A Variable Step Size INC MPPT Method for PV Systems

Fangrui Liu, Shanxu Duan, Fei Liu, Bangyin Liu, and Yong Kang

***Abstract*—Maximum power point tracking (MPPT) techniques are employed in photovoltaic (PV) systems to make full utilization of PV array output power which depends on solar irradiation and ambient temperature. Among all the MPPT strategies, the incremental conductance (INC) algorithm is widely used due to the high tracking accuracy at steady state and good adaptability to the rapidly changing atmospheric conditions. In this paper, a modified variable step size INC MPPT algorithm is proposed, which automatically adjusts the step size to track the PV array maximum power point. Compared with the conventional fixed step size method, the proposed approach can effectively improve the MPPT speed and accuracy simultaneously. Furthermore, it is simple and can be easily implemented in digital signal processors. A theoretical analysis and the design principle of the proposed method are provided and its feasibility is also verified by simulation and experimental results.**

***Index Terms*—Incremental conductance (INC), maximum power point tracking (MPPT), variable step size.**

I. Introduction

PHOTOVOLTAIC (PV) generation is becoming increasingly important as a renewable source since it exhibits many merits such as cleanness, little maintenance and no noise. The output power of PV arrays is always changing with weather conditions, i.e., solar irradiation and atmospheric temperature. Therefore, a maximum power point tracking (MPPT) control to extract maximum power from the PV arrays at real time becomes indispensable in PV generation systems.

In recent years, a large number of techniques have been proposed for tracking the maximum power point (MPP) [1]–[12]. Fractional open-circuit voltage and short-circuit current [1], [2] strategies provide a simple and effective way to acquire the maximum power. However, they require periodical disconnection or short-circuit of the PV modules to measure the open-circuit voltage or short-circuit current for reference, resulting in more power loss. Hill climbing and perturb and observe (P&O) methods are widely applied in the MPPT controllers due to their simplicity and easy implementation [3]–[5]. The P&O method involves a perturbation in the operating voltage of the PV array, while the hill climbing strategy introduces a perturbation in the duty ratio of the power converter [5] and is more attractive due to the simplified control structure [6]. Nevertheless, steady-state oscillations always appear in both methods due to the perturbation. Thus, the power loss may be increased. Incremental conductance (INC) method, which is based on the fact that the slope of the PV array power versus voltage curve is zero at the MPP, has been proposed to improve the tracking accuracy and dynamic performance under rapidly varying conditions [7], [8]. The steady state oscillations would be eliminated in theory since the derivative of the power with respect to the voltage vanishes at MPP. However, null value of the slope of the PV array power versus voltage curve seldom occurs due to the resolution of digital implementation. Although the INC method is a little more complicated compared with the P&O/hill climbing strategy, it can be easily implemented due to the advancements of digital signal processors (DSPs) [9].

Moreover, fuzzy and neural network methods [10], [11] that focus on the nonlinear characteristics of PV array provide a good alternative for the MPPT control. Since the output characteristics of the PV array should be well ascertained to create the MPPT control rules, the versatility of these methods is limited.

The INC MPTT algorithm usually uses a fixed iteration step size, which is determined by the accuracy and tracking speed requirement. Thus, the corresponding design should satisfactorily address the tradeoff between the dynamics and steady state oscillations. To solve these problems, a modified INC MPPT with variable step size is proposed in this paper. The step size is automatically tuned according to the inherent PV array characteristics. If the operating point is far from MPP, it increases the step size which enables a fast tracking ability. If the operating point is near to the MPP, the step size becomes very small that the oscillation is well reduced contributing to a higher efficiency. In the following, the design principle of the modified variable step size INC MPPT is presented on the basis of uniform irradiance for PV array. Both simulation and experimental design examples are then provided, and the corresponding results confirm that the proposed method can effectively improve the dynamic performance and steady state performance simultaneously.

II. PV Array MPPT

A. PV Array Characteristics

Generally, a PV module comprises of a number of PV cells connected in either series or parallel and its mathematical model can be simply expressed as [12]–[14]

$$I_{\mathrm{o}} = n_{\mathrm{p}} I_{\mathrm{ph}} - n_{\mathrm{p}} I_{\mathrm{rs}} \left[\exp \left(K_{\mathrm{o}} \frac{V}{n_{\mathrm{s}}} \right) - 1 \right] \qquad (1)$$

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The authors are with the College of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan 430074, China (e-mail: fangruihust@163.com; dshanxu@263.com; dyj_lf@163.com; lby@smail.hust.edu.cn; ykang@mail.hust.edu.cn).

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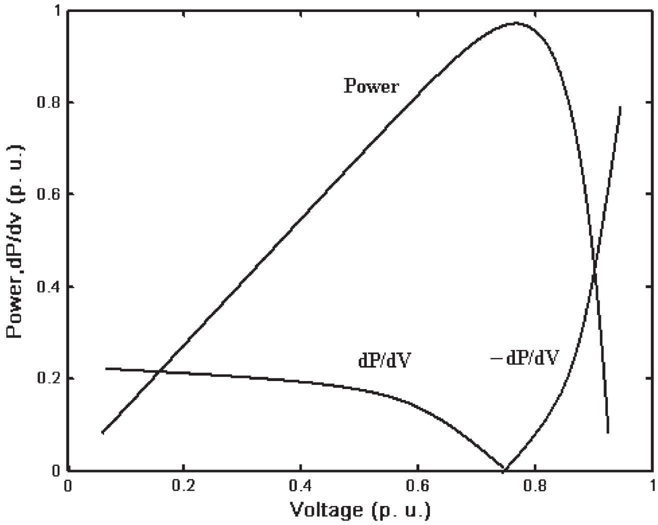

Fig. 1. Variation of the normalized power and slope of power versus voltage curves.

where I_o denotes the PV array output current, V is the PV output voltage, I_{ph} is the cell photocurrent that is proportional to solar irradiation, I_{rs} is the cell reverse saturation current that mainly depends on the temperature, K_o is a constant, n_s and n_p are the numbers of series strings and parallel strings in the PV array, respectively. The corresponding PV output power and slope of output power versus output voltage curves can be obtained as shown in Fig. 1.

B. Variable Step Size INC MPPT Algorithm

The step size for the INC MPPT method is generally fixed. The power drawn from the PV array with a lager step size contributes to faster dynamics but excessive steady state oscillations, resulting in a comparatively low efficiency. This situation is reversed while the MPPT is running with a smaller step size. Thus, the MPPT with fixed step size should make a satisfactory tradeoff between the dynamics and oscillations. Such design dilemma can be solved with variable step size iteration [14]–[16].

However, all these strategies were proposed for P&O/hill climbing MPPT method and the derivation of the essential parameters of variable step size were not provided [14], [16]. In this paper, a modified variable step size algorithm is proposed for the INC MPPT method and is dedicated to find a simple and effective way to improve tracking accuracy as well as tracking dynamics.

In most applications, the MPP tracker is achieved by connecting a dc-dc converter between the PV array and load [17]–[19]. The PV output power is used to directly control the power converter duty cycle to reduce well the complexity of the system [6]. The flowchart of the modified variable step size INC MPPT algorithm is shown in Fig. 2, where the converter duty cycle iteration step size is automatically tuned.

The PV output power is employed to directly control the converter duty cycle, contributing to a simplified control system [6]. Note that $V(k)$ and $I(k)$ are the PV array output voltage and current at time k. In addition, $D(k)$ and step are the duty

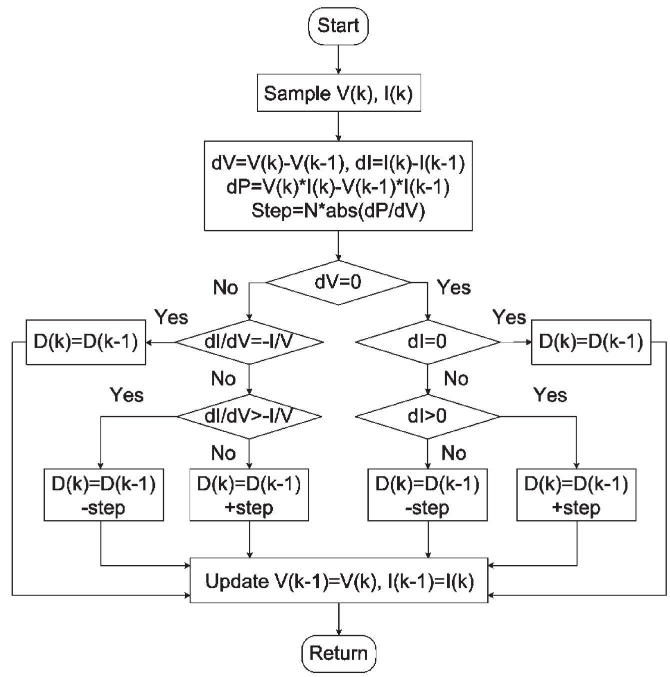

Fig. 2. Flowchart of the variable step size INC MPPT algorithm.

cycle and change of duty cycle (step size), respectively. The variable step size adopted to reduce the problem mentioned above is shown as follows [15]:

$$D(k) = D(k-1) \pm N * \left|\frac{dP}{dV}\right| \tag{2}$$

where coefficient N is the scaling factor which is tuned at the design time to adjust the step size. The variable step size can also be realized from the slope of the P–D curve in [16] for P&O MPPT as

$$D(k) = D(k-1) \pm N * \left|\frac{\Delta P}{\Delta D}\right| \tag{3}$$

where ΔD is the step-change in duty cycle in the previous sampling period. As shown in Fig. 1, the derivative of power to voltage (dP/dV) of a PV array can be seen to be varying smoothly and is recommended in [15] as a suitable parameter for determining the variable step size of the P&O algorithm. Thus, $|dP|/|dV|$ is also employed herein to determine the variable step size for the INC MPPT algorithm. The update rule for duty cycle can be obtained as follows:

$$D(k) = D(k-1) \pm N * \left|\frac{P(k) - P(k-1)}{V(k) - V(k-1)}\right|. \tag{4}$$

Scaling factor N essentially determines the performance of the MPPT system. Manual tuning of this parameter is tedious and the obtained optimal results may be valid only for a given system and operating condition [15]. A simple method to determine the scaling factor is proposed here. Comparatively large step size ΔD_{max} for fixed step size MPPT operation is initially chosen. With such value, the dynamic performance is good enough, while the steady-state performance may not be satisfactory. The steady-state value instead of dynamic value in

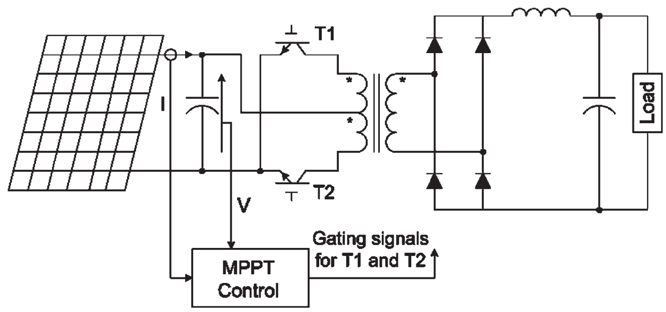

Fig. 3. MPPT system.

the startup process [15] of the derivative of PV array output power to voltage can be evaluated under the fixed step size operation with $\Delta D_{\max}$, which will be chosen as the upper limiter as the variable step size INC MPPT method. It is known that $|dP|/|dV|$ is almost at its lowest value around the PV MPP. To ensure the convergence of the MPPT update rule, the variable step rule must obey the following:

$$N * \left|\frac{dP}{dV}\right|_{\text{fixed step}=\Delta D_{\max}} < \Delta D_{\max} \tag{5}$$

where $|(dP/dV)|_{\text{fixed step}=\Delta D_{\max}}$ is the $|dP|/|dV|$ at fixed step size operation of $\Delta D_{\max}$. The scaling factor can therefore be obtained as

$$N < \Delta D_{\max} / \left|\frac{dP}{dV}\right|_{\text{fixed step}=\Delta D_{\max}}. \tag{6}$$

If (6) cannot be satisfied, the variable step size INC MPPT will be working with a fixed step size of the previously set upper limiter $\Delta D_{\max}$. Equation (6) provides a simple guidance to determine the scaling factor N of the variable step size INC MPPT algorithm. With the satisfaction of (6), larger N exhibits a comparatively faster response than a smaller N, which will be further discussed in Section III. The step size will become tiny as dP/dV becomes very small around the MPP.

III. Simulation and Experimental Evaluation

A simple MPPT PV system shown in Fig. 3 is developed to test the feasibility of the proposed method. A push-pull converter is used as the power interface between the PV array and the load to achieve maximum power. Assuming that the turns of the two primary windings are the same, the output voltage of the converter can be expressed as [17]

$$V_o = 2mDV \tag{7}$$

where m is the turn ratio of the secondary winding to the primary winding and D is the duty cycle. It can be seen that the input dc voltage can be easily shifted to a high level. This converter is suitable for a lower PV output voltage and higher desirable dc-link voltage case, where electrical isolation is also required.

TABLE I
GFM-120 Crystalline Silicon PV Module Specifications

Open-circuit voltage	21.6 V
Typical operation voltage	17.3 V
Nominal output power	120 W

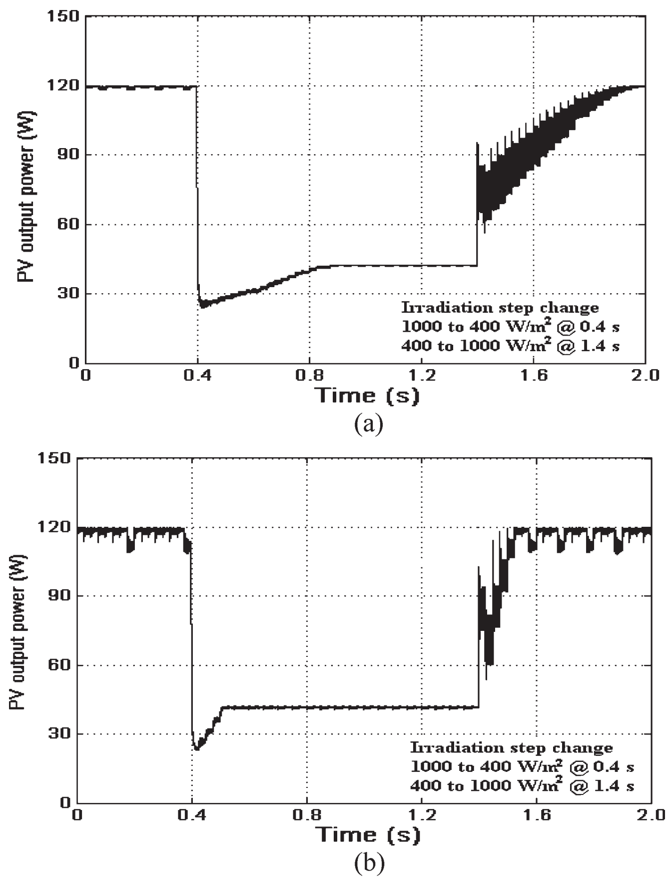

Fig. 4. PV array output power with fixed step size INC MPPT. (a) Fixed step size of 0.01. (b) Fixed step size of 0.05.

A. Simulation Results

To verify the performance of the proposed modified variable step size INC MPPT algorithm, a MATLAB-SIMULINK model of the PV system shown in Fig. 3 is initially developed. GFM-120 Crystalline Silicon PV module is used for the PV array model in simulation and experiment and the specifications are listed in Table I.

To compare the performance of the variable step size INC MPPT method with the ordinary fixed step size INC MPPT method, the simulations are configured under exactly the same conditions to compare the performances. The PV array in simulation is composed of one PV module, and the sampling period [3], [18] used for MPPT algorithm is chosen as 0.025 s. The duty cycle command is therefore updated every 0.025 s. The output power performance of INC MPPT with fixed step size of 0.01 and 0.05 under irradiation step change conditions are shown in Fig. 4. The irradiation was suddenly changed from 1000 to 400 W/m^2 at 0.4 s and changed back to 1000 W/m^2 at 1.4 s. For the comparative purpose, the allowable maximum duty size $\Delta D_{\max}$ [referred to (6)] is set as 0.05 for the proposed variable step size INC MPPT method. The corresponding PV

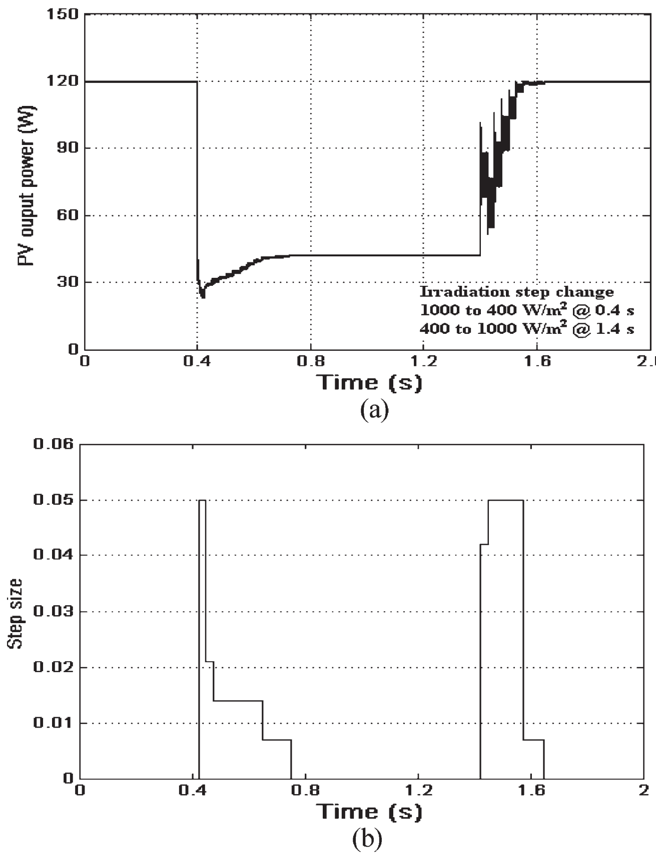

Fig. 5. PV array output power and step size with variable step size INC MPPT ($N = 0.06$). (a) PV output power. (b) Step size.

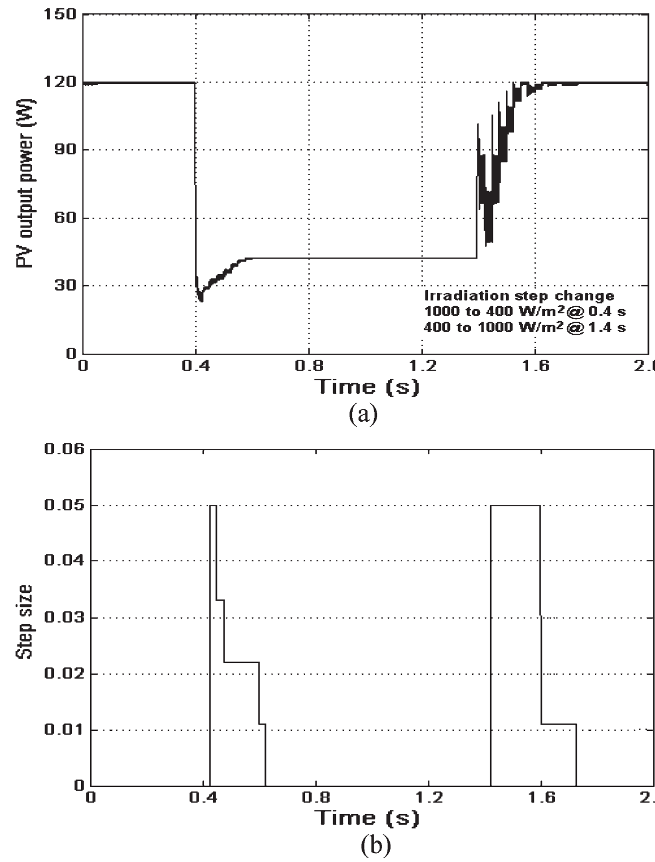

Fig. 6. PV array output power and step size with variable step size INC MPPT ($N = 0.12$). (a) PV output power. (b) Step size.

output power and step size under $N = 0.06$ and $N = 0.12$ are shown in Figs. 5 and 6, respectively. The tracking performance under both fixed and variable INC MPPT methods are presented in Table II. Compared with the MPPT with fixed step size of 0.01 [Fig. 4(a)], the MPPT with fixed step size of 0.05 [Fig. 4(b)] exhibits a good dynamic performance but larger steady state oscillations. The tracking time with fixed step size of 0.05 under irradiation step change conditions is only several MPPT sampling periods and the tracking ability can be further improved with larger step size. However, it is achieved at the sacrifice of MPPT efficiency. The PV array average output power with fixed step size of 0.05 is 114.5 W and decreased by 3.3% compared with the output power of 118.4 W with step size of 0.01. The proposed variable step size method solves the dilemma as evident from Figs. 5 and 6. The oscillations at stead state in these two figures are almost eliminated due to the very small $|dP|/|dV|$ and the PV array output power is above 119.3 W. Moreover, the dynamic performance is obviously faster than that of fixed step size of 0.01. It also can be seen that the proposed strategies with $N = 0.12$ [refer to Fig. 6(a)] shows a faster dynamic response than that of $N = 0.06$ [refer to Fig. 5(a)]. A bigger N [but still with the satisfaction of (6)] can be chosen to achieve a faster response.

B. Experimental Results

The operation of the variable step size INC MPPT method has also been evaluated by experiment. A prototype of the MPPT system depicted in Fig. 3 is constructed and the push-pull converter specifications are chosen as follows:

1) dc capacitance: 470 μF (PV side), 47 μF (filter);
2) filter inductance: 0.35 mH;
3) transformer turn ratio: 8/38 (primary to secondary);
4) switching frequency: 20 kHz.

In the experiment, three PV modules with specifications illustrated in Table I are connected in series. The control system is implemented in a TMS320LF2407 DSP.

The start waveforms with variable step size INC MPPT algorithm are shown in Fig. 7. When the system approaches near the MPP, the step size becomes very small, resulting in a smooth power curve. However, the PV current and power increase with large steps due to the large step size at the beginning (referred to Fig. 2). This can be overcome by adding a simple constant voltage tracking (CVT) start program as shown in Fig. 8. The MPP voltage has been reported to be nearly 78% of the open voltage [6]. The preset voltage V_{set} is set as $0.8V_{\text{oc}}$ to enable the converter duty cycle to increase linearly to approach MPP. Once the PV output voltage goes lower than V_{set}, the control unit switches to the variable step size INC MPPT algorithm. Thus, the PV system reaches the MPPT very smoothly as illustrated in Fig. 9. A variable resistive load was directly connected the PV arrays as well to test the maximum power. The maximum power difference between the PV array could be produced and the array outputs with the proposed variable step size INC MPPT method is within several watts. Thus, the MPPT efficiency of

TABLE II
TRACKING PERFORMANCE COMPARISON BETWEEN FIXED AND VARIABLE STEP SIZE INC MPPT METHODS

Method	Parameters	Average power at 1000 W/m^2	Tracking time with irradiation step change	
			1000→400 W/m^2	400→1000 W/m^2
Fixed step size	ΔD =0.01	118.4 W	0.45s /18 cycles*	0.5s /20 cycles
	ΔD =0.05	114.5 W	0.125s /5 cycles	0.15s /6 cycles
Variable step size	N=0.06	119.4 W	0.325s /13 cycles	0.175s /7 cycles
	N=0.12	119.3 W	0.175s /7 cycles	0.175s /7 cycles

* It denotes the sampling interval used for MPPT algorithm

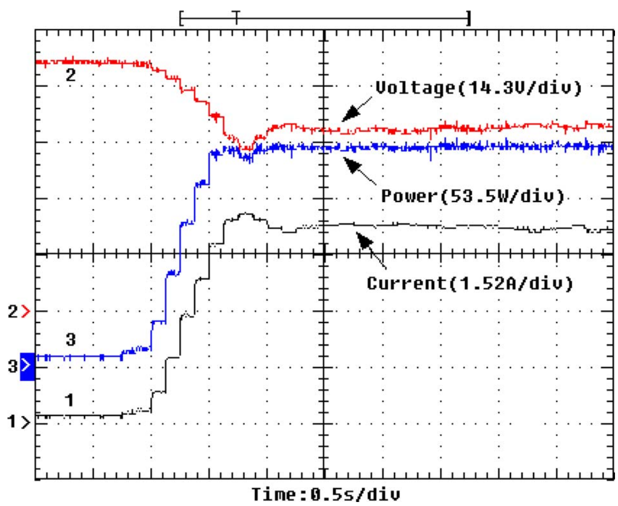

Fig. 7. Start waveforms of PV output voltage, current, and power with variable step size INC MPPT method.

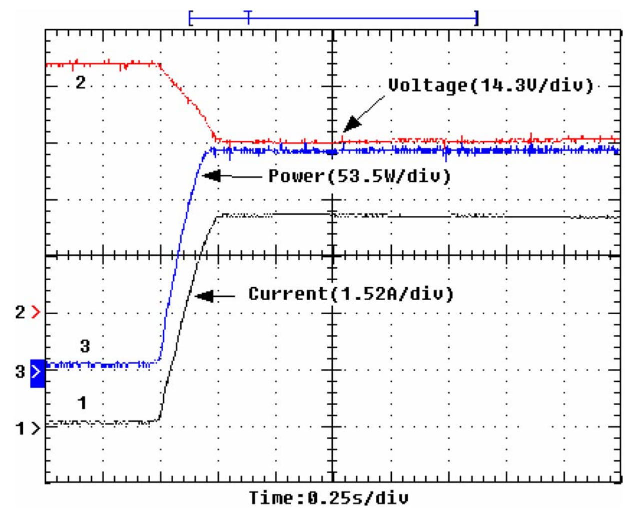

Fig. 9. Start waveforms with variable step size MPPT algorithm and CVT start program.

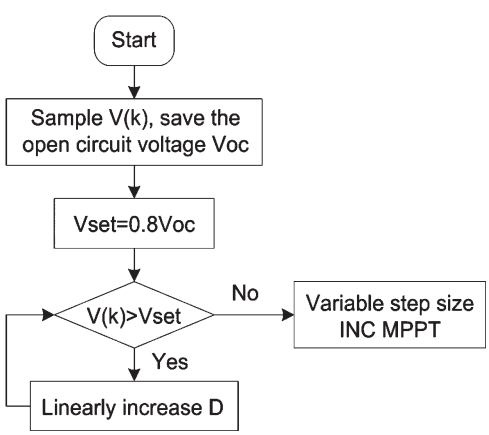

Fig. 8. CVT start program.

the proposed method under the current environment is about 99.2%, while the efficiency for fixed step size INC MPPT strategy is 98.9% with the same experimental setup.

The MPPT efficiency difference is not obvious mainly due to the small step size chosen for the fixed step size INC MPPT algorithm. The purpose of this paper is to improve the dynamic response as well and will be further illustrated in the following figures.

It is recommended in [3] and [18] that the whole system in one MPPT cycle should reach the steady state before another begins. The MPPT sampling interval chosen here for the experiment is comparatively as large as 0.25 s to investigate how the proposed MPPT method functions under dynamic working conditions. The PV system may suffer rapidly changing irradiation under practical operation. According to the characteristics of PV modules, there is a severe variation in the maximum output power while the MPP voltage changes little. A switch is introduced to parallel with one of three series-connected PV modules to simulate the effect of the insulation on the PV system. When the switch is turned on or turned off, both the output power and output voltage of the PV array will suffer a step change, simulating a worse working condition for the MPPT control. When the switch is turned off, PV modules number is changed from two to three. The corresponding PV system output voltage, current and power curves with the proposed variable step size INC MPPT algorithms are shown in Fig. 10(a), while Fig. 10(b) illustrates those waveforms for the PV module numbers is suddenly changed from three to two. The PV array output waveforms with fixed step size INC MPPT under PV module number suddenly changing conditions are shown in Fig. 11. The sampling periods used by both MPPT methods are the same. A small fixed step size is chosen to achieve almost same steady-state accuracy as the variable step size method. From these figures, it can be seen that the PV system with variable step size gets to the MPP within 1.5 s while it takes 7.5 s for the fixed step size method to track the MPP when the PV output power is suddenly changed. Nevertheless, the tracking time is long, the dynamic process is finished within 6 MPPT sampling periods. It is evident that the PV system with variable step size INC MPPT algorithm has a good dynamic performance. Due to the inherent iteration characteristic, the

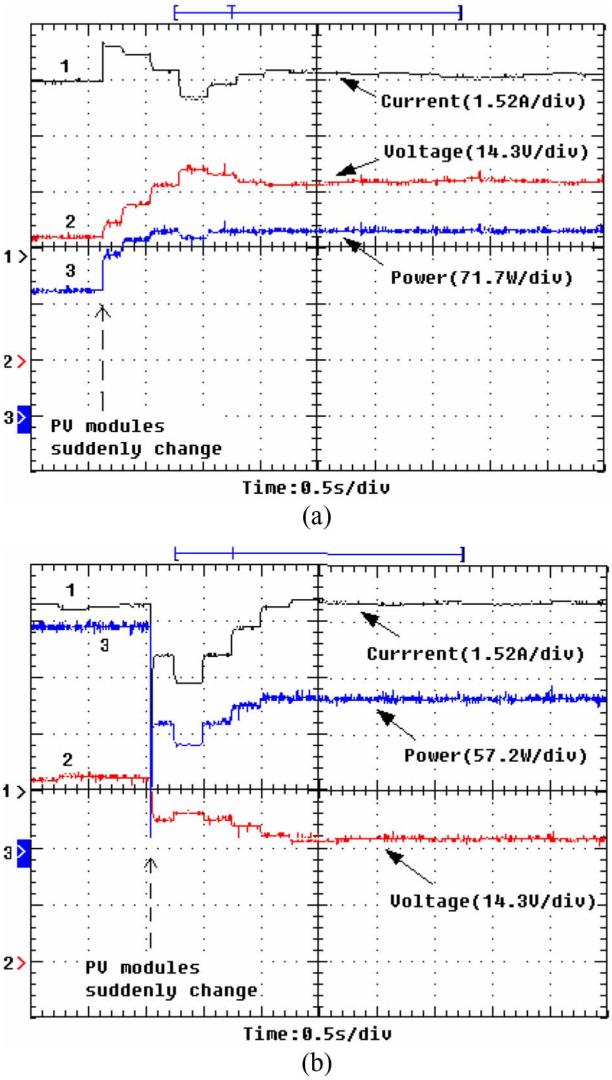

Fig. 10. PV array output performance with variable step size INC MPPT under PV modules suddenly changing conditions. (a) PV module number increases from 2 to 3. (b) PV module number decreases from 3 to 2.

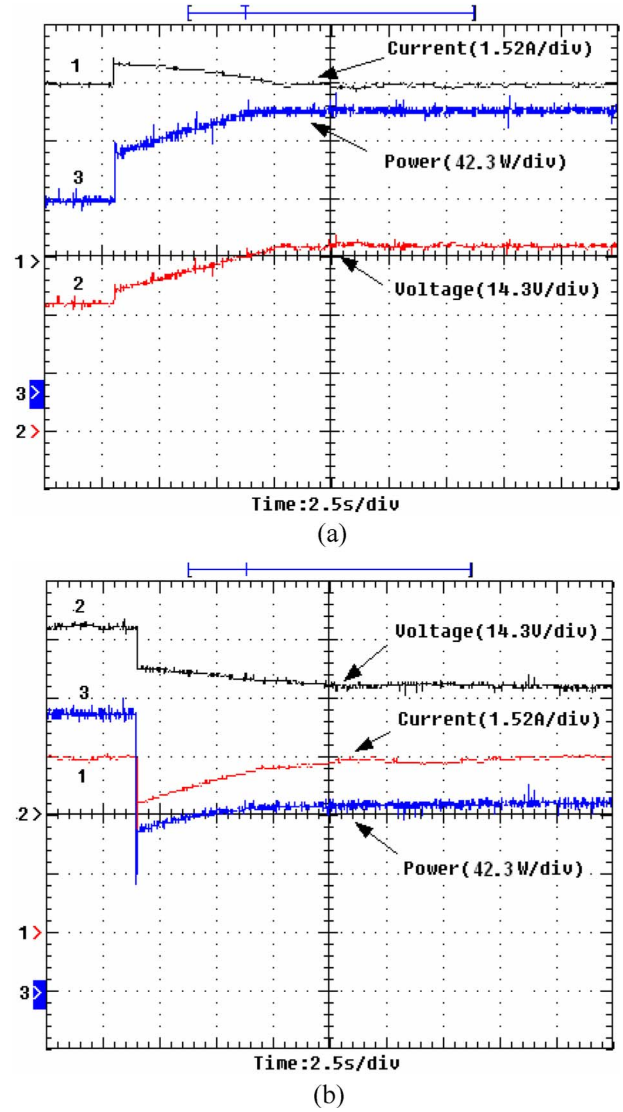

Fig. 11. PV array output performance with fixed step size INC MPPT under PV modules suddenly changing conditions. (a) PV module number increases from 2 to 3. (b) PV module number decreases from 3 to 2.

proposed method may fail to track the real MPP as the general P&O and INC methods suffer at the multiple MPP cases.

IV. Conclusion

In this paper, a modified variable step size INC MPPT algorithm has been presented, which is able to improve the dynamic and steady state performance of the PV system simultaneously. The design issue of variable step size INC MPPT is discussed and a simple design rule is proposed. Moreover, at the start process of the MPPT, the PV system may exhibit comparable large step change in the output voltage and current due to the large step size. A simple CVT start program is introduced to the MPPT algorithm, which enables the smooth start process. Both fixed step size and the proposed variable size INC MPPT methods are implemented with MATLAB-SIMULINK for simulation and a DSP for the hardware experiment. The simulation and experimental results verify the feasibility and effectiveness of the proposed method.

References

[1] J. J. Schoeman and J. D. Wyk, "A simplified maximal power controller for terrestrial photovoltaic panel arrays," in *Proc. 13th Annu. IEEE Power Electron. Spec. Conf.*, 1982, pp. 361–367.

[2] M. A. S. Masoum, H. Dehbonei, and E. F. Fuchs, "Theoretical and experimental analyses of photovoltaic systems with voltage- and current-based maximum power-point tracking," *IEEE Trans. Energy Convers.*, vol. 17, no. 4, pp. 514–522, Dec. 2002.

[3] N. Femia, G. Petrone, G. Spagnuolo, and M. Vitelli, "Optimization of perturb and observe maximum power point tracking method," *IEEE Trans. Power Electron.*, vol. 20, no. 4, pp. 963–973, Jul. 2005.

[4] D. Sera, T. Kerekes, R. Teodorescu, and F. Blaabjerg, "Improved MPPT method for rapidly changing environmental conditions," in *Proc. IEEE ISIE*, 2006, pp. 1420–1425.

[5] T. Esram and P. L. Chapman, "Comparison of photovoltaic array maximum power point tracking techniques," *IEEE Trans. Energy Convers.*, vol. 22, no. 2, pp. 439–449, Jun. 2007.

[6] E. Koutroulis, K. Kalaitzakis, and N. C. Voulgaris, "Development of a microcontroller-based, photovoltaic maximum power point tracking control system," *IEEE Trans. Power Electron.*, vol. 16, no. 1, pp. 46–54, Jan. 2001.

[7] K. H. Hussein, I. Muta, T. Hoshino, and M. Osakada, "Maximum photovoltaic power tracking: An algorithm for rapidly changing atmospheric conditions," *Proc. Inst. Electr. Eng.—Generation, Transmission Distrib.*, vol. 142, no. 1, pp. 59–64, Jan. 1995.

[8] G. J. Yu, Y. S. Jung, J. Y. Choi, and G. S. Kim, “A novel two-mode MPPT control algorithm based on comparative study of existing algorithms,” *Sol. Energy*, vol. 76, no. 4, pp. 455–463, Apr. 2004.
[9] H. Koizumi, T. Mizuno, T. Kaito, Y. Noda, N. Goshima, M. Kawasaki, K. Nagasaka, and K. Kurokawa, “A novel microcontroller for grid-connected photovoltaic systems,” *IEEE Trans. Ind. Electron.*, vol. 53, no. 6, pp. 1889–1897, Dec. 2006.
[10] T. Wu, C. Chang, and Y. 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.
[11] M. Veerachary, T. Senjyu, and K. Uezato, “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.
[12] 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.
[13] I. Kim, M. Kim, and M. Youn, “New maximum power point tracker using sliding-mode observer for estimation of solar array current in the grid-connected photovoltaic system,” *IEEE Trans. Ind. Electron.*, vol. 53, no. 4, pp. 1027–1035, Aug. 2006.
[14] K. Noppadol, W. Theerayod, and S. Phaophak, “FPGA implementation of MPPT using variable step-size P&O algorithm for PV applications,” in *Proc. ISCIT*, 2006, pp. 212–215.
[15] A. Pandey, N. Dasgupta, and A. K. Mukerjee, “Design issues in implementing MPPT for improved tracking and dynamic performance,” in *Proc. IEEE IECON*, 2006, pp. 4387–4391.
[16] W. Xiao and W. G. Dunford, “A modified adaptive hill climbing MPPT method for photovoltaic power systems,” in *Proc. IEEE PESC*, 2004, pp. 1957–1963.
[17] N. Mohan, T. M. Undeland, and W. P. Robbins, *Power Electronics: Converter, Applications, and Design*. New York: Wiley, 1995, p. 315.
[18] N. Femia, D. Granozio, G. Petrone, G. Spagnuolo, and M. Vitelli, “Predictive & adaptive MPPT perturb and observe method,” *IEEE Trans. Aerosp. Electron. Syst.*, vol. 43, no. 3, pp. 934–950, Jul. 2007.
[19] K. K. Tse, M. T. Ho, H. S. Chung, and S. Y. R. Hui, “A comparative study of maximum-power-point trackers for photovoltaic panels using switching-frequency modulation scheme,” *IEEE Trans. Ind. Electron.*, vol. 51, no. 2, pp. 410–418, Apr. 2004.

Fangrui Liu received the B.Eng. degree in electrical engineering from Huazhong University of Science and Technology, Wuhan, China, in 2002, and the Ph.D. degree from Nanyang Technological University, Singapore, in 2006.

He is currently a Postdoctoral Research Fellow in the Department of Applied Power Electronic Engineering, Huazhong University of Science and Technology. His present research interests include renewable energy resources and distributed power systems.

Shanxu Duan received the B.Eng., M.Eng., and Ph.D. degrees in electrical engineering from Huazhong University of Science and Technology, Wuhan, China, in 1991, 1994, and 1999, respectively.

Since 1991, he has been a faculty member in the Department of Applied Power Electronic Engineering, Huazhong University of Science and Technology, where he is currently a Professor. His main research interests include stabilization, nonlinear control with application to power electronic circuit and system, full-digitalized control technique for power electronics apparatus and system, optimal control theory and corresponding applying techniques for high-frequency pulsewidth-modulation power converters.

Fei Liu received the B.Eng. and M.Eng. degrees in electrical engineering from Huazhong University of Science and Technology, Wuhan, China, in 2000 and 2004, respectively, where he is currently working toward the Ph.D. degree in the area of power electronics in the Department of Applied Electronic Engineering.

His major fields of interest include current control of three-phase photovoltaic grid-connected power systems, high-performance voltage-source inverters, and unified power quality conditioners.

Bangyin Liu received the B.S. and M.S. degrees in electrical engineering from Huazhong University of Science and Technology, Wuhan, China, in 2001 and 2004, respectively, where he is currently working toward the Ph.D. degree in the Department of Applied Electronic Engineering.

His major research interests include renewable energy applications and soft-switching converters.

Yong Kang received the B.Eng., M.Eng., and Ph.D. degrees in electrical engineering from Huazhong University of Science and Technology, Wuhan, China, in 1988, 1991, and 1994, respectively.

In 1994, he joined Huazhong University of Science and Technology as a Lecturer. He is currently a Professor. He has authored more than 60 technical papers. His research interests include power electronic converters, ac drives, distributed power systems, electromagnetic compatibility, and their digital control techniques.

Dr. Kang received the honor of “Delta Scholar” in 2005.