Reliability of large-scale PV plants and PV inverters

Inverter reliability | The renewable energy market is currently booming, with large numbers of PV systems being installed throughout the world. However, a primary objective of any PV power system is to ensure that the system operates continuously and reliably. As Vicente Salas from the Universidad Carlos III de Madrid (UC3M) explains, this aspect takes on special relevance in the case of utility-scale PV projects

Figure 1. Inverter reliability is a vital aspect of ensuring the expected performance of a PV power plant.

Reliability is a key risk in any project, including PV plants, but the risk is more significant in the case of large-scale PV plants, where the cost of the project is high. In those projects, where the typical design target lifetime is around 25–30 years, there is a discrepancy between the lifetime of the PV inverters (5–10 years) and of the PV modules (20–25 years). In addition, while inverter interconnection, performance and safety standards exist, there are no well-established reliability standards. A reliability evaluation (simulation and test) must be carried out in order to observe failures of PV inverters and to better understand their failure modes and lifetime characteristics. From this it will be possible to guarantee the lifetime of the inverter. Clearly, PV inverter reliability has an impact on life cycle cost, and is therefore an important aspect to address.

For large-scale PV plants, financing is very important and complex, and involves many different parties, including developers, landowners, utilities, grid operators, government agencies and financing institutions. PV projects are a financial investment, which means they are all about returns. Additional operations and maintenance related to PV inverters, however, can erode returns.

As shown in Fig. 2, many tasks – both technical and non-technical – are involved in the financing process of any PV plant; the plant viability is linked not just to the technical tasks but to all the tasks as a whole. The objectives of any utility-scale PV project include:

- Establishing a trade-off between risk management and crisis management.
- Implementing a long-life power plant, with high energy yield and availability.
- Operating correctly and safely, in compliance with the relevant requirements.
- Keeping costs low and achieving a high return on investment.

Nevertheless, a profitable, reliable PV project is only possible if its components are reliable.

It is clear that a PV power system consists of many vulnerable components whose life cycle reliability is highly sensitive to temperature, power losses and ambient environments. This can lead to high electrical stress, as well as to temperatures in PV modules as high as those in power electronics converters; this may shorten the operational life cycles and consequently result in lower system reliability compared with conventional generation sources. Damage, defects and failures of the equipment and elements therefore affect PV plant production during the exploitation phase (Fig. 2).

The non-functioning of some element of the plant is a sensitive issue from the financial point of view. The PV inverter is always a critical component in the PV system, and for many years the inverter was one of the components most responsible for failures. Fortunately, PV inverters have improved, thanks above all to the advances made in power electronics, and today these products are more reliable. To increase availability and secure maximum return on investment, a PV system requires high PV inverter reliability in order to reduce downtime and ensure regular power generation.

PV module technology has also continued to improve: the robustness of modules is evidenced by the standard 20- to 25-year warranties that accompany most PV modules today. Thus, it is reasonable to expect that the PV system inverters

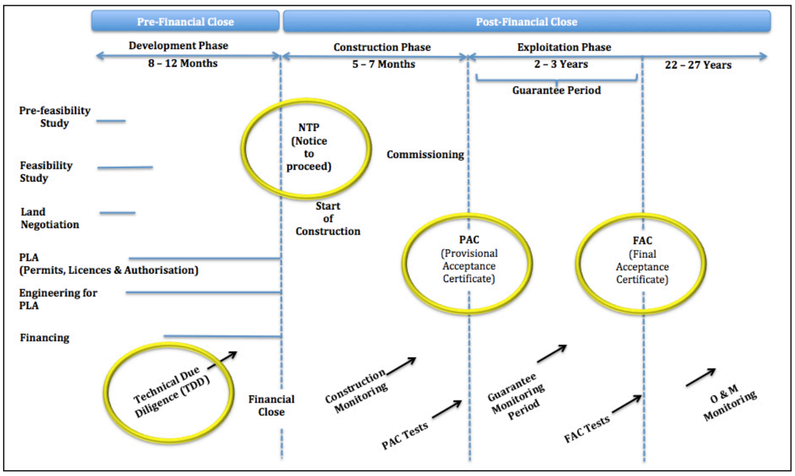

Figure 2. Stages of a typical utility-scale PV plant.

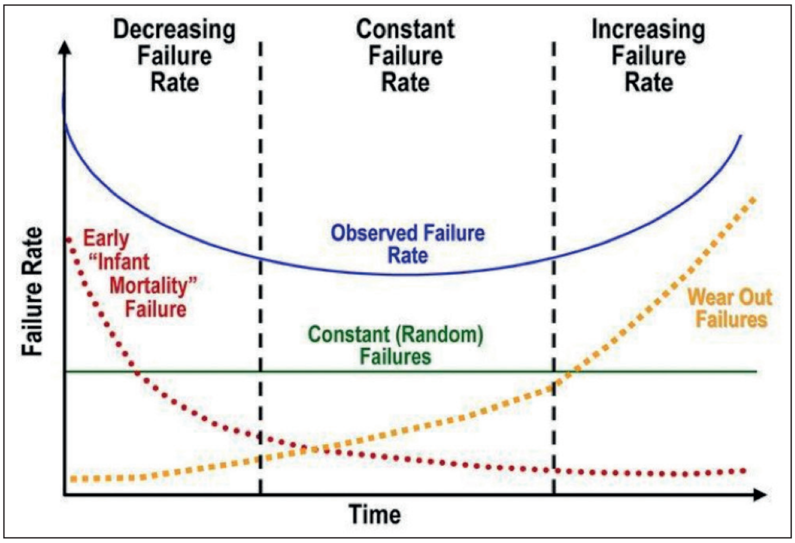

Figure 3. The bathtub curve, describing the correlation between failure rate and time.

have a comparable service life. However, although inverters have made progress over the same period of time, it has only been modest: manufacturers today offer inverter warranties of only 10–15 years, which means that replacement is necessary long before any other components of the PV system.

Failures in PV inverters

Three types of inverter failure can be distinguished: unplanned failure (where the equipment has failed in normal operation and was not expected to fail), planned failure and repeat failure. The most critical, and the most difficult to predict, is the unplanned failure, which can happen at any time. Different factors can cause such failure:

- Latent internal causes that existed in the product from the beginning (predispositions).
- External stressors, such as heat and humidity of the installation environment (external causes).
- Degradation with time.

These unanticipated interruptions will result in a significant amount of economic losses, and are a potential risk (financial risk). The bathtub curve, shown in Fig. 3, expresses the correlation between failure rate and time.

In addition, from the point of view of time, failures can be classified (according to the time of occurrence) into three regions:

- Early failures (initial or 'infant mortality' failures)
- Intrinsic failures (random failures)
- Wear-out failures

Early failures are failures that occur relatively soon after the beginning of operation; the main causes of these initial failures are manufacturing or material defects. The failure rate in this phase decreases over time.

Intrinsic failures are failures that occur at a fairly constant rate after the initial-failure period, until wear-out failures start to occur. The majority of electronic components fail at a constant failure rate during this random-failure stage.

Wear-out failures are failures that are caused by wear and fatigue, and occur because of the physical limits of the materials. The failure rate in this phase increases over time.

In order to achieve a highly reliable system, it is important to reduce the initial failure rate, provide a low rate of intrinsic failures, and ensure that wear-out failures begin to occur only after the system's useful lifetime ends.

Product life cycle

Product defects and failures can be anticipated by managing the product life cycle (PLC). All manufactured products have a limited lifetime, and during this lifetime they will pass through four PLC stages: introduction, growth, maturity and decline. In each of these stages manufacturers face a different set of challenges. PLC management is the application of different strategies to help meet these challenges and ensure that, whatever stage of the cycle a product may be going through, the manufacturer can maximise sales and profits for their product.

Historically, the quality and reliability of products has been approached in different ways. For many years manufacturers paid little attention to historical failures; they assumed that quality and reliability groups were responsible for quality and reliability. Moreover, manufacturers assumed that the product design did not significantly affect quality and reliability, and that quality and reliability failures were not caused by manufacturing and suppliers. However, that approach has now changed, and a revised reliability concept is already beginning to be applied. As mentioned earlier, PV inverter reliability affects life cycle cost, and therefore needs to be dealt with [1].

Reliability management process

The reliability of a PV inverter depends on the reliability of each of its components (for example, semiconductor and soldering failures lead to inverter failure), which is illustrated in Fig. 4. Unfortunately,

> "PV inverter reliability affects life cycle cost, and therefore needs to be dealt with"

in general a PV inverter has no parallel redundancy built into it, which means that a failure in any one of its components will lead to an outage of the entire inverter. It must also be taken into consideration that a PV inverter may handle a high level of power flow and operate under high-temperature conditions, which degrades the inverter reliability and increases the risk of age-related component failures [2].

In a reliability management process, the PV inverters should be designed to last the entire life cycle (up to 30 years) of the product; this process should begin with an initial checklist of requirements, and finish with an evaluation of operation in the field. As shown Fig. 5, the reliability management process must <AQ4>take place in parallel with other company processes, such as product definition, development, manufacturing and customer service (field deployment).

The reliability management process utilises individual sub-processes from other processes, but at the same time adds or superimposes unique and challenging elements (e.g. stringent qualification and test procedures for materials, products and processes, as well as advanced methods and tools for failure analysis).

Reliability approach

The reliability approach involves a physics-based multi-level analysis and identification of the failure points. The ultimate goal is a system operational lifetime with a low failure rate, and the only way to achieve this is to utilise a combination of:

- Reliability-oriented design rules.
- Selection of top-tier suppliers and acceptance testing of their components.
- Manufacturing in well-controlled environments.
- Accelerated lifetime testing of the system (and its components) up to the wear-out point in order to determine when the product will fail, at what rate and which failure mechanisms are at fault.

Reliability prediction methodologies

The newest reliability prediction methodology, the so-called *physics-of-failure (PoF)*, emphasises the root cause of failure, failure analysis, and failure mechanisms as the basis of an analysis of parameter characteristics. The procedure involves a focused examination of failure point locations which takes into account the fabrication technology, process, materials and circuit layout obtained from the manufacturer. This methodology is capable of providing recommendations, using intuitive analysis, for increasing the reliability of components.

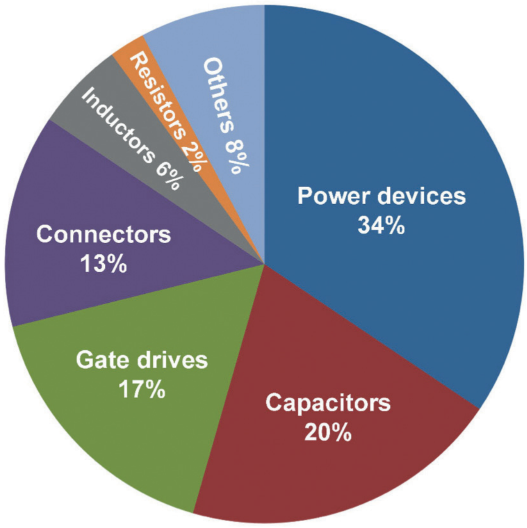

Figure 4. Failure percentages of the most fragile components of electronic power systems. (Taken from an industry survey [2].)

Design for reliability

Reliability should be designed-in from the very beginning of the design phase; this process is referred to as *design for reliability (DFR)*. The DFR process therefore starts from topology selection, circuit design, and component selection and application, and uses a highly accelerated testing method to discover design flaws in the early development stages. The major DFR aspects that should be borne in mind during a PV inverter design include topology selection and design, and thermal design and management [3].

Thermal management

Thermal management is an essential part of the reliability of any electronic system [4] and is even more critical in the case of a PV inverter, which may be required to endure both extremely hot and extremely cold ambient temperatures and daily temperature variations of 30°C or more. Thermal management in commercial PV-powered inverters is accomplished by means of a fully integrated mechanical design that is simple and reliable and which delivers exactly the cooling that is required to each part of the system. Forced convection cooling is used because it provides superior cooling performance at a lower cost, and with less mechanical complexity, than other types of cooling (e.g. liquid cooling).

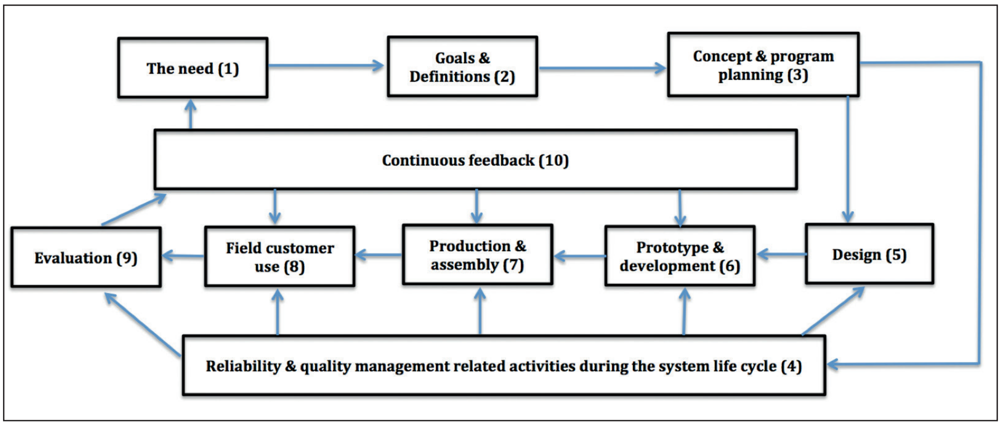

Figure 5. Reliability management process.

Reliability evaluation

A reliability analysis during the design and development of such complex equipment as a PV inverter is important in order to detect and eliminate reliability weaknesses as early as possible and to perform comparative studies. Different reliability evaluation techniques exist for PV systems: they can be classified as either theoretical (simulation tools) or practical (experimental tests). The simulation tool category includes the Markov process method, Monte Carlo simulation, state enumeration method, reliability block diagram and fault tree analysis.

As regards reliability tests, those must be carried out at each stage of development and mass production. When a product is developed, a reliability test will be performed to check the design, material and process; then, during mass production, a reliability test will be performed as a quality-assurance inspection or a failure-rate test for predicting the reliability of the product. The purpose and type of reliability test therefore greatly depends on the device manufacturing stage.

There is a distinction between quality and reliability control. Traditional *quality control* assures that the product will work after assembly and as designed, whereas *reliability* provides the probability that an item will perform its intended function for a designated period of time without failure under specified conditions. In other words, reliability looks at how long the product will work as designed, which is a very different objective from that of traditional quality control. Therefore, certain tools and models can be applicable to reliability but not necessarily to quality, and vice versa.

The reliability test generally has associated time and cost implications. Testing under normal operating conditions requires a very long time, especially for products with long expected lifetimes. The results are only useful for an operating environment which is similar to that in which the tests were conducted; they may not be suitable for predicting the reliability of units operating in significantly different conditions. Alternative methods therefore need to be investigated for 'predicting' the reliability metrics using data and test conditions other than normal operating conditions. The main objective of these methods is to induce failures or degradation of the components, units and systems in a much shorter time, and to use the failure data and degradation observations for these accelerated conditions in order to estimate the reliability in normal operating conditions.

Careful reliability testing of systems, products, and components during the first stage of the product's life cycle (design stage) is crucial for achieving the desired reliability in subsequent stages. During this early stage, the elimination of design weaknesses inherent to intermediate prototypes of complex systems is conducted via the 'test, analyse, fix and test' (TAFT) process. This process is generally referred to as *reliability growth* [5].

Types of accelerated test

Each type of test that has been designated an accelerated test provides different information about the product and its failure mechanisms [6]. Generally, accelerated tests can be divided into three types: qualitative tests, environmental stress screening (ESS) and burn-in, and quantitative accelerated life tests.

Qualitative tests

Qualitative tests yield failure information (or failure modes) only, and have been referred to by many names, including elephant tests, torture tests, highly accelerated life testing (HALT), and shake and bake tests. In the qualitative category, the typical tools are:

- Failure modes
- Effects and criticality analysis (FMEA/FMECA)
- Reliability-centred maintenance (RCM)
- Failure reporting, analysis and corrective action systems (FRACAS)
- Root cause analysis (RCA)

Qualitative tests are performed on small samples, with the specimens being subjected to a single severe level of stress, to a number of stresses, or to a time-varying stress (i.e. stress cycling, cold to hot, etc.). If the specimen survives, it passes the test; otherwise, appropriate actions will be taken to improve the product's design in order to eliminate the cause(s) of failure.

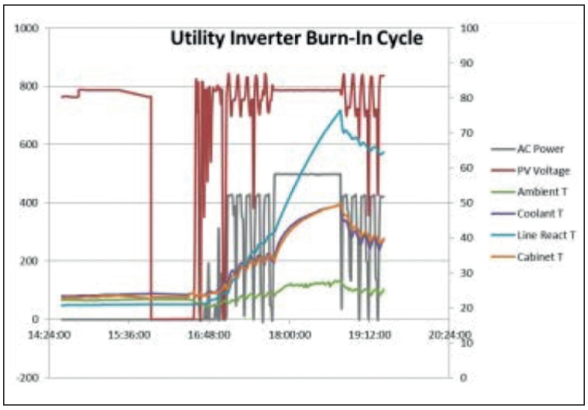

Figure 6. Example of a utility inverter burn-in cycle [7].

ESS and burn-in

The second type of accelerated test is ESS and burn-in testing. *ESS* is a process involving the application of environmental stimuli to products on an accelerated basis; the stimuli can include thermal cycling, random vibrations and electrical stresses. The goal of the test is to expose, identify and eliminate latent defects which cannot be detected by visual inspection or electrical testing, but which will cause failures in the field. ESS is performed on the entire population and does not involve sampling.

Burn-in (Fig. 6) is a test performed for the purpose of screening or eliminating marginal devices, and can be regarded as a special case of ESS. Marginal devices are those with inherent defects, or defects resulting from manufacturing aberrations, that cause time- and stress-dependent failures. As with ESS, burn-in is performed on the entire population. Readers interested in learning more about the subject of ESS and burn-in are referred to Kececioglu and Sun [8,9].

Quantitative test

In the quantitative test category, the typical tools are:

- Life data analysis (a.k.a. *distribution analysis* or *Weibull analysis*)
- Reliability growth analysis
- Accelerated testing (a.k.a. *life-stress analysis*)
- System modelling using reliability block diagrams (RBDs)
- Simulation
- Fault tree analysis (FTA)
- Design of experiments (DOE)
- Standards-based reliability predictions (e.g. MIL-217)

Standards

Design qualification test protocols – such as IEC 61215 and IEC 61730 – have been key to mitigating 'infant mortality' in PV modules, but improvements to these standards are ongoing. They are necessary for ensuring the overall reliability and durability of products going into the field.

The recently published standard IEC TS 62941:2016, Ed. 1.0 ("Terrestrial photovoltaic (PV) modules – Guideline for increased confidence in PV module design qualification and type approval") is a collection of best practices from across the industry. It refers to the basic requirements of ISO 9001, and focuses on PV-specific manufacturing processes and procedures to ensure quality and consistency, and the key metrics and capabilities required for PV. Modules produced in accordance with this standard will be more likely to perform as warranted (25+ years).

A dedicated reliability standard for PV inverters, however, does not yet exist; the standards that do exist – such as ANSI/UL 1741 and IEC 62109 Part 1 and 2 – focus primarily on the safety of PV inverters. Although Ed. 1 of IEC 62093 discusses inverter qualification, it includes all the balance of system (BOS) components. In a new edition of this standard, a well-accepted design qualification standard is being developed specifically for PV inverters that will significantly improve the reliability and performance of these devices. ■

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