Improvement of Power Acquisition Characteristic on PV Generation System by Using Active PV Array

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Abstract. The PV generation system operates in maximum power of PV array by the maximum power point tracking (MPPT) control of power conditioning system (PCS). However, there is a problem that maximum power of the PV array configuration greatly decreases by partial shadow. For this problem, the authors previously proposed the active PV array (APV) system which is able to extract total power of the maximum power of each PV panel with preset PV array voltage, equipping each panel with the buck-boost converter (Unit). This APV system is able to maintain the ideal P-V characteristics under all conditions. In this paper, the effect of this method is demonstrated by simulation and experiment. In this investigated condition, it is clarified that the generated power of the proposed APV system is 1.6 times, compared with the conventional PV array system.

1. Introduction

The PV generation system operates in maximum power of PV array by the maximum power point tracking (MPPT) control of power conditioning system (PCS). Therefore, various MPPT methods have been investigated [1]-[3]. The PV generation systems have the problem that when the panel of a PV array is in partial shadow, the output characteristics of the array become complex, and the array output falls drastically because of a shift in the MPPT operating point of the PCS. To solve this problem, the authors previously proposed and demonstrated the effectiveness of an improved perturbation and observation (P&O) method to refine the general MPPT algorithm for the PCS itself (P&O method) and improve MPPT responsiveness [4]. In addition, the authors proposed and demonstrated the effectiveness of a scan method that can precisely track the maximum power point for each array or string [5], [6]. The authors further proposed and demonstrated the effect of various MPPT control methods to which this scan method was applied [7], [8]. However, conventional MPPT control methods, including those above, have the problem that power losses occur due to the fact that the outputtable power cannot be extracted from a panel in shadow, and that there are mismatches between strings, as a result of operating on the principle of precisely capturing the point of maximum output power in accordance with array characteristics. In the present day, the method that a MPPT unit is installed on each panel of a PV array is in practical use. Therefore, the authors previously investigated the appropriate placement of MPPT units [9], [10]. However, the method has the disadvantage that MPPT operation of PCS is unstable owing to constant output power characteristics of the MPPT unit. To solve the power drop problem of PV array, the following conditions must be satisfied.

Condition 1: The outputtable power (maximum power) of all panels in each string must be extracted
Condition 2: Mismatches between strings must be prevented

So, the authors proposed a new active PV array (APV) system in which a buck-boost DC-DC converter is installed on each panel of a PV array in order to control the characteristics of the PV array...
itself to achieve the ideal P-V characteristics [11]. Because the proposed APV system satisfies Conditions 1 and 2, the total of maximum power for each PV panel can be extracted at a predetermined string voltage point. Consequently, the maximum power from all panels can be extracted by MPPT control of the PCS. This paper investigates the effectiveness of the proposed APV system through simulation and experiment.

2. Proposed APV system

Figure 1 presents the configuration of an actual-scale APV system assumed to be a household PV system. The number of strings is \( M \), and each string is configured with \( N \) panels. Here, we focus on String 1 and show a method for setting buck-boost ratio \( \gamma_{j0} \), where subscript \( j \) is an integer from 1 to \( N \). A unit is connected to each PV panel, and the output side is connected in series. Figure 2 shows the buck-boost DC-DC converter used in the unit. Each unit calculates the buck-boost ratio \( \gamma_{j0} \) in real time through periodic scanning to perform the controlling function. Figure 3 presents a conceptual diagram of the scanning operation. From top to bottom are shown photovoltaic cell voltage \( V_{PV} \), photovoltaic cell current \( I_{PV} \), and photovoltaic cell output power \( P_{PV} \). In the scanning operation, the PV panel is taken from an open-circuit to a short-circuit condition in a very short span of time (about a few tens of milliseconds) to detect the I-V characteristics. This acquires the maximum power \( P_{maxj} \) for each PV panel and the optimal operating voltage \( V_{OPj} \), which is the voltage at that time. Here, the optimal operating string voltage, which is the buck-boost ratio \( \gamma_{j0} \) that satisfies Condition 1 is derived below.

The optimal operating string current \( I_{PCSj0} \) is expressed by the following equation using the maximum power \( P_{maxj} \) for each panel:

\[
I_{PCSj0} = \frac{P_{maxj}}{V_{OPj}}
\]

![Figure 1. Construction of actual-scale APV system.](image)

![Figure 2. Buck-Boost DC-DC Converter (Unit).](image)
Figure 3. Scanning operation diagram(Unit1).

From (1), the output voltages $V_{j0}$ when operated at the optimal operating voltage $V_{PCS0}$ are as follows:

$$I_{PCS0} = \frac{\sum_{j=1}^{N} P_{\max j}}{V_{PCS0}}$$  \hspace{1cm} (1)

$$V_{10} = \frac{P_{\max 1}}{I_{PCS0}}, V_{20} = \frac{P_{\max 2}}{I_{PCS0}}, \ldots, V_{N0} = \frac{P_{\max N}}{I_{PCS0}}$$  \hspace{1cm} (2)

$$\sum_{j=1}^{N} V_{j0} = V_{PCS0}$$  \hspace{1cm} (3)

Where the buck-boost ratios $\gamma_{j0}$ are expressed as

$$\gamma_{10} = \frac{V_{10}}{V_{OP1}}, \gamma_{20} = \frac{V_{20}}{V_{OP2}}, \ldots, \gamma_{N0} = \frac{V_{N0}}{V_{OPN}}$$  \hspace{1cm} (4)

The output voltage $V_{j0}$ of each Unit which is satisfied with above condition, is shown in the following equation.

$$V_{j0} = \frac{P_{\max j}}{\sum_{j=1}^{N} P_{\max j}} V_{PCS0}$$  \hspace{1cm} (5)

The output voltage $V_j$ of each converter in real-time is shown in the following equation.

$$V_j \approx \frac{P_{\max j}}{\sum_{j=1}^{N} P_{\max j}} V_{PCS}$$  \hspace{1cm} (6)

Where, $V_{PCS}$ is the real-time operating voltage at PCS side. Due to the series structure, the output voltage of each converter is approximately determined by the magnitude of solar power generated by its own.

The reference voltage $V_{refj}$ for each panel can be simplified as follows:

$$V_{refj} = \frac{V_{j}}{\gamma_{j0}} = \frac{V_{OPj}}{V_{j0}} \frac{\sum_{j=1}^{N} P_{\max j}}{P_{\max j} V_{PCS}} \frac{V_{PCS}}{\sum_{j=1}^{N} P_{\max j}} = \frac{V_{PCS}}{V_{PCS0}} \cdot V_{OPj} = mV_{OPj}$$  \hspace{1cm} (7)

where, $V_{OPj}$ is MPP (optimal) voltage of each panel acquired from scan. Moreover, due to MPPT at the PCS side, $V_{PCS}$ is always approaching the set constant $V_{PCS0}$ (matching factor $m=1$), allowing the reference voltage of each panel to approach its MPP voltage refreshed after scan. That is, the optimal voltage can be regulated appropriately from the PCS side to each panel. This transfer control ensures
that each panel operates at their own MPP. Figure 4 shows the control diagram. By controlling each unit with figure 4, the output of each PV panel is maximized, and a single output peak point arises for the string at $V_{PCS0}$ to achieve the ideal P-V characteristics. Similarly, other strings are also set according to the same $V_{PCS0}$. Thus, the optimal operating voltage of all strings becomes $V_{PCS0}$, mismatches between strings are avoided, and Condition 2 is satisfied. Note that since the $V_{OPj}$ of (8) are updated by periodic scanning performed by the unit, Conditions 1 and 2 are maintained at all times in response to changes in weather conditions and the like. Consequently, the array operates at the maximum power point through MPPT control of the PCS, and all panels operate at the maximum power. That is, this unit does not have the MPPT function, but has the function of appropriately transmitting the change of the input voltage $V_{PCS}$ based on the MPPT control of the PCS to the PV panel.

![Figure 4. Control diagram.](image)

### 3. Simulation and experiment

#### 3.1. Simulation

Figure 5 shows the conventional PV array configuration in which part of the PV panel is in shadow. A string is made up of 2 PV panels in series, and an array is made up of 2 strings. A bypass diode is connected in parallel with each panel. The PV panels in the figure shown in gray are assumed to be in the shadow of a building or the like, whereby solar radiation intensity falls 50% and 75%, and the solar radiation intensity on the array is in a non-uniform state. A simulation of the P-V characteristics of a conventional PV array system under these conditions was carried out using the I-V properties of a solar cell panel as follows:

$$V_{PV} = \frac{a n k T}{q} \log\left(1 - \frac{I_{PV} - (1 - X) I_{SC}}{I_0}\right) \tag{8}$$

where $a$ is the number of cells, $n$ is the diode factor, $k$ is Boltzmann’s constant, $q$ is the elementary charge, $I_{SC}$ is the PV- panel short - circuit current, $I_0$ [A] is the reverse saturation current, and $X$ is the fraction in shadow (0 to 1.0). Nominal values for the solar cells used in the simulation were open-circuit voltage $V_{OC} = 21.1$ V, short-circuit current $I_{SC} = 3.47$ A, optimal operating voltage $V_{OP} = 17.2$ V, optimal operating current $I_{OP} = 3.26$ A, and maximum power $P_{max} = 56.0$ W. In addition, solar radiation intensity is 1000 W/m² and cell temperature is 25 °C. The total power when all the PV panels of the array configuration are operated at maximum power is defined as potential power $P_O$, which here is 150.4 W. Figure 6 presents the P-V characteristics of a conventional PV array configuration.
can be seen from this figure that the P-V characteristics of strings, which are cast in shadow, are such that the local maximum power point (LMPP) occurs on the high voltage side of the PCS input voltage $V_{PCS}$, and the global maximum power point (GMPP) occurs on the low voltage side of string 2. Because the panels in shadow generate no electricity due to the operation of the bypass diode, there is the problem that the power $P_{\text{max}}$ at the GMPP of each string is lower than the potential power of each string.

![Figure 5. Conventional PV array configuration.](image)

Figure 5. Conventional PV array configuration.

Figure 6. P-V characteristics of conventional array.

Furthermore, because the GMPP of each string has shifted, it can be ascertained that power dissipates (mismatch between strings) and that multiple power peak points occur in the P-V characteristics of the array. At these conditions, the array maximum power $P_{\text{armax}}$ is 112.7 W. With a conventional array configuration, $P_{\text{armax}}$ is confirmed to fall 25.1 % compared to potential power $P_0$. The power on LMPP of array which is actual operation point is 90.7 W. Consequently, the outputtable power of each panel cannot be extracted at the maximum power point of the array.

Figure 7 shows the proposed APV system. Using these buck-boost ratios $\gamma_{j0}$ of (4) and taking the operating current of String 1 to be $I_1$, the I-V characteristics of String 1 are expressed by the following equation:

$$V_{PCS} = \sum_{j=1}^{n} \left\{ \gamma_{j0} \cdot a \cdot \frac{n k T}{q} \cdot \log(1 - \gamma_{j0} \cdot \frac{I_0}{I_0}) \cdot (1 - \frac{X_j}{I_{SC}}) \right\}$$

(9)

Using (9), a simulation was carried out of the P-V characteristics of the APV array shown in figure 7. Figure 7 has a configuration in which a unit is installed on each PV panel of the conventional PV array. The nominal values for the PV panel and shadow conditions are the same as those in figure 5. In this study, the optimal operating string voltage $V_{PCS0}$ for each string is set to 34.4V. Unit efficiency is assumed to be 100%.

Figure 8 presents the P-V characteristics of the APV system. It can be seen from Figure 8 that the maximum power point for each string agrees with $V_{PCS0} = 34.4V$. The array maximum power $P_{\text{armax}}$ is 150.4W. This power can be confirmed to be the same as the potential power $P_0$. The figure confirms that the outputtable power from all panels in each string can be extracted.
The above results confirm that the APV system satisfies Conditions 1 and 2. By comparing figure 6 and figure 8, when each system is operated at maximum power, it is clear that the proposed system can obtain 1.33 times the power of the conventional system. When the conventional array system operates on LMPP, the proposed system can obtain 1.66 times the power of the conventional system.

3.2. Experiment

In order to confirm the validity of proposed APV system, the following experiment is carried out. Figure 9 and figure 10 show the experiment system. The nominal values for the PV panel and shadow conditions are the same as those in section 4.1. In figure 10, two series connected DC-DC converters in string1 and 2 are controlled with the method of figure 4 by DSP (digital signal processor) and connected with the same MPPT controller at PCS side. Here, MPPT operation provided by PCS side was implemented with the conventional P&O approach. In addition, the theoretically optimal operating voltage $V_{PCS0}$, at the PCS side used for calculation was initially set as 34.4 V. It is worth noting that this value is not fixed, and determined by user’s requests. For example, in our research, in order to minimize the power loss of unit, the DC-DC converters are expected to work at mode without switching (the buck-boost ratio $\gamma_{0}=1.0$) on the occasion when in absence of a shadow. Since the total value of MPP voltages at nominal conditions (34.4V) is equal to this set value (34.4V), such that both of converters are able to work at mode without switching. Table 1 shows the Scan parameters using in each unit. Table 2 shows the P&O parameters using in PCS side. Each unit is controlled by control signal of DSP as shown in Figure 11.

### Table 1. Scan parameter.

| Scanning period [s] | 30 [s] |
|---------------------|--------|
| Scanning time span [ms] | 100 [ms] |
| Switching frequency [kHz] | 5 [kHz] |
### Table 2. P&O parameter

| P&O operating period Δt [s] | 1 [s] |
|----------------------------|-------|
| Perturbing voltage ΔV [V]  | 1 [V] |

**Figure 9.** Conventional system.

**Figure 10.** Proposed APV system.

**Figure 11.** Control system of each unit.

**Figure 12.** Generated power characteristics.
Figure 12 shows the total power generation of two array systems in 4 hours (10:00~14:00). The total power generation of conventional array system is 289.3Wh while proposed APV system is 462.5Wh. The generated power of the proposed APV system is 1.6 times, compared with the conventional PV array system. It can be seen that the effect of power in this experiment is in good agreement with the simulation. From these investigations, it is clarified that the proposed APV system is effective and useful.

4. Conclusion
This paper investigates the effectiveness of the proposed APV system through simulation and experiment. In the experiment (4 hours), the generated power of the proposed APV system is 1.6 times, compared with the conventional PV array system. It can be seen that the effect of power acquisition in the experiment is in good agreement with the simulation. From these investigations, it is clarified that the proposed APV system is effective and useful.

5. References
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