PV bypass diode faults: current testing and scope for future test development

Module degradation | A working group of the international PV Quality Assurance Task Force has been undertaking research and testing initiatives aimed at improving the design and long-term reliability of module junction boxes and bypass diodes. Vivek Gade and Narendra Shiradkar, who are active leaders of this work, report on efforts to shine a light on a hitherto poorly understood aspect of module reliability

The PV industry has been through significant price reductions in the recent years. The competition to provide the best at the least cost can lead to compromises in design for long-term reliability and quality. The industry needs to keep growing while reducing risks for investors, reducing cost of capital and avoiding a black eye in the event shortcuts are taken in the highly competitive PV landscape. Component design and evaluation become very critical under such circumstances. A reductionist approach is very important to improve product quality through use of robust components.

PVQAT was formed after the Ministry of Economy, Trade, and Industry (METI) in Japan approached the US Department of Energy (DOE) in late 2010 with a vision to initiate an international effort on PV reliability. In July 2011 an International PV module quality forum was held in San Francisco. This forum helped form an international PV module quality assurance/reliability task force.

Task force group #4 was formed to focus on junction and diode reliability with an aim to propose test protocols and standards that would eventually lead to robust designs and ultimately lower the levelised cost of energy (LCOE) from solar. Several industry experts joined the team, drawn from the US National Renewable Energy Laboratory, solar panel manufacturers, junction box manufacturers and diode manufacturers. Apart from the group in USA, significant contributions have come from teams working in other geographic locations namely Japan, China and Europe.

High diode temperatures in forward bias observed inside a junction box

The group investigated several different aspects of junction box and diode reliability, starting with the accuracy of technical datasheets and exploring and performing new qualification tests. Some of the unique work performed involved collecting information of real failures in the field, with an effort to recreate these failures through controlled chamber testing, and failure analysis of field failures using analytical tools to understand the root cause and failure mechanism.

Bypass diode failures

Bypass diode failures can be encountered in two modes: short circuit and open circuit failures.

Short circuit failure

When a bypass diode fails in short circuit, it shorts the sub-string of 20 or 24 cells within a 60- or 72-cell module respectively. Typically, commercial modules have one diode per sub-string and there are three such sub-strings within a module. Therefore, short circuit failure of one diode results in a one-third power loss for the module. This would immediately put the module out of assured performance warranty. In this case, either the diode or usually the whole junction box needs to be replaced to bring the module power back to normal values. In the worst case, where the junction box cannot be replaced in the field, the entire module needs to be replaced.

Open circuit failure

Bypass diodes are used in PV modules to prevent the application of high reverse voltage across cells under the event of shading. When a bypass diode across a sub-string of cells fails in open circuit, this condition is similar to not having the diode across that sub-string. This type of failure does not affect the module performance under normal (unshaded) conditions. However, in case a cell in the same sub-string experiences shading, there is nothing that can prevent the application of voltage generated by all other cells in the module across the shaded cell in reverse bias. This leads to failure of the shaded cell due to excessive power dissipation. In a worst-case scenario, the temperatures can reach very high values, posing a threat of fire hazard. Therefore, open circuit failures of bypass diodes are regarded as safety risks. In this case, either the diode or usually the whole junction box needs to be replaced to eliminate safety risk. In the worst case, where the junction box cannot be replaced in field, entire module needs to be replaced.

Field failures

The following discusses a junction box failure due to short circuit. The unit containing three ultra-low VF Schottky Barrier Rectifier diodes failed in the field. The part was electrically tested and found to be a total short circuit.

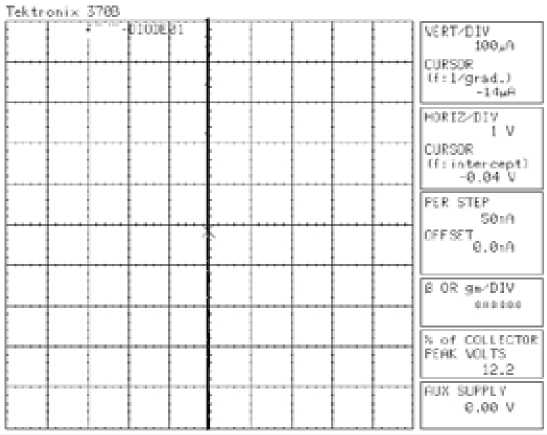

Figure 1. Testing showing total short. As resistance approaches 0, the slope approaches infinity, i.e., the I-V characteristic becomes vertical through the origin. This is an ideal short circuit; the voltage is zero for any current through

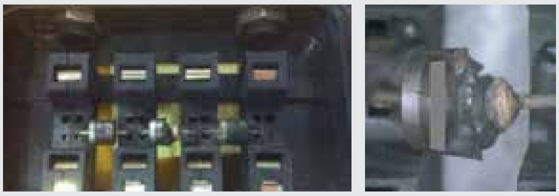

Figure 2. Diode failure involving cracked epoxy packaging potentially due to high temperatures caused by electrical over-stress

It is possible that the centre diode may have been severely damaged by the electrical overstress (EOS) event and diode on the right to a slightly lesser extent. Unfortunately, little could be learned from the failure analysis due to the extent of the damage to the diodes; resulting in the die fracturing in several places and the epoxy mold compound carbonising on the front face of the die, preventing it from being removed by standard chemical methods. It was clear from the damage to the die, packages, and the surrounding plastic unit that the over-stress event was very severe, generating significant temperatures. Significant melting of the surrounding plastic unit has also occurred. This diode has also been extensively damaged.

Failure detection and field failures

Short circuit failures are relatively easier to detect as compared to open circuit failures and can be detected using a variety of techniques. This is because diode failures in short circuit often result in a loss of one-third of the module's voltage in open circuit (Voc). Therefore, even with a simple multi-meter, it would be possible to detect such a significant drop in module Voc. In fact, it is also possible to identify a sub-string of cells with a short-failed bypass diode using infrared imaging. Of course, when a regular I-V trace is performed on the module, diode short circuit failures can be easily identified. In a laboratory, when electroluminescence imaging is performed on a module, the entire sub-string of cells with a short-failed diode appears dark.

On the other hand, open-failures of diodes are not easy to detect as they impact the module performance only under shading. Therefore, I-V tracing under partial shading or use of specialised equipment such as a diode checker is necessary in order to identify open failed diodes.

Failures may or may not have any visible signatures such as burn marks on the diodes or junction boxes. Difficulties in detecting diode failures may be the reason why only very few published studies are available that have reported diode failures in any significant quantity. The box, left, details one detected instance of a diode failure.

Failure mechanisms/stressors leading to diode failures

Temperature over-stress in forward bias

When a PV module is partially shaded, the bypass diode turns ON and its temperate begins to increase due to power dissipation in forward bias. If this condition persists for a long duration, the diode temperature eventually stabilises as the diode reaches a steady state. If the diode temperature exceeds the maximum rated temperature, the diode may undergo failure due to this single event of temperature over-stress. The bypass diode thermal test in IEC 61215 is introduced as a check to screen out designs of bypass diodes/junction boxes that are susceptible to failure under partial shading due to temperature over-stress. Junction box designs qualified under IEC 61215 have demonstrated reduced infant mortality from temperature over-stress events.

Gaps: The current bypass diode test is performed at 75°C ambient temperature and its first part involves passing current equal to short circuit current of the module through the diode for one hour and monitoring if the diode temperature exceeds maximum rated temperature. The maximum temperatures achieved under these test conditions are representative of rack-mounted modules in moderate climates. However, these days modules are increasingly being deployed in hot climates and also in roof mounted configurations, in which the test conditions experienced in field are much harsher. Therefore, it is necessary to revise the test conditions to reflect this reality and reduce the occurrence of false positives under the current test when the module is deployed in hot climates.

Long-term high-temperature operation in forward bias

If a partial shade scenario persists for long duration, and is a daily occurrence, diodes may end up spending significant amount of time at high temperature in forward bias. This may lead to diode failure due to continuous operation at a high temperature. This type of behaviour is not assessed by the bypass diode test in IEC 61215, which only tests a diode at an elevated temperature for a total of two hours.

Gaps: Currently there is no standard to test the susceptibility of junction boxes against failure due to long-term operation at high temperature in forward bias.

Thermal runaway in reverse bias/forward to reverse transition

As explained above, a diode operates at a high temperature if the partial shading is held on the module for significant amount of time. If the shading is suddenly removed, the diode immediately turns to reverse bias. If the power dissipation in reverse bias is more than the power taken out by the junction box cooling system, the temperature of the diode begins to increase further. Since reverse current (and power dissipation) exponentially increases with temperature, this leads to a further rise in temperature until this cyclic process results in diode failure.

Gaps: Until recently, there was no standard available that would test the junction boxes for susceptibility against failure by thermal runaway. Initiatives from the PVQAT diode group members have led to the development of IEC 62979 (drafted by Uchida-san, Japan) to assess the susceptibility of junction boxes towards thermal runaway. However, qualification under this standard is not yet mandatory.

Long-term high-temperature operation in reverse bias

When the module is not subjected to partial shading, the diodes are reverse-biased. This is the normal mode of operation for bypass diodes and they spend significant duration of their service life in this state. When the modules are deployed in moderate climates and/or in rack-mounted configuration, the temperature of bypass diodes in reverse bias is not considerably high. However, for the case of modules deployed in hot climates and/or roof-mounted configurations, the diodes may operate at elevated temperatures (but at a temperature less than necessary to cause thermal runaway) for a long duration and may undergo failure due to increased junction leakage because of the release of impurities on the silicon die surface. Prolonged temperature exposure may lead to degradation of material properties and eventually inferior electrical performance. More testing and research is needed in this area to establish the exact mechanisms.

Gaps: Currently there is no standard to test the susceptibility of junction boxes against failure due to long-term operation at high temperature in reverse bias.

Thermal cycling

PV modules are tested for their robustness for thermal cycling during the tests in IEC 61215. However, when the diodes are in forward biased due to recurrent partial shading, the ΔT (the difference between maximum and minimum temperature) experienced by the diodes is much higher than that experienced by the modules. In this case, the large temperature fluctuations may cause diode failure by solder bond failures at the die or in the worst case crack propagation in the die itself due to thermal cycling.

Gaps: Currently there is no standard to test the susceptibility of junction boxes against failure due to exposure to significant amount of cyclic thermal stresses.

Electrostatic discharge (ESD)

Until recently, ESD was a major cause for diode failures in a PV module manufacturing line. The diodes may fail during module assembly due to high voltage spikes generated through contact by humans/machines or equipment such as a flash tester.

Gaps: Initiatives from the PVQAT diode group members have led to the development of IEC TS 62916:2017, (drafted by Kent Whitfield) to assess the susceptibility of bypass diodes against failure by ESD. The test specification provides the opportunity to perform the tests and measure the efficacy of this test. This also helps address any need to make further changes and if no changes are needed based on the data collected this could be potentially be a test standard in the future and potentially be made a mandatory standard test.

PVQAT diode group initiatives to address the gaps

As discussed, the only mandatory qualification test for bypass diodes/junction boxes is the bypass diode test in IEC 61215-1 and a functionality test at the end of IEC 61730-2, which addresses the issue of temperature over-stress in moderate climates. It was realised that bypass diodes in the field experience several different stressors and may fail by various failure mechanisms. The diode group of PVQAT is focused on developing methodologies and accelerated tests to address diode failures by the different failure mechanisms discussed above. The goal is to make available methodologies to screen for reliable bypass diode/junction box designs that would provide longer service life in field against different failure mechanisms. The work on ESD and thermal runaway has led to development of IEC TS 62916:2017 and IEC 62979:2017 respectively.

For the other failure mechanisms, efforts are focused on understanding the underlying physics and developing models that can explain failure data due to respective stressors such as high-temperature forward bias operation, thermal cycling etc. Once these models are identified, it would be possible to determine the field equivalents of various accelerated tests and develop tests that would simulate 25 years in the field (for a given end use environment and failure mechanism). When new diode/junction box samples are used in such accelerated tests, it would become possible to predict the service life of diodes under various end use environments.

Research efforts are now focused on developing a bypass diode test for hot climates. IEC TS 63126 Guidelines for qualifying PV modules, components, and materials for operation at higher temperatures.

The intent would be to develop a test to simulate service life under mechanisms such as high-temperature forward bias operation (currently assuming the Arrhenius model), and thermal cycling (currently assuming a modified Coffin-Manson model). Moreover, in order to address the issue of failures by thermal cycling, the group has recommended passing current through the diode for at least 50 cycles during the normal thermal cycling test on PV modules followed by a diode functionality test.

Efforts are also underway to develop a framework to establish direct predictive relationships between the failure mode parameters (activation energies for high-temperature forward bias and thermal cycling, thermal runaway crossover temperature) of diodes, the field stressors determined by the thermal resistance, module current, climate of deployment and mounting configuration, and the diode lifetime in the field for the several different deployment scenarios. Even though diode failures have been reported by different entities for several systems, both ground-mounted and rooftop, actual field failures are very hard to come by for investigation in detail.

Authors

Vivek Gade has worked in the PV industry for over 13 years, focusing on reliability and manufacturing. He has been managing the Jabil Solar and Environmental Test Center (JSEC) in St Petersburg, Florida, supporting several gigawatts of manufacturing, quality and reliability, for over seven years. JSEC provides services such as PV component evaluation, module design, prototyping, testing, field evaluation and failure analysis to a wide range of customers. Jabil is primarily into creating unique, automated processes for its customers through several cutting-edge manufacturing service offerings including solar panel manufacturing. He has been a US ANSI TAG 82 and WG2 group member since 2010 and the USA leader of the PVQAT Task Group 4 on diodes and shading since 2011.

Dr. Narendra Shiradkar is a co-leader of the PVQAT Task Group 4 on diodes and shading. He is currently assistant professor at the department of electrical engineering, IIT Bombay and leads the module reliability initiative of the India's National Center for Photovoltaic Research and Education (NCPRE). Before that, he worked as Photovoltaic Research Engineer at Jabil Circuit Inc. He has a PhD with specialisation in module reliability from Florida Solar Energy Center, University of Central Florida.