World Applied Sciences Journal 35 (2): 275-287, 2017
ISSN 1818-4952

DOI: 10.5829/idosi.wasj.2017.275.287

PV Inverters Reliability Prediction

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Abstract: This paper initially discusses the reliability of a 250W Photovoltaic (PV) micro inverter. Using the bill of materials the reliabilities of the main, gate drive, power supply, current and voltage sensing and microprocessor circuits were investigated and the failure rate and Mean Time Between Failure (MTBF) calculated. The sum of component failure rates equals the complete PV micro inverter failure rate. To account for temperature effects the component failure rate was calculated for each inverter operating temperature and multiplied by the percentage occurrence of this operating temperature to obtain a weighted failure rate. A similar procedure was used to calculate the failure rate for the main circuits of a 4.6kW & a 4.5kW multi-string inverter. All calculations are based on MIL-217F N2 method.

Key words: Failure rate · MIL-HDBK-217F N2 · PV micro inverter · PV multi string inverter · Reliability prediction

INTRODUCTION

At the end of December 2016, overall UK solar PV capacity stood at 11, 457 MW across 900, 881 installations as shown in figure 1. This is an increase of 19% (1, 812 MW) compared to December 2015. In December 2016, at this point, 10 MW (2, 324 installations) of solar PV capacity is confirmed as having been deployed throughout the month, with the main drivers (48% of capacity) being small scale 0 to ≤ 4 kW schemes in Great Britain and Northern Ireland. To date, 47.6% (5, 452 MW) of total installed solar PV capacity comes from large scale installations greater than 5 MW, with 21% (2, 459 MW) coming from small scale 0 to 4 kW installations. At the end of September 2016 (end Quarter 3), 57% of capacity (6, 401 MW) came from ground-mounted or standalone solar installations. Within the last 12 months, the largest increase in capacity occurred in March 2016 (1, 114 MW). Of the increase in capacity seen that month, 54% (598 MW) was seen in > 5 MW installations [1].

With this increase in PV energy worldwide there is a respective focus on power electronic converters, because such devices constitute a major part of a PV renewable energy system.

The function of the PV inverter is to convert the solar panel output power from DC to AC efficiently, ensuring the AC has minimum harmonic components and is in phase with the grid supply. A PV inverter is a major component of the PV system and must have a long operating life, low cost and high efficiency.

To ensure a long PV inverter life, in the design phase it is necessary to assess all potential PV inverter failure modes. A retrospective investigation has been carried out here of the MTBF of common inverter types. The analysis method used involves calculating the failure rate for all inverter components and summating their individual failure rates to determine the failure rate for the complete inverter.

PV Inverters

Centralized Inverters: Centralized inverters have a high power rating and are connected to an array formed from many PV modules as shown in Figure 2(a).

The array comprises a parallel set of PV panel strings, each producing several hundred volts DC, at around ten Amps. Bypass diodes (D_A in Figure 2(a)) are connected across each panel [2] to prevent excess reverse voltage under mismatch conditions. Each string has a series blocking diode (D_B in Figure 2(a)) to prevent reverse current.

The major disadvantage of this technology is that there can be power losses if a centralized Maximum Power Point Tracking (MPPT) control system is used [3], since a centralized MPPT system optimizes power output from

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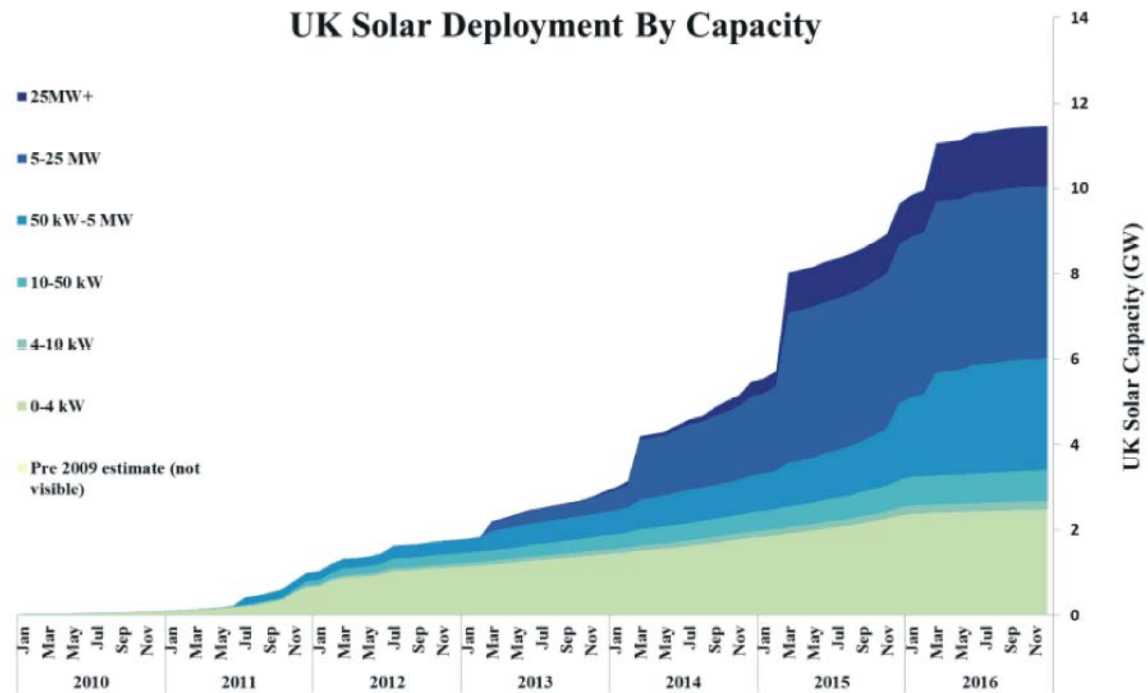

Fig. 1: Growth trajectory and application split to the 11.457GW UK solar [1]

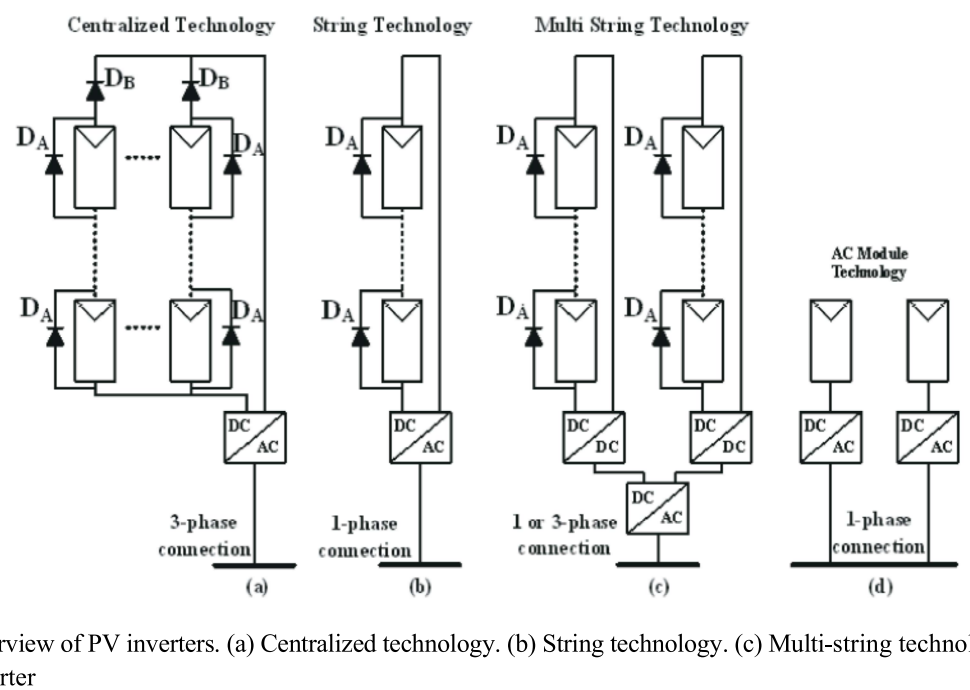

Fig. 2: Overview of PV inverters. (a) Centralized technology. (b) String technology. (c) Multi-string technology. (d) Micro inverter

an array and not individual panels. If there are differences in the maximum power point operating voltages and currents for each panel then maximum power can never be obtained with an overall MPPT system. A DC/DC converter providing MPPT can be implemented between each string and the main inverter to ameliorate some of the losses. However, it is still possible for panel losses to occur in a string, due to mismatch losses between PV modules [3]. There are also losses in the series string diodes (D_B).

Table 1: A selection of typical PV inverters

Inverter Type	Company	Model	Power	η%
Micro Inverter	ABB	MICRO-0.25-I-OUTD	250W (1φ)	96.5
	ABB	MICRO-0.30-I-OUTD	300W (1φ)	96.5
	Siemens	SMIINV215R60XX	215 W (1φ)	96.3
	Siemens	SMIINT250R60xx	250 W (1φ)	96.5
	SMA	Sunny Boy 240	230 W (1φ)	95.8
String Inverter	ABB	PVI-3.0-I-OUTD	3.0kW (1φ)	96.8
	ABB	PVI-4.6-I-OUTD	4.6kW (1φ)	96.8
	ABB	TRIO-5.8-TL-OUTD	5.8kW (3φ)	98.0
	ABB	PRO-33.0-TL-OUTD	33kW (3φ)	98.3
	Siemens	PMV10	10kW (3φ)	98.0
	Siemens	PMV20	19.2kW (3φ)	98.2
	SMA	Sunny Boy 3000TL	3.0kW (1φ)	97.0
	SMA	Sunny Tripower 25000TL	25kW (3□φ	98.3
Central Inverter	ABB	PVI-400.0-TL	400kW (3φ)	98.0
	ABB	ULTRA-1400.0-TL	1560k W (3φ)	98.7
	Siemens	PVS500	500kW (3φ)	98.1
	Siemens	PVS2520	2520kW (3φ)	98.3
	SMA	Sunny Central 630CP-JP	700kVA (3φ)	98.1

PV systems using centralized inverters are used only in solar farms or on industrial sites. Being high power, typically $\geq$100kW, they supply all 3-phases of the grid.

String Inverters: Lower power inverters supplied with a single string of PV panels are known as string inverters. Due to its lower power a string inverter produces a single phase output, as shown in Figure 2(b) [3]. With this PV system, series diodes are unnecessary and MPPT is performed for the whole string. String inverters are frequently found on domestic properties and are usually roof mounted with rating up to around 100kW [4].

Multistring Inverters: In this topology the output of several strings are individually connected to DC/DC converters which provide a higher voltage for a common DC/AC inverter as shown in Figure 2(c). Compared with the centralized system, MPPT can be applied to each string individually via the DC/DC converters. Multi string inverter systems are found on commercial properties and are either roof or ground based. Multi string inverters can be used instead of centralized and string inverter for certain capacities.

Micro Inverters: With a micro inverter system each PV panel has a single phase inverter rated at around 300W as shown in Figure 2(d). The micro inverters are located physically behind their respective PV panel. In this topology every PV panel has its own MPPT control system and the PV system is easy to enlarge. The micro inverter system is used in domestic PV systems since it offers individual panel MPPT control and is potentially more efficient than a string inverter system. However each inverter is exposed to extreme temperatures, must be waterproof, have a long operating lifetime and be very efficient.

The micro inverter system market is very competitive, many householders nowadays choosing to fit micro inverters instead of string inverters. The major selling features are the promise of a high efficiency, long lifetime and competitive cost. These three factors are difficult for the micro inverter designer to achieve at the same time however.

Table 1 [5-7] shows the power rating and efficiency of a selection of manufactured PV inverters.

Reliability Prediction Methods: The term reliability prediction refers to the use of mathematical models and data to estimate the field reliability for systems before empirical data is obtained [8], so as to estimate failure rate over the useful life of the product [9]. Reliability prediction gives an indication of the major decisions that need to be taken in the design stage [10] or later stages such as the development and manufacturing stages [11]. Reliability prediction is based on the assumption that system failure occurs due to a failure of one or several of its component parts. These parts may fail because they are exposed to system stresses [10] or because of incorrect manufacture. Some of the objectives of reliability prediction are [11] to:

- Determine if a reliability requirement is achievable.
- Help achieve a reliable design that meets end-user reliability and safety requirements and provide justification for any such requirements.
- Help achieve a reliable manufacturing process.

- Assess potential warranty risks.
- Provide inputs to a safety analysis.
- Establish a baseline for logistic support requirements (e.g. maintenance spares and upgrades).

Reliability prediction methods are classified into three major groups; the first group is 'Bottom–up statistical methods' (e.g. Mil-Hdbk-217, HRD-5and RIAC), the methods in this group reflect actual field failure rate and defect densities and can be a suitable indicator for field reliability. Their main disadvantages are that they are difficult to keep up to date and it is difficult to collect both good quality field data for use in the methods and to distinguish cause and effect for correlated variables (e.g. quality vs environment). The second group is 'Top–down similarity analysis methods' (e.g. TRACS) based on external failure database, the methods in this group reflect actual reliability and test data can be collected and applied before the system is fielded. The main disadvantages are that translation to field stresses is required and acceleration models are needed. And the third method is 'Bottom–up physics-of-failure' (BP) methods (e.g. CALCE and FIDES), the methods in this group model specific failure mechanisms and are valuable for predicting end of life for known failure mechanisms. Their main disadvantages are that they cannot be used to estimate field reliability, they are highly complex and costly to apply and are not practical for assessing entire system mechanisms [8].

In [8], the authors calculated the failure rate for a digital circuit board and in [10] the authors calculated the failure rate for different electronic components using several methods, they found that each method gave different failure rate and there was a wide range of variation. The reliability prediction obtained by these methods for a certain system or component can't be compared, because each method is sensitive for parameters different from other methods and each method has its own assumptions and data [8], [10].

Failure Rate of Electronic Components: Failure rate (λ) is defined as the number of units failing per unit time. Every product has a failure rate and this failure rate changes throughout the life of the product, producing the 'Bathtub' curve shown in Figure 3 [9].

The Bathtub curve can be divided into three sections. The first is known as the infant mortality period and the relatively high failure rate in this period is a result of manufacturing errors. The aim of the manufacturer is to eliminate the early failure period so that no product in this period reaches the customer [9]. The second section is known as the normal operation or useful life period and the manufacturer aims to increase the duration of this period as much as possible (or in some cases extend it to just past the warranty period). The final section is the wear out period and this section occurs beyond the useful life period, when the product becomes old. Failure of the product in this section is due to material degradation, oxidation, vibration, or temperature and chemical damage. The infant mortality period and useful life period are covered by the manufacturer's warranty.

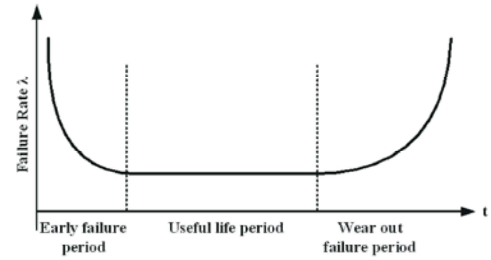

Fig. 3: Bathtub curve

The reciprocal of failure rate is known as the Mean Time Between Failure (MTBF) and this term is often applied to products that can be repaired and returned to service. While Mean Time To Failure (MTTF) was frequently used to measure the time to failure for non-repairable products, in practice MTBF is used for both repairable and non-repairable [12].

From the above, it can be seen that several methods are used to predict reliability. Amongst all these methods MIL-217F N2, developed by the US Department of Defense is internationally used to calculate the failure rate of electronic components used in military and civil equipment. This method has also been used here because it is freely available and is frequently used commercially. As shown in table 2, failure rate equations in MIL-217F N2 include several factors such as temperature, environment, quality and voltage stress ratio [13]. MIL-217F N2 offers a part count method for most electronic components and a part stress method for other components such as microcircuits (operational amplifiers and microprocessors).

The failure of the whole system is given by the sum of the failure rates for all the system components, as shown in equation 1.

$$\lambda = \sum_{i=1}^{n} N_i \lambda_i \qquad (1)$$

where:
λ: Failure rate for the whole system
n: number of component categories
N: quantity of ith component
λi: Failure rate of ith component

Table 2: Failure rate equations for some electronic components (see main text for explanation of the parameters) [13]

Component	*Failure rate (Failures/10^6 hours)*	
Capacitors	$\lambda_p = \lambda_b \pi_T \pi_C \pi_V \pi_{SR} \pi_Q \pi_E$	λ_b = constant depending on capacitor type $\pi_T = \exp\left(\frac{-E_a}{8.617*10^{-5}}\left(\frac{1}{T+273}-\frac{1}{298}\right)\right)$ $\pi_V = \left(\frac{S}{0.6}\right)^y + 1 \quad , \quad S = \frac{\text{Operating Voltage}}{\text{Rated Voltage}}$ $\pi_C = C^x$
Inductors	$\lambda_p = \lambda_b \pi_T \pi_Q \pi_E$	$\lambda_b = 0.00003$ $\pi_T = \exp\left(-1275\left(\frac{1}{T_{HS}+273}-\frac{1}{298}\right)\right)$
Resistors	$\lambda_p = \lambda_b \pi_Q \pi_E \pi_T \pi_P$	λ_b = constant depending on resistor type $\pi_T = 1 \quad , \quad \pi_P = P^{0.39}$
Diodes	$\lambda_p = \lambda_b \pi_T \pi_S \pi_C \pi_Q \pi_E$	λ_b = constant depending on diode type $\pi_T = \exp\left(-3091\left(\frac{1}{T_J+273}-\frac{1}{298}\right)\right)$ $\pi_S = \begin{cases} 0.054 & S \le 0.3 \\ S^{2.43} & 0.3 < S \le 1 \end{cases}$
MOSFET	$\lambda_p = \lambda_b \pi_T \pi_A \pi_Q \pi_E$	$\lambda_b = 0.012$ $\pi_T = \exp\left(-1925\left(\frac{1}{T_J+273}-\frac{1}{298}\right)\right)$
microcircuits	$\lambda_p = (C_1\pi_T + C_2\pi_E)\pi_Q\pi_L$	C_1 and C_2 depend on the component
E_a: activation energy, x and y depend on capacitor type, T_{HS}: hot spot temperature T_J: junction temperature, P: rated resistor power, π_Q: quality factor		

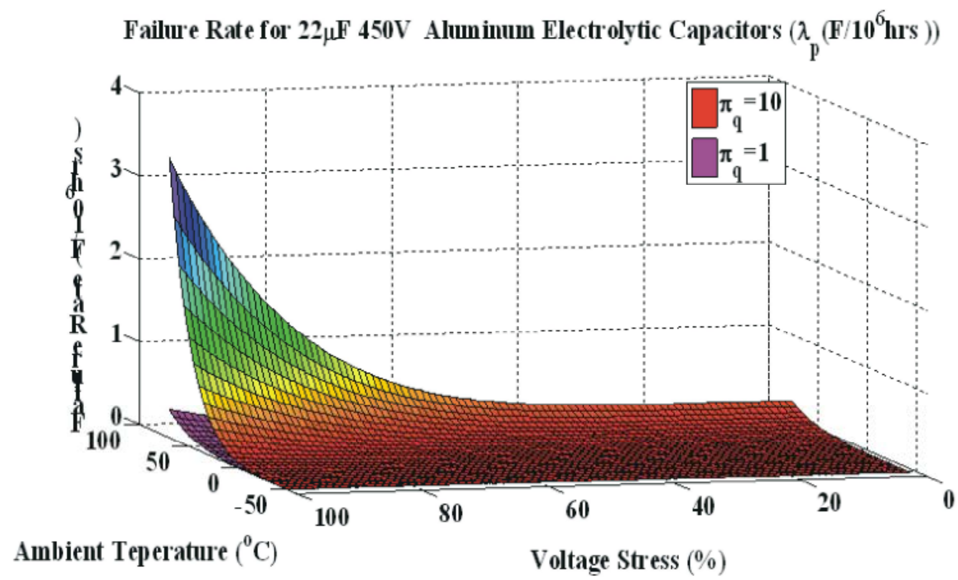

Fig. 4: Al. Elec. capacitor failure rate as a function of Quality factor

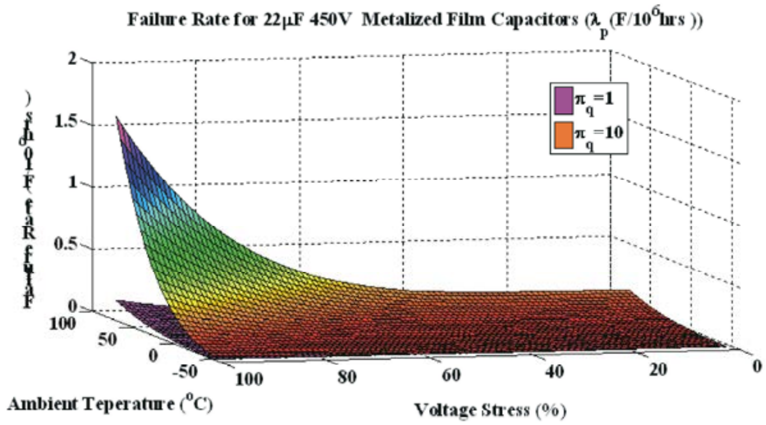

Fig. 5: Metallized film capacitor failure rate as a function of Quality factor

When designing PV inverters, Aluminum Electrolytic Capacitors are sometimes chosen to store DC energy. An alternative capacitor type that the designer may choose is the metal film capacitor.

As an example, to highlight the difference between these two types, Figure 4 depicts the failure rate of a 22µF, 450V, Aluminum Electrolytic capacitor versus voltage stress and ambient temperature and Figure 5 depicts the failure rate for a Metallized Film capacitor. The failure rate equation for a capacitor is shown in Table 2; λb is the base failure rate, π_V is the voltage stress ratio factor, π_T is the temperature factor, π_C is the capacitance factor (failure rate is calculated based on the value of the capacitor in µF), π_{SR} is the series resistance factor and is defined as the ratio between effective resistance voltage drop between capacitor and power supply to the voltage applied to the capacitor, π_E is the environment factor (the environment is considered 'ground fixed' for all components) and π_Q is the quality factor. Figure 4 and Figure 5 show failure rates for quality factors equal to 1 and 10. It is clear that failure rate increases with ambient temperature and voltage stress ratio when the quality factor is equal to 1 or 10. But the failure rate of the Metallized Film capacitor is lower than the failure rate of the Aluminum Electrolytic capacitor by a factor of around 2 as shown in these figures. To reduce the failure rate, the capacitors can be voltage derated. It is usual to derate the capacitor voltage to at most 75% of rated. In some cases this is achieved by connecting equal value capacitors in series to share the voltage. When capacitors are connected in series then care must be exercised to ensure they share voltage over all conditions and over the inverter lifetime. The failure rate of a PV micro inverter is estimated in the following section, as an example.

In [14], the author mentioned that the electrolytic capacitor 2200 µF, 63V (UPW1J222MHD) is used in one kind of the micro inverters; the life time for this capacitor is 8000 hours while operating continuously at 105°C core temperature. So, 20 years warranty could be easily supported when the micro inverter works at 70°C.

PV Micro Inverter Failure Rate: Different papers discussed PV inverters electronic components reliability prediction based on MIL-217F. The authors in [15] discussed in details the failure rate of aluminum electrolytic capacitor to get the weighted failure rate. The authors in [16, 17] presented the reliability estimation of the power stages in three grid-connected photovoltaic systems and the made a comparison between different topologies was performed. In [18, 19], the authors calculated the failure rate for some commercial main circuit inverters.

To calculate the failure rate of a PV micro inverter, a 250W PV micro inverter [20] was taken as an example. The main circuit for this micro inverter is shown in figure 6 and the component details for the main circuit alone are given in Table 3. In determining the micro inverter failure rate all components in the bill of materials were considered, not just the main circuit shown in Figure 6, but also the gate drive circuits, power supply circuits, sensing circuits, microprocessor circuit, etc. Several items are not considered in the calculations such as soldered joints, seals, main board, wiring or thermal dissipation system (e.g. thermal compound which can dry out or thermal pads which can degrade through thermal cycling).

For each component in the micro inverter, the failure rate was calculated from the equations shown in Table 3. Initially the ambient temperature was set at 20°C and the sum of the component failure rates is then equal to the PV micro inverter failure rate, as given in equation 1. The MTBF was calculated from the inverse of failure rate as shown in equation 2.

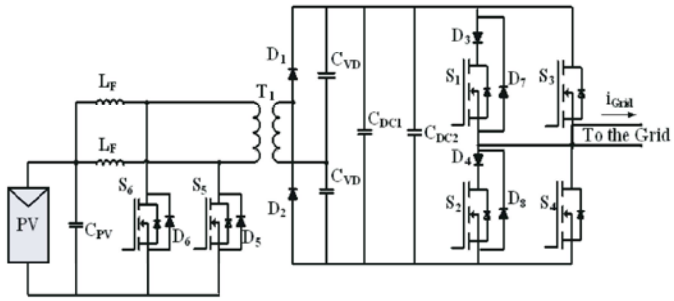

Fig. 6: 250W PV micro inverter main circuit in [20].

Table 3: Main circuit component details [20]

No.	Item	Description
1	C_{PV}	14 ceramic capacitors connected in parallel, each 1µF, 100V and 10% tolerance.
2	S_5, S_6	N-channel power MOSFET 100V, 110A.
3	C_{VD}	Metallized polypropylene film capacitor 2.2 µF, 250 V and 5% tolerance.
4	C_{DC1}	Metallized polypropylene film capacitor 2.2 µF, 630 V_{DC} and 5% tolerance.
5	C_{DC2}	4 Aluminum Electrolytic capacitors connected in parallel, each 22µF, 450V and 20% tolerance.
6	S_1, S_2, S_3, S_4	N-channel power MOSFET 600V, 11A.
7	LF	Power choke inductor 600 µH.
8	D_5, D_6	Transil diode 600W 85 V used as Transient Voltage Suppressors.
9	D_1, D_2, D_7, D_8	SiC high voltage rectifier diode 600V, 6A.
10	D_3, D_4	Schottky Diodes & Rectifiers 45V, 7.5A.

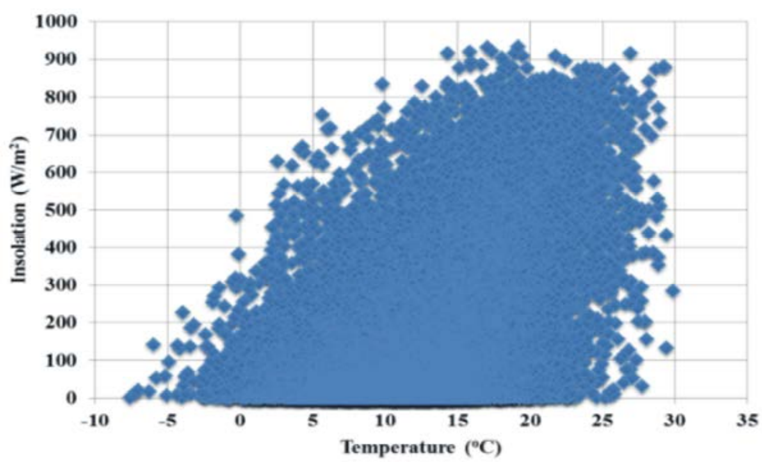

Fig. 7: Hourly measured insolation for four years

$$MTBF = \frac{10^6\,hours}{\lambda_p} \quad (2)$$

So as to more accurately calculate the micro inverter failure rate and MTBF, the failure rate for each component can be calculated for a particular temperature and then multiplied by the percentage occurrence of this temperature.

As an example of this process, the hourly temperature has been recorded for Manchester, UK, by the Whitworth Meteorological Observatory for four years. The insolation for each hourly temperature in this period is shown in Figure 7; the insolation and daytime temperature determine the extracted power from the sun. Figure 8 shows a histogram of temperature versus percentage time spent at that temperature over this four year period. Using this histogram the failure rate can be calculated for each component at each temperature. The failure rate at each temperature for the micro inverter is then found from equation 1 and multiplied by the percentage time spent at that temperature to produce a weighted failure rate. Lastly, MTBF is calculated from the weighted failure rate.

Table 4 shows the failure rate for the PV micro inverter components at 20°C when π_q=low which is used for commercial equipment. Table 5 shows the low quality factors values for different electronic components used in

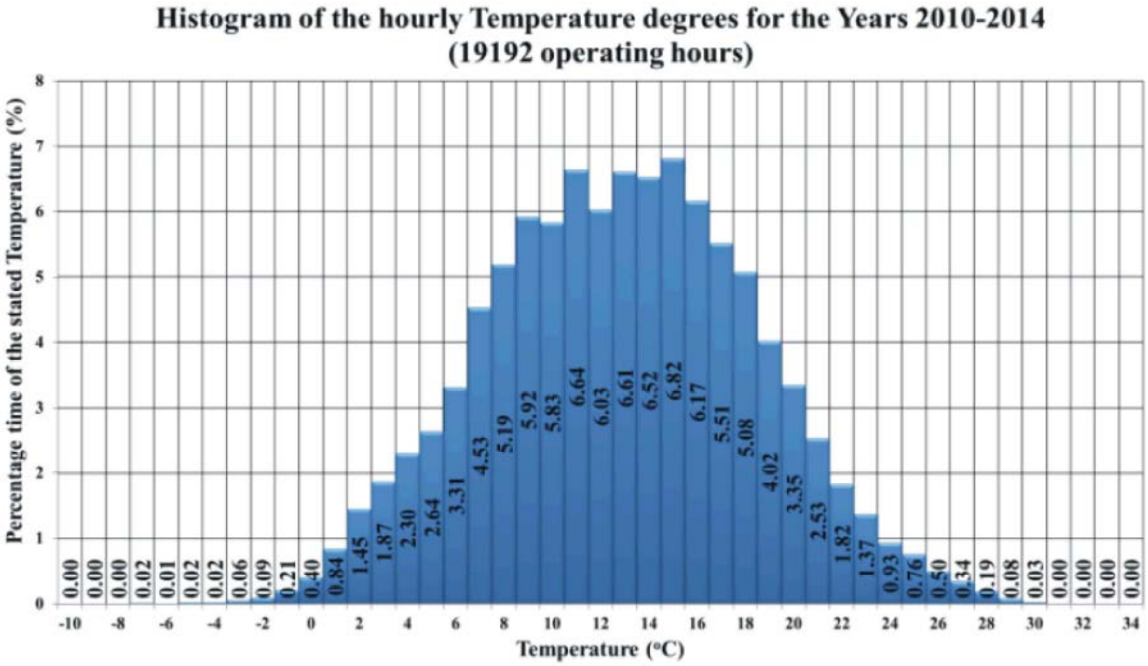

Fig. 8: Daytime temperature histogram for Manchester city for four years

Table 4: Un-weighted failure rate (f/10^6hrs) at 20°C when quality factor is low

Un Weighted Failure Rate at 20°C (F/10^6hrs) when π_q = low	
Capacitors	λp = 23.1103
Diodes	λp = 02.0816
Inductors & Trans formers	λp = 00.1843
Transistors	λp = 22.3440
Resistors	λp = 09.4170
Microcircuits	λp = 00.4752
Optocouplesr & Relays	λp = 00.1665
Connectors	λp = 02.8427
λ_{pt} (F/10^6hrs)	

Table 5: Low quality factor values for different electronic components.

Electronic component	Low quality factor value
Capacitor, Resistor	10
MOSFET, Diode	5.5
Inductor, Transformer	3
OpAmp,	2
Connector	2
Optocoupler	5.5
Relay	1.9

micro inverter. The same calculation was made for all other temperatures when π_q=1 and π_q=low to provide an un-weighted and weighted Failure Rate for the PV micro inverter, as shown in Table 6.

Table 7 summarises the total failure rate and MTBF of the PV micro inverter for the temperature distribution of Figure 8; Table 7(a) shows the results when π_q=1 and Table 7(b) shows the results when π_q=low.

From the above calculations, the PV micro inverter main circuit failure rate was found to be 19.85 F/10^6 hours and the MTBF to be 50369 hours when the quality factor is low.

The analysis shows that in the PV micro inverter main circuit, MOSFETs have the highest failure rate and the failure rate depends on the power harnessed by the PV panel and the ambient temperature. Aluminium Electrolytic capacitors and Metallized Polypropylene Film capacitors have acceptable failure rates if they are derated in voltage by nearly 50% (e.g. the failure rate of a 22µF, 450V Aluminum Electrolytic Capacitor is 0.133 F/106 hours at 50°C and quality factor low when it is derated by 50% and the failure rate is 1.312 F/106hours for the same capacitor at the same conditions when it is derated by 50%). The failure rate for the capacitors also depends highly on ambient temperature.

The other components in the bill of materials have low failure rates, but the complete micro inverter is estimated to have a failure rate between 2.25 and 14.15 years as the quality factor changes.

Table 6: Un-weighted and weighted failure rate of micro inverter (f/10^6hrs) when the quality factor is low & one

Temperatur (°C)	Percentage Time at the Stated Temperature (%)	Un Weighted Failure Rate of PV Micro Inverter (λ_p(F/10^{6}hrs)) when π_q=1	Weighted Failure Rate of PV Micro Inverter (λ_p(F/10^{6}hrs)) when π_q=1	Un Weighted Failure Rate of PV Micro Inverter (λ_p(F/10^{6}hrs)) when π_q=low	Weighted Failure Rate of PV Micro Inverter (λ_p(F/10^{6}hrs)) when π_q=low
-7	0.01563	5.019	0.0007846	30.73	0.004803
-6	0.00521	5.136	0.0002676	31.46	0.001639
-5	0.02084	5.256	0.001095	32.21	0.006713
-4	0.02084	5.379	0.001121	32.98	0.006875
-3	0.05732	5.505	0.003155	33.78	0.01936
-2	0.09379	5.621	0.005271	34.47	0.03233
-1	0.2084	5.753	0.01199	35.31	0.07360
0	0.4012	5.889	0.02363	36.19	0.1452
1	0.8389	6.029	0.05057	37.09	0.3111
2	1.4537	6.172	0.08972	38.01	0.5526
3	1.8654	6.319	0.1179	38.97	0.7269
4	2.2978	6.470	0.1487	39.96	0.9181
5	2.6365	6.625	0.1747	40.97	1.080
6	3.3139	6.784	0.2248	42.02	1.393
7	4.5279	6.947	0.3146	43.11	1.952
8	5.1897	7.115	0.3692	44.22	2.295
9	5.9243	7.287	0.4317	45.37	2.688
10	5.8306	7.463	0.4352	46.56	2.715
11	6.6434	7.644	0.5079	47.78	3.174
12	6.0338	7.830	0.4725	49.04	2.959
13	6.6121	8.021	0.5304	50.34	3.329
14	6.5236	8.217	0.5360	51.68	3.371
15	6.8153	8.417	0.5737	53.06	3.616
16	6.1692	8.623	0.5320	54.48	3.361
17	5.5127	8.834	0.4870	55.95	3.084
18	5.0760	9.051	0.4593	57.46	2.916
19	4.0225	9.273	0.3730	59.02	2.374
20	3.3504	9.501	0.3183	60.62	2.031
21	2.5271	9.735	0.2460	62.27	1.574
22	1.8237	9.975	0.1819	63.98	1.167
23	1.3652	10.22	0.1395	65.73	0.8973
24	0.9275	10.47	0.09714	67.53	0.6264
25	0.7555	10.73	0.08108	69.39	0.5243
26	0.5002	11.00	0.05501	71.31	0.3567
27	0.3387	11.27	0.03817	73.28	0.2482
28	0.1928	11.55	0.02226	75.31	0.1452
29	0.08337	11.83	0.009866	77.40	0.06452
30	0.02605	12.18	0.003173	79.65	0.02075

Table 7: Total failure rate and MTBF of PV micro inverter

Total failure rate of PV micro inverter when π_q=1	
Weighted Failure Rate of PV Micro Inverter (λ_p(F/10^{6}hrs))	8.069
Mean Time Between Failures (MTBF) (hours)	123938.39

(a)

Total failure rate of PV micro inverter when π_q=low	
Weighted Failure Rate of PV Micro Inverter (λ_p(F/10^{6}hrs))	50.76
Mean Time Between Failures (MTBF) (hours)	19699.69

(b)

PV Multi String Inverter Failure Rate: The power circuits of two typical PV multi-string inverters are taken next as an example. The first circuit is shown in Figure 9 [5] and its technical data is given in Table 8. The inverter can be connected to two strings, each of which has its own MPPT system comprising a boost converter. Each string is decoupled by a 15µF film capacitor, CPV [21]. The capacitors C_{Grid} in the half bridge inverter are each comprised of five, 1000µF, 450V, Aluminum Electrolytic capacitors [21] connected in parallel. The voltage across each capacitor C_{Grid} is at least equal to the peak grid voltage

The second multi-string inverter considered is shown in figure 10 [3]. This inverter can be connected to three strings, the input voltage range for each string being 200V-500V. The DC-DC converter in each string has a high frequency transformer allowing the PV panels to be grounded [3]. No details are given for the capacitors C_{PV}, so it is assumed here that they are the same as those in the first multi string inverter. The decoupling capacitors, C_{DC}, are each comprised of three, 310µF, 400V, Aluminum Electrolytic capacitor [3] in series. The three string boost converter outputs are parallel connected to a single-phase, two-level inverter to inject power into the grid.

Table 8: Technical data for inverter shown in Figure 9.

Technical data	
Rated input voltage	400V
Max. input current per string input A /input B	15A/15A
Number of independent MPP inputs	2
Rated output power (@ 230V, 50Hz)	4600W
Nominal AC voltage / range	220V–240V
Max. output current	22A
Power factor at rated power	1
Displacement power factor, adjustable	0.8overexcited-0.8 underexcited
Connection phases	1
Max. efficiency /European weighted efficiency	97 % / 96.5 %
warranty	5 Years

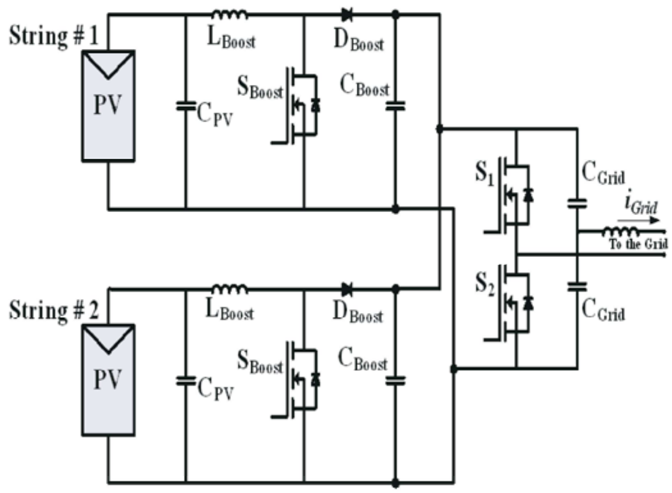

Fig. 9: First multi string inverter main circuit [5]

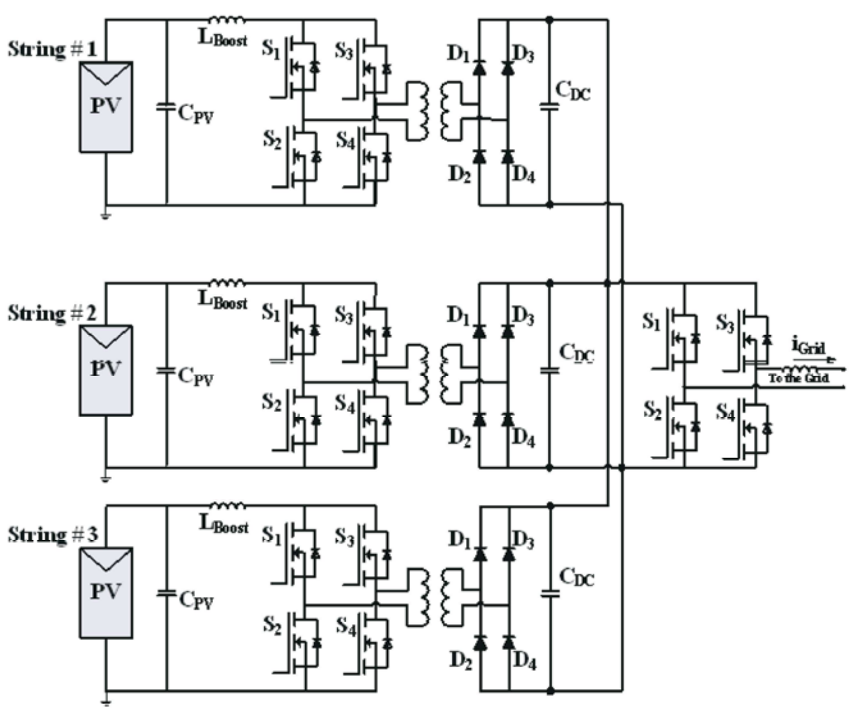

Fig. 10: Second multi string inverter main circuit [3]

Table 9: Unweighted and weighted failure rate of first and second multi string inverters (f/10^6hrs)when quality factor is low

Temperatur (°C)	Percentage Time at the Stated Temperature (%)	Un Weighted Failure Rate of First Multi String Inverter (λ_p(F /10^6hrs))when π_q=low	Weighted Failure Rate of First Multi String Inverter (λ_p(F /10^6hrs))when π_q=low	Un Weighted Failure Rate of Second Multi String Inverter (λ_p(F /10^6hrs))when π_q=low	Weighted Failure Rate of Second Multi String Inverter (λ_p(F /10^6hrs))when π_q=low
-7	0.01563	11.12	0.001739	12.67	0.001980
-6	0.00521	11.43	0.000596	13.00	0.000677
-5	0.02084	11.75	0.002448	13.34	0.002781
-4	0.02084	12.07	0.002516	13.69	0.002853
-3	0.05732	12.40	0.007106	14.05	0.00805
-2	0.09379	12.73	0.01194	14.41	0.01351
-1	0.2084	13.08	0.02725	14.77	0.03079
0	0.4012	13.42	0.05386	15.15	0.06078
1	0.8389	13.78	0.1156	15.53	0.1303
2	1.454	14.14	0.2056	15.92	0.2314
3	1.865	14.51	0.2707	16.31	0.3043
4	2.298	14.89	0.3421	16.72	0.3841
5	2.637	15.27	0.4026	17.13	0.4515
6	3.314	15.66	0.5190	17.54	0.5814
7	4.528	16.06	0.7271	17.97	0.8135
8	5.190	16.46	0.8544	18.40	0.9548
9	5.924	16.88	0.9998	18.84	1.116
10	5.831	17.30	1.009	19.28	1.124
11	6.643	17.73	1.178	19.74	1.311
12	6.034	18.16	1.096	20.20	1.219
13	6.612	18.60	1.230	20.67	1.367
14	6.524	19.06	1.243	21.14	1.379
15	6.815	19.52	1.330	21.63	1.474
16	6.169	19.98	1.233	22.12	1.365
17	5.513	20.46	1.128	22.62	1.247
18	5.075	20.94	1.063	23.13	1.174
19	4.023	21.44	0.8623	23.64	0.9511
20	3.350	21.94	0.7350	24.17	0.8097
21	2.527	22.45	0.5673	24.70	0.6242
22	1.824	22.97	0.4188	25.24	0.4603
23	1.365	23.49	0.3207	25.79	0.3521
24	0.9275	24.03	0.2229	26.35	0.2444
25	0.7555	24.58	0.1857	26.91	0.2033
26	0.5002	25.13	0.1257	27.49	0.1375
27	0.3387	25.69	0.08702	28.07	0.09506
28	0.1928	26.27	0.05064	28.66	0.05525
29	0.0834	26.85	0.02238	29.26	0.02439
30	0.0261	27.44	0.00715	29.87	0.007781

Table 10: Total failure rate and MTBF of first and second inverters

Total failure rate of the first multi string inverter when π_q=low	
Weighted Failure Rate of PV Micro Inverter (λ_p(F/10^6hrs))	18.66
Mean Time Between Failures (MTBF) (hours)	53594

(a)

Total failure rate of the second multi string inverter when π_q=low	
Weighted Failure Rate of PV Micro Inverter (λ_p(F/10^6hrs))	20.71
Mean Time Between Failures (MTBF) (hours)	48279

(b)

A calculation was undertaken of the failure rates for the two inverter systems. Table 9 shows the failure rates for each at the temperatures in the histogram of Figure 8, when π_q=low, to provide un-weighted and weighted Failure Rate results.

Table 10(a) shows the total failure rate and MTBF of the first inverter when πq=low; and Table 10(b) shows the total failure rate and MTBF of the second inverter when π_q=low.

The failure rates given in table 10 are calculated for the main power circuits of the two multi string inverters alone, since details of the subsidiary circuits were not available. MOSFETs have the highest failure rate and the failure rate depends on the power harnessed by the strings and the ambient temperature.

CONCLUSION

Several methods are used for reliability prediction. Some methods have their own statistical data, others depend on additional data from other sources and the rest are updated versions of older methods. Some data is only appropriate for special systems, while other data can be used for any system (military or civil). The reliability prediction of the methods can't be compared because each analysis method is dependent on different data and each focuses on different factors and assumptions.

Failure rate and MTBF are used as reliability metrics for electronic components and for systems. The variation of component failure rate has been analyzed for a single micro inverter and two typical multi string inverters operating over a wide variation in ambient temperature and voltage stress ratio. The failure rate for the micro inverter has been calculated for different quality factors based on the MIL-217F N2 method and the failure rates for multi-string inverters have been calculated for low quality factors.

The MTBF for the micro inverter analyzed is estimated at 123938 hours (14.15 years) for a high quality system, whereas it is 19699 hours (2.25 years) for a low quality system. Unfortunately, there is no any evidence to prove that PV micro inverters are failing at these rates, because manufacturers do not provide data on the failure rate of their micro inverters.

The failure rates are calculated for the main power circuits of the two multi string inverters alone, since details of the subsidiary circuits were not available. The MTBF for the first multi string inverter analyzed is estimated at 53594 hours (6.1 years), whereas it is 48279 hours (5.5 years) for the second multi string inverter at low quality factor.

The UK mean temperature from figure 8 is around 14°C and MTBFs are estimated in a weighted manner from this figure. The temperature inside the PV inverter box will be higher than the ambient temperature. Also, in many places where the insolation and temperature are higher than in the UK, the reliability of the PV inverters will be lower

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