Solar Energy 134 (2016) 211–218

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

A modified bypass circuit for improved hot spot reliability of solar panels subject to partial shading

Santolo Daliento *, Fabio Di Napoli, Pierluigi Guerriero, Vincenzo d'Alessandro

Department of Electrical Engineering and Information Technology, University of Naples "Federico II", Via Claudio 21, 80125 Napoli, Italy

ARTICLE INFO

Article history:
Received 19 November 2015
Received in revised form 31 March 2016
Accepted 1 May 2016
Available online 12 May 2016

Keywords:
Active bypass
Hot spot
Partial shading
Shunt resistance

ABSTRACT

A new bypass strategy for monocrystalline and polycrystalline solar panels allowing significant hot spot temperature reduction in both partial and full shading conditions is presented. The approach relies on a series-connected power MOSFET that subtracts part of the reverse voltage from the shaded solar cell, thereby acting as a voltage divider. Differently from other active bypass circuits, the proposed solution does not require either a control logic or power supply and can be easily substituted to the standard bypass diode. The operation of the new circuit is described with reference to the shading condition prescribed by the EN 61215 qualification procedure. Experiments performed on two commercial solar panels have shown that the shaded cell can be cooled up to 24 °C with respect to the case in which the standard bypass diode is adopted.

1. Introduction

One of the main concerns for the reliability of silicon solar panels (hereinafter also referred to as modules) is the possible occurrence of localized overheating (hot spot), which may induce accelerated aging (Manganiello et al., 2015) and, in severe cases, even irreversible malfunctioning. Hot spot formation is inherently related to the internal structure of solar panels, which are formed by tens of series-connected individual solar cells, each behaving as an independent current source; it is indeed well known that, when for whatever reason the current supplied by one cell is lower than the others, such a cell operates in reverse-bias mode and dissipates power. This occurrence is extremely frequent since it takes place every time a shadow partially covers the panel, thus reducing the corresponding photogenerated current. Whether or not the reverse biasing of a solar cell can be dangerous depends on the reverse current–voltage (*I*–*V*) characteristic of the inherent p–n junction (Moretón et al., 2015), which is impacted by two key parameters, namely, the breakdown voltage BV (assumed positive) and the shunt resistance R_{sh}. The breakdown voltage is the maximum allowed reverse voltage for the safe operation of the junction; approaching this voltage leads to a huge increase of the reverse current and eventually to device destruction. The shunt resistance describes undesired current paths through the inherent cell diode or along the cell edges, that is, it accounts for the non-ideal blocking properties of the junction; the current flow in the shunt resistance produces power dissipation and, consequently, cell heating. In both cases the reverse voltage appearing across the solar cell determines the amount of dissipated power and, hence, the temperature reached by the cell.

As will be recalled in the following sections, the maximum reverse voltage that can be found across one cell depends on the number of series-connected cells; in order to limit the reverse voltage to safe values, bypass diodes are antiparalleled to two or more panel subsections, hereinafter referred to as subpanels. As a common practice, a subpanel comprises about 20 elementary cells so that the maximum reverse voltage across one of them cannot exceed about $19 \times 0.6\,\text{V} = 11.4\,\text{V}$, where 0.6 V is the average voltage drop on forward-biased cells; this value should in principle be low enough to guarantee safe operation in reverse conditions (El Basri et al., 2015).

Before commercialization, the reliability of the solar module design is verified by means of the certification procedure performed according to the European Standard EN 61215 (Crystalline silicon terrestrial photovoltaic modules: design qualification and type approval), which verifies the hot spot tolerance by recreating the worst expected operating conditions (see next section) (Herrmann et al., 1997). In spite of that, hot spot failure is one of the most frequently reported phenomena limiting module lifetime (Review of Failures of Photovoltaic Modules, 2014; DeGraaff et al., 2011). This is due to a twofold reason. First, the actual reverse characteristics of cells embedded in a solar panel – in principle

* Corresponding author.
E-mail address: daliento@unina.it (S. Daliento).

http://dx.doi.org/10.1016/j.solener.2016.05.001
0038-092X/

sharing identical nominal parameters – exhibit widely spread values for both BV (down to 10 V Kim and Krein, 2015) and shunt resistance (down to 20 Ω d'Alessandro et al., 2011a,b). Second, the qualification procedure EN 61215 is limited to few randomly selected panels; as a consequence, panels including anomalous solar cells are most likely to be present among the thousands often needed to build a solar plant. Moreover, some defects, like micro-cracks or delamination, occurring either during installation or during the operating life of the panel (Manganiello et al., 2015; Simon and Meyer, 2010) can affect the hot spot tolerance.

In the past, the increase in the number of bypass diodes (up to one diode for each cell) has been proposed as a possible solution (Suryanto Hasym et al., 1986; Chen, 2012); however, this approach has not encountered the favor of crystalline modules producers since it requires a not negligible technological cost and can be even detrimental in terms of power production when many diodes are conducting because of their power consumption (Daliento et al., 2009).

More recently, it has been shown that the distributed MPPT approach (Coppola et al., 2012) is beneficial for mitigating the hot spot in partially shaded modules with a temperature reduction up to 20 °C for small shadows (Solórzano and Egido, 2014); unfortunately, no advantages were found for totally obscured cells. On the other hand, methods to alleviate the hot spot in PV systems adopting centralized conversion schemes, which are still largely prevalent, are still lacking. In a recent paper (Kim and Krein, 2015) showing the "inadequateness" of the standard bypass diode, the insertion of a series-connected switch (also suggested in Guerriero et al. (2013, 2016), Di Napoli et al. (2015)) suited to interrupt the current flow during bypass events has been proposed; however, the this solution requires a quite complex electronic board that needs devised power supply and suitable control logic for activating the device.

This paper presents a simple bypass solution to appreciably reduce the reverse voltage across shaded cells, thus mitigating power dissipation and cell temperature. The approach is based on the adoption of a power MOSFET that sustains part of the reverse voltage, thus dissipating a portion of the power in the place of the shaded cells. Differently from Kim and Krein (2015), the functioning principle of the proposed approach is fully analog to that of a standard bypass diode, since it does not require either power supply or control logic. In the worst-case conditions, as defined by the EN 61215 discussed in the next section, a temperature reduction up to 24 °C has been achieved. The method is particularly suitable for reducing power dissipation in cells with unexpectedly low R_{sh} or BV; moreover, with respect to the results obtained in Solórzano and Egido (2014), it cools down even fully shaded cells.

The paper is organized as follows: Section 2 recalls the operation of the solar panels in partial shading conditions and illustrates the qualification procedure EN 61215; in Section 3, measurements of the reverse I–V curves of cells embedded in two commercial solar panels are reported; in Section 4, the new bypass approach is addressed and described; Section 5 illustrates the comparison between experiments carried out on solar panels either equipped with the proposed circuit or making use of the standard bypass diode; conclusions are drawn in Section 6.

2. Theoretical background

As outlined above, the hot spot occurrence is significantly related to the internal structure of a solar panel, the typical arrangement of which is reported in Fig. 1.

A solar panel is made by series-connected elementary cells, usually organized in multiples of about 20, forming subpanels (Silvestre et al., 2009; Guerriero et al., 2015) each equipped with

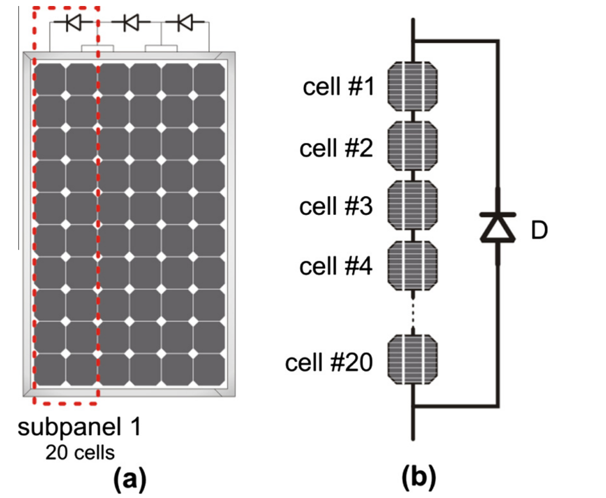

Fig. 1. (a) Sketch of a solar panel partitioned into 3 20-cell subpanels, each equipped with a bypass diode; the section corresponding to the first subpanel is highlighted; (b) simplified representation of an individual subpanel.

an antiparalleled bypass diode. If one or more cells are affected by shading or malfunctioning events that reduce their photogenerated current, these cells are most likely pushed into reverse-bias mode; in this case, the diode (i) plays a protection role, by mitigating the reverse voltage falling on them, and (ii) guarantees an alternative current path, thereby preventing a collapse of the power production. This scenario is schematically illustrated in Fig. 2, which shows the circuit representation of a subpanel, built as the series connection of one-diode cell models (d'Alessandro et al., 2015); the shunt resistances have been taken into account, because they strongly impact the operation in reverse-bias conditions, while, for the sake of simplicity, the series resistances have been neglected.

Whenever for some reason the current photogenerated by a solar cell is less than the others (in the example shown in Fig. 2 the photogenerated current corresponding to cell #1 is assumed zero) the excess current coming from other subpanels (equal to I_{string} in this case, if, in a first-order analysis, the current flow through R_{sh1} is disregarded) is forced to flow through the bypass diode D. As a consequence, the voltage across the whole subpanel coincides with the low voltage drop V_D across the forward-biased diode D (about 0.8–1 V for silicon diodes or 0.3–0.5 V for Schottky diodes depending on the excess current). Meanwhile, the other cells inside the subpanel cannot supply their photogenerated currents, because the series connection is broken by cell #1; hence, these currents are forced to flow through the corresponding intrinsic forward-biased diodes $D_{\#i}$, thus exhibiting a voltage drop V_F. As a consequence, a voltage given by $(N-1)\cdot V_F$ falls from node #1 to node #N (see Fig. 2). By applying the KLV, the reverse voltage V_R across the dark cell #1 can be evaluated as

$$V_R = (N-1)V_F + V_D \quad (1)$$

For a reliable design the number N should be chosen low enough to prevent V_R from exceeding BV.

The above analysis has been performed by neglecting the current flow through the shunt resistance of the shaded cell; in such a hypothesis the power dissipated by the cell would be zero (the cell does not conduct current) unless V_R approaches BV. In order to quantify the power dissipation occurring in real cells ($R_{sh} > 0\ \Omega$), the simple geometric construction (Manganiello et al., 2015) shown in Fig. 3 can be adopted.

This figure shows the I–V characteristic of a shaded cell (the slope in the reverse region depends on the shunt resistance) and