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Parallel-Connected Solar PV System to Address Partial and Rapidly Fluctuating Shadow Conditions

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Abstract—Solar photovoltaic (PV) arrays in portable applications are often subject to partial shading and rapid fluctuations of shading. In the usual series-connected wiring scheme, the residual energy generated by partially shaded cells either cannot be collected (if diode bypassed) or, worse, impedes collection of power from the remaining fully illuminated cells (if not bypassed). Rapid fluctuation of the shading pattern makes maximum power point (MPP) tracking difficult; generally, there will exist multiple local MPPs, and their values will change as rapidly as does the illumination. In this paper, a portable solar PV system that effectively eliminates both of the aforementioned problems is described and proven. This system is capable of simultaneously maximizing the power generated by every PV cell in the PV panel. The proposed configuration consists of an array of parallel-connected PV cells, a low-input-voltage step-up power converter, and a simple wide bandwidth MPP tracker. Parallel-configured PV systems are compared to traditional series-configured PV systems through both hardware experiments and computer simulations in this paper. Study results demonstrate that, under complex irradiance conditions, the power generated by the new configuration is approximately twice that of the traditional configuration. The solar PV system can be widely used in many consumer applications, such as PV vests for cell phones and music players.

Index Terms—Complex illumination, maximum power point tracking (MPPT), partial shading, photovoltaic (PV) solar cell, power converter, solar array.

I. INTRODUCTION

IN PHOTOVOLTAIC (PV) arrays, cells are conventionally connected in series to obtain the desired voltage. In higher voltage applications, bypass diodes may be placed across groups of cells to prevent mismatched or shaded cells [1] from inhibiting production of power by the rest of the array. PV arrays in portable/mobile applications are often subject to partial shading and rapidly changing shadow conditions. For example, a body-worn PV jacket would be subject to variations of illumination because of continuous movements, both temporally and spatially, due to shading from trees, vehicles, and buildings, as well as due to changes of orientation of the array relative to the sun. The complex operation conditions for

portable PV applications are much different from stationary PV applications where typically no obstructions exist and changing of illumination conditions is slow. As a consequence, two problems are generally encountered when using conventional configurations under such complex illumination conditions.

First, although partially shaded cells can still generate a certain amount of energy, that energy cannot be collected in systems of the traditional configuration. If bypass diodes are not used, any shaded cell inhibits power production from the entire series-connected string of cells. If bypass diodes are used, then the fraction of energy that could be generated by the partially shaded cells is still lost even if it does not impede collection of energy from the rest of the cells. Furthermore, in low-voltage arrays, the diode bias voltage may represent a significant fraction of the total PV source operating voltage. These issues are often not significant in high-voltage stationary systems that do not have obstructions, but they are quite significant in low-voltage systems for portable applications where partial shading occurs frequently and quite a fraction of the cells may be partially shaded at any one time. Second, rapidly changing shadow conditions increase the difficulty of maximum power point tracking (MPPT). It is very hard to identify the global maximum power point (MPP) (for diode-bypassed systems) because multiple local MPPs exist, and their locations fluctuate rapidly corresponding to the changing shading conditions. Even if at some instant one could know where the global maximum is, it would probably change before it was possible to shift the MPP tracker to that operating point. In other words, very fast tracking speeds and good control stability are particularly required for a MPP tracker to work in this situation.

Addressing these problems, this paper describes and validates a highly parallel-configured PV system that operates effectively in rapidly varying shaded conditions, which is an expansion of the work presented in [2] and [3]. Series connections of cells, if necessary, are limited only to the minimum necessary to present an adequate input voltage ($\sim$1 V) to the step-up converter connected at the output of the PV array, and by considerations of ohmic losses in the bus work. For Si cells, we are typically considering just two or three cells, but for multijunction PV cells that produce higher voltages, we could use single cells. It is noted that in [4]–[7], PV modules rather than PV cells are connected in parallel and shown to demonstrate better performance in shaded conditions. Each PV module is treated as one unit that tracks its own MPP. Therefore, when a module is shaded, the degradation of performance
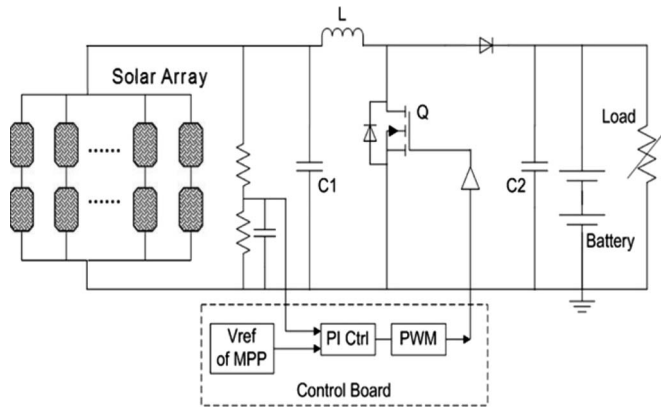
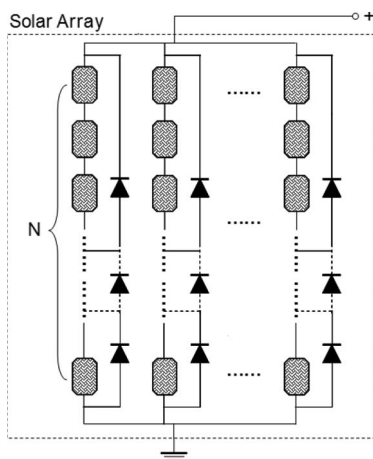Fig. 1. Circuit diagram of proposed maximally parallel PV system.

Fig. 2. PV array using conventional configuration.

will not propagate to other modules. The work we report here extends the concept to the microscale appropriate for portable applications at low power and low voltages. The proposed PV system adopts the parallel configuration at the individual cell level, so that every cell in the PV panel can achieve its MPP under nonideal conditions. In contrast to the electric utility scale applications where one needs as many power converters as PV modules, in the low-power case, only a single low-cost converter is required. This paper shows specifically the performance gain of this arrangement and the efficacy in real-world conditions, and it validates the real-world experiments with simulation data.

II. SYSTEM CONFIGURATION

The developed PV power system, as shown in Fig. 1, has three main characteristics. 1) In contrast to conventional configurations characterized as many cells in series, with or without bypass diodes (shown in Fig. 2), the PV array in the system described here adopts a highly parallel configuration. 2) The MPPT is implemented through controlling the PV array operating voltage to follow a prescribed voltage reference corresponding to the single-cell MPP. 3) A step-up power converter manages the cell loading and boosts the voltage to the system requirements. Considering that in most portable applications there will already be a power converter for battery charge

management, there is thus no extra hardware cost to use this configuration.

A. Parallel Configuration

The PV array is constructed with a highly parallel, rather than serial, wiring configuration. The highly parallel configuration has three important characteristics that are inherited from a single PV cell. 1) The voltage of the MPP is largely independent of illumination, or in other words, even at different irradiance levels, the MPPs of cells connected in parallel occur at nearly a common voltage. 2) Slight deviation from MPP voltage only weakly affects produced power. 3) Voltage of the MPPs is only weakly sensitive to temperature over the usual range (e.g., 20-K difference). As a consequence, the parallel-configured PV array is capable of making every cell in the panel generate nearly maximum power simultaneously, no matter whether the illumination distribution is uniform. Different cells in the panel may supply different currents corresponding to irradiance levels falling on them instantly; however, all the cells share a common voltage that will be controlled to track the MPP.

B. MPPT

Many MPPT methods have been reported, such as perturb and observe [8]–[12], incremental conductance [13], [14], neural network based [15], [16], fuzzy logic control [17], [18], etc. These approaches have been effectively used in stand alone and grid-connected PV solar energy systems [19]–[22] and work well under reasonably slow and smoothly changing illumination conditions mainly caused by weather fluctuations. However, it is not easy to directly apply these approaches into portable PV applications due to low tracking speeds or complex implementations. Recently, [23] proposed and validated an MPPT algorithm working in conjunction with a dc–dc converter to track the global peaks for PV systems operating under partially shaded conditions. While this approach is designed and suitable for high-voltage PV modules with multicells in series and has a relevant fast tracking speed (typically a couple of seconds), it is not easy to implement directly in portable PV applications since the energy generated from partially shaded cells cannot be collected, and the tracking speed is not fast enough for portable applications where shading conditions may changes rapidly (e.g., tenth of a second).

On the other hand, the MPP of any individual cell is actually rather simple to locate since it is located very near to a particular (temperature dependent) operating voltage [1]. Based on this well-known fact, the MPPT methodology of controlling PV array operating voltage was already developed a few decades ago for series-connected PV arrays [24]–[26]. It is easy to implement and has fast dynamic response to illumination changes. For series connected cells, although, uniform illumination is a precondition to make this method work well; shaded cells will defeat the technique because they will reduce the target operating voltage. Therefore, for portable applications, this technology cannot be directly applied if the PV panel were connected using conventional series configurations.

However, for parallel-configured PV arrays, integrating this simple MPPT technology actually excludes this limitation and makes MPPT effective under complex illumination conditions.

C. Input Voltage of Power Converter

In principle, it is preferred to connect all cells in parallel. However, the terminal voltage of a single-junction Si PV cell is so low (e.g., ~0.4 V at MPP); this may increase the difficulty of designing an appropriate power converter. If multijunction PV cells (where the single-cell terminal voltage exceeds 1 or 2 V) were used, the increased energy efficiency of the power converter at the higher input voltage would permit operation with single cells in parallel. As a tradeoff, for single-junction PV cell, a small number (two or three) of cells can be first connected in series. If the cells are small in size compared to the structure size of the illumination patterns, then the whole string can generally be assumed under uniform irradiance. If at some time instants, any one cell in a short string is shaded, then this situation is equivalent to shading of the whole string. Therefore, the study results are the same whether one cell is shaded, or the whole short string of two or three cells is shaded. This paper has adopted and verified this approach, as detailed in next section. Two parallel-configured PV panels were built, in which one had series strings of two cells and the other with series strings of three cells. Study results demonstrate a significant increase of power produced by both of these nominally parallel-configured PV arrays compared to a similarly sized series-connected string.

Most of current commercialized PV devices for consumer electronics just use simple series configurations, such as cell phone chargers, battery maintainers for automobiles, recreational vehicles, etc. The main reason of using series configuration is because it is easy to build up the PV panel output voltage and, thus, avoiding voltage regulation and achieving low cost; however, the PV source performance will be degraded particularly under complex illumination conditions. With significant developments of power electronics, power converters/inverters today are highly efficient and low in cost and, thus, are being more and more integrated into PV generators. It is noted that, for high-voltage applications, some recent works [4]–[6], [27], [28] have demonstrated uses of parallel-connected PV modules (rather than cells) with advanced power electronics to achieve better performance than conventional series-connected PV modules. For example, [27] describes the parallel connection of six PV modules with open circuit voltage at 21 V, which is then boosted to 200 V using a step-up power converter.

It is also noted that converters suitable for use with very low input voltages are becoming increasingly common as they are widely used in single-cell battery-powered consumer electronics. For example, some commercialized converters have allowed the minimum input voltage as low as 0.3 V, allowing connect to one PV cell directly. For most portable electronics, one stage of voltage boosting is generally enough. To further obtain a high voltage (e.g., for electric utility scale applications), a cascade topology of per-panel dc–dc converters connected into series can be adopted [29], [30]. However, cascading of dc–dc converters will decrease the system effi-

TABLE I
COMPARISON OF TWO PV SYSTEMS

Component	Series Configuration	Parallel Configuration
PV panel	20 cells in series, 4 strings in parallel, 2 *cm* × 2 *cm* per cell 5 cells per bypass diode	3 cells in series, 27 strings in parallel, 2 *cm* × 2 *cm* per cell no bypass diodes required
Ultracapacitor	*Maxwell* BCAP0350, 350 *F* per cell, 2 cells in series	*Maxwell* BCAP0350, 350 *F* per cell, 2 cells in series
Power Converter	Step-down, *Maxim* 1653	Step-up, *Maxim* 1676

ciency and increase the difficulty of control design. Therefore, tradeoffs exist in choosing between series-configured PV panels with single stage power conversion or parallel-configured PV panels with cascaded power conversion. That is to say, conventional series-configured PV systems are more suitable for grid-connected applications with high-voltage requirements, while the parallel configurations proposed in this paper are more suitable for portable/mobile applications with low voltage requirements.

III. EXPERIMENTAL RESULTS

Two hardware tests were carried out to validate the performance of the described approach. The first test compared the conventional configuration to the parallel configuration under complex illumination conditions; the other test verified the feasibility of wide bandwidth MPPT. For convenience, in the following, the conventional configuration is referred to as the *series* configuration and any mostly parallel configuration is referred to as the *parallel* configuration even if it contained two or three series cells in each parallel branch.

A. Performance of Parallel Configuration Versus Series Configuration

As summarized in Table I, the series configuration yielded an open circuit voltage around 10 V which was then reduced to 3.3 V by a buck converter; the parallel configuration yielded an open circuit voltage around 1.5 V which was then increased to 3.3 V by a step-up converter. Voltage was converted to 3.3 V in each case to provide power suitable for consumer electronics using typical two cells of NiMH batteries. The 3.3 V was conveniently chosen here for the purpose of comparison, but could otherwise have been any voltage between the lowest or highest voltages produced by the parallel and series arrays, respectively. Both of the power converters are commercial products (as shown in Table I) for general dc–dc power managements with typical efficiency around 90% from their data sheets. In each configuration, two cells of ultracapacitors were connected in series and served as the energy repository. The integrated control algorithms in both of the converters were not designed to track the MPP of the PV arrays because, for the series configuration, based on the analysis in Section I, it is actually very difficult to implement any MPPT under rapidly changing shadow conditions. For the parallel configuration, the MPPT can be implemented and will be detailed in the
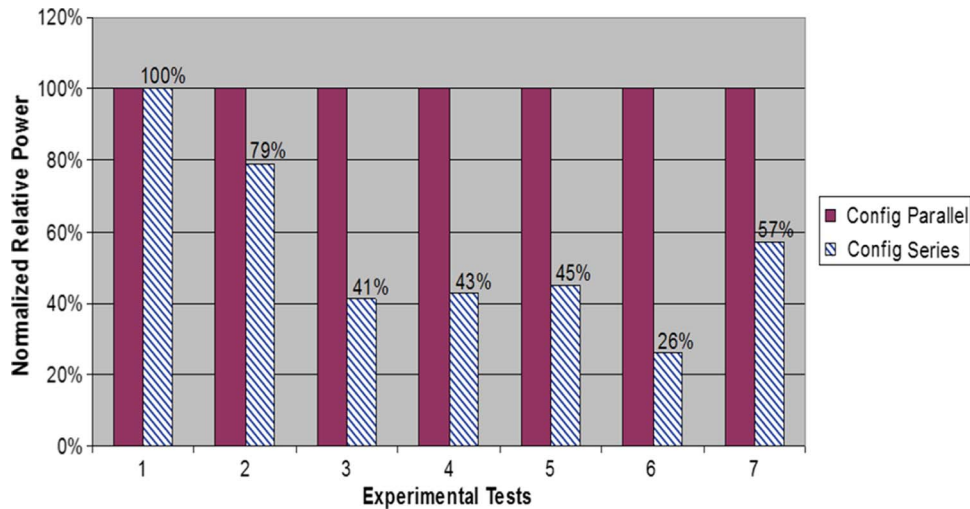
Fig. 3.   Comparison of power generation between two PV systems.

TABLE II
DESCRIPTION OF TEST CONDITIONS

|	Place	Test Description
1	Out-of-doors	* Area has no shade * Panels stationary * Panels positioned horizontally
2	Out-of-doors (Fig. 4 (a))	* Area shaded by trees * Panels constant movement * Panels positioned horizontally
3	Out-of-doors (Fig. 4 (b))	* Area shaded by trees * Panels constant movement * Panels positioned about 70 degrees to the horizon
4	Out-of-doors	* Area shaded by trees * Panels constant movement * Panels positioned about 70 degrees to the horizon
5	Out-of-doors (Fig. 4 (c))	* Area shaded by railing * Panels stationary * Panels positioned horizontally
6	Laboratory (Fig. 4 (d))	* 300 W artificial illumination source * Panels stationary * Shading: vertical lines, shading area 53%
7	Laboratory	* 300 W artificial illumination source * Panels stationary * Shading: squares, shading area 79%
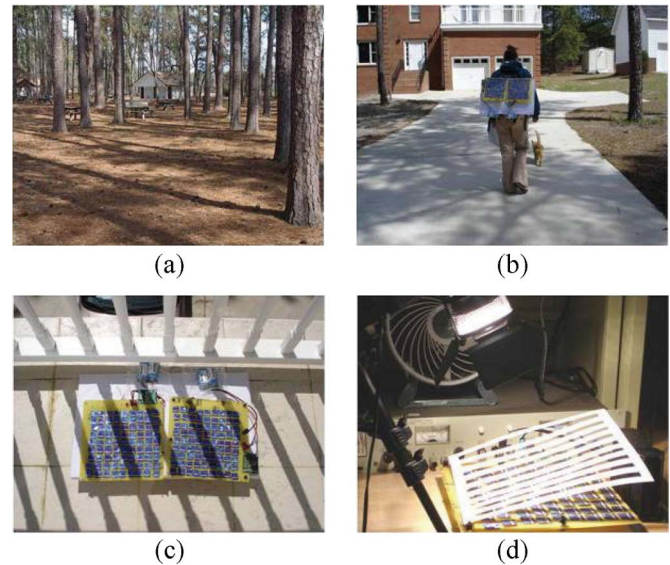
Fig. 4.   Experimental tests under different illumination conditions.

second experiment; however, in this first experiment, no MPPT was integrated in order to generate results that were directly comparable to results from the series configuration.

Both of the PV systems were tested in laboratory conditions and in an outdoor environment. At the beginning and the end of each test, the terminal voltages of the ultracapacitors were measured. These voltages were used to calculate the energy charged into the ultracapacitor, and hence, the average power produced by each PV panel. The ultracapacitor packs were precharged to 2.2 V to simulate two depleted secondary battery cells (e.g., NiMH or NiCd batteries). Seven tests in total were conducted, in which the first five tests were done out of doors, and the last two were done in the laboratory. In each test, the power generated by the parallel configuration was first normalized to 100%, and then it was used as reference to calculate the relative power generated by the series configuration. It can be seen, from Fig. 3, that the parallel configuration showed better

performance and its power generation capability was greater, typically by a factor of two, in partially shaded conditions. Test conditions of seven different experiments are shown in Table II. Pictures in Fig. 4 show the test conditions corresponding to Tests 2, 4, 5, and 6, respectively.

B. Parallel Configuration Integrated With MPPT

As shown in Fig. 5, the PV system described in Fig. 1 was built and tested in the laboratory. The PV panel contained 80 single-junction Si cells in total arranged with two cells in series then 40 strings in parallel. Two cells of AA size NiCd batteries were connected in series and served as the energy repository. A 300-W high-intensity lamp served as the illumination source and an electronic load was connected to the battery. A pulsed load profile was applied with a regular period a 9 s (6 s of high current demand at 0.4 A and 3 s of low current demand at 0.1 A). A step-up power converter was interposed between the PV panel and the battery. The MPPT algorithm was defined
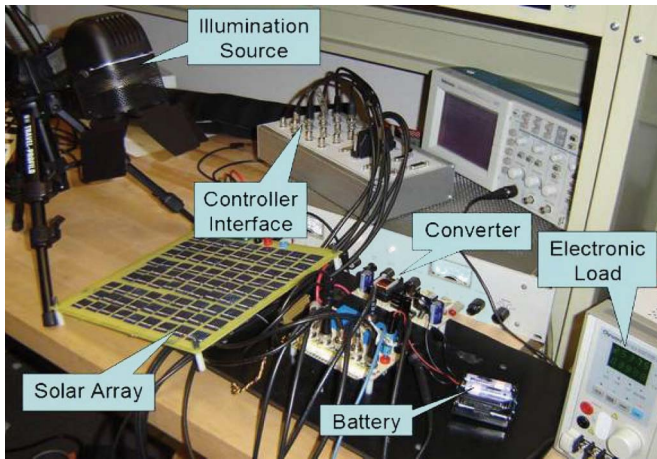
Fig. 5.   Experimental test platform.

TABLE III
COMPONENTS USED IN EXPERIMENT PV SYSTEM

Component	Description
PV panel	2 cells in series, 40 strings in parallel, 2 *cm* × 2 *cm* per c-Si cell
Battery	2 AA size Ni-Cd cells in series
Illumination source	300 *W* high-intensity video lamp
Electronic load	*Chroma* 6310
Controller	*dSPACE* DS1103 controller board
Power Converter	Step-up, efficiency 90% $L = 90uH, C = 470uF, f_s = 50kHz$

by using Matlab/Simulink and then compiled and executed on a general purpose real-time controller that managed switching duty of the power converter. The main parameters of the system are listed in Table III. In the power converter circuit, capacitor $C_1(470\ \mu\text{F})$ filters the switching ripple at $fs = 50$ kHz, which is a much higher frequency than that associated with the solar power fluctuations of interest. Within the control bandwidth, the capacitor voltage is always in equilibrium with the voltage of the PV array which is itself constant since our control objective is to maintain a constant converter input voltage (also equal to the solar array voltage and C_1 voltage). The capacitor voltage ripple Δv_{C1} caused by switching is small enough to ignore (about 10 mV in this paper) and can be estimated as $\Delta v_{C1} = \Delta i_L/(8 \cdot C_1 \cdot fs)$ [31], where Δi_L is the inductor current ripple in one switch cycle.

Fig. 6 shows the measured power generated as a function of voltage using stationary shadings. Three different shadings, which had similar shape patterns, as shown in Fig. 4(d), were applied with shading area 42%, 53%, and 63% corresponding to Shade 1, 2, and 3 in Fig. 6. It is noted that the voltage corresponding to the MPP is 0.62 V, and this voltage was then specified as the MPP reference for the PV array at room temperature. Figs. 7 and 8 show the dynamic performance of the PV system during a 130-s experiment. The illumination conditions during the test changed continually and quickly (~1/10 s) by randomly shading the PV panel surface to simulate movements in a portable application. Fig. 7 shows that the output current of the PV panel changed significantly according to the irradiance variations, but the terminal voltage of the PV panel was controlled to be nearly constant at 0.62 V.
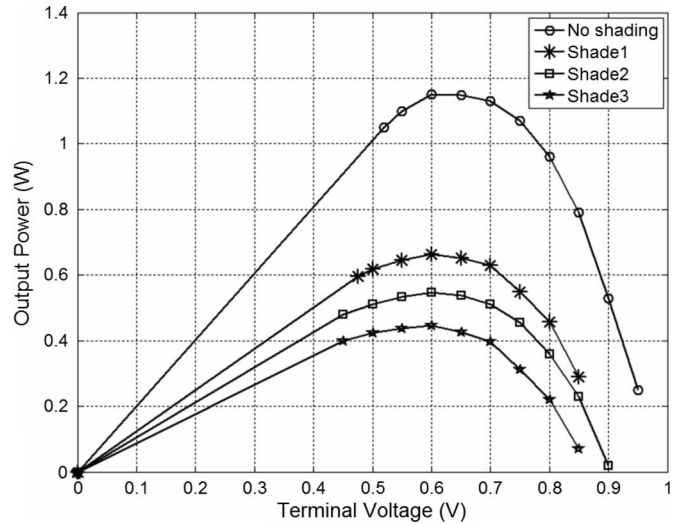

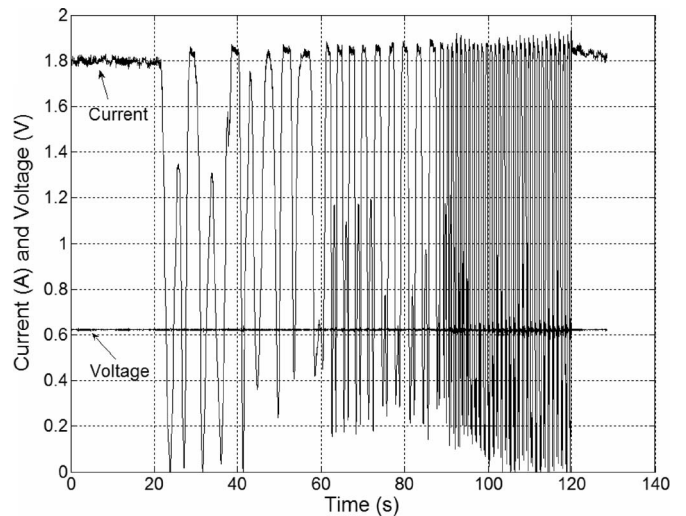Fig. 6.   Experimental *P–V* characteristics.

Fig. 7.   Voltage and current during 130-s experimental test.
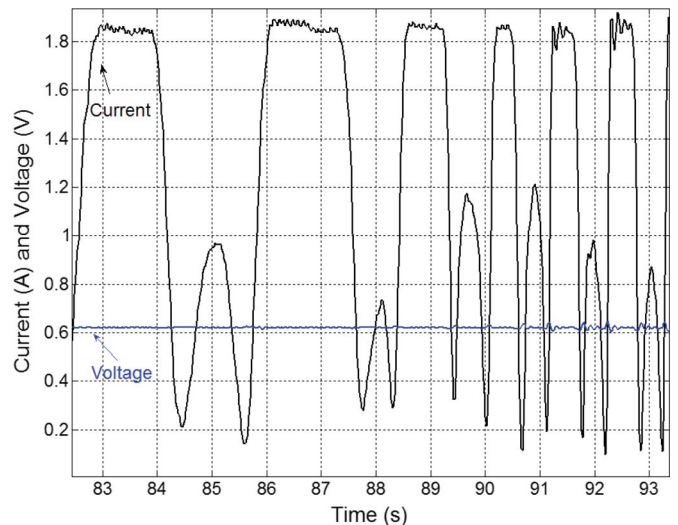

Fig. 8.   Zoom-in view of experimental test from 83 to 93 s.

Fig. 8 shows a zoom-in view of the experimental test from 83 to 93 s. It can be seen that the MPP tracker did follow the rapidly changing illumination well. Therefore, by controlling
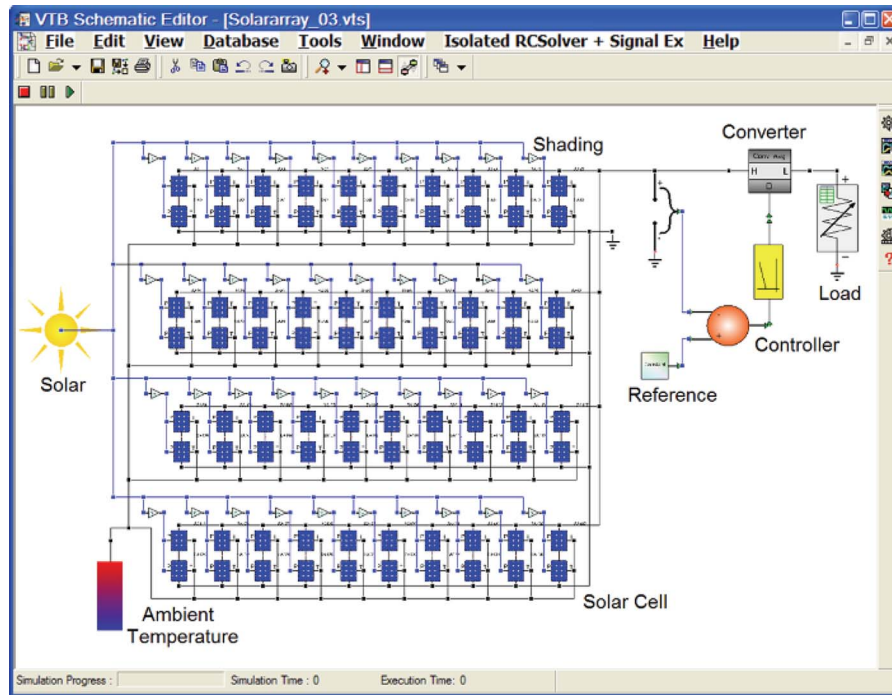
Fig. 9.   Simulation schematic for parallel-connected PV system.

the PV panel operating voltage, the MPPT was implemented, and maximum power was generated under rapid time-varying irradiance conditions.

IV. DISCUSSIONS

A. Compare Ideal Energy Harvest to the Parallel PV System

The ideal maximum energy harvest for a PV panel is that every cell in the panel operates at its MPP, and all the generated energy is collected. Although it is really hard to monitor it in experiments under complex illuminations, the ideal maximum energy harvest can be calculated from the PV cell model assuming every cell in the panel loaded at its won MPP voltage corresponding to the different irradiance levels.

A simulation study was carried out to compare the ideal energy harvest to the proposed PV system under complex illuminations. The PV cell model described in [32] and the Virtual Test Bed simulation tool [33] were applied in this paper. Fig. 9 shows the simulation schematic of parallel-connected PV system. The simulation system was set according to the experimental system in Table III and Fig. 1. Fig. 10 shows a zoom-in view. Each PV string (with two cells in series) was randomly and partially blocked by a shading model. As a result, the received irradiance level was fluctuated in the range from 100 to 1000 W/m^2.

Fig. 11 shows the irradiance fluctuations falling on two arbitrarily chosen PV strings during a 3600-s simulation. Fig. 12 shows the PV panel terminal voltage that was controlled to be constant at 0.62 V. Fig. 13 shows the power generation during the simulation.

The energy generation of the proposed PV system during the simulation was then obtained by integrating the power curve in Fig. 13. Comparing it to the ideal maximum energy harvest, the
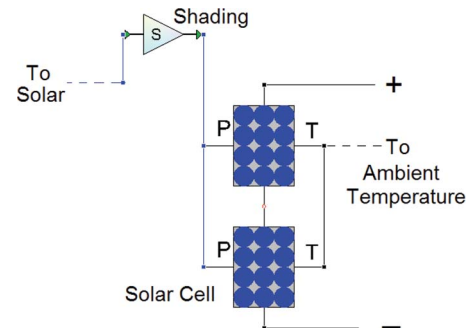

Fig. 10.   Zoom-in view of a PV pair in Fig. 9.

performance of the proposed system achieves around 96% of the ideal maximum value. The 4% of energy loss was mainly due to the fact that the MPP voltages at different irradiance levels are slightly different, which is analyzed as follows by comparing the energy produced by all the PV cells with each loaded at their own ideal voltage to all the cells loaded at one common voltage.

Fig. 14 shows the output power of a PV cell at 300 K as a function of terminal voltage and parameterized by irradiance level from 100 to 1000 W/m^2 at increments of 100 W/m^2. As shown in Fig. 14, the two nearly vertical lines marked with circles bound the region in which the PV cells provide at least 95% of the maximum power at each irradiance level. Between the two 95% power lines, the curves are rather flat, and the peak power is only weakly sensitive to voltage; therefore, loading a partially shaded cell at the same voltage as a fully illuminated cell only slightly reduces the power supplied.

For the case of ten cells each illuminated at the ten levels shown in Fig. 14, the power reduction is estimated and shown in Table IV. It can be seen that with ±5% deviation from the
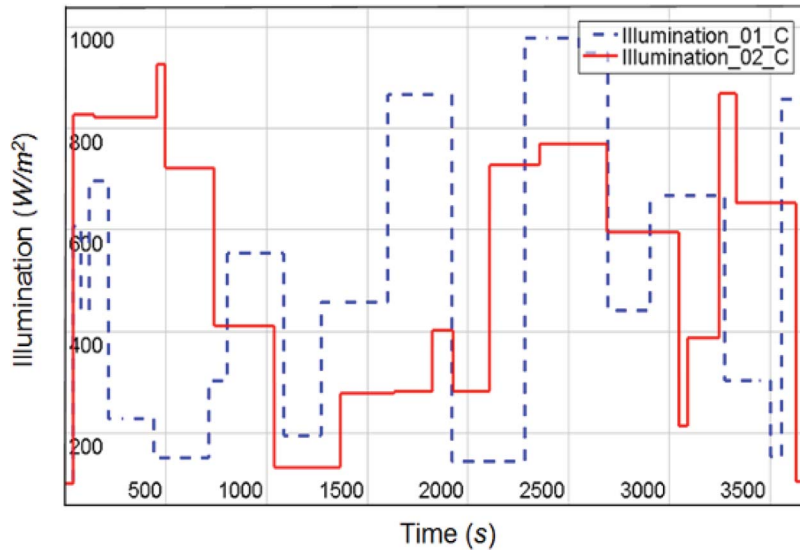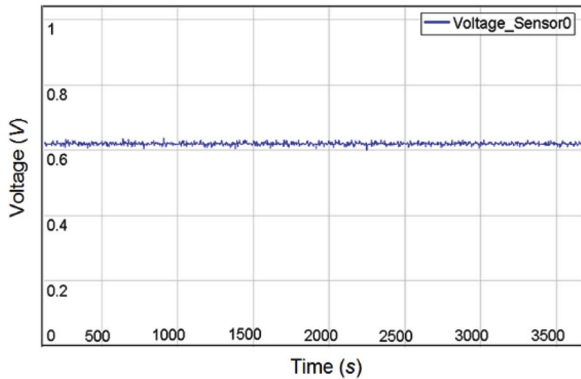
Fig. 11.   Irradiance level versus simulation time.
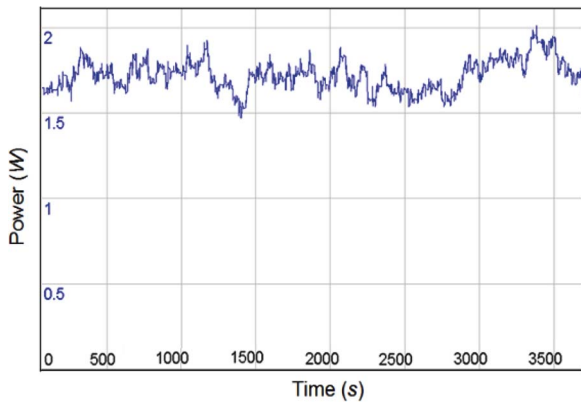

Fig. 12.   PV panel terminal voltage.

Fig. 13.   Power generation from the PV panel.

Fig. 14.   Output power versus terminal voltage.

TABLE IV
POWER GENERATION COMPARISON

i	PV array operation voltage with ten cells-in-parallel	Power generated at operation voltage	$P(i) \div P_{IdealMaxPower}$
1	V_{PMax}	$P(1)$	99.79%
2	$V_{PMax} \cdot (100\% - 1\%)$	$P(2)$	99.71%
3	$V_{PMax} \cdot (100\% - 5\%)$	$P(3)$	98.02%
4	$V_{PMax} \cdot (100\% + 1\%)$	$P(4)$	99.70%
5	$V_{PMax} \cdot (100\% + 5\%)$	$P(5)$	96.85%

voltage corresponding to the MPP V_{PMax} of the PV array, the power reduction is less than 3.5% of the ideal maximum power generation.

B. Compare Serial and Parallel Arrays With MPPT Algorithm

In Section III, the parallel configuration without MPPT has demonstrated better performance than the series configuration without MPPT under various shading conditions. Here,
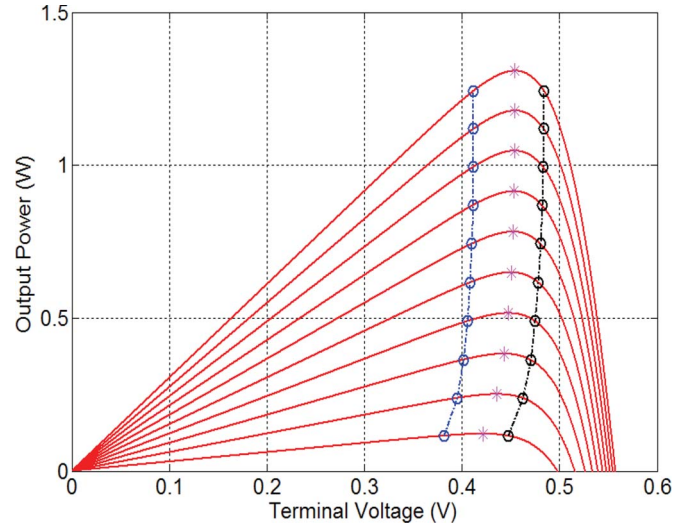
simulation studies were taken to compare them with MPPT, and all simulation parameters were specified according to the experiments in Table I. The MPPT method of constant voltage control was applied for both of the systems in order to yield comparable results. Specifically, 0.93 and 6.2 V were set as the voltage references for the parallel configuration and the series configuration.
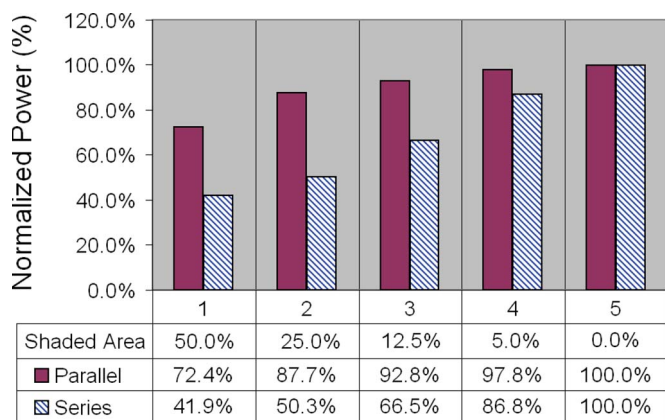
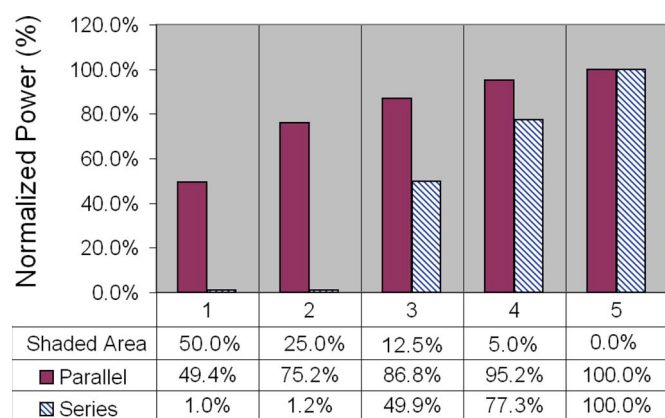Fig. 15.   Performance comparisons using translucent shading spots.

	1	2	3	4	5
Shaded Area	50.0%	25.0%	12.5%	5.0%	0.0%
Parallel	72.4%	87.7%	92.8%	97.8%	100.0%
Series	41.9%	50.3%	66.5%	86.8%	100.0%

Fig. 16.   Performance comparisons using opaque shading spots.

	1	2	3	4	5
Shaded Area	50.0%	25.0%	12.5%	5.0%	0.0%
Parallel	49.4%	75.2%	86.8%	95.2%	100.0%
Series	1.0%	1.2%	49.9%	77.3%	100.0%

Two sets of simulations were taken during which rapid changing shading conditions were applied and different fractions of the PV panel were shaded. Specifically, in the first set of simulations, translucent spots with different sizes dynamically shaded the PV panel. As a consequence, the irradiance level falling on the blocked PV cells was as a half as that on the unblocked cells. While in the second set of simulations, opaque spots were applied thus the blocked cells were fully shaded. During each simulation, different cells were shaded at different time instants, but the total area of blocked cells was constant. Figs. 15 and 16 show comparisons between the two systems and the parallel configurations yielded better performance.

V. Conclusion

This paper has described the configuration of a portable PV power system that produced maximum power under rapidly changing partial shading conditions such as would be encountered in portable applications. Under complex irradiance conditions, the power generating capability of the proposed PV system was approximately twice that of a conventionally configured series system. The developed approach is broadly applicable, but is perhaps most valuable in PV systems having high single-cell voltages where direct input to a high-efficiency converter is most practical.

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