A BLUEPRINT FOR HIGH SMART INVERTER RELIABILITY

Paul Garrity , Aaron Jungreis, KIWI NEW ENERGY

Introduction

This product reliability white paper discusses the KIWI NEW ENERGY (hereafter called "KiWi") approach to smart-inverter reliability assessment and also presents reliability performance data. In isolation, such data become nothing more than a snapshot of the smart-inverter's performance at a particular point in time, but at KiWi they form valuable information that is fed back into the design process so that it can be used to continuously improve smart-inverter design. In the photovoltaic industry product reliability is particularly important, as market concerns drive a constant demand for the smart-inverter's life to align with that of the solar panels from which they harvest power. Product warranty contributes somewhat towards alleviating any reliability concerns, but this comes with a proviso, as warranty commitment has to be aligned with a product life that is not only claimed, but can also be demonstrated.

To achieve high smart-inverter reliability, KiWi employs a Design for Reliability process, which is a systematic program that is executed to ensure that high reliability is weaved into the total product development cycle. The key points in ensuring the success of this process are:

- Reliability is always designed into smart-inverters and all associated processes using the best available science-based methods.
- While it is important to present reliability metrics, KiWi understands how to achieve high reliability, which is equally, if not more, important.
- The deployment of reliability engineering practices begins early in the micro-inverter design process and is well-integrated into the KiWi product development cycle.

Given the complexity of solar smart-inverters, it's essential that a Design for Reliability philosophy is incorporated into the smart-inverter design, something that will become evident from reading this paper. To start with, let's take a look at the KiWi smart-inverter.

The KiWi Smart-inverter

It is a compact unit that is installed on the back of each solar module, converting direct current to alternating current for connection to the electricity grid without the need for a string or central inverter. The AC output from the micro-inverter is synchronized and in-phase with the electricity grid (although KiWi Smart-inverters offer the option of providing VAR correction by changing the phase of the AC output from the electricity grid voltage), a solution that provides several distinct advantages:

- **Optimal energy harvest:** It maximizes the power that is harvested from each solar module and consequently the entire PV array by performing Maximum Power Point Tracking (MPPT), an electronic control technique that ensures that the power harvested from each module is maximized, despite the variable nature of environmental conditions and the presence of partially shaded conditions. **This approach typically results in improved power harvest of 5% to 20% from the PV system.**

- **Improved safety: Because the power is converted from DC to AC at each individual solar module, high voltage DC wiring is eliminated.** This results in the solar PV system being intrinsically safe and removes any need for specialized DC practices or equipment during installation.
- **Increased lifetime and reliability**: his eliminates the single most common cause of failure in any solar PV system, which is the string or central inverter. These can be expected to be replaced at least once over the life of the solar panel to which they are connected. **KiWi solar smart inverters have been designed to be highly reliable and to have a life expectancy of 25 years, which matches the life expectancy of solar panels.**
- **Enhanced monitoring capability**: Monitoring the performance of the PV array is significantly enhanced, as each module's performance can be viewed in real time, a capability that is not available with string inverters. The information that is obtained from each smart-inverter can then be used to promptly detect performance issues and pinpoint the exact location and nature of any problem, which provides precise guidance should maintenance be needed. **This is a capability that is made possible by equipping each smart inverter with a robust built-in wireless communication system that connects to the internet via a gateway to provide detailed performance information online.** This information is available on any web browser, including on cell phones.
- **Simplified PV array design and installation**: For rooftop installations, solar modules can be installed in any available space, resulting in ease of design of the PV array. This is a significant advantage over conventional inverter installations where the design of the PV array module placement can be complicated by shading issues. **This makes solar systems easier, faster and cheaper to install.**

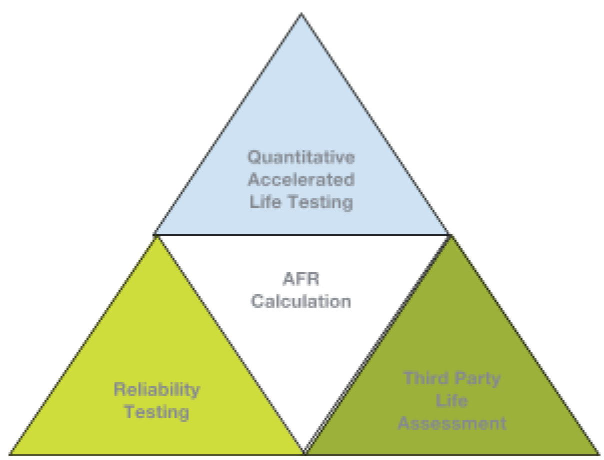
The KiWi smart-inverter design employs an energy storage topology that avoids the use of any limited life components such as electrolytic capacitors or opto-isolators. Low stress levels are maintained on all components, providing additional capacity for higher currents and voltage, and ensuring that stress-related component failures are eliminated. These key characteristics play a vital role in ensuring that KiWi smart-inverters have high reliability, are capable of providing full output power and have high efficiency across an ambient temperature range of -40°C to +85°C.

To provide protection against dust and water ingress KiWi smart-inverters are tested to IP68. IP codes, or to use the full term, International Protection Rating codes, use two digits as defined in IEC-60529 to classify the degree of protection that electrical enclosures have against the intrusion of solid objects, dust and accidental contact and water. During the water ingress test, powerful jets of water are trained on the enclosure from multiple directions for 3 minutes with a volume of 100 litres per minute at a pressure of 100 kN/m^2 from a distance of 3m.

The KiWi reliability engineering approach

The KiWi reliability engineering process subjects smart-inverters to a range of tests and analysis, the data from which is then used to identify reliability improvement opportunities and to determine product life. The foundation of any reliability engineering program is one of extensive product testing, as this enables valuable data to be collected under a range of operating conditions that are carefully controlled and monitored. The KiWi suite of reliability tests are designed to ensure product robustness, with the focus changing at different points in the product life cycle. The overriding goal is to ensure that all data is obtained under similar conditions so that a direct correlation can be obtained between laboratory-based testing and micro-inverter performance when installed in a PV system.

The KiWi reliability engineering process implements a proactive four-segment strategy to reliability test and analysis, each segment differing from the others, but being complementary and having a particular focus. It begins with reliability testing that is qualitative in nature, but which ensures the micro-inverter will withstand the environmental stresses that it will be subjected to in a solar PV system. An independent third-party assessment is then undertaken to validate the smart-inverter life and verify that the design is robust. The results from these two stages are then feed into a calculation of annualized failure rate to determine whether the reliability target has been achieved. The final phase focuses on a quantitative accelerated life test that is performed over an extended period of time, as this provides a verification of earlier reliability conclusions and enables the micro-inverter life under a range of PV system conditions to be accurately determined. The fundamental process strategy is for each segment to build on those conducted previously to gain greater confidence in the projected reliability metrics over time.

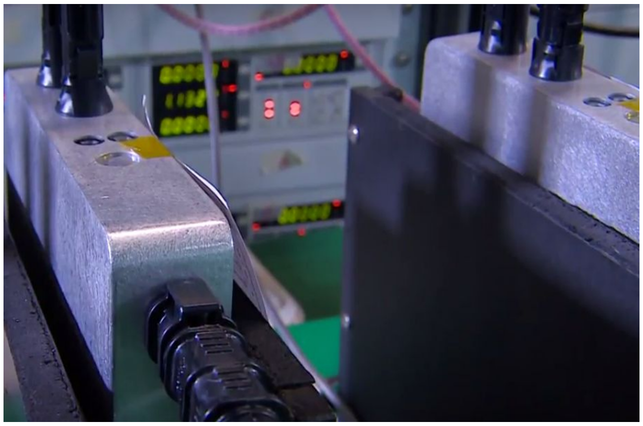


The KiWi reliability pyramid

The KiWi reliability pyramid illustrates these four distinct phases. Let’s take a look at each in turn.

Reliability Testing

This phase consists of a thorough test regimen, which is standard for each smart-inverter. Of particular importance here is that product reliability is often proportional to the degree of design margin that is present beyond the design specification. This is factored into the micro-inverter design, and by way of an example of this, KiWi has an internal requirement that each micro-inverter operates without any performance degradation for a minimum of 500 thermal cycles as conducted per IEC-61215, which significantly surpasses the standard requirement. During this phase, Highly Accelerated Life Testing (HALT) is also deployed, which is key to achieving high product reliability as any failures that occur during this test will likely also occur when the micro-inverter is installed in a solar PV system. It's crucial that latent failure modes are discovered at an early stage in the smart-inverter development process, as this enables them to be addressed during the product design, thus continuously improving the micro-inverter reliability as the design matures.



A KiWi smart-inverter undergoing HALT

During HALT, a range of different stresses are applied to the smart-inverter – hot and cold temperature steps, incrementally increased vibration stress, rapid thermal cycling and a combined temperature and vibration stress that is increased in a stepwise manner. There are many case studies that support the fact that failures occurring during HALT will also occur at some time during the product's end-use, so the object here is to discover and eliminate these failure modes, and further improve the smart-inverter's reliability.

The difference between the micro-inverter's operational specification and the failure thresholds as detected during HALT represents its design margin, or alternatively expressed, its guard band, and the greater this guard band is the more reliable the micro-inverter becomes and the lower the annualized failure rate (AFR) becomes. AFR determination will be focused on at a later stage in the smart-inverter's development to confirm whether the established target has been achieved.

Reliability Test results

Smart-inverter: GT320S		
Activity	**Test Procedure**	**Result**
Highly Accelerated Life Test	KiWi-DOC-103	<-80°C to <130°C 40Grms
High Temperature Operating Life	85°C 3 months	TBD
Mechanical shock	BS EN 60068-2-27: 1993 Test Ea	No issues observed
Random vibration	BS EN 60068-2-64: 2008 Test Fh	No issues observed
Damp heat steady state (non-operational)	BS EN 60068-2-78: 2002: Test Cab	85°C/85% RH 1000 hours, no issues observed
Thermal shock	BS EN 60068-2-14: 2009: Test Na	1000 cycles -40°C to +85°C, 30 min dwells, <10 sec transfer rate. No issues observed
Water and dust ingress	IP66	No issues observed
Salt spray	BS EN 60068-2-11:1999: Test Ka	Inspection deemed enclosure to not be severely affected by salt spray
Thermal cycling	IEC-61215 and IEC 62093	PASSED

Summary of reliability test results for GT320S smart-inverter

Smart-inverter GT300		
Activity	**Test Procedure**	**Result**
Highly Accelerated Life Test	KiWI ENEC-DOC-103	PASSED
High Temperature Operating Life	85°C 3 months	PASSED
Mechanical shock	BS EN 60068-2-27: 1993 Test Ea	No issues observed
Random vibration	BS EN 60068-2-64: 2008 Test Fh	No issues observed
Damp heat steady state (non-operational)	BS EN 60068-2-78: 2002: Test Cab	85°C/85% RH 1000 hours, no issues observed
Thermal shock	BS EN 60068-2-14: 2009: Test Na	1000 cycles -40°C to +85°C, 30 min dwells, <10 sec transfer rate. No issues observed
Water and dust ingress	IP66	No issues observed
Salt spray	BS EN 60068-2-11:1999: Test Ka	Inspection deemed enclosure to not be severely affected by salt spray
Thermal cycling	IEC-61215 and IEC 62093	PASSED

Summary of reliability test results for GT300 smart-inverter

Third-Party Life Testing

This is the second phase of the KiWi reliability engineering program, the intent of which is two-fold. Firstly, a detailed and in-depth assessment of all parameters that can affect the smart-inverter's reliability is undertaken to determine what the expected life of the smart-inverter will be when installed in a solar PV system. Secondly, independent performance assessment provides KiWi customers with confidence that the smart-inverter reliability has been verified by an unbiased, knowledgeable test provider rather than being based on in-house acquired data in isolation, thus enhancing KiWi's market credibility.

This phase is essentially a verification of the conclusions that have already been obtained from internal analysis, but as with any test or analysis activity, it also provides a valuable opportunity to discover possible issues that, when addressed, can be used to further improve micro-inverter reliability. Product reliability is never a given, it demands a great deal of design effort and due diligence to achieve reliability targets. Different micro-inverters may all have similar claims regarding their reliability and may even exhibit identical performance when they are initially installed in a solar

PV system, but over time their performance may differ significantly. By including third-party life assessment in our reliability engineering program we can be confident that our long-term smart-inverter performance is not just predicted, but is fully understood and independently verified.

Before concluding this section it would be appropriate to take a look at the MTBF (Mean Time Between Failures) prediction, which is one of the activities that is conducted during assessment, as it helps estimate the life of the KiWi smart-inverter. Similar to any other form of reliability test or analysis, its real value lies not just in determining whether a reliability target has been achieved, but also the input it provides back into the design process, as this enables any components that have excessively high failure rates to be identified. Because of the mathematical approach that is used to produce an MTBF prediction, this practice often provides a pessimistic reliability metric, and as such returns a worst-case failure rate. Here the actual MTBF number is of less value than it returning a Pareto of component failure rates, which enables “what if” analysis to be conducted and potentially unreliable components to be removed from the design.

When conducting an MTBF prediction, KiWi uses the Telcordia SR332 standard, which is also commonly used in the telecommunications industry to determine the theoretical reliability of systems deployed in outdoor environments, and so lends itself perfectly to the analysis of outdoor installed micro-inverters.

Annual Failure Rate (AFR) Calculation

This is a recent and exciting development in the field of reliability engineering that is being deployed by KiWi for the very first time in the solar PV industry, positioning KiWi firmly at the forefront of reliability engineering technology. AFR calculation enables an accurate micro-inverter annual failure rate to be determined based on the test results obtained from HALT and MTBF prediction. This represents an immediate improvement over obtaining a calculated AFR using MTBF prediction in isolation, as life distribution assumed by the MTBF prediction might be inaccurate, and cannot take into account the smart-inverter’s design margin. This puts to work the information that has been obtained from the reliability engineering program so far.

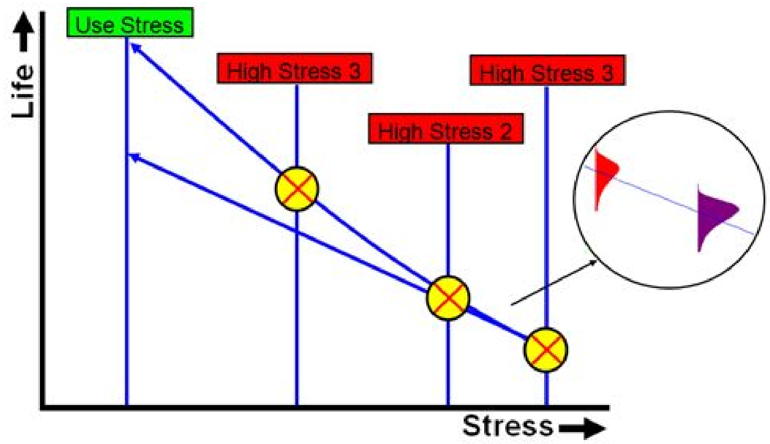
The AFR of the GT320S smart-inverter has been calculated as 0.22%, while the AFR of the GT300 smart-inverter has been calculated as less than **0.1**%.

Smart-inverter: GT320S			
Duration	**Reliability**	**Duration**	**Reliability**
1 year	99.88%	10 years	98.78%
2 years	99.75%	15 years	98.18%
5 years	99.39%	20 years	97.58%

Projected reliability for the GT320S smart-inverter

Quantitative Accelerated Life Testing (QALT)

By far the best method to predict product life and verify that the smart-inverter will actually meet its life target is the Quantitative Accelerated Life Testing, as it promotes smart-inverter wear-out and as a result enables the validation of reliability metrics that have already been obtained using other techniques. Unlike more conventional accelerated life tests that use a single stress, such as that mandated by IEC61215, KiWi QALT uses multiple stresses, such as temperature, humidity and micro-inverter power. Determining micro-inverter life at each individual stress condition allows an accurate product-specific life-stress relationship to be determined that can be used to accurately model the anticipated micro-inverter life in a solar PV system; the following graphic demonstrates this fact.



Example life-stress relationship

If an accelerated life test is conducted at a single stress level, it would be impossible to extrapolate between life at the stress condition and field life, as an infinite number of gradients could potentially be used to link the failure point with the life axis. If two stress levels are introduced, a gradient can be defined, but the life-stress relationship has to be assumed to be linear, but if the micro-inverter is subjected to three or more stress levels, then an accurate life-stress relationship can be obtained.

Manufacturing Reliability

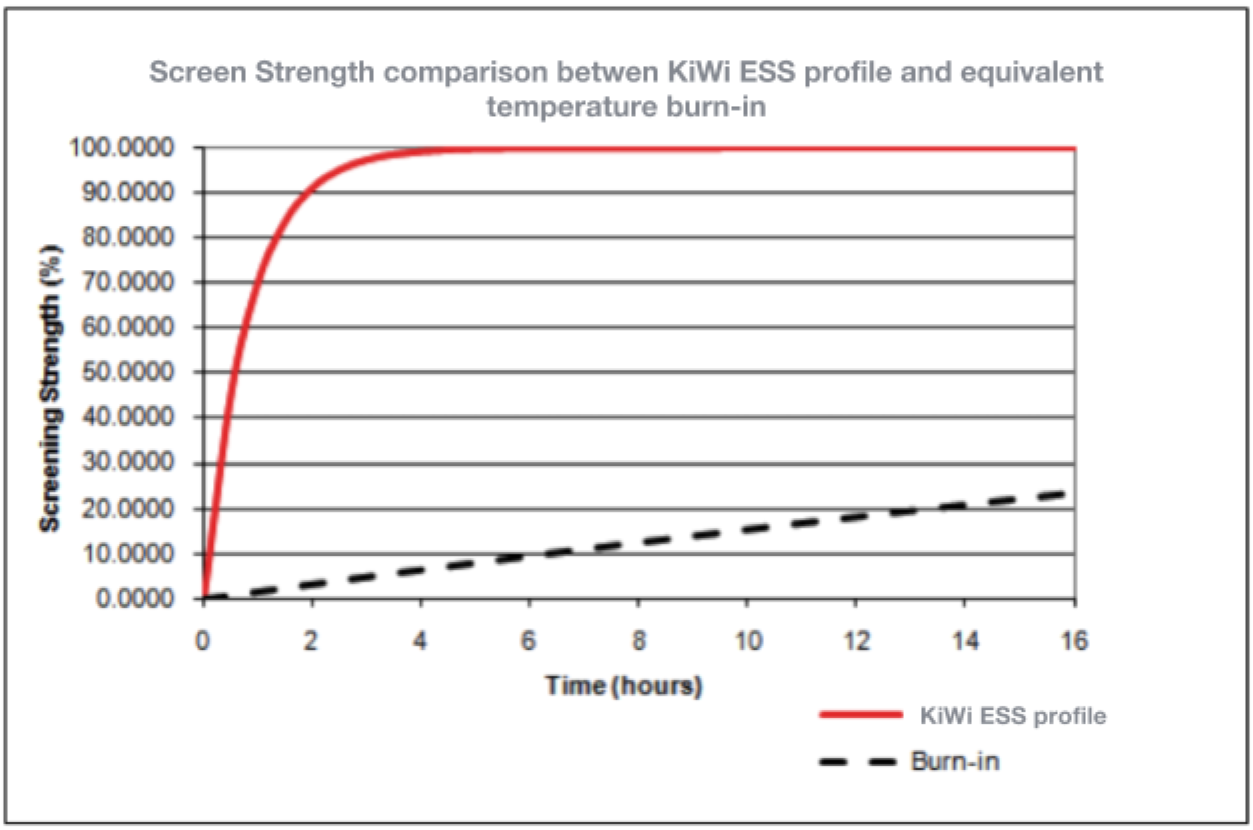
Despite the fact that the reliability target may have been achieved during the micro-inverter development process, product reliability can degrade during high-volume manufacture due to production process issues and component batch defects. Such occurrences often manifest themselves as what is called "infant mortality" failures, which are early life failures that occur shortly after micro-inverter installation. To prevent such occurrences, NEOSEN implements an Environmental Stress Screening (ESS) program.

During the manufacturing process every KiWi Smart-inverter is subjected to Automatic Optical Inspection, two different functional verification tests and an order configuration. All units are also subjected to ESS using customized test racks.

Burn-in is commonly used across multiple industries as a manufacturing screen, which is a technique that was originally popular for products that used vacuum tube technology. For such products, high-temperature burn-in was the best stimuli for precipitating latent defects. Early transistor and integrated circuit technology defects were also efficiently stimulated using high-temperature burn-in. At the time, most product defects were component-related, but as component technology advanced, a much different failure behaviour has become prevalent in electronic products. Components have become so reliable that most product defects are now related to the assembly process. As the product fault spectrum has changed, the screening stimuli for rapid defect precipitation also needs to change to ensure that latent defects are efficiently stimulated to an observable failure.

It is for this reason that KiWi uses an ESS profile that includes rapid thermal cycling and random power cycling, as these are more effective than burn-in for precipitating process-related defects from latent to patent. Conducting this form of screen relies on the micro-inverter already being capable of surviving the high stimulation levels that are needed to accelerate failure mechanisms of assembly-related defects, which is verified by establishing acceptable guard bands using HALT. Prior to implementing the ESS regimen the profile is validated using a proof-of-screen process, which first verifies that failures can be detected in units that have already been "seeded" with defects. Following this initial verification, the proof-of-screen is continued to verify that the ESS will not remove significant micro-inverter life.

A comparison between the KiWi ESS profile and burn-in using the same maximum absolute temperature is provided below. It can be seen that after only four hours of running the ESS profile, the screen strength is at 99%, compared with burn-in which has a strength and thus a probability of precipitating process-related defects of less than 10%.



Comparison of KiWi ESS profile screen strength with constant temperature burn-in

CONCLUSION

This paper briefly outlines some of the techniques that KiWi uses, which constitutes a solid reliability engineering program, but by far the most important aspects of this program are feeding back information into the design process and obtaining an independent performance assessment to ensure that micro-inverter reliability is not just proven internally, but is also verified by an unbiased knowledgeable external test provider.

Because the life of the micro-inverter has to be comparable with that of the solar panels from which they harvest power, it must be designed, tested and analyzed utilizing proven reliability engineering principles. The use of an MTBF metric in isolation to other analysis and accelerated test techniques is inadequate as it can possibly be misleading, although this technique does deliver value when integrated with other complementary reliability engineering activities and is used to identify components that have a theoretically high failure rate.

One of the most challenging aspects of any reliability engineering program is modeling the transition from the reliability data obtained from in-house testing to the reliability data obtained from the performance of the micro-inverter in a solar PV system. This creates a difference in results that needs to be bridged, which requires a great deal of data manipulation and mathematical analysis, but the multiple-segment strategy employed by KiWi enables models to be developed that allow for the mapping of in-house reliability data to make accurate predictions of field performance. The KiWi reliability strategy also enables collected data to be used to implement a continuous reliability engineering improvement process.

In recognition of the demand for high smart-inverter reliability, KiWi continues to make significant investment in reliability software, lab test facilities and the infrastructure needed to effectively screen micro-inverters during the high-volume manufacturing process. This underlines KiWi’s commitment to continuously improving smart-inverter reliability and being positioned firmly at the forefront of micro-inverter reliability engineering technology.