Comparison of Photovoltaic Array Maximum Power Point Tracking Techniques

19 Methods, summary- pp. 75

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Abstract

The many different techniques for maximum power point tracking of photovoltaic (PV) arrays are discussed. The techniques are taken from the literature dating back to the earliest methods.

It is shown that at least 19 distinct methods have been introduced in the literature, with many variations on implementation. This paper should serve as a convenient reference for future work in PV power generation.
I. Introduction

- Tracking the maximum power point (MPP) of a photovoltaic (PV) array is usually an essential part of a PV system. As such, many MPP tracking (MPPT) methods have been developed and implemented.

- The methods vary in complexity, sensors required, convergence speed, cost, range of effectiveness, implementation hardware, popularity, and in other respects.
In fact, so many methods have been developed that it has become difficult to adequately determine which method, newly proposed or existing, is most appropriate for a given PV system.

Given the large number of methods for MPPT, a survey of the methods would be very beneficial to researchers and practitioners in PV systems.
Fig. 1 shows the total number of MPPT papers from our bibliography per year since the earliest MPPT paper we found. The number of papers per year has grown considerably of the last decades and remains strong.

Fig. 1. Total number of MPPT papers per year, since 1968.
This approach tends to repeat what seems to be conventional wisdom that there are only a handful of MPPT techniques, when in fact there are many. This is due to the sheer volume of MPPT literature to review, conflicting with the need for brevity.

This survey is a single reference of the great majority of papers and techniques presented on MPPT. We compiled over 90 papers pertaining to different MPPT methods published up to the date of submission of this manuscript. It is not our intention to establish a literal chronology of when various techniques were proposed, since the publication date is not necessarily indicative of when a method was actually conceived.
As is typical of review papers, we have elected not to reference patents. Papers referencing MPPT methods from previous papers without any modification or improvement have also been omitted. It is possible that one or more papers were unintentionally omitted. We apologize if an important method or improvement was left out.

This manuscript steps through a wide variety of methods with a brief discussion and categorization of each. We have avoided discussing slight modifications of existing methods as distinct methods.
For example, a method may have been first presented in context of a boost converter, but later on shown with a boost-buck converter, otherwise with minimal change. The manuscript concludes with a discussion on the different methods based on their implementation, the sensors required, their ability to detect multiple local maxima, their costs, and applications they suit. A table that summarizes the major characteristics of the methods is also provided.
II. Problem Overview

Fig. 2 shows the **characteristic power curve** for a PV array. The problem considered by MPPT techniques is to automatically find the voltage \( V_{MPP} \) or current \( I_{MPP} \) at which a PV array should operate to obtain the maximum power output \( P_{MPP} \) under a given temperature and irradiance.

![Characteristic PV array power curve](image)

Fig. 2. Characteristic PV array power curve.
It is noted that under partial shading conditions, in some cases it is possible to have multiple local maxima, but overall there is still only one true MPP. Most techniques respond to changes in both irradiance and temperature, but some are specifically more useful if temperature is approximately constant.

Most techniques would automatically respond to changes in the array due to aging, though some are open-loop and would require periodic fine-tuning. In our context, the array will typically be connected to a power converter that can vary the current coming from the PV array.
III. MPPT Techniques

We introduce the different MPPT techniques below in an arbitrary order.

A. Hill Climbing/P&O

- Hill climbing involves a perturbation in the duty ratio of the power converter, and P&O a perturbation in the operating voltage of the PV array.

- In the case of a PV array connected to a power converter, perturbing the duty ratio of power converter perturbs the PV array current and consequently perturbs the PV array voltage. Hill climbing and P&O methods are different ways to envision the same fundamental method.
From Fig. 2, it can be seen that incrementing (decrementing) the voltage increases (decreases) the power when operating on the left of the MPP and decreases (increases) the power when on the right of the MPP.

Therefore, if there is an increase in power, the subsequent perturbation should be kept the same to reach the MPP and if there is a decrease in power, the perturbation should be reversed. This algorithm is summarized in Table I.

<table>
<thead>
<tr>
<th>Perturbation</th>
<th>Change in Power</th>
<th>Next Perturbation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive</td>
<td>Positive</td>
<td>Positive</td>
</tr>
<tr>
<td>Positive</td>
<td>Negative</td>
<td>Negative</td>
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<td>Negative</td>
<td>Positive</td>
<td>Negative</td>
</tr>
<tr>
<td>Negative</td>
<td>Negative</td>
<td>Positive</td>
</tr>
</tbody>
</table>
In [24], it is shown that the algorithm also works when instantaneous (instead of average) PV array voltage and current are used, as long as sampling occurs only once in each switching cycle.

The process is repeated periodically until the MPP is reached. The system then oscillates about the MPP. The oscillation can be minimized by reducing the perturbation step size.

However, a smaller perturbation size slows down the MPPT. A solution to this conflicting situation is to have a variable perturbation size that gets smaller towards the MPP as shown in [8], [12], [15], and [22]. In [24], fuzzy logic control is used to optimize the magnitude of the next perturbation.
In [20], a two-stage algorithm is proposed that offers faster tracking in the first stage and finer tracking in the second stage. On the other hand, [21] bypasses the first stage by using a nonlinear equation to estimate an initial operating point close to the MPP.

Hill climbing and P&O methods can fail under rapidly changing atmospheric conditions as illustrated in Fig. 3.

![Fig. 3. Divergence of hill climbing/P&O from MPP as shown in [9].](image)
To ensure that the MPP is tracked even under sudden changes in irradiance, [18] uses a three-point weight comparison P&O method that compares the actual power point to two preceding ones before a decision is made about the perturbation sign.

In [22], the sampling rate is optimized, while in [24], simply a high sampling rate is used. In [8], toggling has been done between the traditional hill climbing algorithm and a modified adaptive hill climbing mechanism to prevent deviation from the MPP.
Two sensors are usually required to measure the PV array voltage and current from which power is computed, but depending on the power converter topology, only a voltage sensor might be needed as in [7] and [23]. In [25], the PV array current from the PV array voltage is estimated, eliminating the need for a current sensor.

DSP or microcomputer control is more suitable for hill climbing and P&O even though discrete analog and digital circuitry can be used as in [4].
B. **Incremental Conductance**

The incremental conductance (IncCond) [9], [26]–[36] method is based on the fact that the slope of the PV array power curve (Fig. 2) is zero at the MPP, positive on the left of the MPP, and negative on the right, as given by

\[
\begin{align*}
\frac{dP}{dV} &= 0, & \text{at MPP} \\
\frac{dP}{dV} &> 0, & \text{left of MPP} \\
\frac{dP}{dV} &< 0, & \text{right of MPP.}
\end{align*}
\]

(1)

Since

\[
\frac{dP}{dV} = \frac{d(IV)}{dV} = I + V \frac{dI}{dV} \approx I + V \frac{\Delta I}{\Delta V}
\]

(2)
(1) can be rewritten as

\[
\begin{align*}
\Delta I / \Delta V &= -I / V, \quad \text{at MPP} \\
\Delta I / \Delta V &> -I / V, \quad \text{left of MPP} \\
\Delta I / \Delta V &< -I / V, \quad \text{right of MPP.}
\end{align*}
\]

The MPP can thus be tracked by comparing the instantaneous conductance \((I/V)\) to the incremental conductance \((\Delta I/\Delta V)\) as shown in the flowchart in Fig. 4.
Fig. 4. **IncCond algorithm** as shown in [29], [32], [33], and [36].
The increment size determines how fast the MPP is tracked. Fast tracking can be achieved with bigger increments but the system might not operate exactly at the MPP and oscillate about it instead; so there is a tradeoff.

In [31] and [35], a method is proposed that brings the operating point of the PV array close to the MPP in a first stage and then uses IncCond to exactly track the MPP in a second stage.

By proper control of the power converter, the initial operating point is set to match a load resistance proportional to the ratio of the open-circuit voltage ($V_{OC}$) to the short-circuit current ($I_{SC}$) of the PV array.
This two-stage alternative also ensures that the real MPP is tracked in case of multiple local maxima. In [37], a linear function is used to divide the $I–V$ plane into two areas, one containing all the possible MPPs under changing atmospheric conditions. The operating point is brought into this area and then IncCond is used to reach the MPP.

A less obvious, but effective way of performing the IncCond technique is to use the instantaneous conductance and the incremental conductance to generate an error signal

\[
e = \frac{I}{V} + \frac{dI}{dV}
\]  

(4)
as suggested in [27] and [28]. From (1), we know that $e$ goes to zero at the MPP. A simple proportional integral (PI) control can then be used to drive $e$ to zero.

Measurements of the instantaneous PV array voltage and current require two sensors. IncCond method lends itself well to DSP and microcontroller control, which can easily keep track of previous values of voltage and current and make all the decisions as per Fig. 4.
C. **Fractional Open-Circuit Voltage**

The near linear relationship between $V_{MPP}$ and $V_{OC}$ of the PV array, under varying irradiance and temperature levels, has given rise to the fractional $V_{OC}$ method [38]–[45].

\[ V_{MPP} \approx k_1 V_{OC} \quad (5) \]

where $k_1$ is a constant of proportionality. Since $k_1$ is dependent on the characteristics of the PV array being used, it usually has to be computed beforehand by empirically determining $V_{MPP}$ and $V_{OC}$ for the specific PV array at different irradiance and temperature levels. The factor $k_1$ has been reported to be between 0.71 and 0.78.
Once $k_1$ is known, $V_{MPP}$ can be computed using (5) with $V_{OC}$ measured periodically by momentarily shutting down the power converter. However, this incurs some disadvantages, including temporary loss of power.

To prevent this, [40] uses pilot cells from which $V_{OC}$ can be obtained. These pilot cells must be carefully chosen to closely represent the characteristics of the PV array. In [44], it is claimed that the voltage generated by pn-junction diodes is approximately 75% of $V_{OC}$. This eliminates the need for measuring $V_{OC}$ and computing $V_{MPP}$. Once $V_{MPP}$ has been approximated, a closed-loop control on the array power converter can be used to asymptotically reach this desired voltage.
Since (5) is only an approximation, the PV array technically never operates at the MPP. Depending on the application of the PV system, this can sometimes be adequate. Even if fractional $V_{OC}$ is not a true MPPT technique, it is very easy and cheap to implement as it does not necessarily require DSP or microcontroller control.

However, [45] points out that $k_1$ is no more valid in the presence of partial shading (which causes multiple local maxima) of the PV array and proposes sweeping the PV array voltage to update $k_1$. This obviously adds to the implementation complexity and incurs more power loss.
D. Fractional Short-Circuit Current

Fractional $I_{SC}$ results from the fact that, under varying atmospheric conditions, $I_{MPP}$ is approximately linearly related to the $I_{SC}$ of the PV array as shown in [40], [42], and [45]–[48]

$$I_{MPP} \approx k_2 I_{SC}$$

(6)

where $k_2$ is a proportionality constant. Just like in the fractional $V_{OC}$ technique, $k_2$ has to be determined according to the PV array in use. The constant $k_2$ is generally found to be between 0.78 and 0.92.
Measuring $I_{SC}$ during operation is problematic. An additional switch usually has to be added to the power converter to periodically short the PV array so that $I_{SC}$ can be measured using a current sensor. This increases the number of components and cost. In [48], a boost converter is used, where the switch in the converter itself can be used to short the PV array.

In [46], a way of compensating $k2$ is proposed such that the MPP is better tracked while atmospheric conditions change.
To guarantee proper MPPT in the presence of multiple local maxima, [45] periodically sweeps the PV array voltage from open-circuit to short-circuit to update $k_2$. Most of the PV systems using fractional $I_{SC}$ in the literature use a DSP. In [48], a simple current feedback control loop is used instead.

### E. Fuzzy Logic Control

Microcontrollers have made using fuzzy logic control [49]–[58] popular for MPPT over the last decade. As mentioned in [57], fuzzy logic controllers have the advantages of working with imprecise inputs, not needing an accurate mathematical model, and handling nonlinearity.
Fuzzy logic control generally consists of three stages: fuzzification, rule base table lookup, and defuzzification. During fuzzification, numerical input variables are converted into linguistic variables based on a membership function similar to Fig. 5.

Fig. 5. Membership function for inputs and output of fuzzy logic controller.
In this case, five fuzzy levels are used: NB (negative big), NS (negative small), ZE (zero), PS (positive small), and PB (positive big). In [54] and [55], seven fuzzy levels are used, probably for more accuracy.

In Fig. 5, $a$ and $b$ are based on the range of values of the numerical variable. The membership function is sometimes made less symmetric to give more importance to specific fuzzy levels as in [49], [53], [57], and [58].
The inputs to a MPPT fuzzy logic controller are usually an error $E$ and a change in error $\Delta E$. The user has the flexibility of choosing how to compute $E$ and $\Delta E$. Since $dP/dV$ vanishes at the MPP, [58] uses the approximation

$$E(n) = \frac{P(n) - P(n - 1)}{V(n) - V(n - 1)}$$

(7)

and

$$\Delta E(n) = E(n) - E(n - 1).$$

(8)
Equivalently, (4) is very often used. Once $E$ and $\Delta E$ are calculated and converted to the linguistic variables, the fuzzy logic controller output, which is typically a change in duty ratio $\Delta D$ of the power converter, can be looked up in a rule base table such as Table II [50].

<table>
<thead>
<tr>
<th>$\Delta E$</th>
<th>NB</th>
<th>NS</th>
<th>ZE</th>
<th>PS</th>
<th>PB</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NB</strong></td>
<td>ZE</td>
<td>ZE</td>
<td>NB</td>
<td>NB</td>
<td>NB</td>
</tr>
<tr>
<td><strong>NS</strong></td>
<td>ZE</td>
<td>ZE</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td><strong>ZE</strong></td>
<td>NS</td>
<td>ZE</td>
<td>ZE</td>
<td>ZE</td>
<td>PS</td>
</tr>
<tr>
<td><strong>PS</strong></td>
<td>PS</td>
<td>PS</td>
<td>PS</td>
<td>ZE</td>
<td>ZE</td>
</tr>
<tr>
<td><strong>PB</strong></td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
<td>ZE</td>
<td>ZE</td>
</tr>
</tbody>
</table>
The linguistic variables assigned to $\Delta D$ for the different combinations of $E$ and $\Delta E$ are based on the power converter being used and also on the knowledge of the user.

Table II is based on a boost converter. If, for example, the operating point is far to the left of the MPP (Fig. 2), that is $E$ is PB, and $\Delta E$ is ZE, then we want to largely increase the duty ratio, that is $\Delta D$ should be PB to reach the MPP.

In the defuzzification stage, the fuzzy logic controller output is converted from a linguistic variable to a numerical variable still using a membership function as in Fig. 5. This provides an analog signal that will control the power converter to the MPP.
MPPT fuzzy logic controllers have been shown to perform well under varying atmospheric conditions. However, their effectiveness depends a lot on the knowledge of the user or control engineer in choosing the right error computation and coming up with the rule base table.

In [55], an adaptive fuzzy logic control is proposed that constantly tunes the membership functions and the rule base table so that optimum performance is achieved.
Experimental results from [51] show fast convergence to the MPP and minimal fluctuation about it. In [57], two different membership functions are empirically used to show that the tracking performance depends on the type membership functions considered.

F. Neural Network

Along with fuzzy logic controllers came another technique of implementing MPPT—neural networks [59]–[63], which are also well adapted for microcontrollers.
Neural networks commonly have three layers: input, hidden, and output layers as shown in Fig. 6.

The number of nodes in each layer vary and are user-dependent. The input variables can be PV array parameters like $V_{OC}$ and $I_{SC}$, atmospheric data like irradiance and temperature, or any combination of these.
The output is usually one or several reference signal(s) like a duty cycle signal used to drive the power converter to operate at or close to the MPP.

How close the operating point gets to the MPP depends on the algorithms used by the hidden layer and how well the neural network has been trained.

The links between the nodes are all weighted. The link between nodes \( i \) and \( j \) is labeled as having a weight of \( w_{ij} \) in Fig. 6.
To accurately identify the MPP, the $w_{ij}$’s have to be carefully determined through a training process, whereby the PV array is tested over months or years and the patterns between the input(s) and output(s) of the neural network are recorded.

Since most PV arrays have different characteristics, a neural network has to be specifically trained for the PV array with which it will be used. The characteristics of a PV array also change with time, implying that the neural network has to be periodically trained to guarantee accurate MPPT.
G. **RCC**

- When a PV array is connected to a power converter, the switching action of the power converter imposes voltage and current ripple on the PV array. As a consequence, the PV array power is also subject to ripple.

- Ripple correlation control (RCC) [64] makes use of ripple to perform MPPT. RCC correlates the time derivative of the time-varying PV array power $\dot{p}$ with the time derivative of the time-varying PV array current $\dot{i}$ or voltage $\dot{v}$ to drive the power gradient to zero, thus reaching the MPP.
Referring to Fig. 2, if \(v\) or \(i\) is increasing (\(\dot{v} > 0\) or \(\dot{i} > 0\)) and \(p\) is increasing (\(\dot{p} > 0\)), then the operating point is below the MPP (\(V < V_{MPP}\) or \(I < I_{MPP}\)). On the other hand, if \(v\) or \(i\) is increasing and \(p\) is decreasing (\(\dot{p} < 0\)), then the operating point is above the MPP (\(V > V_{MPP}\) or \(I > I_{MPP}\)).

Combining these observations, we see that \(\dot{p}\dot{v}\) or \(\dot{p}\dot{i}\) are positive to the left of the MPP, negative to right of the MPP, and zero at the MPP.
When the power converter is a boost converter as in [64], increasing the duty ratio increases the inductor current, which is the same as the PV array current, but decreases the PV array voltage. Therefore, the duty ratio control input is

$$d(t) = -k_3 \int \dot{v} dt$$

or

$$d(t) = k_3 \int \dot{i} dt$$

where $k_3$ is a positive constant.
The derivatives in (9) and (10) are usually undesirable, but [64] shows that ac-coupled measurements of the PV array current and voltage can be used instead since they contain the necessary phase information.

A different and easy way of obtaining the current derivative in (10) is to sense the inductor voltage, which is proportional to the current derivative. The nonidealities in the inductor (core loss, resistance) have a small effect since the time constant of the inductor is much larger than the switching period in a practical converter.
Simple and inexpensive analog circuits can be used to implement RCC. An example is given in [64]. Experiments were performed to show that RCC accurately and quickly tracks the MPP, even under varying irradiance levels.

The time taken to converge to the MPP is limited by the switching frequency of the power converter and the gain of the RCC circuit. Another advantage of RCC is that it does not require any prior information about the PV array characteristics, making its adaptation to different PV systems straightforward.
There are other papers in the literature that use MPPT methods that resemble RCC. For example, [65] integrates the product of the signs of the time derivatives of power and of duty ratio.

However, unlike RCC, which uses inherent ripple present in current and voltage, [65] disturbs the duty ratio to generate a disturbance in power.
**H. Current Sweep**

The current sweep [69] method uses a sweep waveform for the PV array current such that the $I$–$V$ characteristic of the PV array is obtained and updated at fixed time intervals. The $V_{MPP}$ can then be computed from the characteristic curve at the same intervals.

The function chosen for the sweep waveform is directly proportional to its derivative as in

$$f(t) = k_4 \frac{df(t)}{dt} \quad (11)$$

where $k_4$ is a proportionality constant. The PV array power is thus given by
\[ p(t) = v(t) i(t) = v(t) f(t). \]  \hspace{1cm} (12)

At the MPP

\[ \frac{dp(t)}{dt} = v(t) \frac{df(t)}{dt} + f(t) \frac{dv(t)}{dt} = 0. \]  \hspace{1cm} (13)

Substituting (11) in (13) gives

\[ \frac{dp(t)}{dt} = \left[ v(t) + k_4 \frac{dv(t)}{dt} \right] \frac{df(t)}{dt} = 0. \]  \hspace{1cm} (14)
The differential equation in (11) has the following solution

\[ f(t) = C \exp \left[ \frac{t}{k_4} \right]. \]  \hspace{1cm} (15)

\( C \) is chosen to be equal to the maximum PV array current \( I_{\text{max}} \) and \( k_4 \) to be negative, resulting in a decreasing exponential function with time constant \( \tau = -k_4 \). Equation (15) leads to

\[ f(t) = I_{\text{max}} \exp \left[ -\frac{t}{\tau} \right]. \]  \hspace{1cm} (16)
The current in (16) can be easily obtained by using some current discharging through a capacitor. Since the derivative of (16) is nonzero, (14) can be divided throughout by $df(t)/dt$ and, with $f(t) = i(t)$, (14) simplifies to

$$\frac{dp(t)}{di(t)} = v(t) + k_i \frac{dv(t)}{dt} = 0. \quad (17)$$

Once $V_{MPP}$ is computed after the current sweep, (17) can be used to double check whether the MPP has been reached.
In [69], the current sweep method is implemented through analog computation. The current sweep takes about 50 ms, implying some loss of available power.

In [69], it is pointed out that this MPPT technique is only feasible if the power consumption of the tracking unit is lower than the increase in power that it can bring to the entire PV system.
I. DC-Link Capacitor Droop Control

DC-link capacitor droop control [70], [71] is an MPPT technique that is specifically designed to work with a PV system that is connected in parallel with an ac system line as shown in Fig. 7.

![Diagram of DC-Link Capacitor Droop Control](image)

Fig. 7. Topology for dc-link capacitor droop control as shown in [71].
The duty ratio of an ideal boost converter is given by

\[ d = 1 - \frac{V}{V_{\text{link}}} \]  

(18)

where \( V \) is the voltage across the PV array and \( V_{\text{link}} \) is the voltage across the dc link.

If \( V_{\text{link}} \) is kept constant, increasing the current going in the inverter increases the power coming out of the boost converter and consequently increases the power coming out of the PV array.
While the current is increasing, the voltage $V_{link}$ can be kept constant as long as the power required by the inverter does not exceed the maximum power available from the PV array.

If that is not the case, $V_{link}$ starts drooping. Right before that point, the current control command $I_{peak}$ of the inverter is at its maximum and the PV array operates at the MPP. The ac system line current is fed back to prevent $V_{link}$ from drooping and $d$ is optimized to bring $I_{peak}$ to its maximum, thus achieving MPPT.
- DC-link capacitor droop control does not require the computation of the PV array power, but according to [71], its response deteriorates when compared to a method that detects the power directly; this is because its response directly depends on the response of the dc-voltage control loop of the inverter.

- This control scheme can be easily implemented with analog operational amplifiers and decision-making logic units.
J. Load Current or Load Voltage Maximization

The purpose of MPPT techniques is to maximize the power coming out of a PV array. When the PV array is connected to a power converter, maximizing the PV array power also maximizes the output power at the load of the converter.

Conversely, maximizing the output power of the converter should maximize the PV array power [72]–[78], assuming a lossless converter.

In [78], it is pointed out that most loads can be of voltage source type, current-source type, resistive type, or a combination of these, as shown in Fig. 8.
This is also true for nonlinear load types as long as they do not exhibit negative impedance characteristics [78]. Therefore, for almost all loads of interest, it is adequate to maximize either the load current or the load voltage to maximize the load power. Consequently, only one sensor is needed.

Fig. 8. Different load types. 1: voltage source, 2: resistive, 3: resistive and voltage source, 4: current source, as shown in [78].
In most PV systems, a battery is used as the main load or as a backup [73]–[77]. Since a battery can be thought of as a voltage-source type load, the load current can be used as the control variable.

In [73], [74], and [76], positive feedback is used to control the power converter such that the load current is maximized and the PV array operates close to the MPP.

Operation exactly at the MPP is almost never achieved because this MPPT method is based on the assumption that the power converter is lossless.
K. **dP/dV or dP/dI Feedback Control**

With DSP and microcontroller being able to handle complex computations, an obvious way of performing MPPT is to compute the slope \(dP/dV\) or \(dP/dI\) of the PV power curve (Fig. 2) and feed it back to the power converter with some control to drive it to zero. This is exactly what is done in [79]–[83].

The way the slope is computed differs from paper to paper. In [79], \(dP/dV\) is computed and its sign is stored for the past few cycles. Based on these signs, the duty ratio of the power converter is either incremented or decremented to reach the MPP.
A dynamic step size is used to improve the transient response of the system. In [80], a linearization-based method is used to compute \( \frac{dP}{dV} \). In [81]–[83], sampling and data conversion are used with subsequent digital division of power and voltage to approximate \( \frac{dP}{dV} \).

In [82], \( \frac{dP}{dI} \) is then integrated together with an adaptive gain to improve the transient response. In [83], the PV array voltage is periodically incremented or decremented and \( \frac{\Delta P}{\Delta V} \) is compared to a marginal error until the MPP is reached. Convergence to the MPP was shown to occur in tens of milliseconds in [81].
L. **Other MPPT Techniques**

Other MPPT techniques include array reconfiguration [84], whereby PV arrays are arranged in different series and parallel combinations such that the resulting MPPs meet specific load requirements. This method is time consuming and tracking MPP in real time is not obvious.

In [85], a linear current control is used based on the fact that a linear relationship exists between $I_{MPP}$ and the level of irradiance. The current $I_{MPP}$ is thus found by sensing the irradiance level and a PI controller is used such that the PV array current follows $I_{MPP}$. 
In [86], $I_{MPP}$ and $V_{MPP}$ are computed from equations involving temperature and irradiance levels, which are not usually easy to measure. Once $I_{MPP}$ or $V_{MPP}$ is obtained, feedback control is used to force the PV array to operate at the MPP.

A state-based MPPT is introduced in [87], whereby the system is represented by a state space model, and a nonlinear time-varying dynamic feedback controller is used to track the MPP. Simulations confirm that this technique is robust and insensitive to changes in system parameters and that MPPT is achieved even with changing atmospheric conditions and in the presence of multiple local maxima caused by partially shaded PV array or damaged cells. However, no experimental verification is given.
Unlike common topologies that consist of two power stages (usually a dc–dc converter followed by an inverter), a single stage inverter that performs both MPPT and output current regulation for utility grid distribution is introduced in [88].

Based on the voltage of the PV array, one-cycle control (OCC) is used to adjust the output current of the single-stage inverter such that MPPT is attained. The control circuit consists of discrete digital components but it can also use an inexpensive DSP. Operation is shown to be close to the MPP throughout a day-time period. The slight discrepancy is due to the inability of the controller to account for temperature variation.
The best fixed voltage (BFV) algorithm is introduced in [89]. Statistical data is collected about irradiance and temperature levels over a period of one year and the BFV representative of the MPP is found.

The control sets either the operating point of the PV array to the BFV or the output voltage to the nominal load voltage. Operation is therefore never exactly at the MPP and different data has to be collected for different geographical regions.
The PV array characteristic equation, which needs to be solved iteratively for the MPP, is manipulated to find an approximate symbolic solution for the MPP in [90].

This method, called linear reoriented coordinates method (LRCM), requires the measurement of $V_{OC}$ and $I_{SC}$ to find the solution. Other constants representing the PV array characteristic curve are also needed. The maximum error in using LRCM to approximate the MPP was found to be 0.3%, but this was based only on simulation results.
In [91], a slide control method with a buck-boost converter is used to achieve MPPT. The switching function $u$ of the converter is based on the fact that $dP/dV > 0$ on the left of the MPP and $dP/dV < 0$ on the right; $u$ is expressed as

$$
\begin{align*}
  u &= 0 \quad S \geq 0 \\
  u &= 1 \quad S < 0 
\end{align*}
$$

where $u = 0$ means the switch is open and $u = 1$ the switch close and $S$ is given by

$$
S = \frac{dP}{dV} = I + V \frac{dI}{dV}. \tag{20}
$$
This control was implemented using a microcontroller that senses the PV array voltage and current. Simulation and experimental results showed that operation converges to the MPP in several tens of milliseconds.
IV. Discussion

With so many MPPT techniques available to PV system users, it might not be obvious for the latter to choose which one better suits their application needs. The main aspects of the MPPT techniques to be taken into consideration are highlighted in the following subsections.

A. **Implementation**

The ease of implementation is an important factor in deciding which MPPT technique to use. However, this greatly depends on the end-users’ knowledge.
Some might be more familiar with analog circuitry, in which case, fractional \( I_{SC} \) or \( V_{OC} \), RCC, and load current or voltage maximization are good options.

Others might be willing to work with digital circuitry, even if that may require the use of software and programming. Then, their selection should include hill climbing/P&O, IncCond, fuzzy logic control, neural network, and \( dP/dV \) or \( dP/dI \) feedback control.

Furthermore, a few of the MPPT techniques only apply to specific topologies. For example, the dc-link capacitor droop control works with the system shown in Fig. 7 and the OCC MPPT works with a single-stage inverter.
B. Sensors

The number of sensors required to implement MPPT also affects the decision process. Most of the time, it is easier and more reliable to measure voltage than current. Moreover, current sensors are usually expensive and bulky.

This might be inconvenient in systems that consist of several PV arrays with separate MPP trackers. In such cases, it might be wise to use MPPT methods that require only one sensor or that can estimate the current from the voltage as in [25]. It is also uncommon to find sensors that measure irradiance levels, as needed in the linear current control and the \( I_{MPP} \) and \( V_{MPP} \) computation methods.
C. *Multiple Local Maxima*

- The occurrence of multiple local maxima due to partial shading of the PV array(s) can be a real hindrance to the proper functioning of an MPP tracker.

- Considerable power loss can be incurred if a local maximum is tracked instead of the real MPP. As mentioned previously, the current sweep and the state-based methods should track the true MPP even in the presence of multiple local maxima.

- However, the other methods require an additional initial stage to bypass the unwanted local maxima and bring operation to close the real MPP; such examples are given in [31] and [35].
D. Costs

- It is hard to mention the monetary costs of every single MPPT technique unless it is built and implemented. This is unfortunately out of the scope of this paper.

- However, a good costs comparison can be made by knowing whether the technique is analog or digital, whether it requires software and programming, and the number of sensors.

- Analog implementation is generally cheaper than digital, which normally involves a microcontroller that needs to be programmed. Eliminating current sensors considerably drops the costs.
E. Applications

- Different MPPT techniques discussed earlier will suit different applications. For example, in space satellites and orbital stations that involve large amount of money, the costs and complexity of the MPP tracker are not as important as its performance and reliability.

- The tracker should be able to continuously track the true MPP in minimum amount of time and should not require periodic tuning. In this case, hill climbing/P&O, IncCond, and RCC are appropriate. Solar vehicles would mostly require fast convergence to the MPP.
Fuzzy logic control, neural network, and RCC are good options in this case. Since the load in solar vehicles consists mainly of batteries, load current or voltage maximization should also be considered.

The goal when using PV arrays in residential areas is to minimize the payback time and to do so, it is essential to constantly and quickly track the MPP. Since partial shading (from trees and other buildings) can be an issue, the MPPT should be capable of bypassing multiple local maxima.
Therefore, the two-stage IncCond [31], [35] and the current sweep methods are suitable. Since a residential system might also include an inverter, the OCC MPPT can also be used. PV systems used for street lighting only consist in charging up batteries during the day. They do not necessarily need tight constraints; easy and cheap implementation might be more important, making fractional $V_{OC}$ or $I_{SC}$ viable.

For all other applications not mentioned here, we put together Table III, containing the major characteristics of all the MPPT techniques. Table III should help in choosing an appropriate MPPT method.
<table>
<thead>
<tr>
<th>MPPT Technique</th>
<th>PV Array Dependent?</th>
<th>True MPPT?</th>
<th>Analog or Digital?</th>
<th>Periodic Tuning?</th>
<th>Convergence Speed</th>
<th>Implementation Complexity</th>
<th>Sensed Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hill-climbing/P&amp;O</td>
<td>No</td>
<td>Yes</td>
<td>Both</td>
<td>No</td>
<td>Varies</td>
<td>Low</td>
<td>Voltage, Current</td>
</tr>
<tr>
<td>IneCond</td>
<td>No</td>
<td>Yes</td>
<td>Digital</td>
<td>No</td>
<td>Varies</td>
<td>Medium</td>
<td>Voltage, Current</td>
</tr>
<tr>
<td>Fractional $V_{oc}$</td>
<td>Yes</td>
<td>No</td>
<td>Both</td>
<td>Yes</td>
<td>Medium</td>
<td>Low</td>
<td>Voltage</td>
</tr>
<tr>
<td>Fractional $I_{sc}$</td>
<td>Yes</td>
<td>No</td>
<td>Both</td>
<td>Yes</td>
<td>Medium</td>
<td>Medium</td>
<td>Current</td>
</tr>
<tr>
<td>Fuzzy Logic Control</td>
<td>Yes</td>
<td>Yes</td>
<td>Digital</td>
<td>Yes</td>
<td>Fast</td>
<td>High</td>
<td>Varies</td>
</tr>
<tr>
<td>Neural Network</td>
<td>Yes</td>
<td>Yes</td>
<td>Digital</td>
<td>Yes</td>
<td>Fast</td>
<td>High</td>
<td>Varies</td>
</tr>
<tr>
<td>RCC</td>
<td>No</td>
<td>Yes</td>
<td>Analog</td>
<td>No</td>
<td>Fast</td>
<td>Low</td>
<td>Voltage, Current</td>
</tr>
<tr>
<td>Current Sweep</td>
<td>Yes</td>
<td>Yes</td>
<td>Digital</td>
<td>Yes</td>
<td>Slow</td>
<td>High</td>
<td>Voltage, Current</td>
</tr>
<tr>
<td>DC Link Capacitor Droop Control</td>
<td>No</td>
<td>No</td>
<td>Both</td>
<td>No</td>
<td>Medium</td>
<td>Low</td>
<td>Voltage</td>
</tr>
<tr>
<td>Load $I$ or $V$ Maximization</td>
<td>No</td>
<td>No</td>
<td>Analog</td>
<td>No</td>
<td>Fast</td>
<td>Low</td>
<td>Voltage, Current</td>
</tr>
<tr>
<td>$dP/dV$ or $dP/dI$ Feedback Control</td>
<td>No</td>
<td>Yes</td>
<td>Digital</td>
<td>No</td>
<td>Fast</td>
<td>Medium</td>
<td>Voltage, Current</td>
</tr>
<tr>
<td>Array Reconfiguration</td>
<td>Yes</td>
<td>No</td>
<td>Digital</td>
<td>Yes</td>
<td>Slow</td>
<td>High</td>
<td>Voltage, Current</td>
</tr>
<tr>
<td>Linear Current Control</td>
<td>Yes</td>
<td>No</td>
<td>Digital</td>
<td>Yes</td>
<td>Fast</td>
<td>Medium</td>
<td>Irradiance</td>
</tr>
<tr>
<td>$I_{mpp}$ &amp; $V_{mpp}$ Computation</td>
<td>Yes</td>
<td>Yes</td>
<td>Digital</td>
<td>Yes</td>
<td>N/A</td>
<td>Medium</td>
<td>Irradiance, Temperature</td>
</tr>
<tr>
<td>State-based MPPT</td>
<td>Yes</td>
<td>Yes</td>
<td>Both</td>
<td>Yes</td>
<td>Fast</td>
<td>High</td>
<td>Voltage, Current</td>
</tr>
<tr>
<td>OCC MPPT</td>
<td>Yes</td>
<td>No</td>
<td>Both</td>
<td>Yes</td>
<td>Fast</td>
<td>Medium</td>
<td>Current</td>
</tr>
<tr>
<td>BFV</td>
<td>Yes</td>
<td>No</td>
<td>Both</td>
<td>Yes</td>
<td>N/A</td>
<td>Low</td>
<td>None</td>
</tr>
<tr>
<td>LRCM</td>
<td>Yes</td>
<td>No</td>
<td>Digital</td>
<td>No</td>
<td>N/A</td>
<td>High</td>
<td>Voltage, Current</td>
</tr>
<tr>
<td>Slide Control</td>
<td>No</td>
<td>Yes</td>
<td>Digital</td>
<td>No</td>
<td>Fast</td>
<td>Medium</td>
<td>Voltage, Current</td>
</tr>
</tbody>
</table>
Several MPPT techniques taken from the literature are discussed and analyzed herein, with their pros and cons. It is shown that there are several other MPPT techniques than those commonly included in literature reviews. The concluding discussion and table should serve as a useful guide in choosing the right MPPT method for specific PV systems.
生質能

再生能源發電技術
大綱

■ 摘要
■ 生質能源簡介
■ 台灣生質能發展目的與目標
■ 沼氣發電
■ 生質柴油
■ 結論
近年來，由於地球溫暖化問題嚴重，燃油、燃煤發電將增加二氧化碳排放，及垃圾量不斷增加造成環境的污染，使得「熱污染」問題廣受重視，生質能技術可以減緩能源與環境的困擾，將廢棄物變成可使用的能源。如何有效運用新且潔淨的生質能 (Biomass Energy) 以供未來使用，乃成為一個重要的課題。
生質能源簡介

(一) 何謂生質能源

生質能源是潔淨能源的一種，屬於能永續利用的再生能源。主要來源是由生物產生的有機物質透過轉換獲得可用能源。

來源包括：(1) 牲畜糞便 (2) 農作物殘渣 (3) 薪柴 (4) 製糖作物 (5) 城市垃圾 (6) 城市污水 (7) 水生植物 (8) 能源作物
生質能的轉化技術

* 直接燃燒技術：以直接燃燒方式產生熱能與電力，如垃圾焚化廠。

* 物理轉換技術：經破碎、分選、乾燥、混合等過程而製成易於運輸及儲存之固態衍生燃料，如紙廠廢棄物轉製可用於水泥窯、鍋爐等。

* 熱轉換技術：利用氣化與裂解等熱轉換程序產生合成燃油或瓦斯，可作為燃燒與發電設備之燃料，如廢塑膠、稻殼可轉製燃油、燃氣。
化學／生物轉換技術：經發酵、酯化等化學或生物轉換程序產生沼氣、酒精汽油、生質柴油、氫氣等，作為引擎、發電機與燃料電池的燃料，如垃圾掩埋場廢棄物、廢食用油、作物等。
生質能源的另一個重要特性是碳的循環，生質能源中製作生質柴油和酒精等，其原料為植物，植物在生長的過程中吸收二氧化碳轉化成生質能源，使用後所排放的二氧化碳不會超過植物生長時所吸收的二氧化碳。故使用生質生質柴油和酒精的二氧化碳淨排放量為零。
使用生質能的優點:

1. 使用的原料來源豐富
2. 與其他非傳統性能源相較，技術上之難題較少
3. 可再生利用
4. 提供低硫燃料，不會造成空氣污染
5. 環保：利用都市垃圾和農業廢料轉化有用能量，可減少環境公害
6. 迅速：不需和石化燃料一樣經過八百萬年的作用才可使用
缺點:
1. 轉換效率低
2. 種植原料所需約土地很大
3. 原料含水量高
4. 規模較小
5. 產生的能量不及化石能量
6. 易為環境限制，要注意種植、收割、天候、物種限制，缺乏適合栽種植物之土地。
台灣生質能發展目的與目標

我國能源百分之九十八靠進口，能源消耗密度全世界第一，每平方公里每年燒掉兩千六百噸石油，是美國十倍，日本兩倍。(摘錄自聯合報2004/06/06)

目的
・增進能源安全
・自產能源，降低對國外能源的依賴
・減緩化石燃料過度依賴，減少CO₂排放，降低環境負荷

目標
94年全國能源會議具體結論-生質能發電裝置容量2010年達741 MW。
油價未漲之前，生質能之未受重視，主要是因為生質燃燒所產生之熱量太少，能源密度低，生質轉化技術不成熟，不會把生質轉化成較有利用價值的能源型式。

在農業廢產物方面，稻草年產250萬噸，少部分用做堆肥、菇舍建材、草繩及飼料；甘蔗渣及製糖廢液年產200萬噸，約125萬噸供糖廠當做燃料或供紙廠造紙，稻穀約年產60萬噸，估計能利用10萬噸。

在水產廢棄物方面，各水產加工廠，漁貨批發市場所產生的魚貨廢棄物及廢液，數量龐大，大多直接排放或拋棄，少部分用做飼料。
在畜牧業廢棄物方面，雞糞是磷肥常用做花卉肥料，豬糞液大部分直接排放，污染土地及河川，農發會雖曾推廣小型豬排泄物處理設備，惟效果不彰，事實上豬排泄物之生質產量居全省生質首位〔超過都市垃圾〕，應妥善運用。

在木業廢棄物方面，由於山區運輸不便故砍伐後之廢料，很少能夠利用，而各地製材及木工工廠，對廢料也未見善於利用。其實木材及廢料燃燒熱值很高，一噸木料燃燒所生的熱，相當於兩三桶原油的燃燒熱。
<table>
<thead>
<tr>
<th>發展時程</th>
<th>推廣項目</th>
<th>2005 (MW)</th>
<th>2010 (MW)</th>
<th>配比 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>都市廢棄物</td>
<td>465.2</td>
<td>561.5</td>
<td>1.09</td>
</tr>
<tr>
<td></td>
<td>農工廢棄物</td>
<td>65.3</td>
<td>150.5</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>沼氣發電</td>
<td>23.0</td>
<td>29</td>
<td>0.06</td>
</tr>
<tr>
<td>總計</td>
<td>553.5</td>
<td>741</td>
<td>1.44</td>
<td></td>
</tr>
</tbody>
</table>

增加發電量策略

・提昇現有焚化廠利用率，兼處理農工廢棄物。
・推廣廢棄物、生質物燃料，混燒技術與應用。
・設置「分散製造、集中應用」的區域型生質物電廠。
沼氣發電

來源
- 畜牧廢水
- 家庭污水
- 城鎮垃圾
- 各行業廢水(物)

台南新市統一公司食品廠 160 kWe小型沼氣發電系統（工研院技術）

沼氣純化 → 沼氣貯存 → 沼氣發電
生質柴油

定義與優點

- 以動植物油或廢食用油脂，經轉化技術後所產生之酯類，直接使用或混合柴油使用作為燃料者。

- 如以100% 純生質柴油使用稱之為B100，若以20%(v/v)生質柴油和80%(v/v)市售高級柴油混合使用則稱之為B20。

優點

1. 再生性能源，可被生物分解，具環境友善性。
2. 具能源產出上正面效益。
3. 可直接替代傳統柴油或混合傳統柴油使用。
4. 具有潤滑效用，降低引擎金屬之磨損。
5. 可減少空氣污染物排放。
6. 源自於動植物，屬大自然碳循環之一環，降低CO₂排放。

一般柴油與生質柴油之比較

<table>
<thead>
<tr>
<th></th>
<th>純生質柴油 (B100)</th>
<th>混合生質柴油 (B20)</th>
</tr>
</thead>
<tbody>
<tr>
<td>總碳氫化合物 (THC)可減量</td>
<td>80～90 %</td>
<td>20～30 %</td>
</tr>
<tr>
<td>一氧化碳 (CO)可減量</td>
<td>30～40 %</td>
<td>10～20 %</td>
</tr>
<tr>
<td>懸浮微粒 (PM)可減量</td>
<td>30～50 %</td>
<td>5～15 %</td>
</tr>
<tr>
<td>國家</td>
<td>原料</td>
<td>生質柴油規範</td>
</tr>
<tr>
<td>--------</td>
<td>------------</td>
<td>----------------</td>
</tr>
<tr>
<td>歐聯</td>
<td>油菜(rape)</td>
<td>EN 14214</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>美國</td>
<td>黃豆</td>
<td>ASTM 6751</td>
</tr>
<tr>
<td></td>
<td>廢食用油</td>
<td></td>
</tr>
<tr>
<td>加拿大</td>
<td>菜籽油(canola)</td>
<td>CGSB 3.520</td>
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<tr>
<td>日本</td>
<td>廢食用油</td>
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</tr>
<tr>
<td>泰國</td>
<td>棕櫚油</td>
<td>草案 (EN &amp; ASTM)</td>
</tr>
<tr>
<td></td>
<td>廢植物油</td>
<td></td>
</tr>
</tbody>
</table>
生質柴油:德國為世界產量最高的國家，以優惠稅率鼓勵生產，在最近的十年，產量增加約50倍，生產成本約0.6歐元/公升(約25元台幣)，2006年可達200萬公噸。作物主要以油菜油為主，平均產量高達5000公斤/公頃，且含油量高(約40~50%)，油酸比率高，適合生產生質柴油，約有3/4用於能源。

德國境內已有1900座加油站(約占所有加油站的9%)銷售B100生質柴油，另傳統柴油中亦均已添加5%以內之生質柴油。
國內生質柴油發展目的與目標

目的

・增加自產能源
・活化休耕農地
・擴大使用綠色潔淨能源

推廣
生質柴油道路試行計畫

■生質柴油道路試行計畫試行車輛以行駛於人口密集地區之垃圾車為主。
■93及94年度共補助13縣市執行生質柴油道路試行計畫，約使用1300公秉生質柴油，試行車輛達780輛。
■95年度核定補助16個縣市執行，預計使用超過1600公秉生質柴油。
台灣的生質柴油和生質酒精每公升的成本平均約35元，市售的柴油每公升稅後價格約23元、無鉛汽油約27元，生質燃料雖目前在價格上缺乏競爭力。但未來在許多開發中國家的快速崛起需要大量石油，而石油存量卻日益稀少，油價將會持續攀高，和生質燃料未來能藉技術進步提高效率以及規模生產使生產成本降低相比，生質燃料在未來仍是有相當的發展潛力。

目標

・推廣生質柴油2010年10萬噸，2020年15萬噸。
結論

發展潔淨可再生的能源將是未來世界的趨勢，也是台灣對外能源過度依賴的轉機。台灣先天上的地理氣候環境適合農作物的生長，對於短期輪作的草本能源作物一年能收成好幾期，且目前國內的農藝改良技術發達，依此判斷台灣相當具有發展生質能源的潛力。

面對有限的地球資源及持續增長的人類需求，我們需要更睿智的生活方式，以達到永續發展的目標。
參考資料

台灣生質能源發展現況與展望
http://www.eysc.gov.tw/group/htm/power/%E5%8F%B0%E7%81%A3%E7%94%9F%E8%B3%AA%E8%83%BD%E6%BA%90%E7%99%BC%E5%B1%95%E7%8F%BE%E6%B3%81%E8%88%87%E5%B1%95%E6%9C%9B-2.pdf

http://203.64.53.9/TeachWeb/89hpcontest/c018/Page20.htm

http://203.64.53.9/TeachWeb/89hpcontest/c018/Page20.htm

http://re.org.tw/com/f1/f1bl.aspx
報告結束
能源儲存技術

再生能源發電技術

National Yunlin University of Science & Technology
前言

安全、優質、經濟是對電力系統的基本要求。近年來，隨著全球經濟發展對電力需求的增長和電力企業市場化改革的推行，電力系統的運行和需求正在發生巨大的變化，一些新的矛盾日顯突出，主要的問題有：

(a) 系統裝機容量難以滿足峰值負荷的需求
(b) 現有電網在輸電方面落後用戶的需求
(c) 複雜大電網受到擾動後的安全穩定性問題日益突出
(d) 用戶對供電可靠度的要求越來越高
(e) 電力企業市場化促使用戶端需要能量管理技術的支持
(f) 必須考慮環境保護和政府政策因素對電力系統發展的影響
能源儲存技術可以提供一種簡單的解決電能供需不平衡問題的辦法。這種方法在早期的電力系統中已有所應用，例如在19世紀後期紐約市的直流供電系統中，為了在夜間將發電機停下來，採用了鉛酸蓄電池為路燈提供照明供電。

儲能技術目前在電力系統中的應用主要包括電力調峰、提高系統運行穩定性和提高供電品質。
表一 儲能系統在電力系統中的應用

<table>
<thead>
<tr>
<th>應用領域</th>
<th>發電功能</th>
<th>輔助供電功能</th>
<th>輸配電系統應用</th>
</tr>
</thead>
<tbody>
<tr>
<td>主要方式</td>
<td>能量管理</td>
<td>頻率調節響應</td>
<td>提高系統可靠度與再生能源結合</td>
</tr>
<tr>
<td></td>
<td>負荷調節</td>
<td>備用電源</td>
<td></td>
</tr>
<tr>
<td></td>
<td>峰值發電</td>
<td>無效功率控制</td>
<td></td>
</tr>
<tr>
<td>主要作用</td>
<td>提高發電設備利用率，減少對系統總裝機容量的要求</td>
<td>降低輔助設備成本</td>
<td>提高系統設備利用率，延緩新增投資</td>
</tr>
</tbody>
</table>
抽水儲能電廠是當前唯一能大規模解決電力系統尖峰供電不足的方法。它需要高低兩個水庫，並安裝能雙向運轉的電動水泵機組即水輪發電機組。當電力系統處於低負荷時讓電動機帶動水泵把低水庫的水通過管道抽到高水庫以消耗一部分的電能。當用電尖峰時，高水庫的水通過管道使水泵和電動機逆向運轉而變成水輪機和發電機發出電能供給用戶。

優點：技術成熟，容量大，成本低

缺點：受地理限制
迪诺维克抽水蓄能电站平面布置和引水道纵剖面图
飛輪儲能

大規模儲能另一被看好的方法就是飛輪儲能，這實際上是一種較為古老的技術。在用電離峰時，將多餘電力輸入電動機，使其驅動飛輪加速，這大概需要幾個小時，然後飛輪保持高速轉動，到用電高峰時，讓飛輪驅動電動機作發電機運行，使飛輪的動能變成電能供給電網。此一過程中飛輪轉速下降，直到它的最高轉速的一半左右。由於採用變速定頻的電力電子技術，輸出電能的頻率可保持不變。

優點：功率高
缺點：成本高，技術需完善
飛輪儲能系統
（flywheel storage system）
Piller Triblock CP System
電池儲能

電化學儲能為小規模儲存方式的一種。電池有多種類型：
鉛酸電池：技術成熟，價格便宜，蓄電池儲能主流
鹼性電池：容量大，結構堅固，充放循環次數多，價格貴
鋰離電池：無充放電的記憶效應，價格最貴，污染最低

蓄電池的重要問題就是充放電控制，這是因为合理的充放電是正確使用電池的關鍵因素，由於難以從電池的外在參數來確定充放電程度，也就難以正確實現充放電。
### 表二 蓄電池儲能方式比較

<table>
<thead>
<tr>
<th>系統屬性</th>
<th>鉛酸電池</th>
<th>MH-Ni電池</th>
<th>鋰聚合物電池</th>
<th>鈉硫電池</th>
<th>鈉鹽電池</th>
</tr>
</thead>
<tbody>
<tr>
<td>能量(kW-h-m⁻³)</td>
<td>7.07</td>
<td>176.7</td>
<td>212.0</td>
<td>247.3</td>
<td>176.7</td>
</tr>
<tr>
<td>功率(kW*m⁻³)</td>
<td>106.0</td>
<td>212.0</td>
<td>388.7</td>
<td>530.0</td>
<td>530.0</td>
</tr>
<tr>
<td>效率%(24h)</td>
<td>92</td>
<td>92</td>
<td>88</td>
<td>88</td>
<td>87</td>
</tr>
<tr>
<td>循環壽命/次</td>
<td>400</td>
<td>800</td>
<td>600</td>
<td>1000</td>
<td>800</td>
</tr>
<tr>
<td>成本($<em>kW⁻¹</em>h⁻¹)</td>
<td>125</td>
<td>375</td>
<td>550</td>
<td>350</td>
<td>300</td>
</tr>
</tbody>
</table>
電磁場儲能

磁場儲能目前被看好的是超導線圈儲能，由於超導線圈在運行時沒有電阻，因此儲能效率很高。其電流密度遠高於常規線圈，可以做到很高的儲能密度。另外它可以用極快的速度充放電，缺點需要超低溫設備，即使是高溫超導線圈也要在液氮溫度下運行，能量密度低，電磁波也是缺點之一。

電場儲能是利用電容器儲存電荷的能力來儲存電能。近來超級電容器的出現，電容儲能開始向能源領域進軍。其充放電的速度甚至比超導線圈快，不需低溫設備。缺點工作電壓低，需將多個電容器串聯，因而增加充放電控制迴路。
Superconducting Magnetic Energy Storage System

2MJ SMES外观
圖一  超級電容器循環壽命長，具有很高的功率密度，安全性及效率
圖二 在結構上，超級電容器和電池或電解電容器的主要區別為電極材料
壓縮空氣儲能

壓縮空氣儲能不是像電池儲能那樣的簡單儲能系統，它是一種調峰用燃氣輪機發電廠，對於同樣的電力輸出，它所消耗的燃氣要比常規燃氣輪機少40%，其原因為常規燃氣輪機在發電時大約需要消耗輸入燃料的2/3進行空氣的壓縮，而CAES則可利用離峰的低價電能預先壓縮空氣，然後根據需要釋放儲存的能量加上一些燃氣進行發電。壓縮空氣常儲存在合適的地下礦井或熔岩下的洞穴中。

優點：容量大，成本低

缺點：受地理限制，需氣體燃料
氫儲能

氫儲能的提出主要是受到燃料電池成功開發的影響。在能源應用中，燃料電池目前已達到可供實際使用階段，只是它的發電成本太高，還無法與常規的發電技術相比。另外，氫的制備與儲存的問題仍待解決。不過，它具有無污染、無轉動零件等優點。
Renewable Energy -1

The diagram illustrates a fuel cell, where fuel (H₂) is reacted with oxidant (1/2 O₂) to produce water (H₂O) and electrical current. The depleted fuel product gases (H₂) and depleted oxidant product gases (H₂O) are shown flowing through the electrolyte (ion conductor) membrane. The electrical current is generated at the anode and cathode, with electrons (2e⁻) flowing through the external circuit. The fuel and oxidant are supplied to the anode and cathode, respectively, while the depleted gases are expelled.
<table>
<thead>
<tr>
<th>分類</th>
<th>種類</th>
<th>特點</th>
</tr>
</thead>
<tbody>
<tr>
<td>化學儲能</td>
<td>鉛酸電池</td>
<td>成本低，壽命短，污染環境，需要回收</td>
</tr>
<tr>
<td></td>
<td>氧化還原液流電池</td>
<td>容量大，功率和容量獨立設計，能量密度低</td>
</tr>
<tr>
<td></td>
<td>鈉硫電池</td>
<td>能量密度、功率密度高，成本高，安全性差</td>
</tr>
<tr>
<td></td>
<td>金屬空氣電池</td>
<td>能量密度非常高，充電性能不佳</td>
</tr>
<tr>
<td></td>
<td>超級電容器</td>
<td>壽命長，效率高，能量密度低，放電時間短</td>
</tr>
<tr>
<td></td>
<td>二次電池</td>
<td>能量密度、功率密度高，成本高，大功率電池存在安全問題</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>物理儲能</strong></td>
</tr>
<tr>
<td></td>
<td>抽水儲能</td>
<td>容量大，技術成熟，成本低，受地點限制</td>
</tr>
<tr>
<td></td>
<td>壓縮空氣儲能</td>
<td>容量大，成本低，受地點限制，需要氣體燃料</td>
</tr>
<tr>
<td></td>
<td>飛輪儲能</td>
<td>功率高，能量密度低，成本高，技術需要完善</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>超導儲能</strong></td>
</tr>
<tr>
<td></td>
<td>超導磁</td>
<td>功率高，能量密度低，成本高，需經常維護</td>
</tr>
</tbody>
</table>

表三 各種儲能技術及特點
圖三 各種儲能技術適合的應用領域

功率

- 金屬空氣電池
- 液流電池
- 鈉硫電池
- 高級電池
- 超級電容
- 高能飛輪
- 低能飛輪
- 超導體
- 壓縮空氣
- 泵儲存
- UPS
- 與電力品質
- 備轉容量
- 能源管理
圖四 各種儲能技術的現況及發展
結論

各種能源儲存技術提供了具有寬時間範圍的儲能功能，從幾秒到數十小時等等，這些可以解決電力系統的供電壓力，改善電力系統的穩定性，提高供電品質。正因如此，更加需要積極研究這一領域，讓能源更有效的利用。
報告完畢
謝謝聆聽
結合風力發電機與太陽能電池模組之混合式充電系統之研製

再生能源發電技術
National Yunlin University of Science & Technology
摘要

獨立型再生能源發電系統需要蓄電池來儲存電力，本論文之目的在研製一可結合風力與太陽能發電之混合式充電系統。所提之太陽能與風力發電二系統均使用SEPIC轉換器，其具備昇降壓、正向輸出極性、低脈動輸入電流，輸入電壓範圍大等優點，非常適合小功率風力發電機與太陽能電池模組等電力之轉換。本論文分別從事太陽能電池模組與永磁同步發電機之二充電系統之研製，最後再將二者整合成為一混合式系統。
1997年12月聯合國於日本京都舉行氣候變化綱要公約第三次締約國大會，通過具有約束效力的京都議定書（Kyoto Protocol），以規範工業國家未來溫室氣體減量責任。除了環保的壓力外，未來原油及其他傳統能源之預測所示逐漸短缺。風力及太陽能由於取之不絶且零污染，預測甚至指出其30年後之比重將超越石油與燃煤，成為全球主要之能源來源。
主要內容

論文之主要內容包括:
(1) 電流模式控制且迴授為輸入電壓之SEPIC 轉換器之分析與設計
(2) 太陽能電池模組之最大功率點追蹤控制器設計
(3) 無需感測機械參數之風力發電機最大功率點追蹤控制器設計
(4) 三階段蓄電池充電控制器設計
(5) 太陽能與風力發電二個子系統及電池充電與負載需求等四者之間電力平衡控制方法之研擬
(6) 以半橋式轉換器來實現PV模組之模擬器
(7) 以半橋式轉換器來模擬風車及風力發電機系統

本論文中太陽能與風力發電二次系統之最大功率點追蹤控制器及模擬器中太陽能之I-V 特性與風力發電機之P-V特性等計算為利用MATLAB 的即時控制環境來實現，其餘控制器乃以類比方式製作。論文實際製作各為80W 之太陽能與風力發電之二充電系統並加以結合，最後透過模擬及實驗結果來驗證所提方法之可行性。
再生能源發電系統分類

(a) 市電併聯型
所發出之電力可提供負載使用，多餘電力並可饋入市電，不足時則由市電補償不足的電力。

(b) 獨立型
負載所有電力來源均為風力或太陽能，太陽能提供負載用電之多餘能量乃對蓄電池充電，當太陽能電力瞬間不足以提供負載所需電力時則由蓄電池提供。

(c) 混合型
結合太陽能與風力發電之混合式系統，為較具發展潛力的能源利用方式。
（a）市電併聯型

所發出之電力可提供負載使用，多餘電力並可饋入市電，不足時則由市電補償不足的電力。
(b) 獨立型

負載所有電力來源均為風力或太陽能，太陽能提供負載用電之多餘能量乃對蓄電池充電，當太陽能電力瞬間不足以提供負載所需電力時則由蓄電池提供。
結合太陽能與風力發電之混合式系統，為較具發展潛力的能源利用方式。
結合太陽能與風力發電之混合式系統

較具發展潛力的原因如下:

(1) 單一再生能源往往易受季節、氣候等因素影響，使得系統之供電連續性不佳，缺乏實用性，太陽能及風力發電之混合性系統可彌補上述缺點，以達供電之連續性及穩定性。

(2) 若考量能源管理策略，混合性系統因調度之便利性，易於使用能源管理控制，可提高其供電效率。

(3) 太陽能與風力常具互補性，晝間提供太陽能，而夜間則風力較強，實用上易於達成。
PV 充電器示意圖

PV Module → DC/DC Converter → Load

- Switch Current
- PV voltage current

- Drive
- PWM
- Current-Mode Control

MPPT Controller → Charging Controller

Battery Voltage, current
PV 電池特性介紹

太陽能電池模組等效電路
太陽能電池模組之輸出電壓與電流方程式

\[ I_p = n_p I_{ph} - n_p I_{sat} \left[ \exp \left( \frac{q}{kAT} \frac{V_p}{n_s} \right) - 1 \right] \]

\textit{Isat}：太陽能電池模組之反向飽和電流 (A)

\[ I_{sat} = I_{rr} \left( \frac{T}{T_r} \right)^3 \exp \left[ \frac{qE_{gap}}{kA} \left( \frac{1}{T_r} - \frac{1}{T} \right) \right] \]

太陽能電池模組所產生之電流 \textit{Iph} : 

\[ I_{ph} = \left[ I_{scr} + \frac{K_i}{1000} (T - T_r) \right] \cdot S_i \]

太陽能電池模組之輸出功率：

\[ P = V_p I_p = n_p I_{ph} V_p - n_p I_{sat} V_p \left[ \exp \left( \frac{q}{KAT} \frac{V_p}{n_s} \right) - 1 \right] \]
\( I_p \): PV 模組之輸出電流 (A)
\( V_p \): PV 模組之輸出電壓 (V)
\( N_p \): PV 模組之並聯數
\( N_s \): PV 模組之串聯數
\( q \): 一個電子之電荷量 \((1.6 \times 10^{-19} \text{C})\)
\( K \): 波茲曼常數 \((1.38 \times 10^{-23} \text{ J/°K})\)
\( T \): PV 模組之表面溫度 (°K)
\( A \): PV 模組之理想因數 \((A=1\sim5)\)
\( T_r \): PV 模組之參考溫度 (°K)
\( I_{rr} \): PV 模組在參考溫度 \( T_r \) 時之反向飽和電流。
\( E_{gap} \): 半導體材料跨越能間帶間隙時所需能量。
\( I_{scr} \): PV 工作在參考溫度和1KW/m^2 的日照條件下之短路電流
\( K_i \): PV 模組短路電流之溫度係數 \((\text{mA/°K})\)
\( S_i \): 日照強度 \((\text{KW/m}^2)\)
最大功率點追蹤

PV 模組特性曲線可知，日照強度及環境溫度為影響 PV 模組輸出功率重要因素，當 PV 模組在瞬息萬變之環境下工作時，溫度與日照強度隨時都可能改變，欲使 PV 模組能輸出其最大功率，必須隨工作環境改變其工作點，亦即改變太陽能電池模組之電壓及電流，此種控制稱為最大功率點追蹤 (Maximum Power Point Tracking, MPPT) 控制。
最大功率點追蹤之方法

文獻上雖宣稱有許多種，包括：

1. 電壓回授法
2. 功率回授法
3. 擾動與觀察法
4. 增量電導法
5. 直線近似法等
擾動與觀察法

擾動與觀察法的基本原理，為在固定的週期內，逐步的增加或減少負載，並觀察、比較負載變動前後的輸出電壓及輸出功率的大小。
擾動與觀察法模擬與實驗

Simulated MPPT process
ΔV=0.01 V

Insolation changes between 30 to 90 mw/cm$^2$
Temperature at 60 ℃
Experimental MPPT process

90 mw/cm$^2$
30 mw/cm$^2$
增量電導法

增量電導法則以P-V 曲線為依歸，以dP/dV 斜率來決定電壓調整之方向，即增加了輸出功率對電壓變化率的邏輯判斷，以使其能因應大氣條件的變化，而維持在最大功率點。由PV 模組之P-V 特性曲線可以看到當dP/dV=0 時，即是最大功率點。此有較為複雜的運算過程，在降低能量損失及提升效率上有顯著的效果。
增量電導法方塊圖

\[ \frac{dl}{dv} > - \frac{I}{V} \] when \( V_{PVA} < V_{PP} \)
\[ \frac{dl}{dv} < - \frac{I}{V} \] when \( V_{PVA} > V_{PP} \)

Fig. 12. Block diagram of incremental conductance PPT.
PV 電池之P-V 特性曲線圖

\[ \frac{dP}{dV_p} > 0 \]

\[ \frac{dP}{dV_p} < 0 \]
### Siemens SP75 太陽能電池規格表

<table>
<thead>
<tr>
<th>電氣特性</th>
<th>規格</th>
</tr>
</thead>
<tbody>
<tr>
<td>額定最大輸出功率 (W)</td>
<td>75</td>
</tr>
<tr>
<td>額定電流 (A)</td>
<td>4.4</td>
</tr>
<tr>
<td>額定電壓 (V)</td>
<td>17.0</td>
</tr>
<tr>
<td>短路電流 $I_{sc}$ (A)</td>
<td>4.8</td>
</tr>
<tr>
<td>開路電壓 $V_{oc}$ (V)</td>
<td>21.7</td>
</tr>
<tr>
<td>正常工作電壓 (°C)</td>
<td>45.2</td>
</tr>
<tr>
<td>短路電流溫度係數 $K_{i}$ (mA/°C)</td>
<td>2.06</td>
</tr>
<tr>
<td>開路電壓溫度係數 (V/°C)</td>
<td>-0.77</td>
</tr>
</tbody>
</table>
不同照度、固定環境溫度(25°C)下
I-V特性曲線

![I-V特性曲線](image)
不同照度、固定環境溫度(25℃)下
P-V 特性曲線
不同環境溫度、固定照度(1 kW/m²) 下 I-V 特性曲線
不同環境溫度、固定照度(1kW/m²)下
P-V 特性曲線
DC/DC 昇降壓型轉換器介紹

1. 傳統昇降壓轉換器
2. 邱克轉換器
3. ZETA 轉換器
4. SEPIC 轉換器
5. 全橋式轉換器
6. H-橋轉換器
7. 返馳式轉換器

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傳統昇降壓轉換器
邱克轉換器
ZETA 轉換器
SEPIC 轉換器

PV Module

 Renewable Energy -1
電流模式控制之SEPIC 轉換器設計

1. 在 CCM 下，SEPIC 之輸出與輸入電壓轉換之關係

\[ M = \frac{V_B}{V_p} = \frac{D}{1-D} \]

2. 電感設計在操作在 CCM 之邊界，則輸入電感 L1 之電流

\[ i_{L1,peak} = 2I_{p,min} = \frac{2P_{pv,min}}{V_p} = \frac{V_p}{L_1} D_{max} T_s \]

3. 選擇 L1 = L2, L1 = L2 = \[ \frac{V_B^2}{2M(M+1)P_{pv,min} f_s} \]

4. Cp, Cs 電容之 ESR 值 Re,

\[ R_e = \frac{\Delta V_p}{i_{L1,peak}} = \frac{\Delta V_p}{2I_{p,min}} \]

選擇 Cs = Cp
控制器設計

From MPPT controller

Renewable energy
全橋式轉換器
H-橋轉換器
返馳式轉換器
充電系統的控制方塊圖
PV 模組模擬器

(a) 半橋式轉換器

(b) 模擬器之控制方塊
PV 系統之實作電路架構

PV module Emulator

DC power supply
synchronous buck converter
SEPIC
Electronic LOAD

$V_{corp}$ $V_p$ $I_p$ $V_{p+}$

D/A
A/D
D/A

PV module Emulator controller
MPPT controller

Matlab real-time control

PC
小型風力發電機充電器之研製

3.1 簡介
3.2 風力發電機特性介紹
3.3 WTG 充電系統之設計
3.4 風力充電系統之模擬及實作
  3.4.1 實驗系統之模擬
  3.4.2 實驗系統之製作與驗證
充電器示意圖
水平軸風車示意圖

\[ P_m = \frac{1}{2} \rho C_p A U^3 \]

- \( P_m(W) \): 為渦輪機機械功率
- \( A(m^2) \): 為渦輪機有效面積
- \( U(m/s) \): 為風速
- \( \rho \) (kg/m³): 為空氣密度
- \( C_p \): 為渦輪機的功率係數
小型風力發電機
(wind turbine generator, WTG)
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功率係數與翼端速度比之關係圖

\[ C_p \]

\[ \lambda = \lambda_{opt} \]

\[ C_{p,max} \]

0.4
輸出功率與風速之關係圖

\[ P \]

\[ U = 12 \ m/s \]

\[ U = 8 \ m/s \]

\[ U = 5 \ m/s \]

\( \lambda = \lambda_{opt} \)
發電機部份

過去之研究包括感應式、永磁同步式與雙饋式感應機等式
• 雙饋式感應發電機一般應用於大功率，
• 感應式則應用於中低功率
• 永磁同步式發電機(PMSG)則最常被使用於小功率

本論文所提為小功率之應用，因此使用永磁同步式發電機，而且為節省成本
風力發電系統之控制架構
風力與太陽能混合式簡介

風力與太陽能發電之轉換器輸出為並聯，除提供負載電力並同時對蓄電池充電。風力部分為利用整流子將三相永磁同步發電機（PMSG）之輸出加以整流，再利用升降壓式DC/DC 轉換器對蓄電池充電，升降壓式轉換器亦同時控制發電機之轉速，使風車操作在最大功率點。太陽能部分亦利用一升降壓式DC/DC 轉換器對蓄電池充電，同時控制太陽能電池之電壓使太陽能電池操作在最大功率點。
風力與太陽能混合式充電系統電路架構
風力發電部分之控制架構

風力發電機 → PMSG → 整流子

升降壓式 DC/DC 轉換器

電壓控制器

MPPT 控制器

最小值選擇器

電流控制器

I * → 還電池 + 負載

PWM & 驅動

I → 隨流控制
太陽能發電部分之控制架構
混合型充電器電力電路設計圖
混合型電路實作電路圖
實作電路
混成式太陽光電與風力發電案例
- Guerinda, Spain


Renewable Energy -1
結論與未來研究方向

1. 控制電路乃以類比電路配合PC-based之MATLAB即時控制環境加以實現，未來可以將所有電路以DSP-based之控制電路來加以整合。
2. 以模擬系統取代實際之PV電池模組及風力發電機，未來可以實際系統來加以驗證。
3. 僅著重在充電器部分之研發，未來研究可延伸至負載端，包括於市電並聯型或獨立型供電等系統所需之高效率、高升壓比變流器之研製。
4. SEPIC轉換器之效率約為85%左右，未來可以朝研製更高效能努力。
5. 風力發電機之機械特性屬高度非線性系統，難以量化設計其控制器，未來可以朝向利用智慧型控制技術如Fuzzy、Neural-Network等方式來實現MPPT控制器。
6. 風力發電機類型多元，本文僅著重在永磁同步形式，未來可發展其他類型風力發電機模擬系統。
7. 本論文為小功率系統，未來可以涵蓋較大功率系統的應用，以轉換器並聯來提升容量方式亦為未來可以努力的目標之一。
8. 本論文僅探討昇降壓型式之轉換器，其它降壓、昇壓類型轉換器於再生能源之應用，亦為後續可以探討的方向。
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SUPER CAPACITOR

National Yunlin University of Science & Technology
Outline

前言
EDLC简介
EDLC之工作原理
EDLC之特性
EDLC之应用
結論
參考資料
前言

從系統設計的觀點來看，性能和可靠性是不可或缺的，對工程師來說，能量儲存一直是他們設計中的致命弱點。在過去，備份電源的解決方案就是電池，主要是鉛酸電池。而現在，工程師有更多的選擇來滿足備份電源的需求，包括鋰離子、鎳氫電池等先進的電池技術、燃料電池以及太陽能電池等等。

儘管鋰離子、鎳氫電池和其它電池技術已取得很大進步。但設計工程師終究仍面臨著與使用鉛酸電池時一樣的問題，即這些技術都是基於化學反應，它們的使用壽命有限並受溫度的限制。

因此，另外一個能夠滿足設計需求的解決方案，就是超級電容 (Super capacitor)。
超級電容又名電子雙層電容(electric double layer capacitor)，係藉由將離子吸附於多孔材料表面來儲存電荷，此實驗所使用的材料則是碳。傳統的介電電容通常只能提供微法拉(microfarad)範圍的電容值，而超級電容每公克材料約可產生十幾法拉，其強大的電荷儲存能力來自於帶電離子與碳表面的距離很小(約1 nm)，以及碳具有很高的表面積。大多數超級電容的容量用法拉(F)標定，通常在1F到5,000F之間。
EDLC 簡介

In the picture you see (from left to right)

GoldCap  3,3 F @ 2,5 V
SuperCap  3 F @ 2,7 V
SuperCap 10 F @ 2,3 V
SuperCap 20 F @ 2,5 V
SuperCap 25 F @ 2,3 V
EDLC之工作原理

超級電容的結構，最外部由兩個以活性碳材料製作的電極基板組成，並且浸入電解液中，一層半透膜置於中央；將一電壓跨接於兩個基板上，負端吸引正離子，正端吸引負離子，使電容內部產生一電場。
從圖中可看出，**超級電容**與電解電容或者電池的結構非常相似，主要差別是用到的電極材料不一樣。在超級電容裏，電極基於碳材料技術，可提供非常大的表面面積。表面面積大且電荷間隔很小，使超級電容具有很高的能量密度。
EDLC之工作原理

Reaction Principle of Super Capacitor

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EDLC之工作原理
EDLC之特性

操作特性

- 相較於傳統電容，EDLC之體積較小
- 可無限次數的重複充放電，使用壽命長( 10~12 years )
- 放電速度可快可慢( ms ~ min)
- 充電速度可快可慢( sec ~ min)
- 充電方法簡單，沒有充電過度的危險
- 放電過程並不會排放任何額外的熱量
- 深層放電(Deep discharge)不會對電容本身造成任何影響
EDLC 之特性

操作特性

- 自放電(self-discharge)速率快
- 操作溫度範圍大(-50C ~ 85C)
- 低內阻，且ESR(串聯電阻)很小
- 低耐壓，需串聯使用
- 功率密度高(相較於傳統化學電池)
- 能量密度高(相較於傳統電容)
EDLC之應用

- 3C 產品之電池供電改善
  - a. 相機手機
  - b. 手提電腦
  - c. 數位相機
  - d. 無線傳輸

- 電動車輛
  - a. 電動自行車(機車)
  - b. 煞車回充
  - c. 油電混和車(HEV)
  - d. 電動車(FC)

- 電動手工具
- UPS
- 再生能源儲存裝置
EDLC之應用

EDLC應用實例 - 煞車回充

「超級電容」技術因可能出現在F1賽道內而受到許多關注，「油電混合動力」的理論「回收煞車時所浪費的能源」說來並不困難，在實用化的過程卻遭遇到許多技術瓶頸！汽車工程師一直希望找到一個高速、有效率而且成本低廉的能量儲存媒介，目前多數Hybrid系統使用的充電電池技術其實並不合適：煞車所產生的能量與電流皆以短時間供應。而不論鎳氫、鎳鎘甚至更老舊的鉛酸續電池在設計時都以「長時間充電」為考量，在極短時間內的充電效率都很差。汽車工程師也曾推出一種密封於真空狀態的高轉速飛輪(Flywheel)做為儲能媒介，但如何將轉速超過100000 RPM的高速飛輪與多數時間轉速僅5000 RPM轉以下的離合器飛輪整合？
新能源应用

EDLC之应用

EDLC应用实例 - 煞车回充

Energy generation recovery at braking

Motor
Electricity generation unit
Engine

Decelerating
Charging
Super capacitor

Discharging
Accelerating
Battery
EDLC之應用

EDLC應用實例 - HEV效率提升

以Daihatsu車廠剛推出的DMHS (Daihatsu Mild Hybrid System)系統為例，這具排汽量660 c.c.的Hybrid引擎系統採用鎳氫充電電池及輸出功率9.4 kW的DC直流電無刷馬達，工作電壓則為216V，不可否認、「油電混合動力」(Hybrid)系統的效率已經比現有汽油引擎車型高出30％，但是在現有的技術架構下、仍有不少進步空間。締造突破性發展的關鍵就在「超級電容」！
EDLC之應用

EDLC應用實例 - HEV效率提升

Photo of a bank of Maxwell PowerCache Ultacapacitors under a cars bonnet (Photo copyright Metric Mind)
BMW工程師把超級電容在汽車的應用推向全新的里程碑：一款搭載普通4.4升V8引擎的BMW X5其輸出為286匹馬力(最大扭力為330Nm @ 5400 RPM)，但整合了140個超級電容模組後，其加速時最大扭力瞬間可暴漲至1000 Nm(時間達5-6秒)。這樣的加速表現可與搭載V12引擎的Mercedes CL65 AMG相提並論，其油耗表現卻比普通BMW X5還要好！這款稱為「Blitzmobile X5」向我們勾勒出一個混合動力系統的美好未來藍圖。
EDLC之應用

EDLC應用實例 - 提升瞬間扭力

Blitzmobile X5
結論

隨著科技的進步，各種電子及電力產品紛紛問世，而且朝著輕薄短小的趨勢發展；隨著此一趨勢，高容量、高功率之能源儲存器需求亦應運而生，超級電容的出現，適時滿足各項應用嚴格之電力條件的需求。

目前超級電容已應用於國防，汽車，通訊，醫療設備器材以及資訊產業上；展望未來，將廣泛應用於各項電能應用之動力或電源管理模組及產品上，為人類科技發展再添新的頁。
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