Proposal for an Active PV Array to Improve System Efficiency During Partial Shading

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ABSTRACT
Owing to time-varying external environmental influences, undesirable string mismatches frequently occur in photovoltaic (PV) power generation systems, which will cause conventional PV systems to experience extremely severe power losses. Under partial shading conditions (PSCs) caused by passing clouds, neighboring buildings, and animal excrement, the characteristic curve of the PV string becomes complicated with multiple peaks, which increases the difficulty of determining the maximum power point (MPP) of the array. However, it is essential to ascertain the global maximum power point (GMPP) to extract the full power of each PV module. Therefore, we propose a new type of PV generation module constituting an active PV array (APV) system as well as its control strategy. It can ensure that the system continuously operates in the optimal state when the solar irradiation intensity drops drastically due to unanticipated environmental variables. Depending on the experiment of two PV arrays under identical conditions, the efficiency and reliability of the APV system are substantiated. Meanwhile, in the case where the external environmental conditions are deliberately changed, the experimental results fully illustrate the adaptability of the APV system to diverse harsh conditions.

INDEX TERMS
Active PV array, global maximum power point tracking, PV string, partial shading conditions, real-time scanning method.

I. INTRODUCTION
Currently, among the various existing renewable energy sources, solar energy, as one of the most sustainable and promising energy sources, is utilized widely around the world [1]. It is also considered to be a unique renewable energy process that may be integrated harmoniously in a residential environment [2]. Although photovoltaic (PV) sources have many advantages in terms of cleanliness and renewability, the low efficiency of PV power generation systems is still an inevitable defect due to the variable external atmospheric conditions and nonlinear electrical characteristics of PV generation systems [3]. Meanwhile, to maximize the utilization of solar energy, the installation density of PV modules has greatly increased; however, under partial shading conditions (PSCs), mismatches between strings and severe power loss within PV arrays occur more frequently and easily. The unexpected partial shadows in the PV array are mainly caused by animal droppings, trees, dust, neighboring buildings and other obstacles, which may result in the output characteristic of the PV module becoming complicated with multiple maximum power points (MPPs); hence, finding the global maximum power point (GMPP) becomes increasingly challenging [4]–[6]. To overcome the shortcomings of the traditional maximum power point tracking (MPPT) method, an increasing number of efficient MPPT methods for PV modules under PSCs have been proposed [7]–[10]. In conventional PV systems, however, even the global maximum power point tracking (GMPT) method cannot accurately extract the full power of each PV power generation component in the system because of the existence of a bypass diode.

According to references from other scholars, mismatch power losses due to partial shadowing in PV arrays can be mitigated by using various methods, whereby PV array configuration adjustment is one of the optimal techniques that can significantly reduce mismatch power losses [11]–[13]. Moreover, solutions to enhance the system power generation efficiency by using microconverters to back-end PV modules within PV arrays instead of a large DC-DC converter following the PV array have also been proposed [14], [15],
which concentrate on modifying the power conditioning system (PCS) to improve system generation efficiency, such as Module Integrated Converter (MIC); however, these methods are unable to improve the power generation efficiency of already installed and operating systems.

Therefore, in response to the abovementioned concerns, we inserted DC-DC converters between PV modules and the PCS in currently operating conventional PV systems, which allows each PV module in the array to operate in a time-varying ambient environment optimally [16], [17]. In addition, this system has two excellent features. The first feature is partitioned control, in which the operating mechanism of the PV array side and the power conditioner side implement distinct functions to attain precise control. Furthermore, this can be easily implemented, requiring only the addition of DC-DC converters to the conventional array structure and the corresponding control strategy to accomplish the retrofitting of conventional PV systems.

In this paper, short-term experimentation aimed at shading response capability tests was performed for a novel proposed APV system. In addition, to investigate the power enhancement effect of the APV system, a long-term system operation comparison experiment for two identically configured mini-PV arrays under PSCs was conducted. Overall, by using this control strategy scheme, the GMPP of the system can be identified and tracked accurately.

The rest of this paper is organized as follows. Section 2 provides a theoretical analysis of the conventional PV system and proposed APV system. Section 3 illustrates and verifies the adaptability of the proposed APV system to shadows through short-term experiments. Section 4 depicts the experimental results of long-term comparisons to substantiate the power enhancement effect achieved by the proposed system. Finally, Section 5 gives a summary and conclusion.

II. THEORETICAL ANALYSIS OF A PV ARRAY SYSTEM

A. CONVENTIONAL PV SYSTEM

This section presents a comprehensive explanation for the conventional PV system and problems thereof. The series-parallel PV array configuration is the most commonly used PV array structure due to its economical, practical and user-friendly features [17]–[19]. As an example, the conventional PV system is provided in Fig. 1, where the PV modules with bypass diodes are connected directly to the PCS in series and parallel. Under normal operating conditions with no shadow influences, the traditional MPPT methods provided by the PCS have the capability to ensure that the system operates at its optimal state [20]. When the array is under PSCs, however, there is a risk that using these methods causes the system to operate at the local maximum power point (LMPP) rather than the GMPP [21], [22]. Furthermore, according to the results of tests on various commercially available inverters, the power loss attributed to shadows can be as high as 70% under PSCs [23], [24]. Additionally, it has been documented that PV systems have a 41% probability of operating with the impact of shading, which can result in up to 10% power loss [5]. As a result, mitigating the impact of partial shadows is an essential and critical challenge [25].

Using the array shown in Fig. 1 as a preliminary explanation of partial shading effects on PV systems, the power-voltage (P-V) characteristics of the string are shown in Fig. 2. As illustrated in Fig. 1, PV modules shown in black represent shade produced by objects such as buildings, whereby solar irradiation intensity falls 90%. The parameters of the PV modules in Fig. 1 are shown in Table 1.
in the high voltage range. When the PV module encounters shading problems, however, the MPP of the PV module can only be locked at the low-power point rather than the high-power point given the drawbacks of the traditional MPPT method [26].

Although the GMPPT method may avoid the above problems, due to the existence of bypass diodes in the array, shaded generation modules with zero power output occur, which leads directly to the GMPP of each string being lower than its ideal maximum value. Nevertheless, bypass diodes are essential components in PV arrays to mitigate the influence of the hot spot effect when some parts of the PV generation module receive less irradiance than other parts [27]–[30], which might trigger hazardous incidents such as a fire disaster.

Additionally, because the GMPP has been shifted for each string, it can be ascertained that multiple power peak points and power dissipation (mismatch between strings) occur in the P-V characteristics of the array [31]–[33]. Conclusively, the maximum power of each generation module in a conventional PV system cannot be fully extracted under PSCs. As such, to solve the output power mismatch caused by partial shadowing effects, a growing number of solutions have been proposed, with accuracy and tracking speed being notably paramount among the main criteria for selecting a system controller [28].

To address these problems, as shown in Fig. 3, a system that can seamlessly extract the full power of each PV module in the array and effectively prevent mismatch between strings is required. Meanwhile, as shown in Fig. 4, according to the simulation results of the APV system retrofitted based on the array structure of Fig. 1, the system can transform each string from a multipeak P-V characteristic curve to a P-V characteristic curve with only the ideal MPP as the peak [34], [35].

**FIGURE 3.** P-V characteristics under PSCs.

**B. ACTIVE PV ARRAY**

With reference to the research of other scholars [36], [37], the output power of PV modules in the string will drop drastically due to the nonuniform insolation of the PV array. Furthermore, by forming strings with PV modules in series, the current is limited by the PV module with the minimum irradiance under PSCs. Hence, the shaded modules are operated under reverse bias without power transfer, the energy will be dissipated as heat, which may result in hot spots on the PV modules. To prevent such situations, appropriate adjustments should be implemented to the outputs of the other PV modules in the string that are under normal irradiation intensity to prevent reverse bias states from occurring. Given the variability of the ambient environment, however, it is not possible to track the conditions of individual PV modules inside the system in real time; thus, a system that can automatically identify and mitigate the effects of shadows is necessary.

To address these considerations, as shown in Fig. 5, additional DC-DC converters are added to the conventional PV system between PV modules and the PCS, resulting in the APV system.

**FIGURE 4.** P-V characteristics of active PV array.

**FIGURE 5.** Structure of the APV system.

In this regard, the main feature of our proposed APV system is partitioned control. Additional converters enable each PV module within the array to determine its optimal state, thereby allowing the PCS at the end of the array to...
receive a single-peak P-V characteristic curve instead of a multipeak curve.

1) PROPOSED PV-UNIT MODULE

A novel PV-unit module is therefore being proposed, which comprises a PV module connected in series with a DC-DC converter, as shown in Fig. 6. Each unit calculates the ratio of the buck-boost converter through periodic scanning to perform the controlling function. For instance, when the ratio is greater than 1, the converter should operate in the boost state; otherwise, it should operate in the buck state.

2) REAL-TIME SCANNING METHOD

Fig. 7 provides a schematic diagram of the operational characteristics associated with the real-time scanning method, which we presented previously [39]–[41]. From top to bottom are the characteristic curve of the PV cell power $P_{pv}$, the characteristic curve of the PV cell voltage $V_{pv}$ and current $I_{pv}$ and the fundamental and carrier waveforms of the switch control signal. This method is an efficient GMPPT method that is capable of pinpointing the MPP by traversing all operating states of a given PV module from open-circuit to short-circuit in an extremely short period of time (approximately a few tens of milliseconds), as shown in Fig. 7. The real-time scanning method has the ability to sample the voltage and current values of the module along with the action, which also enables the extraction of the data corresponding to optimal operation conditions.

In addition, due to the series-parallel structure of PV arrays, the optimal operating voltage of each string varies when facing complex PSCs [31], which leads to a multipeak characteristic P-V curve, as shown in Figure 3. Therefore, if merely updating the PCS of the conventional system with the real-time scanning method, data on the PV system ideal MPP become unavailable so that the full power of each PV module cannot be extracted.

To address the problem, as illustrated schematically in Fig. 5, a novel control strategy is now proposed, in which only the scanning function is implemented for the PV-unit modules within the array. In addition, due to the ease of implementation and the simple nature of the control mechanism, the PCS at the end of the system utilizes the most common perturb and observe (P&O) method [42]–[44], rather than the complex GMPPT method [45]. That is, even though the APV system we proposed utilizes the real-time scanning method, the innovation of the APV system comes not from simply applying this method in the PCS but from integrating a novel system-level solution by utilizing this method to address the power loss caused by PSCs while maintaining the PCS unchanged from conventional PV systems.

Moreover, although all PV modules are simultaneously switched from open-circuit to short-circuit modules in a very short scanning duration, as shown in Fig. 6, the outputs of the additional units have been connected in parallel with a capacitance module, so our proposed APV system with PCS, which performs MPPT at the end of the array, ensures that the voltage on the load remains relatively stable.

3) CONTROL PRINCIPLE

Contributing to the characteristics of the buck-boost converter, a broad input range can accommodate the PV power system under any condition. Moreover, the output of the converter can be adjusted by pulse width modulation (PWM) to guarantee independence between the input and the output.

The essential feature of this novel control strategy that we proposed is to independently administer each PV module in the array by monitoring its operating state. This operation mode is switched after the scan operation. That is, the transition interval of the PV module buck-boost mode depends on the duration of the scan. When detecting the arrival time flag of the scan, the APV system will disable the previous transfer operation from scan analysis and then select the next transfer operation mode according to the new computed transfer ratio $\gamma(j)$ after the scan action.

Therefore, the operation mode is manipulated by periodically calculating the transmission ratio $\gamma_{ij}$ of each DC-DC converter. For example, when the ratio is greater than 1,
it means that the output of the converter is greater than the input, and the converter should be set to boost mode, shown as:

\[ V_{\text{out}(j)} = \frac{V_{\text{pcs}0} \cdot P_{\text{max}(j)}}{\sum_{j=1}^{N} P_{\text{max}(j)}} \]  

\[ \gamma(j) = \frac{V_{\text{out}(j)}}{V_{\text{in}(j)}} = \frac{P_{\text{max}(j)} \cdot V_{\text{pcs}0}}{V_{\text{op}(j)} \cdot \sum_{j=1}^{N} P_{\text{max}(j)}} \]  

where \( V_{\text{in}(j)} \) represents the ideal input voltage of each unit and \( V_{\text{out}(j)} \) for each unit is the ideal output voltage, calculated via the MPP of the PV module, which is obtained by a scanning operation. Furthermore, \( P_{\text{max}(j)} \) is the maximum power of each PV module updated with the real-time scanning method, which is executed by unit. Moreover, \( V_{\text{op}(j)} \) represents the optimal operating voltage of the corresponding PV module, which here corresponds with the ideal input voltage \( V_{\text{in}(j)} \) according to each unit. In addition, \( V_{\text{pcs}0} \) is the ideal operating voltage for the system, which can be set arbitrarily before system operation, as indicated in Fig. 3.

Similarly, PV-unit modules in other strings calculate the transmission ratio based on the same \( V_{\text{pcs}0} \), whereby the output voltage obtains the maximum power for all strings and becomes \( V_{\text{pcs}0} \); thus, mismatches between strings are avoided, and the maximum power of the system can be obtained. Additionally, it is necessary to set the scan period and the scan execution time before system operation.

To calculate the above transfer ratio \( \gamma(j) \), according to the control diagram demonstrated in Fig. 8, reference voltages for each PV module need to be computed in real time to optimize the output, as illustrated below:

\[ V_{(j)} = \frac{P_{(j)} \cdot V_{\text{pcs}}}{\sum_{j=1}^{N} P_{(j)} \cdot P_{\text{max}(j)}} \approx \frac{P_{\text{max}(j)} \cdot V_{\text{pcs}}}{\sum_{j=1}^{N} P_{\text{max}(j)}} \]  

\[ V_{\text{ref}(j)} = \frac{V_{(j)}}{\gamma(j)} = \frac{V_{\text{pcs}} \cdot V_{\text{op}(j)}}{V_{\text{pcs}0}} = mV_{\text{op}(j)} \]

Here, \( V_{\text{ref}(j)} \) indicates each PV module reference voltage, and \( V_{\text{pcs}} \) is the sum of the output voltages \( V_{(j)} \) of each PV-unit module within the strings. \( P_{(j)} \) is the output power of each PV module. Here, given the control of the MPPT implemented by the PCS, the output power of each PV module would be approximately at its maximum power \( P_{\text{max}(j)} \), in which case (3) is established. Furthermore, the reference voltage is obtained by calculating the control factor \( m \) from \( V_{\text{pcs}} \) and \( V_{\text{pcs}0} \) (set value) in combination with \( V_{\text{op}} \) obtained by the scanning method, as in (4). In this way, the MPPT control of the PCS can be transferred to each PV module.

That is, the optimum voltage can be precisely and appropriately assigned from the PCS side to each PV module. Conclusively, this transfer control ensures that the maximum power of each PV module can be totally extracted.

III. SHORT-TERM EXPERIMENTAL VALIDATION

A. SYSTEM COMPONENTS

The structure of the PV cells inside the PV module utilized in this experiment along with the effect of adding shadows is illustrated in Fig. 9, in which two series of PV cells are joined in parallel. It is thus clear that the effect of shading conditions on PV modules can be intimately related to their structure.

As illustrated in the conceptual diagram of the 2nd case, which adds 90% shading to an individual cell, because of the presence of the bypass diode, when only one cell is shaded in the two-string PV module utilized in this experiment, only the shaded string is affected. However, adding 50% shading to both the top and bottom cell strings of the 3rd case would be equivalent to 50% shading of the entire PV module.

To verify the practical feasibility of the system, as shown in Fig. 10, an experimental platform for a mini-APV system has been tested. A string consists of 2 PV-unit modules connected in series, and then 2 of these strings are connected in parallel to form an APV system. Shadows were artificially introduced to both the top and bottom cell strings of the 3rd case would be equivalent to 50% shading of the entire PV module.

To observe the electrical parameter distribution within the string and the P-V characteristics of PV modules. The specifications of the PV modules utilized in this mini-APV system experiment are given in Table 2.
B. EXPERIMENTAL RESULTS

To validate the feasibility of the system, a short-term experiment was performed for this mini-APV system to test the APV system’s ability to respond to PSCs. For this experiment the scan period was set to 20 s with 60 ms duration and the switching frequency is set to 15 kHz. In addition, the P&O method executed by the PCS had a sampling period of 1 s with an action amplitude of 1 V, as described below.

In the functional experiment, an evaluation of APV system functionality and adaptability to PSCs, such as fallen leaves, was performed. As shown in Fig. 9, the system was operated for 50 seconds with one of its PV modules being applied to a type 2 shading condition at a fixed time interval to observe the electrical parameters at the input and output of the PV-unit modules. During this experiment, the PV module surface temperature was approximately 33°C, and the solar irradiation intensity was approximately 700 W/m².

Moreover, to enable all converters to operate in boost mode for a high voltage output, the ideal operating voltage of the system, \( V_{pcs0} \), was set to 36 V in accordance with the parameters presented in Table 2. In addition, it can be set to various values depending on the particular requirements.

TABLE 2. Specifications for the PV module.

| Parameter       | Description               | Value   |
|-----------------|---------------------------|---------|
| \( P_{max} \)   | maximum output power      | 56 W    |
| \( V_{oc} \)    | open-circuit voltage      | 21.1 V  |
| \( I_{sc} \)    | short-circuit current     | 3.47 A  |
| \( V_{op} \)    | optimal operating voltage | 17.2 V  |
| \( I_{op} \)    | optimal operating current | 3.26 A  |

1) FUNCTIONAL EXPERIMENT

During continuous operation of 50 s of the system shown in Fig. 10, the specified shading was attached to PV4 within the array at 17 s and thereafter withdrawn after 38 s.

Meanwhile, to facilitate adequate analysis of the APV system, 4 modes were set for the PV4 module with shadows: mode A1 for MPPT when there were no shadows attached; mode B2 for shadows attached before scanning; and mode A2 for GMPPT after scanning; and mode B1 for removal of shadows before scanning, as shown in the P-V and I-V characteristic curves obtained by scanning in Fig. 11. Simultaneously, the input and output waveforms of all PV-units within the APV system have been compared, which validates the control effectiveness for the individual PV-unit modules, as shown in Fig. 12.

In terms of the output of PV modules, as depicted in Fig. 12a, with no shadow attached to PV modules, all modules within the APV system operated in the A1 mode described in Fig. 11a. In this case, all PV modules operate on their own MPP. Furthermore, according to the output voltage of the converters in Fig. 12b, the output voltages of the PV-unit modules under this condition were all half of \( V_{pcs0} \) at 18 V.

By applying the specific shadow to PV4, however, its output current dropped precipitously, as illustrated in Fig. 12a. Nevertheless, variations in output voltage were limited as a result of the control strategy of the converter. Thus, the PV4 module with artificially inflicted shadows was operating around the low power point of the B2 mode depicted in Fig. 11b at this point. Here, as illustrated in Fig. 12b, since the control data have not been updated, the output of the...
PV3-unit module shifted dramatically. However, with the wide range output characteristics of the DC-DC converter, the PV3-unit without shadows was burdened with more voltage output to ensure that the total string output remained at $V_{pcs0}$.

During the scanning action from the 19 s, in Fig. 12a, the control system detected shadow conditions on the PV4 module, which instantly triggered the shadow response mode. Concurrently, the controlled PV4 module operates at the MPP, which was detected by the scanning action, corresponding to the A2 mode shown in Fig. 11b. Here, due to the structure of the PV-unit, each series connected unit shares an identical output current, while output current of each PV module is not identical. The corresponding parameters were approximately [6.9V, 2.3A, 15.7W]. With this, unit 4 was switched from the former boost mode to buck mode, while the other 3 units remained unchanged in the original boost mode after the scanning action, and yet the $V_{pcs}$ was basically unaffected during the process.

Therefore, the strategy of sensing and tracking changes in irradiation intensity is reflected in the optimal output voltage $V_{op}$ and current $I_{op}$ of the PV module derived by periodically executing scanning analysis presented in Fig. 7. These optimal parameters of the PV modules obtained by scanning were substituted into (3) to calculate the voltage distribution of each individual PV-unit module, as shown in Fig. 12b.

For the shadow response mode, by sampling the voltage and current data in the A2 mode in Fig. 12a across the 4 PV modules in combination with the I-V characteristic curves, it can be more intuitively observed that the APV system is capable of operating the PV modules at their optimal state in real-time under PSCs, as shown in Fig. 13. It is a combination of the data between 25 and 27 seconds from Fig. 12 and P-V characteristic curves shown in Fig. 11, from which it can be clearly demonstrated that under this experimental condition, all 3 PV modules (PV1, PV2, PV3) without shadows in the APV system consistently operated around the MPP (15.6 V) in A1 mode, and the PV module (PV4) with specified shadows operated approximately 6.9 V in A2 mode.

Furthermore, it is worth mentioning that since the data used in this manuscript were collected under actual environmental conditions, even if no shadow is present on the PV module, following each scanning period, the module’s operating state will be slightly different from its previous operating state. However, it can still be considered to be operating at its optimal state under the prevailing conditions.

Thereafter, upon stabilization of the system, the shadow was artificially removed, as shown in Fig. 12a. Since the output voltage of PV1 cannot be changed abruptly due to the control strategy, its output current was instantly enlarged to a level that approximated the short circuit current, whereupon the PV1 module operated in mode B1, as shown in Fig. 11a. Meanwhile, as demonstrated in Fig. 12b, the outputs of
PV-unit modules experienced corresponding voltage fluctuations while consistently ensuring that the output voltage matched $V_{\text{pcs0}}$.

Following the next scanning action at approximately 39 s, as shown in Fig. 12, the shadow response mode is removed as the system detects no shadows, while the controller adjusts the operating point of the PV$_4$ module to the MPP without shadows, which corresponds to the A1 mode illustrated in Fig. 11a.

In this experiment, evaluation of the output of the remaining modules in the system reveals that the unshaded modules were operating optimally at mode A1 throughout. Hence, the experiment adequately demonstrated that each module within the APV system is capable of operating at the MPP. Moreover, the proposed APV system is able to compensate for the impact of PSCs such as fallen leaves.

IV. LONG-TERM EXPERIMENTAL VALIDATION

A. SYSTEM COMPONENTS

Although the short-term functional experiment validated the capability of the APV system to enable each PV module within the array to operate optimally under PSCs, a long-term operational comparison experiment was performed to better visualize the power enhancement capability of the APV system in comparison to the conventional control strategy.

As shown in Fig. 14, a conventional PV system constructed with the same structure in reference to the APV system illustrated in Fig. 10 was built for this purpose to conduct a comparative experiment over the same conditions. In this case, compared to the proposed APV system, PV modules of this system are combined in series and parallel and then directly connected to the PCS, where the experimental platform for implementing the control part is shown in Fig. 15.

B. EXPERIMENTAL RESULTS

A comparative experiment between the conventional and proposed systems was executed under identical natural conditions for five hours. In consideration of realistic environments such as large shading conditions from nearby buildings, which have a significant impact on the PV array, the 3rd style of 50% shadow shown in Fig. 9 was added to both systems simultaneously to observe their power generation. Additionally, the APV system was set to a scan period of 20 seconds.
and a duration of 60 ms with an average 32°C panel surface temperature for both arrays. Additionally, the P&O method performed by the PCS of both systems had a sampling period of 1 s and an action amplitude of 1 V, as described below.

1) COMPARISON EXPERIMENT
To substantiate the effectiveness of the proposed system, comprehensive data gathering was carried out by operating both the APV system and the conventional PV system in the practical external environment simultaneously, thus facilitating a reasonable comparison throughout the experiment. Furthermore, the operation started without shading at 9:00 am, and then shadows were added to both systems at 10:00 AM, 50% shadows for PV2 and PV4 in the APV system and for PV6 and PV8 in the conventional PV system. Power from both systems were compared until 14:00 pm. Fig. 16 illustrates the power generation and corresponding solar irradiation intensity of both the conventional PV system and APV system over 5 hours of external operation. Under these experimental conditions, the generation of both systems was virtually the same before the shadows were added, however, the power generation by the APV system was determined to be 1.6 times greater than that of the conventional PV system following the addition of shadows.

Summarizing the results of the long-term experiment, the APV system is capable of considerably enhancing the output power under PSCs in comparison to the conventional PV system.

V. CONCLUSION
A novel APV system is proposed as an option to surmount the irretrievable power loss incurred when the system is under uneven irradiation intensity conditions. The capability of an APV system is to adjust the complex multipeak P-V characteristic curve over the affected string toward a single-peak curve with the ideal MPP of the string. Beneficially, the maximum power of the string becomes fully extractable to optimize the operation of the entire PV generation system. Moreover, the proposed APV system possesses high adaptability with minimal modification to conventional PV systems in practical applications.

From long-term and short-term experimental analyses, the effectiveness of the proposed system has been fully demonstrated. The obtained experimental data indicate that under the present experimental conditions, the APV system is capable of enhancing the power output by approximately 1.6 times compared to a conventional PV system while confronting identical large shadows caused by buildings. From the perspective of economic benefits, although the proposed APV system requires the addition of DC-DC converter devices to the conventional PV system to accomplish the upgrade, it may result in some preliminary investment, especially for the establishment of large-scale PV systems. With the economic benefits generated by the new system in terms of power generation efficiency, however, it is anticipated that the investment cost can be recouped within a few years after the system modification. Moreover, depending on the climatic environmental conditions and the local community’s power recovery policy, APV systems promise continuous positive economic benefits in the future. Furthermore, our research delivers evidence that the APV system is promising for the solar industry.

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