Implementation of a DSP-Controlled Photovoltaic System with Peak Power Tracking

Chihchiang Hua, Member, IEEE, Jongrong Lin, and Chihming Shen

Abstract—Photovoltaic systems normally use a maximum power point tracking (MPPT) technique to continuously deliver the highest possible power to the load when variations in the insolation and temperature occur. It overcomes the problem of mismatch between the solar arrays and the given load. A simple method of tracking the maximum power points (MPP’s) and forcing the system to operate close to these points is presented. The principle of energy conservation is used to derive the large- and small-signal model and transfer function. By using the proposed model, the drawbacks of the state-space-averaging method can be overcome. The T1320C25 digital signal processor (DSP) was used to implement the proposed MPPT controller, which controls the dc/dc converter in the photovoltaic system. Simulations and experimental results show excellent performance.

Index Terms—DC/DC converter, digital signal processor, maximum power point tracking, photovoltaic system, principle of energy conservation, solar array, state-space-averaging method.

I. INTRODUCTION

As conventional sources of energy are rapidly depleting and the cost of energy is rising, photovoltaic energy becomes a promising alternative source. Among its advantages are that it is: 1) abundant; 2) pollution free; 3) distributed throughout the earth; and 4) recyclable. The main drawbacks are that the initial installation cost is considerably high and the energy conversion efficiency is relatively low. To overcome these problems, the following two essential ways can be used: 1) increase the efficiency of conversion for the solar array and 2) maximize the output power from the solar array. With the development of technology, the cost of the solar arrays is expected to decrease continuously in the future, making them attractive for residential and industrial applications.

Various methods of maximum power tracking have been considered in photovoltaic power applications [1]–[8]. Of these, the perturbation and observation method (P&O), which moves the operating point toward the maximum power point by periodically increasing or decreasing the array voltage, is often used in many photovoltaic systems [3]–[6]. It has been shown that the P&O method works well when the insolation does not vary quickly with time; however, the P&O method fails to quickly track the maximum power points.

The incremental conductance method (IncCond) is also often used in photovoltaic systems [7], [8]. The IncCond method tracks the maximum power points by comparing the incremental and instantaneous conductances of the solar array. The incremental conductance is estimated by measuring small changes in array voltage and current. These small changes may be induced by deliberate control action. A method which improves the IncCond method and can identify the incremental conductance of the array more rapidly has been proposed [9]. However, the harmonic components of the array voltage and current need to be measured and used to adjust the array reference voltage.

The MPPT control using a microprocessor with two-loop control [3] is very complex in the circuit implementation. A method which regulates the output power by changing the number of batteries [6] requires extra hardware circuits. Neglecting the variations in output voltage, the approach using only an output current measurement simplifies the control circuits by eliminating the need to sense and multiply voltage and current. However, this approach does not track the maximum power points rapidly and accurately.

In this paper, a photovoltaic system using a digital signal processor (DSP) is proposed. The P&O method is implemented in a software program with a self-tuning function, which automatically adjusts the array reference voltage and voltage step size to achieve the maximum power tracking under rapidly changing conditions. With a DSP-based controller, maximum power tracking can be achieved rapidly and accurately by increasing the sampling frequency. The controller features MPPT, battery charge regulation, and eclipse shutdown.

The state-space-averaging method [9] is widely used to derive expressions for small-signal characteristics of pulsewidth-modulated (PWM) converters [9], [10]. However, this method is sometimes tedious, especially when the converter equivalent circuit contains a large number of elements. To obtain the models of dc/dc converters, the principle of energy conservation is used in this paper to derive the model and transfer function for the system [11]. The models are especially convenient in analyzing complicated converter topologies and for including parasitic components.

II. SOLAR ARRAYS CHARACTERISTIC ANALYSIS

The electric power generated by a solar array fluctuates depending on the solar radiation value and temperature, as...
shown in Fig. 1. The solar array characteristics significantly influence the design of the converter and the control system, therefore, these will be briefly reviewed here. The solar array is a nonlinear device and can be represented as a current source model, as shown in Fig. 1(a).

The traditional $I$–$V$ characteristics of a solar array, when neglecting the internal shunt resistance, is given by the following equation [2]:

$$I = I_0 - I_{sat} \left\{ \exp \left[ \frac{q}{AKT} (V_o + I_o R_s) \right] - 1 \right\}$$  

(1)

where $I_0$ and $V_o$ are the output current and output voltage of the solar array, respectively, $I_o$ is the generated current under a given insolation, $I_{sat}$ is the reverse saturation current, $q$ is the charge of an electron, $K$ is the Boltzmann’s constant, $A$ is the ideality factor for a p-n junction, $T$ is the temperature (K), and $R_s$ is the intrinsic series resistance of the solar array.

The saturation current ($I_{sat}$) of the solar array varies with temperature according to the following equation [2]:

$$I_{sat} = I_{sat} \left[ \frac{T_r}{T} \right]^3 \exp \left[ \frac{qE_GO}{KT} \left( \frac{1}{T_r} - \frac{1}{T} \right) \right]$$  

(2)

$$I_o = [I_{sc} + KT_r(T_r - 25)] \frac{\lambda}{100}$$  

(3)

where $I_{sat}$ is the saturation current at $T_r$, $T$ is the temperature of the solar array (K), $T_r$ is the reference temperature, $E_GO$ is the band-gap energy of the semiconductor used in the solar array, $K_T$ is the short-circuit current temperature coefficient and $\lambda$ is the insolation in mW/cm$^2$.

In the literature, instead of the $I$–$V$ characteristic given by (1), the following $I$–$V$ characteristic is used in many cases:

$$V_o = -I_o R_s + \frac{AKT}{q} \ln \left[ \frac{I_o - I_0 + I_{sat}}{I_{sat}} \right]$$  

(4)
Equations (1)–(3) are used in the development of computer simulations for the solar array. The Matlab programming language is used. Fig. 1(b) and (c) shows the simulated amper–volt and power–volt curves for the solar array at different insulations and different temperatures. From these curves, it is observed that the output characteristics of the solar array is nonlinear and vitally affected by the solar radiation, temperature, and load condition. Each curve has a maximum power point $P_{MAX}$, which is the optimal operating point for the efficient use of the solar array. When the temperature rises, the open-circuit voltage and the maximum power fall, but the short-circuit current increases slowly, as shown in Fig. 1(d).

III. MPPT PROCESS AND CONTROL ALGORITHMS

A. MPPT Process

Fig. 2(a) illustrates the electrical characteristics of the solar array under a given insolation. The internal impedance of the solar array is low on the right side of the curve and high on the left side. The maximum power point of the solar array is located at the knee of the curve. According to the maximum power transfer theory, the power delivered to the load is maximum when the source internal impedance matches the load impedance. Thus, the impedance seen from the converter side (which can be adjusted by controlling the duty cycle) needs to match the internal impedance of the solar array if the system is required to operate close to the MPP’s of the solar array.

Most traditional dc/dc converters have a negative impedance characteristic inherently, due to the fact that their current increases when voltage decreases. This behavior is due to the constant input power and the adjustable output voltage of the power supply. If the system operates on the high-impedance (namely, low-voltage) side of the solar array characteristic curve, the solar array terminal voltage will collapse. Therefore, the solar array is required to operate on the right side of the curve to perform the tracking process. Otherwise, the converter will operate with the maximum duty cycle, and the solar array voltage will only change with the insolation. Thus, the system cannot achieve maximum power tracking and might even mistake the present operating point for the MPP.

The control flowchart of the maximum power tracking system shown in Fig. 2(b) illustrates the details of decision processes. If a given perturbation leads to an increase (decrease) in array output power, the next perturbation is made in the same (opposite) direction. In this way, the maximum power tracker continuously seeks the maximum power point.

B. Control Algorithms for MPPT

Many control algorithms for MPPT have been proposed [1]–[8]. Two algorithms often used to achieve the maximum power point tracking are: 1) the perturbation and observation method and 2) the incremental conductance method. Although the incremental conductance method offers good performance under rapidly changing atmospheric conditions, four sensors are required to perform the measurements for computations and decision making [8]. If the sensors or the system require more conversion time, a large amount of power loss will result. On the contrary, if the sampling and execution speed of the perturbation and observation method is increased, then the system loss will be reduced. Moreover, this method only needs two sensors, which results in the reduction of hardware requirement and cost. Therefore, the perturbation and observation method was used in this paper to control the output current and voltage of the solar arrays.

Two different control variables are often chosen to achieve the maximum power control [7].

1) Voltage Feedback Control: This method assumes that any variations in the insolation and temperature of the array are insignificant and that the constant reference voltage is an adequate approximation of the true maximum power point. The solar array terminal voltage is used as the control variable for the system. The system keeps the array operating near its maximum power points by regulating the array voltage and matches the array voltage to a fixed reference value. The control method is simple; however, it has the following drawbacks.
1) It neglects the effect of the insolation and temperature of the solar array.

2) It cannot be widely applied in the battery energy storage systems.

Therefore, the control is only suitable for use under the constant insolation condition, such as a satellite system, because it cannot track the maximum power points of the array when variations in the insolation and temperature occur.

2) Power Feedback Control: The actual array power, instead of its estimate from measurements of other quantities, is used as the control variable. Maximum power control can be achieved by forcing the derivative \( \frac{dP}{dV} \) equal to zero under the power feedback control. A general approach to the power feedback control is to measure and maximize the power at the load terminal. However, it maximizes the power to the load, not the power from the solar array. A converter with MPPT offers high efficiency over a wide range of operating points. The full power may not be delivered to the load completely, due to the power loss for a converter without MPPT. Therefore, the design of a high-performance converter with MPPT is a very important issue.

IV. SYSTEM MODEL AND CONTROL

A. System Model

The states-space-averaging approach [9] is widely used to derive the expressions and analysis for the small-signal characteristics of PWM-controlled dc/dc converters. It can predict the dynamic performance of the PWM converters. However, this approach has a drawback, in that the computation process is very complicated when the converter equivalent circuit contains a large number of elements (including the parasitic components). The principle of energy conservation [11] is used in this paper to derive the circuit model and transfer function, which has the following advantages.

1) Switched resistors are replaced by the equivalent averaged resistors.

2) It can be used in multiswitch circuits.

3) It can be easily applied in a circuit which consists of many nonswitch elements.

4) The simulation and analysis of the circuit model is easy.

Fig. 3(a) shows the buck converter and the equivalent circuit; two switches can be combined into one network with three terminals \( s, d, \) and \( g \), which stand for active, passive, and common, respectively. The three-terminal network is called the PWM switch. Fig. 3(b) and (c) shows the waveforms for the terminal voltages and currents of the PWM switch operating in the continuous conduction mode, where “_” designates the instantaneous value of the variable.

Fig. 4(a) and (b) shows the system power circuit and the equivalent circuit model when it operates in continuous-current mode (CCM) under PWM control. This model includes the parasitic components and can be used for the analysis of the system under different modes. \( r_{DS} \) is the resistance of the transistor, \( V_F \) is the threshold voltage of the diode, \( r_F \) is the forward resistance of the diode, \( r_L \) is the equivalent series resistance (ESR) of the inductor, \( r_C \) is the equivalent series resistance (ESR) of the capacitor, and \( r_s \) is the equivalent resistor of the solar array. The large-signal and small-signal model of the system can be obtained as shown in Fig. 4(d) and (e).

The small-signal equivalent circuit analysis of the buck converter is carried out with the following assumptions.

1) The ripple of input current is neglected.

2) The ESR of the capacitor is neglected.

The inductor current, as shown in Fig. 4(b), is expressed as

\[
\tilde{i}_L(t) = \begin{cases} 
\frac{\Delta i_L}{D T_S} t + I_L - \frac{\Delta i_L}{2}, & 0 < t \leq D T_S \\
-\frac{\Delta i_L}{(1-D) T_S} (t - DT_S) + I_L + \frac{\Delta i_L}{2}, & DT_S < t \leq T_S
\end{cases}
\]  

(5)

where \( \Delta i_L \) is the peak-to-peak ripple current of the inductor.

1) Switch Loss: The switch current is approximately \( \tilde{i}_L \) during the switch ON interval \( (0 < t \leq DT_S) \), and the rms
value of the switch current is

\[ I_{S,\text{rms}} = \sqrt{\frac{1}{T_S} \int_0^{DT_S} \overline{i_S^2} \, dt} \]

\[ = I_S \sqrt{\frac{1 + K_I^2}{D}} \]

where \( K_I = \frac{V_B(1 - D)T}{\sqrt{2} I_L} \) and \( I_S \) is the average of \( i_S \); thus, the loss of the switch is

\[ P_S = I_{S,\text{rms}}^2 \times r_{DS} \]

\[ = I_D^2 \times r_{DS} \times \frac{1 + K_I^2}{D}. \]

2) Diode Loss: The diode current is approximately \( \bar{i}_D \) during the diode ON interval \( (DT_S < t \leq T_S) \), and the rms value of the diode current is

\[ I_{D,\text{rms}} = \sqrt{\frac{1}{T_S} \int_{DT_S}^{T_S} \overline{i_D^2} \, dt} \]

\[ = I_D \sqrt{\frac{1 + K_I^2}{1 - D}} \]

where \( I_D \) is the average of \( \bar{i}_D \); thus, the loss of the diode is

\[ P_D = I_{D,\text{rms}}^2 \times R_F \]

\[ = I_D^2 \times R_F \times \frac{1 + K_I^2}{1 - D}. \]

3) Inductor Loss: The rms value of the inductor current is

\[ I_{L,\text{rms}} = \sqrt{\frac{1}{T_S} \int_{DT_S}^{T_S} \overline{i_L^2} \, dt} \]

\[ = I_L \sqrt{\frac{1 + K_I^2}{1 - D}} \]

where \( I_L \) is the average of \( i_L \); thus, the loss of the inductor is

\[ P_L = r_L \times I_{L,\text{rms}}^2. \]

The reflection rule can be applied to move parasitic components from one branch to another, which results in another equivalent-circuit model, as shown in Fig. 4(c). In Fig. 4(c), \( r \) is the equivalent averaged resistance and can be expressed as

\[ r = \left[r_L + D \times r_{DS} + (1 - D) \times R_F\right] \times \left(1 + K_I^2\right). \]
as shown in Fig. 4(d) and (e), and the nonlinear terms are neglected.

4) Transfer Function: The charging voltage usually rises slowly, therefore, the voltage is assumed constant as seen from the battery side. The disturbance of the voltage is represented by a voltage perturbation $\tilde{V}_B$. The solar array is taken as a current source, thus, the solar array terminal voltage has to be adjusted to deliver the maximum power. The effect of a small perturbation of solar array terminal voltage to system stability has to be considered carefully. The small-signal model of the control-to-output transfer function is expressed as

\[
T_p(S) = \frac{V_0}{d} \bigg|_{V_B=0},
\]

From the circuit in Fig. 4(e),

\[
v_0 = -(D\dot{q} + dI_L) \times \frac{r_s \times (r_c cs + 1)}{r_s cs + r_c cs + 1},
\]

\[
\dot{q} = \frac{Dv_0 + dV_O}{r + sL}.
\]

Substitution of (16) into (15) yields

\[
v_0 = -\left( D \times \frac{Dv_0 + dV_O}{r + sL} + dI_L \right) \times \frac{r_s \times (r_c cs + 1)}{r_s cs + r_c cs + 1},
\]

\[
\left[ 1 + \frac{D^2}{r + sL} \times \frac{r_s \times (r_c cs + 1)}{(r_s + r_c)cs + 1} \right] \dot{v}_0 = \]

\[
-\left( \frac{Dv_0 + dV_O}{r + sL} + I_L \right) \times \frac{r_s \times (r_c cs + 1)}{(r_s + r_c)cs + 1} \times d.
\]

B. System Control

Fig. 5 shows the power circuit and the flowchart of the proposed control. The system consists of a nonlinear current

- (a) Photovoltaic power system circuit. (b) System control flowchart.

- (a) Control-to-output characteristics with a PI compensator. (a) Root loci. (b) Bode plot.

Rearranging (18) gives

\[
T_p(S) = \frac{V_0(s)}{d(s)} \bigg|_{V_B=0}
= \frac{V_0r_c}{D(r_s + r_c)} \cdot \frac{(S + \omega_c)(S + \omega_t)}{S^2 + 2\xi\omega_t S + \omega_t^2}
\]

where

\[
\omega_c = \frac{1}{r_c}
\]

\[
\omega_t = \frac{1}{L} \left( D^2 r_s - r \right)
\]

\[
\xi = \frac{r_s + r_c + \sqrt{LC(r_s + r_c)(r + r_c D^2)}}{2LC(r_s + r_c)(r + r_c D^2)}
\]

and $r_s$ is the output resistance of the solar array.
source, a dc/dc converter, a battery set, and a digital control circuit based on a DSP. System control consists of two loops; the maximum power point tracking loop is used to set a corresponding $V_{ref}$ to the charger input, and the battery charge regulation loop is used to regulate the solar array output voltage according to the $V_{ref}$, which is set in the MPPT loop. The functions in the two loops are performed by a DSP. The DSP-based controller senses the solar array current and voltage and calculates the solar array output power, power slope, and to track the MPP.

The control algorithm can be expressed as the following equation:

$$V_{ref}(k + 1) = V_{ref}(k) \pm C.$$  \hfill (24)

The $C$ is the amount of disturbance and the sign of $C$ is determined by the power slope. In the battery regulation loop, the proportional-integral (PI) compensator is used to improve the system stability.

V. SIMULATIONS AND EXPERIMENTAL RESULTS

The proposed photovoltaic system is implemented using a digital controller based on the Texas TMS320C25 DSP, as shown in Fig. 5(a). The system consists of a nonlinear current source as the power source, a dc/dc converter power stage as the power processing unit, a battery set as the load, and a DSP-based circuit as the controller. The digital controller consists of two A/D converters, a digital signal processor, and a gate drive circuit.

The prototype photovoltaic peak power tracking converter and the DSP controller were built and tested. Sixteen modules of solar arrays (Solarex MSX60) are used in the system. Each module has a maximum power output of 60 W. The electrical characteristics of the solar module are shown in Table I. The controller software was written in assembly language. This code was tested and debugged using the TMS320 simulator running on the host PC. Finally, the software was downloaded to the DSP’s memory for use with the external hardware.

The system is found to be unstable, and its phase margin is very poor without a PI compensator. Fig. 6 shows the
Fig. 9. (a) Simulated and experimental results for maximum power tracking (at 60 °C). (b) Waveforms of dc/dc converter under the MPPT control.

(a) 
(b)

improvement of the system using a PI compensator; the root loci stays in the unit circle and the phase margin of Bode diagram is better. Fig. 7 shows the simulated result of the system with the PI compensator while the insolation is changing linearly and the temperature is at 25 °C. The MPPT process moves along a zig-zag path close to the maximum power points of the array.

Fig. 8 shows the simulated and experimental results of the MPPT for the system at 50 °C and insolation variations between 70–77.5 mW/cm². Fig. 9(a) shows the simulated and experimental results for the system at 60 °C. Fig. 9(b) shows the solar array voltage and current waveforms. Simulation results are very close to experimental results. Fig. 10 shows the experimental result of the MPPT for the system under the condition of T = 60 °C and λ = (30–90) mW/cm². The rapid changes in the solar power and solar voltage are observed in both figures, and the array output power follows the insolation step by step when rapid changes occur in the insolation. It is shown that increasing the execution speed of the perturbation and observation method makes the system able to follow the rapid changes of the insolation and achieve the maximum power transfer.

The efficiency of the converter with the proposed MPPT control stays higher than 90% under various conditions. The

<table>
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<tr>
<th>TABLE I</th>
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<tr>
<td>ELECTRICAL CHARACTERISTICS FOR SOLAR MODULE (MSX-60)</td>
</tr>
<tr>
<td>Maximum Power (watts)</td>
</tr>
<tr>
<td>Open Circuit Voltage (V_oc) (Volts)</td>
</tr>
<tr>
<td>Short Circuit Current (I_sc)(Amp)</td>
</tr>
<tr>
<td>Voltage at Load (Volts)</td>
</tr>
<tr>
<td>Current at Load (Amps)</td>
</tr>
<tr>
<td>Length<em>Width (mm</em>mm)</td>
</tr>
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<td>Thickness(mm)</td>
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<tr>
<td>Weight (Kg)</td>
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efficiency of the converter is defined as
\[
\eta = \frac{P_{\text{ar}}}{P_{\text{in}}} = \frac{\text{input power to battery}}{\text{output power from solar array}},
\]  
(25)

VI. CONCLUSIONS

The purpose of maximum power tracking is to deliver the highest possible power to the load from the solar arrays. In this paper, the principle of energy conservation has been used to derive the system transfer function. The proposed control algorithm, which uses the power as the control variable based on the perturbation and observation method, only requires two sensors. A better response for the system under rapid atmospheric condition variations can be obtained by increasing the execution speed. The TMS320C25 DSP was used to implement the proposed MPPT controller, and simulated and experimental results verify the performance. The insolation is usually proportional to the business power, therefore, the incorporation of the proposed photovoltaic system with other power electronic equipment can be used in the applications of active power filters, power line conditioners, extra power supplies, uninterruptible power supply systems, and control of power systems.

REFERENCES


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