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High Efficiency PCS with Scan-Type MPPT Control for a Grid-Connected PV Power Generation System

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Abstract: For a standalone PV (photovoltaic) power generation system, the author previously proposed a new MPPT (maximum power point tracking) control method in which the I-V characteristics are scanned with a detection interval control that operates at specified intervals and monitors the maximum power point. The author has obtained satisfactory results using this new MPPT control method. This paper investigates the application of the new MPPT control method for a PCS (power conditioning system) in a grid-connected type PV power generation system. The experimental results clearly demonstrate that the developed PCS offers outstanding effectiveness in tracking the maximum power point in partially shaded environments.

Key words: PV generation system, MPPT control, grid-connecting inverter, DC-DC converter, PCS.

1. Introduction

PV (photovoltaic) sources are used today in numerous applications, such as battery charging, home power supply (grid-connected system [1]) and satellite power systems. They require a power conditioner (DC/DC or DC/AC converter) for the load interface. Since PV modules still have relatively low conversion efficiency, the overall system cost can be reduced by using high efficiency power conditioners that, in addition, are designed to extract the maximum possible power from the PV module.

Therefore, various MPPT (maximum power point tracking) methods have been investigated [2-7]. A very popular MPPT technique is the P & O (perturb-and-observe) method. A small increase or decrease in the PV voltage, v_{PV}, would result in no change in the power output, p_{PV}, as the peak point locally lies in a flat neighborhood. The PV voltage is maintained at the level where $\Delta p_{PV}/\Delta v_{PV}$ is close to zero. Despite the good adaptiveness of this technique, it can also deliver erroneous commands resulting in a low power output when the P-V curve is multimodal due to partial shading or other factors.

The author previously proposed a new method that utilizes a scan-type MPPT control (hereinafter, referred to as the "scan-method") [8-13] for a standalone PV power generation system. In this method, the I-V characteristics are scanned at specified intervals and the maximum power point is monitored. The results clearly demonstrate that more power can be obtained with standalone PV power generation systems than by the conventional P & O method in which panels are partially in shade. Therefore, the current paper describes the development of a grid-connected PCS (power conditioning system) that employs the scan-method [14]. The current paper also compares the power acquisition characteristics that are obtained during partial shading with those of a conventional (commercially available) PCS. The results clearly demonstrate the effectiveness of this control system.

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2. Overall System Circuitry Configuration

Fig. 1 shows the structure of the proposed system. The six solar cells are connected in series on the input side of the DC-DC converter shown in the figure. Table 1 shows the specifications of the solar cell. Table 2 shows the circuit constants.

3. Operating Principle

3.1 P & O Method

The most commonly used algorithm in Japan and around the world for MPPT control is the P & O method. In this method, the solar cell voltage is varied by some level ΔV at regular time intervals ΔT and the solar power output of the cell is observed to determine whether it has increased or decreased, as shown in Fig. 2. ΔV is incremented or decremented continually to augment the power in a search for the point at which the maximum power is attained. Multiple poles occur (Fig. 3) when a solar panel is partially shaded. Since the search is conventionally started from the open-circuit end of the curve, one of the low peaks can be misidentified as the maximum, causing a mismatch power loss. This paper proposes the use of the scan-method to ameliorate that issue.

3.2 Operation of the New MPPT Control

The responsiveness offered by the scan-method is fundamentally superior to P & O for the following reasons. In the scan-method, the I-V curve of the solar cell is examined at regular (e.g., 1 s) intervals. This method is capable of modifying the operating point swiftly to the optimal condition, even when that optimal point has changed by a large margin; i.e., it offers the advantage of avoiding mismatch power loss since it can accurately identify the maximum power point. However, the ordinary time increment Δt in a practical P & O-based PCS is 1 s and ΔV is several volts. This presents a fundamental obstacle to attaining the desired operating condition after a large shift in the optimal condition after an abrupt change in insolation intensity.

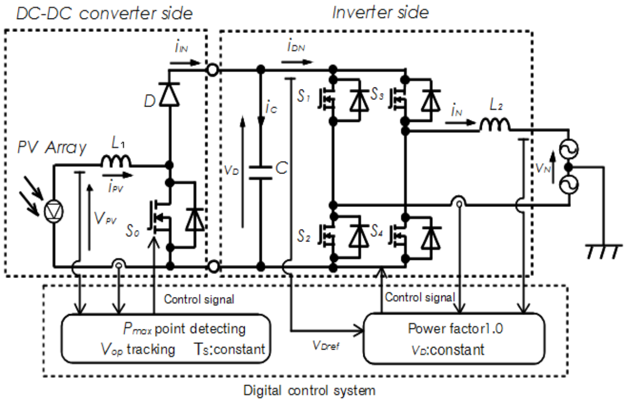


Fig. 1 Overall circuit configuration of the system.

Table 1 Specifications of the solar cell.

Maximum nominal output power	165 W
Maximum nominal output operating voltage	21.3 V
Maximum nominal output operating current	7.74 A
Nominal open voltage	25.7 V
Nominal short circuit current	8.48 A

Table 2 Circuit constants.

System voltage V_N (a single-phase three-wire system)	200 V
C	1,320 μF
L_1	7.5 mH
L_2	7.5 mH
Switching frequency f_S	10 kHz

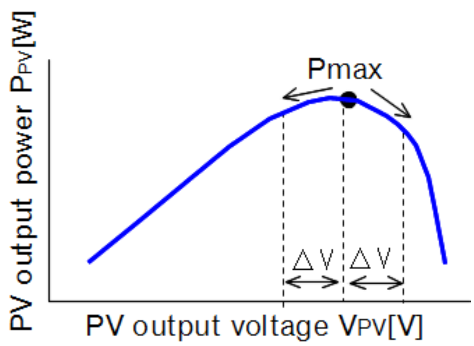


Fig. 2 Ordinary P-V curve.

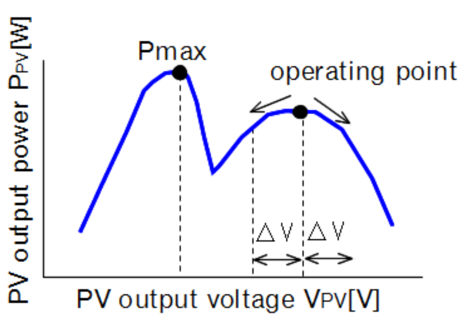


Fig. 3 P-V curve during partial shading.

The following describes the procedure of the scan-method.

With the scan-method, to operate the solar cells at the optimum operating voltage V_{OP} during maximum power P_{max}, the I-V characteristics of the solar cells are scanned instantaneously and the PWM (pulse width modulation) control is used to perform tracking control. Fig. 4 displays a conceptual diagram that depicts the operational waveforms for the scan-method. The carrier wave (serrated wave) is compared to the reference signal wave using a comparator, which yields the PWM control signal. When the maximum power P_{max} is detected by the PWM control, the solar cell current i_{PV} is assumed to be zero when the solar cell voltage V_{PV} is equal to the open voltage V_{OC}. Next, the system transitions into the P_{max} detection interval. In this state, the i_{PV} is controlled to the following reference current I_{ref} by the PWM control:

$$I_{ref} = -\frac{I_{sc}}{T_{Dref}} t + I_{sc} \tag{1}$$

where, I_{SC} is a short circuit current (A) and T_{Dref} is the I-V characteristics scanning interval (s). In this period, the solar cell current i_{PV} is multiplied by the measured solar cell voltage V_{PV} to determine the maximum power point. Hereafter, the solar cell voltage V_{PV} is controlled to trail the resulting optimal operating voltage V_{OP}. As the final step, the tracking operation interval is switched to a high frequency f_S (= $1/T_S$) in the range of tens of kHz to regulate the output voltage of the DC-DC converter. The output voltage is controlled so that the solar cell voltage V_{PV} is equal to the optimal operating voltage V_{OP}. It is possible to obtain the maximum power possible under the current conditions by sequentially performing the maximum power point detection and tracking operation for a fixed number of cycles T. It should be noted that the impact of these intervals on the power acquisition capacity is negligibly small because the P_{max} detection interval is sufficiently small relative to the detection cycle T, and can be therefore ignored.

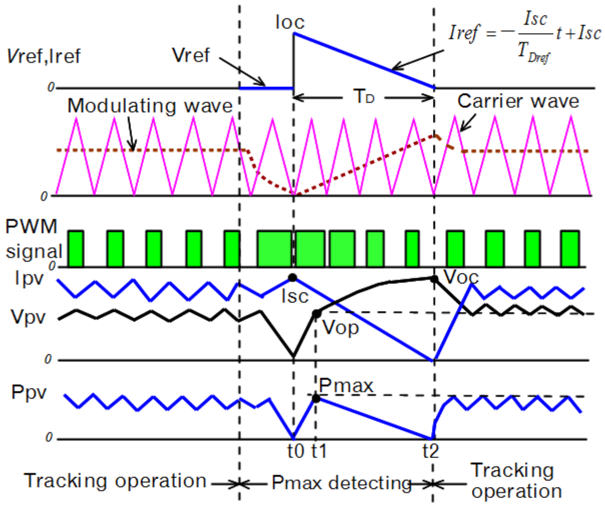


Fig. 4 Schematic diagram of operation.

3.3 Inverter Operation

In the digital control system shown in the control block of Fig. 1, the capacitor voltage V_D, the system voltage V_N, and the system current i_N of the inverter are read by sensors to send the power from the solar cell side to the load or system power supply (as a grid). At the same time, a command is generated to maintain the set value of V_D and a power factor of 1.0. The PWM control signals, based on this command, are applied to the switching elements (S_1-S_4) such as a MOSFET.

4. Operational Testing of the New MPPT Control

4.1 Operational Testing for Scanning

This section examines whether or not the detection time can be ensured using a specified T_{Dref}.

Six of the solar cell modules described in Section 2 were connected in series and were installed on the roof of our institute, facing south. Using this array, the system shown in Fig. 1 was utilized.

At least 100 data points are needed to make an accurate determination of the maximum power point when the sampling rate of an A/D converter is set to 20 kHz when measuring the voltage and current of a solar cell. Therefore, T_{Dref} must be set to 5 ms. T_{Dref} can be set to 1 ms if the sampling rate is 100 kHz.

Fig. 5 shows the operation waveform without the PWM control of the scan-method in which the control of the detection interval was not performed. As the figure shows, the detection time was 500 μs. Thus, the detection time is considered to be too short in this case.

Figs. 6a-6c show the operation waveforms with the PWM control of the scan-method for T_{Dref} set to 1 ms, 2 ms and 5 ms, respectively. As Fig. 6 shows, scanning occurred during the set detection interval.

Thus, it has been shown that the required detection time can be obtained if T_{Dref} is set appropriately to the sampling rate of the A/D converter. This study employed an A/D converter with a sampling rate of 100 kHz, setting the detection time to 1 ms for a detection interval of 1 s. The detection time corresponds to 0.1% of the detection interval, allowing us to sufficiently ignore the detection time.

4.2 Operational Testing of the PCS System

In this section, we show waveforms at various circuit components to examine any disruption on the output side caused by the scanning at the input side.

Fig. 7 shows the waveforms for the overall system when the detection interval in Fig. 6 is set to 1 ms. As this figure shows, the capacitor voltage V_D was maintained at a constant level during scanning and no disturbance was seen in the system current i_N. The operation waveform was confirmed to be stable.

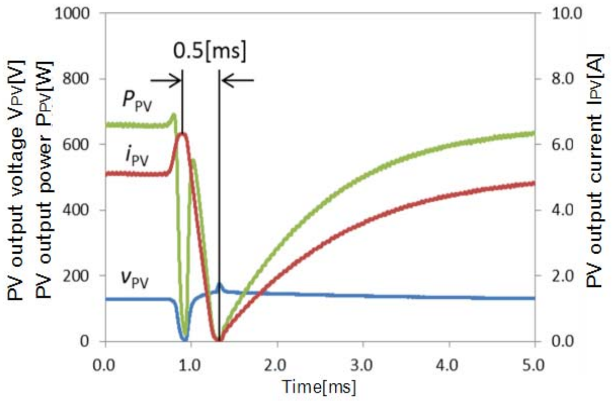
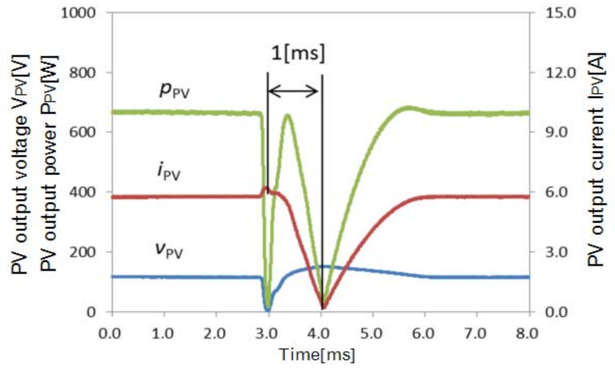
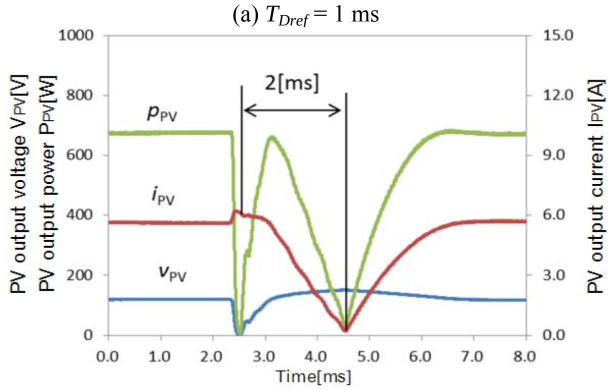


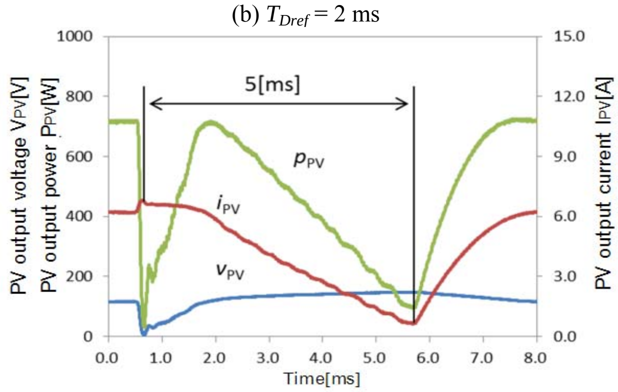
Fig. 5 Operation waveform without the PWM control of the scan-method.



(a) T_{Dref} = 1 ms



(b) T_{Dref} = 2 ms



(c) T_{Dref} = 5 ms

Fig. 6 Operation waveform with the PWM control of the scan-method.

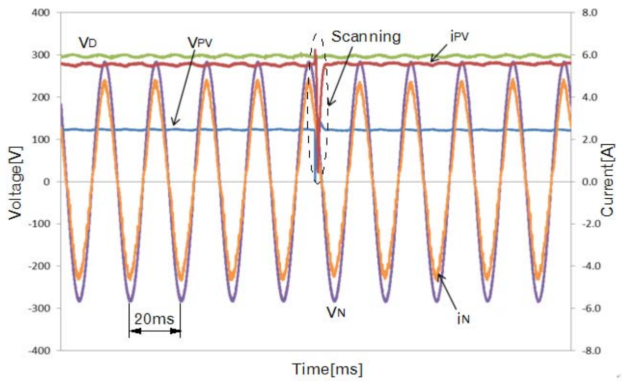


Fig. 7 Operation waveform of the overall system when T_{Dref} = 1 ms.

4.3 MPPT Operational Testing during Partial Shading

This section presents a test to check the effectiveness of the MPPT via the scan-method during partial shading, which is especially prone to cause problems when the conventional control method (P & O) is used.

To confirm the power acquisition characteristics during partial shading, sheets with a light-shielding ratio of 80% were attached to two of the modules that were used for testing (as shown in Fig. 8) and operation under these conditions was verified. The detection time of the developed PCS was set to 1 ms. Fig. 9 shows the P-V characteristics prior to shading and the P-V characteristics of the solar cell array in the partially shaded state shown in Fig. 8. As this figure shows, there is generally only one peak (on the high-voltage side), but there are two peaks during partial shading, one on the high-voltage side and one on the low-voltage side, due to the effects of the bypass diode during partial shading.

Table 3 shows a comparison of the power obtained using the commercially available PCS and the developed PCS during the partial shading shown in Fig. 9.

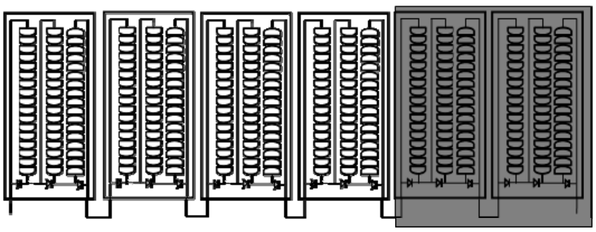


Fig. 8 Partial shading pattern.

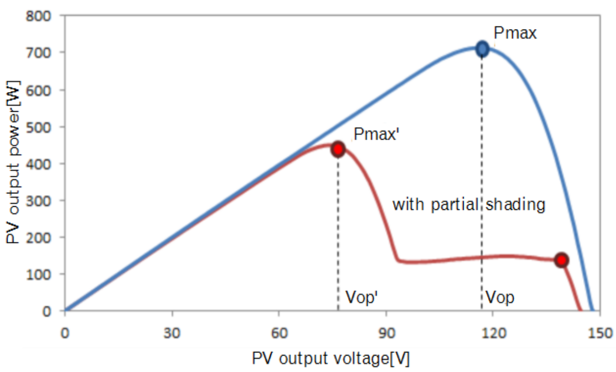


Fig. 9 P-V characteristic during partial shading.

Based on Table 3, this study confirmed that operation with the commercially available PCS is not possible at maximum power during partial shading.

The maximum power was obtained without any problem by the developed PCS. Compared to a commercially available PCS, the power obtained was approximately twice that of the commercially available PCS under the test conditions described here.

Thus, as previously described in terms of fundamental principles, the P & O method searches for a maximum, and can cause mismatch power loss; in contrast, the scan-method scans I-V characteristics and has been shown to be capable of accurately identifying the maximum power point.

4.4 Problems with Using Panels with Different Specifications in Combination

When replacing panels that are inoperable or deteriorated, it may not always be possible to install panels with the same specifications in terms of price, performance, and other considerations. There are various types of solar cell modules available and their characteristics differ depending on the type and capacity of the module. An example of the PV characteristics when different types of modules are used in combination is described below.

Using a simulated PV power supply device, a P-V curve was created using modules with different specifications in combination. Fig. 10 shows an example of the structure of such a simulated PV power supply device. Table 4 shows the specifications for PV1 and PV2. Fig. 11 shows the PV characteristics when these two strings are connected in parallel via a backflow-prevention diode. This figure shows that the profile is the same as that when partial shading was used. In this case, the maximum output is 417 W with a voltage of 77.3 V. However, even under

Table 3 Comparison of power obtained during partial shading (G = 680 W/m^2).

	Operating voltage (V)	Output power (W)
Developed PCS	75.0	440
Conventional PCS	140	185

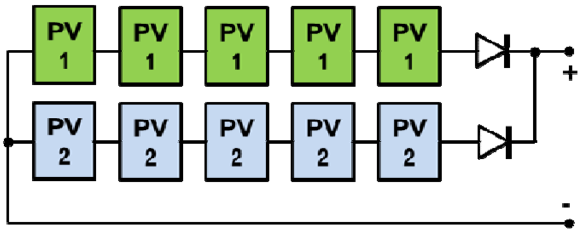


Fig. 10 Panel structure.

Table 4 Specifications for PV1 and PV2.

	PV1	PV2
Maximum output power	63 W	54 W
Maximum output operating voltage	35 V	18 V
Maximum output operating current	1.8 A	3.0 A
Open voltage	45 V	20 V
Short-circuit current	2.0 A	4.5 A
Open voltage of the string (5S)	225 V	100 V

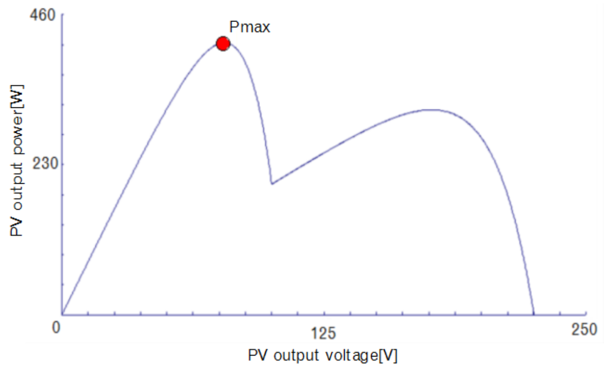


Fig. 11 PV characteristics when different modules are used in combination.

such conditions, a commercially available PCS employing the P & O method will operate with a low power peak on the high-voltage side. However, this study confirmed that reliable operation is possible at the maximum power point on the low-voltage side using our developed PCS.

5. Conclusions

This paper described a grid-connected PCS that employs a new MPPT control (scan-method), and compared the power acquisition characteristics during partial shading with those of a conventional PCS to gauge its effectiveness. The results clearly demonstrated that the developed PCS offers outstanding effectiveness in tracking the maximum power point in partially shaded environments. Problems similar to those of partial shading occur when modules with different specifications are used in combination. Under such conditions, the effectiveness of the operation of the developed PCS was confirmed.

This method provides improved MPPT efficiency because losses due to scanning are reduced as detection time is shortened although an A/D converter with a higher sampling rate is required. When the detection interval is too long, however, the insolation intensity may change before the next scan is initiated, lowering the MPPT efficiency. If the detection interval is too short, this increases the effect of the detection time on output, degrading MPPT efficiency. Therefore, the detection time must be set as appropriate for the functionality of the A/D converter, and the detection interval must be set as appropriate for MPPT efficiency.

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