

# A status review of photovoltaic power conversion equipment reliability, safety, and quality assurance protocols



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## ABSTRACT

Data indicate that the inverter is the element of the photovoltaic plant that has the highest number of service calls and the greatest operation and maintenance cost burden. This paper describes the projects and relevant background needed in developing design qualification standards that would serve to establish a minimum level of reliability, along with a review of photovoltaic inverter quality and safety standards, most of which are in their infancy. We compare stresses and levels for accelerated testing of inverters proposed in the standard drafts, and those proposed by manufacturers and purchasers of inverters. We also review bases for the methods, stress types, and stress levels for durability testing of key inverter components. Many of the test protocols appear to need more comprehensive inclusion of stress factors existing in the natural environment such as wind driven rain, dust, and grid disturbances. Further understanding of how temperature, humidity ingress, and voltage bias affect the inverters and their components is also required. We provide data indicating inconsistent quality of the inverters and the durability of components leading to greater cost for the photovoltaic plant operator. Accordingly, the recommendation for data collection within quality standards for obtaining cost of ownership metrics is made. Design validation testing using realistic operation, environmental, and connection conditions, including under end-use field conditions with feedback for continuous improvement is recommended for inclusion within a quality standard.

## 1. Introduction

### 1.1. Motivation

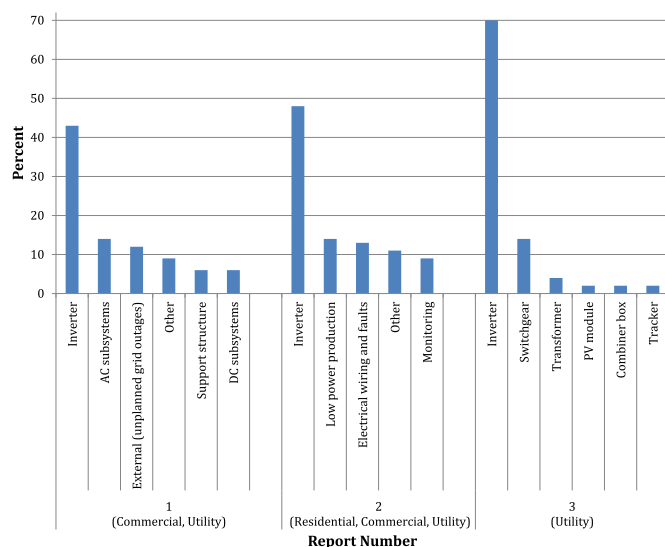
Standards for qualification, reliability, and durability of balance-of-systems (BOS) components, such as power conversion equipment (PCE), for photovoltaic (PV) systems have trailed that of the PV modules. The efforts and approach for the qualification standards development have been mostly focused on the PV modules, rather than PCE. This emphasis on the module has been justified because systemic failures of the PV module design affecting a large number of modules can have substantial financial impact to the manufacturer or power plant owner, whereas failures with string-level or larger inverters can usually be addressed by part or equipment changes as required. [1] PV modules are generally not repairable, with replacement being the only viable option. On the other hand, the arrival of module-level power

electronic equipment (e.g., one device per module) may conceivably lead to systemic problems at each module in a whole PV field or installation, as well.

We first seek to quantify the extent of the problem. Fig. 1 gives a breakdown of operation and maintenance (O & M) events from three different reports, [2,3,4] provided by PV plant operators. The inverter is seen to be by far the largest percentage of service calls, which leads to higher maintenance costs and lost power production.

It is desirable to understand at the outset the cost of ownership of the inverter, including maintenance, repairs, and downtime costs. To understand the financial impact of these factors, Fig. 2 summarizes an analysis of total cost of ownership (cumulative), not including depreciation, for four types of PCE from three vendors for four years [5]. A total of 400 failure reports were analyzed. Two of the four inverter types (types 2 and 4) show that actual total cost of ownership ran significantly above the vendor-projected costs. Trends in improved

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**Fig. 1.** Three reports ranking the service request of power plants by equipment category. “Other” includes roof leaks/water in conduit/boxes, damaged tiles, dirty array, rattling modules, bird/rodent issues, and other damage. AC subsystem comprises everything between the inverter and the generation meter.

reliability can be seen in some cases. Operating cost vary over the inverters' product lifecycle associated with different challenges that need different approaches.

The cost of O & M work necessitated by inverter failures influences the profitability of PV installations. The inverters constitute between 43% and 70% of the PV power plant service requests as seen in Fig. 1. Financial losses additionally accrue due to energy losses. The inverter has been reported to be the greatest factor leading to energy outages, responsible for up to 36% of the energy loss [7]. In view of the high costs associated with inverter failures, understanding the root cause of component failures, methods to access or ensure reliability and forecast lifetime of the PCE and their components through testing and quality standards becomes vital.

While the authors acknowledge it is economically impractical to expect the industry to produce inverters that never fail, never need maintenance, or attain 100% availability, the impact of inverter outages on the revenue streams of PV projects must be dealt with. An impetus for additional testing and quality standards is to minimize unplanned or unexpected outages, and minimize repair/restoration times utilizing quality management principles, design for reliability, and testing approaches as cost effectively as possible while reducing the unpredictability of operating costs for PV power plants.

It is anticipated that this paper will provide the reader an under-

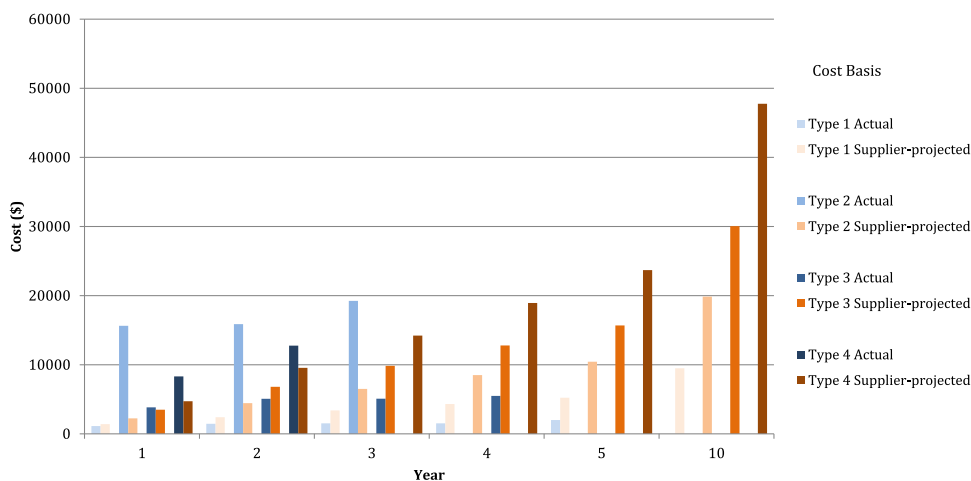
standing of current industrial practices for testing and ensuring quality of inverters and their components and projecting their service life. In addition, areas that require further work will be discussed, including design, testing, and quality protocols and standards. The efforts recommended in view of the reviews presented in this paper are anticipated to result in increased confidence in the quality of inverters used for PV power plants for the goal of lower O & M costs and risk reduction.

## 1.2. Scope and organization the review

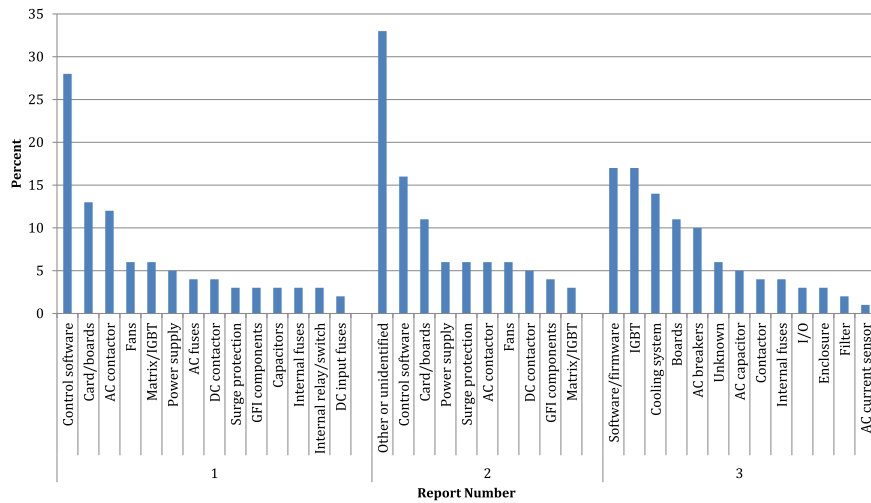
Giving better visibility to the issues of inverters that power plant operators see as the greatest O & M cost factor is a first step—this was introduced above in Section 1. We follow this in Section 2 by going into the next level of detail—reviewing statistics of the components and factors most responsible for inverter failures so that the reader may gain deeper appreciation for which issues are most responsible for the failures. In Section 3, we give an overview of what has been done and the ongoing work on PV inverter standards for the goal of improving inverter reliability from the perspective of testing and quality. Related standards sometimes relied upon from other industries are also discussed. This section will be useful for those not intimately following the standards development process to gain understanding of where development processes stand. It will be seen that the standardization effort is in its infancy and work remains to be done.

With this background, Section 4 gives a discussion of the application of the tests and methods to improve the design, durability, and consistent quality for key inverter components reported to be responsible for some failures in Section 2. The data and information is from cited literature, including evidence reported by the coauthors based on their experience and equipment, and agreed upon in the form of a failure mode and effects analysis created within PV Quality Assurance Taskforce (PVQAT) Task 11 [6]. It should be noted that in many cases, more comprehensive analyses for evaluating component reliability can be found in the scientific literature; however, the purpose of Section 4 is to review the procedures that are currently reported by the industry. Section 5 focuses on the key stress factors of temperature and humidity and how their effects are tested and modeled. Some shortcomings of the traditionally applied damp heat tests and models are also discussed. In Section 6, we discuss how maximizing quality and driving reliability improvement, from the design to the installation process, along with the introduction of design and quality standards, are anticipated to reduce overall technical and financial risks.

Section 7 concludes by summarizing where we are now and where we need to go to achieve higher inverter reliability and reduce the factor that in many studies is highest on the Pareto of O & M costs. It is



**Fig. 2.** Actual and supplier-projected cumulative total cost of ownership for four inverter types.



**Fig. 3.** Three reports detailing the relative frequency (in percent) of inverter component failures, primarily for central inverters. IGBTs are insulated gate bipolar transistors; GFIs are around fault interrupters.

hoped that with greater understanding of the issues and attention to the proposals laid out in this paper, costs and risks associated with purchasing, owning, and operating a PV power plant can be reduced, facilitating the faster promulgation of PV as a renewable energy source with extensive benefits, including reduction of costs and of greenhouse gas generation in electricity production.

## 2. Surveys of component failures

As seen in Fig. 1, inverters are the cause for the greatest number of service tickets in the PV plant requiring O & M. Thus, in this section, we give attention to inverter components that fail most often and have the greatest impact on O & M cost so that these components can be prioritized for attention to reliability.

SunEdison has reported data on more than 600 PV systems in 2012, [7] and on an older set of equipment for the period 2008–2010. [8] The present work additionally includes statistics on about 400 field events for central inverters reported by coauthors. [4] These data are summarized in Fig. 3.

The most frequently occurring failure mode identified in the Pareto of inverter failures is control software or firmware. It is possible that failures attributed here may be due to other events, including electrical parameters (upstream or downstream) out of specified range for the inverter or its components. [8] Also, restarts in some cases can return the inverter to operation reasonably quickly. Control software or firmware failures are significant enough to be the first or second greatest cause of power loss events for inverters. [7] Physical hardware, however, remains important considering that in another binning of failures for SunEdison data, parts and materials lumped together is attributable to at least 57% of failures vs. 16% of failures from software. [8]

Table 1 shows reported component failures in MLPE devices in the literature. One survey called out connectors, capacitor, varistors, and field-effect transistors (FETs) used for DC up-conversion as major components at risk of failure. [12] The large-volume production of MLPE allows for use of compact application-specific integrated circuits (ASICs) to reduce discrete part counts compared to central inverters for the goal lowering cost and the possibility of improved reliability. ASICs are considered within the category of integrated circuits (ICs) in Table 1. Additionally, higher volume production generally allows for increased statistics in testing, which benefits the study and improvement of the reliability of PCE. [8]

After first reviewing the status of the standards for testing and ensuring reliability, safety, and quality in the following section, we move on to the specifics of the failure mechanisms and testing of the

**Table 1**

Reported component failures observed in MLPE devices.

Component	References
Capacitors	[9,10]
Boards, mounting mechanical failure	[9–11]
Component connections (ICs, resistors, diodes), including fatigue, corrosion	[9,10,13]
Enclosure failure (moisture ingress)	[11]
Cabling (UV weathering, mechanical)	[11,13]
Transformer/power conversion	[11,13]
Power devices	[11]
Connectors (AC or DC)	[12]
Control devices (ICs, memory, etc.)	[11]
Die attach (thermal runaway failure)	[13]
Varistor (for AC-side overvoltage protection)	[12]
Potting	[9,10,14]

PCE components and electrical devices that factor highly on the Pareto of failures in Section 4.

## 3. Background and status of standards for PV inverter reliability and safety

### 3.1. Overview of relevant standards

Accepted standardized tests are lacking to ensure reliability of inverters for the PV industry. This section discusses the status of tests used or being developed to gauge reliability, including design qualification tests. Design qualification tests are intended to examine infant failures and some undefined extent of usage in general environments, but do not typically have end-of-life wear out mechanisms covered within their scope. Table 2 compares selected industrial and standardized tests and tests that are currently being developed in the industry to show the evolution of design qualification testing for inverters. Criteria listed in the table and discussed here are likely to change to some extent through subsequent stages of the standard writing process.

Standards also exist and are being developed for inverter safety – these standards intersect with reliability when particular failure mechanisms they examine are considered to potentially lead to shock or fire. Standards for inverter performance, grid connection, and grid protection requirements are outside of the scope of this paper, so the reader is referred to other articles that review these matters. [15] The following sections cover (1) design and quality standards (2) safety

**Table 2**  
Comparison of selected industrial and standardized stress tests and stress tests that are currently being developed in the industry to show the evolution of design qualification testing for inverters.

	Dry heat	Thermal cycling	Damp heat	Humidity freeze	UV and outdoor exposure	Ingress protection	Blowing dust, particle, or salt fog	Surge	HALT	Cold start	Shipping/vibration/shock	Combined/design validation/other <sup>a</sup>
Company 1	85°C, 50 d	-45°C/85°C, 50 d	✓	-45°C/85°C, 85% RH, 10 d -10°C/ T <sub>amb</sub> max, ≥90% RH, 10 c, 10 d	✓			✓				✓
Company 2	1) 45°C, 167 d, power cycling 2) 40°C and 60°C with derating and blocked fan, powered, 16 h	Mnf.-specified temperature range, power cycling, 10 c.	40°C, 90% RH, power cycling, 21 d				Salt fog to IEC 60068-2-52 [81] (severity 4)		Thermal shock: +85°C/-25°C, 900 c., 38 d (without box)	-25°C, 83 d (m.s), 21 d (c);		Chemical exposure; hot, cold, & full power starts; reliability testing in mmf.
Company 3	T <sub>amb</sub> max and 42 d. Verify temperature margins of components		1) 50°C, 85% RH, closed door, 500 h. 2) 30°C, 93% RH, open door, P=0, 6 h., closed door P <sub>max</sub> , 100 h.	-35°C (or -25°C)/55°C 2 d, P <sub>max</sub> . Verify temperature margins of components; insulation test	Hail test, 5.1 cm, 42 km/h 10 c./face	1) 207 kPa Water spray, 30 min/side 2) Wind driven rain 15 cm/h, 31 m/s wind, 30 min/side	1) 106 micron silica, 27–40 m/s; 2) 150–850 micron silica, 27 to 40 m/s			-25°C, P <sub>max</sub> cycling, 8 h.	2M2 vibration & broadband random and half-sine bump; 10g/16ms; +/-z blowing rain [78,80]	Blowing sand, dust (under low & high humidity), blowing rain
IEC 61215 [85]		-40°C/85°C 200 c., ~40 d) power cycling	85°C/85% RH, 42 d	-40°C/85°C, 85% RH 10 c., 10 d <sup>*</sup>	Hail test, 2.5 cm, 23 m/s, 11c. 1) 15 kWh/m <sup>2</sup> UV 60°C <sup>*</sup> 2) 60 kWh/m <sup>2</sup> outdoor							
ANSI/TUV-R 71830 draft (m)	85°C, 42 d or 113 d; or 100°C, 15 d or 73 d	-40°C/85°C, 200 c. or 400 c. (~40 d or 80 d), power cycling	85°C/85% RH (42 d or 113 d)	-40°C/85°C, 85% RH 10 c., 10 d <sup>*</sup>	1) 15 kWh/m <sup>2</sup> UV 60°C <sup>*</sup> 2) 60 kWh/m <sup>2</sup> outdoor		Salt fog: IEC 61701 [86], IEC 60068-2-52 [81] (severity 6)	6 kV; 3 kA; 300 c. (IEEE C62.45 unit 1)		(to be included in thermal cycling)	Based on IPC 9592 [91], IEC 60068-2-27 [79]	surge→fog→shock
IEC 62093 ed. 1 [87]		-20°C/55°C (i), 75°C (p), 85°C (u), 200 c., ~50d	55°C (i), 75°C (p), 85°C RH, 40 d	-0°C/55°C (i), -20°C/75°C (p), -20°C/85°C (u)/85% RH 10 c., power cycling	1) 15 kWh/m <sup>2</sup> UV, 60°C <sup>*</sup> 2) 60 kWh/m <sup>2</sup> outdoor (u)	Protect against splashing (u, p) based on IEC 60529 IP44 [84]	Test against ingress of ≥ 1 mm objects (u, p) ≥ 12.5 mm objects (i) based on IEC 60529 on IP44 and IP20, respectively			(Included in thermal cycling)	IEC 60068-2-6, 10 Hz to 11.8 Hz; 11.9 Hz to load; 150 Hz, 3.5 mm to 2 g, 1 octv/min, 2 h/axis, 6 h. IEC 60068-2-27, 15 g. half-sine 11 ms, 1 s, (6 x 3 c.)	DH→ mechanical load; Mechanical impact
IEC 62093 ed. 2 CD1 [88]	T <sub>amb</sub> max +10°C or +20°C, 21 d or 42 d, power cycling	-20°C/55°C (i), 75°C (p), 85°C (u), 200 c., ~50 d, power cycling	55°C (i), 75°C (p), 85°C RH, 40 d, power cycling	-0°C/55°C (i), -20°C/75°C (p), -20°C/85°C (u)/85% RH, 10 c, power cycling	1) 15 kWh/m <sup>2</sup> UV 60°C <sup>*</sup> 2) 60 kWh/m <sup>2</sup> outdoor (u)	Protect against splashing (u, p)	≥ 1 mm objects (u,p), ≥ 12.5 mm objects (i)		Step stress tests: - Cold - Hot - TC - Vibration - Combined	Covered in HF and TC	IEC 60068-2-6 [78] (6 h), IEC 60068-2-27 [79] (18 c.)	
IEC 62093 ed. 2 CD2 [89]: MLPE (m)	85°C, 42 d, powered <sup>a</sup>	-40°C/ 85°C, 400 c., power cycling	85°C/85% RH, V <sub>max</sub> , 42 d	85°C RH, power cycling 10 c. (10		Rain intrusion test: 1 h perpendicular	(m.s.c) Optional: IEC 60068-2-52 [81] salt mist			-40°C, 21 d; 24 c./d	Same as IEC 62093 ed. 1 [87]	

(continued on next page)

Table 2 (continued)

	Dry heat	Thermal cycling	Damp heat	Humidity freeze	UV and outdoor exposure	Ingress protection	Blowing dust, particle, or salt fog	Surge	HALT	Cold start	Shipping/vibration/shock	Combined/design validation/other <sup>§</sup>
IEC 62093 ed. 2 CD2 [89]: String (s)	60°C (i,p), 70°C (u) 42 d, powered <sup>a</sup>	-25°C/75°C (i,p), -40°C/85°C(u), 400 c. <sup>b</sup> , power cycling	40°C/95% RH, 21 d (i); 65°C 85% RH, $V_{\text{max}}$ 21 d (p), 65°C/85% RH, $V_{\text{max}}$ 42 d (u)	Omit (i), -25°C/65°C 85% RH (p), -40°C/85°C, 85% RH (u), power cycling, 10 c. <sup>c</sup>	d), and 15 min at 45° angle on each side and [82]; Flowing wind driven rain: 30 min rainfall on each side, 15 cm/h, and 31 m/s wind (u) (m, s, c)		(cyclic), IEC 60068-2-60 [82]; Flowing mixed gas corrosion test (H <sub>2</sub> S, NO <sub>2</sub> , Cl <sub>2</sub> SO <sub>2</sub> ), IEC 60068-2-68 [83], La1(i); Lb (p); Lc1(u), IEC 62716 [90], NH <sub>3</sub> testing (m,s) required near livestock			Omit (i), -25°C C <sup>c</sup> (p), -40°C (u), 21 d; 24 c./d	Same as IEC 62093 ed. 1 [87]	
IEC 62093 ed. 2 CD2 [89]: Central (c)	50°C or $T_{\text{max}}$ , 42 d, powered	-25°C/75°C (i,p), -40°C/85°C(u), 400 c. <sup>b</sup> , power cycling	40°C/95% RH, 11 d (i); 65°C, 85% RH, $V_{\text{max}}$ 11 d (p), 65°C/85% RH, $V_{\text{max}}$ 21 d (u)	Omit (i), -25°C/65°C 85% RH (p), -40°C/65°C, 85% RH (u), power cycling, 10 c. <sup>c</sup>						Omit (i), -25°C, 10 d (p); -40°C, 10 d (u), 24 c./d	Same as IEC 62093 ed. 1 [87]	

<sup>§</sup> not a comprehensive list

✓ performed, but details unspecified

<sup>a</sup> exists within a sequential stress test, UV 15 kWh/m<sup>2</sup> → TC (50 c.) → HF (10 c.)

c. cycles

d: days (approximate)

(m): module-level

(s): string

(c): utility/central

(u): outdoor/outdoor unprotected

(p): outdoor protected (= indoor unconditioned)

(i): indoor

<sup>a</sup> stress time is doubled for each 10°C lower when derating.

<sup>b</sup> the number of cycles is increased if derating is required.

<sup>c</sup> or lowest operating temperature as specified by manufacturer.

$T_{\text{amb}}$  max is the maximum specified ambient temperature for the device, whereas  $T_{\text{max}}$  is the maximum specified temperature of the device (such as before derating occurs).

standards, and (3) some related standards that have been referenced for testing the reliability of inverters.

### 3.2. Design qualification and quality standards

IEC 62093 ed.1, “Balance-of-System Components for Photovoltaic Systems – Design Qualification Natural Environments,” was published in 2005 for design qualification of PV BOS equipment, including batteries, inverters, charge controllers, system diode packages, heat sinks, surge protectors, system junction (combiner) boxes, maximum power-point trackers, and switch gear. Many concepts from IEC 61215, “Crystalline Silicon Terrestrial Photovoltaic (PV) Modules – Design Qualification and Type Approval,” were imported or modified for three or four levels of severity according to the intended service environment. Additionally, tests for dust, fungus, inspection, vibration, and shock are also prescribed, depending on the intended service environment of the equipment. However, the standard has been minimally adopted by the industry, attributable to its vague title and that it is spread thin in its attempt to encompass the many BOS components. It must therefore be pointed out that over a period of great increase in installed PV, including a period of 14 years of greater than 41% compounded annual growth rate [16], there has not been a generally accepted method for evaluating or ensuring a basic level of reliability of the inverter, the component of the PV system responsible for the greatest O & M costs of PV systems.

To address the shortcoming of lack of standardization for evaluating a basic level of inverter reliability, IEC 62093 ed. 2, renamed as “Photovoltaic System Power Conversion Equipment Design Qualification Testing,” is currently being developed in follow-up of the above-discussed edition 1. The new name specifies a narrowed scope for application to inverters and DC/DC optimizers. The first completed draft (referred to here as CD1 draft), developed in the 2010–2013 timeframe and led by SolarBridge Technologies Inc. (now SunPower Corp.), relied on concepts from ed. 1 and included philosophies of the Computer and Telecommunications Industries (formerly known as Institute for Printed Circuits) IPC 9592 A standard. Unfortunately, the draft was not adopted due to the lack of IEC working group members attending to bring it to final publication. However, the absence of standards with which to evaluate design qualification or durability led some companies and testing labs to adopt portions of it. The draft went beyond design qualification testing in that it contained clauses for performing highly accelerated life testing (HALT), involving step stress sequences to both low and high temperature levels, rapid thermal cycling, vibration, and combined environment (rapid thermal cycling and vibration) testing. In these tests, levels are increased up to designated limits or until failure is observed, at which point failure analysis must be done to understand the relevance of the failure. Additionally, tests in this document contain variations where the PCE was unpowered and powered. Where environmental testing of the PCE has been given as an option, Table 2 includes the label “power cycling” in the line item for IEC 62093 ed. 2 CD1 stress tests.

The IEC 62093 ed. 2 CD draft was resurrected with leadership at TÜV Rheinland Japan, with focus on PCE design qualification and enabling testing in a short amount of time. IEC 62093 ed. 2 CD2 also maintains (as in ed. 2 CD1) the implementation of powered PCE stress tests. Draft conditions for test are given in Table 2 under the line item IEC 62093 ed. 2 CD2. For module-level power electronics (MLPE), four samples per test sequence (eight total) are run. For string-level power electronics, two samples per test sequence (four total) are considered. For central inverters, one sample per test sequence is run; however, one or two samples total may be used, with the option for sequential testing of one sample through the two test sequences. Sequence one includes damp heat, dry heat, and cold start tests. Sequence two includes shipping vibration, shock, thermal cycling, and humidity freeze tests. Additional tests in a third sequence that are optional at

this time include salt mist, dust and sand, mixed gas and ammonia corrosion tests. However, there are calls to make these mandatory; the issues surrounding this are raised below in the *Enclosure* section.

Qualification testing of the PCE includes functionality testing before, during, and after the environmental stress tests, whereby the PCE-rated input DC power and 10 other operating points across the equipment's specified range of input conditions are additionally applied. Requirements for passing include no degradation in output waveform quality, functionality of services, and components, which include the display, user interface controls, and communication. The device must perform according to its specifications with no abnormal occurrences during powered stress tests. The equipment must also pass the insulation resistance test according to IEC 62109-1:2010 clause 7.5.2 and must meet visual inspection criteria. Major defects examined by visual inspection include broken or damaged parts, dust and water intrusion of the electronic parts, corrosion, adhesive failure or cracks, burns, bubbles, leakage, and any conditions that are visually uncovered that can affect function performance or safety.

In the area of standards for MLPE, the project ANSI/TUV-Rheinland 71830, “Microinverters and Microconverters – Design Qualification and Type Approval,” has been introduced by TÜV Rheinland PTL (TUV-PTL), Arizona. Details about this project, recommended stress tests, and some results of units run through the proposed test procedures for the qualification standard applicable to MLPE were published in 2016. [17] However, a draft of the document has not been distributed as of this writing. Table 2 summarizes stress tests and levels under consideration for the ANSI/TUV-Rheinland 71830 standard. Performance after the stress testing is evaluated by examination of power factor, total harmonic distortion, and inverter efficiency. Although string-level or utility-scale inverters are not included in the scope, the leaders of this project have expressed interest in eventually harmonizing the project or document with IEC 62093 ed. 2 discussed above.

Also being introduced is an IEC inverter quality-assurance technical specification, “Balance-of-Systems (BOS) Components for Photovoltaic (PV) Systems – Guideline for Effective Quality Assurance” approval. This parallels IEC 62941, “Terrestrial Photovoltaic (PV) Modules – Guidelines for Increased Confidence in PV Module Design Qualification and Type Approval.” [18] It seeks to provide guidelines for product design, manufacturing process, and selection and control of components used. The guideline will be used as a basis for factory audits, which would help ensure that the PCE designs—once they pass standards such as those in the IEC 62109 safety standard series and IEC 62093—can be better assured of maintaining their safety and reliability through production and deployment.

### 3.3. Safety standards

The IEC 62109 series is the international safety standard for PV power conversion equipment. Part 1 is IEC 62109-1:2010, “Safety of Power Converters for Use in Photovoltaic Power Systems – General Requirements.” Part 2 is IEC 62109-2:2011, “Particular Requirements for Inverters,” which covers the particular safety requirements relevant to DC-to-AC inverter products. Insofar as they are stress tests, IEC 62109-1 and -2 primarily examine electrical isolation for various fault conditions at the electrical and thermal extremes according to the rated mounting environment, which is classified by “pollution degree”—a category for the amount of dry pollution and condensation present in the environment. The safety standards also include weathering tests for exposed polymeric components and for resistance to deflection, impacts, and drop. This is in contrast to the IEC PV module safety test, IEC 61730-2:2016, “Photovoltaic (PV) Module Safety Qualification – Part 2: Requirements for Testing,” which has numerous environmental stress tests to the extent that it is considered by some to be a *de facto* supplemental design qualification standard for PV modules. As a result, modules on the market experience a greater

number of stress tests to qualify to a basic level of reliability with respect to safety problems than inverters.

Presently in draft stage is IEC 62109-3 Ed. 1.0, “Safety of Power Converters for Use in Photovoltaic Power Systems – Part 3: Particular Requirements for Electronic Devices in Combination with Photovoltaic Elements.” It is intended to cover the safety requirements for module-integrated and module-applied electronic elements that are mechanically or electrically incorporated with PV modules (i.e., MLPE). In its current draft form, it extensively adopts the stress tests of IEC 61730-2, “Photovoltaic (PV) Module Safety Qualification, Part 2: Requirements for Testing” and IEC 61730-1, “Photovoltaic (PV) Module Safety Qualification, Part 1: Requirements for Construction.” This is because MLPE experiences similar use environments and stress conditions as the PV modules they are mounted in or on.

UL 1741, “Standard for Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources,” is the applicable safety standard for PCE for PV applications in the United States. This standard contains environmental stress tests, including temperature tests, to ensure that critical components operate at or below their manufacturer’s specified temperature (margins) when the inverter is operating at its maximum operating ambient temperature. Additionally, thermal cycling, humidity freeze, and water spray (rain) testing are performed on the PCE in the unpowered state, after which insulation resistance is evaluated. These tests presently serve as minimum basic required stress tests that PV inverters must pass.

In the United States and several other countries, there are codes to limit the possibility of electrical shock and danger of high current from PV equipment, especially to fire fighters. Devices known as PV rapid-shutdown equipment (PVRSE), which are designed to achieve a tolerable level of electrical hazard in compliance with National Electric Code article 690.12 (2017), are installed on residential PV systems. In addition to electrical performance tests, compliance requires UL 1741 included shipping and storage tests, thermal cycling, humidity, dust, vibration, and jarring tests based on UL 991 “Standard for Tests for Safety-Related Controls Employing Solid-State Devices.” The equipment is cyclically powered during the thermal cycling and humidity cycling tests.

### 3.4. Related standards

In this section, standards from other industries that have been referenced for the development of the above discussed inverter qualification and safety standards are reviewed. Additionally, portions of standards from other industries are sometimes implemented in the absence of dedicated standards for inverter qualification, reliability and quality.

The development of IEC 62093 ed. 1 used many of the test sequences and concepts of the PV module qualification and type approval test, IEC 61215. Described elsewhere [19] is the development of this PV module qualification test through the work of the Jet Propulsion Laboratory (JPL) Block purchases, the European Joint Research Center (JRC), and others. Example similarities with IEC 62093 ed. 1 include the extent of thermal cycling (TC), 200 cycles; humidity freeze (HF), 10 cycles; duration of damp heat (DH) testing, 1000 h; and extent of outdoor exposure and ultraviolet (UV), and the combined test sequence of UV (15 kWh/m<sup>2</sup>)/TC 50 cycles /HF 10 cycles, where the UV stress is applied to modules with the intent to weaken the interfaces under the module glass superstrate (i.e., glass/encapsulant interface), followed by the application of TC and HF to stress and expand the weakened interface. This mechanism does not have an exact parallel in PCE if they do not comprise glass or transparent parts.

Some in the inverter reliability industry draw heavily from the IPC-9592A 2010 “Requirements for Power Conversion Devices for the Computer and Telecommunications Industries” standard. It specifies the requirements for design, qualification testing, conformance testing, and manufacturing quality/reliability processes. Important design for reliability guidelines are given, as are environmental, mechanical, and

electrical stress tests, which may be referenced for factors and levels of stress recommended for the service life in the scope—telecommunications equipment in controlled (i.e., indoor) environments. It includes HALT testing, and power and temperature cycling testing, which are test types that were incorporated into IEC 62093 ed. 2 CD1.

Companies have found that additional environmental tests based on ingress protection (IP) are necessary to evaluate inverters for outdoor, uncontrolled environments. IEC 60529 describes test levels for classifying the degree of protection provided by enclosures (IP Code); but some companies prefer to follow telecommunications equipment standard based on Telcorida GR-487-CORE and MIL-STD-810 G. These standards include rain intrusion testing, whereby rain is sprayed onto the cabinet, and wind-driven rain testing, whereby rain is blown with high-velocity air. The requirement is that water does not come in contact with the electronic assemblies, does not collect in the cabinet, and that the PCE continues to function. Additionally, the inverters need to withstand humidity when the cabinet doors are open, and be resistant to hail damage.

In summarizing the status of standards for PV inverters, there is no generally applied design and type approval test for PV inverters at this time. International standards for qualification testing and for quality assurance of inverters are in development. Some tests applied to PV modules adapted for use in inverters are for mechanisms in PV modules, without a clear analog mechanism in inverters. Applied safety standards for PV inverters provide a rudimentary level of reliability testing, insofar as they relate to safety. Considering the lack of generally accepted reliability standards, some apply draft standards in development and portions of standards from other industries. Development of generally accepted testing methods for the reliability of inverters is in its infancy.

The following Section discusses in more detail the reliability issues and mechanisms in inverter components. It is anticipated that such understanding will lead to more informed decisions about methods, test types, and stress levels for evaluating inverter reliability.

## 4. Reported failures in PCE and tests for their evaluation

### 4.1. General challenges

Despite the limited number of public reports detailing the nature of PV inverter failures, a large body of field experience exists for inverters with other uses including welding, [20] wind power generation, [21] and backup power. In welding, electro-mechanical wear-out of capacitors and other components, over- and under-voltage, and vibrations are cited as key mechanisms or factors that lead to failure [20]. In wind turbines, salt and corrosion, in addition to dust and debris leading to spurious conductive paths have been found in power module driver boards. Thermal conductive paste transporting heat from power modules have been found degraded, and a significant correlation between lighting strikes and inverter failure has been observed. [21] It is therefore seen that inverters placed outdoors in uncontrolled environments can additionally experience elevated humidity, condensation, salt mist, freeze cycles, dust, temperature swings of significant magnitude, and even stress factors such as lightning strikes that cannot be readily quantified beforehand.

While some information from the PV inverter industry and related fields exists, information from PV inverter manufacturers about failures affecting reliability and safety has not generally been forthcoming, whether due to intellectual property or marketing concerns. Moving to a philosophy of increased sharing of the field experience for the goal of safety and reliability will however be helpful for the industry as a whole.

The following sections describe some of the key components implicated in inverter failures, along with a discussion of commonly applied stress tests, levels, and analyses used to evaluate the components in the inverter for the required service. In many cases, more advanced, scientifically rigorous tests and analyses exist; however, this

paper serves to document what representatives in the PV PCE industry report that they do.

## 4.2. Printed-circuit boards and solder joints

### 4.2.1. Thermomechanical fatigue

Thermal cycling-induced fatigue failure of solder joints leading to resistance rise or open circuits is one of the major concerns among MLPE manufacturers. [12,14] Failure of printed-circuit boards (PCBs) ranks in the top four in the Pareto of causes of failures for larger inverters, within which fatigue failure may be a component (Fig. 3), and it appears on the reported component failures of concern for MLPE devices (Table 1). Warpage or tilt between components and board, and stretched solder joints tend to be causes of failure that may be activated by additional stress. [22] Additional PCB failures associated with shocks, vibration, and stress are through-hole plating cracks, via cracks, package cracking, die cracking, and wire bond breaks. [23]

**4.2.1.1. Coffin-Manson and Engelmaier Models.** Solder joints serve as mechanical and electrical interfaces between PCBs and surface mount components. They experience cyclic strain due to mismatch in coefficient of thermal expansion (CTE). The number of cycles to failure is often related to the cyclic strain range experienced by the solder joints with the Coffin-Manson equation, [24]

$$\frac{\Delta\epsilon_p}{2} = \epsilon'_f (2N)^c, \quad (1)$$

where  $\Delta\epsilon_p$  is the plastic strain range,  $\epsilon'_f$  is an empirical constant referred to as the fatigue ductility coefficient that is approximately equal to the true fracture strain,  $N$  is the number of cycles to failure, and  $c$  is an empirical constant known as the fatigue ductility exponent.

The Coffin-Manson model does not take into account parameters such as the temperature, frequency of cycling, and geometry of the solder joint. Engelmaier [25] developed a semi-empirical model for solder-joint fatigue life estimation that incorporates these parameters not considered in the Coffin-Manson model. Since then, the Engelmaier model has been incorporated into various industry standards such as those of the IPC. [26,27]

Per the Engelmaier model, the cyclic strain range  $\Delta\epsilon_p$  (for a leadless component) can be estimated using the following relationship in combination with Eq. (1),

$$\Delta\epsilon_p = \frac{L\Delta\alpha\Delta T}{h}, \quad (2)$$

where  $\Delta\alpha$  is the difference in CTE of the component and PCB,  $\Delta T$  is the effective cycling temperature swing,  $L$  is the maximum distance of the most remote component solder joint to the center of the component, and  $h$  is the solder joint height. [28] The fatigue ductility exponent  $c$ , in turn, depends on the mean cyclic solder-joint temperature and half-cycle dwell time and is given by

$$c = c_0 + c_1 T_m + c_2 \ln\left(1 + \frac{360}{t_D}\right), \quad (3)$$

where  $T_m$  is the mean cyclic solder-joint temperature,  $t_D$  is the half-cycle dwell time in minutes, and  $c_0$ ,  $c_1$ , and  $c_2$  are model constants that depend on the solder material (i.e. lead-free and SnPb solders). The  $2\epsilon'_f$  value is 0.65 and 0.57 for tin-lead solder and lead-free solders, respectively. [29] The values for  $c_0$ ,  $c_1$ , and  $c_2$  may be found in literature for various solder alloys. [30]

### 4.2.2. 25-year life for thermomechanical fatigue

It is still under debate in the PV industry how to demonstrate a 25-year service life. Cluff and Barker [31] demonstrated a method to translate field thermal-cycling conditions to equivalent “test” thermal-cycling profiles using a rainfall counting algorithm. This was used along with Miner’s rule to calculate the number of  $-40^\circ\text{C}$  to  $+85^\circ\text{C}$

temperature cycles required to demonstrate 25 years in Davis, CA, using temperature data obtained from that location. On this basis, Vasan *et al.* calculated that for a representative MLPE unit, more than 1000 cycles from  $-40^\circ\text{C}$  to  $+85^\circ\text{C}$  are required to accumulate the same amount of damage as an exposure of 25 years in Davis, California, USA. [14] This can be compared with thermal cycling tests sought in standards under development in Table 2, which is on the order 200 or 400 cycles. 400 Cycles will provide an acceleration of 10 y for the Davis climate; however, the test will represent lesser durations in the field for hotter climates, that can lead to faster degradation of solder joints with thermomechanical fatigue.

### 4.2.3. Coffin-Manson-based acceleration factor approach

Because strain is directly related to the TCE mismatch and the temperature extremes, plots of cycles to failure are frequently plotted against  $\Delta T$  ( $^\circ\text{C}$ ) on a log-log scale. Consequentially, Eq. (1) simplified to  $\Delta T$  instead of  $\Delta\epsilon_p$ , an exponent  $n$ , and a linear constant  $k$  can be used to fit thermal-cycling failure data with the equation  $N = k \Delta T^{-n}$ . The exponent  $n$  is in the range of 1–3 for ductile materials, 3–5 for hard metal alloys and intermetallic compounds that can form at solder joints, and 6–9 for brittle fracture. [32] As an example, cycles to failure using the Coffin-Manson model for thermal cycling of chip solder bonds found in IGBT modules has been tested as a function of thermal-cycling range  $\Delta T_j$  and modeled as  $N = 1.4 \times 10^{16} \Delta T_j^{-6}$ . [33] The exponent  $n = 6$  suggests a brittle fracture, a value suggested for package failures (which may include package cracking, die cracking, wire bond opening, and contact resistance rise). [34]

The Coffin Manson Eq. (1) can be adapted to determine the acceleration factor for thermal cycling [35] for equivalent mean temperature, neglecting effects of dwell time and ramp rate:

$$AF_{TC} = \frac{N_{Use}}{N_{Stress}} = \left( \frac{\Delta T_{Stress}}{\Delta T_{Use}} \right)^n, \quad (4)$$

where an exponent  $n$  value of 2.5 is commonly used for solder-joint fatigue, and 4 is used for IC interconnection failures. The value of 2.5 has been recommended for use as a conservative estimate of  $n$ . [35] If the use condition of a device is such that it sees temperature swings of  $\Delta T_{Use} = 70^\circ\text{C}$ , as has been reported in one extreme for MLPE, [10] and the proposed IEC 62093 ed. 2 test is  $-40^\circ\text{C}$  to  $+85^\circ\text{C}$ , or  $\Delta T_{Stress} = 125^\circ\text{C}$ , there is forecast to be an approximately  $(125/70)^{2.5}$ , or 4.3 acceleration factor. With this factor, the 400 cycles proposed in the draft standard translates to 1700 daily cycles in the field, or 4.7 years. If there are numerous significant thermal cycles per day in the use environment, as may be with cloud coverage cycles, then the field equivalence of the test is of lower duration. On the other hand, if the field temperature swing is less than  $70^\circ\text{C}$ , then the field equivalence of the test would be of higher duration.

### 4.2.4. IGBT case

IGBT module vendors run comparisons of cycles to failure vs.  $\Delta T$  and publish them on log-log plots. [36] PV inverter companies have reported employing such analyses for establishing service life. In one such application by a central-inverter vendor, considering solder joints of the IGBT power module for thermal excursions of  $\Delta T = 50^\circ\text{C}$  (somewhat above their measured worst case of  $45^\circ\text{C}$ ), and assuming 5 cycles per day, they estimated failure at 40,000 cycles based on the power module vendor’s  $\Delta T$  versus life (cycles) expectancy curve. Considering the 5 cycles/day, 21.9 years to failure could be inferred. [37] Accordingly, the IGBT module lifetime may be projected so that replacement of the module can be scheduled and appropriately considered in the O & M budget, or considered in the warranty if there is no option to replace the IGBT module.

### 4.2.5. Temperature range for thermal cycling tests

For a qualification test standard development, discussion has been

whether to limit the temperature extremes used in thermal cycling to values that are within the design ratings of the equipment and component devices, or to exceed them for achieving accelerated testing. Increasing  $\Delta T$  reduces the test duration because the acceleration factor is increased. However, there is also a concern about precipitating a failure mechanism that is not seen in the field, which would lead to error in the service life estimation. On the other hand, some express concern about the long test time if the PCEs are tested to the narrow band of their specified ambient temperature range. The consensus seems to allow options to test for shorter duration at the higher temperature range beyond specifications as given in the standard drafts (e.g.,  $-40^\circ\text{C}$  to  $+85^\circ\text{C}$  for MLPE, Table 2), or to test longer if maintaining the equipment to a reduced specified temperature band according to the Coffin-Manson-based analyses (this is discussed more in the Derating section below). Also contributing to the thermal profile, we see a trend to test with the device powered, or pulse powered, to replicate equipment starts at various temperatures and to dissipate heat in the active devices as would exist in fielded equipment.

#### 4.2.6. Commercial reliability modeling tools for assessing thermal stress, vibration, and shock

For stresses associated with vibration and shock, inverter qualification tests being developed reference other existing standards (see Table 2). Assessment of risk of failure due to thermal stress in addition to vibration and shock may be done with physics-of-failure modeling tools, whereby the bill of materials and the design of the PCB, along with its materials and assembly details, are used as input and analyzed considering information about the operations and use environment. Examples of such modeling tools for the assessment of thermal stress, vibration, shock, and other stress factors and mechanisms include CALCE Simulation Assisted Reliability Assessment (SARA) [38] and DfR Solutions Sherlock. [39]

### 4.3. Capacitors

#### 4.3.1. Types

A number of capacitor types exist, including polymer, liquid electrolyte, ceramic, and film capacitors. Inverters may use various capacitor types for different functions based on electrical mechanical, and use environment considerations. For example, DC electrolytic capacitors are frequently used to maintain the DC bus voltage at a constant level. AC polymeric film capacitors may be used in a variety of functions, but they cost more. [40]

#### 4.3.2. Degradation processes

Capacitor degradation can be broadly categorized into two processes. The first degradation type is chemical processes accelerated by heat. For electrolytic capacitors, degradation can occur due to electrolyte evaporation, and contaminants including oxygen, moisture, and halogens that diffuse and react. Failure can occur when dielectric materials including polymeric films or the aluminum oxide fail under the applied voltage. Polymeric film and electrolytic capacitors can also experience gas build-up from reaction products. The second degradation type is when leakage current under applied voltage causes localized heating (internal hot spots), ion transport, and chemical processes causing eventual degradation of the capacitance, increased equivalent series resistance (ESR), and failure such as by short circuit of the device. [40,41] Electrolytic capacitors are available with various specified temperature ranges; for example, between  $-20^\circ\text{C}$  and  $+55^\circ\text{C}$ , whereas more capable capacitors can be specified for the range of up to  $-55^\circ\text{C}$  to  $+125^\circ\text{C}$ , with various temperature ranges in between [42].

#### 4.3.3. Service life of capacitors

For polymeric capacitors, the multiplier for lifetime  $L_V$  as a function

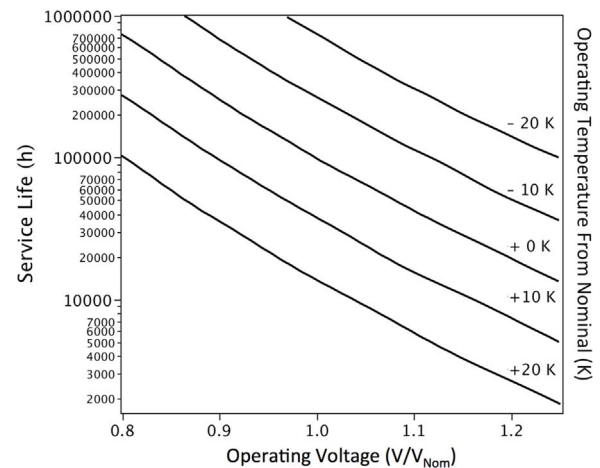


Fig. 4. Service life as a function of deviation from nominal operating temperature and operating voltage for a DC bus capacitor.

of voltage has been given as  $L_V = \left(\frac{V_r}{V_o}\right)^n$ , where the exponent  $n$  varies for the device between 7 and 9.4.  $V_r$  is the rated voltage and  $V_o$  is the operating voltage for usage. The thermal multiplier is sometimes approximated as a factor of two for every  $10^\circ\text{C}$  reduction from the maximum rated temperature. [40] Additionally, MIL testing specifications are well established for capacitors and are frequently referred to for ensuring their durability for the application. [43] These test methods include thermal shock, high temperature tests (i.e.,  $125^\circ\text{C}$ , 96–168 h), voltage applied ( $V_r$  to  $2 \times V_r$ ), humidity (steady state) with voltage bias, dielectric withstand voltage, insulation resistance, and partial discharge, with levels chosen depending on the use environment, reliability required, and cost.

Service life of capacitors may be indicated by the capacitor manufacturer as a function of operating voltage and temperature on a plot as in Fig. 4, and may be chosen by inverter manufacturers accordingly. [37] However, the distribution in the time to failure can be quite large, for example, from 10,000 h to 400,000 h. [40] As a result, manufacturers may choose to run lower than their rated  $V_r$  to achieve some design margin for reliability. [37]

### 4.4. Contactors

#### 4.4.1. Ratings of contactors

Contactors are relays designed for switching of high current, with mechanical contact springs, coils, and electromagnets. They are typically rated for number of operations, current at the contact pole, voltage, frequency, duty cycle, coil voltage, faults, temperature operating range, and a number of other parameters. They may be rated for given operation environments through demonstration of passing specified levels of test in IEC 60068-2-78 (damp heat) and IEC 60068-2-30 (cyclic damp heat). [44]

#### 4.4.2. Failure mechanisms

Failure to open or close can be due to factors such as an open circuit of the coil, which can stem from breakdown of the coil insulation, arcing of contacts, welding of the contacts due to heat from arcing, leakage currents, and coil burnout due to heat reducing available current, mechanical wear, moisture ingress, pollution ingress, over-voltage, and overcurrent. Additionally, manufacturing issues such as PWB washing have been known to lead to water ingress with a compromised device package.

#### 4.4.3. Application example

One central-inverter manufacturer reported using a main DC contactor designed for 30,000 operations at 1000 V and 2050 A, whereas the

typical use application for the equipment was in the range of 310 V and 1652.3 A to 480 V and 1070 A. Considering the specified 30,000 operations and assuming two cycles every day, a life expectancy of 30,000/(2×365) suggested a 41-year life. Using the contactor at lower than rated power was anticipated to provide additional margin. [37]

#### 4.5. Insulated-gate bipolar transistor and field-effect transistors

##### 4.5.1. Failure mechanisms

Insulated-gate bipolar transistor (IGBT) failures may not necessarily involve the transistor itself as the root cause, but the IGBT module and surrounding circuitry including diodes, thermistors, capacitors, gate drivers, and optical isolators for the gate drivers. We have observed IGBT module failures originating from drive-board failures (18%), diode failures (11%), defective components (9%), overcurrent (5%), loose connections (5%), other wire management issues (4%), capacitor failure (4%), and a number of other electronic equipment failures. The root cause of failure cannot always readily be determined—27% of the failure causes remain unknown, but some fraction of these may be the IGBT device within the module. [45] Note that the specific case of thermal cycling for testing IGBT modules to detect thermomechanical failure was discussed above in Section 4.2.4.

##### 4.5.2. Transistor

As for the transistor itself, we observe that IGBT devices fail because of overvoltage, overcurrent, electrostatic discharge (ESD), high temperatures, and single-event burn-out associated with ionizing radiation. These may lead to hot carrier current leaking through and damaging the gate oxide. Additionally, thermal runaway associated with excessive reverse recovery charge [46] and die-attach delamination may occur. [47] A study focusing on the IGBT failures can be found in a reference by Flicker and coworkers. [47] Tests applied to evaluate the above-discussed degradation mechanisms include high-temperature reverse bias (HTRB), high-temperature gate bias (HTGB), thermal cycling, damp heat, power cycling, steady-state temperature humidity bias life test (H<sup>3</sup>TRB), and highly accelerated stress testing (HAST), including the factor of humidity. [48]

##### 4.5.3. Arrhenius-based acceleration factor approach for projecting service life

As with diodes, materials can break down due to preexisting defects, by ion migration, and reactions with contaminants under voltage bias in IGBTs. The acceleration factor for degradation has been modeled with an Arrhenius relationship,

$$AF = e^{\left( \frac{E_a}{k} \left( \frac{T_2 - T_1}{T_2 \times T_1} \right) \right)} \quad (5)$$

Activation energy of  $E_a = 1.0$  eV has been determined for the case of the HTRB stress, which tests the junction integrity by monitoring leakage current. On the other hand,  $E_a = 0.4$  eV under the HTGB test applied for examination of the stability of the gate oxide. [49,50]

##### 4.5.4. Statistics-based reliability prediction approach

Mitigation of the degradation mechanisms of IGBTs for PV inverter application includes providing sufficient margins under all the operating conditions of the devices. [51,52] IGBT manufacturers will sometimes publish their failure-in-time (FIT) statistics at several different temperatures, from which failure rates and mean time to failure (MTTF) can be roughly estimated in the design phase to meet the anticipated use condition. [48] These data are based on models developed from statistical curve fitting of historical failure data, which may have been collected in the field, in house, or by manufacturers. The assumption in its use is that equipment or component failure causes are inherently independent of each other. Additionally, concerns exist about applicability due to changes in the component design or manufacturing process. Reliability of components is not always due

to component-intrinsic mechanisms but can be caused by the system design. It is difficult to collect good-quality field and manufacturing data, which are needed to define any adjustment factors.

##### 4.5.5. Selection by device ratings

Component selection may be based on device ratings. As an example, Schneider Electric has specified the use of IGBTs with maximum voltage bias levels for worst-case junction temperature (which, in this example, is the lower temperature of  $-25^\circ\text{C}$ ) of 75% of rated  $V_{DS}$ , and 80% of  $V_{GS}$  (where D, S and G refer to drain, gate, and source, respectively). [37] A number of other design considerations to achieve reliability are considered, including: running within switching safe operating area (SwSOA) [52,53] and total power dissipation [53] (including consideration of switching periods when the current-voltage product is a maximum [54]).

##### 4.5.6. FETs

Field-effect transistors (FETs) are used in smaller MLPE devices. Temperature cycling and power cycling leading to thermal stress and the degradation of solder layers by fatigue and wire bond lift-off are key failure modes of concern. [55] Reliability issues include ionic contaminants and water molecules that are polar, which can distort the electric field of the gate. This can be tested with the HTRB test as discussed above for IGBTs. [56] Oxide defects can cause random infant failures, but these can also be activated by high-temperature burn-in testing and be modeled with fitting to an Arrhenius rate equation. Additionally, metal corrosion associated with voltage bias, solder flux, or other impurities (discussed elsewhere in the paper) can lead to elevated leakage current that eventually can cause parametric failure of the drain-source current  $I_{DS}$  or a shift in the on-resistance  $R_{DS}$  and eventual open circuit. FETs have however been manufactured for many years and can be produced to perform reliably. Maintaining the transistors in their module, within the inverter, in their specified operating range (temperature, voltage, current) is critical for realizing the manufacturers' specified life.

##### 4.5.7. Grid disturbances and out-of-specification operation

Also of concern are grid disturbances or line transients leading to oscillations in the power train, confusing the controller circuitry or firmware, leading to an electrical overstress conditions. In such instances, the transistor may fundamentally be good, but the controller or the surrounding circuitry places the transistor in an overstress condition, leading to its failure. Relatedly, lightning strikes have been correlated to inverter failure in wind turbines [21]. Diagnosing the actual cause of failure in such cases is frequently difficult.

#### 4.6. Fans and cooling systems

MLPE may have a simple cooling device such as heat fins and a metal-metal contact to the module frame, whereas larger inverters often rely on convection cooling and active cooling systems that may include fluid coolants, liquid-to-air heat exchangers, phase transition, and thermosiphon methods. [57,58] Active cooling systems (including fans) comprise important positions (#4, #7, and #3) for inverter components that failed in the three reports in Fig. 3.

Our statistics for causes for cooling system failure include leakage of coolant (13%), improper parts (11%), shipping/handling issues (9%), loose connections (9%), and wiring issues (7%). Specification problems with replacement parts or their installation add up to (11%), foreign particles in coolant (4%), unknown (24%), and miscellaneous items each account for a small fraction of the causes and account for the remainder. [45]

Failing fan motors are sometimes considered a normal operation maintenance item. The lifetimes of motors are usually given as a function of operating temperature, which affects factors such as grease life. Additionally, usage speed and torque are compared to their rated values

to forecast lifetime. In one analysis for lifetime of the cooling fan for a PV inverter application, usage temperature was measured at its highest to be 56.5 °C. The fan was rated by the manufacture to operate for 12.5 years at 60 °C. To allow for some margin, the fan was recommended to be replaced at year 10 within the projected O & M budget. [37]

#### 4.7. Enclosures

Problems concerning fans, filters, gaskets, along with chamber integrity, may lead to dust getting into switches, contactors, and other electromechanical devices and cause about 4–6% of failures in these devices based on our data. Dust impedes airflow, leading to overheating, and when landing on circuitry metallization, it can promote corrosion, dendrite growth, chemical interactions, and contamination of contacts. These may lead to open or short circuits. To test for this and the effectiveness of filters, some companies test with blowing dust. Various particles sizes in separate tests (106–805 µm) are suspended in 27–90 m/s wind. The integrity of protection coatings is examined, as well as the degradation in equipment performance, and any possible effects of dust on openings, bearings, joints, and dust accumulation in the cabinet are examined.

Seals and gaskets are another source of issues. The inspection and replacement schedules for such components should ideally be specified considering climate-specific operating conditions. Local conditions having finer dust, or hot and humid climates may require environment-specific materials or additional maintenance beyond that typically specified.

Hail resistance of cabinets and exposed parts is also examined to verify that the exterior surfaces are resistant to deformation that could then allow dust, sand, water, ice, and other debris to enter. Hail resistance of windows, displays, or user interface panels is also checked. An example test level carried out by some in industry involves 5.1-cm hail balls at 42 km/h, with 10 hail balls per face.

Apart from environmental stress factors, shipping and handling are responsible for 29% of non-environmental stress failures and are the largest cause of failure in the enclosure category. Additionally, at about equal levels of occurrence, other root causes of enclosure problems that can be identified include design deficiencies, manufacturing deficiencies, product not meeting contract or code, and production process issues that can be traced back to lack of training of manufacturing personnel.

#### 4.8. Other components

PV inverters are complex pieces of equipment. Naturally, the entire piece of equipment must be tested as a unit despite specifying components to meet the intended use conditions. We see many various parts and processes in the field as being causes of inverter failure. These include the control panel, whereby panel buttons do not work or the LCD display fades; failing crystal oscillators designed to maintain timing or clocks, commonly by connection or termination failure; coin batteries losing power between the time of equipment manufacture of the equipment and install; optical isolators degrading because of reduced LED emission; improper torqueing of parts and fasteners; wiring errors in hookup or loose connections at wiring terminals; wire connections to the PCB being of insufficient durability or having unstable connections (which have been cause for fires); thermal conductor paste being improperly applied or thermal conduction being insufficiently maintained due to warping of the components; grid configuration settings being inappropriate for the application; communication failures either in hardware or software; transistor driver software malfunctioning and causing failure of the transistors; and failing communication ports and connections.

These issues are a mix of design and process issues, but they are not insignificant. For example, in Report 3 of Fig. 3, AC breakers are responsible for the fifth-largest cause of inverter failure. Incorrect torqueing (18%), loose connections (15%), incomplete assembly (12%),

and improper installation (9%) round out the top four identified causes of failure of the AC breakers. [45] Also of concern to industry is wire management employed within PCE, which can lead to fatigue or other failure modes and result in cascading failures. Such issues are again discussed below in the Quality factors section.

### 5. Environmental conditions

#### 5.1. Temperature and other operating environment considerations

Temperature affects numerous materials and components of inverters. We discuss some of the temperature effects on selected inverter components in more detail in other sections; but here, we review more generally how temperature affects many of the various components of the system.

Examples of the degradation effects of elevated temperature on components of the inverter are in the solder joints, by grain coarsening and formation of brittle intermetallics. Capacitors are affected by heat to various extents and depending on the type. Degradation may include dielectric breakdown, heat contraction of the dielectric, electrolyte evaporation, degradation of anode and cathode, cracking of the packaging, gas evolution, and drift in electrical parameters that may lead to system failures. High temperature can also affect IGBT degradation, which can be described by Arrhenius processes as discussed above. Diodes may be affected by temperature due to increased ion migration and current leakage through the junction and thermal runaway. Relays can be affected by heat through insulation degradation and coil burnout. Inductors or transformers can experience degradation of insulation, the internal solder connections, packaging materials, and the iron-core binder material. Depending on the specific formulation, potting and conformal coatings are affected; for example, hardening of pottants can lead to stress on components during temperature excursions. Elevated temperature can lead to oxidation and hardening of seals and polymeric used in the wire harness.

The component temperature of several PV inverters has been studied at Sandia National Laboratories. [59] They found the control board and transformer peaking at slightly above 60 °C during the summer months, with the control board always on and at higher mean temperature than ambient. Other monitored components did not rise significantly above ambient temperature according to their published data. Cumulative distribution curves were determined using the thermal profiles and failure rates employing the activation energy for failure determined from published mean-time-to-failure vs. temperature data.

Temperatures for capacitors, IGBTs, and heat sinks considering ambient temperature, power consumed by string inverters, and wind speed have also been measured and modeled. [60] The greatest component temperature rise as a function of irradiance that was measured was for the IGBT. For MLPE, strong effects have been reported for position of the device (including module-to-roof air gap) and type. Depending on these variables, data show a rise above ambient from several degrees up to 35 °C above ambient. [17] These data can vary with the evolving variety of cooling methods employed, inverter size, and type.

Advanced Energy published 25 °C as an operating temperature for their central inverters with active cooling. By partially disabling the cooling and operating at 67 °C for acceleration—and assuming an activation energy of 1 eV and 8.55 h of operation a day—30 years of operation could be accelerated to less than 83 days (with margin to spare) by Eq. (5). [61] Components in test may go to higher temperatures; for example, the IGBT unit, to 150 °C ± 5 °C ; PCB to 97 ± 2 °C; and transformer to 164 °C ± 5 °C. If individual components failed in this general test, then actual activation energy for failure for such individual components were measured and established so that service life could be more precisely evaluated. [61] Subsystems of central inverters are sometimes tested separately, as Advanced Energy reported doing for the low-voltage ride-through (LVRT) assemblies. [61]

## 5.2. Humidity

In capacitors, humidity corrodes electrodes, which reduces the effective electrode area. [62] Polymer films (as in polymer capacitors) may swell and degrade with humidity, [63] changing the dielectric properties. [64] Humidity facilitates the migration of ions (metals, halogens) or particles, leading to increases in leakage currents and reduction in insulation resistance in various electronic components. [65] Humidity and other gases present can lead to inhomogeneities in the electric field due to a decrease of dielectric strength and to concentrations in the electric field that lead to the appearance of corona discharge. Humidity and other gases present can additionally lead to "popcorning," whereby the capacitor blows out due to outgassing. In film resistors, humidity can accelerate the degradation of coatings, which may lead to sulfurization and consumption of Ag-based metallization causing open circuits. [66] Humidity can lead to corrosion, accelerated by residual halogens in various devices including film resistors. [67] On the PCB and other metallization in the circuits, electromigration and conductive anodic filaments may develop, driven by electric fields and facilitated by ionic solubility, with higher humidity leading to shorts. Humidity can lead to some dimensional changes and loss of adhesion of encapsulants, potting, or conformal coatings such that humidity may condense in voids, accelerating corrosion processes. [68]

Humidity can affect metallization within electronic components and in IC packages. Increased surface conduction between metal lines driven by voltage potential is a failure mechanism within IC devices. Moisture can diffuse through polymeric encapsulants such as the epoxy resins. Degradation by ion transport on surfaces driven by voltage potential and enhanced by humidity and temperature is frequently described by the Hallberg-Peck equation. [69] Time to failure may be described as

$$t_F = A_0 RH^m f(V) e^{\frac{E_a}{kT}}, \quad (6)$$

where  $A_0$  is a scaling factor depending on the specifics of the device and conditions and  $RH$  is relative humidity. For degradation of metal lines under bias in epoxy-encapsulated ICs,  $m = 2.66$  and  $E_a = 0.79$  eV ( $E_a = 0.7$ – $0.8$  eV has been given as appropriate for aluminum corrosion when chlorides are present [70]), a function of voltage depending on the device  $f(V)$ , Boltzmann constant and temperature. Damp heat tests according to IEC 62093 CD2 are performed under maximum specified voltage and less than 5% current load applied on both the electrical inputs and outputs of the PCE. Ion migration, conductive anodic filament growth, and shorts associated with condensation are most likely to occur when the voltage stress is a maximum.

Hallberg and Peck published that humidity equilibrated in epoxy-chip carriers in about 3000 h at 35 °C, whereas at 85 °C, equilibration took about 200 h. They determined that 1,000-h failure-free at the accelerated condition of 85 °C and 85% RH corresponded to 100 failures in time (FITS), or 100 failures per  $10^9$  hours of device operation in a 20-year operation of use condition of 35 °C and 60% RH, which are conditions relevant to indoor use of telecommunications equipment. On the other hand, 1900 h at 85 °C and 85% RH failure-free in an accelerated test would correspond to a 40-year life assuming 100 FITS. In a survey of various industries to determine expectations of PCE reliability, with automotive companies and utilities being the largest fraction of responders, 10–100 FITs was by far the largest response for acceptable failure rate (34%). [71] In a separate analysis for MLPE, at 85 °C/85% RH, the recommended time to test for equivalence in Miami is 612–971 h, and in Chennai, India, it is 1192 h to 3417 h. [72] These ranges are reasonably consistent with the Table 2 levels for DH testing in the IEC 62093 ed 2 CD2 draft for MLPE.

There are studies about the interaction between humidity, temperature, electrical voltage bias, metallization and flux. Observed corrosion reactions associated with residues of flux differ depending on the temperature. Fluxes that do not require cleaning have acid components that volatilize at elevated temperatures such as 85 °C. [73] Considering

this, and in view that devices do not actually operate in the field with a temperature of 85 °C and 85% relative humidity, performing tests for failures associated with electrochemical corrosion have been proposed to be performed instead at 40 °C and 93% relative humidity or at 60 °C, as adopted by Bellcore/Telecoria testing standards. In view of this, we recommend also testing inverters with the factors of humidity and electrical voltage bias in the lower temperature regimes.

## 5.3. Derating

Many inverters derate, whereby their tracking moves off the maximum power point of the PV array to reduce conversion power if the equipment-specified temperatures are exceeded. For example, the SMA STP 60 is string inverter designed for outdoor use with a specified chassis operating temperature range between  $-25$  °C and  $+60$  °C. Additionally, the equipment reduces the power when the detected internal temperature increases beyond a certain threshold. This threshold is 45 °C, and the power is linearly reduced from the rated power at 45 °C until zero output power is converted at 60 °C, which is the maximum allowed. [74]

Some manufacturers are concerned about testing beyond the equipment-specified temperatures because components that are contained in the equipment may not be rated for temperatures outside of this range. For example, at the low temperature range, aluminum electrolytic capacitors exhibit increased ESR. The relative resistance may increase more than an order of magnitude as the temperature reduces from 20 °C to  $-40$  °C. [75] On the other hand, function verification will require testing outside of specifications to validate that the inverter can demonstrate its capabilities to protect itself. This requires consideration about appropriate testing methods for characterizing the equipment design, qualifying the equipment design, or for durability testing.

For the purpose of thermal cycling, there are cases where the standard may require thermal cycling in the temperature range of  $-40$  °C and 85 °C ( $\Delta T_{Stress}$  of 125 °C), but the manufacturer prefers not to exceed the rating of  $-25$  °C and 60 °C for a  $\Delta T_{Use}$  of 85 °C.

Using Eq. (4),  $(\Delta T_{Stress}/\Delta T_{Use})^n$  for this situation is  $(125/85)^{2.5} = 2.6$ ; therefore, 2.6 times the stress cycles prescribed by a qualification test can be one approach for thermal cycling at the extremes of the nominal use condition. Of course, this increases cost because of the additional testing time, but also, because a chamber must be dedicated to the particular temperature range specified by the manufacturer.

Similarly, if an 85 °C 85% RH test exceeds the manufacturer's specified use condition, Eq. (6) may be written as [35]

$$AF_{DH} = \frac{t_{Use}}{t_{Stress}} = \left( \frac{RH_{Stress}}{RH_{Use}} \right)^m e^{\left( \frac{E_a}{k} \left( \frac{1}{T_{Use}} - \frac{1}{T_{Stress}} \right) \right)} \quad (7)$$

to determine the time for test at lower temperature ( $T_{Use}$ ), and, if desired, a different relative humidity,  $RH_{Use}$ .

## 6. Quality factors

Product development involves design verification and design validation tests, third-party verification testing to meet code and safety requirements, and qualification and reliability testing. There is substantial pressure to bring new designs to market sooner and to keep costs low. These pressures, combined with the extremely rapid evolution of the technology, have apparently led to numerous problems associated with the software and hardware each time new equipment is deployed. In an analysis of the manufacturing process steps responsible for failure in central inverters based on 400 field events, the design process was found to be responsible for the greatest fraction of failures, 34%; the manufacturing, 26%. [76]

Best practices for greater quality include consistent implementation of a design, including requiring definition and control of the manufacturing process. ISO 9001 certification of a process goes a long way toward ensuring consistent implementation. However, the quality

assurance may be improved by ensuring that:

- the manufacturing process has been well defined, including qualification of incoming materials, and tolerances defined to guide assembly;
- testing is used to confirm control of the process;
- testing is used to confirm functionality within the required boundary conditions;
- testing is performed on a reasonably large sample size of fielded products and learnings are immediately addressed through reliability growth programs;
- the final product is confirmed to meet the specifications given on the data sheet;
- the manufacturing process is tracked so that if defective components or processes are identified, the problem may be traced to all affected serial numbers and appropriate customers are notified; and,
- when failures are identified, root-cause analysis is applied and the quality-assurance program is modified to prevent subsequent occurrences of a similar nature.

Customers and manufacturers have reported that a reduction of failures in the field could be achieved with a thorough implementation of quality-assurance programs containing such elements.

Testing for the effects of the grid on inverters can be challenging. For example, a lightning strike and other anomalies on the grid can affect inverter function, but can be very difficult to test for. So, interactions with the grid are not well understood until inverters are deployed in the field in fairly large numbers. The tests done by the manufacturer in the lab are usually done under conditions that represent typical conditions, rather than the full range of field conditions.

As a result, there appears to be a need to perform more detailed design validation testing, and qualification tests should be expanded in scope to include realistic use, environmental, and connection conditions. In considering this, some PV power plant developers require pilot testing under realistic field conditions as part of equipment qualification testing. Standardized use (and test) environment parameter ranges, tradeoffs, overlaps, and boundary conditions should also be generated for real field applications. Additionally, comprehensive firmware validation tools are recommended such as hardware in the loop (HIL), which has been used in industries such as electric vehicles [77] to verify firmware logic of inverters for cases like operational mode change, start up, behavior after field outage, interaction with grid, and harmonics. Better quality is expected from tests that validate interfaces (e.g., the inverter/transformer interface), with sufficient sample size of fielded beta units with performance tracking to foster learning cycles, and improved manufacturing controls to catch errors on the production line.

O & M costs can be reduced by designing for serviceability (DFS) to reduce mean time to repair (time required to repair and return failed equipment to service) along with preventative maintenance schedules based on anticipated life of critical components. High modularization, easy troubleshooting, easy access for repair, low skill and effort for replacements, and time-optimized supply logistics are highly desirable attributes for DFS. For example, Schneider Electric has reported their recommend replacement of cooling and circulating fans (discussed above), DC bus capacitor assemblies, gate driver boards, and the front panel and control board at year 10. [37] They forecast a 20-year service life for the inverter including such DSF measures, along with ensuring sufficient design margins in the inverter and its components.

## 7. Summary

The reviewed data from PV power plant operators show that inverters are the most costly O & M area of PV systems, responsible for between 43% and 70% of the service tickets. These are in addition to planned maintenance activities. Software or firmware is the component frequently responsible for the largest fraction of inverter outages; however, the hardware components in aggregate lead to more than half the inverter

failures. This paper introduced various standards being developed for testing of inverters for reliability, safety, and quality. The reliability testing protocols for inverters and components that some companies are implementing were discussed. However, generally accepted tests and methods for ensuring quality and reliability of PV inverters are in their infancy.

### 7.1. Metrics for tracking cost performance

PV power plant availability is a metric sought to be maximized in the PV industry. Additionally, to be competitive, there is an emphasis on capital expenditure reduction. However, a critical piece that we reviewed is the operational costs to attain the availability. Since availability is a blended number based on the reliability and repairs, a more suitable approach is to additionally track the ongoing operating costs to secure a given availability. Such data may be collected by deploying PCE prototypes in the field environment for achieving a continuous feedback loop that is also essential for reliability growth. The obtained data can be compared to what the manufacturer estimates for the cost of ownership, and is useful as an overall bankability metric and to optimize and balance the cost versus quality equation. It is desired to minimize unplanned or unexpected outages, and minimize repair and power restoration times. While the authors acknowledge it is economically impractical to attain inverters that never fail or need maintenance, or achieve 100% availability, the impact of inverter outages on the revenue streams of PV projects must be recognized.

These needs motivate reliability testing and quality standards utilizing quality management principles, design for reliability and testing approaches as cost effectively as possible to reduce the unpredictability of operating costs for owners and operators. Life of serviceable components must be properly estimated, and their total replacement costs included in the total cost of ownership calculation. Standards are sought to aid quality management systems by (among other things) defining the required data gathering to support total cost of ownership and leveled cost of energy (LCOE) metrics.

### 7.2. Overview of the status of standards for inverter reliability, safety, and quality

Accepted standardized tests are lacking for ensuring reliability of inverters for the PV industry. The status of test methods being used or being included in draft standards to gauge reliability, including design qualification tests, were reviewed to show the areas of consensus as well as to contrast areas where they differ. Design qualification tests cover infant failure and an extent of general usage, but do not typically have end-of-life wear out mechanisms covered within their scope. At this time, safety standards such as UL 1741 and IEC 62109 series are more developed for inverters, compared to those for reliability and quality. These safety standards for inverters include some basic stress testing, but are minimal in extent compared to the extensive testing that PV modules undergo for safety certification.

To move PCE reliability forward, research and characterization into degradation mechanisms, and openly published results of executed candidate standardized test protocols with industry collaborations are sought. Actuation and optimization of the tests and protocols for determining the relationships with field failures in specific use environments are further required. This includes longer-term tests of the stress factors of the natural environment and electric grid, including dust, electrical discharge, and the examination of interdependencies of software, hardware, and the stress factors. Careful analysis is often necessary to identify actual cause and effect. The work spans the design, manufacture, and installation. Such efforts will lead to improved methods to evaluate wear-out mechanisms and product life, along with reduced O & M costs for PV. Studies of these above items should inform the improvement of reliability standards (IEC 62093) and future quality standards, and potentially safety standards for PCE for PV power plants.

### 7.3. Failure modes of PCE, testing, and service life determination

Inverters are complex systems exposed to both electrical and environmental stresses. Components inside the PV inverters may reach high temperatures, such as when mounted behind PV modules on rooftops. It was seen that on the discrete component or device level, methods for test to evaluate service life in view of the most common stress factors (*i.e.*, temperature) are frequently well developed. Examples of how inverter manufacturers specify components were given, and comparisons between levels used to test PCE in industry and qualification test standards under development could be compared using a provided table. We reviewed an example of how an inverter manufacture tested their equipment at high temperature for acceleration. With knowledge of the actual operating temperature, they performed more specific acceleration factor studies for the weakest components that show failures.

Specific challenges that we must address henceforth include understanding moisture ingress into devices and their effects on the materials and electrical performance, such as condensation effects in cold starts and moisture absorption leading to corrosion or conductive anodic filament growth. This requires understanding temperature and moisture levels in various components of fielded inverters, and the corresponding levels in accelerated tests. In conjunction with considerations for acids in solder flux, soiling, and pollution, achieving appropriate acceleration of the temperature and humidity-related degradation mechanism is sought. In view of these challenges, we must determine how to test power conversion electronics for the combined stress factors of the natural environment and electrical parameters to which they may be exposed. Water vapor ingress usually occurs over the long-term even if using potting or coatings on printed circuit boards, or if sealed enclosures are used. Performance of potting and conformal coatings specific to the PCE is sought, including detailed analysis of degradation mechanisms and any failures.

Many individual components are tested for their failure-rate distribution, which can be extrapolated to use conditions. But understanding the reliability of the assembly of components of the PCE in a complex environment becomes more difficult. This challenge becomes greater as the inverter capacity rating becomes larger, with more components. Just as with PV modules having 25 year warranties, the long lifetimes expected of PV PCE, especially those under roof-mounted PV modules, lead to stringent testing requirements and long testing times to validate the warranty periods. Considering actual use environment stress levels and differing reactions that occur as a function of temperature, implementing pulsed biased damp heat (including condensation) tests at lower temperature is proposed, such as in the range of 40 °C–60 °C.

We must include not only the conventional stressors applied in tests used in the electronics industry, but also all the factors of the natural environment that inverters experience. These include stresses associated with shipping and delivery, sun, hail, dust, sand, wind driven rain, and electrical disturbances, including understanding effects of lightning strikes. Many of these operating environment-related tests may be adapted from telephone, communications, and military standards.

Considering the nascent stage of reliability testing protocols for inverters and the need to examine the inverter in conditions where the combination of stresses in the natural environment act together, field tests in the intended operating environment remain necessary at this time to examine reliability and confirm O & M costs. Additionally, these outdoor tests are useful for design validation testing of the PCE, to examine the complex relationship between operating conditions, software/firmware, and hardware and show any associated failures, as with failures in software or errors in the controller circuitry for the transistors, leading to an electrical overstress conditions and possible hardware failure. Accelerated tests must similarly strive to reproduce the range of electrical and environmental conditions of the natural environment.

### 7.4. Quality

There is substantial pressure to bring new designs to market quickly and to keep costs low. This leads to the appearance of failures when new equipment is deployed. The design process was found to be ultimately responsible for the greatest fraction of failures at 34%. Additionally, quality issues in the manufacture lead to failures. For example, process errors including incorrect torqueing, loose connections, incomplete assembly, and improper installation lead to more than half of the failures of some critical inverter components such as AC breakers. Customers and manufacturers have reported that a reduction of failures in the field could be achieved with a thorough implementation of quality-assurance programs.

To improve quality, detailed design validation testing and qualification tests should be performed using realistic operation, environmental, and connection conditions, including pilot testing under end-use field conditions. Standardized use (and test) environmental parameter ranges, tradeoffs, overlaps, and boundary conditions should also be generated for real field applications. Additionally, verification of all firmware, functionality, interaction with grid, and other electrical or signal interfaces, should be performed.

Quality can be improved with well defined manufacturing processes, use of tolerances, and incoming materials specifications supplemented by testing for process control and adherence to the specified design. Testing must be performed on fielded products in numbers to obtain statistics because effects of the grid on inverters are difficult to predict, with feedback to the process along with root-cause analysis when problems are discovered to prevent repetition of the problem. Additionally, customers with products potentially effected by the problem (based on serial number) must be informed and any resulting preventative procedure must be scheduled.

O & M costs can be reduced by designing for serviceability to reduce mean time required to repair and return failed equipment to service along with preventative maintenance schedules based on anticipated life of critical components. These should be fully accounted for in cost of ownership calculations.

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