

RELIABILITY IN PV INVERTER DESIGN: BLACK ART OR SCIENCE-BASED DISCIPLINE?

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Inverters have historically been the leading cause of PV system failures. The useful life of a central inverter typically does not exceed ten years, and the cost to maintain and eventually replace a central inverter once or even twice during a PV system's lifetime drives up system costs with every truck roll.

PV microinverters are a compelling alternative to central inverters that offer greater system flexibility, safety and energy harvest advantages. But to decrease installation and replacement costs and capture the greatest return on investment, microinverters must be part of an integral ACPV solution guaranteed for 25 years. This means the microinverter must provide the same 25-year warranty as the PV module itself. This article highlights the issues that make reliability a critical issue in microinverter design and the importance of a science-based, best practices approach to reliability to ensure an end-to-end, 25-year warranty for AC modules.

Defining Reliability

Some companies attempt to define reliability by calculating mean time between failure (MTBF) using published component failures rates and parts count models such as Telcordia SR-332 or MIL HDBK-217. MTBF modeling tools provide a relative measure of steady state reliability but do not effectively identify the potential reliability weaknesses of a product's design or manufacturing process. Specifically, these models do not take into account variations due to component and system package technology, manufacturing variation, derating based on Physics of Failure plus many aspects of harsh use environments such as those found in PV applications.

MTBF models are not designed to identify product wearout mechanisms. They only apply to the useful life or steady state region of the bathtub curve (Fig. 1) where failure rates are constant. An MTBF of 5 million hours or 571 years corresponds to an annual failure rate of approximately 0.2%/year. It does not mean the product has a useful life of 571 years. Two products can both have the same MTBF yet one has a useful life of only 10 years while the other is 50 years. The difference is that the first product has component wearout failure mechanisms which significantly limit useful life. Reliability results in the first years of a product's life say nothing about the performance in later life due to the fact that wearout mechanisms have not yet appeared.

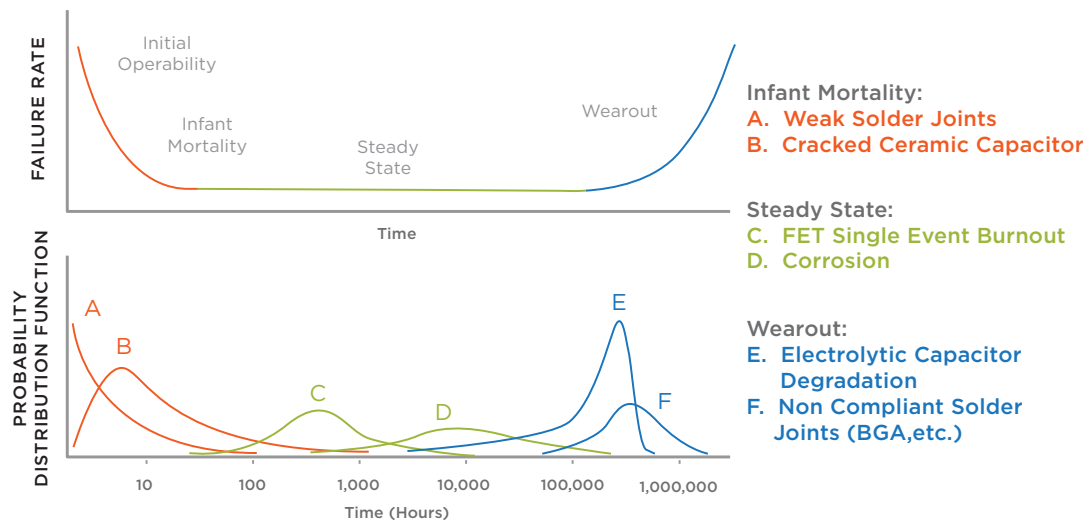


FIGURE 1 Contribution of Individual Failure Mechanisms to the Bathtub Curve

PV test strategies follow industry standards such as UL 1703 and IEC 61215 which contain tests to accelerate failures. However, these standards are not intended to prove long-term reliability. They only demonstrate a relative measure of a product's ruggedness and ability to meet safety standards.

In the PV industry, there is no consensus on which tests or numbers of samples are needed to demonstrate reliability or even how long tests must run to meet the equivalent useful life under field use environments. A broad range of accelerated stresses are required and acceleration factors are dependent on specific component failure mechanisms and stresses experienced in their application environments.

While testing plays an important role in reliability, decisions made during the concept and early design phases of a product play the most crucial role in determining reliability.

Component Technology Selection

Power supplies such as inverters are designed with solid state switches to control the flow of power through circuits containing energy storage and filtering components such as inductors and capacitors.

Designers have a number of component technologies to choose from. For example, when identifying which capacitor technologies to use, designers must choose between aluminum electrolytic (e-caps), tantalum, film, and ceramic capacitors. Each of these component families have unique degradation mechanisms that can lead to failure. Designers working with component and reliability engineers must be aware of these mechanisms to select the best capacitor technology to meet the reliability expectations of the product.

Certain topologies require relatively large capacitances that can only be provided by aluminum electrolytic capacitors (e-caps). E-caps contain a complex liquid chemical called an electrolyte to achieve high capacitance and low series resistance. As e-caps age, the volume of liquid present decreases due to evaporation and diffusion. This process is accelerated with temperature, eventually leading to performance degradation over time. This often results in total failure of the power supply which limits useful life.

To meet the same lifetime objectives of PV modules, design engineers at SolarBridge Technologies selected components that avoid premature wearout such as that seen with e-caps by developing an architecture for the Pantheon™ microinverter that enables them to “design in” reliability through the use of higher reliability film capacitor technology.

In power electronics, there are hundreds of potential failure mechanisms, dependent on component technologies used. A reliability-focused engineering team must familiarize themselves with these mechanisms and make design decisions to minimize risk. Key decisions like this must be made early in the design of a microinverter.

Managing Failure Risks

E-caps are just one example of component technologies that must be avoided to ensure long life in harsh outdoor environments. Even with low-risk capacitor technologies such as film and ceramic, there are voltage, power and temperature stresses which can lead to premature failure. Component electrical and thermal derating is required to manage this risk.

Some materials such as solder and printed circuit boards (PCBs) are always present in power supplies and exhibit their own unique wearout mechanisms. Fortunately, there is a long history of these and other established component technologies with failure prediction models coupled with decades of field use to verify the accuracy of these models. This level of detail is only useful once all other weaker components are designed out.

For failure mechanisms such as solder joint fatigue, these models coupled with accelerated test data and known field use conditions can accurately predict onset of wearout. Results of these models can then be compared to lifetime objectives. When reliability objectives cannot be met, alternate component package geometries or materials may have to be used to reduce stress created by daily thermal cycles experienced in PV applications.

Role of Testing in Reliability

There are a variety of accelerated tests required at the assembly level to confirm that failure mechanisms were not missed during the design review process. Each test applies a set of stresses to induce specific failure mechanisms. Common tests and typical failure mechanisms they may identify is shown below.

Highly Accelerated Life Test (HALT)

- Design margin
- Confirmation of soft shutdown at operation limits

Thermal Cycle (TC)

- Solder joint fatigue
- PCB via fatigue

Damp Heat

- Conductive Anodic Filament (internal PCB short)
- Cracked ceramic capacitor

Humidity Freeze (HF)

- Interfacial stresses leading to delamination
- Dendrite growth

High Temperature Operating Bias (HTOB)

- E-cap electrolyte vaporization
- Ceramic capacitor oxygen vacancy migration

All test standards require that a minimum sample size pass a prescribed test duration under specified test conditions. One example is the PV module Thermal Cycle test specified in IEC 61215. Section 10.11 requires 2 modules be exposed to 200 cycles from -40C to 85C. The test is considered passed if there are no failures and <5% performance degradation.

There are two problems with applying this approach to demonstrating reliability. First, there is often not a clear understanding of how the stress conditions relate to real-world environments in order to determine how the test duration relates to useful life. In other words, how many diurnal cycles under normal use conditions are equivalent to a single accelerated test thermal cycle.

Second, the low sample size does not allow for statistical validation of reliability. If both samples pass after 200 cycles, the product could be deemed to be reliable. However, if the test is extended and one module fails at 250 cycles and the other fails at 300 cycles, what does that say of a larger population of modules? If the 2 test failures represent a predominant wearout mechanism, the actual time to first failure in a population of 100 modules exposed to accelerated test may be much lower than 200 cycles. Is this considered acceptable? In this scenario, as the sample size is increased, the likelihood of experiencing a failure within 200 cycles increases.

In designing microinverters to match the lifetime of PV modules, reliability engineers must go beyond the test cycles and sample sizes typically used. Failures require corrective action and a repeat of testing must be conducted to ensure the problem is corrected.

Manufacturing for Reliability

Even with appropriate design for reliability best practices and accelerated test evaluation, reliability risks can be introduced in high-volume manufacturing due to supplier and assembly process variation. Once in production, close monitoring of suppliers and production test yields is a crucial part of a Quality and Reliability strategy. Early field reliability issues often correlate with factory test yields.

Field Feedback

While shipping with zero defects is a goal all manufacturers should target, in practice it is rarely achieved. To round out a reliability strategy, field failures should be captured along with any available details surrounding failure. Failure Analysis should identify design, component, manufacturing or application-related failure mechanisms. Lessons learned from field experience should be fed back into design for reliability guidelines which are continually updated and result in ongoing reliability improvements for future generations of products.

Conclusion

The potential for ACPV solutions to greatly expand the solar market is compelling but must be balanced by an understanding of the reliability issues at stake. To realize the full advantages of AC modules, microinverters must be designed for reliability at the outset. Component technologies must be selected that can withstand the harsh environments of a rooftop application. Only then can a best practices approach to testing and manufacturing yield management produce a microinverter that is worthy of factory integration with a PV module.