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Journal of Electrical Engineering & Technology

ISSN 1975-0102

J. Electr. Eng. Technol.

DOI 10.1007/s42835-020-00627-y



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High Efficiency Operation of Photovoltaic System with Differential Power Processing Based on Voltage Reference Model

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Abstract

The purpose of this paper is to quickly and accurately perform the maximum power point tracking (MPPT) of a photovoltaic panel in accordance with the surrounding environment of variously changing photovoltaic systems. In this photovoltaic system, a power conversion system is configured with a differential power processing (DPP) structure to perform MPPT, and a method for improving this MPPT performance is proposed. MPPT is performed using the charging characteristics of the attached capacitor for voltage smoothing of the MPPT PV panel based on the proposed voltage reference model. The voltage reference model-based MPPT was applied to the proposed DPP structured photovoltaic system. Therefore, by enabling the expansion of the application of a high-efficiency photovoltaic system that has better power generation performance and can be adapted to various climate and temperature changes, a safer power generation system having less power loss was implemented to verify performance. It is also expected that by reducing the number of sensors in the system, annual maintenance costs will be reduced.

Keywords Capacitor charging characteristic · DPP (differential power processing) · MPPT · Photovoltaic · Voltage reference model-based MPPT

1 Introduction

Buried fossil fuels are limited, but energy consumption is increasing daily and energy alternatives to fossil fuels are needed. As such, the interest in renewable energy is increasing due to the exhaustion of fossil fuels, environmental pollution, and the need for safe energy. Photovoltaic (PV) power

generation capacity, which currently accounts for the largest share of renewable energy in the world, is also expected to increase [1].

A PV power generation system consists of a PV panel that converts solar energy to electricity and a power conversion device that connects the PV panel to load or system [2, 3]. The current power conversion device used in the PV system has a fourth-generation differential power processing (DPP) structure [4].

In the DPP structure, the power conversion devices are connected in parallel between PV panels that are connected in series with one another. The power conversion devices in DPP structure only process the difference of power produced by PV panels. The DPP structure allows the minimum power produced by the PV panel to pass through the power conversion device. Therefore, it reduce the loss of power conversion [5, 6].

Recent PV systems adopt the perturb and observe (P&O) algorithm to track the maximum power point (MPP) of PV panels, but this P&O algorithm is vulnerable to rapid environmental changes [7–10].

In this paper, a voltage reference model-based MPPT control method is proposed. The method involves tracking the

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MPP by using the charge and discharge characteristics of a capacitor attached to each PV panel in a PV system. In the MPP tracking (MPPT) process, there is no need to measure current, which can be replaced by a switching element to charge and discharge the capacitor. Thus, switching elements are added, and the components are similar.

Consequently, this DPP-structured system that performs MPPT based on a voltage reference model was verified to perform the smooth MPPT control of the PV panels even without the current sensors. Through this, enables the system to operate the PV system stably and efficiently with low loss even in various environments with accurate and fast MPPT.

2 Photovoltaic Power Generation System Configuration

2.1 The DPP Structure in a Photovoltaic Power Generation System

The power conversion device of the photovoltaic power generation system has reached the differential power processing (DPP) structure, which is currently the fourth generation through the first, second, and third generations.

Among them, the DPP structure, which is the 4th generation, is a structure in which power conversion devices bear only the power difference between the photovoltaic panels by attaching power conversion devices in parallel between the series-connected photovoltaic panels. Besides, it is a system to maximize the power conversion efficiency while increasing the reliability of each photovoltaic system.

The flow of processing power in this DPP structure is shown in Fig. 1. As Fig. 1 shows, the DPP structure operates

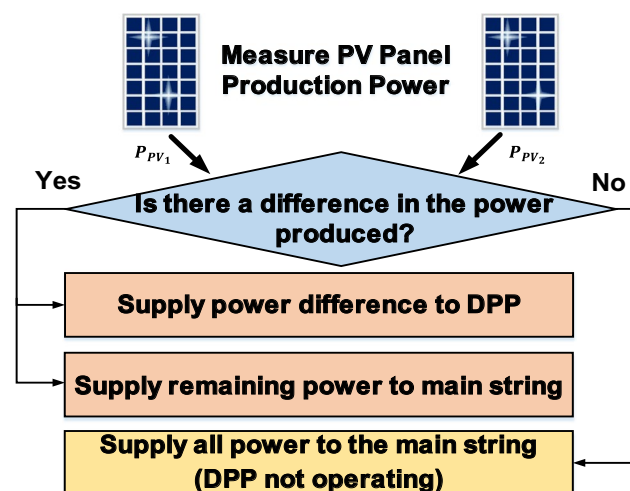


Fig. 1 Flow diagram of power process in the DPP structure

selectively only when there are differences in production power between photovoltaic panels, and only the power difference is borne by the DPP converter. If no power difference occurs, the DPP converters do not work.

2.2 MPPT of Photovoltaic Panels

PV panel features a nonlinear change in the relationship between voltage, current and power generated by irradiance. Figure 2 shows the P–V characteristic curves according to the irradiance to the photovoltaic panels.

As Fig. 2 shows, the characteristic curve itself changes when the amount of irradiance changes. To increase the power production efficiency of PV panels, it is necessary to track MPP, where the PV panel produces the most power, under the current irradiance conditions. This is called maximum power point tracking (MPPT) of the photovoltaic system.

Various control methods for MPPT in photovoltaic systems have been studied to date. The most widely used control method of the photovoltaic panel MPPT method is the Perturb & Observe (P&O) method.

This P&O method is most widely used for MPPT control of photovoltaic systems because it is easy to design due to its simple control algorithm. Because the P&O method has problems in which the MPP convergence speed and the vibration near the MPP may increase according to the designed cycles or the size of the voltage reference, various methods are being studied.

3 MPPT based on Voltage Reference Model

In this paper, a new MPPT control algorithm to be applied to the DPP structured photovoltaic systems is proposed. The proposed MPPT control algorithm performs the MPPT of the photovoltaic panels with only the voltage sensor without the current sensor using the charging characteristics of the capacitor attached to the photovoltaic panels the system.

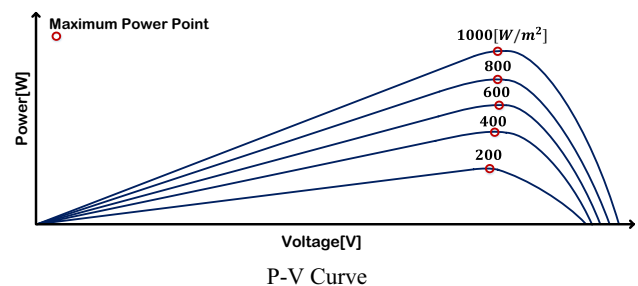


Fig. 2 Characteristic curves according to the irradiance to the photovoltaic panels

3.1 Charging Characteristics of Capacitor in Photovoltaic Panels

In the photovoltaic system, a capacitor is attached to a photovoltaic panel as shown in Fig. 3.

As shown in Fig. 3, if the power produced by the photovoltaic panel is $p(t)$, the photovoltaic panel produces DC power, so $p(t)$ can be expressed as the following formula.

$$p(t) = v(t) \times i(t) \quad (1)$$

In this, the current $i(t)$ produced by the photovoltaic panel is the same as the current flowing through the capacitor and thus can be expressed as follows.

$$i(t) = C \cdot \frac{dv(t)}{dt} \quad (2)$$

The formula (1), therefore, can be expressed as follows.

$$p(t) = v(t) \cdot C \cdot \frac{dv(t)}{dt} = \frac{C}{2} \cdot \frac{dv^2(t)}{dt} \quad (3)$$

Thus, the power $p(t)$ produced by the photovoltaic panel becomes maximum where the differential value of the square of the capacitor voltage is the largest, which is equal to the point where the slope of the graph of the capacitor voltage square is the maximum. Figure 4 shows the characteristics of the capacitor charging voltage and voltage square of the photovoltaic panel, and it can be seen that the slope of the square graph (V^2) of the capacitor charging voltage becomes maximum at the portion where power is maximized.

In this paper, therefore, the MPPT is performed by finding the point where the slope of the graph of the capacitor voltage square becomes the maximum using the charging characteristic of the capacitor of the photovoltaic panel. To this end, additional switching elements for charging and discharging the capacitor are required.

Figure 5 is a circuit diagram of the photovoltaic system with the DPP structure for the application of MPPT based on the proposed voltage reference model; Switching elements for charging and discharging capacitors are added to

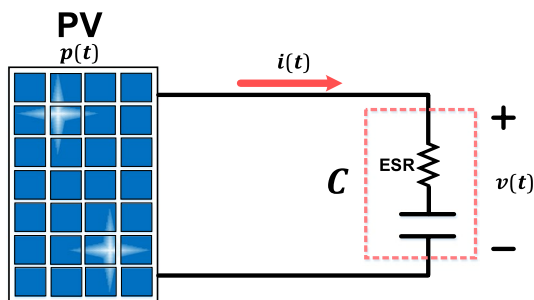


Fig. 3 Capacitor modeling in photovoltaic panel

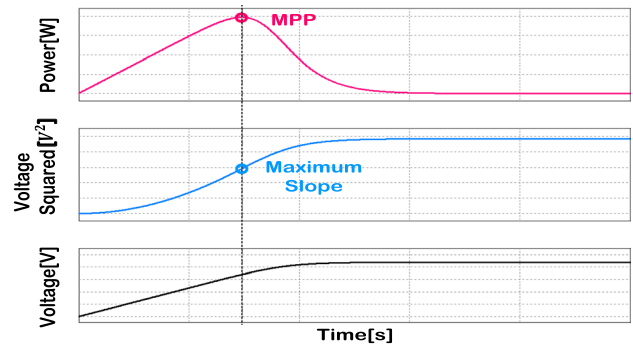


Fig. 4 Characteristics of charging voltage of capacitor attached to photovoltaic panel

the configuration of the DPP-structured photovoltaic system shown in Fig. 2. Although switching elements are added, the circuit is modified in a direction that does not significantly deform the entire DPP structure and current sensors can be reduced.

3.2 Operation of Voltage Reference Model-based MPPT

The proposed voltage reference model-based MPPT is a method to find the MPP of photovoltaic panels using the charging characteristics of capacitors and requires three steps of operation for fast MPP searching.

(1) Stage 1

Stage 1 is a step of finding V_{mpp} during charging a capacitor. At this stage, the capacitor is charged with charging and discharging switch open. Simultaneously with the capacitor charging, the voltage sensor measures the capacitor charging voltage V and controller calculates V^2 . The slope of V^2 is obtained by averaging the V^2 , measured 25 times in a very short period of time. This is to reduce the calculation of the controller. The calculated slope is continuously computed, compared with the past slope, and the larger slope value is stored to update the V_{ref} value.

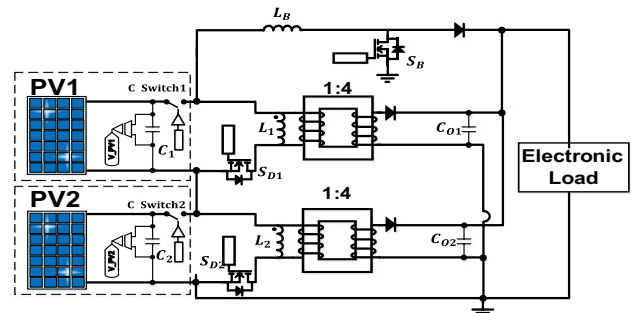


Fig. 5 Voltage reference model-based MPPT-applied DPP structure

The capacitor voltage is set to charge up to $V_{ref} + 1$ [V], which is a margin for continuously computing and comparing the slope.

The capacitor voltage V is charged and the slope of V^2 continues to increase until it reaches V_{mpp} , so V_{ref} is updated before reaching $V_{ref} + 1$ [V], and the capacitor continues to charge. V_{ref} is fixed to the voltage V when the slope of V^2 no longer increases, and the voltage at that time is V_{mpp} .

After finding V_{ref} , which is V_{mpp} , the slope does not increase and the V_{ref} value is not updated to a new V , so the capacitor charge/discharge switch is on after charging up to $V_{ref} + 1$ [V], and then Stage 2 begins.

(2) Stage 2

Stage 2 is the step of stabilizing the voltage to V_{ref} calculated in Stage 1. At this stage, the converter switch controlling the photovoltaic panel stabilizes the voltage of the photovoltaic panel by generating PWM duty with V_{ref} obtained in Stage 1. Stage 2 is a step of stabilizing the capacitor voltage to discharge the capacitor again and is carried out for a very short time.

(3) Stage 3

After stabilizing the capacitor voltage to V_{ref} in Stage 2 and then Stage 3 begins. Stage 3 is the process of discharging the capacitor of the photovoltaic panel to move back to Stage 1. In this process, the PWM duty of the switch that controls the photovoltaic panel is one (1).

After discharging the capacitor voltage from V_{ref} to $V_{ref} - 1$ [V] previously computed in Stage 1, $Slope_past$ is initialized to 0, and it goes back to Stage 1 to recalculate V_{mpp} .

Then, after operating the system with the obtained V_{mpp} for 1 s, and the system is operated in the order of Stage1 $\rightarrow$ Stage2 $\rightarrow$ Stage3 to re-measure V_{mpp} .

Figure 6 shows this flow of operations in an algorithmic flow diagram.

4 Simulation and Results Comparison

4.1 Simulation of Reaching Steady-state

A simulation was conducted to verify the capability of the proposed voltage reference model-based MPPT. In the circuit used in the same way as in Fig. 5, PV1 was always set to be with the maximum irradiance condition, and it was set that only the irradiance of PV2 was variable. It can be said that the power transmission method of the DPP structured photovoltaic system is a feed-forward method, and the DPP converter of PV2, which always produces less power, does not work, so it can be considered as the converter is off. The DPP converter is a flyback converter, and the main converter configures with a boost converter. The output end capacitor of the flyback converter and the output end capacitor of the boost converter are shared.

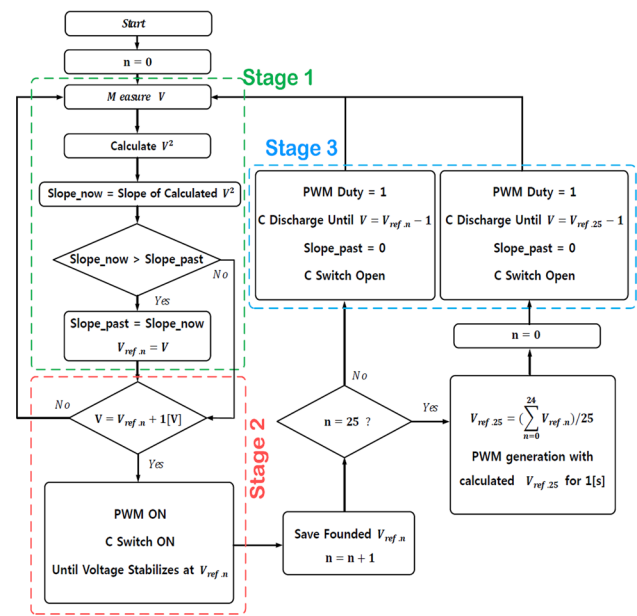


Fig. 6 Operation flow diagram of voltage reference model-based MPPT

Through the simulation, the performance for MPPT was verified by comparing it with the most widely used P&O method and Fractional open circuit voltage (FOCV) method in the DPP structured photovoltaic systems, and the setting for this is the same as in Table 1.

Figure 7 shows the results of the reaching steady-state simulation of each MPPT method. The convergence rate of the FOCV method and the proposed voltage reference model MPPT is very fast, but it was confirmed that the MPPT convergence rate of the P&O method takes about 32 [s] to reach steady-state according to the set V_{ref} . In Fig. 7, the black letters indicate the ideal MPPT performance results, and the results of finding the MPP with each MPPT method are shown in the figure. In comparison with the ideal values, it appears that all MPPT methods perform MPPT well. The P&O method, however, takes relatively long time to reach the steady-state due to the set V_{ref} , and the FOCV method shows a large perturbation in the resulting waveform.

4.2 Variable Irradiance Simulation

Using the comparison of the voltage reference model-based MPPT with the conventional MPPT methods, a simulation was conducted under the changing irradiance after reaching a steady-state to find out whether the MPPT performs well even under the changing irradiance.

For PV1, the condition of always maximum irradiance of 1000 [W/m²] was applied and the power generated from it was indicated. In the case of PV2, its power produced under the conditions of changes like 500[W/m²

Table 1 Set-up table for simulation

MPPT	Settings		
P&O method	Variation of $\Delta V_{ref} = 0.5$ [V] Variation of Time Reference = 1 [s]		
FOCV method	Re-measure every second		
Voltage reference model method	Re-measure every second		
	Stage 1	Stage 2	Stage 3
	C charge until $V = V_{ref} + 1$ [V]	Create PWM until Voltage Stabilizes at $V = V_{ref}$	C discharge until $V = V_{ref} - 1$ [V]

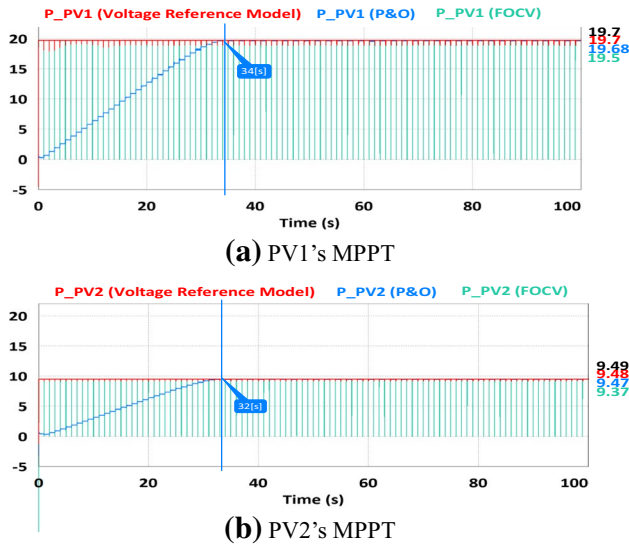


Fig. 7 Results of reaching steady-state simulation of each MPPT method

$] \rightarrow 200[\text{W}/\text{m}^2] \rightarrow 800[\text{W}/\text{m}^2]$ was presented. Besides, the total power production when PV1 and PV2 ideally generated power was indicated. The irradiance of PV2 changed first in 30 s and second in 60 s. The total simulation time was 100 s.

Figure 8 shows the results of the variable irradiance simulation of each MPPT method. PV1 was always under the same irradiance and the changes of the irradiance were applied only to PV2. In Fig. 8, it was confirmed that the P&O method takes more time than the FOCV and voltage reference model-based MPPT when the irradiance changed, and it was less accurate than the proposed voltage reference model-based MPPT due to frequent vibration even though it was negligible. Also, the tracking speed of the FOCV method was almost similar to that of the proposed voltage reference model-based MPPT, but the perturb occurred in the resulting waveform due to the characteristics of the method that MPPT is performed with complete circuit separation, accurate MPPT was not possible.

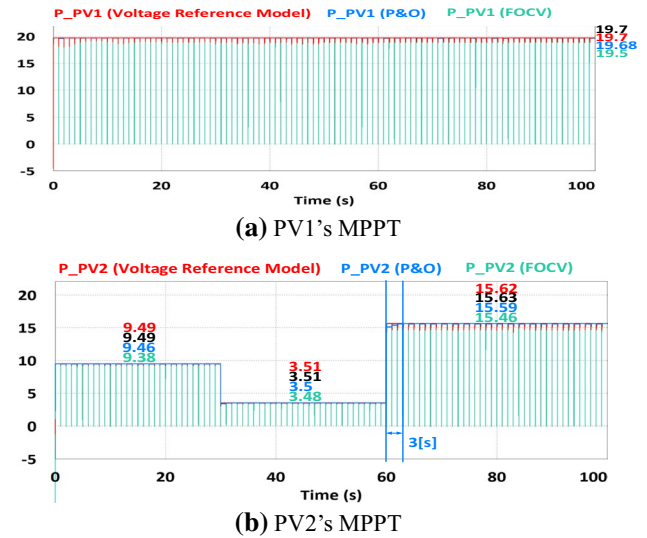


Fig. 8 Results of variable irradiance simulation of each MPPT method

Therefore, it was verified that the proposed voltage reference model-based MPPT has superior MPPT performance compared to the P&O method and FOCV.

This result indicates that MPPT based on a voltage reference model in a DPP-structured photovoltaic system can perform MPPT of photovoltaic panels by replacing the existing MPPT methods. It has an advantage over the P&O method in terms of that it does not require the use of any current sensor, and it can be said to be advantageous compared to the existing FOCV due to less perturb in the tracking process.

5 Experiment and Results Verification

5.1 DPP-structured Photovoltaic System Implementation

Figure 9 shows the control block of this system composed of two 20 [W] photovoltaic panels in the DPP structure for applying the proposed voltage reference model-based MPPT.

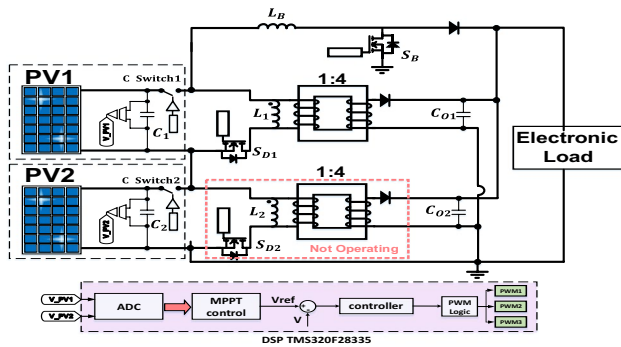


Fig. 9 Control block diagram of photovoltaic system for verification of experiment

Table 2 Elements configuration table for hardware experiment

Device	Model	Value
Photovoltaic Panel	YL 020 17p	20 [W]
C switch 1	IRFP450	—
C switch 2	—	—
S_{D1}, S_B	—	—
Gate Driver	TLP350	—
Transformer	Core: PQ 40–40/ Bobbin: PQ 40–40-3C95	1: 4
C_1, C_2	—	220 [μ F]
C_{O1}, C_{O2}	—	470 [μ F]
L_1	—	500 [μ F]
L_B	—	600 [μ F]
Diode	MBR20200CT	—
Frequency	—	30[kHz]
DSP	TMS 320F28335	—
Electronic load	IT8511 dc electronic load	—

The capacitor charging/discharging switching element for tracking the V_{mpp} of the photovoltaic panels is composed of MOSFET, and the current sensor is not configured because the MPPT is performed only with the voltage.

The DPP structured photovoltaic system in this paper uses a feed-forward power transmission method. In both simulation and hardware experiments, the less irradiance environment condition was applied to PV2, which means that PV1 always produces more power than PV2.

Since it is a DPP structure with feed-forward method, it can be expected that the DPP converters for PV2 do not operate, so the DPP converter of PV2 is off and PV2 is controlled by the boost converter, which is the main converter.

In Table 2, selected detailed elements for hardware implementation are indicated. The experimental environment, like the simulation, artificially shaded PV2 to make a difference in the production of power.

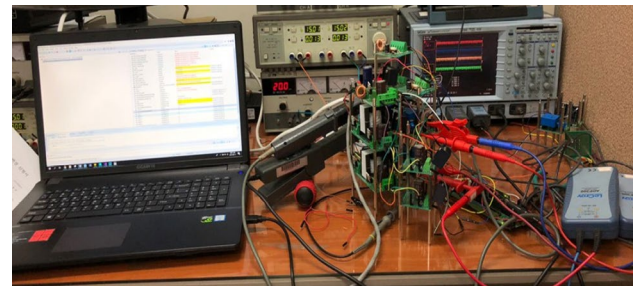


Fig. 10 The picture of experimental environment

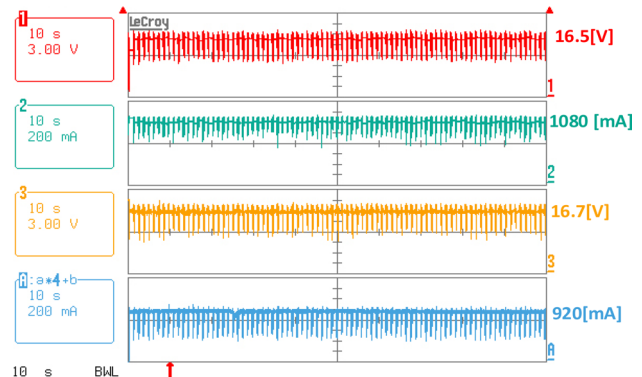


Fig. 11 Voltage and current waveforms of steady-state reaching experiment

5.2 Experiment of Reaching Steady-state

Figure 10 shows the voltage and current waveforms of the photovoltaic panels in the performing steady-state reaching experiment based on the proposed MPPT. The experiment was carried out for a total of 100 s, and a hardware experiment was performed from the initial starting point to reaching the steady-state by conducting the voltage reference model-based MPPT.

The voltage reference model-based MPPT resulted in a V_{mpp} of about 16.5 [V] and an I_{mpp} of 1080 [mA]. The V_{mpp} and I_{mpp} of PV2 are about 16.7 [V] and about 920 [mA] respectively.

MPPT based on the proposed voltage reference model is a method that performs MPPT using the capacitor charging characteristic of a photovoltaic panel, and it is also shown in the hardware experiment to reach MPP very quickly.

Figure 11 shows the produced power waveforms of the photovoltaic panels obtained by multiplying the photovoltaic panels' voltage and current in Fig. 12, respectively. When reaching the steady-state of PV1, the produced power per second is 17.8 [W] and the total power produced by PV1 for 100 s is 496.2 [mWh]. When reaching the steady-state of PV2, the produced power per second is 10 [W] and the total power produced by PV2 for 100 s is 425.3 [mWh].

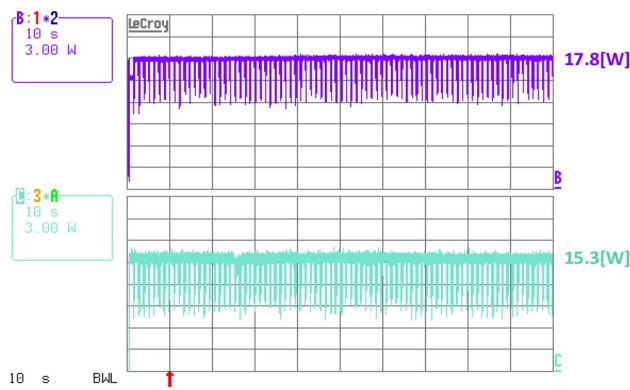


Fig. 12 Power waveforms of steady-state reaching experiment

5.3 Variable Irradiance Experiment

Figure 13 shows the voltage and current waveforms of the photovoltaic panels where the experiment of the proposed voltage reference model-based MPPT was carried out under the changing irradiance environment. The experiment was conducted for a total of 100 s. When the irradiance was changed under the condition that the steady-state had already been reached, it was verified whether the proposed voltage reference model-based MPPT performed well according to the changes of irradiance.

It can be seen from Fig. 13 that the constant irradiance environment was applied to PV1, and the condition that only irradiance was changed was applied to PV2. The V_{mpp} and I_{mpp} of PV1, which performed the MPPT, are about 16.9 [V] and about 964 [mA] respectively. V_{mpp} and I_{mpp} of PV2, to which change of irradiance applied, was changed like about 16.8[V] $\rightarrow$ 15.7[V] $\rightarrow$ 16.8[V], and about 865[mA] $\rightarrow$ 370[mA] $\rightarrow$ 870[mA], respectively.

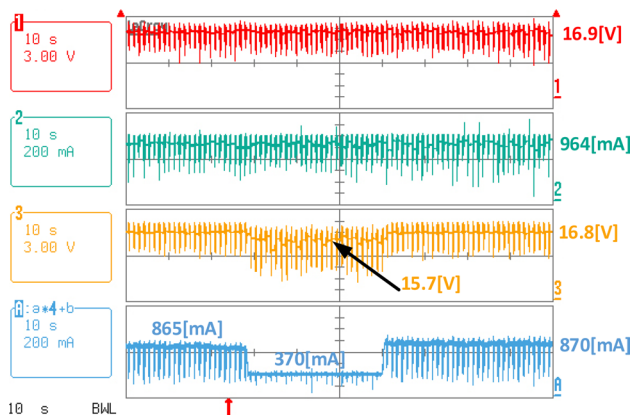


Fig. 13 Voltage and current waveforms of variable irradiance experiment

As a result of performing the variable irradiance experiment, it was confirmed that when the irradiance was changed, the MPP was rapidly converged.

Figure 14 shows the produced power waveforms of the photovoltaic panels obtained by multiplying the photovoltaic panels' voltage and current in Fig. 13, respectively. During the experimental process of PV1, the produced power per second was 16.4 [W], and the total power produced by PV1 for 100 s was 451.6 [mWh]. During the experimental process of PV2, the produced power per second was changed like 14.5 [W] $\rightarrow$ 5.4 [W] $\rightarrow$ 14.6 [W], and the total power produced by PV2 during 100 s was 320.7 [mWh].

Consequently, it was confirmed that the actual experiment and simulation results of the MPPT based on the voltage reference model appear similarly under varying irradiance. In the actual experiment, however, as in the simulation, V_{mpp} was re-measured every 1 s to apply the perturb period in the same way as the existing P&O method. Nevertheless, if the V_{mpp} re-measurement cycle of the voltage reference model-based MPPT is adjusted according to the surrounding environment, the ripple is expected to decrease.

6 Conclusion

In this paper, a high-efficiency differential power processing structure of the voltage reference model-based MPPT is proposed for the high-efficiency operation of a photovoltaic power generation system.

The power conversion device of the latest photovoltaic power generation system can individually control the photovoltaic panel. Differential power processing (DPP) structure that minimizes the loss of power generated by the power conversion device is a preferred trend. The DPP structure also changes non-linearly according to the photovoltaic panel installation environment, and maximum power point

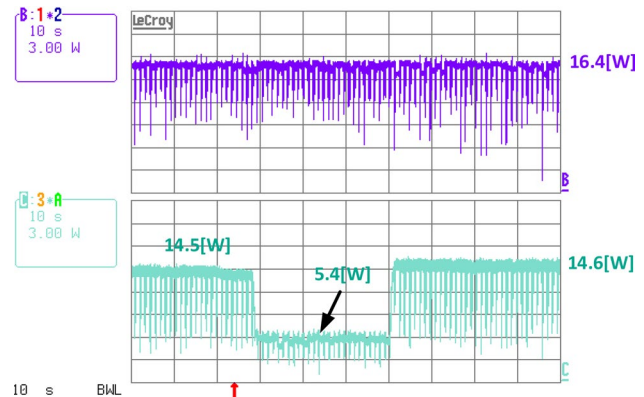


Fig. 14 Power waveforms of variable irradiance experiment

tracking (MPPT) control is needed to find the point that can produce the maximum power in this state.

In this paper, the voltage reference model-based MPPT control method is proposed. The voltage reference model-based MPPT control method is a method of tracking the maximum power point by using the charge and discharge characteristics of a capacitor attached to each photovoltaic panel in a photovoltaic system. In the MPP tracking process, no current measurement is necessary, which can be replaced by a switching element for charging and discharging the capacitor, so a switching element is added, but as a result, the components are similar.

Through simulation, it was verified that the tracking performance of the voltage reference model-based MPPT control method is excellent when compared with the existing P&O method and FOCV. The reliability of the voltage reference model-based MPPT control method was verified by comparing the results when the steady-state reaching MPPT and irradiance changes.

In the actual manufacturing experiment, the MPPT capability was verified using photovoltaic panels, and as a result, excellent MPPT performance was proved.

In conclusion, it is expected that by applying the voltage reference model-based MPPT proposed in this paper to the differential power processing structure, the photovoltaic system can improve its adaptability to its installation environment and enable excellent power generation. In other words, it was verified to perform smooth MPPT control of the photovoltaic panels even without the current sensors. Through this, it is considered that it will be advantageous to operate the photovoltaic system stably and with the low loss even in various environments with accurate and fast MPPT.

Considering the possibility of generating renewable energy in the future, if a larger-scale power generation system is implemented and applicable research is continued, the benefits such as reduction of the annual system maintenance cost when applied to an actual solar system can be considered. If additional research is conducted in the future, it is planned to study whether it is possible to reduce actual cost.

Acknowledgements This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry and Energy (MOTIE) of the Republic of Korea (No. 20194030202290) and was supported by the Construction Test and Certification Department, Korea Institute of Civil Engineering and Building Technology (KICT) in 2020.

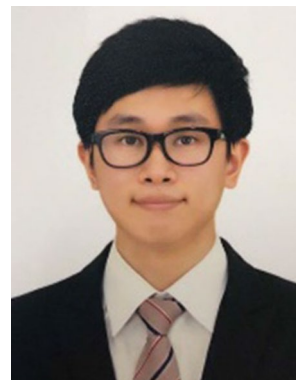
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