



Improving the Efficiency of a Photovoltaic System Using a Hybrid Control Method Based on a DPP Structure

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Abstract

In this paper, a hybrid control method is proposed, based on a differential powerprocessing (DPP) structure for a maximum-efficiency photovoltaic (PV) system. The DPP structure has the least power-conversion loss among PV system structures. When applying some maximum power-point tracking (MPPT) control methods to the DPP structure, the structure needs to change. However, the hybrid control method proposed in this paper can be applied without changing the DPP structure. Moreover, it is possible to quickly reach the initial maximum power point (MPP) zone and to generate power at the correct MPP. Through simulations, the method's operation and superiority were confirmed. In addition, this method was tested experimentally with hardware, based on a digital signal processor (DSP) (TMS320F28335). Hence, we can improve the reliability of this method.

Keywords Differential power processing (DPP) structure · Digital signal processing · Hybrid control · Maximum power point (MPP) · Maximum power point tracking (MPPT) · Photovoltaic (PV)

1 Introduction

The fossil fuels and nuclear energy that are currently the world's main energy sources cause environmental pollution and risk issues. Because of this, interest is increasing in using renewable-energy methods that can recycle fossil fuels or regenerate energy. According to the International Renewable Energy Agency (IRENA), the photovoltaic (PV) power-generation capacity in 2017 was 386,107 [MW], and in 2018, it was 480,357 [MW]. It had the largest increase among all of the renewable-energy generation systems [1].

A photovoltaic power-generation system uses solar cells, which convert sunlight directly into electricity. The conversion efficiency of the solar cells currently being commercialized is low, less than about 20 [%]. A solar panel made of these solar cells has a non-linear power-voltage (P–V) curve. Unfortunately, it is sensitive to the surrounding environment, e.g., irradiance and temperature changes.

Because of this characteristic, the solar panel must be controlled to maximize its power generation. This control is called maximum power-point tracking (MPPT). Many MPPT methods have been studied, thus far, and methods to quickly and accurately find the point that can generate the maximum power and obtain a stable waveform are currently being studied [2].

For MPPT, perturb and observe (P&O) and incremental conductance (InC) methods are widely known. These methods are easy to use because they are composed of simple algorithms; however, their power-production capacity and control performance vary, depending on the magnitude of the MPPT's voltage variation [3].

The constant voltage (CV) method maintains a constant voltage at the PV panel. This can reduce the sensor use; however, the voltage can move far away from the MPP when the irradiance fluctuates, and not generate power from the correct MPP [4].

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The fractional short-circuit current (FSCC) method, using the short current characteristic of the PV panel, and the fractional open-circuit voltage (FOCV) method, using the open-voltage characteristic, can quickly follow the MPP; however, they can only be used in a structure that can short or open the exact PV panel in the circuit. Moreover, they can greatly perturb the waveform and cannot produce power at the correct MPP [5, 6].

The variable step-size method is a method that adjusts the magnitude of the voltage fluctuation, based on the P&O or InC method [7, 8]. This can produce power at an accurate MPP; however, it requires an ancillary element for the PV panel or a complex formula.

For the above MPPT control, a power-conversion device is required. Various structures have been proposed as connection methods for the controlling power-conversion device. Among them, the structure with the lowest power-conversion loss and greatest efficiency is a differential power-processing (DPP) structure.

However, there are structural limitations when applying the various MPPT methods described above to the DPP structure; and a circuit change is frequently required.

Therefore, this paper proposes a hybrid control method to improve efficiency of power that can be applied to the DPP structure without changing the circuit.

Hybrid control method in DPP structure without changing the circuit can improve the production of power as well as reduce power losses from power conversion.

2 Power-Conversion Structure for Photovoltaic Power Generation

First- to fourth-generation power-conversion structures for photovoltaic power generation have been developed, as follows: Centralized (the initial structure), multi-string, module integrated converter (MIC), and differential power processing (DPP) [9].

The DPP structure can compensate for the shortcomings of the previous-generation ones. In the DPP structure, no shading occurs, and the generated power is transmitted to the main power-conversion device without going through the DPP converter. When shading occurs, some power is transmitted through the DPP converter to minimize the loss caused by the power-conversion device.

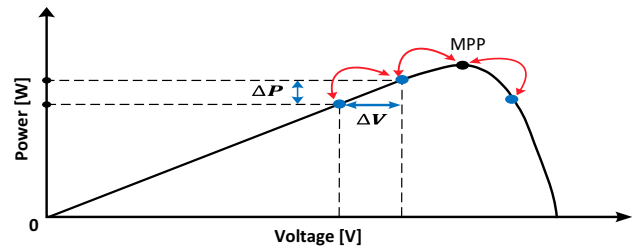


Fig. 1 P–V curve changes in the PV panel, power, and voltage

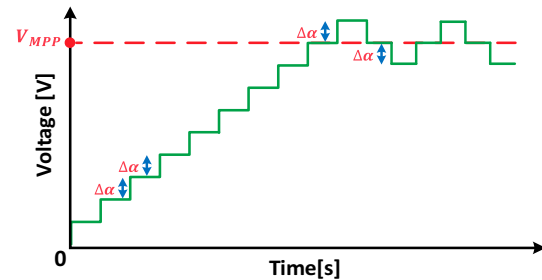


Fig. 2 Performing the existing P&O method

3 Maximum Power-Point Tracking and the Hybrid Control Method

3.1 Maximum Power-Point Tracking (MPPT)

Since the PV panel has a non-linear power-voltage (P–V) curve, as shown in Fig. 1, it is necessary to generate power at the maximum power point (MPP) to maximize power production. Therefore, a maximum power-point tracking (MPPT) method is required to maximize power production of the PV panels.

The most basic MPPT method is the P&O method. It controls the MPP using the present voltage, the amount of change in the previous voltage ($\Delta\alpha$), and the change in the present and previous power (ΔP), as shown in Fig. 1.

The P&O-method operation can be simplified, as shown in Fig. 2. To reach the MPP voltage, a voltage fluctuation (α) is provided to generate power in the vicinity of the MPP voltage.

3.2 Hybrid Control Method

The P&O method described above can easily perform the MPPT using a simple algorithm; however, the size of α determines the amount of time to reach the MPP zone, i.e., the power-generation range, and the size of the perturbation [3].

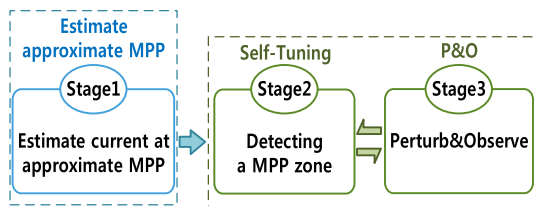


Fig. 3 Hybrid control-method block diagram

In addition, as mentioned above, the FSCC method, FOCV method, and variable step-size P&O method may require a circuit change when applied to the DPP structure.

For this reason, this paper proposes a hybrid control method that can be applied to the DPP structure without modifying the circuits. It is capable of quickly reaching the MPP zone and producing power at an accurate MPP, using only the advantages of the FSCC method and the variable step-size P&O method. It is performed in three steps. A simple block diagram is shown in Fig. 3.

Stage 1 calculates the current at the approximate MPP and quickly adjusts the voltage's position to the vicinity of the MPP. Subsequently, when the MPP zone is detected via self-tuning in Stage 2, the size of the MPP zone decreases to produce power at the correct MPP. The P&O method in Stage 3 occurs simultaneously, and then Stages 2 and 3 are repeated.

The overall flow diagram of the hybrid control method is shown in Fig. 4.

3.2.1 Stage 1: Estimate the Approximate MPP Current

When the hybrid control method is initiated, Stage 1 must be performed first. Stage 1 infers an approximate MPP, in a manner similar to FSCC, to quickly track the MPP zone. It is conducted using the circuit shown in Fig. 5.

Since the PV panel must be short-circuited when using the FSCC method, circuit changes are inevitable when the method is applied to the DPP structure. Because the hybrid control method uses the inductor of the power-conversion device to obtain the current of the PV panel, no circuit change is required when it is applied to the DPP structure.

As shown in Fig. 6, I_L , the current flowing through the inductor, has a value similar to the short-circuit current (I_{SC}); using this, the approximate MPP current, $I_{A.MPP}$, can be estimated.

The PV panel used in this paper is a YL020 P-17b, manufactured by YINGLI SOLAR. The proportional constant k for $I_{A.MPP}$ was obtained using the product datasheet. 'k' generally has a range of 0.78–0.92 and is set to 0.90622 in this paper.

In Stage 1, a circuit consisting of only PV panels and inductors are configured for 1 [ms]. Using this, the inductor

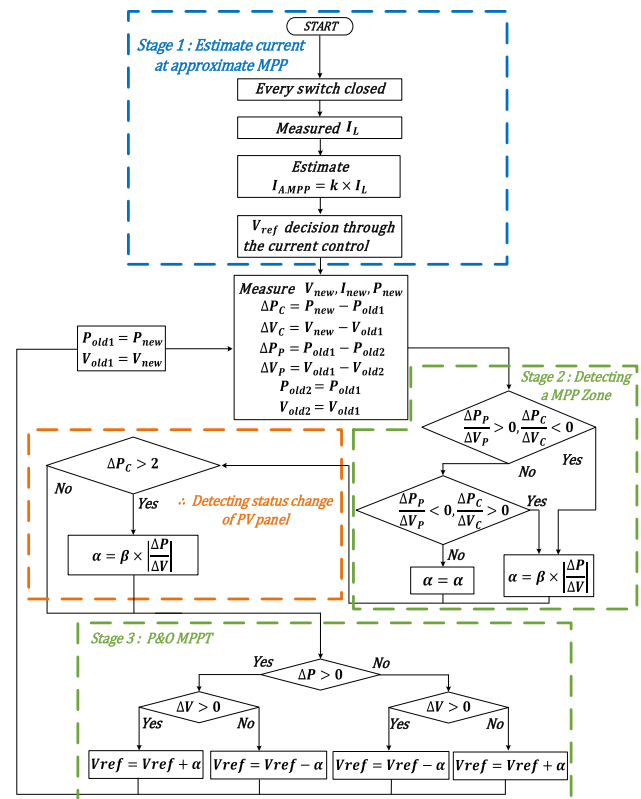


Fig. 4 Hybrid control-method flow diagram

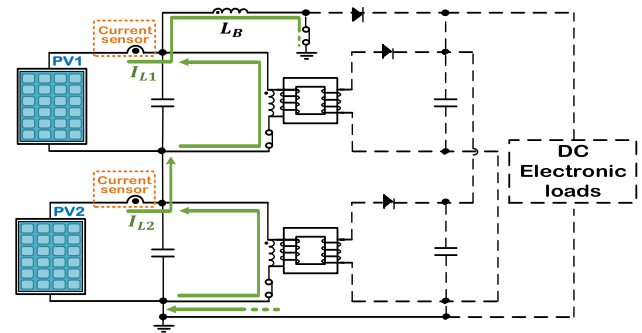


Fig. 5 Operation of stage 1 in the hybrid control method

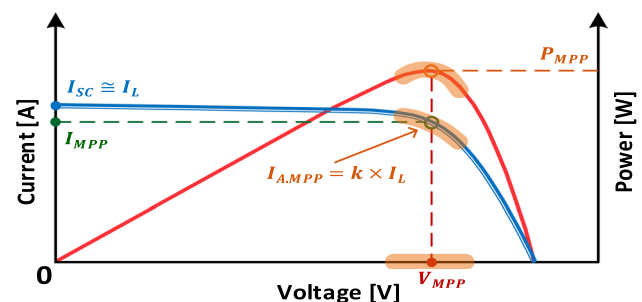


Fig. 6 I-V and P-V curves of the PV panel

current of the PV panels, I_L , is measured. $I_{A.MPP}$ is measured after 1 [ms] and the current is controlled according to it.

When performing the MPPT operation, Stage 1 is executed only once. It is not repeated unless the photovoltaic power-generation system stops and restarts.

This is because the voltage of the PV panel during the initial MPPT is significantly different from the MPP voltage. When operating in a normal state, after the initial operation, it is not necessary to additionally perform Stage 1.

3.2.2 Stage 2: Self-Tuning Method

In the hybrid control method, the current is controlled suitably for $I_{A.MPP}$ through Stage 1; then, Stage 2 is carried out.

In Stage 2, the magnitude of the voltage fluctuation (α) decreases when detecting the MPP zone's generating power. This maximizes the power production by reducing the size of the MPP zone.

This can compensate for the shortcomings of the existing P&O method, in which the power production and the speed of reaching the MPP zone vary, depending on the magnitude of the voltage fluctuation (α).

Case 1 and Case 2 present forms that can reduce the size of the MPP zone in the self-tuning method.

In Case 1 of Fig. 7a, $V(k)$ is the present voltage, $V(k-1)$ is the previous voltage, and $V(k-2)$ is the voltage before $V(k-1)$. In the P–V curve of Case 1, the slope between $V(k-2)$ and $V(k-1)$ is positive, and $V(k-1)$ and $V(k)$ are negative.

These can be expressed as formulae (1) and (2).

$$\frac{\Delta P_P}{\Delta V_P} > 0, \frac{\Delta P_C}{\Delta V_C} < 0 \quad (1)$$

$$\frac{P(k-2) - P(k-1)}{V(k-2) - V(k-1)} > 0, \frac{P(k-1) - P(k)}{V(k-1) - V(k)} < 0 \quad (2)$$

In Case 2 of Fig. 7b, the meanings of $V(k)$, $V(k-1)$, and $V(k-2)$ are the same as in Case 1. In the P–V curve of Case 2, the slope between $V(k-2)$ and $V(k-1)$ is negative, and $V(k-1)$ and $V(k)$ are positive.

These can be expressed as formulae (3) and (4).

$$\frac{\Delta P_P}{\Delta V_P} < 0, \frac{\Delta P_C}{\Delta V_C} > 0 \quad (3)$$

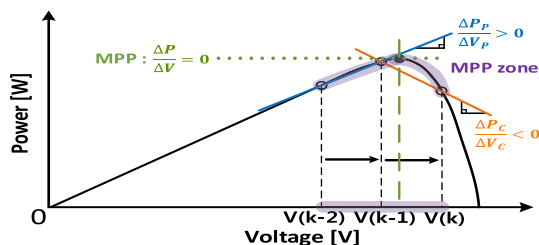
$$\frac{P(k-2) - P(k-1)}{V(k-2) - V(k-1)} < 0, \frac{P(k-1) - P(k)}{V(k-1) - V(k)} > 0 \quad (4)$$

In Cases 1 and 2, the MPP zone can be searched, indicating that the MPP exists between $V(k)$ and $V(k-2)$. Performing MPPT within the corresponding voltage range is more efficient for power generation. Hence, it is necessary to minimize the corresponding range; for this, the magnitude of the voltage fluctuation (α) must be reduced. The magnitude of the voltage fluctuation (α) is adjusted as in formula (5). Formulae (6) and (7) are used for setting the sizes of α and β , respectively [10].

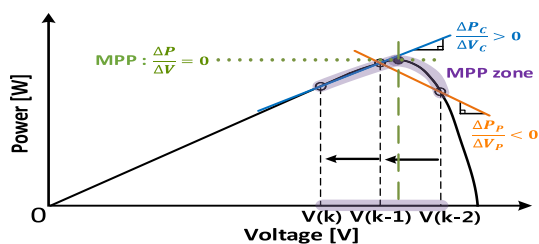
$$V_{ref}(k) = V_{ref}(k-1) \pm \alpha \quad (5)$$

$$\alpha = \beta \left| \frac{\Delta P}{\Delta V} \right| \quad (6)$$

$$\beta = \frac{|V_{ref}(k) - V_{ref}(k-1)|}{\left| \frac{\Delta P}{\Delta V} \right|} = \frac{|V_{ref}(k) - V_{ref}(k-1)|}{\left| \frac{P(k) - P(k-1)}{V(k) - V(k-1)} \right|} \quad (7)$$



(a) Case 1's shape



(b) Case 2's shape

Fig. 7 Two shapes of the MPP zone **a** Case 1's shape. **b** Case 2's shape

3.2.3 Detecting the Solar Panels' State Changes

When α is very small at the MPP of the PV panel, if the MPP changes, because of changes in the state around the PV panel, it takes a long time to reach the MPP. α , therefore, should be increased to quickly reach the changed MPP. Thus, it is necessary to detect the state change of the PV panel.

Looking at the P–V curve of the PV panel (YL020 P-17) used in this paper, the MPP power decreases by approximately 2 [W] when the irradiance decreases by 0.1 [kW/m²]. Therefore, if the irradiance changes by more than 0.1 [kW/m²], it is determined that the variation is large, and α is increased so that the new MPP zone can be quickly tracked.

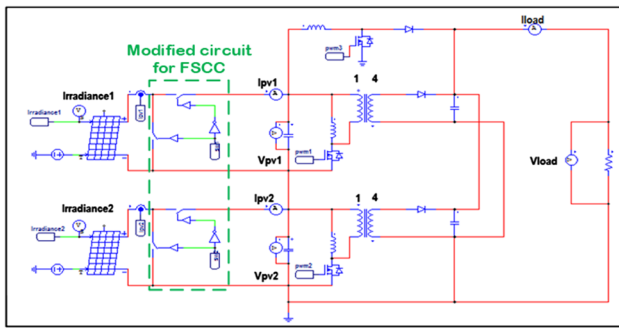


Fig. 8 Modified DPP circuit for applying the FSCC method

Table 1 State conditions and MPP voltages of the PV panel

Case	Irradiance [W/m ²]	Temperature [°C]	MPP voltage [V]
PV1	200	25	15.26
PV2	1000	25	17.02

4 Experiment Results and Discussion

4.1 Simulation

4.1.1 Steady-State Convergence

To verify the superiority of the hybrid control method proposed in this paper, the FSCC method and the variable step-size P&O method were simulated. The modified DPP circuit, configured to apply the FSCC method, is shown in Fig. 8.

The steady-state simulation was conducted under the conditions in Table 1. According to the irradiance and temperature set in PV1 and PV2, the MPP voltages of PV1 and PV2 are 15.6 [V] and 17.02 [V], respectively.

Figure 9 shows the PV's voltage and current waveform, and each method's cumulative power from 0 to 20 [s], when

the FSCC method, variable step-size P&O method, and hybrid control method are applied under the conditions in Table 1.

Figure 9a indicates that, when applying the FSCC method, variable step-size P&O method, and hybrid control method, the initial times for reaching the MPP zone of PV1 are 767 [ms], 2 [s], and 583 [ms], respectively.

Figure 9b shows PV2's voltage and current waveforms, and the initial times for reaching the MPP zone are 633 [ms] for the FSCC method, 2 [s] for the variable step-size P&O method, and 528 [ms] for the hybrid control method. The hybrid control method reaches the initial MPP zone faster than the other two methods.

Figure 9c presents the cumulative power of each method. When generating power for 20 [s] using the FSCC method, the cumulative power of PV1 is 19 [mWh] and PV2 is 108.5 [mWh], totaling 127.4 [mWh]. Under the conditions of Table 1, the ideal maximum cumulative power amount is 129.1 [mWh], so the FSCC method has a power-generation efficiency of 98.7 [%].

The variable step-size P&O method produces a total of 121.1 [mWh] and has a power-generation efficiency of 93.8 [%].

The hybrid control method has a power-generation efficiency of 99.2 [%] with a total of 128.1 [mWh], and excellent power-generation capability.

4.1.2 Convergence When Irradiance Varies

In the variable-irradiance simulation, the irradiance amount of PV1 was reduced from 700 [W/m²] to 200 [W/m²] at 20 [s] and returned to 700 [W/m²] at 40 [s]. Figure 10 shows the results.

Figure 10a presents the convergence states of PV1 and PV2, for the FSCC method application. Because the short-circuit current is measured once every 1 [s], the MPP zone can be quickly found by changing the value immediately after the irradiance changes. However, the power cannot be

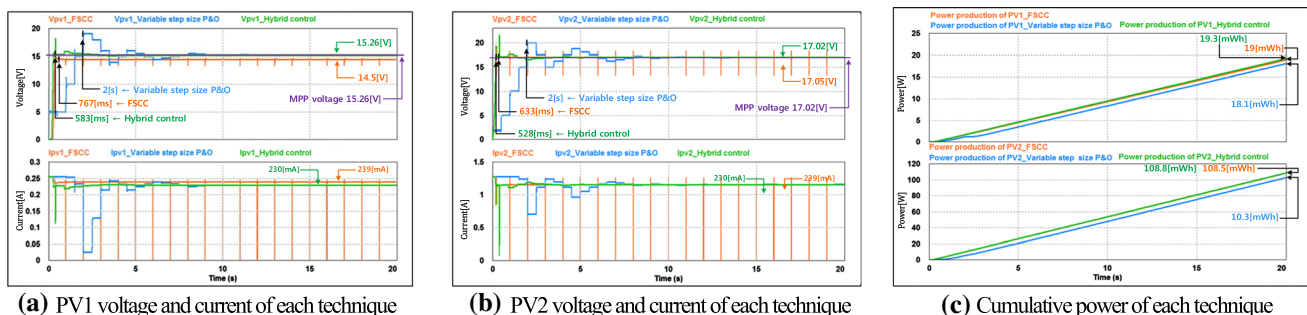


Fig. 9 PV voltage, current, and cumulative power of the FSCC, P&O, and hybrid methods. **a** PV1 voltage and current of each method. **b** PV2 voltage and current of each method. **c** Cumulative power of each method

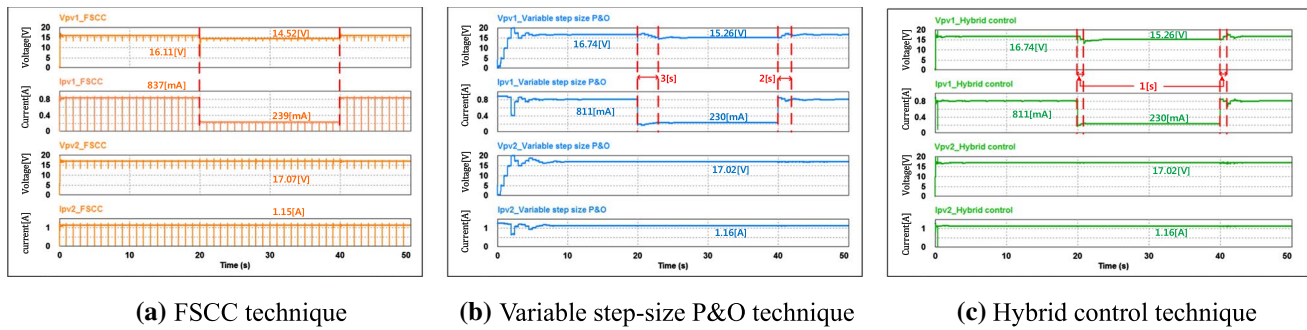


Fig. 10 Convergence states of PV1 and PV2 for each method when the irradiance varies. **a** FSCC method. **b** Variable step-size P&O method. **c** Hybrid control method

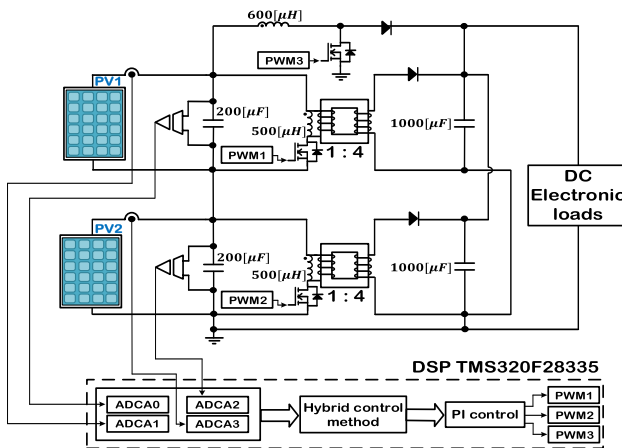


Fig. 11 DPP circuit configured without circuit modification

produced at an accurate MPP and the perturbation is large when measuring the short-circuit current.

The variable step-size P&O method was able to find the MPP zone in about 3 [s], when the irradiance was reduced to 200 [W/m^2], and about 2 [s] when the irradiance was increased to 700 [W/m^2]. The convergence rate was slower than that of the FSCC method, but power could be generated at the MPP after finding the MPP zone.

The hybrid control method tracked the MPP zone in about 1 [s], both when the irradiance was decreased and increased. Power could be produced at the correct MPP and a stable waveform could be obtained.

Therefore, the hybrid control method uses the advantages of the FSCC method and the variable step-size P&O method, and compensates for the disadvantages of the FSCC method.

4.2 Experimental Results

The hardware was built using a digital signal processor (DSP) (TMS320F28335). The circuit configuration is shown in Fig. 11. The experiment compared the behavior of the

hybrid control method in the simulation with its behavior in the actual experiment to verify its reliability.

Figure 12a shows the voltage and current waveforms of PV1 and PV2 when shading occurs in PV1. Both PV1 and PV2 reach an approximate MPP value at about 500 [ms]. After that, Stage 2 and Stage 3 are performed, and power is generated at the correct MPP.

The power of the corresponding waveform is as shown in Fig. 12b, and the maximum powers of PV1 and PV2 are 14.48 [W] and 15.61 [W], respectively. If the value is the ideal maximum power, the cumulative power of PV1 and PV2 from 0 to 20 [s] will be 80.44 [mWh] and 86.72 [mWh], respectively.

If the measured value at the bottom of Fig. 12b is replaced with mWh, the cumulative powers of PV1 and PV2, produced from 0 to 20 [s], are 79.81 [mWh] and 85.94 [mWh], respectively. Therefore, the power-production efficiencies of PV1 and PV2 are 99.13 [%] and 99.08 [%], respectively.

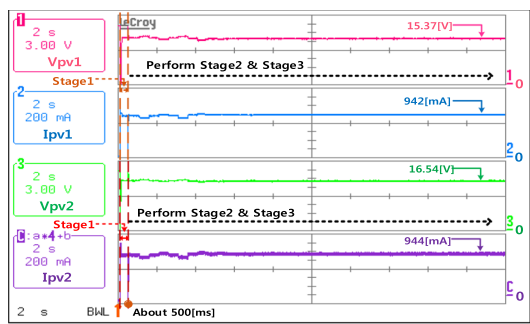
Figure 12c shows the voltage and current waveforms of PV1 and 2 when shading changes are made in A_{r1} and B_{r2} .

As in the simulation, it can be seen that the MPPT is well adjusted, according to the irradiance variation due to shading. The ripple between t_1 and t_2 occurs because artificially created shading constantly fluctuates.

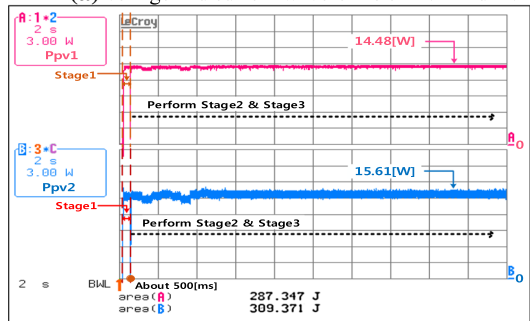
Figure 12d shows the value of (c) as electric power. If the measured value of the corresponding waveform is the ideal power, the cumulative powers of PV1 and PV2 are 172.4 [mWh] and 322.4 [mWh], respectively.

The cumulative powers of PV1 and PV2, measured from 0 to 100 [s], are 171.21 [mWh] and 318.13 [mWh], respectively. Through this, it can be seen that the power-generation efficiencies of PV1 and PV2 are 99.31 [%] and 98.68 [%], respectively.

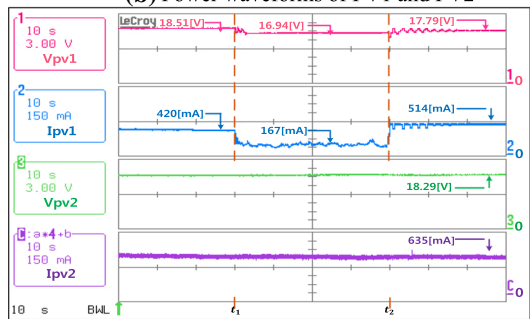
Table 2 summarizes the experimental results in Fig. 12. It was confirmed that, when comparing the ideal amount of power with the actually measured power under the



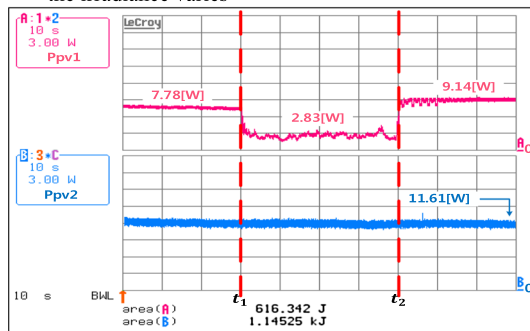
(a) Voltage and current waveforms of PV1 and PV2



(b) Power waveforms of PV1 and PV2



(c) Voltage and current waveforms of PV1 and PV2 when the irradiance varies



(d) Power waveforms of PV1 and PV2 when the irradiance varies

Fig. 12 Results of the hybrid control method experiment. **a** Voltage and current waveforms of PV1 and PV2. **b** Power waveforms of PV1 and PV2. **c** Voltage and current waveforms of PV1 and PV2 when the irradiance varies. **d** Power waveforms of PV1 and PV2 when the irradiance varies

steady-state and fluctuating-irradiance conditions, both

Table 2 Power-generation efficiency of the hybrid control method

Case	Irradiance of PV1 < Irradiance of PV2			
	Steady status		Variation status	
Time [s]	0–20		0–100	
PV	PV1	PV2	PV1	PV2
Value [mWh]	80.44	86.72	172.4	322.4
Measure [mWh]	79.81	85.94	171.21	318.13
Efficiency[%]	99.13	99.08	99.31	98.68

efficiencies were approximately 99 [%]. The hybrid control method operated well, in both the simulation and the actual experiment, and excellent results were obtained.

5 Conclusion

In this paper, a hybrid control method for improving power-production efficiency based on a DPP structure was proposed. The hybrid control method could be used without additional circuit modification if the DPP circuit was applied. Moreover, it could improve the power-production efficiency of the PV panel because it could quickly track the MPP zone during the initialization. In addition, by reducing the size of the MPP zone, it was possible to produce power at an accurate MPP and provide stable power generation.

In the simulated and experimental results of the hybrid control method, the initial MPP zone was tracked in about 600 [ms], and the power-production efficiency proved to be excellent, at about 99 [%]. Therefore, the hybrid control method is considered an easy method to use with the DPP structure.

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