Marrying Quality Assurance with Design Engineering – A Winning Partnership! But, a Cultural Divide?

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Marrying Quality Assurance with Design Engineering – A Winning Partnership! But, a Cultural Divide?

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***Abstract* — Investors would like to be confident that a PV plant will work as promised before investing large sums of money. Data showing that PV modules can withstand thousands of hours of accelerated testing are a comfort, but are not sufficient to characterize the economic useful life (EUL) of the whole PV system. An inability to be confident of every aspect of the system can motivate less favorable contract terms. In the end, a winning partnership is obtained when a carefully engineered, durable design is married with a robust quality management system and the marriage is extended across all parts of the value chain. However, this marriage is challenging because of the conventional cultural divide between design engineers and quality management specialists. International standards are being developed to facilitate this partnership and include technology-specific requirements in the quality management systems used for component manufacture and system design, construction and operation.**

I. INTRODUCTION

Excellent quality assurance is important to PV module customers because it can 1) improve upfront performance, 2) decrease degradation rates, 3) decrease operating costs, and 4) decrease safety risks. Achieving the desired final result starts with the design, but it doesn't end there.

Success requires that all elements work as promised from day one to the end of the warranty. However, once the design phase is completed, there can be substantial pressure to implement the design with ultra-low-cost materials, components, and mass production techniques, tempting some companies to neglect partnering the design engineers with quality management specialists. Although the design and implementation phases require different skills, both sets of skills are essential to optimize the final design and manufacturing process to provide a functional product at the lowest cost.

Management of quality assurance becomes even more challenging at the PV system level; where both the design and the quality assurance require that elements be selected to be of high quality, to function well together, and to be easily serviceable in the field. Additionally, the installation process must be optimized to give the best outcome at the lowest cost.

This paper discusses the motivation for increased emphasis on quality assurance and describes three new standards that detail requirements for a higher level of quality assurance for 1) PV module manufacturing, 2) power electronics manufacturing, and 3) control of the system installation and operation. The paper concludes with a discussion of the challenges and benefits of marrying the quality assurance program with further optimization of the PV system design toward the end goal of maximizing the return on investment (nominally, the electricity production relative to lifecycle costs).

II. WHY QUALITY ASSURANCE SHOULD BE PRIORITIZED

There is substantial evidence that many failures observed in PV systems today result from failures in quality assurance during manufacturing of the components, during installation, or during operation of the system.

Figures 1-3 show examples of failures that may have been caused by poor quality assurance. Figure 1 shows two burn marks (inset) imaged from the backside of the module and corresponding delamination on the front (larger image). Only one cell of one module was affected in this residential system, implying that the problem may have been the result of a manufacturing defect that was not identified during manufacturing. Alternatively, the module may have been damaged during shipping or installation. The observation of burn marks for a small fraction of modules has been reported many times. For example, Degraaff, et al, reported 0.3%, 1.5% and 2.9% failure rates for modules made by three manufacturers, respectively [1]. Although the root causes of these failures were not reported, the observation that only a small fraction of modules were affected suggests that the failures could have been avoided by better quality assurance during manufacturing.

Figure 2 shows a catastrophic failure apparently caused by a ground fault. Although this could have been a design problem, the problem was not observed throughout the array, implying that for the affected modules the cells may have been laminated too close to the frame and were not identified at the time of manufacture. The higher DC voltages being used in today's PV systems can lead to need for tighter quality control to avoid this sort of problem.

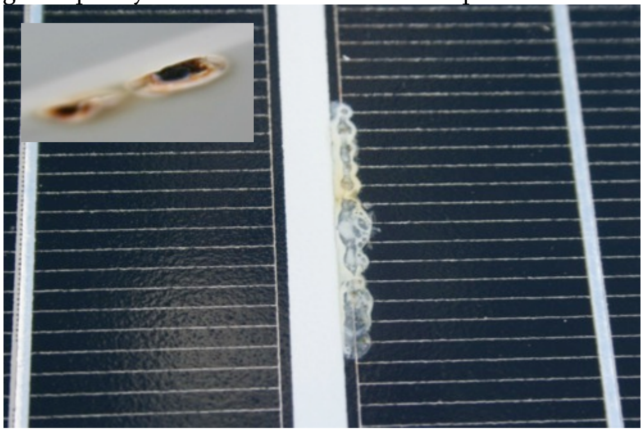

Fig. 1. Quality problem example. The photo shows delamination observed from the front side of the module. The inset shows burn marks on the backside of the module (opposite the delamination).

Fig. 2. Example of problem probably caused apparently by DC arcing between the frame and cells because the cells were too close to the frame to withstand the DC voltage between them.

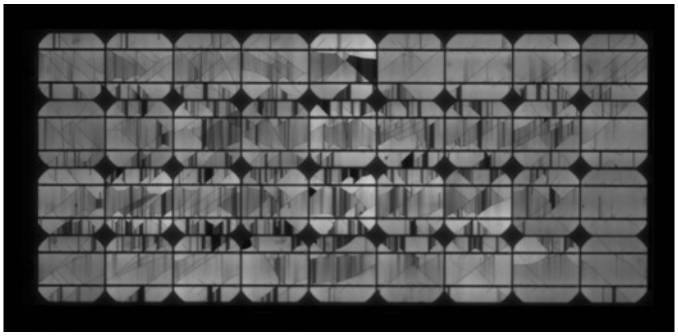

Fig. 3. Third example of apparent problem with quality assurance. The electroluminescent image shows how some parts of cracked cells have become disconnected from the circuit, reducing the power output of the module.

Figure 3 shows an electroluminescent image of a module that was, apparently, damaged (cracking of cells) during manufacture, shipping, or installation, and, after about a year in the field, showed decreased performance, presumably as a result of the pieces of some cracked cells becoming disconnected from the rest of the active circuit [2]. As silicon wafers, module frames, and glass frontsheets have become thinner, reports of cracked cells have increased and this type of power loss (as shown in Fig. 3) has become more common in the field. The extent to which the cracked cells lead to power loss is a subject of research [3]. This issue could be classified as a design problem (e.g. a more robust design might have avoided damage) or a quality-assurance problem (e.g. by controlling the handling process as part of the control plan so that the cells are not broken during manufacture, shipping, or installation). If the cracking is caused by mechanical stress during operation, then the problem is more clearly a design issue. This example underscores the importance of the marriage between the design optimization and quality assurance across all parts of the value chain, as discussed below.

III. KEY ELEMENTS OF NEW SPECIFICATIONS

A. Three specifications

Table I describes the three Technical Specifications that have been or are being developed by the International Electrotechnical Commission (IEC) Technical committee 82 to gain more confidence in quality assurance. Key elements of these are described in the following three sections.

TABLE 1

TARGET PRODUCTS AND ANTICIPATED PUBLICATION DATES FOR TECHNICAL SPECIFICATIONS BEING DEVELOPED BY IEC

Target	**Specification**	**Publication schedule**
PV modules	IEC TS 62941	Released January 2016
PV systems	IEC TS 63049	Anticipated June 2017
Power electronics	IEC TS TBD	Anticipated in 2018

B. PV module quality assurance

The technical specification: IEC/TS 62941 *Terrestrial photovoltaic (PV) modules - Guideline for increased confidence in PV module design qualification and type approval* has been described previously [4,5] and was released in January 2016. This technical specification assumes that the module manufacturer has already satisfied Quality Management System requirements based on ISO 9001 and, hence, describes additional requirements to be included in the IEC/TS 62941 audit including [4,5]:

- Alignment of design lifetime with product warranty,
- Verification of incoming materials to maintain a consistent bill of materials,
- Traceability (so as to notify customers of defective product),
- Ongoing testing program to confirm consistency of design implementation during manufacturing,
- Control of solar simulator calibration for use in determining nameplate power rating,
- Use of statistical methods for monitoring and improving the process, and
- Continual improvement based on field experience.

IECRE is overseeing implementation of IEC/TS 62941 and started accepting applications from Certifying Bodies (for both PV plant inspections and Factory Audits) in 2016. A list of organizations accredited to certify for IEC/TS 62941 may be found on IECRE's website [6].

A set of training materials has been developed to improve the consistency of the interpretation of IEC/TS 62941 internationally. Having been trained with these materials and, later, having participated in peer reviews between the various accredited Factory Auditors, these Auditors can provide consistent implementation of IEC/TS 62941. The validity of IEC/TS 62941 certificates issued by auditors who have not participated on this process is unclear, since the training of these auditors is unknown.

As industry-leading manufacturers demonstrate compliance with IEC/TS 62941, it is anticipated that many more manufacturers will begin to follow, resulting in improvement in PV module reliability worldwide. Careful control of the manufacturing process will become increasingly critical as cost reduction squeezes design margins in coming years.

C. Quality of PV installation and operation

The technical specification: IEC/TS 63049 *Terrestrial photovoltaic (PV) systems – Guideline for effective quality assurance in PV system installation and operations and maintenance* is scheduled for publication in 2017. Similar to IEC/TS 62941, it provides for certification of the organization that is installing or operating the PV system rather than certifying each system separately. However, in contrast to IEC/TS 62941, it does not assume that the organization already has an ISO 9001 certification, so is written to include many ISO 9001 requirements. Key requirements for *installation* include:

- Training of workers,
- Using quality components (switches, overcurrent protection and combiner boxes) that meet relevant standards,
- Ongoing oversight of installation,
- Record keeping and maintaining traceability to enable both learning and correction of mistakes, and
- Tracking of system performance after completion to identify opportunities for continual improvement.

IEC/TS 63049 expects design and installation to be guided by IEC 62548 *Photovoltaic (PV) arrays – Design requirements* and IEC/TS 62738 *Design guidelines and recommendations for ground-mounted photovoltaic power plants*. It requires a final inspection program that is compliant with IEC 62446-1 *Grid connected PV systems – Minimum requirement for system documentation, commissioning tests and inspection* and uses IEC/TS 61724-2 *Photovoltaic system performance – Part 2 Capacity evaluation method* to document initial performance of the completed system.

Key requirements for management of system *operation* are similar, but emphasize continual improvement to reduce the cost of the maintenance and inspection relative to the improved power output while avoiding safety issues. IEC/TS 63049 uses IEC 62446-2 *Grid connected PV systems – Part 2: Maintenance of PV systems* as a guide for defining the maintenance program.

Some PV customers worry that untrained low-cost labor hired to install today's PV systems may be introducing defects. For example, common concerns include (but are not limited to):

- Rough handling of modules (bouncing during transportation, stepping on, dropping, twisting, scratching of back sheets, carrying modules on hard hats, etc.)
- Over/under tightening of assemblies,
- Under tightening of electrical connections, and
- Improper cable management.

Rough handling may crack cells within the module as discussed for the module shown in Fig. 3. Thus, the PV system may perform acceptably at commissioning, but later degrade in performance. Modules that have been dropped or have scratches in the backsheets should be discarded, but some workers may be hesitant to do so. Similarly, over tightening of clamps can lead to broken modules and under tightening of electrical connections can lead to ground-fault problems, Fig. 2. Cables that dangle in such a way that they swing in the breeze may abrade and cables that aren't protected by conduit may be chewed by rodents or otherwise be damaged. These exemplify the many problems that can occur and that are addressed by consistent training and oversight of workers, as described in IEC/TS 63049.

For rapidly evolving PV technology, a very critical element of quality assurance is continual improvement. IEC/TS 63049 requires not only that the installers check to confirm that the PV plant is constructed to meet the design, but that they track the performance of the plant during years of operation. As noted above, failures caused by some installation mistakes may show up after months or years of operation. This requirement may be difficult for installers who usually have no access to the plant after completion. However, while IEC/TS 63049 does not require access to the raw data, it requires confirmation that the plant is performing as designed and without failures over a specified time period. Customers should be reassured by their installer insisting that a mechanism be in place for this information to be communicated.

IEC/TS 63049 describes a different philosophy for quality assurance of the operations and maintenance compared with that for installation. While the goal of the installation process is to approach the 100% metric in assembling the plant correctly, maintenance procedures are designed to optimize the return on investment, which reflects both the electricity generated and the cost of the maintenance. Thus, the goal is to clean the system at a frequency that optimizes the output of the system relative to the cost of the cleaning rather than to strive for cleanliness at all times. Similarly, the frequency of inspection for nests, plant growth, water intrusion, etc., is optimized to balance the maintenance costs with the associated benefits.

The exception to the optimization strategy is when there is a safety risk or preventative maintenance requirement to meet warranty obligations. If delaying maintenance could lead to a fire, an injury (e.g. from a shock hazard), or voiding an equipment warranty, then maintenance is required, even if it increases cost.

D. Quality of inverters and other balance-of-system components

Almost universally, PV system failures are dominated by problems with the inverters. The technical specification: *Guidelines for effective quality assurance of power conversion equipment for photovoltaic systems* is being written to address this problem. It has been submitted as a New Work Item Proposal to the IEC and is expected to be published in 2018. It is largely focused on inverters and is anticipated to emphasize:

- Initial design to provide the desired performance and durability in the expected use environment and to be serviceable (especially important for central inverters)
- Control of the manufacturing process,
- Ongoing testing to ensure that the manufactured product matches the advertised product specifications, and
- Continual improvement of the design and manufacturing process to address problems identified in the field.

It does not explicitly assume that the organization already has a certification to ISO 9001, though that is a common situation. A key challenge for developing a consensus on this document is the specification of design margins. Statistics from field deployment of inverters suggest that failures are related both to inconsistent manufacturing and to poor design. While designs may be greatly improved by IEC 62093 Edition 2, a key element of quality assurance is selecting components that meet the design requirements including a margin to reflect the variability in the applications and construction. This document is still in the early draft stages.

E. Cost pressures on quality systems

Today's oversupplied market is putting painful cost pressures on the industry as a whole. This is manifested in many ways in the designs and in the quality systems. Thinner cells, glass, and frames and less expensive materials are obvious design targets for reducing cost in modules. Less expensive racking, omission of conduit, and less durable materials are example design targets for reducing cost of systems. The design engineer, who plays a primary role in reducing cost, must work with the quality expert to determine whether these design changes will introduce reliability issues. The quality manager has the priority of taking the time to do this assessment correctly, while the design engineer is working to launch the product or complete the PV system as quickly as possible, demonstrating once again the cultural divide that must be dealt within the partnership.

A second example of the effects of cost pressure is the introduction of warranty exclusions. While the customer may see that the product carries a 25-y warranty, upon closer inspection, the customer may find that some common reasons for replacing the module may not be included or that, although the module may be replaced, the labor and shipping associated with the replacement may not be covered.

Improved quality assurance can help reduce the cost experienced over the life of a product even though the initial cost of the product may be higher, but this benefit can be difficult to quantify at the time of manufacture. The temptation to cut corners because of cost pressure could be reduced if added quality could attract a higher price. Of course, customers prefer higher quality and reliability, but how much more will they pay for it? Large investors and insurance companies develop models to assess anticipated return on investment, risk, necessary reserves, and other financial quantities. Hearing that a component or system has passed a test or an inspection may not give information that is useful. However, if the degradation rate of a system has been demonstrated to be lower than the industry standard, the investor may be willing to estimate a higher return on investment and be willing to negotiate more favorable terms. Similarly, if a warranty reserve can be reduced of because demonstrated low warranty return rates, capital can be freed, providing the value needed to justify the added investment in quality control. The design engineer and quality manager must work together to collect the necessary data to quantify the value of their collective work.

On the other hand, added attention to quality does not always pay for itself. Just as the performance and cost of a product are optimized by the design engineer, the quality assurance program must also be optimized to respond to the cost pressure by streamlining processes without decreasing customer satisfaction. Again, the partnership is key to success.

IV. PARTNERSHIP BETWEEN DESIGN ENGINEERING AND QUALITY ASSURANCE

Successful design engineering requires technical knowledge of the desired function of the product and how to test that the established design will be successful in meeting the warranty in the intended use environment. In contrast, successful quality management during manufacturing sometimes requires motivating workers to execute repetitive tasks consistently, often requiring an in-depth understanding of human psychology. A worker in the field may be taught to discard a module that is dropped, but may be embarrassed by having dropped a module and try to hide it. Successful quality management requires understanding both the technical requirements and having the skills to motivate workers. Experts in quality management may have different training than design engineers and prioritize attendance at different professional meetings than design engineers. Because of the substantial cultural divide, bringing these two professional groups together can be a challenge. The cultural divide is also driven by role-based motivations. While the design engineer is focused on value engineering and time to market, the quality engineer is focused on assuring quality. Herein lies the conflict and tradeoff. The relationship between the two and corporate motives drive outcomes; partnership is essential to success.

IEC and ISO standards writing reflects this cultural difference with IEC taking the mandate to write technical standards while ISO writes the quality management standards. The IEC documents discussed here (Table 1) are intended to form a bridge between these by providing the technical requirements for robust quality assurance.

Design qualification is the first step. For a PV module, IEC 61215 and IEC 61730 are applied to a small number of handpicked modules to qualify the design from both functional and safety perspectives. If one module fails a test, IEC 61215 allows submission of a second pair of modules. If these two pass, then the test is given a “pass”, implying that an IEC 61215 certification may be based on only 75% of the tested modules successfully passing the tests. To improve the consistency, historically, an ISO 9001 certification is obtained as part of the quality assurance program. However, any manufacturing process allows for some variation in the process window. The modules that passed IEC 61215 and IEC 61730 initially are unlikely to represent the full range of products that may result from small variations in the manufacturing process. A recent study by DNVGL [7] found that 6% of more than 300 modules did not pass the IEC 61215 test for thermal cycling (200 cycles). This 6% failure rate could easily explain common statistics of field failures (above, we noted 0.3%, 1.5% and 2.9%) [1]. A marriage between the design engineering and the quality management uses statistical methods for sampling and testing combined with an in-depth technical understanding of the product to facilitate continual improvement of the design and the manufacturing process window. IEC/TS 62941 is designed to facilitate this marriage by identifying important technical details that need to be considered when creating the quality assurance system.

This marriage must extend across the value chain from incoming material control to PV system completion. A change in the bill of materials may not appear to affect a product, but could cause a problem in the field years later. Field failures must be evaluated to identify the root cause and an appropriate improvement plan to be implemented. Putting all of the pieces together to not only connect design engineering with quality assurance but also to connect across the value chain to ensure that the system design fully takes into account variations in the bill of materials and other details is a real challenge. IECRE was created to tackle this bigger challenge [8]. The three documents described here are key elements of IECRE's certificates for the design of the plant (components must be designed and manufactured under IEC/TS 62941 or the new document for power electronics) and plant commissioning (which must be done by an installer certified to IEC/TS 63049). The IECRE is working to create training materials to ensure consistent implementation of IEC/TS 62941 and has created a process to identify the organizations that are qualified to issue IECRE certificates.

A partnership between the design engineer and the quality management expert can be successful in reducing the cost over the product's lifetime and improving the final outcome. The three Technical Specifications described here provide a first step toward creating that partnership.

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