A Global Maximum Power Point Tracking Method for PV Module Integrated Converters

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***Abstract*—This paper proposes a maximum power point tracking (MPPT) method to seek the global maximum power point (MPP) in photovoltaic (PV) modules. The method infers partial shading—and hence the possibility of multiple maxima—by monitoring bypass-diode voltages and initiates a global search routine only if a bypass diode turns on. Under nominal conditions, conventional MPPT is implemented through a perturbation-based approach. This technique provides a significant advantage over existing methods to counter partial shading that periodically scan the entire PV power profile. Experimental results demonstrate the ability of the algorithm to track the global MPP for string and cell-level shading scenarios.**

***Index Terms*—Bypass diodes, dc-dc boost converter, maximum power point tracking, microinverter, microconverter, module-integrated converter.**

I. Introduction

Conventional residential-scale PV energy-conversion systems are built with large arrays of series-connected PV modules connected to a central inverter. Figure 1(a) depicts an example of such a system. Since the performance of the array is dictated by the weakest performing module, it is conceivable that these systems do not extract the maximum possible power from the PV array when individual PV modules are partially shaded. Module-integrated converters (MICs) have been proposed as a solution to partial shading. In such systems, power electronics circuits are integrated directly with PV modules, and the power output of each individual module is maximized irrespective of the operation of other modules. Two examples of MIC architectures are shown in Figs. 1(b)-(c). Figure 1(b) depicts a system comprised of module-integrated dc-dc converters (also known as microconverters) integrated with individual modules, and the series string connected to an inverter which interfaces with the grid [1]. Figure 1(c) depicts a system comprised of module-integrated inverters (also known as microinverters) that can independently be connected to the grid without the need for a central inverter [2].

While MIC architectures can yield higher energy harvest when individual PV modules are shaded, more realistic shading scenarios (especially in residential-scale systems) involve partial shading of parts of the PV module, i.e., strings of cells or individual cells in the modules may be shaded (examples of module-, string-, and cell-level shading scenarios are shown in

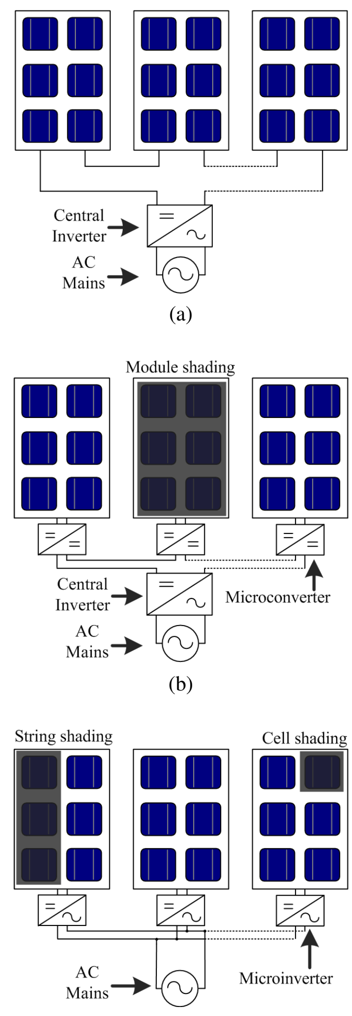

Figure 1. (a) Central architecture comprised of PV array connected to a central inverter that is interfaced to the grid, (b) Microconverter architecture with module-integrated dc-dc converters, (c) Microinverter architecture with module-integrated inverters.

Fig. 1(b), (c)). This work proposes a maximum point tracking (MPPT) method to address such shading condtions. In the proposed method, partial shading is inferred when the bypass diodes (connected across series strings of cells in a module) conduct. This triggers the search for the global MPP.

Several algorithms have been proposed to seek the global MPP in partially shaded PV modules [3]–[5]. Circuit-level solutions have also been proposed to this effect [6], [7]. Our method utilizes relevant circuit information (bypass diode voltages) to supplement conventional MPPT techniques. The following advantages are envisioned: i) periodic scanning of the entire PV power-voltage characteristic (referred as $p - v$ characteristic subsequently) is largely unnecessary for many shading scenarios, and thus, time spent away from an optimal operating point is minimized, and ii) the algorithm can be easily implemented in existing MICs with minimal retrofitting (bypass diode voltages need to be sensed).

The remainder of this paper is organized as follows. In Section II, we provide a brief overview on the need for bypass diodes in PV modules. In Section III, we describe the MPPT method, and the digital-compensator design. In Section IV, we provide experimental results that validate the proposed approach. Concluding remarks and opportunities for future work are discussed in Section V.

II. Partial Shading in PV Modules

In this section, we provide a brief overview on partial shading effects on PV modules, and subsequently introduce the proposed MPPT algorithm.

A. Impact of shading on PV modules and need for bypass diodes

Crystalline-Silicon PV modules are constructed by connecting PV cells in series. We subsequently refer to series-connected PV cells as a string, and the corresponding voltage as the string voltage (note that the series connection of PV cells is also commonly referred as a sub-string). To increase energy harvest and reduce localized cell-level heating when modules are partially shaded, bypass diodes are connected in parallel to the strings. When strings are shaded, they produce less photocurrent compared to non-shaded strings. As a result, the cells in the shaded string might be forced to conduct a current greater than their photocurrent due to the non-shaded strings. The shaded cells then become reversed biased and dissipate power. This limits the output from the rest of the panel, and can lead to localized heating of the shaded cells. The bypass diodes help limit these effects by turning on when the voltage across the string drops below their turn on voltage and diverting the current sourced by the non-shaded strings. Readers are referred to [8] for more details on partial shading effects and the need for bypass diodes.

B. Principle of proposed MPPT method

The basic concept of the proposed MPPT method is illustrated in Fig. 2(a), which depicts a PV module coupled with a MIC. The voltage across the bypass diodes (i.e., the string voltage) is critical information that can be sensed in MIC topologies (notice from Fig. 1, that in central architectures these string voltages are not readily accessible in the inverter). Under nominal irradiance conditions with no partial shading,

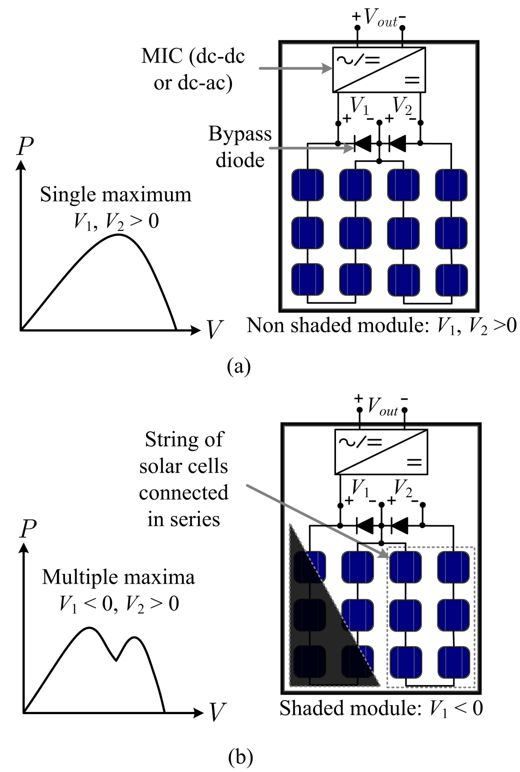

Figure 2. String voltages are employed as indicators of partial shading. (a) Under nominal non-shaded conditions there is a single maximum in the $p-v$ characteristic, and the string voltages $V_1, V_2 > 0$, (b) String 2 is shaded which results in multiple maxima in the $p-v$ characteristic. This might force the bypass diode to turn on due to which $V_1 < 0$ at the local maximum.

the string voltages are non-negative and the module $p - v$ characteristic has a single global maximum as shown in Fig. 2(a). In certain shading conditions, the bypass diode connected across the affected string may turn on to support the current generated by the non-shaded string. This produces local maxima in the $p - v$ characteristic which conventional MPPT algorithms might lock on to [9]. Operating at a local maximum for a prolonged period of time forfeits available energy that could have been extracted by operating at the global maximum.

The proposed technique continuously monitors the string voltages (V_1, V_2 in Fig. 2). Partial shading is inferred when either of them drops negative (for instance, in the scenario depicted in Fig. 2(b)). Subsequently, the controller initiates a search to seek the global MPP. Note that the method described above is restricted to applications involving MICs, since partial shading detection is based on sensing the string voltages (as pointed out earlier, these voltages are not accesible to the central inverter in a conventional system). Once partial shading is detected, an exhaustive search for the global MPP may be triggered. The search may also be restricted to voltages that are multiples of the rated string voltage. It is worth noting that certain shading conditions may produce local maxima at which the bypass diodes don't conduct. Techniques to detect such local MPPs are being developed as part of ongoing research.

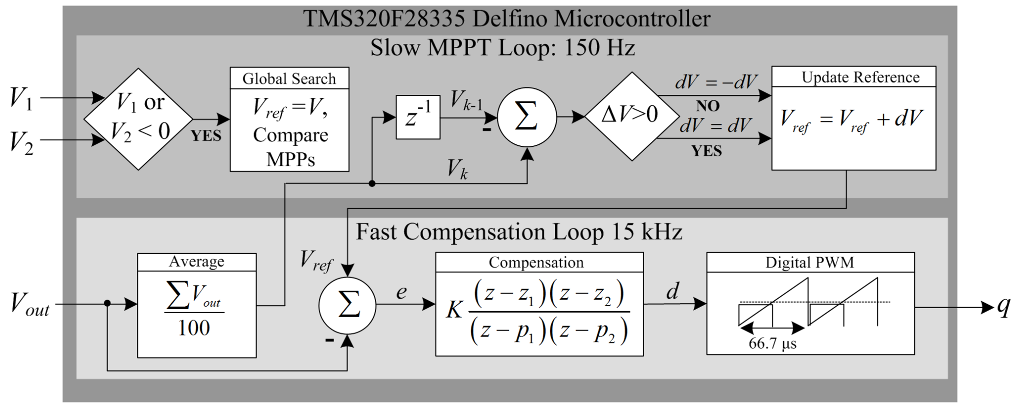

Figure 3. Block diagram that illustrates the operation of the controller.

In the forthcoming discussion, we make no assumptions on the topology of the MIC (microconverter/microinverter), but we presume that it includes a front-end dc-dc converter that implements an MPPT algorithm to maximize the power output of the module.

III. Implementation Details

This section provides an overview of the proposed MPPT algorithm. Our experimental setup employs a dc-dc boost converter controlled by a TMS320F28335 microcontroller. However, the algorithm can be easily implemented on other similar microcontrollers with alternate dc-dc converter topologies. The controller is comprised of two loops (executed at different rates), which are described separately below. Figure 3 depicts a block diagram of the controller.

A. Outer MPPT loop

The outer loop is a *slow* MPPT-control loop that sets the reference for the output voltage V_{ref} (as described subsequently, the inner loop regulates the output voltage of the converter V_{out} to the set-point reference). The MPPT control loop is typically executed at a fraction of the switching frequency (in our case 1/100 of the switching frequency). We use a simple perturb and observe (P&O) algorithm to maximize the output voltage of the dc-dc converter. For dc loads, maximizing the output voltage/current amounts to maximizing the output power [10]. In fact, such MPPT approaches offer several advantages including reducing sensor requirements (output/input current need not be sensed for MPPT purposes) and compensating for converter efficiency. The voltage reference V_{ref}, is updated by an amount $+dV$ $(-dV)$ if a previous update by $+dV$ increased (decreased) the average output voltage and vice versa. As shown in Fig. 3, the average is computed from a sample of 100 points. Note that while the average is computed in the fast compensation loop, reference update decisions are made in the slow MPPT loop. Implemented as such (with no inferences drawn from the string voltages), the above MPPT technique ensures operation at a (possibly local) maximum in the $p-v$ characteristic.

String voltages V_1 and V_2 (refer Fig. 2(b)), are also available as inputs to the controller. While operating at a maximum, if a negative string voltage is detected (implying diode turn on), conventional MPPT is halted, and a global search is initiated by reinitializing the duty cycle. Once a new MPP is found, the new and old MPPs are compared, and the operating point is moved over to the global MPP. In our experimental setup, this algorithm has been tuned for two PV strings. If there are more strings, a point-wise global search will be necessary. Search can also be focussed to regions that are multiples of the rated string voltages.

B. Inner compensation loop

The inner *fast* loop is utilized to regulate the output voltage V_{out} of the converter to the set-point reference V_{ref}, which is set by the outer MPPT loop as described above. This is accomplished with a two-pole, two-zero digital compensator, which is designed using conventional frequency-domain design methods.

IV. Experimental Results

In this section, we provide a brief overview of the hardware setup. Next, the performance of the digital compensator and the operation of the MPPT algorithm under two shading conditions are investigated.

A. Description of hardware setup

The proposed MPPT algorithm has been implemented and tested on a laboratory prototype. The test setup comprises a dc-dc boost converter that delivers power from a PV module to a resistive load. The experimental setup is depicted in Fig. 4. The testing is done indoors with artificial lighting to ensure uniform insolation. Field testing of this MPPT technique is part of future work. The PV module utilized for this setup is built with two PV strings (labeled String 1 and String 2 in Fig. 4). Each PV string has six cells connected in series. Bypass diodes are connected externally across each string of cells. This prototype mimics a scaled-down version of a conventional PV module. As mentioned previously, the

Table I
MIC (DC-DC BOOST) PARAMETERS

Symbol	Quantity	Value
L	Inductance	2.2 mH
C_i, C_o	Input, output capacitance	220μF
f_{SW}	Switching frequency	15 kHz
R	Load	51Ω
K	Controller gain	0.164
z_1, z_2	Controller zeros	0.9965, 0.8484
p_1, p_2	Controller poles	1, -0.0176

power produced by the PV module is processed by a dc-dc boost converter that is controlled with a TMS320F28335 microcontroller. Specifications of the dc-dc boost converter are listed in Table I. Also listed are the controller parameters (please refer Section III for details on the controller).

B. Performance of the digital compensator

The first aspect investigated in the experimental studies is to tune the MPPT algorithm for an optimum response to output variations. This involves choosing the perturbation size and the MPPT update rate. With regard to the algorithm implementation described in Section III, the perturbation size (dV) is the amount by which the voltage reference is changed, while the MPPT update rate is the frequency at which this change is made. For the controller specifications listed in Table I, Fig. 5 depicts the output voltage V_{out}, input current I_{in}, and input voltage V_{in} as the output voltage reference is stepped down from 7 V to 5 V. Similarly, Fig. 6 depicts V_{out}, I_{in}, and V_{in} as the output voltage reference is stepped up from 5 V to 7 V. Based on the converter dynamic response, perturbation sizes of the order of 0.01 V (reduced when operating close to an MPP), and an MPPT update rate of 150 Hz (1/100 of the switching frequency) are chosen. These can be tuned based on the application.

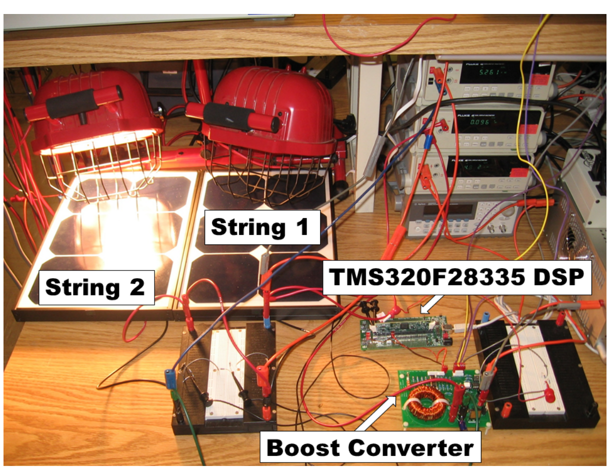

Figure 4. Experimental setup to demonstrate the operation of the MPPT algorithm.

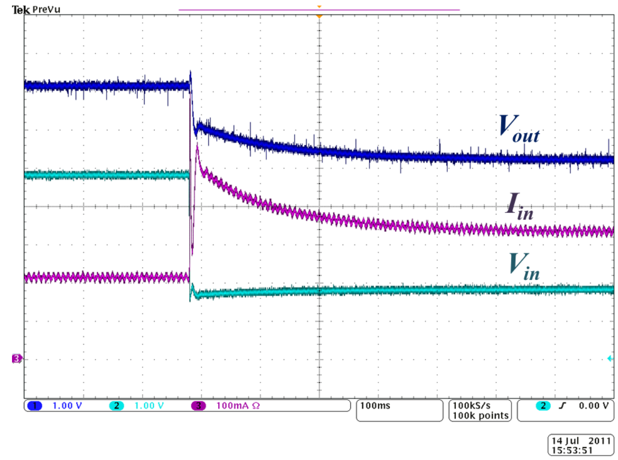

Figure 5. Reference step down from 7 V to 5 V.

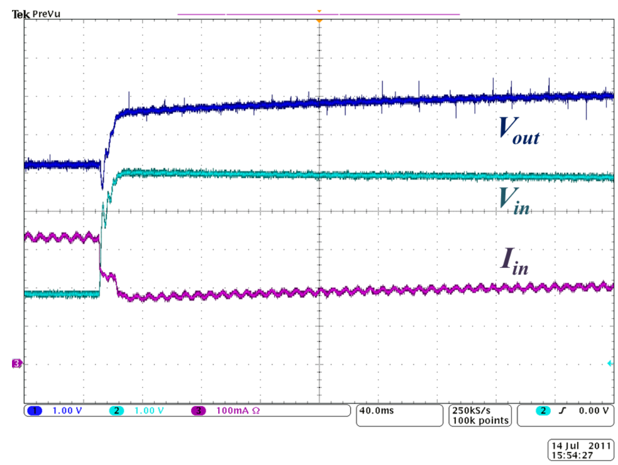

Figure 6. Reference step up from 5 V to 7 V.

C. Performance of the MPPT algorithm

In this section, we evaluate the performance of the MPPT algorithm under two shading conditions: i) cell-level shading, and ii) string-level shading. The setup and results obtained in each case are described next.

1) Cell-level shading: This case investigates the performance of the proposed MPPT technique when a single cell in the PV module is shaded. The shading setup is illustrated in Fig. 7a. Figure 7b plots the output voltage of the boost converter V_{out} (proportional to the output power), as a function of the input voltage $V_{in} = V_1 + V_2$, where V_1 and V_2 are the string voltages illustrated in Fig. 7a. Figure 7c plots the string voltage V_1 as a function of the input voltage V_{in}. In each case, the dashed lines are obtained prior to executing the MPPT algorithm by manually sweeping the duty cycle of the boost converter. This allows us to characterize the setup and obtain a benchmark to validate the MPPT algorithm. As seen in Fig. 7b, there are two maxima in the voltage (and hence the power) profile with the given shading scenario. The maximum to the left is a global maximum, while the maximum to the right is the local maximum. As shown in Fig. 7c, at the

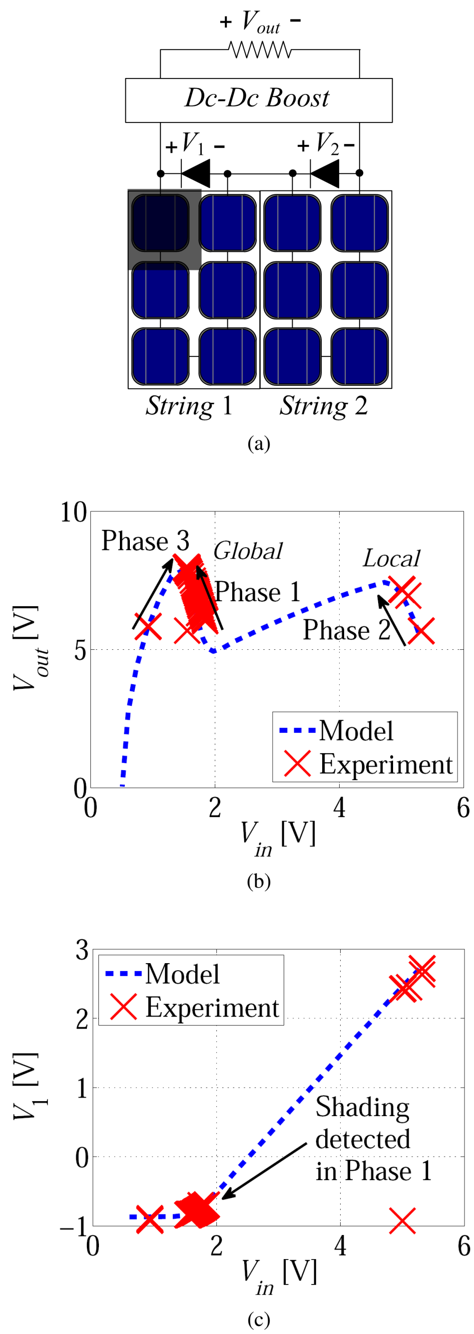

Figure 7. Cell-level shading scenario: (a) Shading setup, (b) V_{out} as a function of V_{in}, (c) V_1 as a function of V_{in}

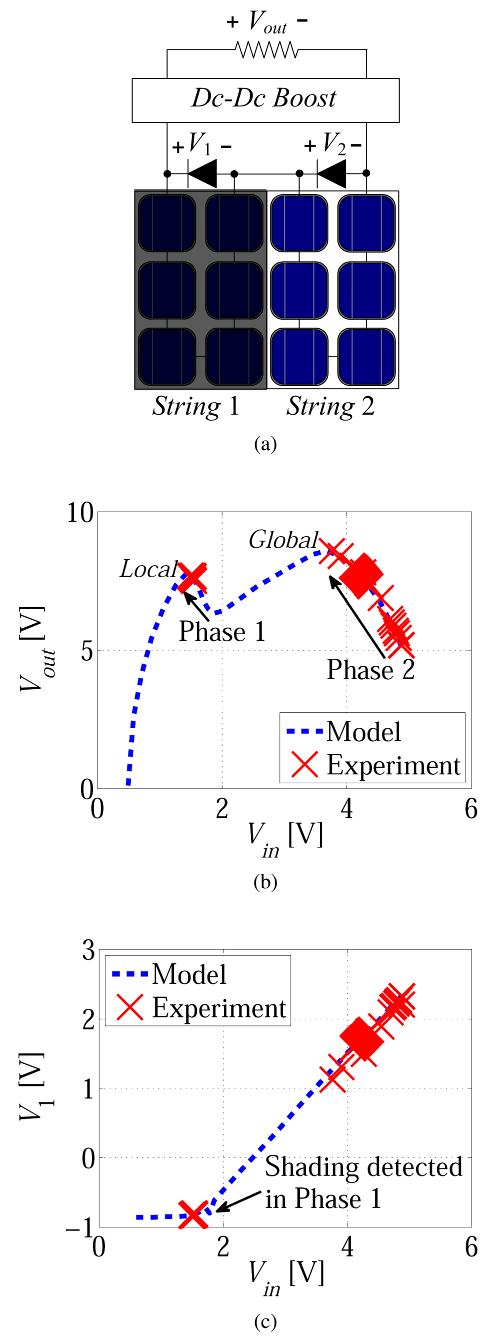

Figure 8. String-level shading scenario: (a) Shading setup, (b) V_{out} as a function of V_{in}, (c) V_1 as a function of V_{in}

global maximum, the bypass diode is on, and the string voltage is negative (i.e., $V_1 < 0$). The experimental results obtained with MPPT initiated are plotted with x's in Figs. 7b-7c. In this setup, the MPPT algorithm tracks the global maximum in three phases. In Phase 1, conventional P&O is implemented with a goal of maximizing the output voltage. At the end of this phase, the controller ensures that the PV module is operating at the maximum on the left (note that at this point, it is unclear if this is a global/local maximum). However, shading is inferred since the string voltage is negative. Therefore, in Phase 2, a global search is initiated (starting with a low value of duty cycle) at the end of which the MPP on the right is found. Comparing the two values of output voltage, it is clear that the MPP found at the end of Phase 1 is the global MPP. Therefore, in Phase 3, MPP is reinitiated (starting with a high duty cycle) and at the end of this phase, the PV module operates at the global MPP. Note that if the controller locked on to the MPP at the right in Phase 1, shading would not have been inferred.

2) String-level shading: This case investigates the performance of the proposed MPPT technique when an entire string in the PV module is shaded. The exact shading setup is illustrated in Fig. 8a. Figure 8b plots the output voltage of the boost converter (proportional to the output power) V_{out}, as a function of the input voltage $V_{in} = V_1 + V_2$, where V_1 and V_2 are the string voltages illustrated in Fig. 8a. Figure 8c plots the string voltage V_1 as a function of the input voltage V_{in}. As before, in each case, the dashed lines are obtained prior to executing the MPPT algorithm by manually sweeping the duty cycle of the converter. As seen in Fig. 8b, there are two maxima in the voltage (and hence the power) profile with the given shading scenario. The maximum to the left is a local maximum, while the maximum to the right is the global maximum. It is clear from Fig. 8c, that at the local maximum, the bypass diode is on, and the string voltage is negative (i.e., $V_1 < 0$). The experimental results obtained with MPPT initiated are plotted with x's in the two figures. The MPPT algorithm tracks the global maximum as follows. In Phase 1, conventional P&O is implemented with a goal of maximizing the output voltage. At the end of this phase, the controller ensures that the PV module is operating at the maximum on the left (note that at this point, it is unclear if this is a global/local maximum). However, since the string voltage is negative, shading is inferred. Therefore, in Phase 2, a global search is initiated (starting with a low value of duty cycle) at the end of which the MPP on the right is found. Comparing the two values of output voltage, it is clear that the MPP found at the end of Phase 2 is the global MPP. Therefore, the MPPT controller continues to operate the PV module at this global maximum. Note that if the controller locked on to the MPP at the right in Phase 1, shading would not be inferred, however, in this case the PV module would be operating at the global MPP.

V. Conclusions and Future Work

A MPPT technique is proposed for module integrated dc-dc/dc-ac converters that have access to the PV-module bypass diode voltages. Partial shading at the sub-module (string/cell) level can be inferred by monitoring the bypass-diode voltages. An exhaustive search to seek the global MPP can be initiated if a bypass diode turns on. As part of ongoing work, we are investigating techniques to detect operation at the local maximum when the corresponding bypass diodes are off.

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