研究論文

Generation Power Compensation System using Electric Double Layer Capacitor for Partially Shaded Series PV Modules

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Abstract

Generation power of a photovoltaic (PV) array deeply depends on surrounding conditions like temperatures and solar insolation. In particular, the power generated from PV modules in series is drastically reduced when they are partially covered by shade. To address the problem, a power compensation system using Electric Double Layer Capacitors (EDLC) is presented in this paper. In this system, the output power of the shaded PV module is efficiently obtained and utilized, so that the total output power is controlled to maximum according to the solar insolation.

The control characteristics of the proposed system are examined by simulation and experimental verification. From those results, it is confirmed that the control strategy are valid to avoid the significant reduction of generation power due to the partial-shading.

Key words: PV module, Shade, Power Generation Control, EDLC, MPPT, Boost Chopper.

1. Introduction

As a renewable energy source, Residential PV Power Generation system has been widely disseminated, especially in developed countries, and is acting an important role as an autonomous power generation system owing to its clean and inexhaustible energy source.

Generally, in the utility-interactive PV generation systems, the PV array is constructed in parallel and series of PV modules to obtain a few kilowatt of power. In particular, the series connection is essential to establish a DC voltage for operating with the interactive inverter [1].

In order to increase the generation capacity and utilize the limited space more efficiently, it is projected that PV modules will be installed not only at roofs but also wherever the sunlight is available. In those cases, the sunlight might be obstructed by surrounding structures as following factors:

1) many houses and building located near around the PV system in an urban area.

2) changes of insolation-angle due to the daytime or season.

Depending on the array configuration, this partial shading has a significant impact on PV generation capability. According to the several studies, power reduction caused by partial shading on the series-PV module is more significant than that of parallel-PV module [2]-[5].

As conventional measures to avoid the power-reduction, bypass diodes are installed in parallel with PV modules [1], [3], [6]. If it cannot flow through one or more modules in series, the PV current will flow through the bypass diodes instead of them. The total output power of the PV modules, however, is less than the sum of the maximum power of each module, which results in the significant power-reduction, compared with the normal condition.

To obtain the potential power in the shaded module and boost the utilization of PV generation power, a new control method using EDLC is proposed in the study. On the basis of the simple control principle, the output power of the shaded PV module can be obtained.

In this paper, at first, the power-reduction caused by partial shading is discussed theoretically with the output characteristics curves. At second, the system configuration and the control principle are described. Next, the design procedure of the capacitance of EDLC is shown in view of the practical installation. Furthermore, the system operation and the control characteristics are analyzed by simulation, and finally the compensation effects of the proposed control strategy are verified by experiments.

2. Partial Shading and Control Strategies

2.1 Problems of Bypass Diodes

Fig.1(a) and (b) illustrate the conventional system using bypass diode and the conceptually-proposed EDLC-based system, respectively. Here, the series of PV modules are split into two groups, i.e. PV1 and PV2.

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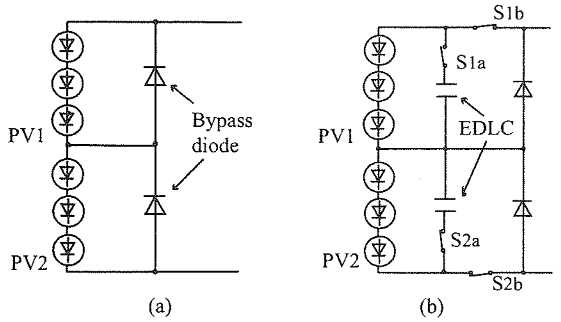


Fig.1 Series connection of PV modules, (a) bypass diode-based configuration, (b) the proposed EDLC-based configuration.

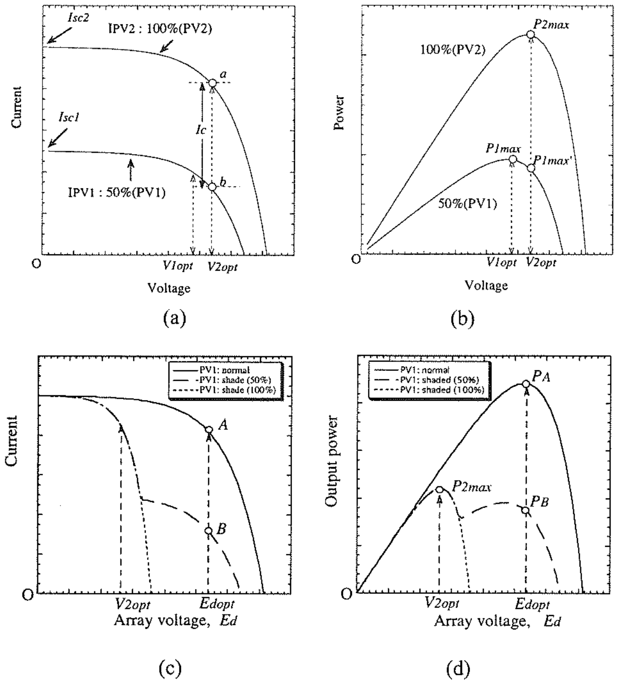


Fig.2 Charactersitics curves of PV modules: (a) I-V curve of each module, (b) P-V curve of each module, (c) I-V curve in series, (d) P-V curve in series.

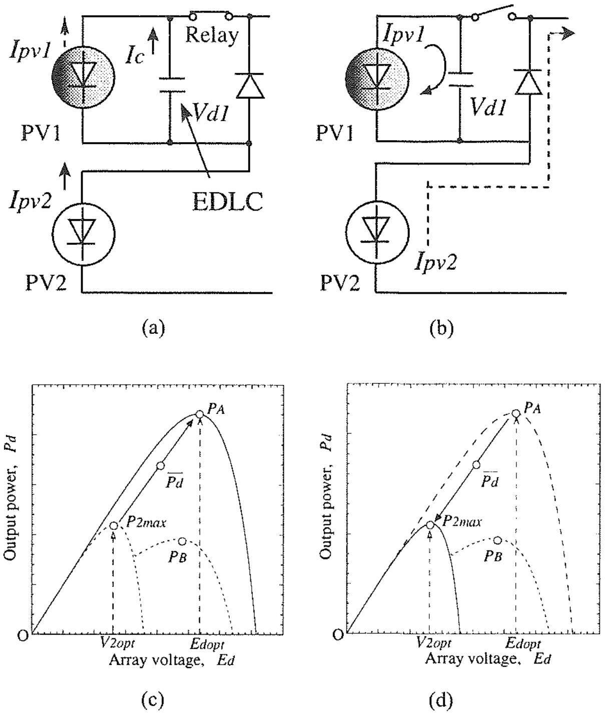


Fig.3 Operation principle of the proposed system: (a) equivalent circuit of the EDLC-discharge mode, (b) equivalent circuit of the EDLC-charge mode, (c) P-V curves of the discharge mode, (d) P-V curves of the charge mode.

Now, let it assumed that two PV modules are exposed to the different solar insolation as shown in Fig.2(a) and (b). In Fig.1(a), the operating current of PV2, which is greater than that of PV1, flows through the bypass-diode of PV1. Therefore, the total I-V characteristic curves are expressed in Fig.2(c) according to the shading condition. Consequently, the corresponding P-V curve has multiple local maximum power points P_{2max} and P_B as shown in Fig.2(d). On this curve, some complicated control algorithm will be required to detect the greater maximum power P_{2max}. Moreover, even if it is detected and the operating point is tracked there, no power is generated from the shaded module PV1.

2.2 Control Principle of the Proposed System

Fig. 3 shows the basic system configuration deriving from Fig.1(b), and the P-V characteristics. Note here that an Equivalent Series Resistance (ESR) of the EDLC and its power loss are not considered to simplify the description of the control principle.

Considering the practical system, it could be justified that the EDLC is employed to only one of series-modules. As seen in Fig.3(a), the EDLC-discharge current compensates the current difference between I_{PV1} and I_{PV2}. In this mode, the P-V curve of the total system is transformed to the solid line in the Fig.3(c), where the maximum power is give by only P_A. On the other hand, the EDLC is charged by the operating current of PV1 when the relay is turned off. During the charging mode, the energy for the power compensation is stored in the EDLC. In this mode, the P-V curve is transformed to the solid line in the Fig.3(d), where the maximum power is given by only P_{2max}.

Thus, the mode-exchange repeats while PV1 is covered by shade. Moreover, the maximum power appears in only one point without any local maximum power point on either mode. Therefore, the maximum power point of each mode can be detected and tracked by the simple and conventional Maximum Power Point Tracking (MPPT) algorithm, i.e. Hill Climbing Method [7],[8].

In the case of a non-shading condition, EDLC should be disconnected with the compensated module so that the total generation power is controlled by only MPPT controller as in the normal manner. Hence, S1a (S2a) is OFF, while S1b (S2b) remains ON in Fig.1(b).

2.3 Power Compensation Effect of the Proposed System

On the basis of the proposed control strategy, the charged or discharged power in the EDLC $\Delta P1$ can be given as follow:

$$\Delta P_1 = P_{2\max} - P_{1\max}, \quad (0 \le t \le T_{on}) \tag{1}$$

$$\Delta P_1 = -P_{1\max}, \quad (T_{on} < t \le T) \tag{2}$$

where Ton and T are the period of the discharging mode and the

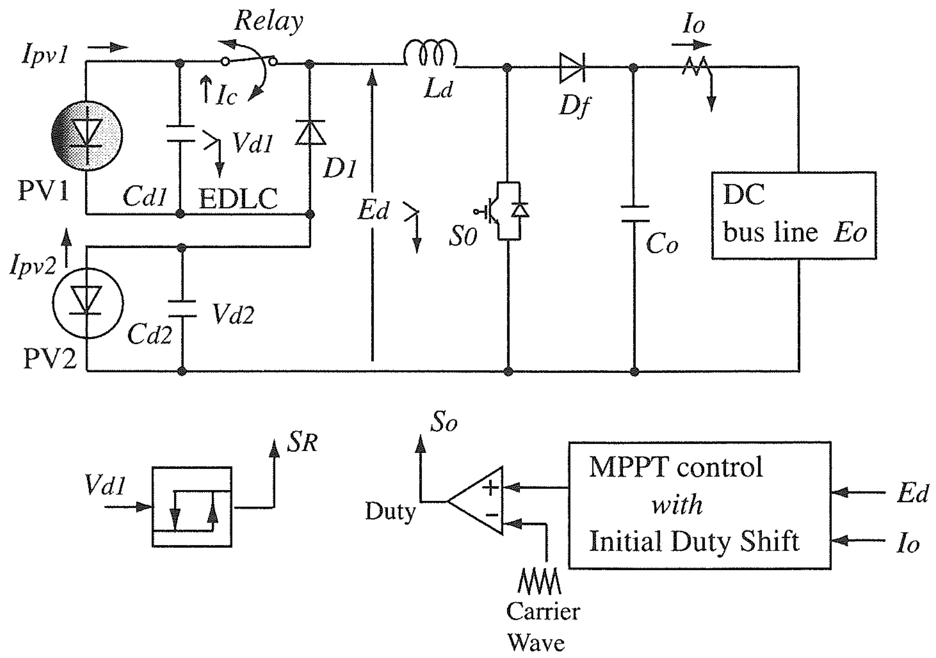


Fig.4 Proposed EDLC-based generation power compensation system for series PV modules.

control one cycle, respectively.

Moreover, ΔP_1 explicitly satisfies (3) in view of the energy flow of the EDLC for the control one cycle:

$$\int_0^T P_1 dt = 0 \tag{3}$$

At the same time, the relationship between P_{1max} and P_{2max} can be expressed as follow:

$$P_{1\max} = \frac{T_{on}}{T} P_{2\max} = \alpha P_{2\max} \tag{4}$$

$$\alpha = T_{on}/T = P_{1\max}/P_{2\max}. \tag{5}$$

As a result, by tracking each maximum power on both modes, the total generation power on average $\overline{P_d}$ is expressed as follows:

$$\begin{aligned}\overline{P_d} &= \frac{1}{T}\int_0^{T_{on}} \left(P_{1\max} + \Delta P_1\right) dt + P_{2\max} \\ &= \left(1+\alpha\right) P_{2\max} = P_{1\max} + P_{2\max}.\end{aligned} \tag{6}$$

Eq.(6) indicates that the average output power of PV1 is equivalent to its maximum power P_{1max}. Thus, it is theoretically proven that the maximum power of each module can be obtained according to the insolation condition by the proposed system.

3. Main Circuit and Control System

3.1 Main Circuit Configuration

The proposed power compensation system is shown in Fig.4. In this system, the EDLC-based power compensator and the boost converter are applied in parallel with a array DC bus line E_o where several other PV strings are connected in parallel.

Originally, the EDLC-based power compensator should be applied to each of PV modules in series as shown in Fig.1(b). However, for simplifying the further discussion of the system operation, the targeted module for power compensation is limited to one of the two series, as shown in Fig.4.

In this system, the Boost Chopper operates not only for regulating the PV array voltage E_d but also for limiting the excessive current discharged from the EDLC.

Moreover, the terminal voltage of the EDLC V_{dl} is sensed to estimate the stored energy level. Since the capacitor's voltage varies with charging and discharging, the monitoring system is much simpler than a battery-based power compensator.

3.2 Control System

The relay-switching is controlled by a hysteresis comparator, the timing chart of which is illustrated in Fig.5. The hysteresis band ΔV_{d1} is set around the module optimum voltage V_{opt} where it generates maximum power, so that output power of the compensated PV module doesn't deviate drastically from its maximum power. Here, note that an optimum voltage of PV module is almost constant against insolation variation [1].

The MPPT algorithm in this system consists of a Hill Climbing Method and Initial Duty Shift of the boost chopper, as shown in Fig.6. Since E_d shifts up or down by V_{d1} at the instant of the relay-switching, the chopper duty should be moved toward a value which corresponds to E_d/E_o. After that, this duty shift is followed by the conventional hill climbing method.

3.3 Design of MPPT Cycle

It can be known from Fig.4 that the time constant of V_{d1} is larger than that of V_{d2} because of a large capacitance of the EDLC. As a result, the MPPT operation depends on the voltage regulation capability of the boost chopper. Hence, the MPPT cycle T_M should be so small that the voltage variation ΔVd1 can be neglected as shown below:

$$\Delta V_{d1} = \frac{I_c T_M}{C_{d1}} \cong 0 \qquad (7)$$

where Ic is the EDLC-discharge current.

4. DESIGN OF THE EDLC CAPACITANCE

In order to realize a cost-effective implementation of the proposed power compensator, the capacitance of the EDLC C_{d1} should be designed in view of the PV generation power.

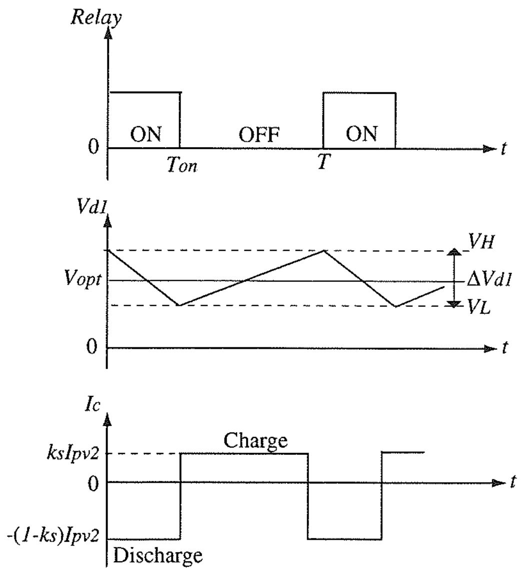


Fig.5 Relay-switching sequence based on the EDLC operation voltage.

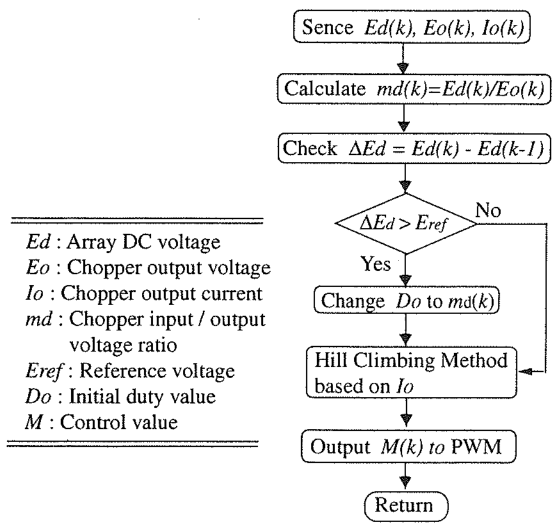


Fig.6 MPPT algorithm with the initial duty shift control.

Given that ks is an insolation ration of PV1 and PV2, the operating current I_{PV1} is expressed with I_{PV2} as follows:

$$I_{PV1} = k_s I_{PV2} \qquad (8)$$

Here, note that ks is equivalent to α in (5). Then, Ic can be written in (9) and (10) from (8):

$$I_c = -\left(I_{PV2} - I_{PV1}\right) = -\left(1-k_s\right) I_{PV2}, \quad (0 \le t \le T_{on}) \qquad (9)$$

$$I_c = k_s I_{PV2}, \quad \left(T_{on} < t \le T\right) \qquad (10)$$

Next, the operating voltage range of the EDLC, i.e. ΔVd1 can be described on the basis of Fig.5 as follows:

$$\Delta V_{d1} = V_H - V_L = k_H V_{opt}, \qquad (11)$$

where k_H is defined as a proportional gain. At the same time, ΔV_{d1} can also be expressed with C_{d1} and Ic as shown below:

$$\Delta V_{d1} = \frac{1}{C_{d1}} \int_0^{T_{on}} I_c dt = \frac{-\left(1-k_s\right) I_{PV2} T_{on}}{C_{d1}} \quad (0 \le t \le T_{on}), \qquad (12)$$

$$\Delta V_{d1} = \frac{1}{C_{d1}} \int_{T_{on}}^{T} I_c dt = \frac{k_s I_{PV2}\left(T - T_{on}\right)}{C_{d1}} \quad (T_{on} < t \le T). \qquad (13)$$

From (12) and (13), T_{on} can be written by (14):

$$T_{on} = k_s T. \qquad (14)$$

Then, T can be defined by (12) - (14) as follows:

$$T = \frac{k_H V_{opt} C_{d1}}{k_s \left(1-k_s\right) I_{PV2}}. \qquad (15)$$

Here, considering the system installation, T should be larger than the minimum value that corresponds to the relay's lifetime To. Therefore, C_{d1} satisfies the following condition:

$$C_{d1} > \frac{T_o I_{PV2}}{k_H V_{opt}} \cdot k_s \left(1-k_s\right) = C_{d1\min}. \qquad (16)$$

In addition, it is explicitly known from (16) that C_{d1min} is maximum when ks is 0.5. Thus, the capacitance of the EDLC required in the compensator is determined as follows:

$$C_{d1} = \frac{T_o I_{PV2}}{4 k_H V_{opt}} = \frac{T_o P_{2\max}}{4 k_H V_{opt}^2}. \qquad (17)$$

From (17), it can be known that the capacitance is in proportion to PV generation power under the normal condition and inversely proportion to the operating voltage range of the EDLC.

The relationship between solar insolation and a capacitance of the EDLC is shown in Fig.7, where k_H is normalized by its standard value k_H*.

5. SIMULATION AND EXPERIMENTAL VERIFICATION

5.1 Simulation Result

The system operation of the proposed control strategy are investigated by a circuit simulation. Here, it is assumed that the

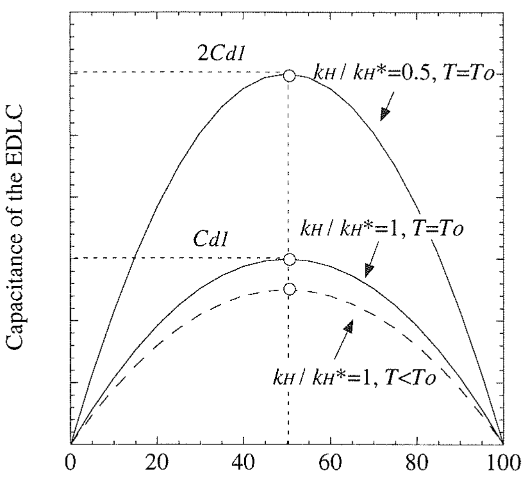


Fig.7. Relationship between the EDLC capacitance and solar insolation.

insolation of PV1 is weaken to 40% against the full insolation for PV2, and accordingly k_s is 0.4. On the basis of this condition, the maximum power of PV1 and PV2 are defined 100W and 250W, respectively. Other simulation setups are indicated in TABLE I.

The simulation waveforms are shown in Fig.8. While V_{d1} doesn't reach to V_H of 52.5V, the relay remains OFF and the EDLC is charged by I_{PV1}. After that, once V_{d1} increases to V_H and the relay turns on, it is observed that the capacitor current I_C is discharged so as to compensate the difference between I_{PV1} and I_{PV2}. In this term, the total output power P_d boosts to 500W that corresponds to the maximum generation power under the non-partial-shading condition.

On the other hand, as the capacitor is discharged, V_{d1} linearly declines. Once V_{d1} goes down to V_L of 47.5V, the rely turns off. In this term, it can be observed that P_d is controlled to the maximum power of the non-shaded module PV2.

5.2 Experimental Results

The configuration of the prototype experimental system is shown in Fig.9. Since the experimental system is an in-house type, characteristics of the PV modules are modeled by a DC power supply and a resistor. The characteristics of the PV module-models are illustrated in Fig.10, whereby three kinds of maximum power points, i.e. P_A, P_{2max} and P_B, are defined, respectively. Here, suppose that insolation for PV 1 decreases from 100% to 50%.

In addition, to simply construct experimental system and focus on analyzing the compensation effects of the control strategy, a DC power supply is applied instead of the EDLC.

Furthermore, the MPPT cycle T_M is set to 1.5s and the MPPT controller is realized by a one-chip microcomputer PIC 16F874 where A-D converter and PWM function are embedded.

The results of the MPPT operation of the power compensator are shown in Fig.11. Fig. 11 (a) shows the operation point trajectory controlled by the bypass diode, while Fig. 11(b) is the result obtained by the proposed compensator. By comparing the two

TABLE I Simulation setup.

Mian Circuit		
Capacitance of EDLC	C_{d1}	15F
Smoothing capacitor	C_{d2}	2000μF
DCL	L_d	8mH
DC voltage source	E_o	200V
Control System		
EDLC voltage range	V_L/V_H	47.5V/52.5V
PV optimum voltage	V_{opt}	50V
MPPT control cycle	T_M	0.75s
Switching frequency	f_S	8kHz

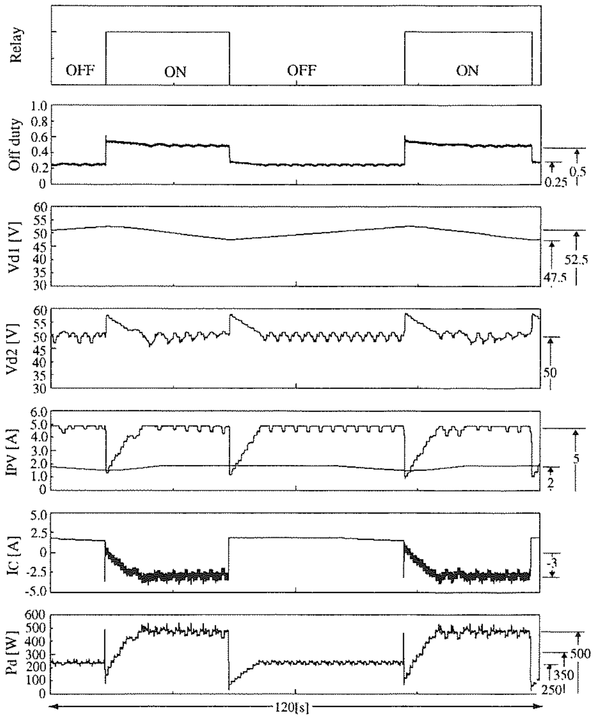


Fig.8. Simulation result of the EDLC-based power compensator.

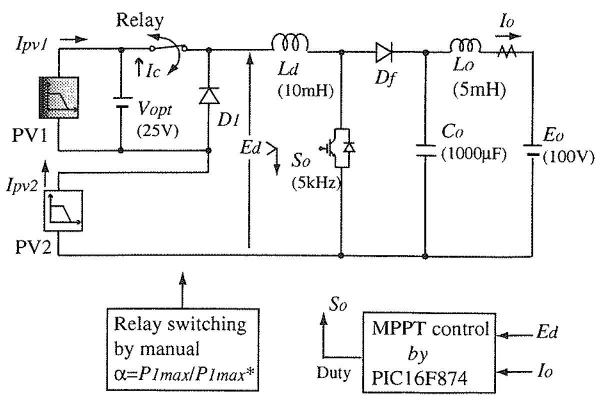


Fig.9. The experimental system configuration.

results, it can be known that P_d is controlled between P_A and P_{2max} by implementing the compensator. As a result, the average output power is larger than P_B by the non-generation control.

Output power obtained in the experimental setup is summarized in TABLE II. Thus, it is confirmed that output power increases with 70 W on average by means of the power compensator.

Next, characteristics of the Initial Duty Shift are examined. The dynamical waveforms of the output power and PV array voltage with the relay-switching are shown in Fig.12. Fig. 12 (a) shows the result without the duty shift, while Fig.12 (b) is the result with the duty shift control. By comparing these results, it can be confirmed that the drastic power reduction due to the relay-switching is attenuated by the initial duty control.

6. CONCLUSION

A novel control strategy and power compensator using Electrical Double Layer Capacitor are presented to avoid significant power reduction due to partial shading in a series of PV modules. The system operation of the compensator and the control characteristics are investigated by the simulation and experimental analyses.

From those results, it is confirmed that the maximum power of the shaded module can be obtained without reducing the generation power of the other non-shaded modules. In addition to that, the compensator can be realized by the simple control principle with an EDLC and relay. Hence, the power compensator is valid not only for recovering the potential generation power but for

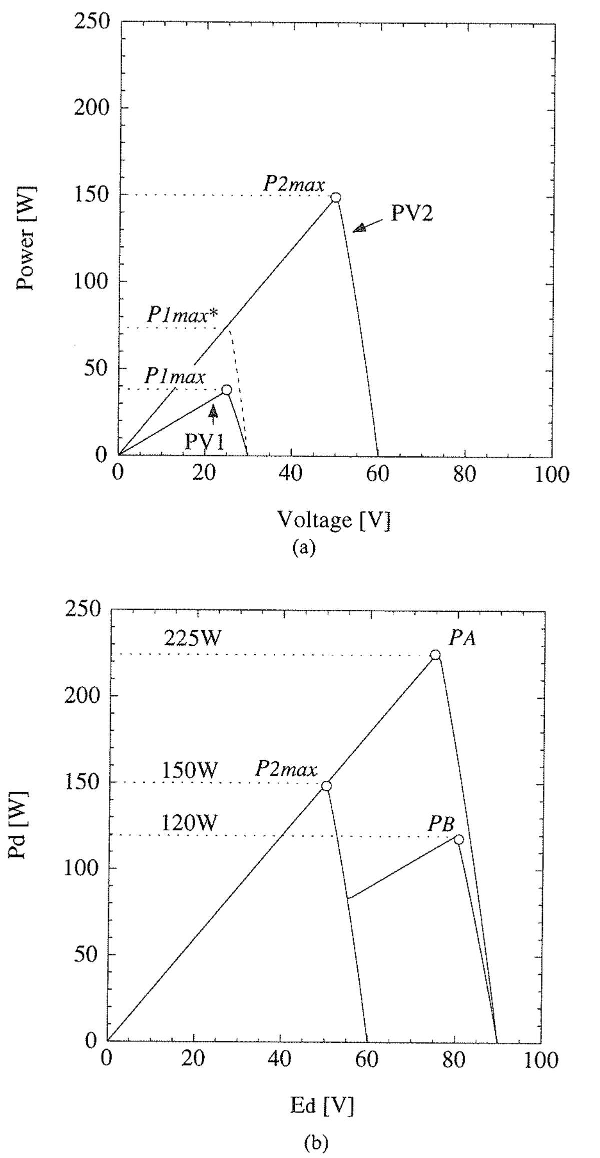


Fig.10. Characteristics of the experimental PV models: (a)P-V curves of each module, (b)P-V curves in series.

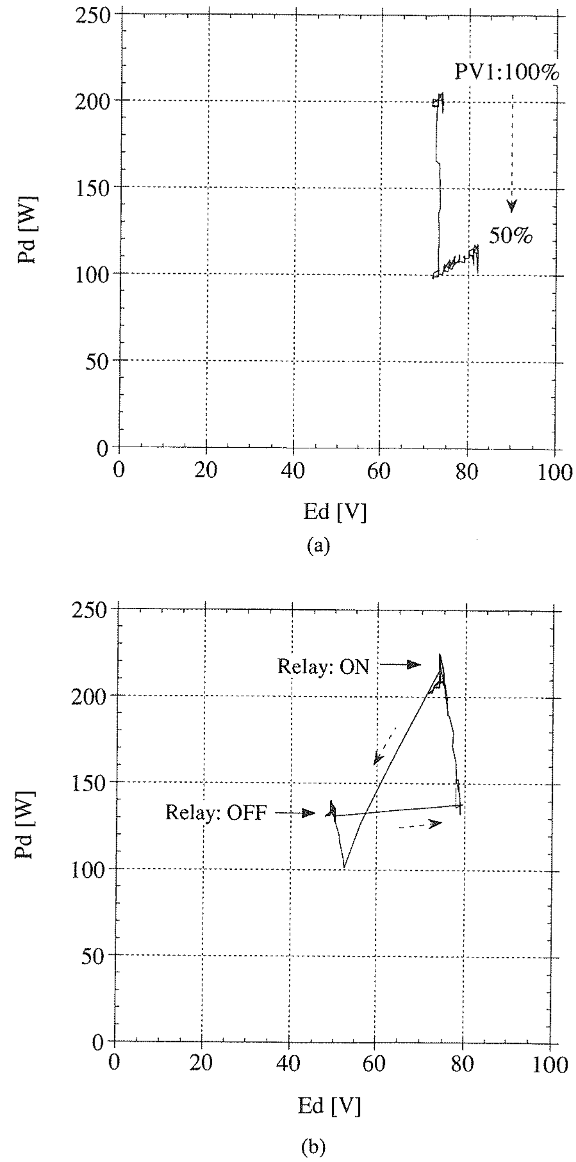
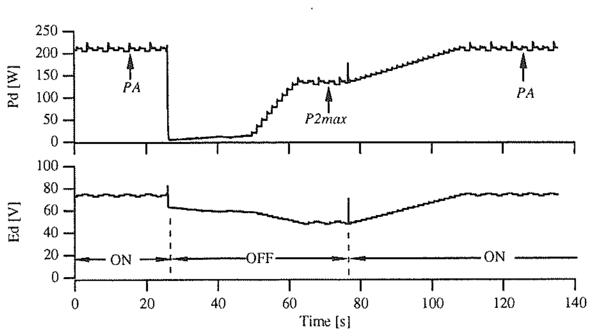


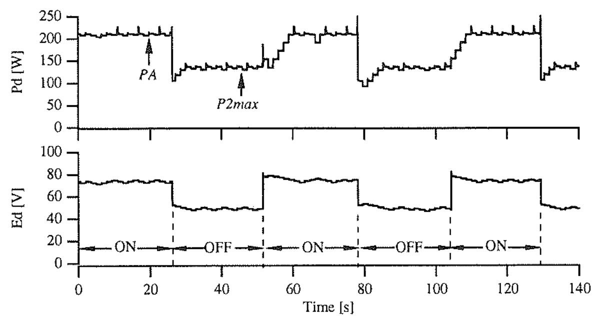
Fig.11. Experimental results of operation point trajectry of the PV module, (a) bypass diode-based system, (b) EDLC-based system.

TABLE II Comparison of output power on generation conditions.

Total PV generation power Pd		
Normal cond.	Shading (bypass diode)	Shading(compensator)
225w	120W	190W(on average)



(a)



(b)

Fig.12. Experimental results of the output power and array bus voltage: (a) without Initial Duty Shift control, (b) with Initial Duty Shift control.

utilizing the shaded module efficiently.

In conclusion, the proposed compensation system is useful as one of the measures to address the partial shading problem in PV generation systems. Realizing the selector circuit for the EDLC-assisted PV module is a future challenge in this research.

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