# Reexamination of Photovoltaic Hot Spotting to Show Inadequacy of the Bypass Diode

Katherine A. Kim, *Member, IEEE*, and Philip T. Krein, *Fellow, IEEE*

***Abstract*—Hot spotting is a reliability problem in photovoltaic (PV) panels where a mismatched cell heats up significantly and degrades panel performance. High temperatures due to hot spotting can damage cell encapsulant and lead to second breakdown; both cause permanent damage to the PV panel. Although bypass diodes are used for protection and qualification tests are used to reduce cell mismatch, these strategies are shown to be insufficient for hot spot prevention. This paper reexamines the hot spot problem in PV strings through simulation and load-line analysis. Results show that cells in typical panel string lengths are susceptible to hot spotting because of reverse bias behavior. A number of existing and emerging solutions aimed at hot spot prevention are discussed and evaluated. Commercially available active bypass switches are an improvement over passive diodes but do not prevent hot spotting. Cells with low breakdown voltages limit power dissipation but are not fully vetted as a long-term solution. A combination of hot spot detection and open-circuit protection is a complete solution to hot spotting.**

***Index Terms*—Bypass diode, hot spot protection, photovoltaic (PV) hot spot, PV string, solar cells.**

## I. Introduction

STARTING in the 1950s, photovoltaic (PV) or solar cell systems were used to power satellites in space from ambient solar power. In these early satellite systems, *hot spotting* was identified as a condition that could permanently damage the PV cells and reduce its power generation capability [1].

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K. A. Kim is with the School of Electrical and Computer Engineering, Ulsan National Institute of Science and Technology, Ulsan 689-798, Korea (e-mail: kkim@unist.ac.kr).

P. T. Krein is with the Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61820 USA (e-mail: krein@illinois.edu).

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Although this hot spotting problem was identified early on, a precise hot spot definition is not well established in the PV industry. Here, hot spotting is defined as temperature increase above the temperature of its surroundings due to power dissipation in a reverse-biased PV cell, which can occur in the entire cell or a portion of the cell. A *hot spot* refers to the portion of the cell with a higher temperature due to hot spotting. The term *hot spot damage* is permanent damage or degradation to a PV cell as a direct result of hot spotting [2].

The main prevention method for hot spotting is a passive bypass diode that is placed in parallel with a string of PV cells. The use of bypass diodes across PV strings is standard practice that is required in crystalline silicon PV panels [3]. Their purpose is to prevent hot spot damage that can occur in series-connected PV cells [1], [4], [5]. Bypass diodes turn ON to provide an alternative current path and attempt to prevent extreme reverse voltage bias on PV strings. The general misconception is that bypassing a string "protects" cells against hot spotting. Numerous long-term field studies on systems employing bypass diodes have found that hot spotting still occurs, which results in accelerated panel degradation [6], [7]. In addition, various simulation and experimental studies have shown that partial shading on a bypassed string of PV cells has the potential to dissipate substantial amounts of heat and form hot spots [8]–[10].

Hot spot endurance tests are part of the IEC 61215 Si PV panel qualification testing standard and are meant to identify PV panels that are susceptible to hot spotting [3]. These tests identify susceptible cells based on shunt resistance but do not identify cells with localized shunts, which can also lead to hot spotting [5]. Qualification tests identify and eliminate some panels that are prone to hot spotting but not all of them. They also do not address system-level challenges, such as response to local shading that will be discussed in this paper.

Field, simulation, and experimental studies presented here contradict the notion that current practices of bypass diodes and qualification testing are sufficient to protect against hot spotting. PV hot spotting is still a prevalent problem that limits reliability. It is also a safety concern, as hot spotting can damage panels and potentially lead to fires [11]. The purpose of this paper is to reexamine PV hot spotting through detailed simulation, show why bypass diodes are inadequate for protection, and discuss solutions to prevent hot spotting. Hot spotting and the damage it causes is overviewed in Section II. Section III shows how power dissipates in a string with a bypass diode through model-based analysis. Section IV overviews hot spot prevention methods and discusses their limitations and challenges. Section V gives the conclusion.

## II. Reverse Breakdown in Photovoltaic Cells

When a PV cell becomes reverse biased, it will sink rather than source power and heat up owing to the resulting power dissipation. Ideally, power dissipated through a reverse-biased cell is distributed over the full cell area, but this is not always the case [12]. As cell temperature increases, a phenomenon can occur called second breakdown or thermal breakdown [13]. Second breakdown in a p-n junction is observed when the reverse voltage magnitude decreases rather than increases as current is increased and local thermal runaway is triggered. The current is driven into 1-D channels, which can result in high internal temperatures, well above 400 °C. Second breakdown generally leads to permanent cell damage [12].

Even if second breakdown does not occur, high cell temperatures can lead to secondary degradation effects. PV panels are typically rated up to 85 °C, but hot spotting can push the cell temperature far above the rated temperature. If cell surface temperatures surpass 150 °C, the encapsulant and isolative material surrounding the cells may be damaged [4], [9], [14]. Once the encapsulant is damaged, cells are exposed to environmental elements that can cause corrosion and further damage to the cell. Hot spotting with or without second breakdown can lead to PV degradation. Thus, proper measures must be taken to prevent hot spotting in PV panels.

## III. Hot Spotting Conditions

### A. Reverse-Bias and Power Dissipation Levels

The amount of power dissipated in a reverse-biased PV cell depends on its *I–V* characteristics, which vary widely among cells; most manufacturers do not control for reverse breakdown characteristics [8]. There are two cell categories recognized by the PV industry: Type A and Type B. Type A cells have a reverse-breakdown voltage greater in magnitude than the subpanel string's maximum power point (MPP) voltage; Type B cells have a reverse-breakdown voltage magnitude lower than the subpanel string's MPP voltage [1], [9].

A common subpanel string length is 24 cells, and the nominal MPP voltage for such a substring is approximately 12 V. Fig. 1 shows the *I–V* curve for two representative PV cells, modeled according to [15], shaded at 0 W/m$^2$ and illuminated at the nominal irradiance of 1000 W/m$^2$. Fig. 1(a) shows the forward characteristics, where an illuminated cell produces power while operating in the first quadrant with positive voltage and current. Fig. 1(b) shows the reverse characteristics, where a cell dissipates power while operating in the second quadrant with negative voltage and positive current. Note the voltage scale difference between the plots. As shown, the sample Type A cell breaks down beyond −18 V and the sample Type B cell around −8 V. Both cell types will be examined under reverse-biased conditions.

Hot spotting occurs when a PV cell becomes reverse biased and is forced to carry positive current by adjacent cells connected in series, with sufficient current to locally heat the p-n junction. Reverse bias occurs when there is a current characteristic mismatch between PV elements in a series connection.

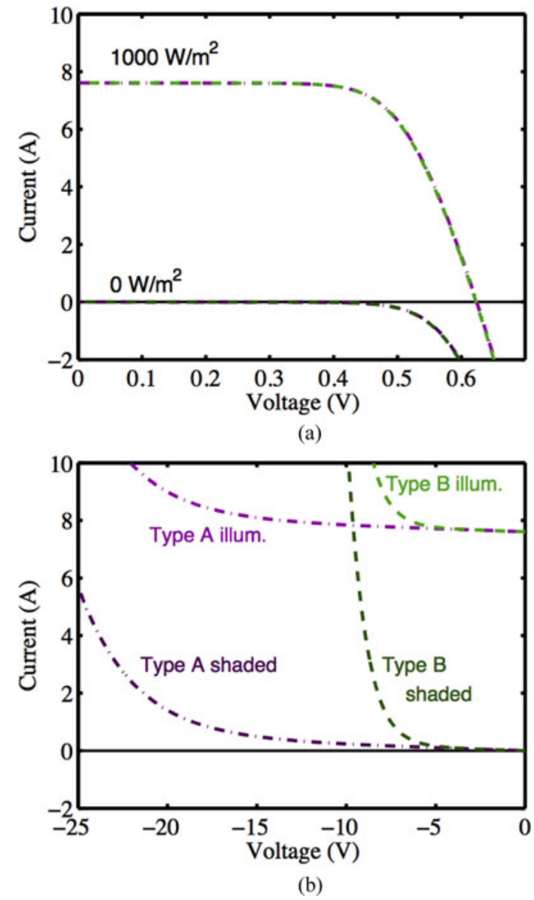


Fig. 1. *I–V* curve in (a) forward and (b) reverse voltage region for illuminated and shaded Type A and B cells.

Partial shading is the most common culprit behind severe mismatch that leads to hot spotting, but uneven cell degradation and temperature gradients also cause mismatch. The bypass diode across the substring may or may not turn on when mismatch occurs in a panel substring; it depends on the *I–V* operating point of the string. In the next two sections, we examine how a mismatched string operates when it is bypassed or not.

*1) String Under Bypass:* A partial shading case is shown in Fig. 2(a), where a leaf has fallen on PV Cell 1 of a 24-cell subpanel string. The bypass diode is turned ON based on the string current and bypass diode's passive behavior. A Schottky bypass diode will impose approximately −0.5 V across the substring. Although the bypass diode is ON, current also flows through the partially shaded substring. This behavior is examined using load-line analysis to investigate the shaded cell's operation within the bypassed substring. Fig. 2(b) redraws the connection to depict the shaded cell as the effective load and the 23 illuminated PV cells and bypass diode as the effective source. In reality, the bypass diode is a load and does not actually generate power. Here, the diode is sinking power generated in another part of the panel, but the resulting forward voltage is seen by the shaded PV cell and can be modeled as a constant voltage when the string is bypassed. Thus, the diode voltage and illuminated PV cells together act as an effective source. According to Kirchhoff's voltage law, the bypass diode drop plus the other 23 PV

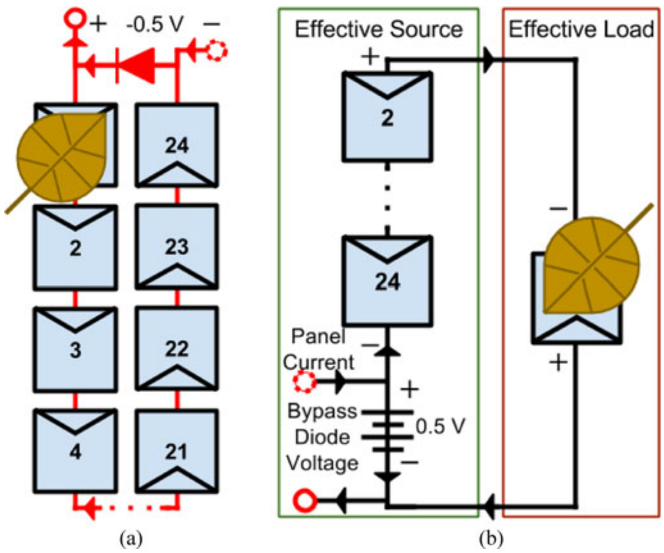


Fig. 2. (a) Bypassed subpanel string reorganized to show (b) the shaded cell as the load and the other PV cells and bypass diode voltage as sources.

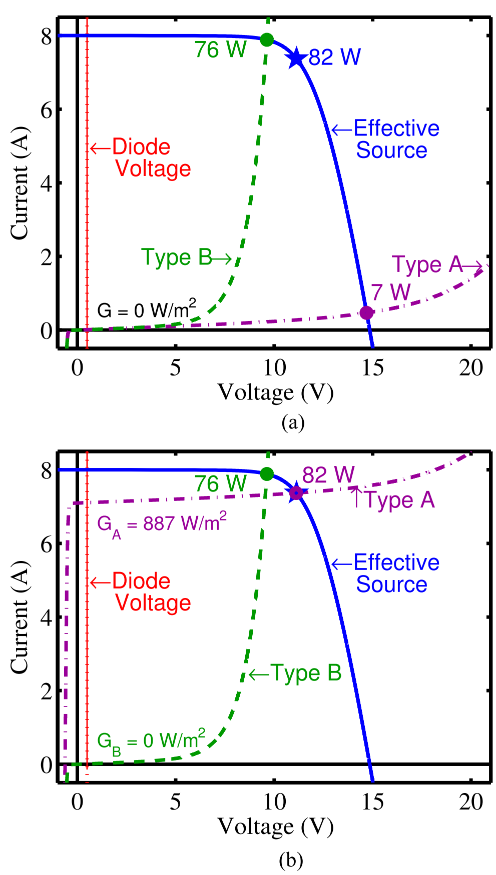


Fig. 3. Load lines for a bypassed string where the cell is shaded (a) at 0 W/m$^2$ and (b) at the worst-case illumination for each cell.

cell voltages must equal the reverse voltage seen by the shaded cell. Note that the shaded PV cell voltage will be negative.

Consider an example in which nominal power per cell is 3.4 W, each with local maximum power at 0.46 V and 7.34 A, based on the nominal irradiance of 1000 W/m$^2$. In Fig. 3, the effective source (bypass diode and 23 unshaded PV cells) and load cell *I–V* characteristics are overlaid; the source and load intersection point is the operating point. Note that the MPP of the illuminated string is 78 W, but the MPP of the effective source is 82 W; the additional power comes from the other substrings in the panel and is imposed on the shaded cell due to the bypass diode voltage bias. If the leaf completely shades one cell such that its irradiance is 0 W/m$^2$, then the load lines and operating point for cell Type A and B are as shown in Fig. 3(a). The Type A cell operates at relatively high negative voltage and low current, dissipating twice the nominal cell power at 7 W. The Type B cell operates at a lower voltage and higher current, dissipating over 22 times the nominal cell power at 76 W. When the cell is completely shaded, the Type B cell has much higher power dissipation than the Type A cell. In practice, heavy partial shading is a common scenario, whether from vegetation, chimney shadows, or uneven soiling. Some studies argue that Type A cells have reliability advantages over Type B cells [1], [4], [14], and Fig. 3(a) tends to explain such claims. However, a review of more in-depth studies [5], [8], [9] shows that Type A cells can also dissipate significant power from hot spotting.

The worst case for power dissipation through a shaded cell occurs when its load line exactly intersects the MPP of the effective source. If the Type A cell in this example is illuminated at 887 W/m$^2$, the load line shifts upward, intersects the MPP, and the shaded cell dissipates the maximum power of 82 W, as shown in Fig. 3(b). For any Type A cell, there exists an illumination level at which the cell dissipates the MPP of the entire effective source. In Type B cells, the worst-case power dissipation is when the cell is at 0 W/m$^2$; under illumination, the load line shifts upwards and the power dissipation decreases. Fig. 3(b) shows the worst-case scenario for both cell types, where each cell dissipates its worst-case maximum power. Type B cells exhibit the highest power dissipation under heavy partial shading, whereas Type A cells can dissipate up to the full string power under light partial shading conditions (or the equivalent level of cell degradation). In each case, a cell dissipating more than 20 times is rated MPP and subject to extreme stress as a result. Thus, typical PV panel substrings of either cell type with bypass diodes are not "safe" from hot spotting.

*2) String Under Maximum Power Point Tracking Control:* When a mismatched string is not bypassed, the total voltage of the string is a positive value determined by an external power converter, employing maximum power point tracking (MPPT) control to maximize system output. Consider an example in which the optimal string voltage for maximum power output is 8 V, as shown in Fig. 4(a). Here, the substring terminal is a positive voltage rather than a negative voltage from the bypass diode. The system is rearranged into the source and load setup, as shown in Fig. 4(b). The string terminal voltage subtracts from the PV string voltage, such that the *I–V* curve of the illuminated cells is shifted to the left by 8 V; the resulting effective source curve is shown in Fig. 4(c). Here, the worst-case illumination level of the shaded cell is 745 W/m$^2$, in which power dissipated through the shaded cell is 23 W, the MPP of

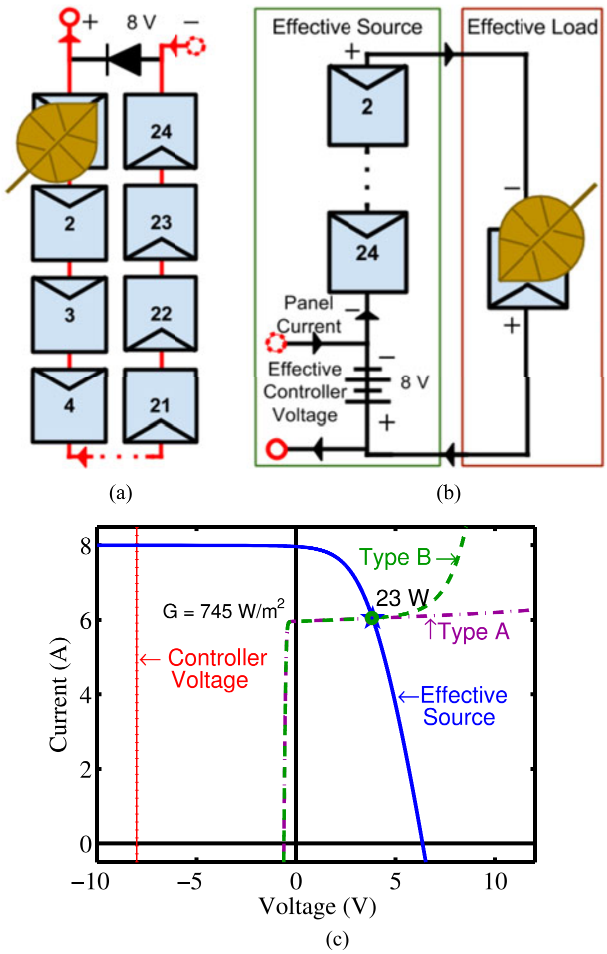


Fig. 4. (a) Nonbypassed subpanel string shown with (b) the shaded cell as the load and (c) load-lines for each cell type at its worst-case illumination.

the effective source. This power level is significantly lower than the maximum power in the bypassed case, but still more than six times the nominal cell power, which has potential to cause hot spot damage [12]. In this example, 8 V was chosen as the effective controller voltage, but this voltage may vary based on the controller and characteristics of the other subpanel strings. If the controller voltage decreases, the *I–V* curve of the illuminated cells will shift to the right, increasing the potential power dissipated through one cell. Conversely, if the controller voltage increases, the *I–V* curve shifts to the left, decreasing the potential power dissipation. In short, higher effective controller voltage is better to mitigate hot spotting.

These examples have shown that both A and B cell types have the potential for reverse bias and hot spotting. As shown, a mismatched Type A cell in a 24-cell string can potentially dissipate the full power produced by the other 23 cells and the bypass diode. A bypassed string has a higher potential power dissipation level and a higher chance of hot spotting compared with a nonbypassed string with positive voltage across the terminals. Using a dc–dc converter to control a substring at MPP reduces power dissipation, but is not sufficient to prevent hot spotting or hot spot damage.

## IV. Hot Spotting Prevention Methods

In addition to the widely used hot spot prevention method of bypass diodes, recent developments include active bypass switches, PV cells with low-magnitude reverse-breakdown characteristics, and open-circuit protection. The advantages and limitations of each approach will be discussed.

### A. *Conventional Bypass Diodes*

Bypass diodes help limit maximum power that can be dissipated though a reverse-biased cell, but that power level depends on the length of the cells in the string. Series strings with more cells will dissipate more heat than strings with fewer cells [8]. Thus, bypass diodes are more effective in mitigating hot spots for short string lengths. For example, placing bypass diodes over every two cells would ensure that a PV cell never dissipates more than the nominal power of two cells—a power level that is unlikely to damage the cell [12].

Previously, some designers even advocated bypass diodes across every cell [16]. In the 1980s, the concept of fabricating a bypass diode into the PV cell was explored [17]–[19]. However, the addition of discrete or integrated bypass diodes at the individual cell level increases cost. In the terrestrial PV industry, this additional cost is prohibitively expensive such that individual bypass diodes have generally not been implemented and are unlikely to be adopted in the near future. Thus, other low-cost and practical hot spot prevention methods are needed.

### B. *Active Bypass Switches*

When a bypass diode turns ON, it has a forward voltage that increases the voltage imposed on a hot spotting cell and it also dissipates additional power. Active switch solutions have been proposed in [20]–[22] that short the PV substring when it is bypassed, which have also been commercialized as “smart bypass diodes” [23]. The active bypass switch approach reduces the voltage over the PV string during bypass and the resulting power loss. Active bypass switches are incrementally better for hot spot mitigation than bypass diodes. As illustrated in Fig. 5(a), short-circuiting the substring reduces the maximum possible power dissipation (from 82 to 78 W) but not enough to prevent hot spotting.

### C. *Photovoltaic Cells With Low Reverse-Breakdown Voltage*

As was shown in Section III, Type B cells exhibit worst-case power dissipation when fully shaded and the power dissipated is proportional to the breakdown voltage. Lowering the breakdown voltage magnitude also lowers the maximum possible power dissipated in the cell. At least one major manufacturer produces PV cells with a low (magnitude) reverse-breakdown voltage of −5.5 and −2.5 V for this reason [24]. However, cells with low reverse-breakdown characteristics still become reverse biased and dissipate heat. This approach is only effective if the cell dissipates the imposed heat without causing damage. Preliminary research in [12] suggests that losses at levels above three times the MPP rating have potential to permanently damage the cell. As shown in Fig 5(b), even cells with −2.5-V

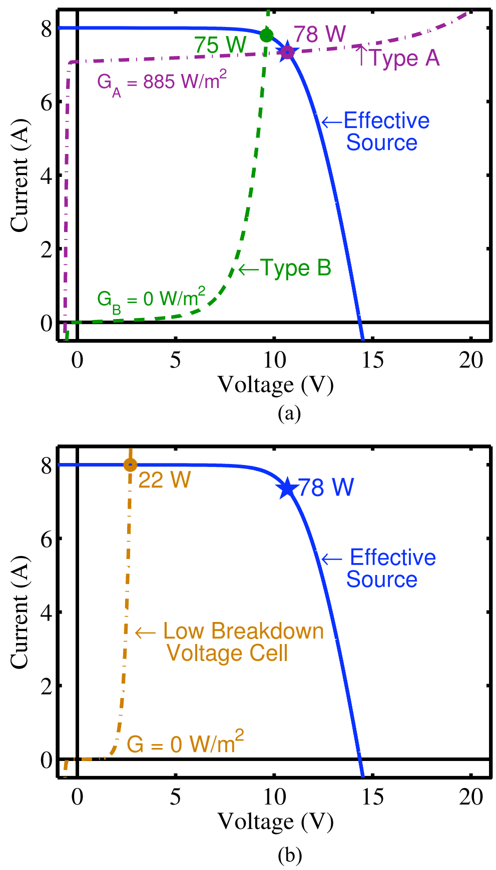


Fig. 5. Load lines for (a) an actively bypassed string and (b) a cell with a low reverse-breakdown voltage.

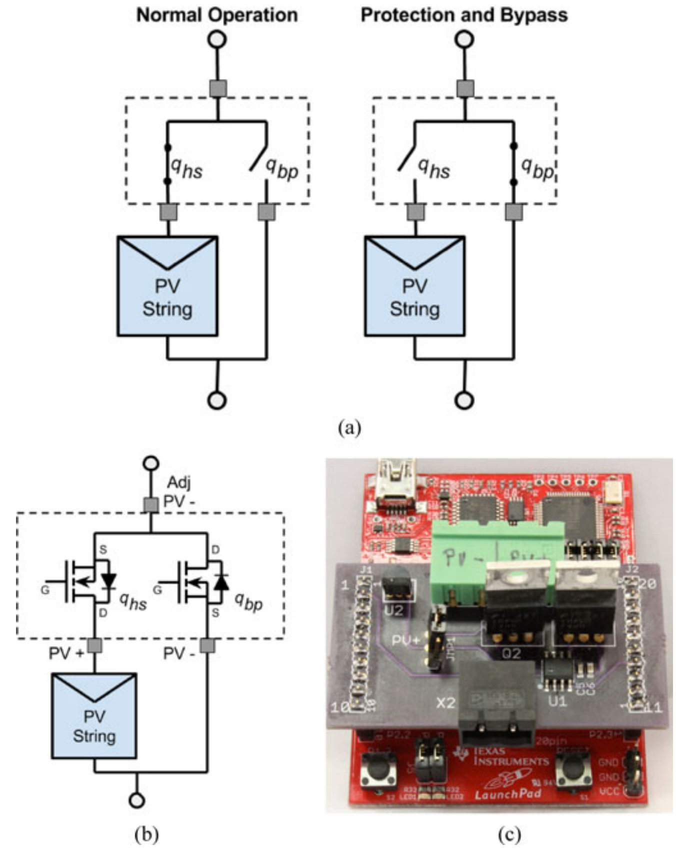


Fig. 6. (a) Protection device switch states in normal and bypass/hot spot prevention mode, (b) device schematic using MOSFETs, and (c) the prototype device.

reverse-breakdown could potentially dissipate up to 22 W, which is over six times the cell MPP. This is a substantial improvement but not likely to be sufficient for prevention. Thus, further endurance and field studies are needed on PV cells with low breakdown voltage magnitudes to determine their hot spot susceptibility.

### D. Active Hot Spot Detection and Protection

Another prevention method is to monitor the PV string during operation to detect when hot spotting occurs and actively protect the string when a hot spot condition is detected.

*1) Hot Spot Detection:* For hot spot detection, a concept was proposed in [25] that uses the impedance of the PV string to detect hot spotting conditions. A distinct change is observed in substring impedance parameters when partial shading occurs. Experiments on typical substring lengths of Si PV cells have shown that the parallel capacitance and parallel resistance both increase significantly. If the PV substring impedance characteristics are monitored during operation, a distinct change in these characteristics indicates that part of the substring is hot spotting. The hot spot detection algorithm can work in tandem with MPPT control, periodically interrupting the MPPT to measure PV string impedance, with marginal tracking loss. Effective implementation methods for this hot spot detection method are still under development.

*2) Photovoltaic Cell Protection:* Once hot spotting is detected, open-circuiting the substring that contains the mismatched cell is a guaranteed method to prevent hot spotting because no current or power will flow through any cell in the substring. When a substring is bypassed, it produces no net output power. Since the substring contribution is zero in such an event, why not open-circuit the string to protect it from hot spotting? This open-circuit protection concept has been proposed in [26] using three switch elements as a bypass and protection circuit, but it can also be implemented using two switches, as shown in Fig. 6(a). Switch $q_{hs}$ is in series with the PV string and is normally on; it opens when a hot spot condition is detected to prevent further hot spotting. Switch $q_{bp}$ is in parallel with the PV substring and is normally open; it turns ON to allow a bypass current path when the PV string is open-circuited. The two-switch PV protection device has been implemented as a prototype that utilizes MOSFET switches; the basic schematic showing the MOSFETs is shown in Fig. 6(b), and the initial hardware prototype is shown in Fig. 6(c).

*3) Experimental Results:* The open-circuit protection technique was tested in an experimental setup with a resistive load powered by two 20-cell PV strings, where one cell is partially shaded on a clear sunny day. First, a bypass diode is used across the shaded string. The illuminated portion of the partially shaded cell raised in temperature, as shown in the infrared image in Fig. 7(a). In the test, the condition was not adjusted for worst

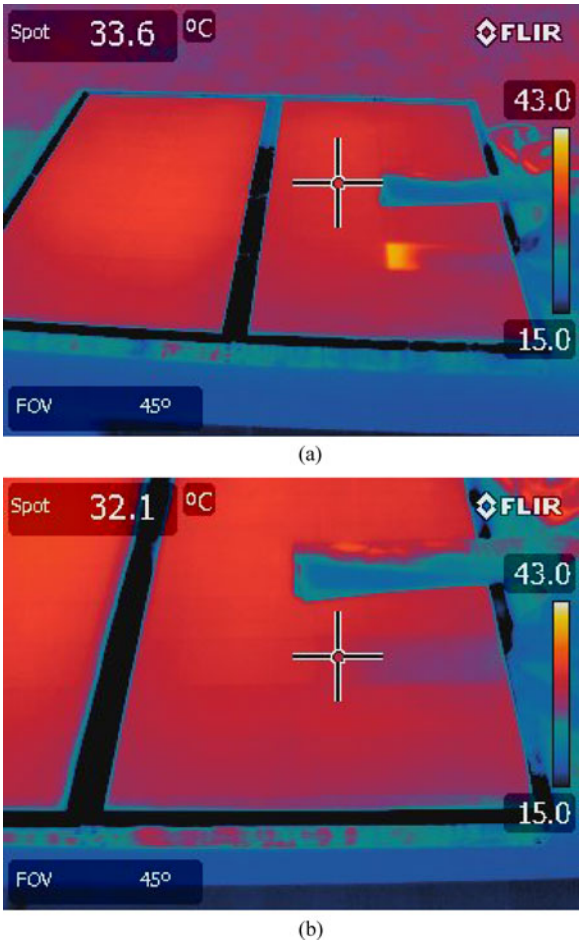


Fig. 7. Infrared images of PV strings under partial shading with (a) bypass diode and (b) hot spot protection device.

case to avoid driving the cell to failure. The hot spot temperature stabilized after a few minutes, and then, open-circuit protection was activated using the prototype device. When protection was activated, the temperature dropped immediately. After approximately 20 s, the hot spot temperature reduced to the temperature of the surrounding cells, as shown in Fig. 7(b). This experiment confirms that localized hot spotting is possible with bypass diodes employed and that active open-circuit and bypass using the proposed two-switch protection device is effective in truly preventing hot spotting.

## V. Conclusion

Although it is often presumed that bypass diodes across subpanel PV strings protect against hot spotting, simulation and experimental results show that hot spotting and hot spot damage can still occur in PV cells. Hot spotting can lead to second breakdown or cell encapsulant damage and permanently degrade the PV panel or leads to safety concerns. Both Type A and B cells are susceptible to hot spotting, particularly when the PV substring is bypassed. Even if each substring is controlled at its MPP, there is still potential for hot spotting, albeit the potential power that can be dissipated through a reverse-biased cell is lower than in bypass.

Bypass diodes are more effective at mitigating hot spots for very short PV string lengths, but this is not conventionally implemented in modern panel construction. Active bypass switches are an improvement over the bypass diode but do not resolve hot spotting. Ultimately, there are two methods to prevent hot spotting: open-circuit the PV string or ensure that the cell can fully dissipate the worst-case power scenario without damaging the cell. Cells with low reverse-breakdown voltages limit the power dissipated in during hot spotting and may be an effective prevention method if dissipation at several times the rated maximum power can be managed without damaging the cell. Further studies are needed to determine the susceptibility of cells with low reverse-breakdown voltage to hot spot damage. Impedance-based hot spot detection in combination with open-circuit protection guarantees that hot spotting does not occur. The effectiveness of active open-circuit protection against hot spotting was shown experimentally using a prototype protection device.

The purpose of this paper has been to demonstrate that bypassing a typical PV string length with a diode or active switch is inadequate to protect against hot spotting and that active open-circuit prevention methods have promise. Once a true hot spot prevention methods is fully developed and implemented, it will reduce system degradation, increase longevity, and improve lifetime energy harvest in modern PV systems.

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**Katherine A. Kim** (S'06–M'14) received the B.S. degree in electrical and computer engineering from the Franklin W. Olin College of Engineering, Needham, MA, USA, in 2007 and the M.S. and Ph.D. degrees in electrical and computer engineering from the University of Illinois, Urbana-Champaign, IL, USA, in 2011 and 2014, respectively.

She is currently an Assistant Professor of electrical and computer engineering with the Ulsan National Institute of Science and Technology, Ulsan, Korea. Her research interests include power electronics, modeling, and control for photovoltaic and renewable energy systems.

Dr. Kim received the National Science Foundation's East Asia and Pacific Summer Institutes Fellowship in 2010 and Graduate Research Fellowship in 2011. She served as the Chair of the IEEE Power and Energy Society/Power Electronics Society (PELS) Joint Student Chapter at the University of Illinois during 2010–2011 and Co-Director of the IEEE Power and Energy Conference at Illinois in 2012. She served as the Student Membership Chair for IEEE PELS during 2013–2014 and currently organizes the IEEE PELS Young Engineers Webinar series.

**Philip T. Krein** (S'76–M'82–SM'93–F'00) received the B.S. degree in electrical engineering and the A.B. degree in economics and business from Lafayette College, Easton, PA, USA, and the M.S. and Ph.D. degrees in electrical engineering from the University of Illinois, Urbana, IL, USA.

He was an Engineer with Tektronix, Beaverton, OR, USA, and then returned to the University of Illinois at Urbana-Champaign, where he currently holds the Grainger Endowed Director's Chair in Electric Machinery and Electromechanics as a Professor and Director of the Grainger Center for Electric Machinery and Electromechanics, Department of Electrical and Computer Engineering. He published an undergraduate textbook entitled *Elements of Power Electronics* (Oxford, U.K.: Oxford Univ. Press, 1998). In 2001, he helped initiate the IEEE International Future Energy Challenge: a major student competition involving fuel cell power conversion and energy efficiency. He holds 25 U.S. patents with additional patents pending. His research interests include all aspects of power electronics, machines, drives, and electrical energy, with emphasis on nonlinear control and distributed systems.

Dr. Krein is a Registered Professional Engineer in the States of Illinois and Oregon. He was a senior Fulbright Scholar with the University of Surrey, Surrey, U.K., and was recognized as a University Scholar: the highest research award at the University of Illinois. In 2003, he received the IEEE William E. Newell Award in Power Electronics. He is a past president of the IEEE Power Electronics Society and served as a member of the IEEE Board of Directors. From 2003 to 2014, he was a Member of the Board of Directors of SolarBridge Technologies: the leading innovator of integrated ac solar panels. He serves as a member of the Steering Committee for the Edison Awards. He is an Associate Editor for the IEEE TRANSACTIONS ON POWER ELECTRONICS and for the IEEE JOURNAL OF EMERGING AND SELECTED TOPICS IN POWER ELECTRONICS. During 2005–2007, he was a Distinguished Lecturer for the IEEE Power Electronics Society. He is currently the Chair of the IEEE Transportation Electrification Community.