failures, while the 24 inverters only 4.98% (Table 5).

If considering twenty years of operations, the reliability estimates drop radically. For a 2.5 MW_p system, faults will occur with more than 99% probability to the PV modules, string protections, inverters, and AC circuit breakers (Table 6).

The overall system failure rates and reliability probability in one and twenty years are reported in Table 7.

With the failure rates and *pdf* adopted (see Table 3), in twenty years of operations at least 11 out of 10,868 modules would fail. To compute the energy loss due to a module fault, two fundamental parameters are needed: the time to detect the fault and the time needed to change the faulty component (known as the *Mean Time To Repair* or MTTR). In case the 11 modules failed on year 10, they were not replaced and were all placed in different strings, 11 strings out of 572 strings would indeed stop converting energy for the remaining 10 years. Assuming that 10 years would provide 50% of total production (this way neglecting the performance decay of the PV plant due to aging of components that would shift a higher percentage of energy conversion in the first 10 years rather than in the final 10 years), the energy loss would amount approximately to only 1% of the overall production (i.e. $11/572\cdot 50\% = 0.96\%$).

In case the module failure rate was found (through more precise accelerated life tests) to be ten times higher than the estimation used here (i.e. 1.52E-07 instead of 1.52E-08), the number of faulty modules would climb up to around 103. Always in the previous case scenario, the energy loss would climb to an unsustainable 9% of the total potential production.

As far as the inverters are concerned, using the failure rate in Table 3, 23 inverters out 24 would have a fault over the twenty years period. The energy loss caused by one inverter would be easily traceable, but for a 2.5 MW_p PV system, two weeks of lost production per each inverter (assuming two week as the MTTR) would entail a loss of more than 4% of the overall system production.

To understand the impact of each single component on the reliability of the overall system, the *Fussel–Vesely relative importance measures* are calculated by means of Equation (18):

$$I_{FV}(i|t) = \frac{\Pr(E_1 + E_2 + \ldots + E_{n_i})}{F(t)} \quad (18)$$

where E_{n_i} is the event that the components in the minimal cut set containing component i are all failed, with n_i the total number of the minimal cut sets containing component i, and $F(t)$ is the failure probability of the system at time t [14]. The results for a period of twenty years of operations are outlined in Table 8.

The *Fussel–Vesely measures* confirm the impact of the inverters, string protections, PV modules and AC circuit breakers on the reliability of large-scale grid-connected PV systems.

5. Conclusions

In order to extract useful information from this reliability analysis, Table 9 reports the list of components ranked by relative importance, and proposes some possible strategies to cope with the issues introduced by large numbers of components in PV systems.

The only likely way to figure out faults occurring in PV modules and string protections is to use automatic monitoring and diagnostic systems to capture reduced power output from small defaults which can result, if not detected, in potential sources of serious economical loss.

Periodical verification and politics of preventive substitution of string protections (if present) and inverters can greatly improve energy conversion output. Inverters can also be easily monitored automatically.

Finally, circuit breakers can be equipped with automatic switches that trip in case of malfunctioning.

A tentative interpretation of the degree of effort needed to proceed with preventive maintenance or monitoring is also given in Table 9. Advances in monitoring and diagnostic equipment will greatly reduce these issues related with the use of large number of components especially in very large PV power systems.

Further research on the subject will have to relax the assumptions set by considering, for instance, repairable failures or degradation of components, and evaluate related energy and economic losses in order to find means to improve real-life PV power plant efficiency.

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