Shading Analysis & Improvement for Distributed Residential Grid-Connected Photovoltaics Systems

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Abstract

Despite incentive reductions, distributed residential PV Systems continue to be installed throughout Australia in large numbers. Currently there are more than one million residential Photovoltaic (PV) systems installed across Australia (Australian Clean Energy Council, 2013). One of the significant challenges for residential roof top systems is the shading effects caused by various obstructions including trees, roof top structures and neighbouring buildings. Different levels of shading will lead to extraordinary performance variations in both individual solar modules and the entire PV array. This is primarily due to the operation of module bypass diodes contained inside the junction box. This paper will explain various shading scenarios and describe shading categories and classifications. Following the comprehensive research and analysis of module bypass diodes functionality and their pros and cons, a series of proposed installation solutions will be recommended to reduce shading losses.

1. Introduction

Numerous factors can affect Photovoltaic (PV) system performance. Shading is one of the most significant issues for designers and installers to contend with. Generally, shading refers to a shadow on the PV panels on a rooftop that will reduce the system energy yield. PV shading issues can present complications in addressing true PV de-rating factors since the three primary PV panel characteristics of Power, Voltage and Current may each be affected by varying degrees. As a consequence, there are a limited number of documents systematically analyzing the impact of shading on PV system performance. (Masoum, Padovan and A.S. Masoum, 2010) This paper will explain the different types of shading, suggest a shading classification system and offer practical solutions to improve system output in the event that the PV array will be subjected to shading effects.

2. Shading Types

Shading is not a simple phenomenon. Haze, cloud, dust, trees, bird droppings, buildings and roof-top structures can create infinitely variable shading. Different orientations and tilts can lead to different shading shapes. These can be large or small spots, dappled or hard edged, linear or irregular in nature. Some shading types can cover an entire single cell of a module, some can cover an entire module of the array and some create various shading on either strings, module or cells. To categorize, there are two broad groups of shading and these are **Objective Shading** and **Subjective Shading**. Refer to figure 1. Within Subjective Shading there is a further two categories and these are **Dynamic Shading** and **Static Shading**.

1.1 Objective and Subjective Shade

Objective Shading that is formed by the weather or heavy pollution, such as heavy cloud or haze, will inevitably reduce overall sunlight intensity. Subjective Shading is caused by proximity objects both near and far that can block sunlight and thereby create solid shade shapes. Objective Shade is unavoidable but Subjective Shade can largely be improved or prevented with good design, installation and periodic cleaning.

1.2 Static and Dynamic Shade

Subjective Shading is further divided into either Static Shading or Dynamic Shading. Static Shading refers to shade caused by close proximity obstructions that have typically adhered to the glass, such as bird droppings, leaves or accumulated dirt on a module's bottom edge. This type of shade is dependent on the initial random positioning of the shade barrier only and does not change during the course of the solar day. Static Shading is fixed and unaffected by the angle of the sun. Dynamic Shading is typically caused by buildings, trees, narrow spaced array tilt frames and other such objects that create a shadow based on sun angle. Dynamic Shading is subject to the angle of the sun and therefore changes dynamically during the course of the solar day.

1.3 Whole and Partial Shade

There is simply too much ambiguity when trying to use the term Partial Shading in reference to a solar module, string or PV array. To maintain consistent language, Whole Shading and Partial Shading should only refer to cell shading ratio $\frac{shaded\ area}{cell\ area}$.

Whole Shading and Partial Shading references the threshold point below which there is insufficient irradiance to generate cell voltage (Whole Shade) and above which there is sufficient irradiance to generate cell current (Partial Shade). Whole or Partial shading of a cell will lead to different effects on module voltage or current or both. A system to quantify shading of modules, strings, and PV arrays will be proposed in this paper.

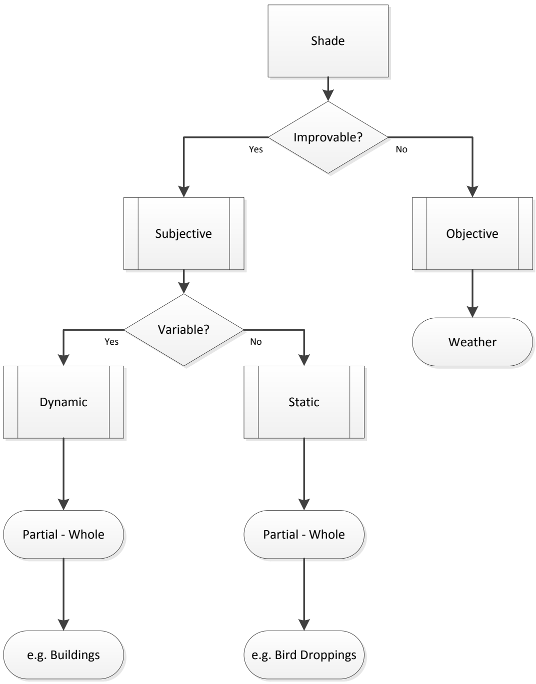

Fig. 1 Shade categories

3. Shading Effects

Conventional thinking on shading effects is generally limited to the ensuing Power reduction. However, the specific effects of shade on either PV *voltage* or *current* or *both* can be significant and an understanding is essential when tasked with installing PV arrays, reviewing system performance, optimizing energy production and increasing system reliability. (Chin, Neelakantan, Yang, etc. 2010)

When Objective Shading appears, on a heavily cloudy day for instance, irradiance will be significantly reduced. However, once irradiance reaches the minimum required threshold (typically around 50W/m^2) the PV array open circuit voltage (Voc) may be significant. Thus under an Objective Shading condition, even though the output current may be extremely low or even zero, it doesn't mean the system is dormant. **The PV array may still generate a high voltage**. Figure 2 shows how Objective Shading affects a PV IV curve: the current is strongly influenced by the irradiance whilst voltage is comparatively not.

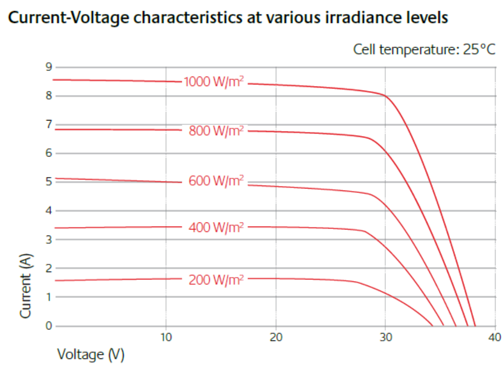

Figure 2. Objective Shading effect on IV curve of Kyocera KD240GH-2PB solar module

The effects of Partial and Whole Shading are very interesting as the ratio of shade covering a cell determines whether the cell is operating in a current or voltage mode. As a cell becomes Partially Shaded, the unshaded portion remains operational with virtually no change to voltage and it continues generating albeit at a reduced current. As the partial shade increases there is a threshold point at which the cell transitions to Whole Shading and the cell voltage collapses. The practical implication here can be very important. For example, let's say there is a bird dropping, (and it's a large Pelican one!), circular in shape, approximately 100mm, diameter and it is positioned at the centre of four cells. A corner of each cell is partially shaded. In this case each cell is partially shaded only 25% and there is a proportional drop in cell current, but each cell's voltage remains virtually unchanged. If the same bird dropping was positioned over a single cell however, the effect couldn't be more different. In this case not only current is proportionally reduced but the cell has transitioned to a Whole Shade voltage mode in which cell voltage collapses. This can have serious consequences on module output power as will be explained in detail later.

In order to fully understand Subjective Shading effects, it is necessary to introduce the module's built in protection device, the "Bypass Diode".

4. Bypass Diode Effects

The purpose of Bypass Diodes is to shunt module current around Whole Shaded cells. This is so as to minimise possible overheating, cracking or potentially burning due to localised cell hot-spot effects. (Pachpande and Zope, 2012). The operating principle of a solar cell with a Bypass Diode (Wenham, Green, Watt and Corkish) is such that during normal operation without shade, the Bypass Diode is reverse biased and has high impedance, therefore it is ***inactive*** and no current flows through it. When the cell is Whole Shaded, neighbouring cell voltages forward bias its Bypass Diode which then transitions to an ***active*** state. In the active state, the Bypass Diode impedance becomes lower than the shaded cell and module current shunts around the shaded cell through the diode. This prevents the unshaded cells from forcing a current against the reverse biased state of the shaded cell; therefore hot spot overheating is prevented.

Unfortunately, for c-Si modules it is not cost effective to provide a Bypass Diode across each cell. Instead, the cells are grouped into three sub-strings and one Bypass Diode per sub-string is installed as per Figure 3. The above described Bypass Diode operation is now grouped into each sub-string rather than each cell. Therefore in the event of Whole Shading of a single cell, the neighbouring sub-strings forward bias the Bypass Diode associated with the shaded cell's sub-string. As a result, the voltage of the entire Whole Shaded cell sub-string collapses down to the forward bias voltage of the Bypass Diode (approximately 0.6V). This represents the equivalent loss in module voltage of approximately 1/3. This is certainly not good, but by far a lesser evil than an overheating, cracking or burning cell. (Figure 4)

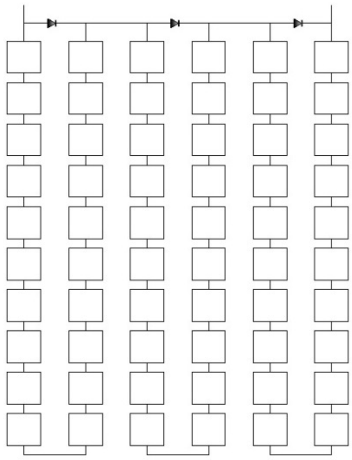

Figure 3: Bypass Diode arrangement in a 60 cell module

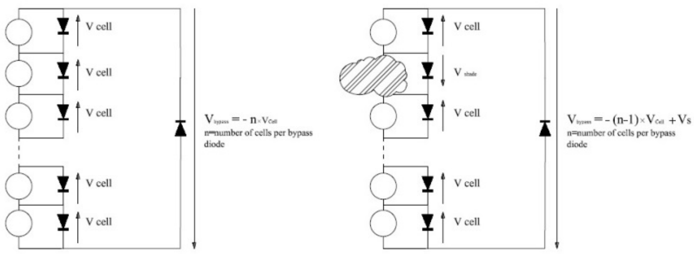

Figure 4: Voltage variation when Whole Shading apply

In the case of Partial Shading of a cell, the effect is vastly different. According to Masoum, Padovan, and A.S. Masoum, when irradiance is above the minimum required, only current will be significantly affected. This means that cell voltage will remain normal, but current will significantly drop according to the cell shade ratio. Refer to Figure 5, it is only when irradiance cannot meet the minimum requirement and cell voltage collapses that module current is shunted through its associated Bypass Diode.

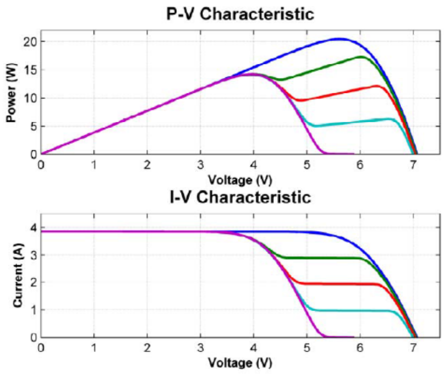

Figure 5: I-V curve and P-V curve characteristics of 12 series connected solar cells (with bypass diode) experiencing non-uniform partial shading of 25 (green), 50 (red), 75 (mint) and 100 (purple) percent, respectfully. (Masoum, Padovan and A.S. Masoum, 2010)

Hence, module current drop may be caused by Objective Shading due to weather, or Partial Shading due to an object (Figure 6c Partial Shaded cell) and a module voltage drop may be caused by Whole Shading as well as the more widely remembered cause of high ambient temperature (Refer to Figure 6, a. Module with unshaded cells, b. Whole Shaded cell and c. Partial Shaded cell).

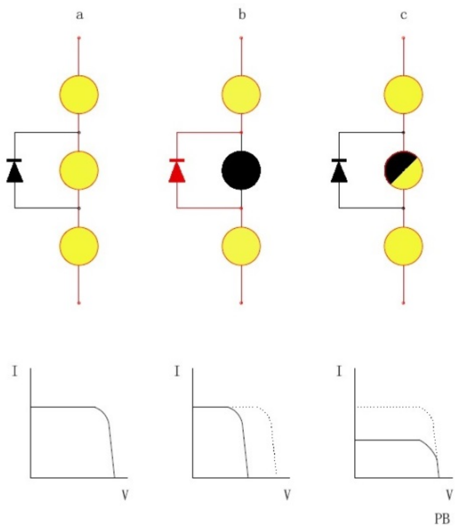

Figure 6: a. Module with unshaded cells, b. Whole Shaded cell and c. Partial Shaded cell

From a practical sense, it should never be forgotten that Bypass Diodes can and do fail. This can be due to long periods at high current and high temperature when they are actively bypassing shaded cells, or due to their Peak Inverse Voltage rating being exceeded such as when a nearby lightning strike occurs. (Haerberlin, 2007). The practical way to determine the health of Bypass Diodes is with an I-V curve tracer such as the Solmetric PVA-1000 (Solmetric Inc). By analysing PV array, string, or module I-V curves, it is possible to quickly identify anomalies due to short circuit Bypass Diodes.

Conventional thinking around Bypass Diodes tends to focus on “Bypass Diodes can prevent power dissipated by heat in shaded cells and greatly improve system performance and ensure output efficiency”, which of course is true, but the fact is that Bypass Diodes can also lead to unexpected performance based on the above described points.

Consider for example the 60 cell portrait oriented modules in Figure 7 (60 cell modules with Whole Shaded cells. Figure 7a indicates a single Whole Shaded cell on the bottom row. The active Bypass Diode disables the entire 20 cell sub-string and module output voltage will drop by approximately 1/3. Even more dramatic is Figure 7b in which all bottom row cells are shaded causing all three Bypass Diodes to be active, and the entire module to be effectively disabled. This disproportional effect scales upwards from cells to modules to strings to arrays and ultimately results in I-V curves that may be severely distorted and include multiple maximum power points.

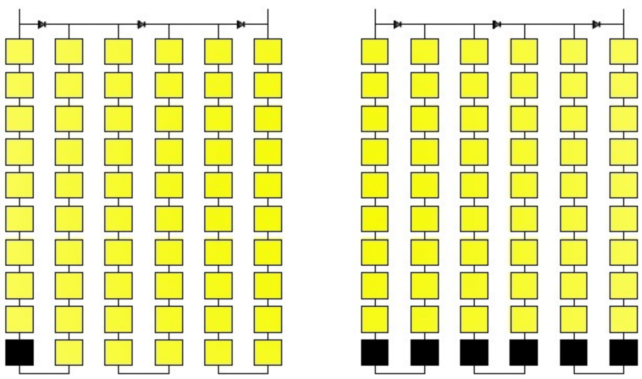

Figure 7: 60 cell modules with Whole Shaded cells

A distorted PV array IV curve can have serious consequences when inverter Maximum Power Point Tracking is introduced into the PV system. If sufficient Bypass Diodes become active, it is possible that the string voltage collapses below the inverter’s minimum tracking voltage. As a consequence, during the duration of the shade effect, inverter on/off cycling may enter a loop that reduces the life of the inverter’s grid protection relays. Also, depending on the MPPT algorithm employed, the inverter may lock onto an incorrect sub-power point for significant periods of time resulting in significantly reduced energy yields. Refer to Figure 8, Partial Shade effects on a PV array with two parallel strings.

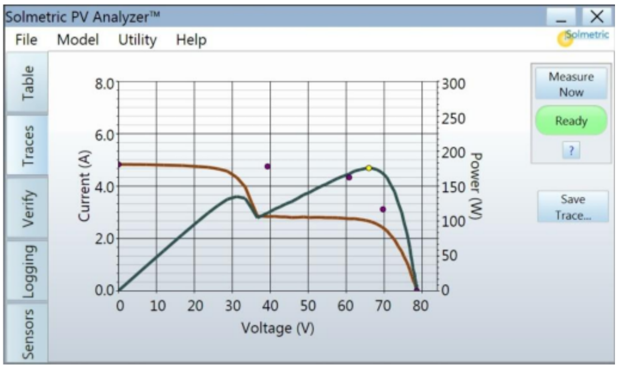

Figure 8: Partial Shade effects on a PV array with two parallel strings – with multi MPPs

Whilst it is undeniable the benefits and safety that Bypass Diodes provide, the problem is that no matter whether one cell or all of the module sub-string is Whole Shaded, the consequence is actually the same. *Therefore it is not the number of Whole Shaded cells that determine output power, but the number of active Bypass Diodes.*

5. Shade Classification System

To allow PV installers, electricians, technicians and engineers to communicate effectively with regards to shade effects a new system of shade classification is proposed. The system speaks in terms of *Active Bypass Diodes.* For example a shaded module that has one active Bypass Diode is referred to as 1BP, two active bypass diodes is described as 2BP, and three as 3BP. Refer to Figure 9.

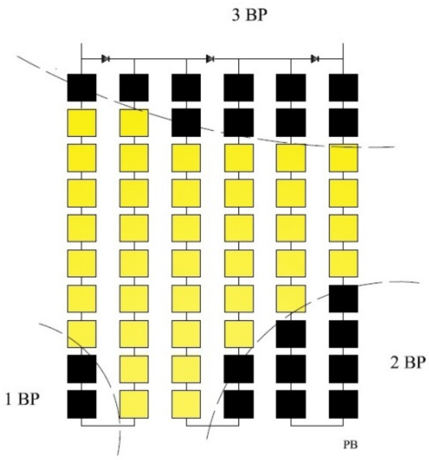

Figure 9 Active Bypass Diode shade classification (e.g. three active bypass diodes = 3 BP)

To scale the shade classification up to a string of modules, the number of Bypass Diodes in the string is tallied and becomes a dividend in the description. For example, in Figure 10 a string of five modules has $5\times3 = 15$ Bypass Diodes, therefore the dividend is 15. The active Bypass Diode are then tallied as the divisor, in this case 3 and the resulting shade classification becomes 3BP/15, which is much easier and more accurate for anyone to describe than “there’s quite a lot of shade on the bottom panel, and a bit also on the next one up”.

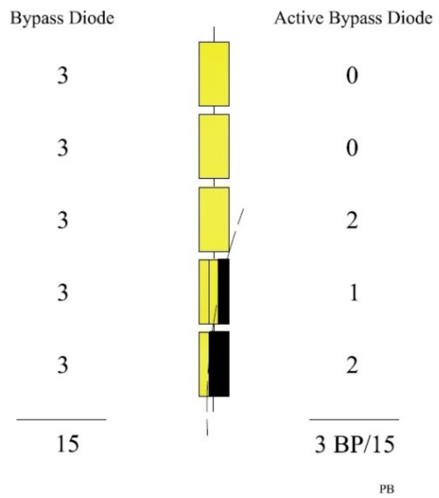

FIGURE 10 String shade classification

To scale the shade classification up to a PV array of multiple strings, each string has its active Bypass Diodes tallied, then separately listed in the divisor. The dividend remains as the tally of string Bypass Diodes, which of course remains constant across the PV array. For example, referring to Figure 11, there is one string with no active Bypass Diodes, and one string with 7 active Bypass Diodes, resulting in a shade classification of (0BP + 7BP)/15. Again, this is an accurate and simple way to record and communicate shade effects. In turn, this becomes useful to installers to consider how an array may be configured to an inverter, or for an engineer to model expected performance.

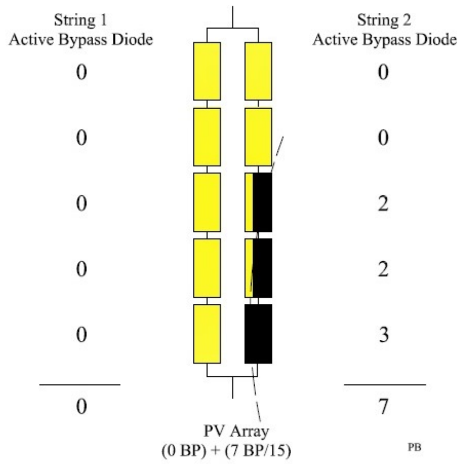

Figure 11 PV array shade classification

6. Improvement Methods

Currently there are no economical methods to significantly improve Objective Shading due to weather. Static Shading due to bird droppings, leaves or dirt can be easily removed with a regular cleaning schedule. For sites affected by Dynamic Shading the following methods are recommended to minimize losses.

1. A site inspection with a shade analysis device such as the Solmetric SunEye 210 (Solmetric inc.) is a desirable method to accurately quantify the shading. Its built in instrumentation and wide-angle fisheye lens capture the PV array's skyline including any Dynamic Shade objects. Image analysis and computation of the clear sky to shade ratio may then be directly displayed in various formats. Energy yields may be calculated with optional modeling software.
2. Installation orientation is another significant factor. For example, if shading along the bottom edge of a module is inevitable, using landscape orientation instead of portrait may reduce the module losses by as much as $\frac{2}{3}$.
3. If Dynamic Shading affects up to 10% of the array modules, the shaded modules may be evenly distributed across each string and the inverter MPPT functionality will minimise array output losses. If Dynamic Shading affects up to 20% of the array modules it is recommended to quarantine the shade affected modules into the same string and utilize a multi-MPPT inverter keeping "healthy and unhealthy" strings separated. It is not recommended to wire heavily shaded strings to unshaded strings due to voltage mismatch. If Dynamic Shading affects 20% or more of the PV array modules it is time to consider switching topology to Microinverters or Power Optimizers.
4. For a non-shaded east-west facing roof top system, in order to maximize daily energy production, it is critical to keep string modules on the same orientation. Strings must **not** be wired across the gable to include both east and west facing modules. It is preferable to utilize a dual MPPT inverter with one input connected to the east facing strings, and the other input connected to the west facing strings. In the event that a single MPPT inverter must be installed this is possible. The shade effects in this case with the rising or setting sun are akin to Objective Shading on a whole string and are affecting current output rather than voltage output. In all east plus west roof top systems, the North/South aligned gable orientation should not be more than a few degrees off True North/South, otherwise one of the arrays will have a non-Equator orientation and East-West sloping tilt frames may be the best option for the installation.
5. Front row Dynamic Shading is always a serious problem for tilted rooftop or ground mounted arrays. (Passias and Kallback, 1984) It is recommend to mathematically calculate the unshaded row spacing before installation by
$$D_{row\ spacing} = \sin(\ tilt\ angle) \times L_{module} \times \frac{cos(azimuth\ angle)}{\tan\ (altitude\ angle)} \times 1.2$$
Also it is recommended to simulate the row spacing with professional software to double check and improve the design accuracy.
6. Inverter selection cannot be neglected. Inverters with excellent flexibility including a broad input DC voltage window can improve the power loss due to shade induced voltage mismatch. Single MPPT inverters with multiple parallel

strings should be avoided where Dynamic Shading may create multiple power points on the array P-V curve. The MPPT tracker can lock onto the wrong peak power point and significant yield losses may occur. According to Masoum, Padovan and A.S. Masoum's testing results, several popular algorithms (P&O, CMPPT and VMPPT) show limitations in correctly locating the true Maximum Power Point. Otherwise module level MPP tracking devices like power optimisers and microinverters can be applied to effectively resolve this issue.

7. Conclusion

Bypass diodes are a necessity to minimize c-Si "hot spot" damage. They can however have a disproportionally negative impact in that one active Bypass Diode can take out an entire module sub-string when Subjective Shading is affecting as little as one cell. This disproportional problem scales up as modules affect strings and strings affect arrays. ***Therefore if shade affects a single solar module, or modules in a string, or strings in an array it is important to think not in terms of cells that are shaded, but to think in terms of Bypass Diodes that are active.***

Shading can be a seriously challenging factor when designing and installing a roof top PV system. Shade diversity and variability can make performance unpredictable. PV systems are difficult, if not physically, impossible to relocate once installed which highlights the critical nature of shade affects. This paper has explained and demonstrated different types and effects of shading. The recommended mitigation methods can assist to effectively increase PV system energy production and the proposed shade classification system can assist all who are associated with shade affected PV to communicate with increased speed and accuracy.

In conclusion, when shade affects a string there is no formula to overcome the shading de-rating. However, by combining theoretical knowledge and practical experience a responsible and satisfactory outcome for many installations that are affected by shade is possible.

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