20 January 2020

1. Introduction

PWM and MPPT charge controllers are both widely used to charge batteries with solar power.

The PWM controller is in essence a switch that connects a solar array to the battery. The result is that the voltage of the array will be pulled down to near that of the battery.

The MPPT controller is more sophisticated (and more expensive): it will adjust its input voltage to harvest the maximum power from the solar array and then transform this power to supply the varying voltage requirement of the battery plus load. Thus, it essentially decouples the array and battery voltages so that there can be, for example, a 12V battery on one side of the MPPT charge controller and panels wired in series to produce 36V on the other.

It is generally accepted that MPPT will outperform PWM in a cold to temperate climate, while both controllers will show approximately the same performance in a subtropical to tropical climate.

In this paper the effect of temperature is analyzed in detail, and a quantitative performance comparison of both controller topologies is given.

2. The current-voltage curve and the power-voltage curve of a solar panel

The examples throughout the following pages are based on an average 100 W / 36 cell monocrystalline solar panel, with the following specifications:

100 W panel 36 cells				
Pm	100 W	Temp. coeff. of Pm	γ	-0.45 %/°C
Vm	18 V	Temp. coeff. Of Vm	ε	-0.47 %/°C
Im	5.56 A	Temp. coeff. Of Im	δ	0.02 %/°C
Voc	21.6 V	Temp. coeff. Of Voc	β	-0.35 %/°C
Isc	6.12 A	Temp. coeff. Of Isc	α	0.05 %/°C

Table 1: Specifications of the solar panel as used in the examples below

The current-voltage curve of this panel is shown in figure 1

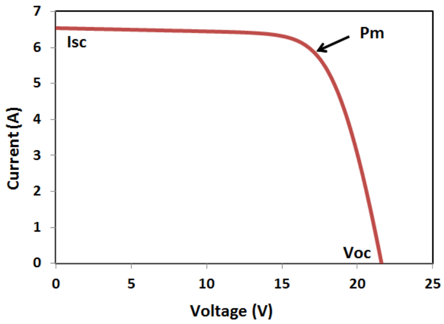

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Fig 1: Current-voltage curve of a 100W / 36 cell solar panel
Standard Test Conditions (STC): cell temperature: 25°C, irradiance: 1000 W/m², AM: 1.5

From this basic curve the power-voltage curve can be derived by plotting P = V x I against V.
The result is the blue curve in figure 2 below.

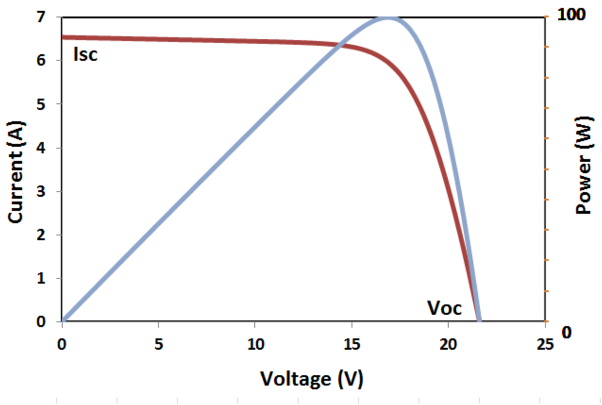

Fig 2: Current-voltage curve (brown) and power-voltage curve (blue, P = V x I)

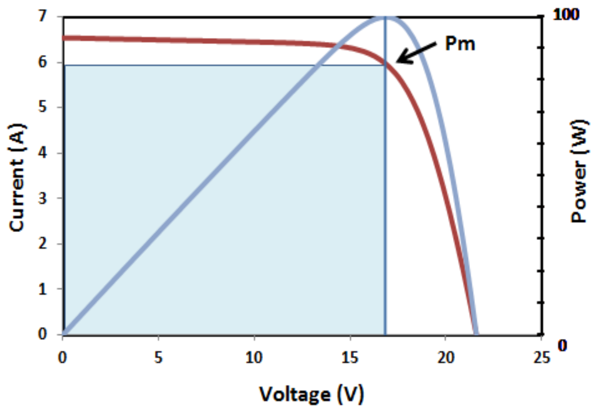

Fig. 3: The area of the blue rectangle is proportional to the product Pm = Vm x Im

Obviously, the power obtained from the panel is zero when it is short circuited (0 x Isc = 0) or when no current is drawn from the panel (Voc x 0 = 0).
In between those two zero power points the product P = V x I reaches a maximum: the Maximum Power Point (Pm = Vm x Im).

The importance of the Maximum Power Point can be visualized as follows:
The product Vm x Im is proportional to the area of the rectangle shown in figure 3. Pm is reached when the area of this rectangle is at its largest. Figure 4 and 5 show two less optimal results obtained when power is harvested at a voltage which is too low or too high.

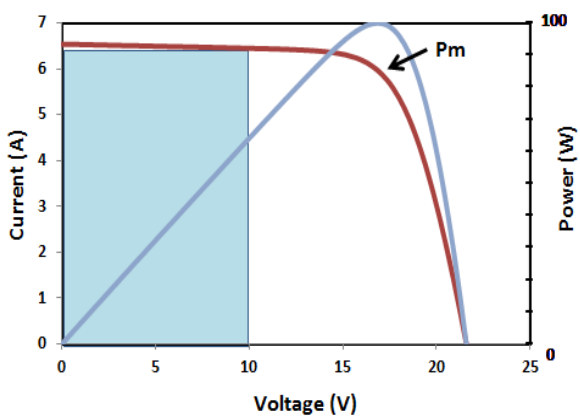

Fig 4: Less power harvested: voltage is too low

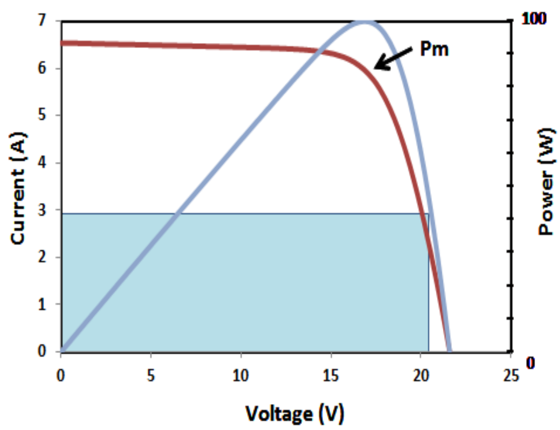

Fig 5: Less power harvested: voltage is too high

The maximum output of a 100 W solar panel is, by definition, 100 W at STC (cell temperature: 25°C, irradiance: 1000 W/m², AM: 1.5).

As can be seen from figure 3, in the case of a 100 W / 36 cell crystalline panel the voltage corresponding to the Maximum Power Point is Vm = 18 V and the current is Im = 5.56 A.
Therefore 18 V x 5.56 A = 100 W.

Conclusion:
In order to get the maximum out of a solar panel, a charge controller should be able to choose the optimum current-voltage point on the current-voltage curve: the Maximum Power Point. An MPPT controller does exactly that.
The input voltage of a PWM controller is, in principle, equal to the voltage of the battery connected to its output (plus voltage losses in the cabling and controller). The solar panel, therefore, is not used at its Maximum Power Point, in most cases.

3. The MPPT charge controller

As shown in figure 6, the voltage Vm corresponding to the Maximum Power Point can be found by drawing a vertical line through the top of the power-voltage curve, and the current Im can be found by drawing a horizontal line through the intersection of the Vm line and the current-voltage curve. These values should be equal to the values specified in table 1.

In this example Pm = 100 W, Vm = 18 V and Im = 5.56 A.
With its microprocessor and sophisticated software, the MPPT controller will detect the Maximum Power Point Pm and, in our example, set the output voltage of the solar panel at Vm = 18 V and draw Im = 5.56 A from the panel.

What happens next?
The MPPT charge controller is a DC to DC transformer that can transform power from a higher voltage to power at a lower voltage. The amount of power does not change (except for a small loss in the transformation process). Therefore, if the output voltage is <u>lower</u> than the input voltage, the output current will be <u>higher</u> than the input current, so that the product P = V x I remains constant.

When charging a battery at Vbat = 13 V, the output current will therefore be
Ibat = 100 W / 13 V = 7.7 A.
(Similarly, an AC transformer may supply a load of 4.4 A at 23 VAC (4.4 x 23 = 100 W) and therefore draw 0.44 A from the 230 V mains (230 x 0.44 = 100 W)).

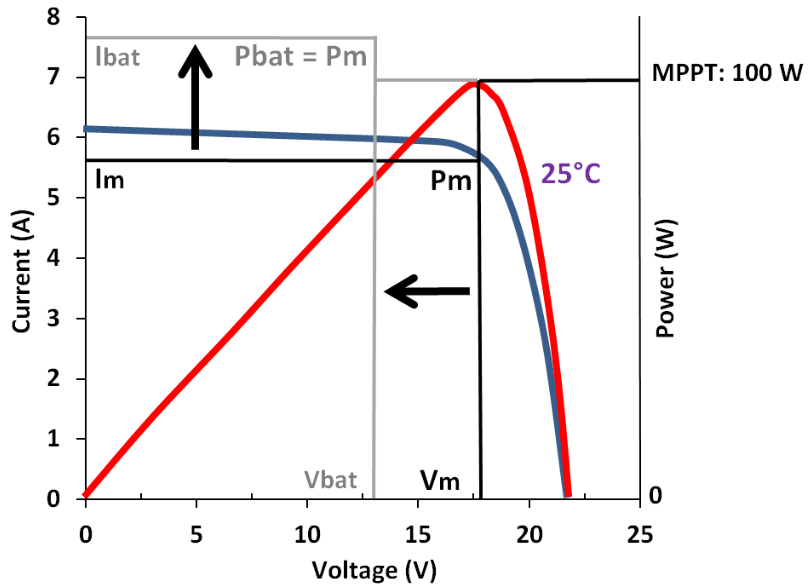

Fig 6: MPPT controller, graphical representation of the DC to DC transformation
Pm = Vm x Im = 18 V x 5.6 A = 100 W, and
Pbat = Vbat x Ibat = 13 V x 7.7 A = 100 W

4. The PWM charge controller

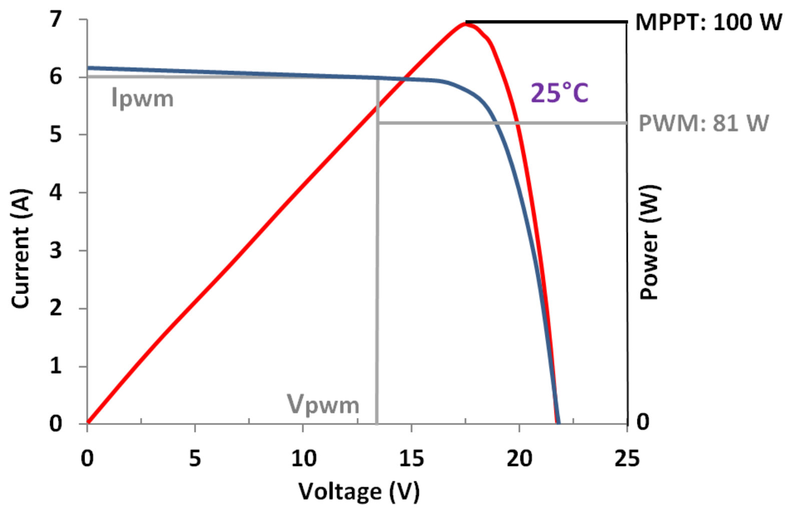

Fig 7: PWM charge controller

In this case the charge voltage imposed on the solar panel can be found by drawing a vertical line at the voltage point equal to Vbat plus 0.5 V. The additional 0.5 V represents the voltage loss in the cabling and controller. The intersection of this line with the current-voltage curve gives the current Ipwm = Ibat.

A PWM controller is not a DC to DC transformer. The PWM controller is a switch which connects the solar panel to the battery. When the switch is closed, the panel and the battery will be at nearly the same voltage. Assuming a discharged battery the initial charge voltage will be around 13 V, and assuming a voltage loss of 0.5 V over the cabling plus controller, the panel will be at Vpwm = 13.5 V. The voltage will slowly increase with increasing state of charge of the battery. When absorption voltage is reached the PWM controller will start to disconnect and reconnect the panel to prevent overcharge (hence the name: Pulse Width Modulated controller).

Figure 7 shows that in our example, with Vbat = 13 V and Vpwm = Vbat +0.5 V = 13.5 V, the power harvested from the panel is Vpwm x Ipwm = 13.5 V x 6 A = 81 W, which is 19% less than the 100 W harvested with the MPPT controller.

Clearly, at 25°C a MPPT controller is preferable to a PWM controller.

Temperature, however, does have a strong effect on the output voltage of the solar panel. This effect is discussed in the next section.

5. The effect of temperature

5.1 The effect of temperature is much too large to neglect

When a panel heats up due to the sun shining on it, both the open circuit voltage and the Maximum Power Point voltage become lower. The current however remains practically constant. In other words: the current-voltage curve moves to the left with increasing temperature, as shown in figure 8.

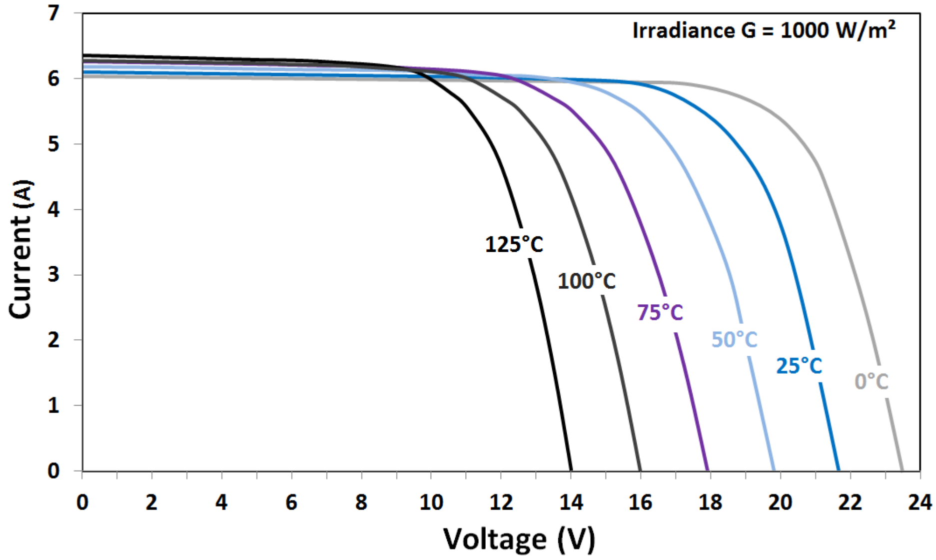

Fig 8: The current-voltage curve moves to the left with increasing temperature

Obviously, as shown in figure 9 below, the Maximum Power Point also moves to the left, and downwards because the product Vm x Im decreases with increasing temperature.

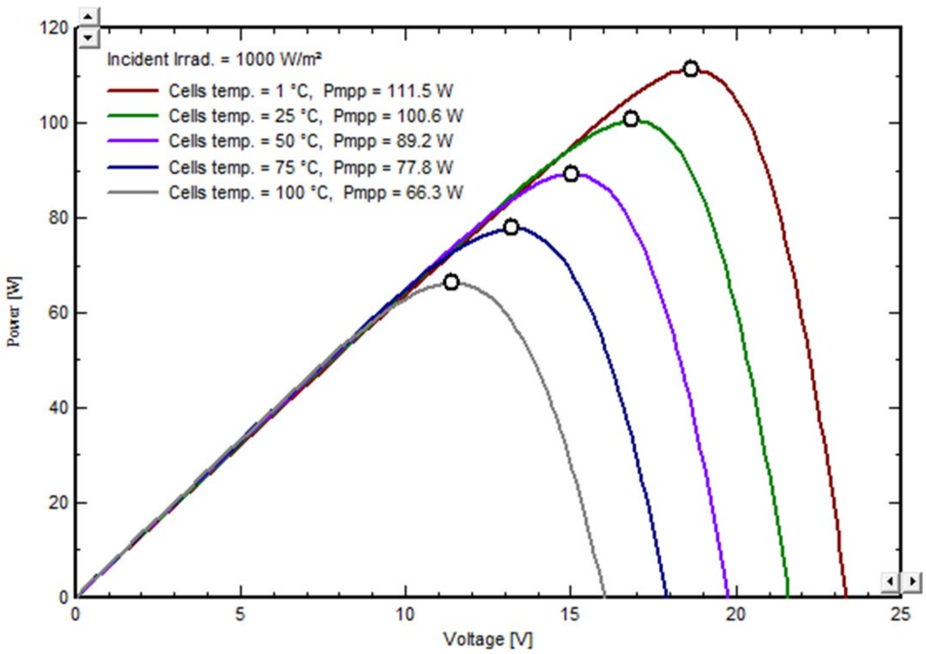

Fig 9: The Maximum Power Point moves to the left and downwards with increasing temperature

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5.2. The MPPT controller when cell temperature is 75°C

MPPT power, current and voltage can be derived as follows from the specification of the solar panel:

Pm (75°C) = Pm (25°C) x (1 + (75°C - 25°C) x γ) = 100 x (1 + (50 x – 0.45 / 100) = 77.5 W

And, following the same method:

Im (75°C) = 5.6 A

Vm (75°C) = 13.8 V

And a check: Im (75°C) x Vm (75°C) = 5.6 x 13.8 = 77.3 W. This is a difference of 0.2 W compared to the Pm (75°C), as calculated earlier, so this is close enough and correlates.

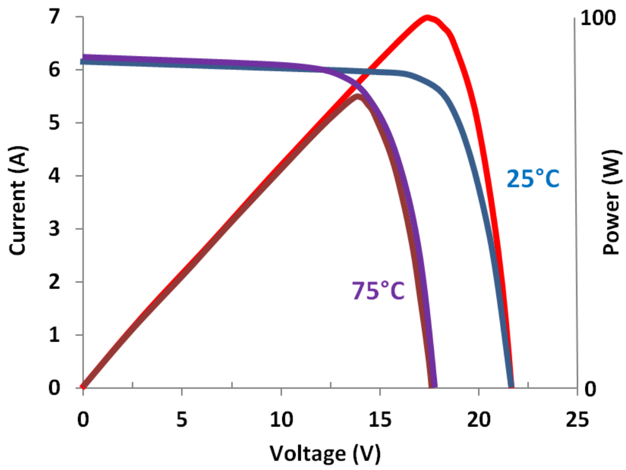

Fig 10: Current-voltage and power-voltage curves at 25°C and 75°C

Note:

Most panel manufacturers do not specify the temperature coefficients of Im (δ) and Vm (ε), and if they do, ε is often given a value which is far too low. The result is that calculating Vm with the help of its temperature coefficient gives an incorrect value (which is far too optimistic in most cases) and Im x Vm will also be wrong, i.e. Im x Vm ≠ Pm which is mathematically impossible.

5.3 The PWM controller when cell temperature is 75°C

Still assuming a battery voltage of 13 V, the voltage imposed on the panel will be 13.5 V. With the help of figure 11 the PWM current can be found by drawing the vertical voltage line and the horizontal current line. The resulting PWM current is 5.95 A and solar panel output is
13.5 V x 5.7 A = 77 W.

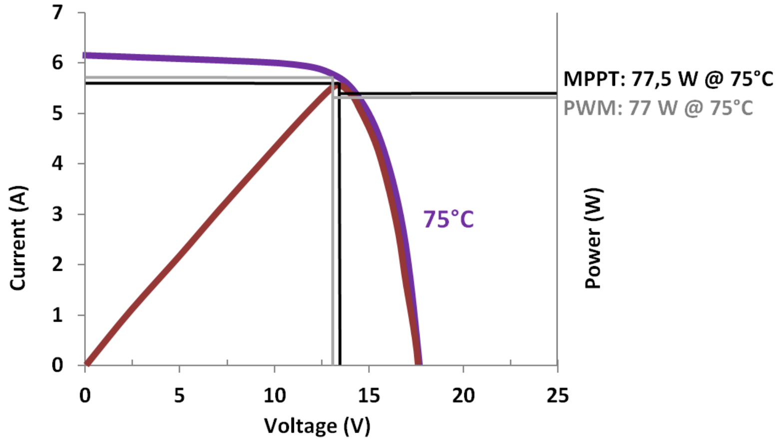

Fig 11: Comparison of MPPT and PWM performance at 75°C panel temperature
Black lines: MPPT (77.5 W).
Grey lines: PWM (77 W). MPPT performance advantage: nil

Conclusion: at Tcell = 75°C and Vbat = 13 V the difference in performance between the two controllers is negligible.

5.4 Cell temperature 100°C

It is interesting to see what happens at even higher temperatures.
Figure 12 shows what happens at 100°C.

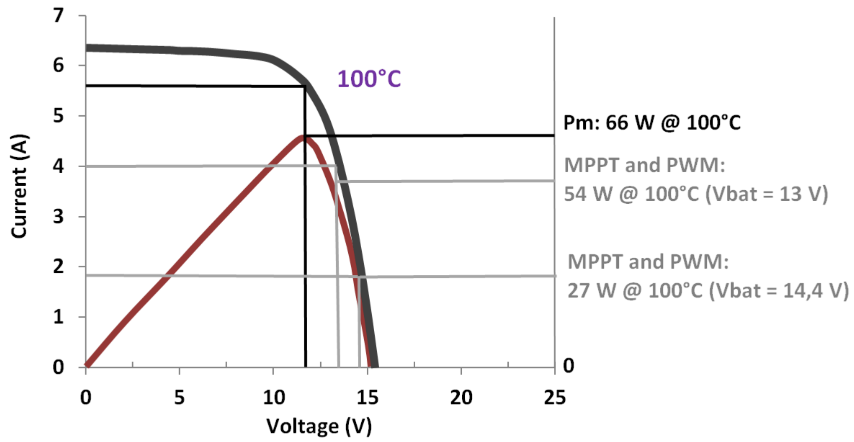

Fig 12: At 100°C panel temperature the Maximum Power Point voltage is 11.7 V

Most MPPT controllers cannot transform a lower voltage to a higher voltage, as that's not what they are made for. If the MPPT voltage Vm becomes lower than Vbat, they will therefore operate like a PWM controller, connecting the panel directly to the battery.
As shown in figure 11: if Vbat = 13 V, the current harvested from the panel will be limited to 4 A.

And the situation becomes worse with increasing battery voltage (or increasing temperature): the charge current quickly reduces to only a few amps.
However, if the MPPT controller could in this situation still operate at the Maximum Power Point, it could harvest 66 W, whether Vbat is low or high!

6. The solution

Clearly, in our example, both MPPT and PWM controllers do not perform at high cell temperatures.

The solution to improve MPPT controller performance at high cell temperatures is to increase panel voltage by increasing number of cells in series.
Obviously, this solution is not applicable to PWM controllers: increasing the number of cells in series will reduce performance at low temperature.

In case of the MPPT controller: replace the 12 V / 100 W panel by a 24 V / 100 W panel or by two 12 V / 50 W panels in series. This will double the output voltage and the MPPT controller will charge a 12 V battery with 66 W (5.1 A @ 13 V), at 100°C cell temperature, see figure 13.

An additional advantage: because the panel voltage has doubled, the panel current is reduced by half (P = V x I and P has not changed but V has doubled).

Ohm's law tells us that losses due to cable resistance are Pc (Watt) = Rc x I^2, where Rc is the resistance of the cable. **What this formula shows is that for a given cable loss, cable cross sectional area can be reduced by a factor of four when doubling the array voltage.**

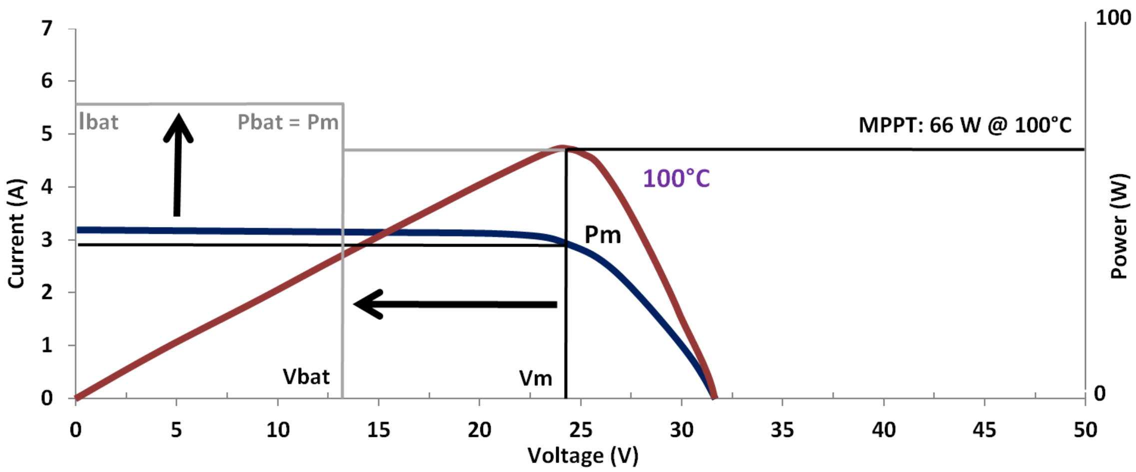

Fig 13: Two 12 V / 50 W panels in series instead of one 12 V / 100 W panel
Pm = Vm x Im = 23.4 V x 2.8 A = 66 W and
Pbat = Vbat x Ibat = 13 V x 5.1 A = 66 W

Conclusion:
When using an MPPT charge controller there are two compelling reasons to increase the PV voltage (by increasing the number of cells in series):

a) **Harvest as much power as possible from the solar array, even at high cell temperature.**
b) **Decrease cable cross sectional area and therefore decrease cost.**

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7. Relative performance graphs

7.1 Relative performance as a function of temperature
Let us now assume that the MPPT controller is connected to a solar array with sufficient cells in series to achieve an MPPT voltage several volts higher than the highest battery voltage.
For example:
12 V battery: 72 cells (a 24 V array) or more
24 V battery: 108 cells (a 36 V array) or more
48 V battery: 216 cells (a 72 V array) or more

The PWM controller is connected to a solar array of exactly the same Wp power, with the usual number of cells in series and used to charge a 12 V, 24 V or 48 V battery: respectively 36, 72 or 144 cells.

The relative performance of the two controllers as a function of cell temperature can be compared as shown in figure 14.

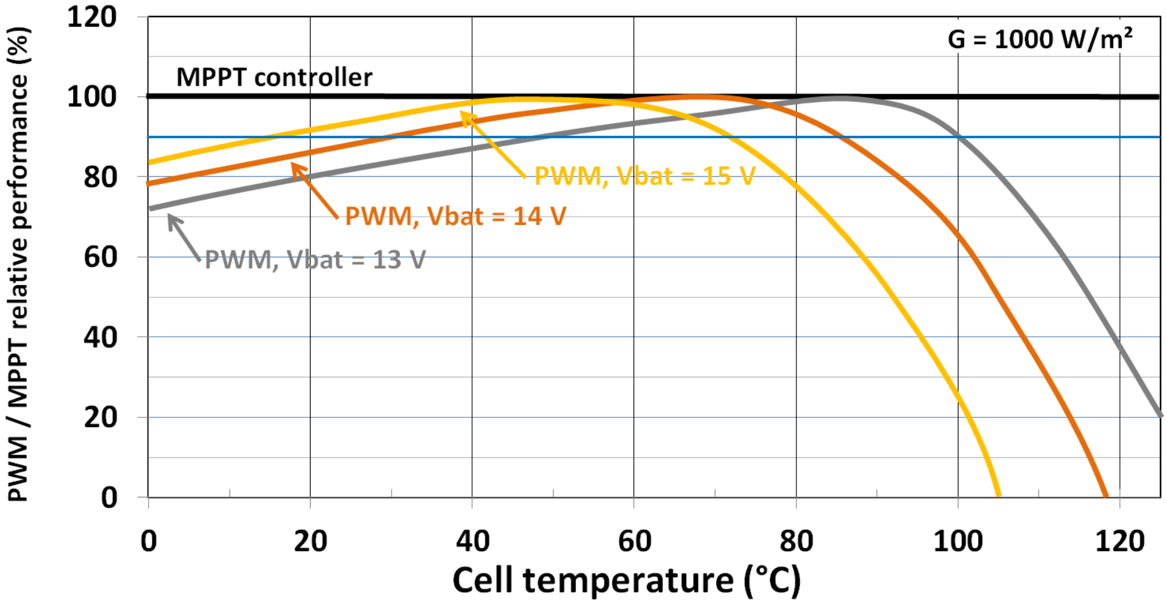

Fig 14: Relative PWM / MPPT performance comparison as a function of cell temperature and battery voltage under STC and assuming 0.5 V loss in the cabling plus controller.

The performance of the MPPT controller is set at 100%. PWM performance will match MPPT performance (100% relative performance) when the battery voltage plus losses in the cabling and the controller happens to be equal to the MPPT voltage. Three PWM relative performance curves are shown, based on three different battery voltages, and, as expected, the 100% point is achieved at lower temperatures when the battery voltage increases.

7.2 Absolute performance as a function of temperature

Including temperature dependence of Pm results in figure 15 below.
The performance of the MPPT controller is set at 100% at 25°C using STC.

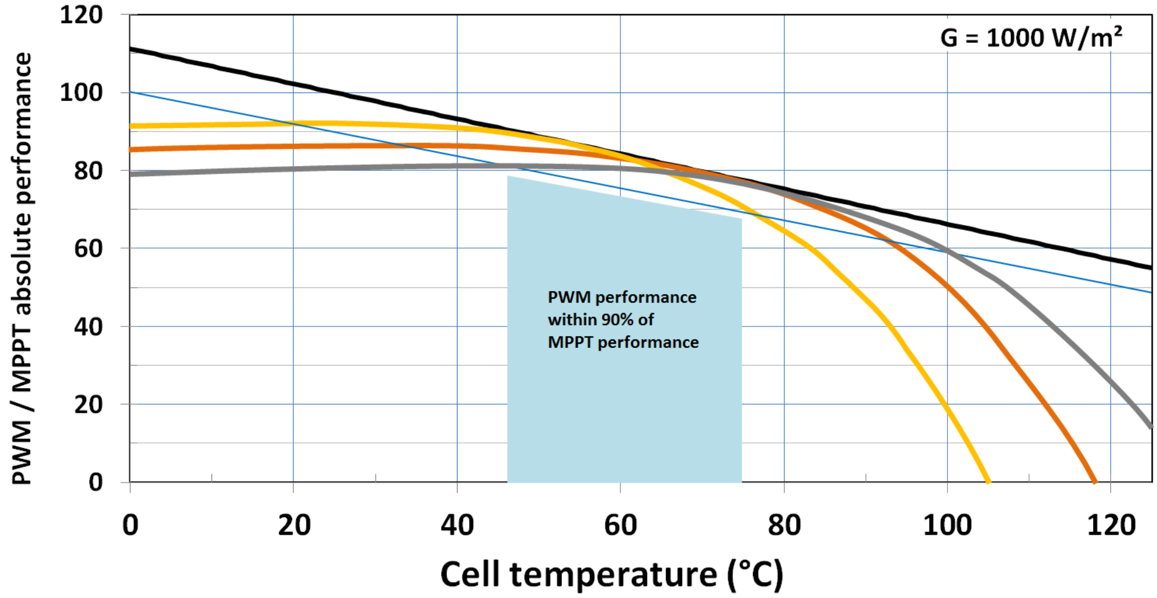

Fig 15: Absolute PWM / MPPT performance comparison as a function of cell temperature and battery voltage under STC and assuming a 0.5 V loss in the cabling plus controller.

The blue area shows that a PWM controller performs nearly as well (within 10%) as an MPPT controller over a relatively wide battery charge voltage (13 V to 15 V) and temperature range (45°C and 75°C).
The 10% limit is given by the thin blue line in figure 14 and 15.

Before drawing any conclusions a few other solar cell and system parameters have to be considered.

7.3 The influence of irradiance

The output of a solar panel is approximately proportional to irradiance, but Vm remains nearly constant as long as irradiance exceeds 200 W / m². Irradiance therefore does not materially influence the MPPT / PWM performance ratio as long as irradiance exceeds 200 W / m² (see figure 16).
But at low irradiance (overcast sky, wintertime) Vm drops rapidly and an MPPT controller connected to an array with a much higher nominal voltage than the battery, will perform far better than a PWM controller.

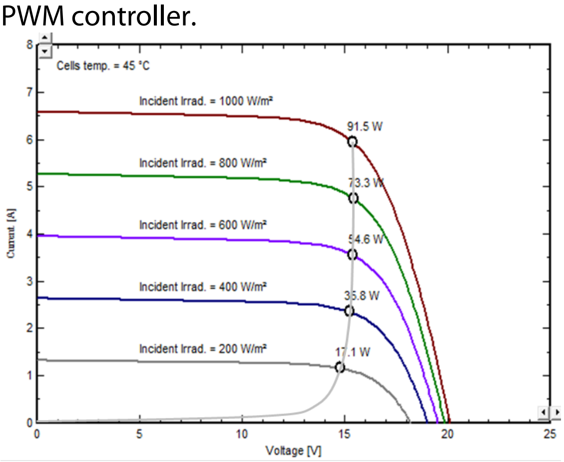

Figure 16: Dependence of Mp and Vmp on irradiance

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7.4 Monocrystalline or Polycrystalline

According to manufacturer's datasheets Vm is, on average, slightly lower in the case of polycrystalline panels. In the case of a 12 V panel the difference is 0.35 V to 0.7 V and the temperature coefficient is similar for both technologies. The consequence is that the PWM curves in figure 13 and 14 move 5 to 10°C toward the left in the case of a polycrystalline panel.

7.5 Partial shading

Partial shading lowers the output voltage. MPPT therefore has a clear advantage over PWM in the case of partial shading.

7.6 Losses in cabling and the controller

In a good installation these losses are small compared to the effect of temperature. Note that throughout this paper, power, voltage and current are taken at the panel output and do not take any losses into account, unless stated otherwise.

7.6 Cell temperature

The next question to answer is: what is the temperature of the solar cells in practice.

A first indication is given by the NOCT (Normal Operating Cell Temperature) which nowadays is specified by most solar panel manufacturers.

NOCT conditions are defined as follows:

- Ambient temperature: 20°C
- Irradiance: 800 W/m^2
- Air Mass: 1.5
- Wind speed: 1 m/s
- Mounting: open back side (free standing array)
- No electrical load: no power is drawn from the panel

According to manufacturer's data, on average NOCT = 45°C. This means that under the conditions as stated, solar cell temperature is 25°C higher than ambient temperature.

A more general formula to calculate cell temperature T_c is:

$T_c = T_a + G/U$ or $\Delta T = T_c - T_a = G/U$

With

Ta: ambient temperature

G: irradiance (W/m^2)

U: thermal loss factor (W/m^2·ΔT)

And a simple model for the thermal loss factor is:

$U = U_c + U_v \cdot W_v$

Where U_c is a constant component and U_v a factor proportional to wind speed W_v (m/s) <u>at the array</u>.

The resulting thermal formula is:

$T_c = T_a + G/(U_c + U_v \cdot W_v)$ or $\Delta T = T_c - T_a = G/(U_c + U_v \cdot W_v)$

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Extrapolating from http://files.pvsyst.com/help/index.html?noct_definition.htm and some other websites, the approximate values for Uc and Uv are:

Freestanding arrays:
Uc ≈ 20 W / m²·ΔT
Uv ≈ 12 W / m²·ΔT/m/s

Arrays with the back side fully insulated:
Uc ≈ 10 W / m²·ΔT
Uv ≈ 6 W / m²·ΔT m/s

Figure 17 shows the resulting cell temperature increase with respect to ambient temperature for free standing arrays and for arrays with the back side fully insulated.

Clearly, air flow is extremely important.

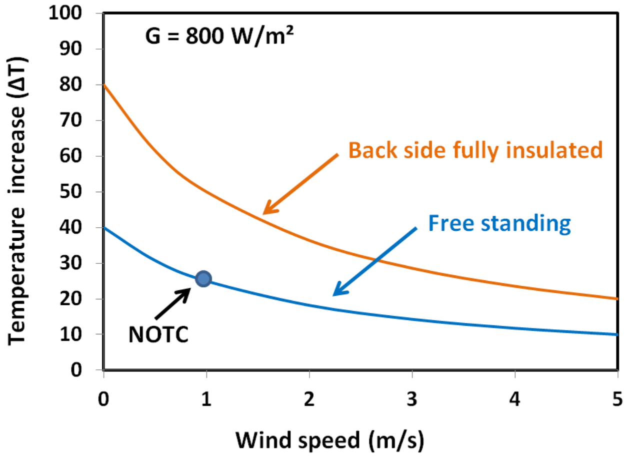

Fig 17: Wind speed and temperature increase

Free standing array
Without wind, the temperature increase of 40°C of a free standing array can result in cell temperatures of 70 to 80°C on a hot sunny day in Europe. Under such conditions PWM performance lags MPPT performance by 10%.

Back side fully insulated
In an array with a fully insulated back side the cell temperature can routinely exceed 100°C. Fully charging the battery with a PWM controller then becomes impossible because charge current will be very low or even zero before the absorption voltage is reached.

In most installations the back side of an array is not fully insulated. When mounted on a sloped roof for example, normally care has been taken to allow for some air flow between the roof and the back side of the solar panels.
The heat capacity of air, however, is very low. The flowing air under the panels may quickly attain equilibrium with the temperature of the panels, leading to no heat exchange at all except for the first few decimeters of the air duct. Therefore, for most of the array, the back side-U value may be the fully insulated U-value.

8. General conclusion

Temperature
A standard crystalline solar panel with a nominal voltage of 12 V consists of 36 cells in series. At 25°C cell temperature, the output current of this panel will be nearly constant up to about 17 V. Above this voltage, current drops off rapidly, resulting in maximum power being produced at around 18 V.

Unfortunately the voltage point at which the current starts to drop off decreases with increasing temperature. Below that voltage point the current however remains practically constant, and is not influenced by temperature.

The output power and output voltage both decrease by about 4.5% for every 10°C of temperature increase.

PWM controller
When a solar array is connected to the battery through a PWM charge controller, its voltage will be pulled down to near that of the battery. This leads to a suboptimal power output wattage (Watt = Amp x Volt) at low and at very high solar cell temperatures.

In times of rainy or heavily clouded days or during heavy intermittent loads a situation may occur where the battery voltage becomes lower than is normal. This would further pull down the panel voltage; thus degrading the output even further.

At very high cell temperatures the voltage drop off point may decrease below the voltage needed to fully charge the battery.

As array area increases linearly with power, cabling cross sectional area and cable length therefore both increase with power, resulting in substantial cable costs, in the case of arrays exceeding a few 100 Watts.

The PWM charge controller is therefore a good low cost solution for small systems only, when cell temperature is moderate to high (between 45°C and 75°C).

MPPT controller
Besides performing the function of a basic controller, an MPPT controller also includes a DC to DC voltage converter, converting the voltage of the array to that required by the batteries, with very little loss of power.

An MPPT controller attempts to harvest power from the array near its Maximum Power Point, whilst supplying the varying voltage requirements of the battery plus load. Thus, it essentially decouples the array and battery voltages, so that there can be a 12 volt battery on one side of the MPPT charge controller and two 12 V (Vmax =18 V) panels wired in series to produce 36 V on the other.

If connected to a PV array with a substantially higher nominal voltage than the battery voltage, an MPPT controller will therefore provide charge current even at very high cell temperatures or in low irradiance conditions when a PWM controller would not help much.

As array size increases, both cabling cross sectional area and cable length will increase. The option to wire more panels in series and thereby decrease current, is a compelling reason to install an MPPT controller as soon as the array power exceeds a few hundred Watts (12 V battery), or several hundred Watts (24 V or 48 V battery).

An MPPT charge controller is therefore the solution of choice:

a) *If cell temperature will frequently be low (below 45°C) or very high (more than 75°C).*
b) *If cabling cost can be reduced substantially by increasing array voltage.*
c) *If system output at low irradiance is important.*
d) *If partial shading is a concern.*

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