



Reliability of Enphase Micro-inverters

The overriding philosophy at Enphase Energy is that quality and reliability cannot be tested into any product - they must be part of every aspect of the business.

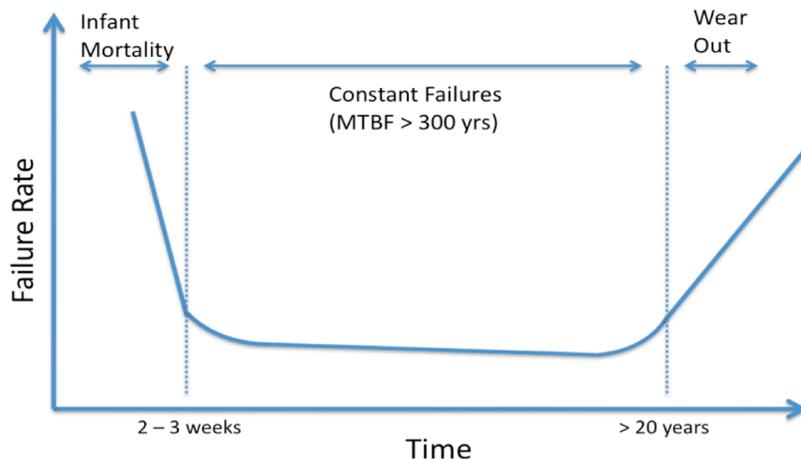
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Summary

The current generation of Enphase Micro-inverters has a Mean Time Between Failures (MTBF) of over 300 years. The concept of MTBF is often confused with a component's expected useful life. This paper describes MTBF as it relates to the Service life of the product, Infant Mortality Failures and Wear Out, and also describes the standards and techniques used in estimating these failures.

Introduction

All products when deployed in large numbers exhibit a characteristic failure rate curve over their service life similar to that shown below. This is known as the Bathtub Curve due to its characteristic shape. The curve can be divided into three different segments according to the types of failures: early failures (known in the industry as Infant Mortality Failures), Constant Failures and Wear Out. The Enphase Micro-inverter also exhibits this typical failure curve.





Infant Mortality Failures

This area of the curve represents the quality of the manufacturing process and these failures typically manifest themselves very soon after installation. The duration of this period in which Infant Mortality occurs is ascertained by analyzing field data. In the case of the Enphase Micro-inverter, it has been our experience that if Infant Mortality occurs, it typically occurs within two to three weeks of installation.

In order to ensure that Infant Mortality is minimized, every Enphase Micro-inverter undergoes extensive testing during manufacturing including Visual Optical Inspections, Functional Test, and System Test. Rather than using generic test equipment, Enphase made the decision to develop custom test stations in order to subject every Micro-inverter to a rigorous manufacturing test standard.

Enphase analyzes each field failure and applies rapid corrective action to an already strictly-controlled manufacturing quality process. In this manner, there is a continual improvement in Infant Mortality.

Wear Out

The Wear Out mechanism dictates the useful service life of any product. Wear Out causes an increasing failure rate at the end of the useful service life of a product. The service life of the product is therefore dictated by the level of field failures that become objectionable to the user and operator of the product.

Estimating Wear Out

The Enphase Micro-inverter has been designed for a service life of over 20 years. The Wear Out segment of the curve is a representation of the longevity of the construction and component choices of the product for the designed operating environment. There are various methods to determine the onset of Wear Out of a product. The most obvious method would be to observe failure over the duration of interest of previous generations of similar products and use failure data to model the failure mechanisms of the new product.

For entirely new products with long service life goals such as the Enphase Micro-inverter with its service life design goal of greater than 20 years, this is not practical. The second method is to subject the new design to a theoretical study by evaluating Wear Out of each component based on data provided by component vendors. The third and most practical method is to subject the new product to an Accelerated Lifecycle Test, which simulates the entire service life of the product in an extremely short period of time.

Enphase uses the Accelerated Lifecycle Test (ALT) method to estimate Wear Out. One of the techniques used is to subject the Enphase Micro-inverters to a group of extremely stressful environmental tests as prescribed by the test standard known as IEC61215. This is the same test standard used by solar module vendors to determine the modules' Wear Out period. Three key tests are performed over a period of 110 days as noted below.

During all three tests, the Micro-inverters are operated at rated power. The tests are conducted on the same unit and are done sequentially. One caveat is that such ALT tests do not simulate effects of UV rays on the device. Enphase believes that the effects of UV on the Micro-inverter are not significant since the product is installed underneath the module and the wiring used is UV rated. All new Enphase designs are subject to these IEC61215 tests in order to estimate their Wear Out.

First Test

The first test is conducted over a period of 10 days where the product is cycled over a temperature range from -45°C (-49°F) to +85°C (185°F) at 85% relative humidity. During the low temperature part of the test cycle, the product is subject to hard freeze.

Second Test

The second test is conducted over a period of 50 days where the product is cycled over a temperature range from -45°C (-49°F) to +85°C (185°F).

Third Test

The third test is also conducted over a period of 50 days where the product is subject to a constant 85°C (185°F).

Mean Time Between Failures (MTBF)

MTBF is not an indication of the actual service life of a product, but is rather an indication of the statistical probability that a unit will fail under specific operating and environmental conditions during the period defined by the MTBF.

The MTBF is, in turn, related to the failure rate in the constant failure segment part of the bathtub curve between the Infant Mortality and Wear Out segments. This segment of the curve is a representation of the reliability of the design for the chosen operating environment. The MTBF evaluation for Enphase Micro-inverters was done theoretically under the guidelines of the *Telcordia SR332* standard. This is the standard that is applied to determine MTBF for telecommunications equipment deployed in outdoor environments similar to those in which the Enphase inverter is installed.

As the bathtub curve indicates, just because a deployed unit has survived Infant Mortality, it does not guarantee that all units fielded will last until the onset of Wear Out. As the curve indicates, there will continue to be a small rate of failures until the onset of Wear Out. These are random statistical failures. The larger the MTBF number, the fewer the failures due to random events. Enphase Energy has succeeded in minimizing these random failures via packaging design, thermal management, and by significantly integrating semiconductor technology into the design of the Micro-inverter.

The concept of MTBF (Mean Time Between Failures) is often confused with a component's expected useful life. In fact, these concepts are not the same. For example, a battery may have a useful life of four hours and have an MTBF of 100,000 hours. These figures indicate that in a population of 100,000 batteries there will be approximately one battery failure every hour during its four-hour lifespan.¹

¹ High Availability Fundamentals - **Sun Microsystems, Inc.**

One way to look at the Enphase Micro-inverter MTBF rating of more than 300 years is to compare it in context of MTBF ratings for other common devices and solar equipment:

Device	MTBF
Traditional central or string inverter	10 - 15 years
Disk drive in a personal computer	57 years
Enphase Micro-inverter	>300 years
Solar panel/module	>600 years
Solid state memory (used in computers)	800 – 1000 years

Relx, a respected reliability engineering company that performs reliability testing for organizations such as Boeing and the U.S. Military, determined the Enphase Micro-inverter MTBF of greater than 300 years.

System Availability

One of the key benefits of an Enphase Micro-inverter System is that it eliminates the single point of failure resulting from deploying a central or string inverter. Since all the PV modules and associated Micro-inverter are all connected in parallel and each of these pairs acts as an independent energy producer, the failure of a single module or Micro-inverter does not affect the performance of the rest of the modules. While there are more inverters in a given installation compared to a single central or string inverter, the high MTBF of each of the Micro-inverters, combined with the parallel connection, ensure that there is a very high level of system availability. In large commercial systems, it has been shown through simulation that system availability of greater than 99.8 percent can be achieved compared to 95 to 97 percent for a central or string inverter.

Why Enphase Micro-inverters Have Such High MTBF

The distributed architecture of the Enphase Micro-inverter System provides the foundation for various design features that enable high reliability:

Components Unlike traditional inverters that process many kilowatts of power at very high DC input voltages, Enphase Micro-inverters process low amounts of power at low DC input voltages, thereby reducing component stress. In addition, processing low amounts of power enables a high degree of semiconductor integration, thereby dramatically reducing the number of components; semiconductor components have extremely high reliability.

Thermal Footprint Because micro-inverters only process a small portion of the power of the entire PV array, the internal temperature rise for any one micro inverter is small, in the order of 5° to 15° C. This reduction in thermal cycling, and the use of passive cooling rather than a cooling fan, significantly reduces component stress.

Enclosure Rating The Enphase Micro-inverter has been rated to NEMA 6. The test for NEMA 6 is that the unit is submerged under a meter of water and must operate for 24 hours. Traditional inverters are typically rated to NEMA 3R which allows for the intrusion of dust, external air, water and possibly insects (i.e. pad-mount transformers are NEMA3R rated). A NEMA6 rating ensures the device is hermetically sealed from any environmental intrusion.

Potting The Enphase M190 Micro-inverter is a potted design. This means that the internal chamber of the enclosure is filled with an encapsulating compound. This extends the life of the device through improved heat dissipation and component protection.

One important metric is to verify theoretical predictions with field failure rates. One of the advantages of an Enphase system is that each and every Micro-inverter is capable of transmitting its performance data to the Enphase servers. Enphase continually monitors this performance and uses it to corroborate field failure rates with theoretical predictions.

Conclusion

Considering the negative impact of historically high inverter failure rates on installers and customers in the solar industry, Enphase knew that a successful new micro-inverter technology must have unparalleled reliability. Enphase chose MTBF as one of the key metrics to use to predict reliability. The company also chose test methodologies used in the telecommunications industry (which has some of the highest availability standards in the world) and to invest heavily in developing specialized test equipment to support these extra-rigorous standards.

The result of this fixation on reliability is an inverter technology that exhibits an order of magnitude improvement in MTBF compared to existing inverter technology. This improvement was enabled by the integration of semiconductor technology, by controlling the environmental exposure of the components, and precisely managing thermal elements. Enphase continues to focus on reliability improvements with each successive generation of inverter, with the goal of reaching an MTBF of 600 years, comparable to PV modules.