

The Bypass Diode – A Weakness in today's PV Systems

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Abstract

Remarkable progress has been made in the technology of photovoltaic power systems over the past 40 years. Even though the vast majority of all solar modules are still based on crystalline silicon cells, the efficiency of these modules has more than doubled, which has a considerable impact on the electrical parameters of the solar generator. This is particularly noticeable in the operating current. Because of the higher efficiency, but especially due to the increase in cell area, this current has more than tripled in the last four decades. The string current of modern PV arrays is so high, that with partial shading, a danger exists that the bypass diodes may overheat and be damaged or destroyed. This can lead to consequential damage and in the worst case lead to a fire. This contribution focuses on the problems of today's bypass diode concepts. It also discusses current and possible future developments to solve these problems.

Aim and approach

The aim of this contribution is to show that bypass diodes are a distinct weakness in photovoltaic power plants and addresses how the problems with bypass diodes can be solved. In the first part, the contribution deals with the function of bypass diodes, how this function can be compromised and what is to be expected if the bypass diodes have failed. The bypass diode is a key element to ensure the safe operation of PV power plants under inhomogeneous irradiation conditions, namely in the case of partial shading. Where there has been huge progress in solar cell technology, bypass diodes are basically still the same as they were 40 years ago: Schottky diodes with a forward voltage drop of typically 300 to 500 millivolts. Multiplied by the operating current of 10 amperes of a modern 6-inch solar cell, this leads to a worst-case power dissipation of 3 to 5 watts per diode. It must be considered that the bypass diodes – typically three in a standard PV module – are placed inside the junction box located at the backside of the module. In building-integrated photovoltaics particularly, where the ventilation is poor, the temperature behind the modules can easily reach 60°C or more. This means that there is a total power dissipation of more than 10 watts in a thermally insulating junction box located in an environment that is already unfavourably hot. As a result, the temperature inside the junction box can reach 100°C or more – a very stressful environment for power electronic components! Thus, the risk of damage to bypass diodes due to overheating has increased significantly in modern solar modules. However, stressing in forward bias mode is not the only failure mechanism of a bypass diode. There is also the possibility of thermal runaway of the diode [1]. The reverse current of a Schottky diode rises exponentially with its temperature. If a critical temperature is exceeded in reverse bias mode, the power dissipation caused by the reverse current will heat the diode even further. Consequently, reverse current and power dissipation will rise even more until the diode is destroyed. In PV arrays, this can happen if a bypass diode is forward-biased and heated because of partial shading and then quickly reverse biased because of a sudden disappearance of the shadow. The third known failure mechanism of bypass diodes are surge damages, mainly caused by nearby lightning strikes. If a solar generator is subject to lightning surges (induced or galvanically coupled), the bypass diodes usually are the first parts that fail [2]. If bypass diodes are destroyed, they usually cause an interruption in the circuit. It is also possible that at first, they fuse to create a non-perfect short-circuit which later burns out to an interruption (which already poses a risk for electric arc faults). After the diode has failed, it obviously cannot serve its purpose anymore. As a result, the solar cells are no longer protected against operation in breakdown mode as it might occur with partial shading. In breakdown mode, hotspots are formed which with high probability will damage the shaded solar cells or may even burn holes in the module's back sheet.

Due to the high thermal stress – hotspots can reach 200°C or more – even the front glass might crack. This creates a considerable fire hazard and nullifies the electrical insulation of the module. After operation in breakdown mode, the solar module is irreparably destroyed.

In the second part of the contribution, several approaches to deal with the problems of bypass diodes are investigated. A basic problem is, that damaged bypass diodes are usually not even noticed at first. Only after subsequent damages caused by the defective diodes have occurred (i.e. if the solar modules are damaged due to hotspots) the effects become visible. But then it's already too late. Also, periodic checks of the bypass diodes are costly and are not normally carried out on PV installations. Because of this, it is important that the risk of damaged bypass diodes is minimized as much as possible. There are several approaches to achieve this:

- The stress to bypass diodes can be reduced by decreasing the cell's operating current. The easiest way to achieve this is the reduction of the cell area. One possible approach is the use of half-cut solar cells. There are already several such solar modules on the market. They typically have 120 half-cut cells in 6 strings with 20 cells each. However, they have only three bypass diodes and virtually the same nominal operating voltage and current as a 60-cell module with full cells, implying that always two half-cell strings are connected in parallel. This nullifies the potential advantage to the bypass diodes. From this point of view, a better approach would be to use a bypass diode on each cell string and to connect all six cell strings in series. With this, the voltage of the module would be doubled while its current would be cut in half (which, as a nice side effect, would also decrease the ohmic losses in the wiring of the solar generator). Another approach are solar modules with a shingle design in which the solar cells are cut into even smaller pieces. However, just like the wiring of half-cut modules, the internal wiring of today's shingle modules is usually not done in a way that keeps the string current low.
- The diodes can be cooled using heatsinks. With enough cooling effort, the bypass diodes can be kept at acceptable temperature. However, solar modules are subject to enormous cost pressure and heatsinks would be a relevant cost factor. Moreover, the use of metallic heatsinks leads to insulation problems. Today, most solar modules are designed according to IEC protection class II (double insulation). A metallic heatsink penetrating the junction box makes the electrical insulation much more difficult and more costly.
- The Schottky diodes can be replaced by electronic circuits with near-ideal diode characteristics. Such circuits are based on a semiconductor switch (typically a MOSFET), a control logic and a charge pump for their own power supply. There are a few such products on the market. Their forward voltage drop is about 5 times lower compared to Schottky diodes and their reverse current is negligible. Some of these "ideal bypass diodes" even have a much higher tolerance against power surges than Schottky diodes [3]. However, due to the high cost pressure in photovoltaics, electronic bypass diodes could not yet establish themselves on the market. Moreover, these complex, integrated circuits have yet to prove their reliability in long-term field use.
- The use of one individual MPP tracker per cell string would make bypass diodes obsolete. Today, a cell string of a standard 60-cell module consists of 20 cells. This means that for a 60-cell module, three MPP trackers would be needed. These MPP trackers don't necessarily have to be independent but can be integrated into the same microinverter or power optimizer. The benefit of this solution would be a very good tolerance against partial shading of the PV array. Also, it would easily allow other features such as monitoring on module level or implementation of the NEC2017 rapid shutdown [4]. However, just like bypass diodes, MPP trackers at module level have to cope with the harsh environmental conditions on the backside of solar modules. Also, the costs of PV installations with power optimizers or microinverters are generally higher than the costs of standard installations with string- or central-inverters.
- Diodes with an extended temperature range can be used. There are dedicated bypass diodes on the market with a specific junction temperature rating for DC forward mode. As an example, a bypass diode can be rated to a junction temperature of up to 150°C in normal mode, but up to 200°C in DC forward mode. However, the DC forward rating usually has the restrictions that this temperature can only be tolerated for a limited amount of time (typically one hour) and that no reverse voltage is allowed with this junction

temperature. Because of these restrictions, the DC forward rating should under no circumstances be used in any good design. Although the diode will not be damaged for a limited time at more than 150°C, the reverse current of the diode after a sudden change of polarity (i.e. if the module changes quickly from bypass mode to normal mode) will be so high, that a thermal runaway and subsequently the destruction of the diode is virtually certain. We assume that the DC forward rating is a specific property to overcome the bypass diode test according to IEC 61215, in which the diode must survive 1.25 times the module's STC short circuit current in a climate chamber with a temperature of 75°C for one hour. To the authors, this clearly shows the dilemma of the manufacturers of bypass diodes who are faced with the fact that classic bypass diode concepts with Schottky diodes have reached or already exceeded their limit. In a good design, the rating for normal, continuous operation of the diode should always be respected with a sufficient safety margin (generally, no component should ever be stressed near and surely not above its limits). However, with today's high cell currents, this has become virtually impossible.

Scientific Innovation and relevance

Based on the market size of roughly 100GW we can estimate that in 2019, more than 300 million solar modules have been manufactured worldwide. The vast majority of these modules uses the classic bypass diode concept with one Schottky diode per 18 to 24 solar cells (i.e. 3 diodes per module). This means that roughly one billion solar bypass diodes were put into operation in the last year alone. Our contribution shows that under sub-optimal conditions, these very diodes can be stressed close to or even beyond their limit. It also shows that damaged bypass diodes can lead to severe consequential damage – in the worst case even to danger to life. It is therefore of the utmost importance, that industry, researchers and standardisation committees recognise this problem and respond appropriately. This contribution is intended to layout a basis for this. The major scientific innovation of the contribution lies in the investigation of the different approaches to deal with the problems of today's bypass diode concepts. These approaches are discussed, and their advantages and disadvantages are weighed against each other. Special attention is paid to the DC forward rating of the diode's junction temperature. The contribution shows that this is not a viable solution. This rating may help the diode to pass the normative test procedures, but extended operation with such high junction temperature is more than critical. Since the use of such diodes is not an uncommon practice in today's solar modules, the subject is very relevant.

Results and conclusions

The contribution shows that the classic bypass diode concept with one Schottky diode per 20 6-inch solar cells has reached its limit. Due to the high operating current of modern solar cells, a good design with enough safety margin is no longer possible. Higher currents – namely with 8-inch solar cells – can no longer be handled with this concept. Due to the huge drop in the price of photovoltaics, it can be assumed that in the future, more and more PV plants will be installed at non-ideal locations with distinct partial shading. This will further add to the problem.

However, the contribution also presents several approaches to solve the problem with today's bypass diodes. This can be done by reducing the stress of the diodes (smaller cells, heatsinks), by replacing them (electronic bypass diodes) or even making them obsolete (one MPPT per cell string). From a technical point of view, all of these approaches can lead to a satisfying solution of the problems discussed. On the other hand, the authors consider the approach with the additional DC forward rating of the diode's junction temperature to be unsuitable. It rather shows that the manufacturers have to go to great lengths to push the limits even further, and that it is time to break new ground.

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