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Enhancement of A Photovoltaic Inverter Efficiency Using A Shade-Tolerant MPPT

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Abstract— **The objective of this paper is to implement experimentally a maximum power point tracking (MPPT) technique on the Solantro DC-PODX Platform under different operating conditions. The MPPT technique operates in two modes. The perturb and observation (P&O) MPPT algorithm functions in a local MPPT mode when PV cells receive uniform irradiance. When the PV array is likely to be partially shaded, a global MPPT (GMPPT) subroutine is called to optimize the PV system operation through finding the absolute peak. The method holds two main features, i.e., i) detecting the occurrence of partial shading on a PV panel using the measurement of the sub-strings voltage and ii) fast and reliable tracking of the true maximum power point. The experimental results confirm that the performance of the PV inverter is considerably enhanced as the partial shading condition (PSC) can be properly detected. In addition, the true peak of the PV array under different PSCs can be reliably tracked, yielding a more efficient PV energy harvest.**

Key Words—photovoltaic systems, shade-tolerant maximum power point tracking, perturb and observe algorithm, partial shading conditions

I. INTRODUCTION

In recent years, photovoltaic (PV) systems integrated into power grid have been gaining popularity as one of the most promising and reliable energies among existing renewable energy sources. PV sources offer several advantages in terms of being clean, renewable and low maintenance. However, the low efficiency of the PV systems often due to their non-linear power-voltage (PV) characteristic and variable atmospheric conditions remains a great challenge. The efficiency of PV systems is considerably affected by local atmospheric conditions such as moving clouds, dust, neighboring buildings and trees. Due to these barriers, PV systems generate lower power [1]. More importantly, PV systems show a lower performance when the solar irradiance is not uniformly distributed over the PV array surface, known as partial shading phenomenon [2]. In fact, the shaded cells could become reverse biased, behaving as a load, and dissipating power from the irradiated cells. The PV manufacturers normally use bypass diodes to prevent hot-spot problem and to stop unproductive cells from disrupting the production of active cells. The PV characteristics become more complicated in partial shading condition (PSC) if the PV array includes bypass diodes [3]. The latter changes the P-V characteristics of PV systems by generating multiple local power maxima [4] . This situation would degrade the efficiency of the PV system significantly if the optimal operation point cannot be effectively tracked [5]. It remains a challenge of global optimization to ensure that PV systems operate at their global maximum power point (GMPP) rather than at the local ones. Therefore, to overcome this main drawback a PV system needs to operate at its maximum power point (MPP). Over recent years, several maximum power point tracking (MPPT) techniques in combination with power electronic devices have been proposed to deliver maximum power from the PV array. These techniques vary in some general parameters such as complexity, accuracy, cost and speed [6]. Among these, Hill climbing [7], Incremental Conductance (IC) [8] perturb and observe (P&O) [9] are the most common used algorithms due to the ease of implementation and their simple control algorithms. Despite of simplicity in operation of theses algorithms, they are unable to find the GMPP under PSC. In order to improve this major drawback, several methods in the family of soft computing techniques. For example, in the field of artificial intelligence techniques, fuzzy logic controllers [10], artificial neural-network [11] methods have shown effective solution in dealing with the nonlinear characteristics of the current-voltage (I-V) curve, in particular, under PSC. However, they require extensive computation to deal with the complex operating process including fuzzification, defuzzification, and rule-based storage and interface mechanism. In addition, they need a large amount of data for training that is more critical when the PV pattern varies with changes in insolation and temperature. Thus, the implementation of powerful high-cost processors in these methods is inevitable. The evolutional algorithm (EA) techniques as a stochastic optimization methods appear to be very efficient in tracking the MPP [8, 9]. The EA is able to find the global peak regardless of insolation pattern as it is based on search optimization. Despite the remarkable accuracy of the EA methods compared to conventional MPPT

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algorithm under PSC, the time required for convergence is still long. Methods in [12, 13] could achieve a successful GMPPT by smoothly sweeping all the possible operating points of the P-V curve. In [14], the multi-peak PV characteristic is split into several single-peak curves based on a PV equivalent model. Then, an improved beta GMPPT algorithm is proposed. However, the value of beta and its bounding range depend on the environmental conditions such as irradiance and temperature. The method also needs information about the configuration of the PV array.

This work aims at improving the efficiency of the DC-POD platform through a MPPT controller to track the global peak of a PV panel under partial shading. When the PV array is partially shaded, a global MPPT (GMPPT) subroutine scans the PV profile to optimize the PV system operation. The method is capable of detecting the occurrence of partial shading on PV panels using the measurement of the sub-strings voltage. Hence, the GMPPT subroutine is called only if the PV panel is shaded. This useful feature prevents unwanted restarting of the GMPPT subroutine and associated loss of energy under uniform irradiance condition. The MPPT method is successfully implemented in the Solantro DC-PODX Platform under different operating conditions.

The orientation of the paper is organized as follows: the partial shading detection is firstly presented in section II. Section III presents the improved MPPT controller. It is followed by the experimental results in section IV. Finally, the concluding remarks are presented in section V.

II. PARTIAL SHADING DETECTION

Fig. 1 shows a PV panel consisting of three sub-strings connected to the DC-POD platform [15]. Fig. 2 illustrates typical P-V and I-V curves when the PV panel is irradiated uniformly. To detect the PSC, a technique, based on the MPPT technique proposed in [16] for detecting the onset of partial shading, based on previous and present values of the MPP voltage is implemented. The P&O MPPT tracks the single peak of the P-V curve, and the three sub-strings would equally contribute to the output voltage of the PV panel. In other words, the operating voltage of the sub-strings would be almost equal under uniform irradiance condition. This is verified with several readings from Helios with a real PV panel in Fig. 3. However, this state changes when there is a partial shading on a PV panel. Fig. 4, as an example, illustrates the I-V and P-V curves of the PV panel when one sub-string is shaded. The two unshaded sub-strings are exposed to an irradiance of 900 W/m^2 and the shaded sub-string is exposed to an irradiance of 200 W/m^2. The resultant P-V curve possesses two peaks: a local peak and a global peak. The P&O MPPT cannot distinguish between the peaks and may track the rightmost local peak. At this point, the operating voltage of the sub-strings exposed to different irradiance levels are different. In the case of Fig. 4, the operating voltage of the sub-strings are: VSTR1=11.7 V, VSTR2=14.5 V, and VSTR3=14.5 V. Hence, the mismatch in operating voltage of the sub-strings could be a very useful indication to detect the existence of shading on a PV panel connected to the DC-POD. This is verified with several readings from Helios with a real PV panel under shading condition in Fig. 5.

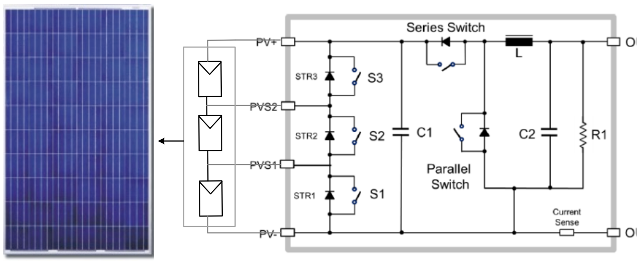


Fig. 1. Functional block diagram of a PV panel connected to the DC-POD.

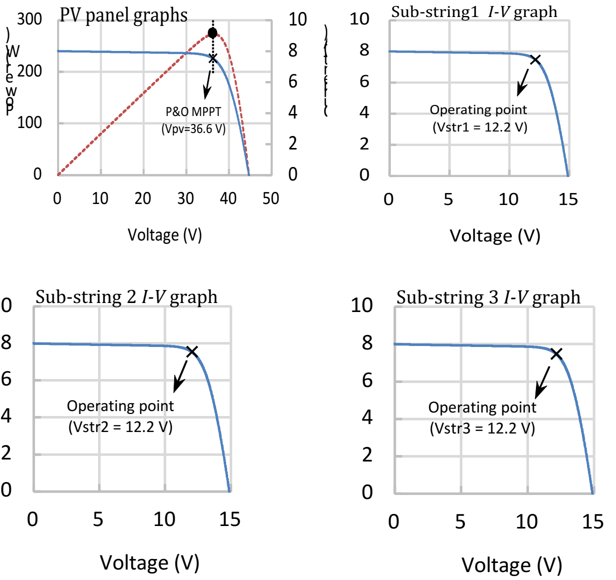
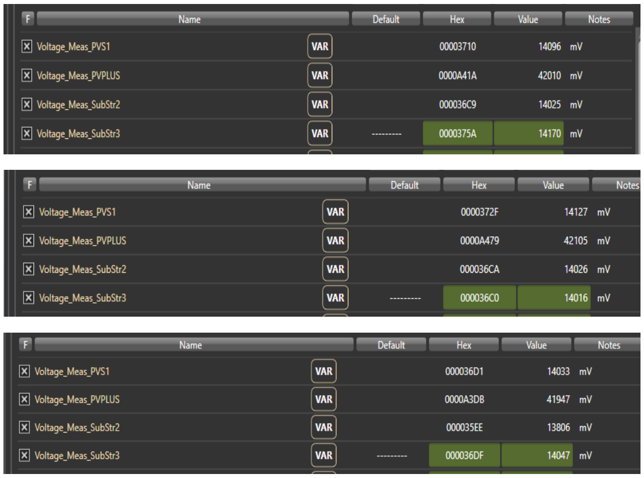


Fig. 2. PV graphs for a typical panel with three sub-strings under uniform irradiance condition of 900 W/m^2.



F	Name		Default	Hex	Value	Notes
☒	Voltage_Meas_PVS1	VAR		00003710	14096	mV
☒	Voltage_Meas_PVPLUS	VAR		0000A41A	42010	mV
☒	Voltage_Meas_SubStr2	VAR		000036C9	14025	mV
☒	Voltage_Meas_SubStr3	VAR	---------	0000375A	14170	mV

F	Name		Default	Hex	Value	Notes
☒	Voltage_Meas_PVS1	VAR		0000372F	14127	mV
☒	Voltage_Meas_PVPLUS	VAR		0000A479	42105	mV
☒	Voltage_Meas_SubStr2	VAR		000036CA	14026	mV
☒	Voltage_Meas_SubStr3	VAR	---------	000036C0	14016	mV

F	Name		Default	Hex	Value	Notes
☒	Voltage_Meas_PVS1	VAR		000036D1	14033	mV
☒	Voltage_Meas_PVPLUS	VAR		0000A3DB	41947	mV
☒	Voltage_Meas_SubStr2	VAR		000035EE	13806	mV
☒	Voltage_Meas_SubStr3	VAR	---------	000036DF	14047	mV

Fig. 3. Different readings from Helios with a real PV panel under uniform irradiance condition showing almost equal sub-strings voltage.

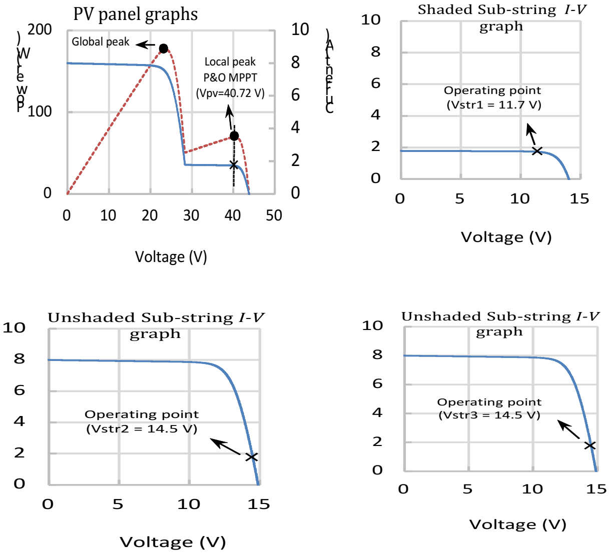
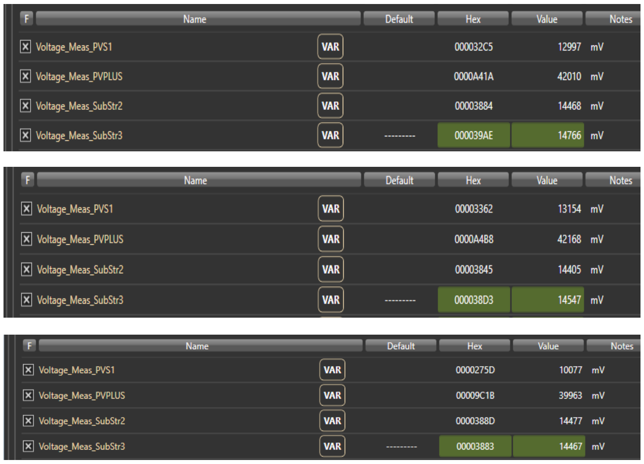


Fig. 4. PV graphs for a typical panel with three sub-strings under PSC.



F	Name		Default	Hex	Value	Notes
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☒	Voltage_Meas_PVPLUS	VAR		0000A41A	42010	mV
☒	Voltage_Meas_SubStr2	VAR		00003884	14468	mV
☒	Voltage_Meas_SubStr3	VAR	---------	000039AE	14766	mV

F	Name		Default	Hex	Value	Notes
☒	Voltage_Meas_PVS1	VAR		00003362	13154	mV
☒	Voltage_Meas_PVPLUS	VAR		0000A4B8	42168	mV
☒	Voltage_Meas_SubStr2	VAR		00003845	14405	mV
☒	Voltage_Meas_SubStr3	VAR	---------	000038D3	14547	mV

F	Name		Default	Hex	Value	Notes
☒	Voltage_Meas_PVS1	VAR		0000275D	10077	mV
☒	Voltage_Meas_PVPLUS	VAR		00009C1B	39963	mV
☒	Voltage_Meas_SubStr2	VAR		0000388D	14477	mV
☒	Voltage_Meas_SubStr3	VAR	---------	00003883	14467	mV

Fig. 5. Different readings from Helios with a real PV panel when one substring is partly shadowed with paper sheets showing a mismatch among sub-strings voltage.

III. MPPT CONTROLLER

Fig. 6 shows the flowchart of the improved MPPT algorithm based on the MPPT technique proposed in [16] . A timer program is used to ensure regular checking of the shading condition (Block 3) through a comparison among the voltage of the sub-strings (Block 4). If there is not a partial shading on the PV panel, the Shading_flag remains 0 and the variable step-size P&O MPPT maintains the operation at the maximum power point under uniform irradiance (Block 7). When the absolute difference between any two of VSTR1, VSTR2, or VSTR3 is greater than a predetermined constant (used to eliminate sample disturbance and minor differences due to slight changes in irradiance), the Shading_flag is set to 1 (Block 5) and the main program calls the GMPPT subroutine (Block 8).

The basic concept of the GMPPT is to simply sweep the MPPT voltage range using an adjustable ramp change of duty-cycle. The procedure of the GMPPT mode is demonstrated with an example in Fig. 7. First, the right-hand-side of the present operating point is scanned (Block 15). When the operating point reaches a point near the open-circuit voltage (Block 10), the scanning direction is reversed (Block 11). Hereafter, the DC-POD smoothly goes through the operating points of a PV panel starting from the point near the open-circuit voltage towards left (Block 16). The scanning process is finished at a predefined minimum MPPT voltage (Block 12). During the GMPPT scanning, the controller records the duty-cycle associated with the global maximum peak (Block 17 & 18). After the scanning process (Block 12), the GMPPT function moves the operating point of the converter to the true global peak and clears the Shading_flag to 0 (Block 13), and then passes the control onto the main program, where the P&O MPPT maintains the operation at this new global peak.

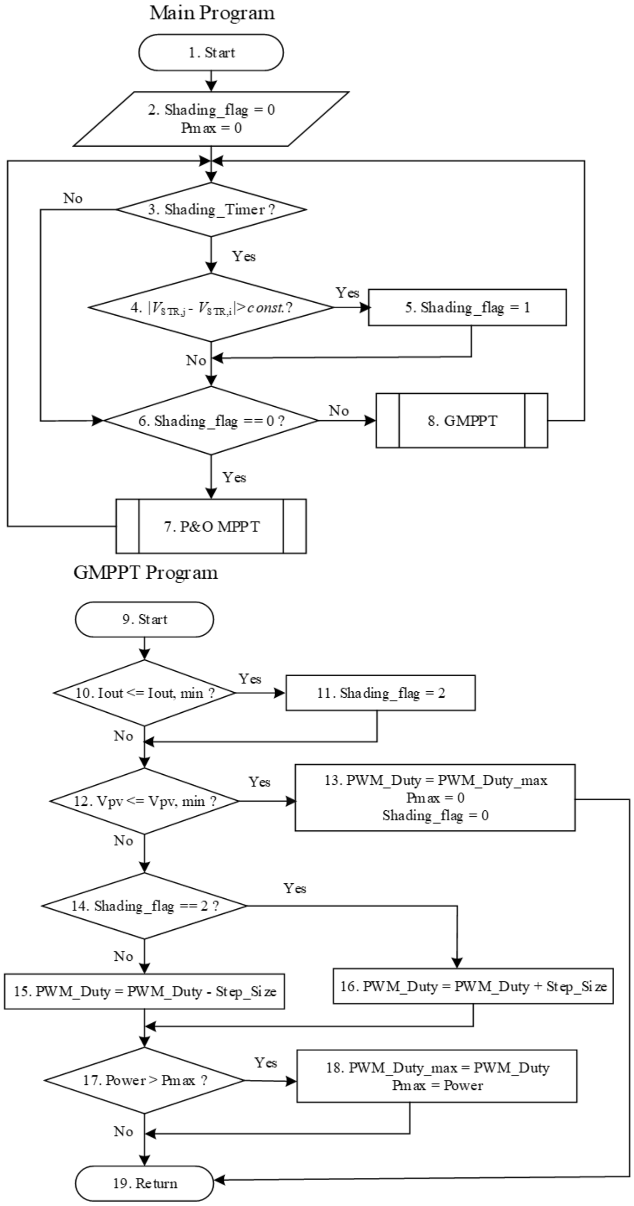


Fig. 6. Flowchart of the improved shade-tolerant MPPT algorithm.

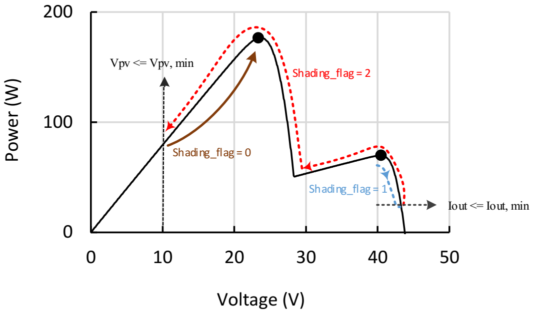


Fig. 7. Tracking principle of the GMPPT mode for a shaded PV characteristic.

IV. RESULTS AND DISCUSSION

In order to verify the effectiveness of the improved MPPT, a PV panel with three sub-strings is simulated in the TerraSAS PV simulator. Fig. 8 shows the experimental setup. Two partial shading cases are examined as presented in Table I where the sub-strings receive different levels of irradiance.

Fig. 9 shows the results for Case 1 where the P-V curve exhibits two peaks. When this shading condition happens, the P&O will continue to track the right-most peak at the point (1.55 A, 41 V, 63.54 W), as shown in Fig. 9(a), and the efficiency drops significantly. Thereafter, the GMPPT subroutine is called and track the true maximum peak at point (4.69 A, 26 V, 122.35 W), as shown in Fig. 9(b), and the efficiency recovers to more than 99%. Fig. 9(c) illustrates the experimental waveforms. After sweeping the PV profile, the algorithm returns the operating point to the global peak (left-most peak in this case), and the P&O MPPT will make fine adjustments. The expanded waveforms for Case 1 are shown in Fig. 10 to show the sweeping process during the GMPPT mode. The speed of the GMPPT mode can be adjusted by varying the step-size of duty-cycle during the search process. The GMPPT mode can find the global peak very quickly, less than 100 ms.

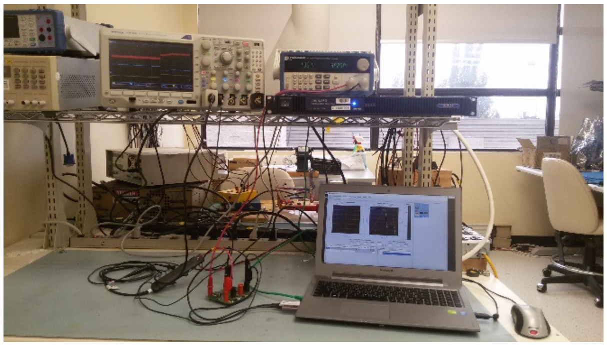
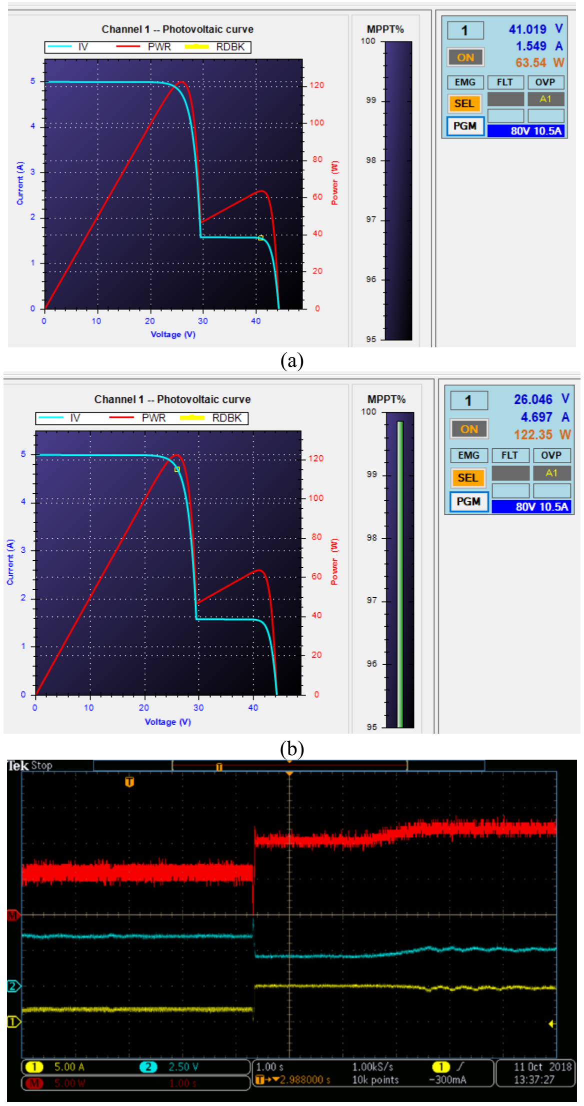


Fig. 8. Experimental setup.

1. TABLE I. DIFFERENT PARTIAL SHADING CASES

	Sub-string1 (W/m^2)	Sub-string2 (W/m^2)	Sub-string3 (W/m^2)
Case 1	300	1000	1000
Case 2	50	150	1000



(c)

Fig. 9. Experimental results for case 1 (a) operating point on PV profile before GMPPT, (b) operating point on PV profile after GMPPT, (c) Experimental waveforms.

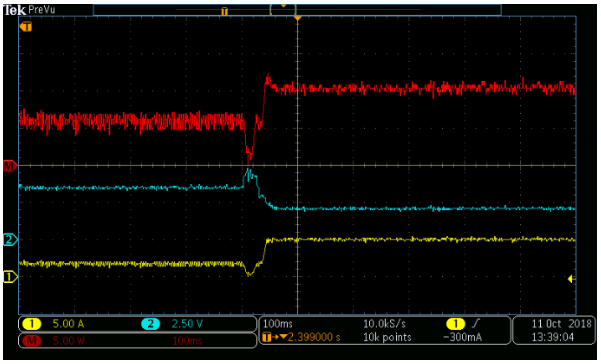
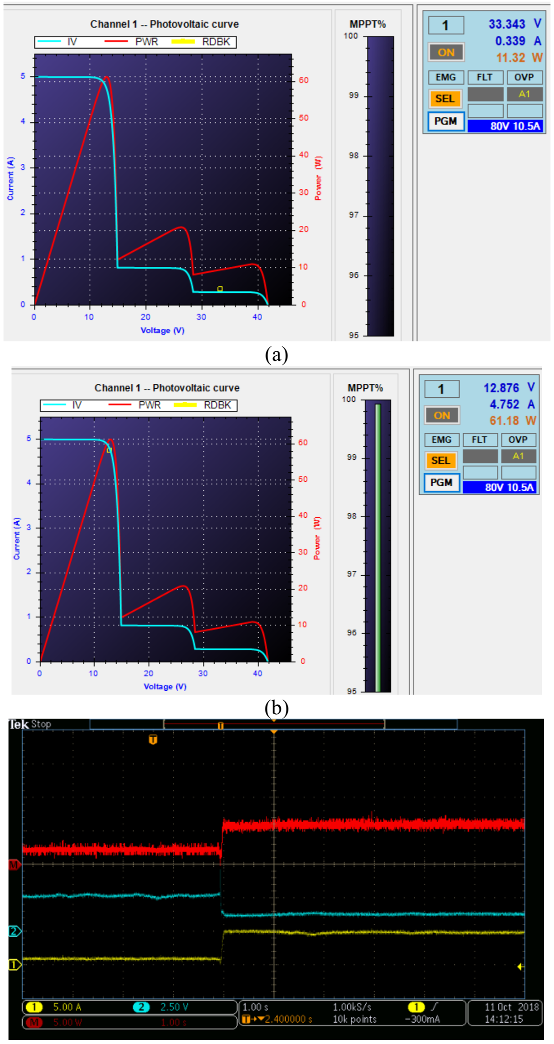


Fig. 10. Expanded waveforms for Case 1.



(a)

(b)

(c)

Fig. 11. Experimental results for case 2 (a) operating point on PV profile before GMPPT, (b) operating point on PV profile after GMPPT, (c) Experimental waveforms.

Fig. 11 shows the results for Case 2 where the P-V curve exhibits three peaks. In this PSC, the P&O method tracks either of the local peaks, as shown in Fig. 11(a), and the efficiency drops significantly. Thereafter, the GMPPT subroutine is called and track the true peak at point (4.7 A, 12.8 V, 61.18 W), as shown in Fig. 11(b). Fig. 11(c) illustrates the experimental waveforms.

V. CONCLUSION

The MPPT program of the DC-POD platform was improved to maximize the PV system energy production under partial shading. The MPPT program scans the PV profile to optimize the PV system operation under shading condition. The MPPT program can recognize the occurrence of the shading on a PV panel by comparing the voltage readings of sub-strings. Moreover, when a PV panel is partially shaded, it reliably tracks the global peak in less than 100 ms. Hence, a faster GMPPT with a reduced search space considerably lessens the associated energy loss that can improve the efficiency of the PV inverter considerably.

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