A Control Method to Charge Series-Connected Ultraelectric Double-Layer Capacitors Suitable for Photovoltaic Generation Systems Combining MPPT Control Method

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***Abstract*—A control method is described to charge series-connected ultraelectric double-layer capacitors (ultra-EDLCs) suitable for photovoltaic generation systems in combination with a maximum power point tracking (MPPT) control method. The EDLC charge control method allows the maximum power acquired by the MPPT control to be quickly charged into series-connected ultra-EDLCs no matter how the weather conditions may change. In the MPPT control, the output current of the solar arrays is controlled so that the output power converges on the maximum power in the prediction line previously determined based on the linearity between the maximum output power and the optimization current. The proportionality coefficient of the prediction line is automatically corrected using the hill-climbing method when the panel temperature of the solar arrays is changed. The EDLC charge control is performed with the three charge modes, i.e., the constant current charge mode, constant power charge mode, and the constant voltage charge mode while supervising the maximum voltage and allowable temperature of each series-connected EDLC. Effectiveness of the methods is verified by simulations and experiments.**

***Index Terms*—Maximum power point tracking (MPPT), photovoltaic (PV), power supply, ultraelectric double-layer capacitors (ultra-EDLCs).**

I. Introduction

STUDIES of photovoltaic (PV) generation systems are actively being promoted in order to cope with environment issues such as the green house effect and air pollution. PV generation systems have two big problems that the efficiency of electric-power generation is very low, especially under low irradiation states, and the amount of the electric power generated by solar arrays is always changing with weather conditions, i.e., the intensity of the solar radiation. A maximum power point tracking (MPPT) method, which has quick response characteristics and is able to make good use of the electric power generated in any weather, is needed to cope with the former problem. Many MPPT control methods have been proposed that search for the maximum operating conditions from the output power and voltage characteristics of solar arrays using differential techniques like perturbation and observation [1], [2] or fuzzy rules [3], [4]. However, methods to make the output power generated from the installed solar arrays quickly arrive at its peak value have not been discussed. Although an enhanced hill-climbing method was recently reported [5], [6], there are difficulties in the algorithms because parameters are needed during the tracking process. This leads to a larger time to reach the maximum power. A method to refine the response characteristics of the output power was also proposed [2] that searches for the maximum point so that the derivative of the output power with respect to the output voltage of solar arrays becomes zero. However, there are problems in controllability to search for the maximum point at lower solar radiation, because the derivative of the output power with respect to the output voltage also drops as the solar radiation decreases. Thus, a new practical MPPT method is studied here that can quickly reach the maximum output power determined by the solar radiation at that time, even in poor weather conditions, by simplifying the tracking process. The inherent features of solar arrays regarding the maximum output power should be well understood to realize a practical MPPT controller. To do so, there are two approaches, theoretical and experimental ones. The former has difficulties in identification of parameters involved in the maximum power because the parameters are always changing according to environmental conditions such as temperature and solar radiation. Thus, it is very difficult to find control conditions regarding the maximum theoretically. Therefore, control conditions regarding the maximum power are determined here based on the facts found through experimental results obtained in measurements for more than six months [7].

Next, in order to use the maximum power obtained by the MPPT control efficiently, high-speed energy storage means with a huge capacity which can accumulate quickly and efficiently the acquirable maximum power changing according to weather conditions is needed. Here, ultraelectric double-layer capacitors (ultra-EDLCs), which can charge and discharge quickly, are used as the storage means. The EDLC is characterized by having a low voltage (rated voltage: 2–3 V) and a huge capacity (more than 10 000 F). Therefore, a number of ultra-EDLCs have to be connected in series in order to enable EDLC application to PV generation systems to generate high voltage

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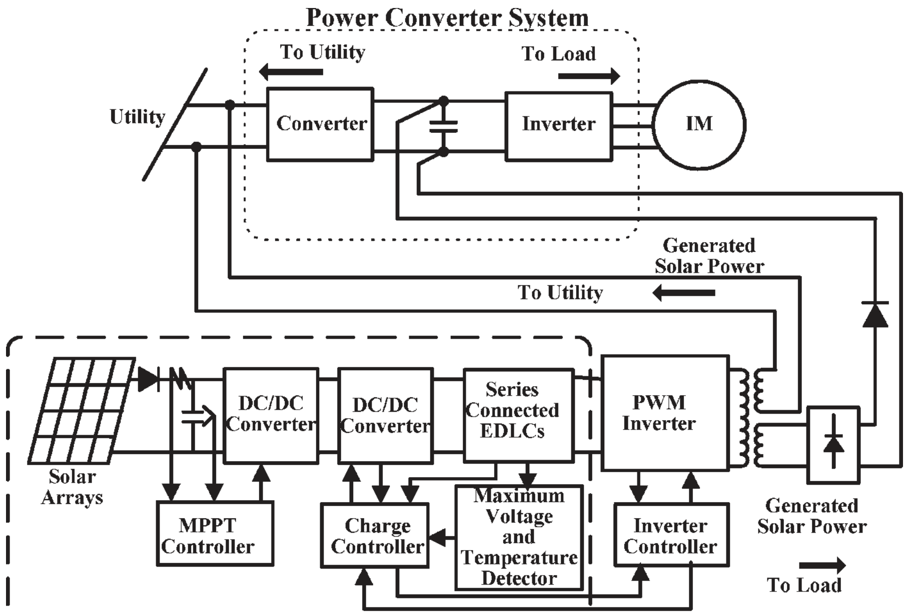

Fig. 1. PV generation system to link the utility and loads through charging means using series-connected ultra-EDLCs.

by connecting solar arrays in series and parallel. Investigations regarding applications to PV power generation systems are actively being done that use EDLCs for load leveling [8] and as uninterruptible power supplies [9]. However, hardly any control methods to charge uniformly series-connected EDLCs while maintaining MPPT control conditions changing according to weather have been studied until now [10], [11].

Then, a control method to charge series-connected EDLCs for PV generation systems combined with MPPT control is proposed here [12] that can regenerate a surplus of the acquired power to utility lines while maintaining MPTT control conditions. This method is characterized by charging a number of series-connected ultra-EDLCs while managing the maximum voltage in the EDLCs and the allowable temperature of each ultra-EDLC without adding a circuit, which supervises the voltage of EDLCs individually. Thus, the reliability, which is the most important subject when used as a power source, can be improved. Moreover, since the maximum power acquired by the MPPT control under various solar radiations is charged into ultra-EDLCs, the utilization effectiveness of the acquired solar energy can be improved.

II. PV Generation System to Link a Utility and Loads

Fig. 1 shows a structure of the PV generation system, which makes it possible to distribute the electric power generated by solar arrays to utility and loads. In the system, the first dc/dc converter driven by the MPPT controller acquires the maximum power that solar arrays can generate at that time. The second dc/dc converter regulates the voltage output from the first dc/dc converter so as not to exceed the isolation voltage of all the series-connected ultra-EDLCs. Further, charging control for series-connected EDLCs is performed while supervising the maximum voltage and allowable temperature of each EDLC, so that the maximum power acquired by the MPPT control, which the solar arrays can generate at solar radiation of that time, can flow into the EDLCs. The charged solar power is transmitted to the utility through the pulsewidth-modulation (PWM) inverter or it is transmitted to loads or the utility through the dc intermediate circuit of the power converter system composed of a converter (rectifier) and an inverter. The goal of this paper is to realize an EDLC charging controller for the PV generation system to make it possible to charge a number of series-connected ultra-EDLCs with the maximum power acquired through the MPPT control according to the solar radiation at that time even if weather conditions change. To do so, by combining the MPPT controller with the function which can acquire the maximum power without being influenced by weather conditions with the EDLC charging controller, it is necessary to constitute the EDLC charging controller so as to be controlled based on the optimization current and voltage references determined from the maximum power acquired by the MPPT controller.

Thus, MPPT and charging control methods to respond to these demands for PV generation systems are studied here.

III. Control Rule for Performing High-Speed MPPT Control

In order to perform the MPPT control, a control rule to determine references for controlling the optimization current or voltage, which gives the maximum power, is needed. Although various methods to determine these references have been proposed until now, there are no easy methods to overcome the inherent features of solar arrays that it is hard to precisely and quickly obtain the references in regions where the intensity of the solar radiation becomes small. In order to solve this problem, a new control rule should be found. If relationships between the maximum power $P_{\max}$ output from solar arrays and the optimization current $I_{\max}$ are clarified, it is possible to comparatively easily form an MPPT control rule. Here, the

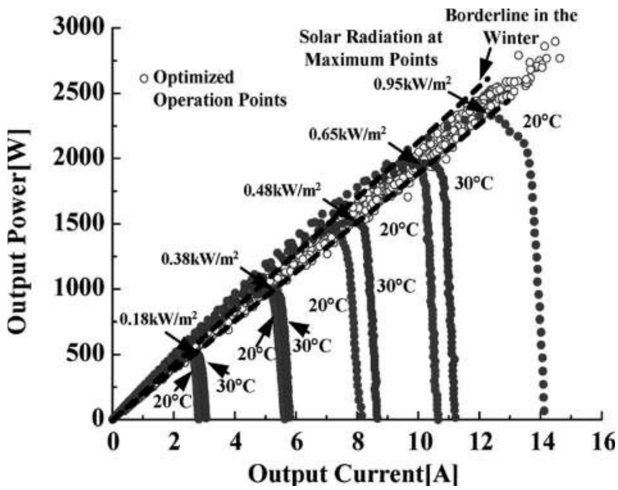

Fig. 2. Temperature dependencies of the optimization operation points under low-temperature conditions during winter.

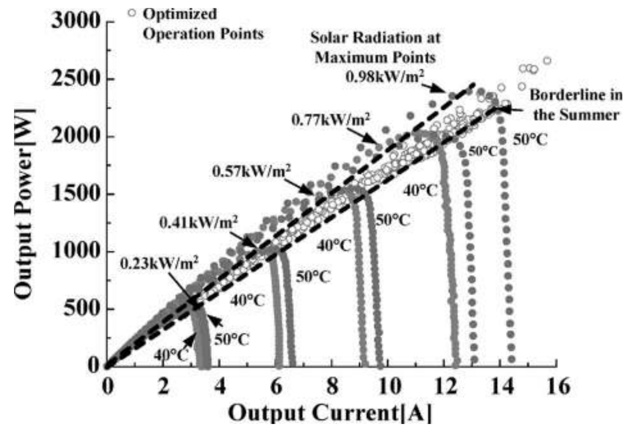

Fig. 3. Temperature dependencies of the optimization operation points under high-temperature conditions during summer.

theoretical and experimental approaches are studied. First, the theoretical relationships are given by (1) and (2) based on PV characteristics equations [13]

$$P_{\max} = V_{\max} \times I_{\max} \tag{1}$$

$$V_{\max} = (nkT/e) \times (I_{\max}/\{(J_{s0} + I_0) - I_{\max}\}) \tag{2}$$

where I_0 is the reverse saturation current, T is the junction temperature, n is the free electron density related to conduction current, e is the electronic charge, k is the Boltzmann's constant, and J_{s0} is the current component flowing in reverse to the following dark current I when light is irradiated on the p-n junction. Then

$$I = I_0 \times (\exp(eV/nkT) - 1) \tag{3}$$

where V is the terminal voltage of solar arrays. Accordingly, the numerical analysis of (1)–(3) must be done to prove the linearity of $P_{\max}$ and $I_{\max}$ theoretically [14]. To do so, it is necessary to grasp concretely the physical parameters which have appeared in (1)–(3). Since these parameters must be estimated from the completed solar arrays while also considering various changes of environmental conditions, it is almost impossible for general users to evaluate. Then, the MPPT control rule is built up here experimentally based on P–V (I–V) characteristics that are inherent characteristics of the solar arrays which can actually be measured.

A. Construction of the MPPT Control Rule Through Experiments

Measurements were made in three seasons from summer (August) to winter (the following February) and times from sunrise to sunset. The data, for about every 5-min interval, were automatically collected by a PV curve tracer. As a result, Fig. 2 shows that the optimization current which gives the maximum power output from the solar arrays linearly varies with the maximum power as long as the temperature is kept constant even if the solar radiation changes. Thus, from the viewpoint of controlling output power of solar arrays, attention is paid especially to the linearity between the optimization current and the maximum output power. In order for the obtained linearity between optimization current and the maximum output power to be useable as the MPPT control rule under the condition that weather changes variously, it should be further proved under different weather conditions, especially, those conditions when the temperature becomes high. Then, the linearity between optimization current and the maximum output power was further examined during the summer season when the panel temperature of solar arrays increased to 50 °C. As shown in Fig. 3, experimental results prove that the linearity between the optimization current and the maximum output power is maintained even when the panel temperature of solar arrays is high. However, since the comparison between Figs. 2 and 3 shows that the proportionality coefficient of the linearity varies with the temperature, variations of the proportionality coefficient which occur due to the temperature change should be compensated for. Thus, based on the facts, a control rule can be derived that makes the optimization current converge on the prediction line with the proportionality coefficient estimated before the panel temperature of solar arrays changes. Here, the proportionality coefficient can be estimated from the peak value of P (output power)–I (output current) characteristics obtained using the hill-climbing method. The estimation has to done more quickly than the panel temperature change.

B. Verification of the Linearity Between the Optimization Current and the Maximum Output Power Using Other Solar Arrays

In order for the control rule proposed in Section III-A to be accepted as a general rule for the MPPT control, it is necessary to examine whether the linearity between the optimization current and the maximum output power holds true for other solar arrays. Figs. 4 and 5 show the relationship between the optimization current and the maximum output power for solar arrays made by Solarex and Kyosera, respectively. Experimental results indicate that the linear relationship between the optimization current and the maximum power is maintained for each temperature. Thus, it is guessed that the linear relationship between the optimization current and the maximum output power, which was found through experiments, is generally satisfied for solar arrays made from silicon. Therefore, the

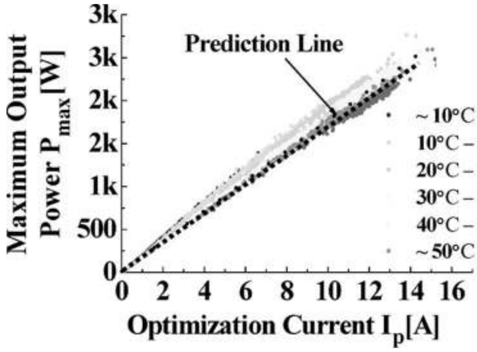

Fig. 4. Optimization current versus maximum output power for solar arrays (MSX-64) made by Solarex.

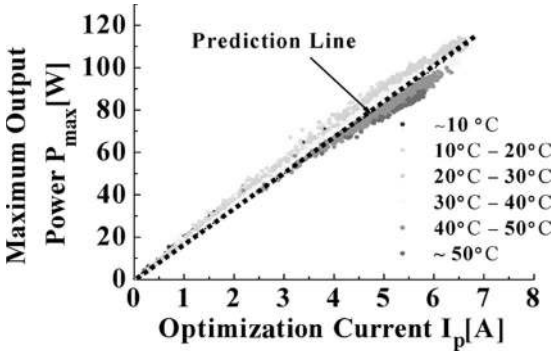

Fig. 5. Optimization current versus maximum output power for solar arrays [R421-1(B)] made by Kyosera.

linearity between the maximum output power and optimization current is adopted as the cardinal rule of MPPT control.

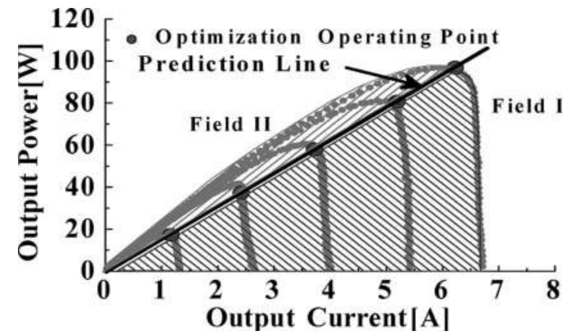

Fig. 6. Prediction line made by the optimized operating point on the output power and current characteristics and control fields I and II divided by the made prediction line.

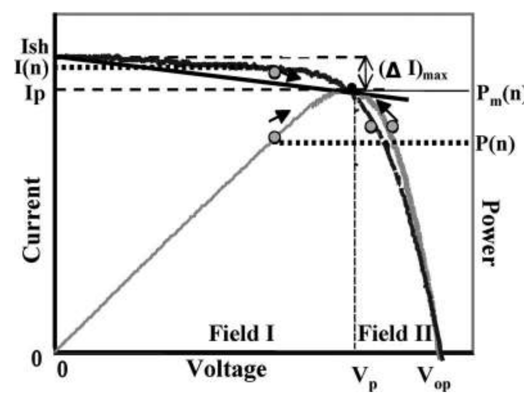

Fig. 7. Control processes in fields I and II for the output current until the operating point on P–V (I–V) characteristics reaches its maximum point.

IV. MPPT Control Method Using the Linearity Between the Maximum Output Power and the Optimization Current

A. Principal of the MPPT Control Method

As shown in Fig. 6, the prediction line corresponds to the locus drawn when the maximum point on the characteristic curves of the output current and power moves according to solar radiation. The output current decides the capability for solar arrays to generate an output power on P–I characteristics. Then, no matter how the solar radiation varies with weather, the output current is appropriately controlled so that the operating point always reaches the maximum on the prediction line. Since how to control the output current differs between the lower side (Field I) and the upper side (Field II) of the prediction line, the output current control is executed by dividing into two regions; Fields I and II. As shown in Fig. 7, the maximum output power point is reached in Field II by making the current increase, whereas it is reached in Field I by making the current decrease.

First, the region where the operating point exists is judged by comparing between the output power $P_n(n)$ generated from solar arrays at time n and the maximum power $P_{\rm m}(n)$ on the prediction line which corresponds to the output current $I(n)$ detected at time n. That is, the operating point lies in Field I if $P(n)$ is less than $P_{\rm m}(n)$, whereas, it lies in Field II when the opposite is true $[P(n) > P_{\rm m}(n)]$. Here, the output power $P_n(n)$ can be estimated from (4) using the output current $I(n)$ and voltage $V(n)$ detected at time n

$$P_n(n) = V(n) \times I(n). \tag{4}$$

The maximum power $P_{\rm m}(n)$ on the prediction line which corresponds to the output current $I(n)$ flowing from the solar arrays at time n can be estimated from the previously obtained prediction line given by (5)

$$P_{\rm m}(n) = a(T) \times I(n). \tag{5}$$

Here, $a(T)$ is a parameter which is automatically determined by the MPPT controller using the hill-climbing method in order to compensate for temperature change of the solar arrays.

1) Control Rule in Field I: When it is judged that the output power $P_n(n)$ at time n is less than $P_{\rm m}(n)$, the following procedure for Field I is executed. The current reference $I_{\rm pr}(n)$ in this region must be controlled so as to reach the maximum power $I_p(n)$ while making the output current decrease by $\Delta I(n)$. Then, the permissible maximum amount is examined here so that the operating point can reach its targeted maximum most quickly

$$I_{\rm pr}(n) = I(n) - \Delta I(n). \tag{6}$$

Judging from Fig. 7, as the controllable range of the output current is between the short-circuit current $I_{\rm sc}$ and the optimization current I_p, it is given by inequality

$$I_p \le I(n) \le I_{\rm sc}. \tag{7}$$

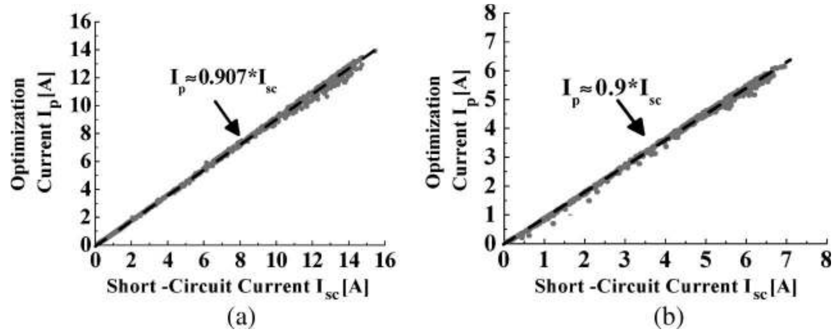

Fig. 8. Relationship between the short-circuit current and the optimization current when the panel temperature was changed from 0 °C to 50 °C. (a) Solar arrays made by Solarex (MSX-64). (b) Solar arrays made by Kyosera [R421-1(B)].

On the other hand, Fig. 8 shows that I_p is proportional to $I_{\rm sc}$ even if temperature is changed as given by (8) [15]. This is because the short-circuit current is almost the same as the photocurrent which relates to irradiation, and the optimization current is proportional to irradiation [16]

$$I_p = k_{\rm sc} \times I_{\rm sc} \tag{8}$$

where the proportionality factor $k_{\rm sc}$ is around 0.9, which is independent of temperature. Thus, the reducing rate $\Delta I(n)$ of the current reference is given by

$$I(n) < (\Delta I(n))_{\max} \, (= I_{\rm sc} - I_p). \tag{9}$$

If (8) is substituted for (9), $\Delta I(n)$ can be obtained as

$$\Delta I(n) < (1 - k_{\rm sc}) \times I_{\rm sc}. \tag{10}$$

Therefore, as $\Delta I(n)$ should be less than the value of the right term of (10), $(1 - k_{\rm sc}) \times I(n)((1 - k_{\rm sc}) \times I_{\rm sc})$ is applied as the value of $\Delta I(n)$, which satisfies (10). As a result, the current reference $I_{\rm pr}(n)$ is given by (11) as the control rule by which the detected $I(n)$ arrives at I_{p1} on the prediction line of Fig. 9. This procedure enables the output current to arrive at the maximum point within the minimum time as the optimization current reference is made using the largest possible reducing rate $\Delta I(n)$

$$I_{\rm pr}(n) = I(n) - \Delta I(n) = k_{\rm sc} \times I(n). \tag{11}$$

2) Control Rule in Field II: This is the region where the output power arrives at its maximum by increasing the output current of the solar arrays until the output current becomes the optimization current I_{p2} on the prediction line of Fig. 9. The prediction line shown in Fig. 9, which corresponds to Fig. 6, is approximately given by

$$P_{\max} = k_p \times I_p. \tag{12}$$

For example, k_p, which is equivalent to $a(T)$ in (5), is 16.3 in the case of Fig. 6. If the output current $I(n)$ at time n agrees with the optimization current $I_p(n)$, the maximum output power $P_{\rm m}(n)$ on the prediction line is given by (13). However, in this case, as shown by Fig. 9, when the actual

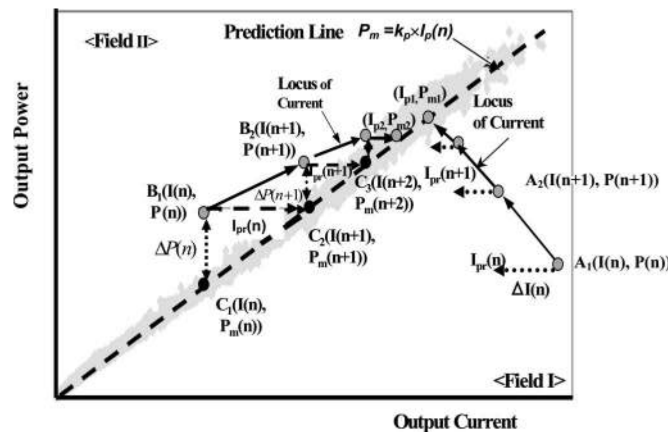

Fig. 9. Skeleton of the proposed MPPT method to control the output current of the solar arrays so the prediction line is followed.

operating point $B_1(I(n), P(n))$ exists in Field II, $P_{\rm m}(n)$ is smaller than the generated output power $P(n)$, as given by (14). Accordingly, the targeted maximum power should be larger than $P_{\rm m}(n)$. Then, the optimization current reference $I_{\rm pr}(n)$ is increased by (15) so that the output current $I(n)$ can arrive at the point where the power difference $\Delta P(n)(= P(n) - P_{\rm m}(n))$ becomes less than the given error. This procedure is repeated until the detected current $I(n)$ agrees with the optimization current I_{p2} on the prediction line. In this process, as the optimization current reference is determined by the shortest possible distance between the operating point and the prediction line, the output current can arrive at the maximum power within the minimum time

$$P_{\rm m}(n) = k_p \times I(n) \tag{13}$$

$$P(n) \geq P_{\rm m}(n) \tag{14}$$

$$I_{\rm pr}(n) = P(n)/k_p. \tag{15}$$

B. Algorithm for Performing the Proposed MPPT Control Method

The control procedure cited above is summarized in the flow chart shown in Fig. 10. First, the generated power $P(n)$ output from the solar arrays is estimated by detecting the output current $I(n)$ and voltage $V(n)$ of the solar arrays. Next, the detected output current $I(n)$ is supposed to agree with the optimizing current on the prediction line, then, the maximum

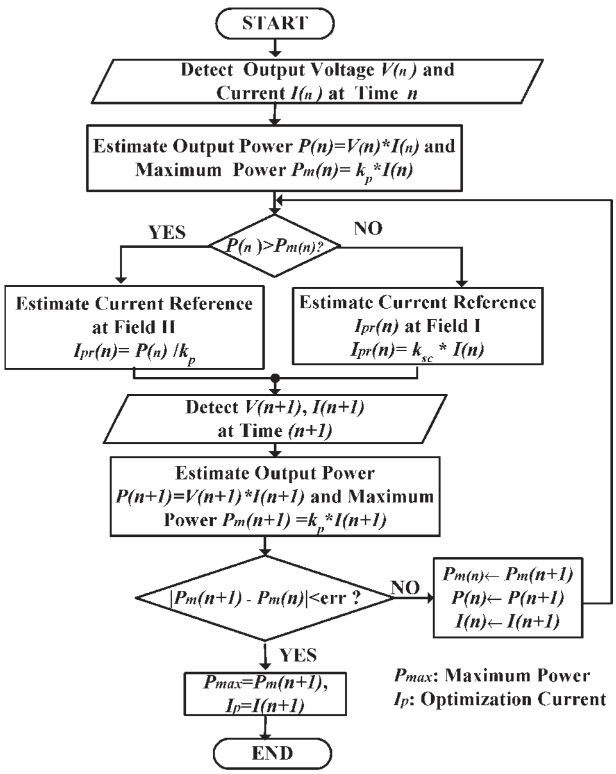

Fig. 10. Procedures to acquire the maximum power that the solar arrays can generate with the solar radiation at that time.

output power $P_{\mathrm{m}}(n)$ is calculated using (13). The region where the output current $I(n)$ is involved is judged by comparing between the estimated $P(n)$ and the calculated $P_{\mathrm{m}}(n)$. When the estimated power $P(n)$ is larger than the calculated power $P_{\mathrm{m}}(n)$, it is judged as Field II. Otherwise, it is Field I. In the case of Field II, the optimization current reference $I_{\mathrm{pr}}(n)$ is calculated using (15), and in the case of Field I, it is done using (11). The output current $I(n)$ is regulated by the current controller so as to agree with the obtained optimization current reference $I_{\mathrm{pr}}(n)$. This procedure is repeated until the maximum output power $P_{\mathrm{m}}(n+1)$ at $(n+1)$ time is equal to $P_{\mathrm{m}}(n)$ obtained in the former process, that is, the output current equals the targeted optimization current. When this condition is obtained, the maximum power that can be generated at the solar radiation at that time is output from the solar arrays.

C. Verification of the Proposed MPPT Control Method by Experiments

The proposed MPPT controller is characterized by having the ability to control the generated power output from the solar arrays even under lower solar radiation. Thus, in order to verify the performance, it is necessary to evaluate the generated power and its power response at low solar radiation. Fig. 11 shows the experimental results of these characteristics at low solar radiation around $18\% (= 0.18\ \mathrm{kW/m^2}/1\ \mathrm{kW/m^2})$ of the maximum solar radiation which determines the rated output power of PV generation systems. P–V (V–I) characteristics of Fig. 11(a) show that the solar radiation lies in low states which can generate only the maximum power of around 17.5 W. However, Fig. 11(b) shows that the proposed MPPT control method has the ability to quickly acquire the maximum power of 17.5 W that solar arrays can generate with the speed of about 0.15 s.

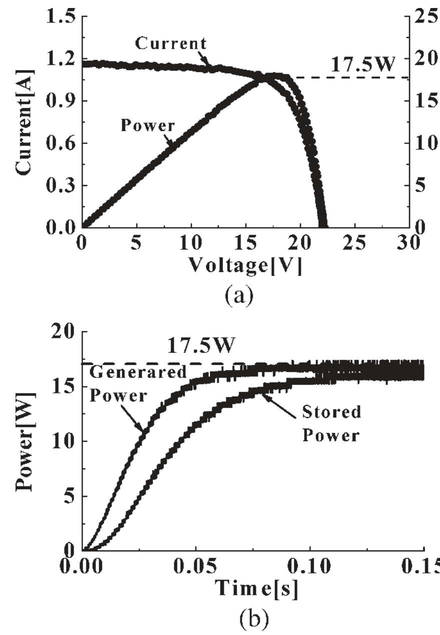

Fig. 11. Output characteristics of solar arrays and output power response at low solar radiation $(0.18\ \mathrm{kW/m^2})$. (a) Voltage versus output current and power. (b) Generated power and stored power.

V. ULTRA-EDLC CHARGING METHOD FOR PV GENERATION SYSTEM

A. Principal of an Ultra-EDLC Charging Method

Fig. 12 shows the block diagram of a method to charge the power generated by the solar arrays to a number of series-connected ultra-EDLCs, and Fig. 13 shows a flow chart for explaining the operations of the ultra-EDLC charge controller. Here, an ultra-EDLC is applied that has the capacity of 2000 F; the rated voltage V_{c1} of 2.3 V; the maximum voltage $V_{\mathrm{c\,max}}$ of 2.6 V; the rated current I_{RL} of 10 A; and the permissible maximum temperature T_{c}^{*} of 50 °C. The ultra-EDLC charge control is performed using the following control rule made based on these electrical characteristics peculiar to ultra-EDLCs.

1) Temperature Management: Temperature management of ultra-EDLCs is very important for the protection of the ultra-EDLC charge system together with over voltage protection. Then, if the maximum temperature of each ultra-EDLC is detected, the flow of electric power will be changed to the direction of P'_{3Nor} shown in Fig. 13 so that the electric power P_2 generated by the solar arrays may not flow to the ultra-EDLC side: $P_{\mathrm{3Nor}} (= V_{\mathrm{cs}} \times I_{\mathrm{cs}})$. This power flow of the generated power P_2 is changed by the power flow selector. As shown in the figure, the maximum power that can be generated in solar arrays is taken into the capacitor C_1 by the MPPT controller as P_1, and this acquired electric power P_1 is accumulated once in the capacitor C_2 as P_2 on the input side of the ultra-EDLC charge control system. Moreover, the electric power P_2 is accumulated into capacitor C_4, as P'_{3Nor} and finally the power P'_{3Nor} is returned to the utility through the PWM

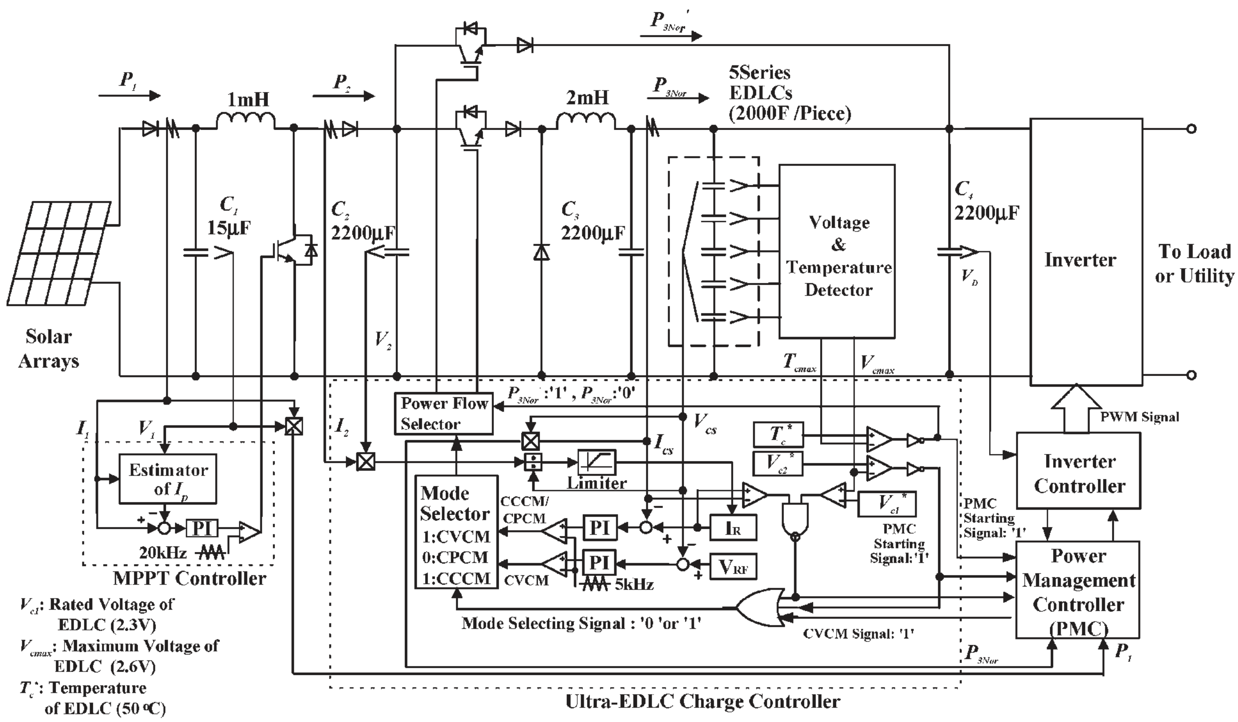

Fig. 12. Block diagram of series-connected ultra-EDLCs charge control for PV generation systems.

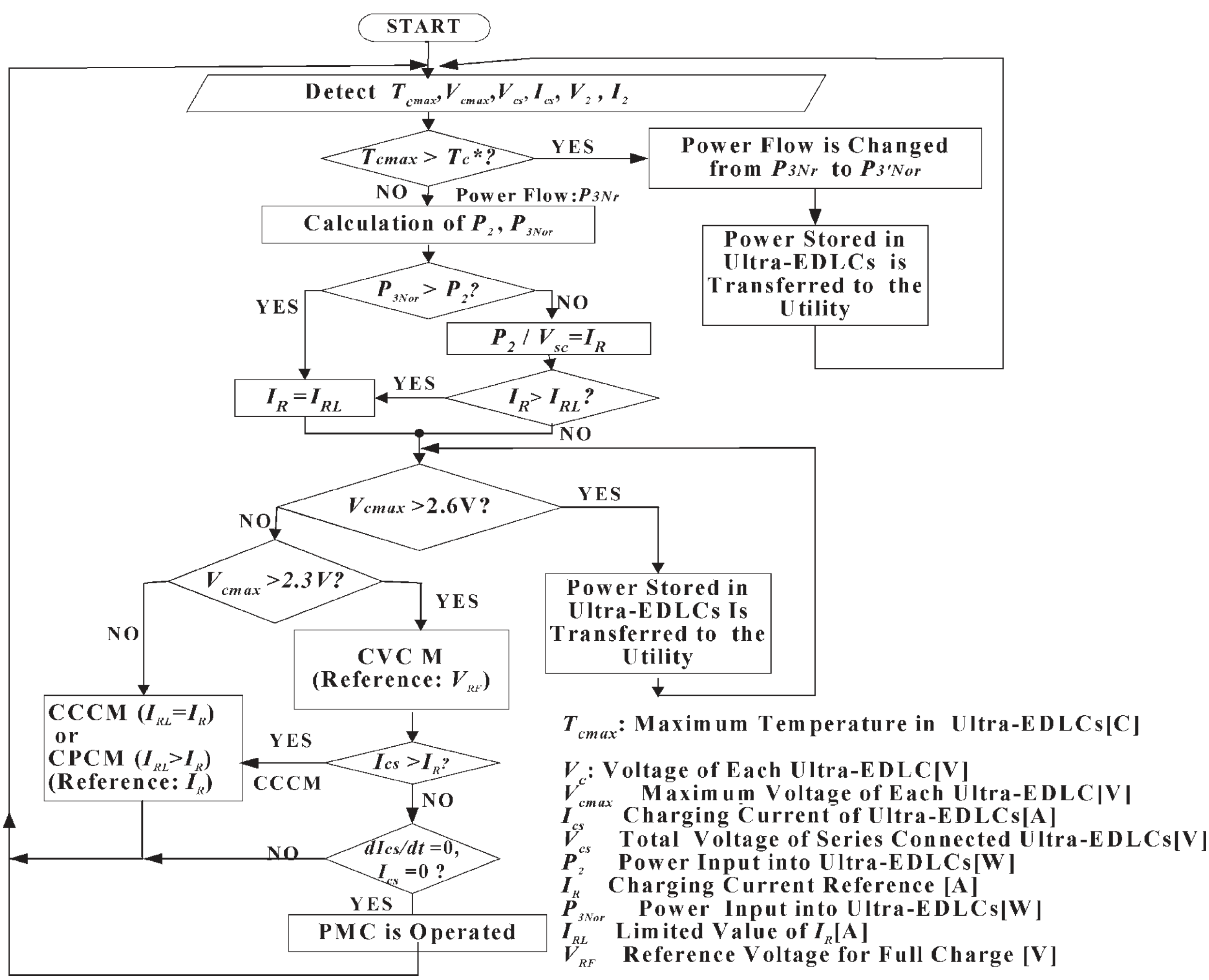

Fig. 13. Flowchart for explanation of the proposed method to charge series-connected ultra-EDLCs.

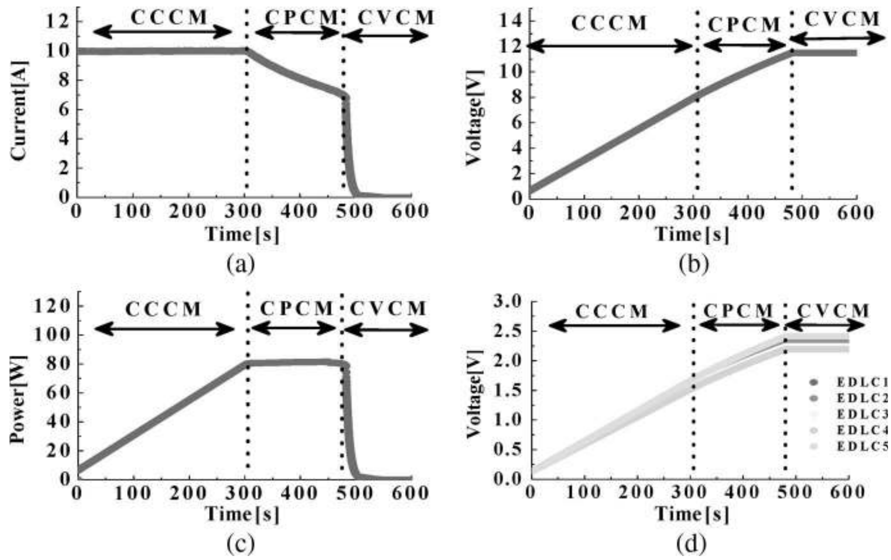

Fig. 14. Verification of the proposed ultra-EDLC charge control method by simulations. (a) Charging current for various charge modes. (b) Total voltage charged by various charge modes. (c) Power input into ultra-EDLCs for various charge modes. (d) Voltage characteristics of each ultra-EDLC for various charge modes.

inverter. In the states that the generated power is flowing to the direction of $P'_{3\mathrm{Nor}}$, the system does not have the ability to accumulate the maximum power acquired by the MPPT control according to the electric power generated in the solar arrays. Thus, applications like this which directly return the generated electricity to the utility side, or which directly use it for loads are limited. When the temperature of each ultra-EDLC is less than T_c^*, the following normal charge control is performed.

2) Charge Modes: As the proposed ultra-EDLC charge controller controls the charging current based on the maximum power acquired by the MPPT control, it has the ability to quickly charge a number of series-connected ultra-EDLCs with the maximum power that can be generated in solar arrays for the weather conditions of that time. The ultra-EDLC charge control has three charge modes, i.e., the constant current charge mode (CCCM), constant power charge mode (CPCM), and the constant voltage charge mode (CVCM).

In the CCCM and CPCM, the charging current reference I_{R} is made through the following procedures. The large charging current flowing into the EDLCs occurs in the initial charging state when the ultra-EDLCs are hardly charged, i.e., the state that the total voltage V_{CS} of the series-connected ultra-EDLCs is small. Thus, in order to avoid this phenomenon occurring in the initial state, the EDLCs are charged with the charge mode so that the current reference I_{R} is kept at the rated current I_{RL} (10 A in case of this paper), as given by (16). Thus, the initial charge mode is called CCCM since the ultra-EDLCs are charged while controlling the charging current with constant I_{R}

$$I_{\mathrm{R}} = I_{\mathrm{RL}}. \tag{16}$$

When continuing charging into the ultra-EDLCs with the CCCM, the value of V_{CS} gradually increases, and the situation appears that it is impossible to control I_{R} at the rated current I_{RL}, i.e., the situation occurs that I_{R} drops rather than the rated value I_{RL}. Then, the charge mode is shifted to another mode. In this charge mode, the charging current reference I_{R} is determined based on the power P_2 input into the ultra-EDLCs that is acquired through the MPPT control, as given by

$$I_{\mathrm{R}} = P_2/V_{\mathrm{CS}} = I_2 \times V_2/V_{\mathrm{CS}}. \tag{17}$$

Since the power input into the ultra-EDLCs is kept at P_2 for this mode, this charge mode is called CPCM here.

When the largest voltage $V_{\mathrm{c\,max}}$ in series-connected ultra-EDLCs reaches the rated voltage V_{c1} by charging the ultra-EDLCs through the CPCM, the charge mode is shifted to the CVCM, which is controlled so that the largest voltage $V_{\mathrm{c\,max}}$ is kept at the rated voltage V_{c1}. Here, if the charging current I_{cs} exceeds the rated current I_{R} when the charge mode is shifted to the CVCM, the charge mode will be changed after suppressing the over current by current control of the CCCM. The charging processes are completed when the charging current stops changing and hardly any charging current flows under the CVCM.

After finishing the charging processes, the resultant signal is sent to the power management controller, and the power stored in ultra-EDLCs is transferred to the loads or the utility via the PWM inverter, as shown in Fig. 1.

B. Verification of the Proposed Ultra-EDLC Charge Control Method

Figs. 14 and 15 show the verifications of the proposed ultra-EDLC charge control method by simulations and experiments, respectively. The simulations were performed under the conditions when the electric power P_2 obtained by the MPPT control was 80 W and the rated current I_{R} was 10 A. The EDLC was connected to five-piece series. In the CCCM, the charging current was controlled while being kept at 10 A and then the charged power was regulated at the desired power (80 W) by the charge control of the CPCM. When the largest voltage in

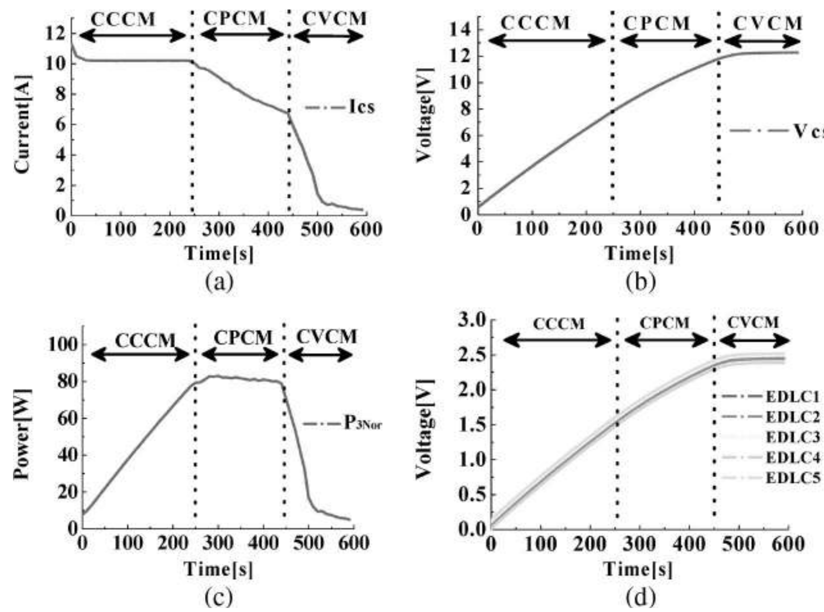

Fig. 15. Verification of the proposed ultra-EDLC charge control method by experiments. (a) Charging current for various charge modes. (b) Total voltage charged by various charge modes. (c) Voltage characteristics of each ultra-EDLC for various charge modes. (d) Power input into ultra-EDLCs for various charge modes.

five series-connected EDLCs increased to 2.3 V, the charge mode was shifted to the CVCM, as shown in Fig. 14(d). After shifting to CVCM, the changing of the charging current was stopped and then the charge processes were finished, and there was hardly any flow of the current. As shown in Fig. 15, even in experiments, the same characteristics could be obtained, and then effectiveness of the proposed ultra-EDLC charge control method was verified as making efficient use of the power generated from the solar arrays.

VI. Conclusion

This paper proposed a control method to charge series-connected EDLCs for a PV generation system in combination with the MPPT control method. The MPPT control was performed based on the fact that is a linear relationship between the maximum power and the optimization current giving its maximum. The linearity was satisfied even if the solar radiation was changed as long as the temperature of the solar arrays was kept constant. When the temperature changed, the proportionality factor was corrected by the proper value determined through the hill-climbing method. As the MPPT control used the linearity, which made it possible to quickly obtain even a small power generated under low-solar-radiation states, it could make good use of the acquired solar energy, regardless of the weather. The maximum power acquired by the MPPT control was stored into the series-connected EDLCs by performing the ultra-EDLC charge control with the three modes, i.e., CCCM, CPCM, and CVCM. The CCCM and the CPCM operated the charging current so as to keep it at the rated current and the current determined from the power obtained by the MPPT control, respectively. The CVCM operated so that each voltage of the ultra-EDLCs was uniform. The ultra-EDLC charge controller with these three modes made it possible to obtain quickly and precisely the power generated from the solar arrays.

References

[1] T. Ouchi, H. Fujikawa, S. Masukawa, and S. Iida, “A control scheme for three-phase current source inverter in interactive photovoltaic system,” *Trans. Inst. Electr. Eng. Jpn.*, vol. 120-D, no. 2, pp. 230–238, 2000.

[2] H. Dong, H. Sugimoto, N. Nishio, “A maximum power tracking control method for photovoltaic power generation system based on derivation of output power with respect to output voltage,” *Trans. Inst. Electr. Eng. Jpn.*, vol. 118-D, no. 12, pp. 1435–1442, 1998.

[3] T.-F. Wu, C.-H. Chang, and Y.-K. Chen, “A fuzzy-logic-controlled single-stage converter for PV-powered lighting systems applications,” *IEEE Trans. Ind. Electron.*, vol. 47, no. 2, pp. 287–296, Apr. 2000.

[4] M. Veer char, T. Sanyo, and K. Legato, “Neural-network-based maximum-power point tracking of coupled-inductor interleaved-boost-converter-supplied PV system using fuzzy controller,” *IEEE Trans. Ind. Electron.*, vol. 50, no. 4, pp. 749–758, Aug. 2003.

[5] T. Kitano, M. Matsui, and D. Xu, “A maximum power point tracking control scheme for PV system based on power equilibrium and its system design,” *Trans. Inst. Electr. Eng. Jpn.*, vol. 121-D, no. 12, pp. 1263–1269, 2001.

[6] T. Kitano and M. Matsui, “A MPPT control scheme for PV system utility limit cycle operation and its system design,” *Trans. Inst. Electr. Eng. Jpn.*, vol. 122-D, no. 4, pp. 382–389, 2002.

[7] N. Mutoh, T. Matuo, K. Okada, and M. Sakai, “Prediction-data-based maximum-power-point-tracking method for photovoltaic power generation systems,” in *Proc. IEEE PESC*, Cairns, Australia, Jun. 2002, vol. 3, pp. 1489–1494.

[8] M. H. Rahman, J. Nakayama, K. Nakamura, and S. Yamashiro, “An intelligent grid-connected PV-ECS system with load leveling function,” in *Proc. Euro PES*, Marbella, Spain, Sep. 3–5, 2003.

[9] T. Monai, I. Takano, H. Nishikawa, and Y. Sawada, “A collaborative operation method between new energy-type dispersed power supply and EDLC,” *IEEE Trans. Energy Convers.*, vol. 19, no. 3, pp. 590–598, Sep. 2004.

[10] T. Mishima and T. Ohnishi, “Experimental evaluation of the EDLC-based power compensator for a partially shaded PV array,” in *Proc. IEEE IECON*, Roanoke, VA, Nov. 2–6, 2003, pp. 1308–1313.

[11] K. Seita, I. Takano, H. Nishikawa, and Y. Sawada, “A study of operation characteristics of UPFC type dispersed power supply system with FC, PV and EDLC by improved EMAP model,” in *Proc. IEEE Power Syst. Conf. and Expo.*, New York, Oct. 10–13, 2004, vol. 1, pp. 289–294.

[12] N. Mutoh and T. Inoue, “A controlling method for charging photovoltaic generation power obtained by a MPPT control method to series connected ultra-electric double layer capacitors,” in *Proc. 39th Annu. Meeting IEEE Ind. Appl. Soc.*, Seattle, WA, Oct. 3–7, 2004, vol. 4, pp. 2264–2271.

[13] A. Luque and S. Hegedus, *Handbook of Photovoltaic Science and Engineering*. Hoboken, NJ: Wiley, 2002, pp. 87–111.
[14] N. Mutoh, M. Ohno, and T. Inoue, "A method for MPPT control while searching for parameters corresponding to weather conditions for PV generation systems," *IEEE Trans. Ind. Electron.*, vol. 53, no. 4, pp. 1055–1065, Aug. 2006.
[15] T. Noguchi, S. Togashi, and R. Nakamoto, "Short-current pulse-based maximum-power-point tracking method for multiple photovoltaic-and-converter module system," *IEEE Trans. Ind. Electron.*, vol. 49, no. 1, pp. 217–223, Feb. 2002.
[16] J. H. R. Enslin, M. S. Wolf, D. B. Snyman, and W. Swiegers, "Integrated photovoltaic maximum power point tracking converter," *IEEE Trans. Ind. Electron.*, vol. 44, no. 6, pp. 769–773, Dec. 1997.

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