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Implementation of a Switched PV Technique for Rooftop 2 kW Solar PV to Enhance Power during Unavoidable Partial Shading Conditions

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Abstract

We propose maximum power extraction from a rooftop solar photovoltaic (PV) array during partial shading conditions. Partial shading is unavoidable during power extraction from rooftop PV systems due to nearby tall buildings (construction of additional floors) and trees (growth of trees). Many reconfiguration techniques can be used to extract maximum power in partial shading conditions, but in several cases, the real maximum power output is not achieved. In this study, a new switched PV technique is proposed to enhance the power output. The proposed technique is simple to use and more cost effective than other reconfiguration techniques. Therefore, it is suitable for rooftop applications. The power output of the proposed technique is compared with that of existing techniques with similar shading patterns. Eight panels with ratings of 250 watts (2 kW) each are used for testing. MATLAB simulation and hardware verification are done for the proposed and existing techniques. The proposed technique is implemented on a 4×2 PV array, although it can be extended to a number of arrays.

Key words: Maximum Power Point (MPP), Partial Shading, Reconfiguration, Solar PV

I. Introduction

Solar power is an immense energy resource. Abundant solar power is a result of nuclear fusion reaction in the sun. Solar power can be harvested in many ways, one of which is by using photovoltaic (PV) panels. These panels operate based on the PV effect. Power is generated when sunlight falls on PV panels. The power output is reduced when irradiation is lacking. This lack of irradiation is due to the uneven falling of sunlight on Earth. Another reason for power reduction is the shading effect, which emerges when trees, buildings, clouds, and other factors interfere with sunlight.

Shading affects power extraction from PV panels. Maximum power point tracking (MPPT), reconfiguration, and reallocation are common techniques used to obtain maximum power even in conditions of partial shading. However, the shifted PV array technique and module reconfiguration require many conductors and considerable manpower to obtain maximum power [1], [2]. The Sudoku pattern of reconfiguration and positioning may produce maximum power, but it is too complex to construct [3]. The couple-matching best-generation algorithm for partially shaded conditions can produce ideal maximum power, but the cost of switching matching circuits is comparatively high [4]. Reconfiguration of aged solar PVs is highly effective but requires detailed analyses of panel conditions [5]. The maximum power point (MPP) technique tracks the point at which maximum power is produced [6]. It searches for MPP to obtain peak power that is comparable to that obtained at the previous best point. This technique is well suited for PV

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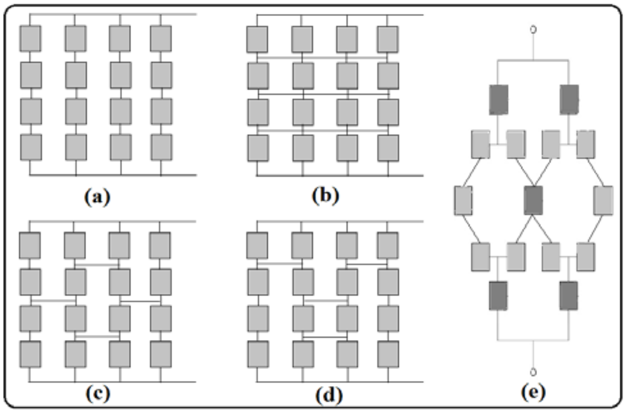

Fig. 1. Types of connection configurations: (a) series parallel, (b) total cross tied, (c) bridge linked, and (d) honeycomb with (e) the structure of the honeycomb.

panels under normal conditions because of the unique MPP, and it is an effective technique for extracting maximum power. However, in partial shading conditions, PV panels have various operating points. Therefore, locating the global maximum power point (GMPP) from various local maxima is difficult for the MPPT technique [7].

Conventional MPPT techniques may fail to find GMPP due to partial shading [8]. Many artificial intelligence techniques have been developed to avoid this tracking problem [9]-[11] and ensure rapid convergence. Four types of configuration (Fig. 1) are adopted in practice for conventional PV power systems. These four types are series parallel (SP), total cross tied (TCT), bridge linked (BL), and honeycomb (HC). The various types of inverters typically utilized for conventional PV systems are central-type inverters, string-type inverters, PV-integrated converters (i.e., separate MPPT converters), and differential power processing (DPP)-based solar PV systems [12], [13].

Modeling of PV cells for simulation was conducted in this study using a single-diode model and its equivalent circuit (Fig. 2). In Fig. 2, PV is a current source given as I_g, resistance is denoted by series R_s, the diode is denoted by D, and R_s refers to the internal resistance of a PV cell. The difference between diode current I_D and photocurrent I_g is net current I_{PV} from the solar PV cell, and it is expressed as

$$I_{PV} = I_g - I_S\,(\exp\,(q(V_{PV}+I_{PV}.R_s))/\,nkT) - 1\,), \quad (1)$$

where

n – diode ideality factor,
k – Boltzmann's constant,
q – electron charge,
T – temperature in °C,
I_S – saturation current.

The solar cell model was used to build a PV array of 2 kW in MATLAB/SIMULINK, and the shading levels were determined by varying the values of irradiance. The four main types of connection configurations are possible with this model [14]. Voltage mismatch frequently occurs in a

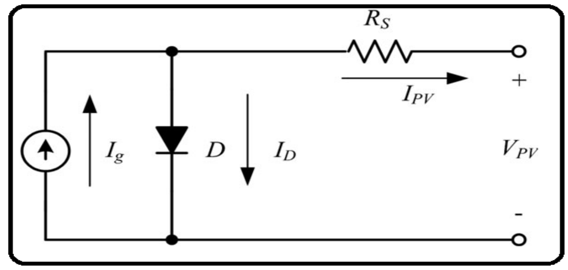

Fig. 2. Equivalent circuit of a single-diode PV cell.

string-connected DC bus due to partial shading. This mismatch in voltage causes a large loss in output, and several inverter-based techniques are utilized to reduce mismatch loss [12], [13].

Central-type inverters cannot extract all the power from a PV array due to mismatch loss during shading. However, central-type inverters are simpler and more reliable than other converters, including string-type inverters in which each string has its own inverter in the PV array. When shading is present, string-type inverters provide individual string MPPT to reduce mismatch losses. An integrated PV converter is connected to an individual PV panel to allow MPPT to extract the exact maximum power. The full power of each module is processed by this type of integrated converter. Meanwhile, the differential power processing-based solar PV system has become highly efficient recently [15]; it extracts the maximum power, but it is not cost effective. Shunt-series compensation in partial shading conditions has been proposed for extracting maximum power [16], but it requires many switches. Many other algorithms and approaches have been developed [17]-[23] to extract maximum power in partial shading conditions. An example is dynamic electrical reconfiguration [17] of PV panels for maximum power extraction. However, this approach requires a large number of switches in the switching matrix circuit, which is a major drawback.

In this work, a smart-switched PV technique is proposed to boost power extraction from PV arrays in partial shading conditions. The proposed technique can also be used for domestic applications. It can be easily applied to conventional and modern solar PV systems. In this approach, we assumed a conventional PV system with an ($m \times n$) panel dimension (i.e., m number of series-connected panels in a string and n number of parallel-connected panels in a string).

In the proposed technique, in partial shading conditions, each m string panel is reconfigured as two parallel strings with $m/2$ number of panels in each string, thus forming an array with a dimension equal to ($m/2 \times 2n$). Therefore, the n number of parallel-connected panels is automatically doubled to $2n$. Owing to this array reconfiguration, the entire system extracts better maximum power in partial shading conditions than conventional configurations; furthermore, the parallel-connected panels are invulnerable to uneven shading

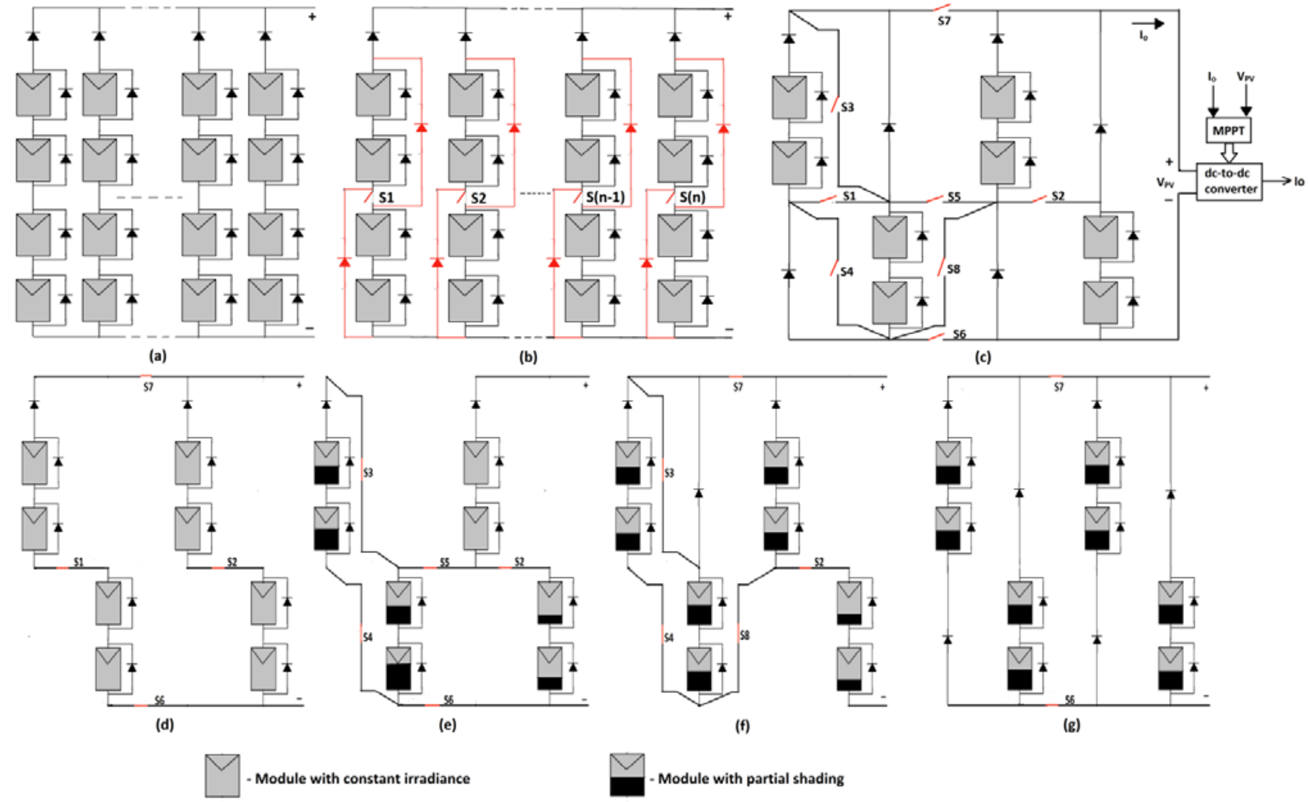

Fig. 3. Altering a conventional PV system to a switched PV system. (a) Existing PV array, (b) proposed reconfiguration by the switching system, (c) Mode 1: switches S1 and S2 are closed (constant irradiance on all string modules), (d) Mode 2: switch S1 is opened and switch S2 is closed (partial shading on the second string modules), (e) Mode 3: switch S1 is opened and switch S2 is closed (partial shading on the first string modules), and (f) Mode 4: switches S1 and S2 are opened (partial shading on all string modules).

[24]-[28]. When the array dimension is changed by switching (i.e., ($m \times n$) to ($m/2 \times 2n$)), the parallel paths are increased to $2n$, which in turn increases the output short-circuit current from the array. The maximum short circuit is constrained to an allowable safe limit in accordance with predefined current of the system. This setup reduces conductor and converter sizes. The selection of this reconfiguration dimension was based on the power production in partial shading conditions; the dimension may vary for high power production in relation to irradiance. Fig. 3(a) shows the existing PV configuration in SP with a by-pass diode in each panel.

The proposed technique was simulated with MATLAB and verified experimentally. The proposed switched PV technique is simple to use and more cost effective for household applications than other reconfiguration methods. This technique can also be easily incorporated into conventional PV systems with multiple arrays for use on partial-shading and cloudy days. The following sections present a detailed explanation of the proposed approach along with the simulation and experimental results. The discussions and findings prove that the proposed approach effectively enhances the maximum extracted power output.

II. Proposed Technique – Switched PV

In the proposed switched PV, each leg is divided into two strings with an equal number of panels by switching the reconfiguration, as shown in Fig. 3(b). A string is divided by a single controlled switch (S_1 and S_2 primary switches) placed at the center of each string. ($n+1$) diodes are required for each leg. Primary switches play a major role in the switching system depending on the irradiance. Each string is separated by a switch, as shown in Fig. 3(b). The switching connection of the proposed system is also shown in this figure. The remaining switches, namely, the secondary switches, are used only to reconfigure the panels depending on the requirements of the primary switches. The number of panels equals the number of switches, that is, eight panels and eight switches are used in the proposed system. Similarly, n number of panels use n number of switches. The switches and diodes used are rated with half of the panel's short-circuit current and open-circuit voltage. This system is proposed for a 4 × 2 PV array. The rating of each panel is shown in Table II. The proposed system of topology has four modes of operation and is illustrated in the following sections as modes 1 to 4 (Table I). The modes may increase or decrease depending on the number of switches used (i.e., 2^i modes). Two switches are used; hence, the number of modes is four. Fig. 4 provides an illustration of different shading levels in a PV array caused by nearby buildings at different time intervals.

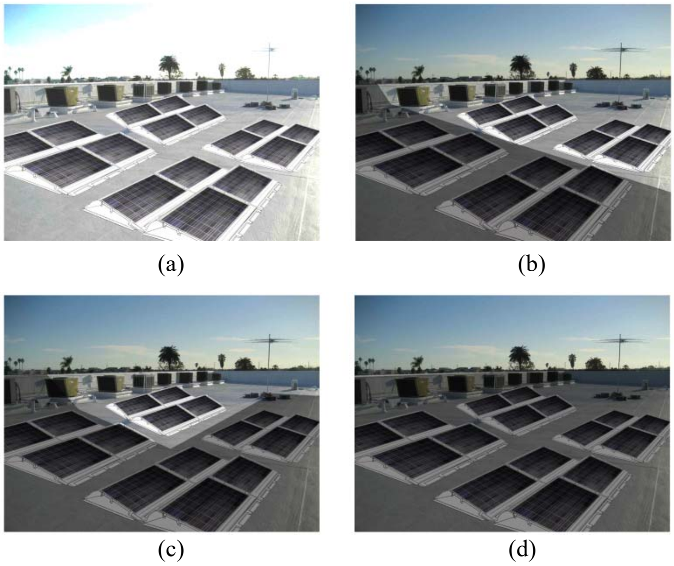

Fig. 4. Illustration of a 4 × 4 PV array with different unavoidable shading levels caused by nearby buildings: (a) PV array with no shading, (b) shading in one string of the array, (c) shading in all strings, and (d) fully shaded PV array.

TABLE I
DIFFERENT PV SWITCHING MODES

	Switching Logic							
Modes	S1	S2	S3	S4	S5	S6	S7	S8
Mode 1	1	1	0	0	0	1	1	0
Mode 2	0	1	1	1	1	1	0	0
Mode 3	0	1	1	1	0	0	1	1
Mode 4	0	0	0	0	0	1	1	0

TABLE II
PANEL DETAILS IN STANDARD TESTING CONDITIONS

S. No.	Parameters	Rating
1	Maximum power (P_{max})	250 W
2	Voltage at maximum power (V_{max})	30.7 V
3	Current at maximum power (I_{max})	8.15 A
4	Open circuit voltage (V_{oc})	37.4 V
5	Short circuit current (I_{sc})	8.63 A

A. Mode 1

Table 1 shows the various switching logics of the reconfiguration. In mode 1, primary switches S_1 and S_2 are closed (Fig. 3(c)). This mode illustrates full irradiance without partial shading on the PV array, which is typical in conventional connections. In this mode, V_{oc} is designated as the possible maximum voltage output, and nI_{sc} is the possible maximum current output (i.e., short-circuit current multiplied by the number of parallel-connected panels in a string). The output values must be able to withstand the converter.

B. Modes 2 and 3

Mode 1 is activated only when the PV array is unshaded. In comparison, partial shading on any of the strings causes the system to activate either mode 2 or 3, as shown in Fig. 3(d) and Fig. 3(e), respectively. Mode 2 is activated when partial shading occurs fully on the first string and the lower part of the second string. The shaded parts are reconfigured to the parallel-connected circuit and then to the series-connected less-irradiated part of the string (Fig. 3(d)). Mode 3 is activated when partial shading occurs fully on the first string and in the upper part of the second string. Mode 2 opens switch S_1 and keeps switch S_2 closed (partial shading on the second string modules). Mode 3 opens switch S_1 and keeps switch S_2 closed (partial shading on the first string modules). In these modes, the voltage in the partially shaded leg is reduced to half of the maximum open-circuit voltage (i.e., $V_{oc}/2$). The current in the partially shaded leg is equal to the sum of the divided short circuit currents of the string (i.e., $2I_{sc}$).

C. Mode 4

When all the panels in the PV array are partially shaded, mode 4 is activated, that is, the primary switches are open (Fig. 3(f)). In this mode, only half of the V_{oc} from the PV array is generated as the maximum voltage output (i.e., $V_{oc}/2$). The maximum current output is twice the I_{sc} of the panel multiplied by the number of legs (i.e., $2nI_{sc}$). Mode 4 increases conductor and converter sizes because of the maximum short-circuit current rating. The size increase is the only drawback of the proposed technique, but it is ultimately compensated for by MPPT. The size increase also limits the reference current output to the current rating of the semiconductor. As a process, current limiting is expressed as nkI_{sc}, where k is a constant given as $1 < k < k_{max}$ and k_{max} is a value that does not exceed 2 ($k_{max} < 2$). In addition, K is a current-limiting factor used to maintain the array current output below the rated value to avoid damaging the conductor. The possible maximum voltage output of mode 4 is nearly equal to the semi of the maximum voltage output of mode 1.

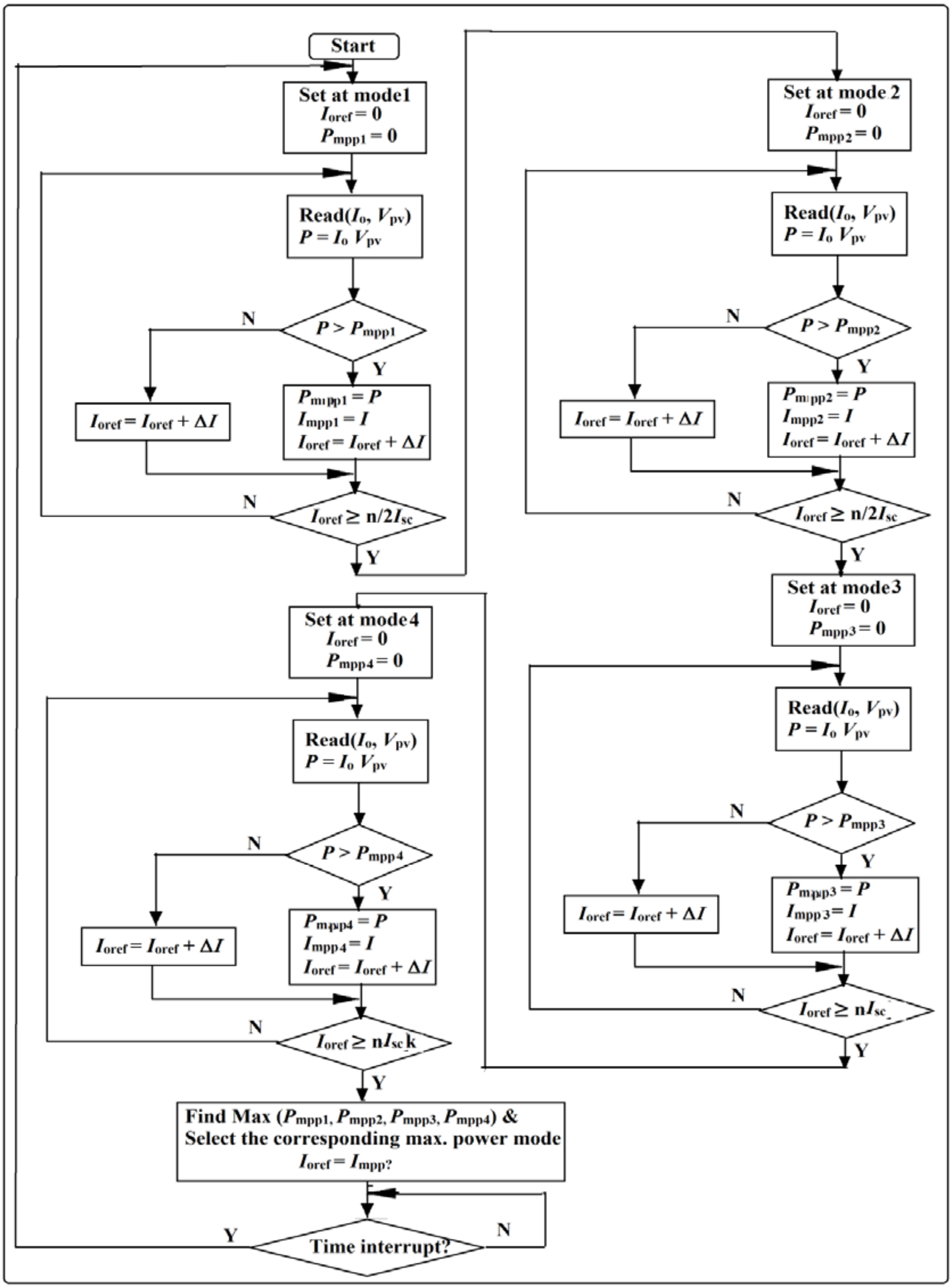

Fig. 5. MPPT and switching algorithm for the proposed concept.

Hence, the converter used should have both bucking and boosting capabilities to provide power successfully to resistive and battery loads irrespective of the voltage input. The converter used in this work was of SEPIC type, which can satisfy these needs. A SEPIC converter draws the required current from PVs with similar input and output voltage polarities to ensure a continuous current input. For two-stage conversion applications, such as grid connections or three-phase AC loads, SEPIC or boost DC–DC converters are used with three-phase voltage source inverters or single-stage quasi Z-source inverters.

D. Mode Selection

In partial shading conditions, the power generated in the proposed PV system (modes 2, 3, and 4) should be higher than that in the conventional PV connection (mode 1) depending on the k value. Mode selection was implemented with MPPT. First, the MPPT algorithm switches to mode 1 and saves the maximum power in the mode as P_{max1}. Similarly, this algorithm switches to all other modes and saves the maximum powers of the corresponding modes as P_{max2}, P_{max3}, and P_{max4}. Second, the MPPT algorithm settles at the corresponding mode that produces the maximum power. MPPT runs routinely at predetermined time intervals using a timer flag that updates the powers in the modes for varying shading conditions. Fig. 5 presents the flowchart of the MPPT algorithm and the switching of various modes depending on the shading levels. In normal PV panels, current is directly proportional to irradiance. Hence, the rated current output corresponding to irradiance was compared with the real output to determine the levels of partial shading. In this algorithm, I_{oref}, the current output from PV, is used as a reference; I_o is the actual current output from PV; V_{PV} is the voltage output from PV; P is the power output from PV; ΔI is the increment current; I_{sc} is the PV short-circuit current; k is a constant ($1 < k < k_{max}$); and P_{max1}, P_{max2}, P_{max3}, and P_{max4} are the powers at GMPP in modes 1, 2, 3, and 4, respectively.

E. Effects of Converter Rating in the Proposed Technique

Except for that in mode 4, the current ratings of the semiconductor switches in the three other modes do not exceed 150%. However, in the mode 4 reconfiguration, the current rating exceeds $nI_{sc}k_{max}$. By limiting the value of k to 1.5, the current rating is maintained at 150% as the maximum.

F. Example of the Proposed Approach

The proposed switched PV technique was applied to a 2 kW PV array with 4 × 2 dimensions. The irradiance of each panel differed in the PV array (i.e., the array is in a partially shaded condition). Partial shading is unavoidable in rooftop solar PVs because of nearby trees and high buildings. The system outputs of the proposed method for different cases and modes are shown in Fig. 6. Initially, the system was operated in mode 1 (no partial shading), similar to a conventional connection method. The output of mode 1 is shown in Fig. 6(a). For the varying irradiance level, the same system was operated with the proposed switched PV technique, and the corresponding output is also shown. A different shading pattern of a PV array by nearby buildings is shown in Fig. 4, and these shading patterns occur at various time intervals. The proposed 2 kW PV array is shown in Fig. 7. In the simulation output shown in Fig. 6(a), case 1 has no shading, and no local MPPs (LMMPs) occur. Only one MPP exists; the power at this point is 1,950 W, and the point operates in mode 1 and depends on the irradiance on the panels in the array.

Case 2, which operates in mode 2 with the GMPP of all LMPPs, was then analyzed. The power from the proposed method was 895 W. This power is comparatively higher than that of other methods of configuration, as shown in Fig. 6(b). Similarly, cases 5 and 8 were analyzed. They operate in modes 3 and mode 4 and produce 1,115 and 610 W of power, respectively, as shown in Figs. 6(c) and 6(d). In partial shading conditions, the power from the proposed method is higher than that of the conventional connection system. For the illustrated case, the current is less than $2I_{sc}$ at the maximum power of the proposed method. This finding was proven by the other cases of shading patterns (shown in Table III).

III. Proposed System Assessment

A case study was conducted to compare the proposed system with other available methods in various shading conditions (Table III). This comparison also aims to establish the pros and cons of the proposed technique. Rooftop PV arrays can be permanently affected by partial shading caused by nearby trees and high buildings. A number of cases were considered for MPPT assessment, simulated in MATLAB, and verified for hardware application. For this assessment, a PV array with two legs was considered. Each leg has four panels (8 modules in total).

The ratings of the panels are listed in Table II. Eight shading patterns were considered, and the shading patterns were created by varying the insulation level on each panel (Table III). The proposed scheme and an existing method were assessed, and the total powers extracted with both methods are shown in Table IV (a lossless system was assumed). A detailed analysis was performed for the proposed approach with different types of configuration (Fig. 1). A central inverter can extract the maximum power, which is the global MPP power of the PV array characteristics. However, in the case of a string inverter, the maximum power is the sum of individual string global MPP power. In integrated and DPP-based converter systems, the maximum power is the sum of the global MPP power of the individual panel or module. To obtain the highest extracted power from the PV array in all modes by using the proposed switched PV method, the values of k was set to 1.33 (k = 1.33). The maximum current to the converter in mode 4 is 33% higher than the maximum current in mode 1. The enhanced powers for all the aforementioned converter types and those for the proposed method are listed in Table IV.

The results in Table IV show that all of the previously established connection configuration methods can produce the same maximum power in the no shading condition (i.e., 1000 W/m^2). At varying irradiation levels (partial shading conditions), the TCT configuration-based solar PV system produces the highest power among the techniques. The results prove that the proposed switched PV approach can produce higher maximum power during partial shading compared with the central-type inverter scheme. Depending on the value of k and the shading pattern, the string-type

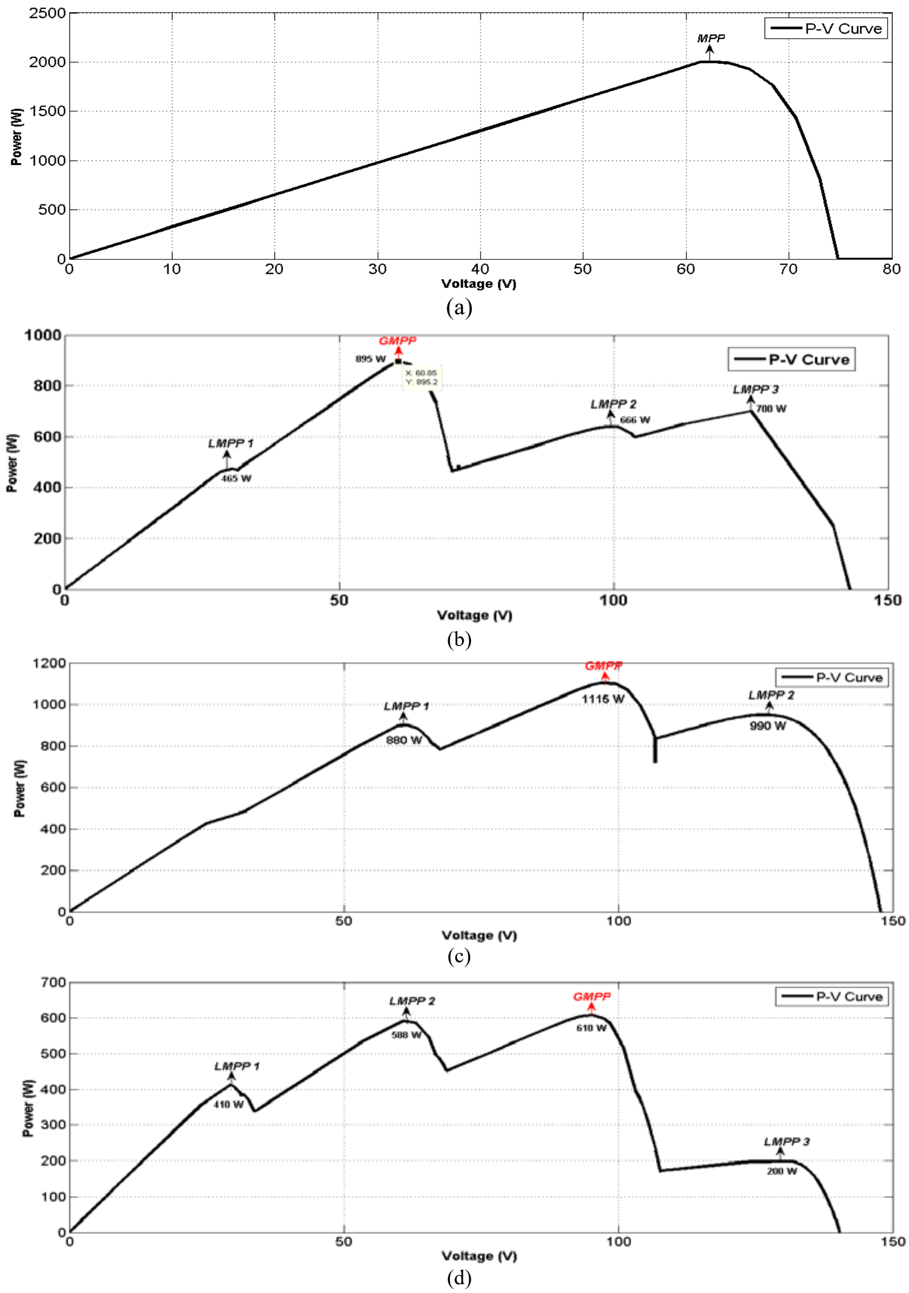

Fig. 6. PV characteristics for the case study: (a) mode 1, (b) mode 2, (c) mode 3, and (d) mode 4.

TABLE III
DIFFERENT CASES OF SHADING PATTERNS FOR ASSESSMENT

		Different irradiance levels of the panels in W/m^2							
S. No.	Cases	P1	P2	P3	P4	P5	P6	P7	P8
1	Case 1	1000	1000	1000	1000	1000	1000	1000	1000
2	Case 2	1000	200	800	300	1000	1000	500	500
3	Case 3	500	1000	500	1000	500	1000	500	1000
4	Case 4	1000	1000	800	200	200	800	300	300
5	Case 5	800	800	1000	1000	800	200	600	800
6	Case 6	800	200	800	800	1000	1000	1000	1000
7	Case 7	600	400	800	200	800	800	1000	1000
8	Case 8	600	400	800	200	600	400	800	200

TABLE IV
POWER OUTPUTS FOR DIFFERENT CASES FOR THE CONVENTIONAL AND PROPOSED METHODS

DC power extracted for different cases and configurations in W								
Simulation results								
Connection Configurations	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Series–parallel	1956	453	1132	410	896	802	703	420
Bridge-linked	1956	670	1088	432	1008	1241	865	599
Total-cross-tied	1956	902	1124	975	1110	1363	1353	619
Proposed switching technique with k = 1.33	1956 (mode1)	914 (mode2)	1138 (mode4)	1114 (mode2)	1123 (mode3)	1399 (mode3)	1349 (mode3)	627 (mode4)
Experimental results								
Series–parallel	1950	430	1123	391	880	788	684	400
Bridge-linked	1950	643	1070	420	995	1231	843	588
Total–cross–tied	1950	880	1100	957	1101	1350	1336	600
Proposed switching technique with k = 1.33	1950 (mode 1)	895 (mode 2)	1120 (mode 4)	1095 (mode 2)	1115 (mode 3)	1380 (mode 3)	1330 (mode 3)	610 (mode 4)

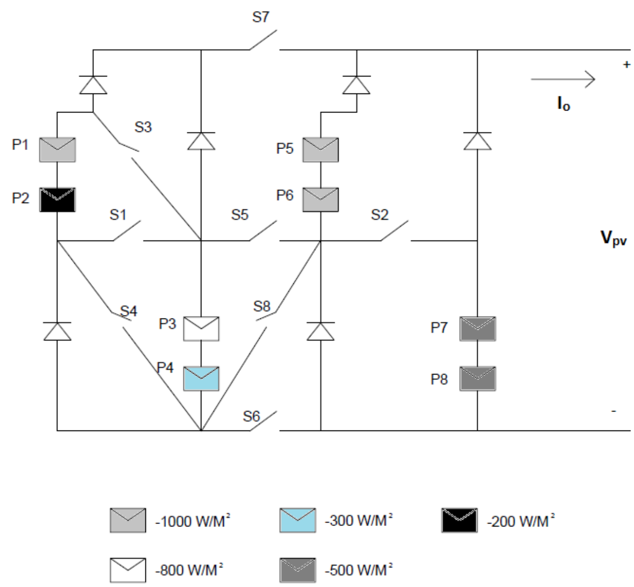

Fig. 7. Architecture of the proposed switched system for the case study.

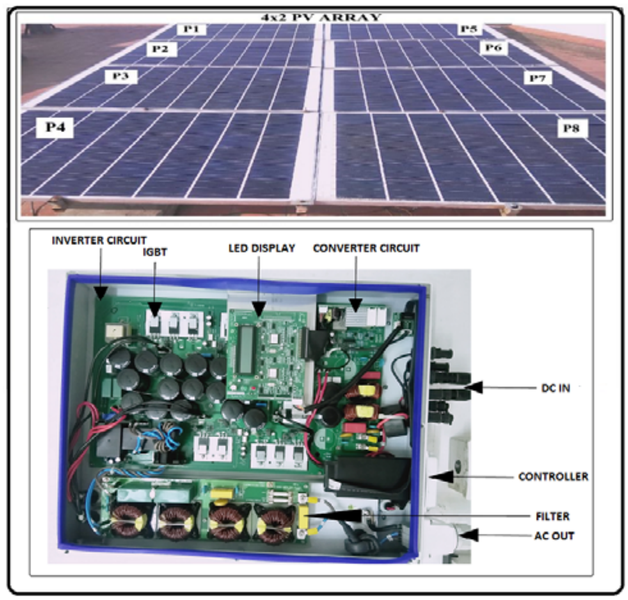

Fig. 8. Experimental setup of the proposed system.

inverter may produce power equal to that of the proposed scheme, but not consistently. In shading case 2, the power produced is higher than that of the proposed technique. However, in all other cases, the proposed scheme leads to power enhancement. The TCT-based system can also produce maximum power in several cases of partial shading. The main advantages of the switching circuit over the TCT-based PV system are (1) small size, cost, and weight; (2) low complexity; (3) easy maintenance; and (4) high reliability. The power devices use simple contactors as controlling switches.

IV. PRACTICAL IMPLEMENTATION

Simulation and hardware implementation were conducted for the proposed system. A prototype of the proposed PV system was built to verify the hardware results against the

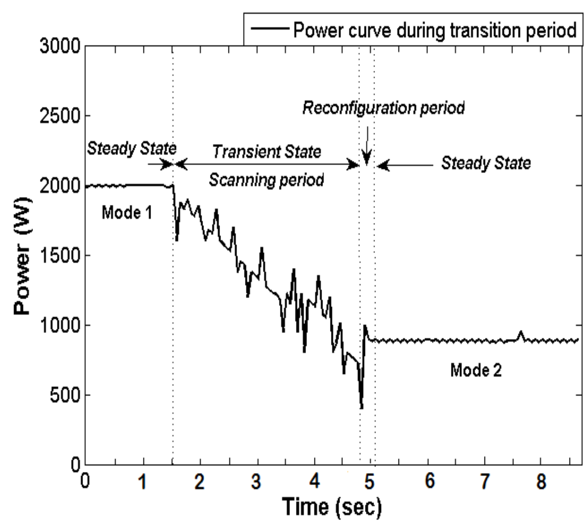

Fig. 9. Test result of the transient condition when mode 1 is changed to mode 2.

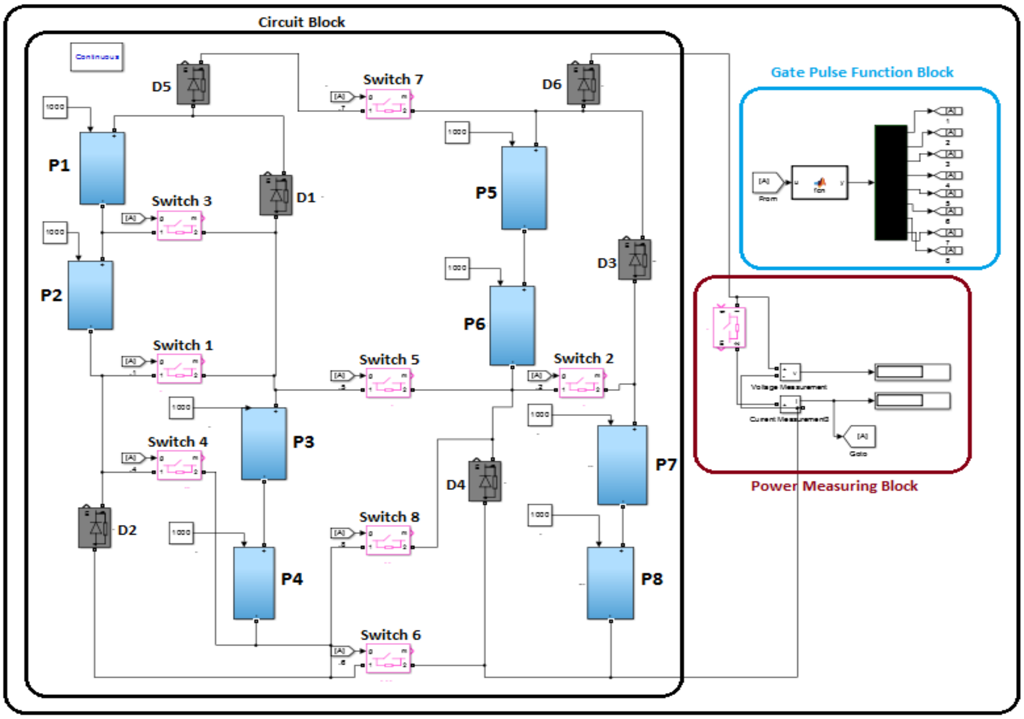

Fig. 10. Simulation of the proposed reconfiguration by the switching method in MATLAB.

simulation results. For this procedure, a 2 kW, 4 × 2 PV array was created. The hardware prototype is shown in Fig. 8. The same process was performed with MATLAB simulation (Fig. 10). The panel rating used for implementation is given in Table II. This rating was obtained from standard testing conditions (STC), i.e., 1000 W/m^2 at 25 °C. The hardware setup included the converter and inverter circuit, as shown in Fig. 8. Experimental validation was conducted for all the cases of partial shading (Table III), after which the extracted powers for the proposed method were determined (Table IV). Shading was conducted by hiding the panels from insolation using cardboard sheets. The percentage of shading by cardboard sheets was converted into respective insolation levels in W/m^2. The hardware and simulation results were on par. The PV current output reference was between 0 and 2I_{sc} for the conventional method (mode 1). For the proposed method, it was between 0 and 2kI_{sc} (k = 1.4). The scanning time and the value of k were fixed by the MPPT algorithm, which limited the current reference value and produced GMMP. During partial shading or reduced irradiance, the actual current reached its highest value, but it was limited to the reference current level and did not exceed it. This is proof that the current level of the proposed system cannot exceed the reference value, and the size of the converter is the same. During full irradiance (i.e., at STC), the current output reached the current reference within the scanning period.

As shown in Table IV, the proposed switched PV system did not enhance the power extracted in mode 1 (no shading), but it improved power by 15% in all the other modes (partial shading), assuming that k = 1.4.

The power curve of the transition from one mode to the next is shown in Fig. 9. This curve was obtained by using power samples during the switch transition from mode 1 to mode 2. At the initial phase of the experimentation (i.e., mode 1), the PV panels were unshaded, and the produced power was nearly 2,000 W. After some time, with the shading of the panels, the output power continuously varied; this period is called the transient period. Then, the panels were reconfigured to mode 2, and the produced power was nearly 950 W. Transition occurred from one mode to the next in different shading conditions.

V. Conclusion

In this work, a new switched PV reconfiguration method was proposed to enhance power extraction from PV arrays in partial shading conditions. The proposed method was compared with conventional techniques in terms of maximum power extraction. Experiments and simulations were conducted for a 2 kW solar PV system with eight 250 watt panels (polycrystalline). The proposed method was implemented in a 4 × 2 array. The comparison results showed that the proposed switched PV technique enhanced power by about 15% as opposed to existing techniques. The proposed technique also has fewer switching requirements compared with conventional ones, and it operates with a simple control. The effectiveness of the proposed system makes it attractive for rooftop applications.

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