UC Irvine

UC Irvine Previously Published Works

Title

A new maximum power point tracking controller for photovoltaic power generation

Permalink

<https://escholarship.org/uc/item/6mx4w5xc>

Authors

Chen, Y
Smedley, K
Vacher, F
[et al.](#)

Publication Date

2003

DOI

10.1109/apec.2003.1179176

Copyright Information

This work is made available under the terms of a Creative Commons Attribution License, available at <https://creativecommons.org/licenses/by/4.0/>

Peer reviewed

A New Maximum Power Point Tracking Controller for Photovoltaic Power Generation

Yang Chen, Keyue Smedley, Francois Vacher

Dept. of Electrical and Computer Engineering
University of California, Irvine
Irvine, CA 92697, USA
smedley@uci.edu

Jack Brouwer

Advanced Power & Energy Program
University of California, Irvine
Irvine, CA 92697, USA
jb@nferc.uci.edu

Abstract—This paper proposes a new maximum power point tracking (MPPT) method in combination with One-cycle control for photovoltaic power generation. This control scheme is based on the automatic current-adjusting feature of One-cycle control. The output current of the inverter can be adjusted according to the voltage of the photovoltaic (PV) array so as to extract the maximum power from it. In the mean time, One-cycle control guarantees that the output current is in the same shape of and in phase with the grid voltage. All these are accomplished in one power stage and a simple control circuit. No detection and calculation of power are needed. Compared with previously proposed approaches, this method is much more efficient and more cost-effective and yet exhibits excellent performance. The principle is explained qualitatively and extensive experiments have been carried out to verify and validate the proposed method.

Keywords—One-cycle control; maximum power point tracking; MPPT; photovoltaic; PV

I. INTRODUCTION

Photovoltaic (PV) power generation is very desirable since it is renewable and does not contribute to pollution or global climate change. PV is especially attractive for applications in where sunshine is available for most of the year. The commercial viability of PV power generation, however, heavily relies on further improvement of conversion efficiency and reduction of the cost. The effort presented in this paper aims to realize input maximum-power-point tracking (MPPT) and output sinusoidal current injection to the utility grid with a simple and cost effective power electronic solution.

Since the output power of a PV array varies according to the sunlight conditions, atmospheric conditions, including cloud cover, local surface reflectivity, and temperature, MPPT is necessary in order to extract the maximum power from the array at all times. Typically, a PV system employs two-stages of power conversion to transfer the solar power to grid lines: a DC/DC converter is controlled so as to track MPP; and a DC/AC inverter produces a sinusoidal current which is in phase with the grid voltage. This type of system is large, heavy, and expensive, with many components that lead to increased maintenance and reliability concerns. Various approaches have been reported to implement MPPT. The Perturb and Observe (P&O) method needs to calculate dP/dV to determine the maximum power point (MPP) [1,2]. Though it is relatively simple to implement,

it can't track the MPP when the irradiance changes rapidly; and it oscillates around the MPP instead of directly tracking it. The Incremental Conductance method can track MPP rapidly but increases the complexity of the algorithm, which employs the calculation of dI/dV [3]. Though this method can get accurate MPPs, a digital signal processor (DSP) or a microprocessor is usually needed for these complex calculations. The Constant Voltage method [4], which uses 76% open circuit voltage as the MPP voltage, and the Short-Circuit Current method [5] are simple, but they do not always accurately track MPPs.

A single-stage PV generation system was presented by Liang et al. [6], but it needs nontrivial calculations for MPPT and the control loop is complex.

In this paper, a new MPPT control method integrated with One-cycle control is presented. There is only one power conversion stage that realizes both MPPT control and dc-ac inversion. With the proposed controller, the new PV power generation system features:

- 1) Constant switching frequency;
- 2) Low output current harmonics and $PF \approx 1$;
- 3) Accurate maximum input power point tracking;
- 4) A simple main circuit with one stage power conversion;
- 5) A simple controller that only needs some linear components, no DSP, and no multipliers;
- 6) Potential for low cost and high efficiency.

In the following sections, the basic principle of One-cycle control is introduced. Then the new MPPT control method is explained qualitatively. Finally, the experimental results are presented to prove the concept and validate the proposed method.

II. POWER STAGE CIRCUIT AND ONE-CYCLE CONTROL

Fig.1 shows the PV power generation system that is comprised of a PV array, a DC bus buffer capacitor, and an H-bridge inverter. The output is directly connected to the utility grid (grid voltage V_o), and the power flows from the PV array to

Figure 1. Power stage circuit.

grid. The H-bridge inverter can be decoupled into a buck converter in each half line cycle with $M_1 \sim M_4$ operating at the switching frequency [7].

During the first half line cycle ($0 \sim T/2$), V_o is positive. Switch M_3 is kept on and M_2 & M_4 off in this entire region while switch M_1 is controlled at the switching frequency. Fig. 2(a) shows the decoupled buck converter. Similarly, when V_o is negative, M_2 is kept on, M_1 & M_3 off and M_4 is controlled at the switching frequency in the second half line cycle ($T/2 \sim T$). Fig. 2(b) shows the equivalent buck converter.

(a) The positive half cycle

(b) The negative half cycle

Figure 2. Equivalent circuits of the inverter

For a buck converter:

$$V_o = V_g \cdot D \quad (1)$$

where, D is the duty ratio.

The control goal is to force the output current i_o to follow the grid AC voltage V_o . Thus, a unity power factor can be achieved. The control goal equation is:

$$V_o = i_o \cdot R_e \quad (2)$$

where R_e is the emulated resistance, which is related to the output power level. Equation (2) can be rewritten as:

$$i_o = \frac{V_o}{R_e} = (K_1 - K_2)V_o \quad (3)$$

where K_1 and K_2 are introduced as positive constants that determine the power level: K_1 limits the maximum output power, and K_1 & K_2 together determine the real output power. Considering the current sensing resistance R_s , (3) becomes:

$$R_s \cdot i_o = R_s \cdot K_1 \cdot V_o - R_s \cdot K_2 \cdot V_o \quad (4)$$

Substituting (2) into (3) and letting $K = R_s \cdot K_1$, $V_m = R_s \cdot K_2 \cdot V_g$, equation (4) becomes:

$$R_s \cdot i_o = K \cdot V_o - V_m \cdot D \quad (5)$$

where, K is an introduced constant, and V_m ($V_m > 0$) is constant during each line cycle. The unity power factor of the system can be achieved by controlling the current to satisfy the control key equation (5), which can be implemented by One-cycle control as shown Fig. 3.

III. PROPOSED MPPT CONTROLLER INTEGRATED WITH ONE-CYCLE CONTROL METHOD

Fig.3 shows the MPPT controller integrated with the One-cycle control method. The One-cycle controller is comprised of an integrator with reset, a comparator, a flip-flop and other linear components. The MPPT is implemented by an adder in front of the One-cycle controller.

At the beginning of each switching cycle, the clock sets the flip-flop high ($Q=1, \bar{Q}=0$) to turn on switch M_1 of

Figure 3. MPPT controller with One-cycle control method

Fig. 2 (for example, in the positive half line cycle) and turn off the Reset switch of Fig. 3. The current i_o starts to increase in this state. Meanwhile, the output voltage of the integrator decreases ($-V_m \cdot t / T_s < 0$). When $R_s \cdot i_o$ reaches the ramp signal ($K V_o - V_m \cdot t / T_s$) at $t = DT_s$, the comparator changes its state and the flip-flop is reset correspondently. At this point, switch M_1 is turned off and the integrator is reset. The current i_o subsequently decreases and the output of integrator is kept zero until the next clock signal comes. In this manner, the output current i_o is controlled to the same shape and is maintained in phase with the grid voltage V_o . The operation waveforms for this configuration are shown in Fig. 4.

Figure 4. Operation waveforms

The output power of the inverter P_o is a function of two parameters: K determines the up-bound of i_o , which limits the maximum output power; and K and V_m together determine the real output power. Normally, K is fixed according to the output power level. MPP tracking can be realized by automatically adjusting V_m according to environmental factors.

In Fig. 3, during the period between 0 and DT_s of each switching cycle,

$$V_m = \frac{V_c - K_g V_g}{R_1 C_1} T_s \quad (6)$$

where, $R_1 C_1 < T_s$, K_g is a constant and V_c is a DC voltage.

$$\Delta V_m = -\frac{T_s}{R_1 C_1} \cdot K_g \Delta V_g \quad (7)$$

Thus, a small change in the PV array voltage V_g causes V_m to change sufficiently, leading to a change in the output power P_o . By this means, the circuit can work stably at the MPP and track it automatically.

Fig. 5 shows how the operating points work steadily at the MPP. V_g is the output voltage and $P_g (= V_g \cdot I_g)$ is the power generated by the PV array.

Figure 5. Operating principle at MPPs

If the operating point is first set at the maximum power point (MPP₁) and a small perturbation moves the MPP left into Region I, V_g decreases. According to (6), V_m increases and so i_o decreases significantly. Since V_o doesn't change, the output power P_o of the inverter decreases significantly while P_g doesn't drop much for this same perturbation. Since the input power is larger than the output power at the DC bus capacitor C , V_g tends to increase, which pulls the operating point back to MPP₁. On the contrary, if the perturbation makes the operating point move to the right of MPP₁ into Region II, V_g increases. This causes V_m to decrease, and initiates large increases in i_o and P_o while P_g doesn't increase. As a result, V_g on the capacitor C tends to decrease, which pulls the operating point back to MPP₁ again.

Therefore, the system design inherently stabilizes the operating point at the MPP.

If the P-V curve moves up (for example, when the solar irradiance rises), P_g will increase while P_o remains unchanged because V_g doesn't change immediately. Then the voltage V_g on C will rise, which results in an increase in P_g . So the operating point moves up and to the right, towards a new MPP (for example MPP_2). On the contrary, if the P-V curve moves down (for example, when the solar irradiance drops), P_g will decrease while P_o remains unchanged. In this case V_g will fall, which results in the decrease of P_g . As a result, the operating point moves down and to the left, towards another MPP (for example MPP_3). In this way, the MPPT controller can automatically adjust the operating point towards MPPs according to the change of environmental factors. Fig. 6 presents an example of how this MPP tracking scheme works.

Figure 6. MPP tracking scheme

IV. EXPERIMENTAL RESULTS

Based on the above theoretical analysis, a 600W experimental system (Fig. 7) was designed and implemented as follows. Fig. 7 presents a photograph of the system that was installed on the rooftop of the Engineering Laboratory Facility at University of California, Irvine. The system is comprised of 8 panels installed at a 45° angle of incidence and facing roughly 15° east of due south. This configuration was decided based upon building orientation, yearly average angle of direct solar incidence, and needs for sturdy mounting of the support structure. This orientation is not optimized for the months of October and November in Southern California, when the experiments were conducted.

Specifications of the PV panels used in the experiments are presented in Table I. Note that each of the PV array modules is specified to produce 75W of peak power with direct irradiance levels of 1000W/m² of spectrum AM 1.5 when the cells are at 25°C.

Figure 7. PV array comprised of 8 PV modules

TABLE I. SPECIFICATIONS OF THE PV ARRAY MODULE (8 MODULES USED IN THE CURRENT EXPERIMENT)

PV module : Shell SP75	Specifications for each panel
Peak power	75W
Peak power current	4.4A
Open circuit voltage	21.7V

The 8 individual array modules were connected in series to produce a peak, open circuit voltage potential of 173.6V (for conditions of the specifications). Specifications of other system parameters are as follows:

Switching frequency: $f_s = 33$ kHz;

DC bus capacitor: $C = 3$ mF;

Inductor $L = 1.65$ mH;

$V_c = 5.28$ V; $K_g = 0.037$; $R_1 \cdot C_1 = 2.43$ μ s;

$R_s = 1.78$ Ω ; $K = 0.065$;

Fig. 8 shows the actual power P_g drawn from PV and P_{max} at MPPs. (All the data are based on the experiments on November 19, 2002, Irvine CA. It was sunny 12-28 °C, winds ENE at 10 to 15 mph.) They are very close to each other. Due to the temperature effect, there is still a relative error (4.5% at the largest) at some points. The method to include the temperature factor in MPPT is still in consideration.

Figure 8. P_g and P_{max} vs. time

Fig. 9 shows a representative sample of the output voltage V_o and current i_o (tested at 9:25 AM on the same day) of the inverter system described above. Because the typical output of the PV panels is not sufficient to supply a voltage that can be directly inverted to the line voltage by the H-bridge inverter (the range of voltage experienced during the experimental period was 0-165V), the output was connected to the AC power grid via an autotransformer in this experiment. The resistance of the autotransformer causes some distortion to the waveform presented in Fig. 9. In Fig. 9, $V_o = 79.7V$ (rms), $i_o = 4.4A$ (rms) $P_o = 350.7W$ and $\eta = 95.6\%$. The THD of i_o is 5.769% (note that the grid voltage V_o itself has a THD of 5.215%).

Figure 9. Output voltage V_o (curve 1, 100V/div) and i_o (curve 2, 10A/div)

V. CONCLUSIONS

In this paper, a new MPPT control method combined with One-cycle control is proposed. The MPPT controller can automatically adjust the operating point of the PV system to the MPP according to changes in environmental factors. In the mean time, the output current of the inverter is sinusoidal with unity power factor. The system is simple and efficient comprised of only one power stage and one simple controller to implement two functions: MPPT and dc/ac inversion. Due to this simple control circuit, this method shows promise for reducing the cost and complexity and increasing the efficiency for commercial PV systems. The approach could also be applied to fuel cells or other distributed generation technologies that also need simple and efficient inverter technology.

ACKNOWLEDGMENT

The authors thank Mr. Michael D. Crespin, a technician at the National Fuel Cell Research Center of University of California, Irvine, for his assistance in the PV array installation.

REFERENCES

- [1] O. Wasynczuk, "Dynamic behavior of a class of photovoltaic power systems," *IEEE Trans. Power App. Syst.*, vol. PAS-102, pp. 3031-3037, Sept. 1983
- [2] E.Koutroulis, K.Kalaitzakis, N.C.Voulgaris, "Development of a Microcontroller-Based, Photovoltaic Maximum Power Point Tracking Control System", *IEEE Transactions on Power Electronics*, Vol.16, No.1, pp.46-54, January 2001
- [3] K.H.Hussein, I.Muta, "Maximum Photovoltaic Power Tracking: An Algorithm for Rapidly Changing Atmospheric Conditions", *IEEE Proceedings on Generation, Transmission, and Distribution.*, Vol.142, No.1, pp.59-64, January 1995
- [4] T. Noguchi, S. Togashi, R.Nakamoto, "Short-Current Pulse-Based Adaptive Maximum-Power-Point Tracking for a Photovoltaic Power Generation System", *Electrical Engineering in Japan*, Vol.139, No.1, pp65-72, 2002[*Denki Gakkai Ronbunshi*, Vol.121-D, No.1, pp.78-83, January 2001]
- [5] J.H.R.Enslin, M.S.Wolf, D.B.Snyman, W.Swiegers, "Integrated Photovoltaic Maximum Power Point Tracking Converter", *IEEE Transactions on Industrial Electronics*, Vol.44, No.6, pp.769-773, December 1997
- [6] T.J.Liang, Y.C. Kou, J.R.Chen, "Single-Stage Photovoltaic Energy Conversion System", *IEE Proceedings on Electrical Power Application*, Vol.148, No.4, pp339-344, July 2001
- [7] Y.Chen, K.Smedley, "High Power Quality Inverter for Renewable Energy Power Generation", 6th IASTED International Conference on Power and Energy Systems, pp.414-418, May 2002