# Simple maximum power point tracker for photovoltaic arrays

Yan Hong Lim and D.C. Hamill

A new technique is presented for tracking the maximum power point (MPP) of solar arrays. Although the control circuit is extremely simple and robust, its dynamics are complex. The MPP becomes inherently the global attractor of the system, thus ensuring optimum operation under transient and steady-state conditions. Experimental results confirm excellent tracking effectiveness and rapid dynamic response.

*Introduction:* Solar arrays are used in many terrestrial and space applications. For best utilisation, the photovoltaic cells must be operated at their maximum power point (MPP). However, the MPP varies with illumination, temperature, radiation dose and other ageing effects. Most maximum power point trackers (MPPTs) are based on the perturb and observe approach (P&O), implemented by a hill climbing algorithm often on a microcontroller [1]. This approach is complex, can be slow and thus can become 'confused' if the MPP moves abruptly [2]. Alternatives to P&O have recently been suggested [2 – 4].

We have drawn on nonlinear dynamics to develop a control strategy that inherently makes the MPP the only attractor of the system, exhibiting a global basin of attraction. The system should inherently follow the MPP under steady-state and transient conditions, without imposition of any external control or perturbation. (Details of the derivation are beyond the scope of this Letter.)

The system to be considered is shown in Fig. 1. It comprises a solar array, a buck DC-DC converter feeding a battery, and a controller.

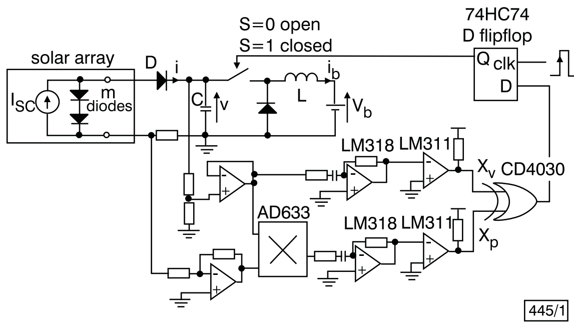


**Fig. 1** *Schematic diagram of proposed MPPT*

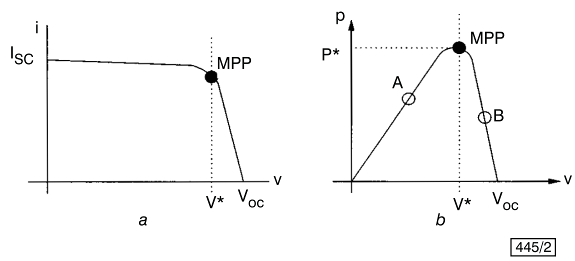


**Fig. 2** *Typical v-i and v-p characteristics of solar array*

*a v-i* characteristics
*b v-p* characteristics

*Solar array characteristics:* Typical voltage-current and voltage-power characteristics are shown in Fig. 2*a* and *b*, respectively. Assuming an evenly illuminated array of identical cells, each of which is modelled by the well-known exponential model of an ideal *pn* junction, the *v-i* characteristic of the array can be written

$$i(v) = I_{sc}\left(1 - \frac{\exp(v/V_{th}) - 1}{\exp(V_{oc}/V_{th}) - 1}\right) \qquad (1)$$

where $i$ and $v$ are the array's terminal current and voltage, and $I_{sc}$ and $V_{oc}$ are its short-circuit current and open-circuit voltage, respectively. The thermal voltage of the array is $V_{th} = mkT/q$, where there are $m$ cells in series, $k$ is Boltzmann's constant, $T$ is the absolute temperature and $q$ is the electronic charge. Eqn. 1 (Fig. 2*a*) gives a unimodal *v-p* characteristic (Fig. 2*b*); the MPP ($V^*$, $P^*$) is where $\partial p/\partial v = 0$, $p = vi$ being the power. The characteristic can be modelled electrically by a current source $I_{sc}$ shunted by $m$ diodes, as in Fig. 1. In practice, a blocking diode $D$ is connected in series with the array to prevent reverse terminal current, i.e. $i \in [0, I_{sc}]$. Here the diode is assumed ideal.

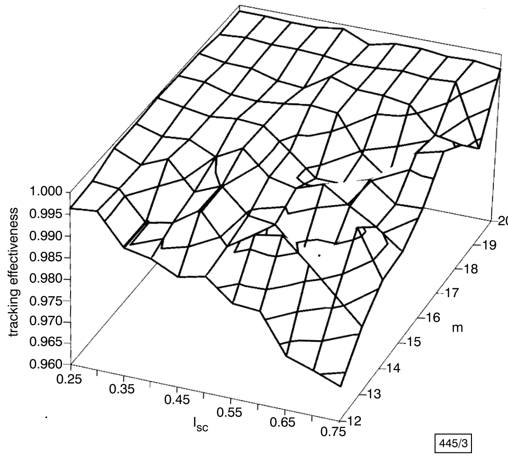


**Fig. 3** *Experimental tracking effectiveness against number of diodes (m) and short-circuit current ($I_{sc}$) of array*

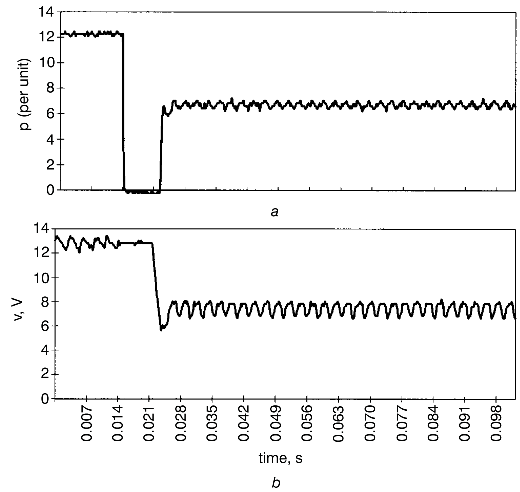


**Fig. 4** *Experimental waveforms of power p from output of multiplier and array voltage v*

Scenario with $I_{sc}$ = 0.75 A and switched from 20 to 12 diodes at $t$ = 0.014 s
*a* Power
*b* Array voltage

*Battery and DC-DC converter:* The battery is modelled as a voltage source $V_b$. The buck DC-DC converter, assumed ideal, impresses a voltage $v \in [V_b, V_{oc}]$ on the array. Assuming the inductance of the converter is sufficiently large to ensure operation in continuous conduction mode, the state equations of the converter are

$$dv/dt = (i - Si_b)/C \qquad (2)$$

$$di_b/dt = (Sv - V_b)/L \qquad (3)$$

where $S$ = 0 or 1 denotes switch open or closed, respectively.

*Controller:* A multiplier evaluates the power $p$ of the array. A first-order highpass filter with time constant $T$ yields an approximation $\dot{p_T}$ to its true time derivative, $\dot{p}$. The output is fed to a comparator, producing a binary signal $X_p$ the value of which is 0 if $\dot{p_T} \leq 0$ or 1 if $\dot{p_T} > 0$. The voltage $v$ is treated likewise, producing a second binary signal, $X_v$. The approximated derivatives can be expressed as

$$\dot{p_T} = \dot{p} - T\frac{d\dot{p_T}}{dt} \qquad (4)$$

$$\dot{v_T} = \dot{v} - T\frac{d\dot{v_T}}{dt} \qquad (5)$$

From eqns. 4 and 5, $T$ should be small to minimise the error. The filters add two state variables to the system.

The two comparator outputs are exclusive-ORed, then sampled by a D-type latch clocked at a constant frequency, $1/T_s$. The output of the latch provides the signal $S$ that drives the switch.

**Table 1**: Principle of controller operation

| Condition | $\dot{p}$ | $\dot{v}$ | Comparator output | | $S$ | Switch | $v$ |
|---|---|---|---|---|---|---|---|
| | | | $X_p$ | $X_v$ | | | |
| $v \le V^*$ | $> 0$ | $> 0$ | 1 | 1 | 0 | opens | increases |
| $v \le V^*$ | $\le 0$ | $\le 0$ | 0 | 0 | 0 | opens | increases |
| $v > V^*$ | $> 0$ | $\le 0$ | 1 | 0 | 1 | closes | decreases |
| $v > V^*$ | $\le 0$ | $> 0$ | 0 | 1 | 1 | closes | decreases |

*System operation:* The complete system is described by a four-dimensional nonlinear equation of the form $d\mathbf{x}/dt = \mathbf{f}(\mathbf{x}, t)$. This means it has the potential for complex dynamics, including chaos. However, the qualitative operation is straightforward. Each comparator has two states so there are four basic modes, displayed in Table 1. Consider point A in Fig. 2*b*, where $v < V^*$. If $v$ decreases, $p$ also decreases, retreating from the MPP. To counter this, the controller opens the switch so that $C$ can charge. This corresponds to row 2 of Table 1. With the switch open, $v$ now increases towards $V^*$, increasing $p$ and approaching the MPP as desired (row 1). By contrast, if $v > V^*$ (point B), the controller takes the reverse action, decreasing $v$ towards the MPP by closing the switch (rows 3 and 4).

Hence, the controller creates an inherent attractor at the MPP. However, it is impossible to reach the MPP exactly, because if $v = V^*$, the switch opens, making $v$ increase. However, this subsequently leads to the switch closing, making $v$ decrease; thus the voltage wanders around $V^*$. Limit cycles, quasi-periodicity and chaos are possible behaviours.

*Experimental verification of static tracking:* An experimental prototype was constructed, with the array simulated by a constant-current source of 0.25 A to 0.75 A shunted by a string of 12 to 20 diodes. The battery was simulated by a 4 V constant-voltage sink. The parameters used are: $L = 1.5$ mH, $C = 470$ µF, $T_s = 50$ µs and $T = 100$ µs.

A figure of merit for the static performance of an MPPT is its tracking effectiveness, defined as $P/P^*$ (ideally unity), where $P$ is the mean power extracted from the array and $P^*$ is the power available at its MPP under the same conditions.

With the controller disabled, and the buck converter driven by a pulse generator at a frequency $1/T_s$, the value of $P^* = \max(vi)$ was found by manual adjustment of the duty ratio. The controller was then enabled, and $P = vi$ was measured. Over most of the experimental range, the tracking effectiveness was better than 0.98, as shown in Fig. 3, and always better than 0.968.

*Experimental verification of dynamic tracking:* Apart from exhibiting good tracking effectiveness, an MPPT should also respond quickly to large abrupt changes to the MPP. This can be simulated by changing $I_{sc}$ or the number of diodes in the string. The performance can be measured by the settling time.

Two extreme scenarios are presented here. The first was performed with the full string of 20 diodes and $I_{sc}$ was switched from 0.25 A to 0.75 A, simulating a sudden increase in illumination. The settling time was ~5 ms. Next, with $I_{sc} = 0.75$ A, the number of diodes was reduced abruptly from 20 to 12 (simulating a sudden drop in $V_{oc}$). The response time was about 10 ms (Fig. 4). Other scenarios were tried and, in all cases, the MPP was reacquired within milliseconds.

*Conclusion:* We have proposed an MPPT derived from the principles of nonlinear dynamics. Excellent tracking effectiveness and rapid dynamic response are evidenced by experiment. Although its dynamics are complex and are presently under investigation, the circuit appeals because it is far simpler than most MPPTs, is robust and performs well.


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