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Photovoltaic Modified β-Parameter-based MPPT Method with Fast Tracking

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Abstract

Maximum power point tracking (MPPT) is necessary for photovoltaic (PV) power system application to extract the maximum possible power under changing irradiation and temperature conditions. The β-parameter-based method has many advantages over conventional MPPT methods; such advantages include fast tracking speed in the transient stage, small oscillations in the steady state, and moderate implementation complexity. However, a problem in the implementation of the conventional beta method is the choice of an appropriate scaling factor N, which greatly affects both the steady-state and transient performance. Therefore, this paper proposes a modified β-parameter-based method, and the determination of the N is discussed in detail. The study shows that the choice of the scaling factor N is determined by the changes of the value of β during changes in irradiation or temperature. The proposed method can respond accurately and quickly during changes in irradiation or temperature. To verify the proposed method, a photovoltaic power system with MPPT function was built in Matlab/Simulink, and an experimental prototype was constructed with a solar array emulator and dSPACE. Simulation and experimental results are illustrated to show the advantages of the improved β-parameter-based method with the optimized scaling factor.

Key words: Maximum power point tracking (MPPT), Modified Beta method, Photovoltaic (PV) energy

I. Introduction

Photovoltaics (PV) is now widely regarded globally as one of the most important sustainable energy sources. However, because of the nonlinear characteristics of PV modules, how the maximum possible power can be extracted from installed PV systems is still a challenging problem. Therefore, maximum power point tracking (MPPT) is necessary and widely adopted in PV power systems to extract the maximum possible power under any environmental condition.

Many MPPT methods are discussed in the literature [1]-[3]. These methods can be categorized into four categories in terms of perturbation step size: 1) methods without step size; 2) methods with a fixed step size; 3) methods with variable step size; and 4) methods with both fixed and variable step for different tracking periods.

The fractional open-circuit voltage method [4] originates from the relationship between the maximum power point (MPP) voltage and open-circuit voltage (V_{oc}). Similarly, the basic principle of fractional short-circuit current method [5] is the relationship of the MPPT current with the short-circuit current (I_{sc}). They are simple and effective ways to obtain the maximum power. These methods can determine the MPP directly without any perturbation steps; thus, they belong to the first category. However, because these methods can provide only approximate calculations of the voltage and current at the MPP, the PV array technically never operates at the true MPP.

For the fixed-step methods, perturb and observe (P&O) [6], [7], hill climbing (HC) [8], and incremental conductance (INC) [8]-[10] are widely used because they are easy to implement. However, during the steady-state stage, these methods always fluctuate around the MPP because of truncation error in digital processing [11]. Apart from steady-state oscillations, these methods are easily confused when the solar irradiation

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increases [9]. Furthermore, a small step size is usually adopted in these fixed step size methods to achieve small steady-state oscillations. Thus, dynamic tracking speed would be sacrificed, especially under quickly changing irradiation conditions. Therefore, many modified HC, P&O, and INC methods with variable step have been proposed to address the problem between small steady-state oscillations and quick dynamic behavior [12]-[20].

The basic idea of variable step methods is to create a large step size during the transient stage and then a small step size during the steady state. Generally, the step size can be adjusted automatically according to the derivative of power with respect to the PV voltage (dP/dV) or converter duty cycle (dP/dD). Therefore, on the basis of the slope of the Power–Voltage (P-V) curve [12]-[15] and the P–D curve [16], the variable step is illustrated as a linear equation:

$$\mathrm{D(k)} = \mathrm{D(k\text{-}1)} \pm \mathrm{N} \times \left|\frac{P(k)-P(k-1)}{V(k)-V(k-1)}\right| \tag{1}$$

and

$$\mathrm{D(k)} = \mathrm{D(k\text{-}1)} \pm \mathrm{N} \times \left|\frac{P(k)-P(k-1)}{\mathrm{D}(k)-D(k-1)}\right| \tag{2}$$

where k and k−1 refer to the present and the previous instants, respectively, and N is the scaling factor determined at the sampling period to tune the step size. From (1) and (2), the step size is large when the operating point is far from the MPP and becomes small when it is close to the MPP. One difficulty in the implementation of the variable step size methods is how to choose and optimized the scaling factor N [17]. Once the scaling factor N is assigned, it cannot be changed during the tracking process [18]. A large value of N can lead to undesired performances for the steady-state condition, such as large oscillations around the MPP [19]. Therefore, a small value of N is usually used. However, the step size becomes small when the operating point is close to the peak of P–V curve and P–D curve, and the convergence of the system toward the MPP becomes slow. Although adaptive scaling factor method is implemented in [20], this method improves efficiency by only 0.2% under a low irradiation condition. Furthermore, the adaptive scaling factor method increases the computational load and implementation cost; such increase is unfavorable. Moreover, these variable step methods are unable to respond accurately with the change of solar irradiation [9].

Many hybrid methods, which consist of more than two methods, have been proposed recently [21]-[27]. Hybrid methods usually include at least two stages: the transient stage, which will bring the operating point to a region near the MPP for fast tracking, and the steady-state stage, which will allow the fixed-step method to gradually approach the exact MPP. Among these hybrid methods, the Beta method proposed by Jain and Agarwal [25] adopts a variable and a fixed step size for the transient stage and the steady-state stage, respectively. Unlike other hybrid methods, the Beta method tracks an intermediate variable β rather than the change of the power. Comparison results [26] indicate that the Beta method has a fast tracking speed in the transient stage, small oscillations in the steady-state stage, and moderate implementation complexity.

However, the potential of this method is not fully exploited in terms of dynamic response speed and tracking factor [25], [26]. Although the conventional Beta method has been optimized by identifying the range of the parameter β for various weather conditions, determining the optimal scaling factor N is still a problem. In [27], a trial-and-error approach is utilized to adjust this scaling factor N. However, the optimal value obtained from this process is suitable for specific operating conditions only. Therefore, this paper proposed a modified Beta method, where the choice of the scaling factor N is determined by the changes of the value of β during changes in irradiation or temperature. Two different values of the scaling factor N are implemented in the proposed method to generate the appropriate step sizes. Furthermore, because the modified Beta method can identify the direction of irradiation changes by the parameter β, the proposed method can respond accurately during a change in irradiation or temperature, unlike the conventional Beta method.

II. MODIFIED BETA METHOD

A. Review of the Conventional Beta Method

The theory of the conventional Beta method has been explained by Jain and Agarwal in [25], and the intermediate variable β is given as

$$\beta = \ln(\frac{I}{V}) - \mathrm{c} \times \mathrm{V} \tag{3}$$

where V and I are the PV module output voltage and output current, respectively, and c=q/(N_sAKT) is the diode constant.

The flowchart of the conventional Beta method is shown in Fig. 1. First, the voltage and current are measured, and the value of β_a can be calculated continuously. If tβ_a is not within the bounding range of (β_{min} , β_{max}), then the Beta method turns into the transient stage; otherwise, the Beta method switches into the steady-state stage, and P&O or other fixed-step methods will be implemented. In the transient stage, a guiding parameter β_g is adopted in calculating the variable step ΔD, which is expressed by

$$\Delta\mathrm{D} = \mathrm{N} \times (\beta_a - \beta_g) \tag{4}$$

The algorithm of the Beta method indicates that the range of the parameter β, such as β_{min}, β_{max}, and β_g, needs to be identified. According to [25]-[27], the range of parameter β depends on the working conditions of the PV module, namely, the irradiation and temperature. In this paper, the assumed working conditions and the corresponding magnitudes of β are shown in Fig. 2 and Table I. Therefore, the range of parameter

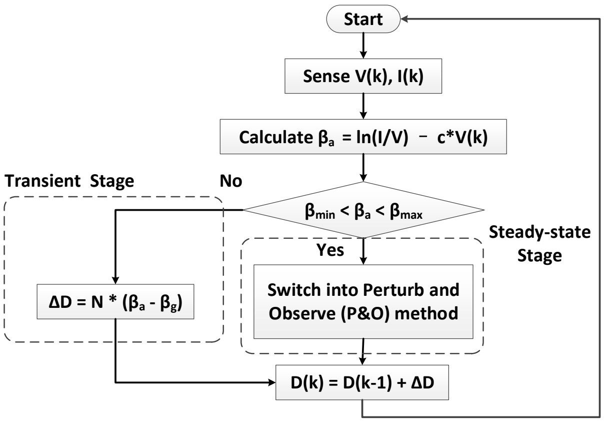


Fig. 1. Flowchart of the conventional Beta method.

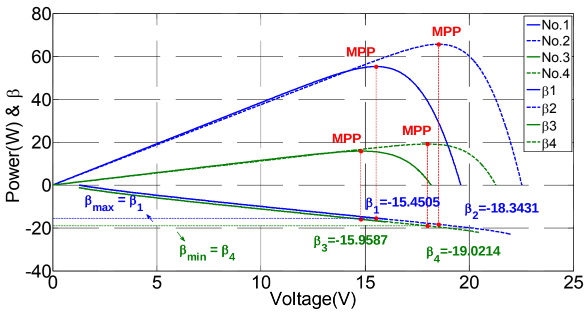


Fig. 2. Range of β with voltage and power under various irradiation and temperature conditions.

TABLE I
VALUES AT VARIOUS IRRADIATIONS AND TEMPERATURES

No.	Irradiation	Temperature	β
1	1000 W/m^2	45 °C	-15.4505
2	1000 W/m^2	5 °C	-18.3431
3	300 W/m^2	45 °C	-15.9587
4	300 W/m^2	5 °C	-19.0214

β, namely, $\beta_{min} = -19.02$ and $\beta_{max} = -15.45$, is determined. Furthermore, the middle value between β min and β max is chosen for β_g, namely, $\beta_g = -17.24$.

B. Scaling Factor N for the Beta Method

After the range of the parameter β is identified, the scaling factor N needs to be determined to attain the best performance. The different values of the scaling factor N are implemented for the Beta method, as shown in Fig. 3.

Fig. 3(a) shows that the larger value of N achieves better performance when the irradiation changes significantly. However, an excessively large value of N can cause an overly large duty cycle, which can result in undesired performance, namely, large steady-state oscillations, as shown in Fig. 3(b). By contrast, the smaller N can avoid this undesired situation. However, the tracking speed is relatively slow with increasing irradiation. Therefore, the medium value of the scaling factor N was chosen in [27] as a compromise to this dilemma.

C. Proposed MPPT Method

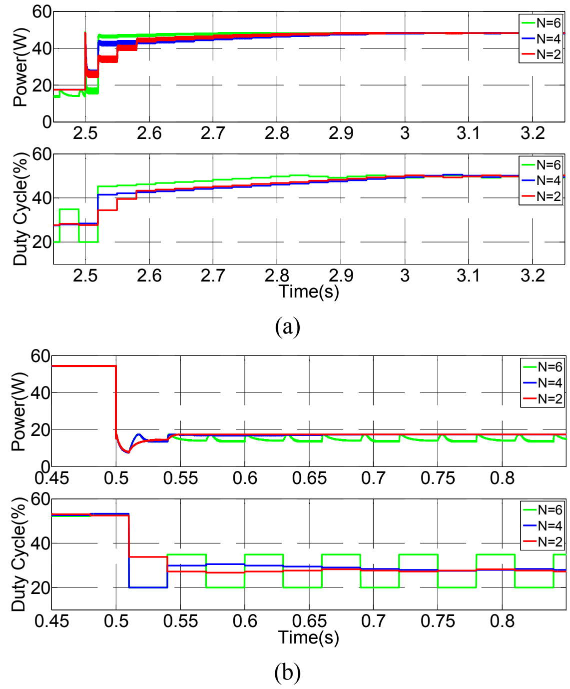


Fig. 3. Different values of scaling factor N for the conventional Beta method. (a) During increasing irradiation. (b) During decreasing irradiation.

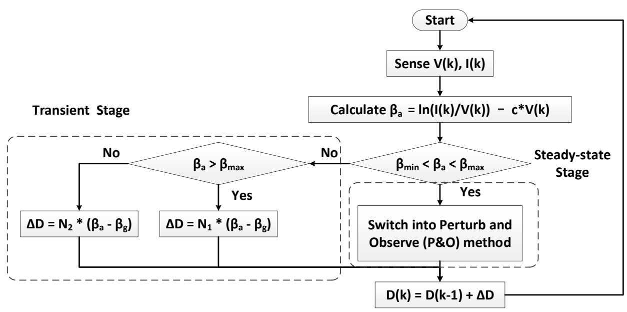


Fig. 4. Flowchart of the modified Beta method.

A modified Beta method is proposed to solve the issue of the choice of scaling factor *N* [27], as shown in Fig. 4. Unlike the conventional Beta method, a new judgment is added in the proposed method to determine whether the value of β_a is above or below the bounding range. Then, two different scaling factors, *N1* and *N2*, are used to generate the variable step size ΔD. The expressions are shown below:

$$\Delta D = N1 \times (\beta_a - \beta_g) \text{ for } \beta_a > \beta_{\max} \quad (5)$$

$$\Delta D = N2 \times (\beta_a - \beta_g) \text{ for } \beta_a < \beta_{\min} \quad (6)$$

Fig. 5 illustrates the value of β when the irradiation varies between 1000 and 400 W/m^2. As shown in Fig. 5, when the irradiation suddenly decreases from 1000 W/m^2 to 400 W/m^2, the duty cycle of the PV converter remains unchanged and the operating point will be located at load line 1. Thus, the operating point switches immediately from point A to point B, which is the intersection point of the load line 1 and the I-V curve at 400 W/m^2. Considering that the value of β_a at the point

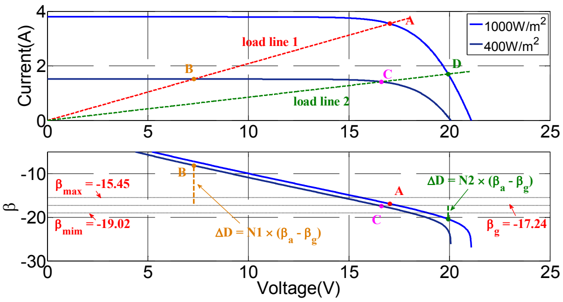


Fig. 5. I-V and β-V curves of 1000 and 400W/m^2 irradiation.

B is larger than β_{max}, *N1* is used to generate ΔD. Then, the operating point continues to move towards point C, which is the MPP for 400 W/m^2. Similarly, when the irradiation suddenly increases from 400 W/m^2 to 1000 W/m^2, the operating point first switches immediately from point C to point D. The value of β at the point D is smaller than β_{min}; thus, *N2* is used to generate ΔD.

N1 and *N2* are determined according to the variation of β due to a change in the environment, such as solar irradiation. As shown in Fig. 5, the term "$\beta_a - \beta_g$" shown in (5) is much larger than the same item in (6). If a scaling factor is used for both (5) and (6), then ΔD for (5) is larger than ΔD for (6), which will result in low tracking speed for some cases. Thus, the proposed method utilizes a small value of scaling factor N1 to compensate for the large value of the term "$\beta_a - \beta_g$" in (5) and a large value of *N2* to compensate for the small value of "$\beta_a - \beta_g$" $_{in}$ (6). Therefore, the proposed method can avoid the excessively small or excessively large step size.

Furthermore, because the proposed method can identify the direction of irradiation changes by parameter β, the proposed method can respond accurately during changes in irradiation unlike the fixed-step and other variable step methods.

III. Results and Discussion

A. Simulation Results

Fig. 6 shows the structure of the entire MPPT system in Matlab/Simulink; the structure includes the PV module, a boost converter, and an MPPT controller. The PV module model is designed based on the PV module MSX-60W, as shown in Table II. The values of the components in the boost converter are as follows: C_{in} = 470 µF, C_{out} = 47 µF, L = 0.1 mH, R_{load} = 87 Ω. The switching frequency of the converter is set to 10 kHz.

To investigate the performance of the proposed method under fast irradiation, the initial irradiation level for the simulation is 900 W/m^2. At t = 0.5 s, the irradiation level decreases to 300 W/m^2, increases to 800 W/m^2 at t = 2.5 s, and finally decreases to 400 W/m^2 at t = 4.5 s. The sampling time for the MPPT controller is 0.03 s [28]. Furthermore, P&O [6], the variable-step method variable-step-size INC (VSSINC) [13], and the conventional Beta method with two typical

TABLE II
Main Product Parameters of the MSX-60W

Parameter	Symbol	Value
Maximum power	P_{mpp}	60 W
Voltage at MPP	V_{mpp}	17.1 V
Current at MPP	I_{mpp}	3.5 A
Open-circuit voltage	V_{oc}	21.1 V
Short-circuit current	I_{sc}	3.8 A

scaling factors [27] are implemented; they are compared with the proposed method under the same condition. The fixed step size for P&O is set as 0.5%. The scaling factor for VSSINC is set as 0.7. The scaling factors for the proposed method, N1 and N2, are set as 2 and 6, respectively, in the simulation. The simulation results are illustrated in Fig. 7.

As shown in Fig. 7(a), P&O has a slow tracking speed when the irradiation level varies rapidly. Consequently, power loss during the transient stage is extremely high compared with the other methods. Compared with the P&O method, VSSINC has a faster tracking speed especially when the irradiation increases, as shown in Fig. 7(b). However, the tracking speed of VSSINC is relatively slow when the irradiation decreases. Furthermore, P&O and VSSINC are unable to respond accurately when the irradiation increases.

The conventional Beta method with scaling factors N = 2 and N = 6 are illustrated in Figs. 7(c) and 7(d), respectively. When the irradiation increases, the conventional Beta method with the larger scaling factor has a faster tracking speed and lower power loss than that with a smaller scaling factor. However, when the irradiation increases, the conventional Beta method with the larger scaling factor is unable to track the MPP because of the excessively large step size. By contrast, the conventional Beta method with the smaller scaling factor has a faster tracking speed under increasing irradiation. Fig. 7(e) illustrates the simulation result for the proposed method. The proposed method implements two different scaling factors, N1 and N2, for decreasing and increasing irradiation, respectively. Therefore, the step size for the proposed method in the transient stage is regulated properly. Unlike the conventional Beta method, the proposed method increases the tracking speed and avoids undesired performance. Furthermore, the proposed method can respond accurately when the irradiation changes, unlike P&O and VSSINC.

Fig. 7(f) illustrates the variation of the value of β for the conventional Beta method and the proposed method. As shown in Fig. 7(f), the conventional Beta method with a small scaling factor has a slower convergence speed of β when the irradiation increases. Furthermore, a large scaling factor could cause the β to be unable to converge when the irradiation decreases. The proposed method can avoid these drawbacks, and the convergence speed of β is fast. Both the conventional Beta method and the proposed method implement P&O in the steady state; thus, the value of β also oscillated.

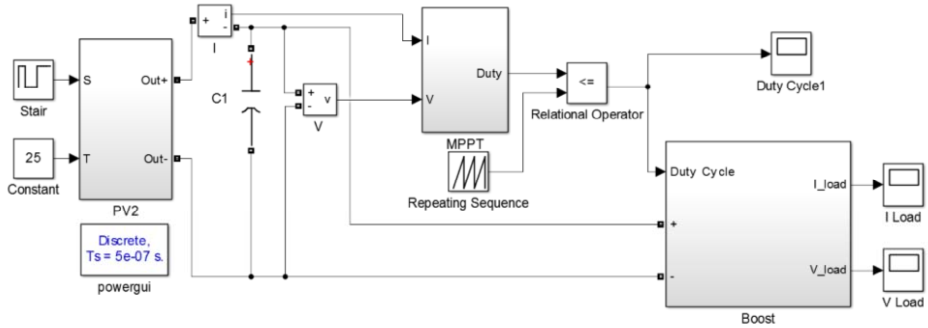


Fig. 6. Structure of the MPPT system in Matlab/Simulink.

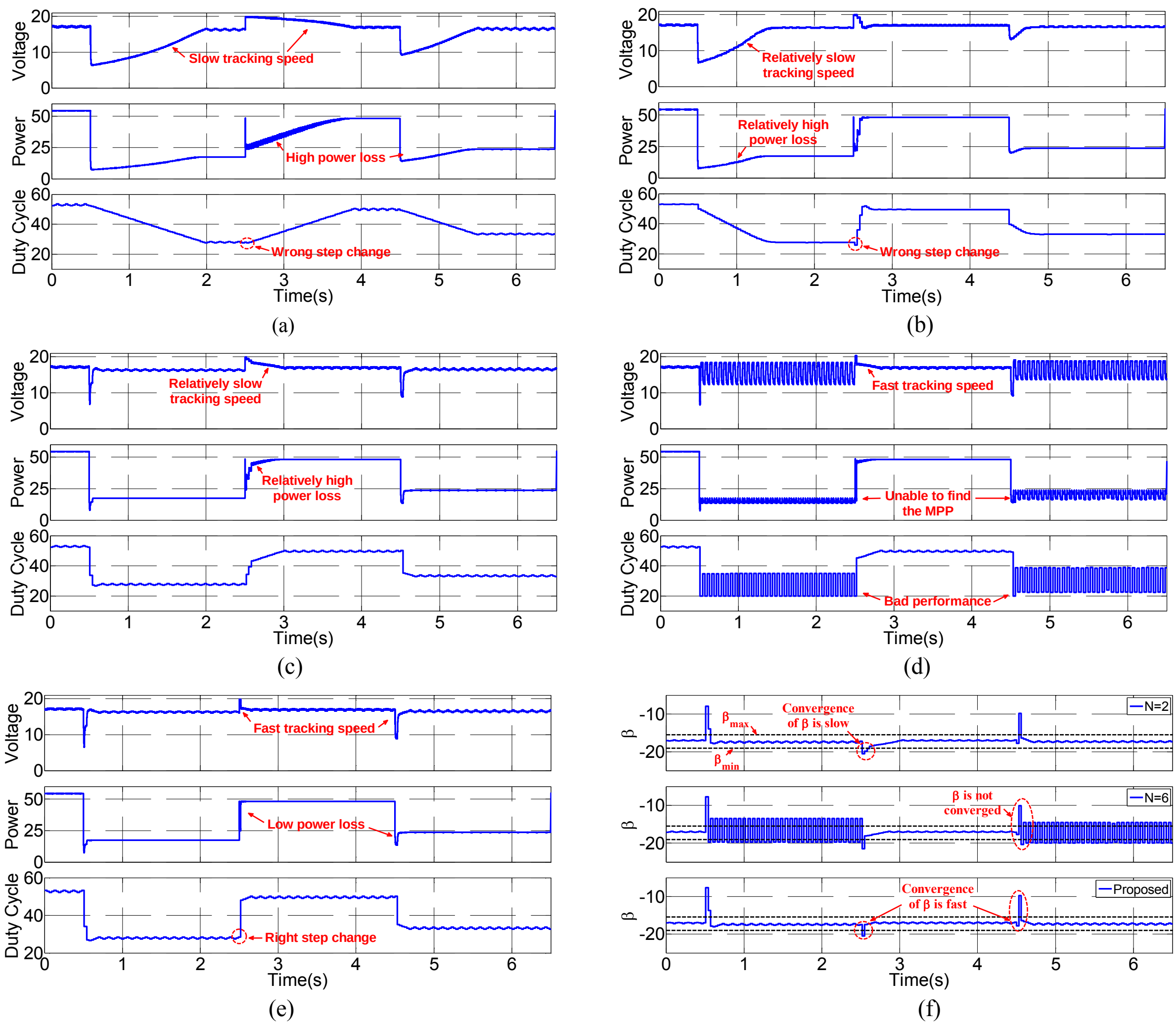


Fig. 7. Simulation results for the conventional MPPT methods: (a) P&O, (b) VSSINC, (c) the conventional Beta method with N=2, (d) the conventional Beta method with N=6, (e) the proposed method, (f) the variation of the value of β.

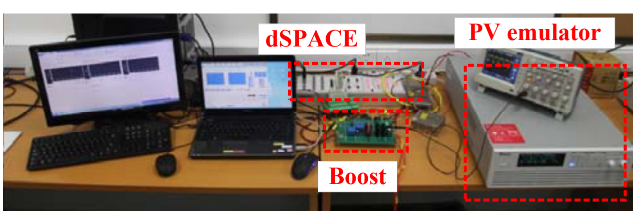


Fig. 8. Experimental prototype of the MPPT system.

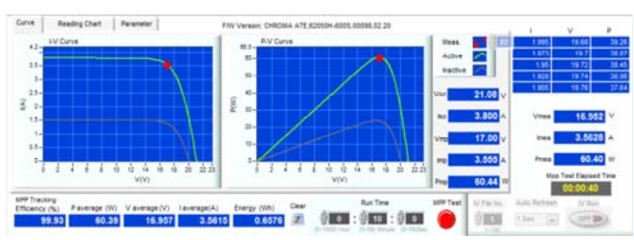


Fig. 9. Soft panel of the PV emulator.

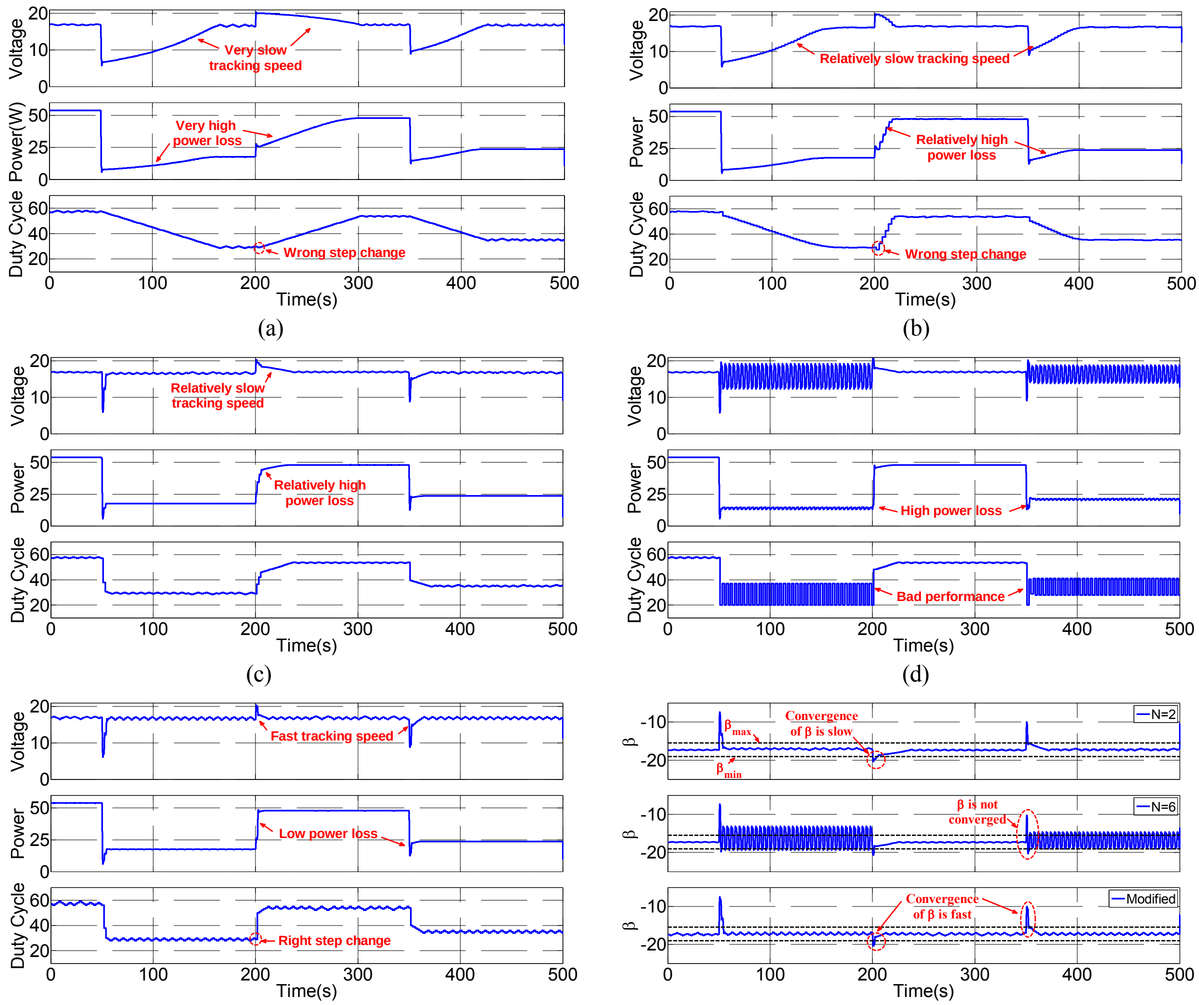


Fig. 10. Experimental results for the conventional MPPT methods: (a) P&O, (b) VSSINC, (c) the conventional Beta method with N=2, (d) the conventional Beta method with N=6, (e) the proposed method, (f) the variation of the value of β.

B. Experimental Results

To verify the simulation performance, an experimental prototype of the MPPT system was proposed, as shown in Fig. 8. This prototype includes a boost converter, a PV emulator, and a dSPACE controller.

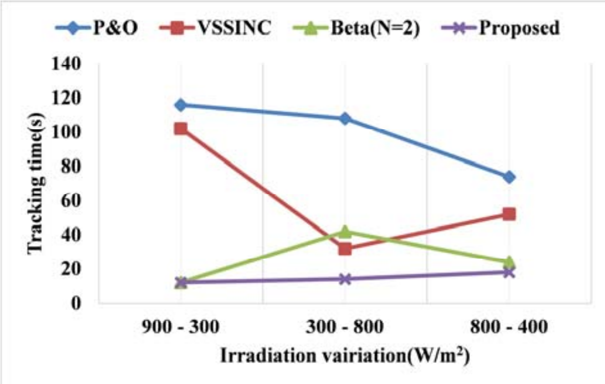
The specifications of the main components for boost converter are the same as those in the simulation. Current (LA25-NP) and voltage (LV25-P) sensors were used to sense the current and voltage of the PV emulator.

dSPACE DS1104 is used as a control platform to employ Matlab/Simulink tools for the development of the control algorithm and for hardware implementation. The controller parameters for the experiments are the same as those in the simulation.

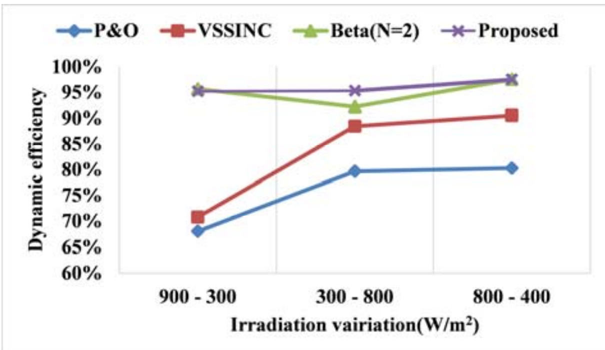
The PV emulator Chroma ATE-62050H-600S was used; this emulator has a programmable DC supply with solar array I-V simulation. The soft panel of the PV emulator is shown in Fig. 11 and is used to edit multiple I-V curves and simulate the MPPT trace test under environmental changes. The PV emulator has dynamic constraints and has a slower response speed than a practical crystalline PV [29]. Therefore, the sampling time for the MPPT controller is 3 s in this experiment.

Compared with the other methods, P&O requires the longest time to track the MPP when the irradiation changes suddenly, as shown in Fig. 10(a). Consequently, the power loss during the transient stage is also the highest among these methods. The tracking time for the VSSINC is generally shorter than that of P&O, especially when the irradiation increases, as shown in Fig. 10(b). However, the VSSINC also needs a long time to track the MPP under decreasing irradiation. Furthermore, P&O and VSSINC are unable to respond accurately when the irradiation increases, especially VSSINC.

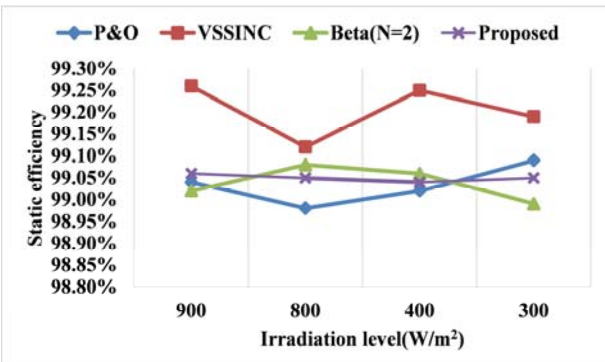
The conventional Beta method with the scaling factor N = 2 has a much faster tracking speed than P&O and VSSINC, as shown in Fig. 10(c). Consequently, the power loss during the transient stage is also smaller than that in P&O and VSSINC. However, the tracking speed under increasing irradiation is



(a)



(b)



(c)

Fig. 11. Experimental result comparison for P&O, VSSINC, the conventional Beta method, and the proposed method: (a) tracking time, (b) dynamic tracking efficiency, (c) static tracking efficiency.

relatively slow. By contrast, the tracking speed of the conventional Beta method with N = 6 is faster than that with N = 2 when the irradiation increases, as shown in Fig. 10(d). However, it cannot track the MPP under decreasing irradiation.

The proposed method overcomes the drawbacks of the conventional Beta method and has the fastest tracking speed and lowest power loss among all methods, as shown in Fig. 10(e). Furthermore, the proposed method can respond accurately under irradiation changes, unlike P&O and VSSINC.

Fig. 10(f) illustrates the variation of the value of β for the conventional Beta method and the proposed method; this variation is similar to that in the simulation.

Finally, to evaluate the performance of these methods, the experimental results are summarized in terms of tracking time, dynamic tracking efficiency, and static tracking efficiency in Fig. 11. Dynamic tracking efficiency and static tracking efficiency are defined according to the EN50530 standard [30]

$$\eta_{MPPT} = \frac{\int_0^{Tm} P_{PV}(t)dt}{\int_0^{Tm} P_{MPP}(t)dt} \tag{7}$$

where T_m refers to measured time, $P_{PV}(t)$ refers to instantaneous power drawn by the PV emulator, and $P_{MPP}(t)$ refers to the MPP power provided theoretically by the PV emulator. For the dynamic tracking efficiency comparison, the tracking time for irradiation variations, T_m, changes for various methods. For example, when the irradiation increases from 900 W/m^2 to 300 W/m^2, T_m of P&O and the proposed method is 116 and 12 s, respectively. For the static tracking efficiency comparison, the parameter T_m is set as 20 s for all these methods.

Fig. 11 indicates that the tracking time of the proposed method is the shortest among all methods. Therefore, the dynamic tracking efficiency of the proposed method is the highest. However, because the proposed method implements the fixed-step size P&O in the steady-state stage, the static efficiency of the proposed method is similar to that of P&O and the conventional Beta method, and is slightly lower than that of VSSINC.

IV. Conclusion

This paper proposed a modified Beta method that is based on the changes of the value of β during changes in irradiation. Two different values of scaling factor N are implemented in the proposed method to solve the difficulty of selecting the scaling factor N for the conventional Beta method. The proposed method can respond accurately during changes in irradiation. A comparison among the proposed method, P&O, VSSINC, and the conventional Beta method is conducted through simulations and experiments. Simulation and experiment results verify that the proposed method has the fastest tracking speed and the lowest power loss among these methods during the transient stage.

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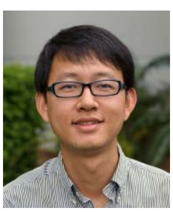

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