Study of Different Implementation Approaches for a Maximum Power Point Tracker [1]

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Abstract: This paper studies the design of a Maximum Power Point Tracker (MPPT) for low power portable solar array applications. The discussion will compare different digital and mixed signal implementation approaches of the same Perturb and Observe algorithm, in particular: simple P&O algorithm on the duty cycle, P&O algorithm using an analog inner voltage control loop and finally using a digital voltage control loop programmed into the micro-controller. This research shows that the method of implementation (analog, digital) has an influence on the robustness of the MPPT particularly in suddenly changing illumination conditions.

Solar Panels have been used for decades to generate electricity in various applications: small electronics, spacecrafts, remote locations… However, the little efficiency of solar panels has limited their use. As the efficiency is limited, harvesting the maximum amount of energy from the panel is of prime interest. Recently, the arrival on the market of several types of flexible and lightweight solar panel has unlocked many applications as they can deliver power where no other source is available. However, these solar panels have lower efficiency than average solar cells (although increasing). This emphasizes the need for maximum power extraction even more.

Maximum power is produced by the solar panel at a specific point on the I-V curve of the solar panel. That maximum power point fluctuates with temperature and light intensity. To deliver the maximum amount of power to a load, a DC-DC converter is placed between the solar panel and the load. Different control methods exist to achieve maximum power point tracking. Some rely on the open circuit voltage of the solar panel or short circuit current and then control the voltage to be a fixed fraction of that value [1]. Another widely used method is the "Perturb and Observe" method in which the duty cycle of the converter is modified and the power generated measured [2,3]. If the power increased following that modification of the duty cycle, then the duty cycle will be again be changed in the same direction. If the power generated by the solar panel has reduced, the duty cycle will be changed in the other direction. That will cause the duty cycle to drift and eventually oscillate around the maximum power point of the solar panel. That method has proven to be efficient in optimizing the power output [4].

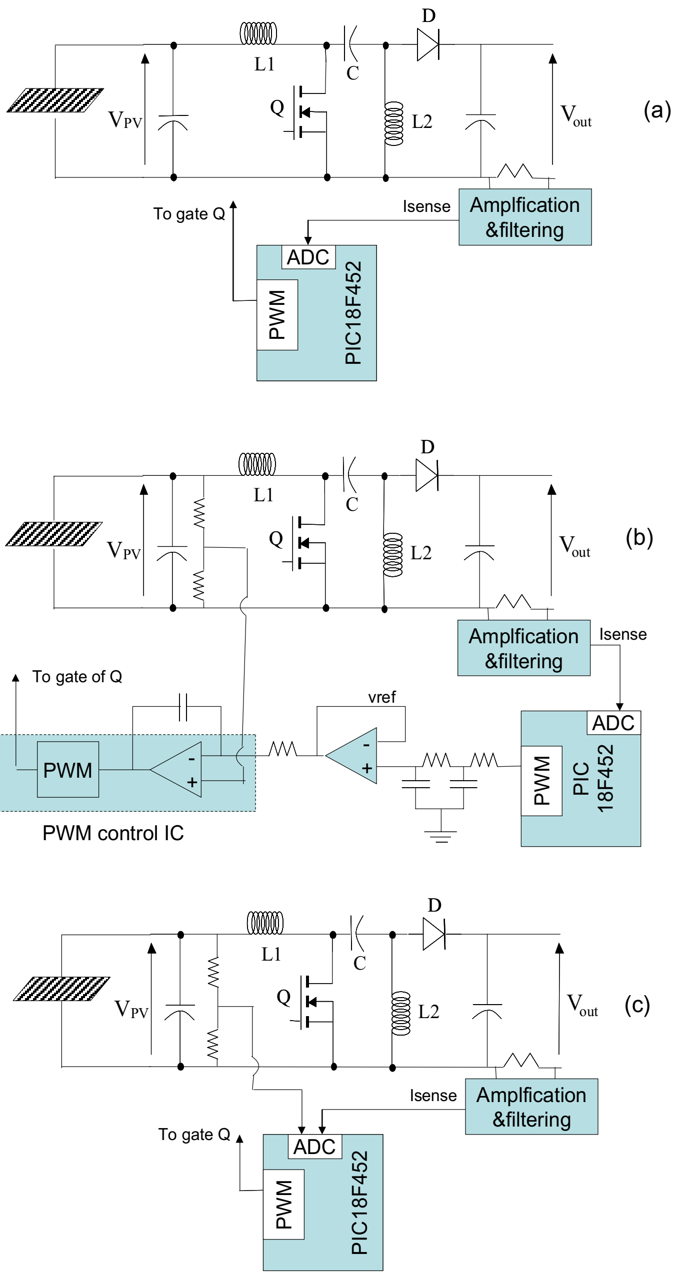

Fig. 1: Three possible implementation of MPPT studied: (a) MPPT directly controls the duty cycle of the converter, (b) MPPT controls the reference voltage of an analog feedback loop. (c) MPPT controls the reference voltage of a digital feedback loop programmed in the microcontroller.

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In this paper we will study the design of a maximum power point tracker for low power solar panels (10-50W). In the process we will discuss three different possible configurations and compare their characteristics:

1- Perturb and Observe on the duty cycle
2- P&O with input voltage control using an input voltage reference and an analog feedback loop
3- P&O with input voltage control using an all digital feedback loop

All the configurations are shown in Fig.1 and rely on the same Perturb & Observe concept shown in Fig. 2.
We will then discuss the interest and limitation of each configuration with specific attention to changes in external conditions.

All experiments use a P3-48 (48W) solar panel from Global Solar. The algorithms and the digital controller are programmed on a PIC18F452 running at 20MHz. The DC/DC converter topology is SEPIC which allows voltage step up and step down to accommodate various loads. We have tested the system with various loads of resistors ranging from 5 to 20 ohms and constant voltage sources from 5 to 24V.
In our SEPIC L1=L2=65uH, C=88uF Cout=66uF f=100kHz.

I. P&O on the duty cycle

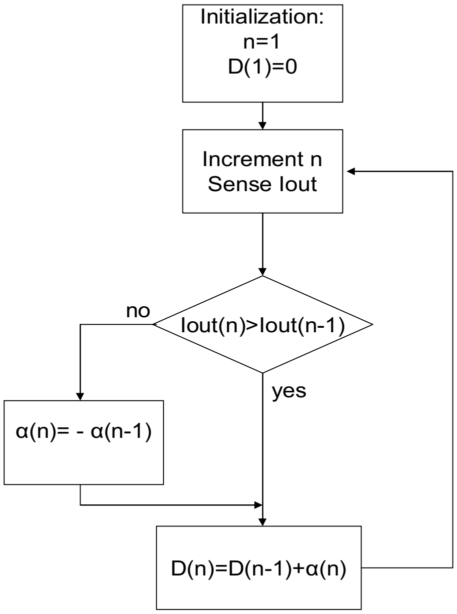

Fig. 2: The standard Perturb and Observe algorithm using output current sensing. Iout is the load current, D is the duty cycle of the converter and α is a step in the duty cycle: +ΔD or – ΔD.

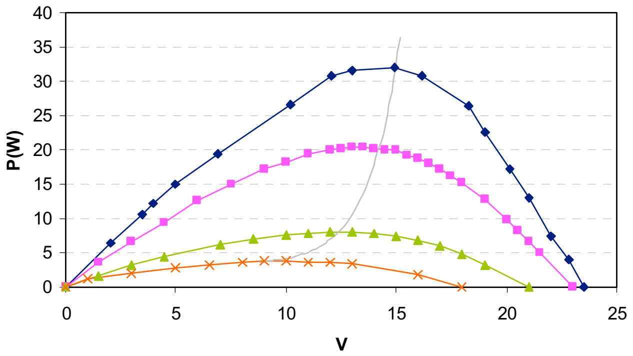

Fig. 3: Solar panel output power as a function of the voltage for different level of irradiance.

Perturbing the duty cycle to achieve Maximum Power Point Tracking as shown in Fig. 2 and Fig. 3 is the simplest implementation of the technique. It requires very few components (apart from the power circuit): a current sensor, an IC with A/D conversion capability and PWM output where the algorithm is programmed (a microcontroller in our case).

If the load is fixed or, if the load variations do not happen often, the changes in the power generated by the solar panel can be estimated from the output parameters and specifically the load current [5]. Otherwise, power has to be calculated by multiplying the solar panel output voltage and current.

The timing of the Perturb and Observe algorithm has to be selected longer than the settling time of the converter and sensing circuitry to ensure correct behavior [6].
The response to a step in duty cycle in our circuit is measured to have a settling time of 2ms. The total response with the output current sensor and filter takes about 8ms to settle. Therefore, the time steps in the perturb and observe algorithm has to be chosen higher than 8ms.
We retained 20ms in our algorithm.

Fig. 4 shows the behavior of the MPPT algorithm.

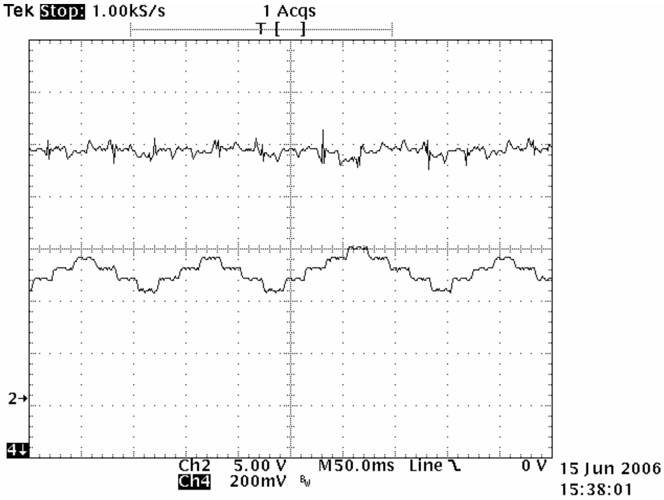

Fig. 4: Top: Output current (!V⇔1A). Bottom: PV array voltage. The Perturb and observe algorithm oscillate around the Maximum Power Point of the solar panel

The problem is that drops in light intensity or significant load change (as shown in Fig. 5) can result in a large drop in the input voltage at a given duty cycle, especially when the DC/DC converter enters discontinuous conduction mode. That drop results in longer times for the algorithm to reacquire the Maximum Power Point and can result in erratic behaviors including reset of the microcontroller [7]. Fig. 6 shows an example of such phenomena.

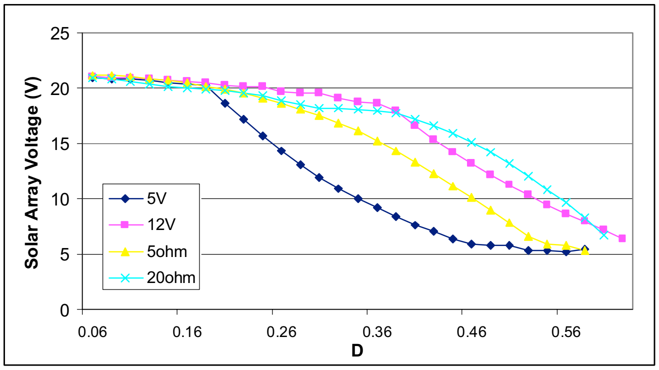

Fig. 5: Solar panel voltage curve for various loads for a given light intensity. A load change can result in a large solar panel voltage change for a constant duty cycle.

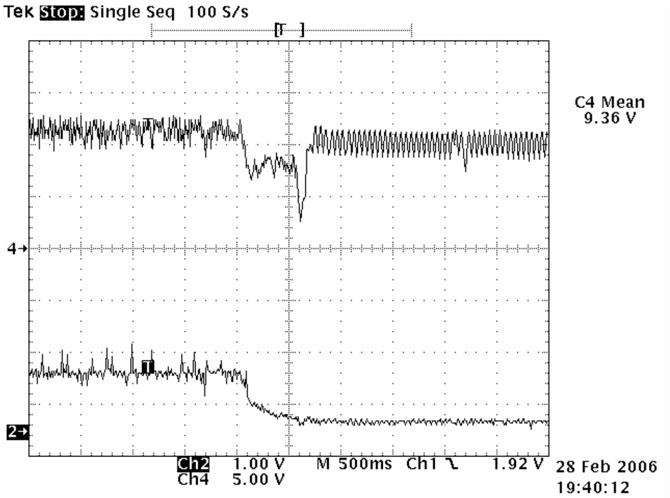

Fig. 6: Ch2: Solar panel voltage. Ch4: output current. A sudden drop in the light intensity can make the system react erratically and cause large drop in the input voltage

Additionally the fact that the Perturb and Observe method gets fooled during the time of the transition of the light intensity increase the possibility of voltage collapse.

II. P&O with inner voltage control loop (mixed signals)

To make sure the voltage doesn't drop to a dangerous level, the input voltage can be controlled to a reference value and the Perturb & Observe function realized on the reference voltage instead of the duty cycle.

This usually requires the addition of a feedback loop between the input voltage and the PWM generator.

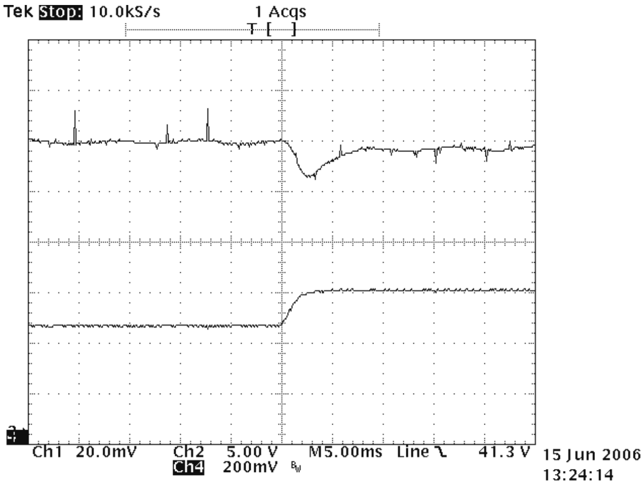

Fig. 7: Response to a step of the voltage reference. Top (Ch2): Solar Panel Voltage. Bottom (Ch4): Output current measurement.

We use a PI controller to achieve proper control:

- The Integral gain is set to 160. The settling time of the input voltage with feedback is 2.5ms
- The output filter consists of an RC filter with 1.9ms time constant and the overall settling time for the current measurement to a step in Vref is about 8ms.

Fig. 7 shows the response of the system to a change in voltage reference.

The reference value will be output by the microcontroller using ideally a D/A converter and the switching waveform will now be generated by a specific PWM controller IC.

The PIC18F452, like many microcontrollers does not incorporate a digital to analog converter.

An alternate solution is to use the PWM output of the microcontroller and filter it to create a steady voltage reference that can be controlled by changing the duty cycle.

Filtering can easily be realized using a simple RC circuit. In our design we opted for a double RC network which provides easy and efficient filtering. The transfer function of the filter is:

$$V_O = \frac{1}{R^2C^2s^2 + 3RCs + 1} V_i$$

The filter is designed to have a response time of 1ms (from 0 to 98%) to avoid increasing the settling time of the system.

By selecting R=10k and C=10e-9nF, the 100kHz ripple is kept at less than 1mV (ripple/reference=1/1000).

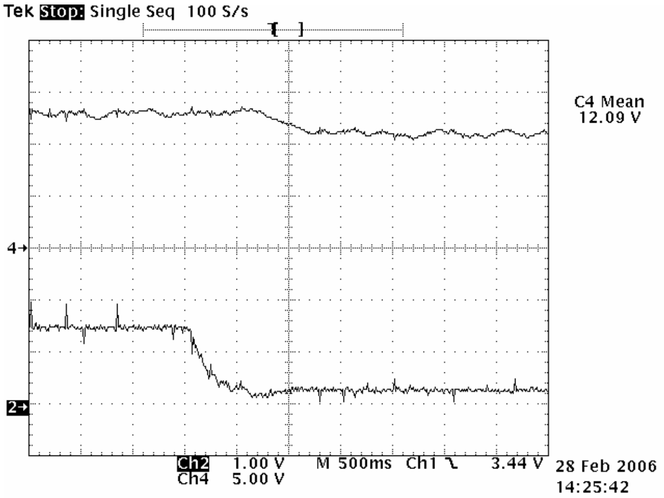

Fig. 8: Response of the MPPT with voltage control to a sudden change in light intensity. Ch2: Input voltage, Ch4: output current (1V⇔1A). The voltage response of the controller is smooth thanks to a fast response of the voltage feedback loop.

Fig. 8 shows that sudden drops in power do not affect the input voltage. After the light settles to its lower intensity, the voltage drops due to the maximum power point tracking algorithm (the maximum power point has moved to a lower voltage as seen in Fig. 3).

Remark:

It has to be noted that slower reference variation would lead to acceptable performance as long as the overall response is faster than the MPPT period (20ms in our design.) That means that for the same ripple amplitude, the frequency of the PWM waveform used for the voltage reference can be made slower to accommodate slower CPU frequencies without sacrificing the resolution of the reference since resolution is a function of the clock frequency. For the microcontroller used it is given as:

$$PWM_{resolution} = \frac{\log\left(\frac{F_{OSC}}{F_{PWM}}\right)}{\log(2)}$$

Where FOSC is one 4th of the clock frequency and FPWM is the frequency of the PWM waveform [8].

So for an analog 0-2.5V reference, created using a 100kHz 0-5V PWM generator with a microcontroller running at 20Mhz, a resolution of 2 times 5.6 bits=6.6bits or 26mV is achieved. Because the input voltage sensing is achieved through a division by 129, that means that the system will be able to control the input voltage of the DC/DC converter (solar panel voltage) by steps of 330mV.

In conclusion, the addition of an analog voltage control loop to the maximum power point tracker increased the reliability of the system without sacrificing speed. It required the addition of a PWM control IC and several passive components. The increase in size and cost that this method implies could be eliminated by considering an all-digital solution.

III. P&O with fully digital inner voltage loop

To reduce the size and cost a digital controller is designed.

We investigated the possibility of using the same microcontroller to achieve digital control of the voltage of the solar panel and MPPT.

To achieve correct control of the system, the sampling period has to be kept as small as possible while all the tasks are performed. In particular, the microcontroller possesses only one A/D converter multiplexed to 8 inputs. Therefore, to ensure that no sample is lost, we need to have the ability to take two samples and process them every sampling period. (to ensure that the program will run in the allotted time, assembly language is preferred over C language.)

The digital PI control routine takes 12.8us to execute. The acquisition time of the A/D converter is 13us while the conversion time is about 20us. Therefore, considering the need to perform 2 sampling in one cycle (output current for MPPT, input voltage for feedback control) we achieve a maximum loop execution time of

$$T_{loop} = 2 \cdot T_{aqu} + 2 \cdot T_{conv} + T_{PI} = 79 \mu s$$

That means that the sampling period will have to be selected greater than 79us (Additional data to be sampled will add 13+20us per line of data to the required period length).

Remark: The Perturb & Observe algorithm routine is not included in the calculation as it is performed at a slower pace and does not need to be part of the interrupt code.

Fig. 9 shows the response of the input voltage to a change in the reference value in the memory of the microcontroller.

It can be noticed, however, that some limit cycling is introduced due to the limitation in the resolution of the PWM generator. At 100kHz, the resolution is 5.6 bits or 2%.

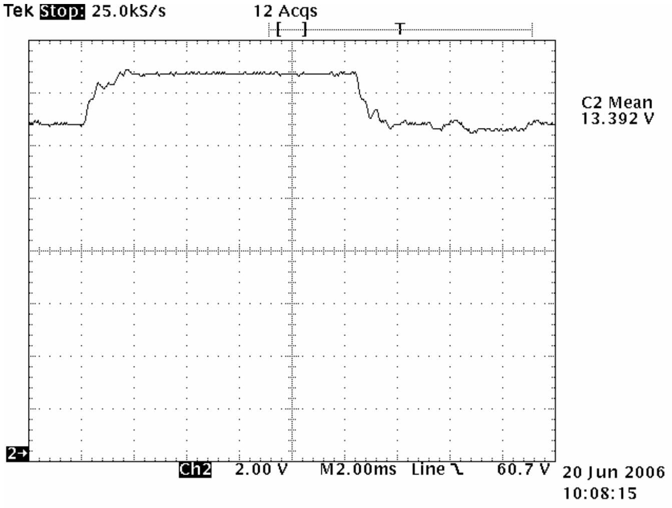

Fig. 9: Response of the solar panel voltage to a step in the voltage reference in the digital control feedback loop with T_{sample} *of 200us.*

To avoid limit cycling, the apparent resolution of the PWM waveform can be increased using digital dithering [9]. Dithering can be programmed in software by interrupting the program every cycle and alternating the value in the duty cycle latches.

The principle is to of dithering is to alternate the duty cycle by one LSB for a certain number of cycles to create an averaged duty cycle that will be in between the levels reachable by the PWM generator.

A 2 bits dither routine is programmed in the microcontroller. There are several patterns possible for achieving dithering, some being more efficient in the harmonic content generated [9]. If programmed on a microcontroller, there are also ways to simplify the dither function.

We name dither function a function which output is 0 or 1 and which takes a dither value (between 0 and 4) and a counter value (between 0 and 4) as arguments. The value of that function will be added to the duty cycle latch. The counter is increased every cycle. Table 1 shows the Karnaugh's map of the function used to set the function.

For example the position of the '1' on the second row of the map does not change the resulting pattern. However, placing it on the second column allows simplification of the function and therefore more compact and faster code.

The value of the function retained is:

$$f(C,D) = \overline{C_1} D_2 + \overline{C_2} C_1 D_1$$

Where C=[C_2,C_1] is a counter incremented each cycle and D=[D_2,D_1] is the 2 bits dither value.

		C_2,C_1			
		0,0	0,1	1,1	1,0
	0,0	0	0	0	0
D_2,D_1	0,1	0	1	0	0
	1,1	1	1	0	1
	1,0	1	0	0	1

Table 1: Karnaugh map of the dither function with the appropriate simplification to the function being circled.

This way, the resolution can be increased to 7.6bits or 0.51% in our case.

Figure 10 shows the comparison of the digital controller with 5.6bits PWM and 5.6bits+2bits from dithering.

It is shown that the addition of dither eliminates the possible limit cycles.

The dither subroutine takes 5.6us to execute. It is run every 10us leaving only 4.4us each cycle for the PI controller. Therefore T_{PI} will increase to 30us (the A/D converter period does not change as A/D conversion is hard wired and runs in parallel with the program.)

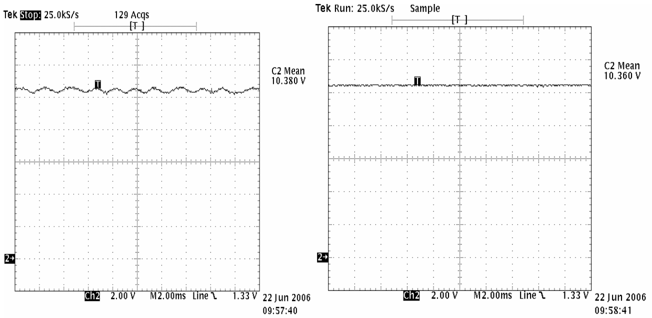

Fig. 10: Left: Solar panel voltage with digital feedback control without dithering. Limit cycles can be observed. Right: Same controller with digital dithering implemented. Limit cycles have disappeared.

IV. Discussion and conclusion:

We will now summarize the result of our work and discuss the different implementation methods.

The Perturb and Observe method for MPPT based on the duty cycle alone performs well in slow changing environment. However issues arise with sudden change in load or light intensity. In that situation, the slow response can lead to important drop in the input voltage and cause shutdown of the converter and reset of the microcontroller.

To solve that issue, a feedback loop can be added in the circuit, controlling the input voltage. MPPT can then be performed by changes in the voltage reference. This ensures that the system will keep the voltage between safe boundaries. Resolution has also increased. However resolution of the previous method can be increased using the dither technique discussed in III

The disadvantage of the above configuration is that its implementation adds a PWM IC along with several resistors and capacitors. (An op-amp may also be required between the microcontroller and the PWM IC's error input to provide correct impedance to the feedback loop).

Those additions increase board space and cost.

To keep the component count minimal, a digital controller has been realized using the same microcontroller. A digital control loop has been designed in agreement with the limitation of the device. It provides similar response to the mixed signal system described above. The component count now reduces to the same number as for the first method. However, unlike the mixed signal approach, this system is very dependent on the frequency of the clock for proper operation (the need for dithering is a symptom of clock frequency limitation).

	Simple P&O	Mixed signals (Analog voltage feedback loop)	All Digital
Robustness to changing conditions	Low: Change in light intensity can introduce large swings in the input voltage which can result in erroneous behavior of the microcontroller or the DC/DC converter.	High: The feedback loop on the input voltage allows a much faster response.	High: The feedback loop on the input voltage allows a much faster response.
Component count	Low	Higher : The addition of an external PWM generator and the need for filtering of Vref (in some cases) increases the number of components.	Low: There is no change in the hardware configuration compared to the simple P&O method.
Microcontroller requirements	Clock frequency limits the resolution of the PWM generator and therefore the steps.	The requirement for D/A conversion can be overcome with the PWM generator. The frequency of the waveform can be adjusted to achieve compromise between resolution and response speed (due to the need of filtering.)	Clock frequency is a strong limiting factor for the speed of the feedback loop and the resolution of the PWM generator (limit cycles.)

Table 2 : Summary of the comparison between the different configuration

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