19
Components of PV Systems

In this chapter we discuss all the components of PV systems, except PV modules that were already treated in Chapter 15. We start with discussing *maximum power point tracking* in Section 19.1, which is followed by a treatment of *photovoltaic converters* in Section 19.2. Further, we we look at *batteries* in Section 19.3 and *cables* in Section 19.5.

19.1 Maximum power point tracking

In this section we discuss the concept of *Maximum power point tracking* (MPPT). An MPP tracker is never an actual component itself but always connected to a DC-DC converter in a PV inverter or a charge controller. However, as it is a very important concept we will discuss it here. MPPT is very unique to the field of PV Systems, and hence brings a very special application of power electronics to the field of photovoltaics. The concepts discussed in this section are equally valid for cells, modules, and arrays, although MPPT usually is employed at PV module/array level.

As discussed earlier, the behaviour of an illuminated solar cell can be characterised by an I-V curve. Interconnecting several solar cells in series or in parallel merely increases the overall voltage and/or current, but does not change the shape of the I-V curve. Therefore, for understanding the concept of MPPT, it is sufficient to consider the I-V curve of one solar cell. The I-V curve is dependent on the module temperature and on the irradiance, as we will discuss in detail in Section 20.3. For example, an increasing irradiance leads to an increased current and slightly increased voltage, as illustrated in Fig. 19.1. The same figure shows that an increasing temperature has a detrimental effect on the voltage.

Now we take a look at the concept of the *operating point*, which is the defined as the particular voltage and current, at that the PV module operates at any given point in time. For a given irradiance and temperature, the operating point corresponds to a unique (I, V)

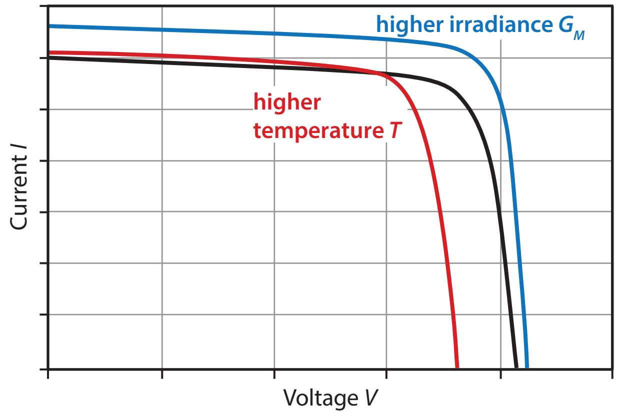

Figure 19.1: Effect of increased temperature T or irradiance G_M on the I-V curve.

pair which lies onto the I-V curve. The power output at this operating point is given by

$$P = I \cdot V. \tag{19.1}$$

The operating point (I, V) corresponds to a point on the power-voltage (P-V) curve, shown in Fig. 19.2. For generating the highest power output at a given irradiance and temperature, the operating point should such correspond to the maximum of the (P-V) curve, which is called the *maximum power point* (MPP).

If a PV module (or array) is directly connected to an electrical load, the operating point is dictated by that load, as we have already seen in Section 9.3. For getting the maximal power out of the module, it thus is imperative to force the module to operate at the maximum power point. The simplest way of forcing the module to operate at the MPP, is to force the voltage of the PV module to be that at the MPP (called V_{mpp}).

However, the MPP is dependent on the ambient conditions. If the irradiance or temperature change, the I-V and the P-V characteristics will change as well and hence the position of the MPP may shift. Therefore, changes in the I-V curve have to be tracked continuously such that the operating point can be adjusted to be at the MPP after changes of the ambient conditions.

This process is called *Maximum Power Point Tracking* or MPPT. The devices that perform this process are called *MPP trackers*. We can distinguish between two categories of MPPT:

- *Indirect* MPPT, where the position of the MPP is estimated via a hard-coded algorithm.
- *Direct* MPPT, where the actual I-V data is used to determine the position of the MPP.

All the MPPT algorithms that we discuss in this section are based on finding the and tuning the voltage until V_{MPP} is found. Other algorithms, which are not discussed in this section, work with the power instead and aim to find I_{MPP}.

19.1.1 Indirect MPPT

First, we discuss *indirect* MPP Tracking, where simple assumptions are made for estimating the MPP based on a few measurements.

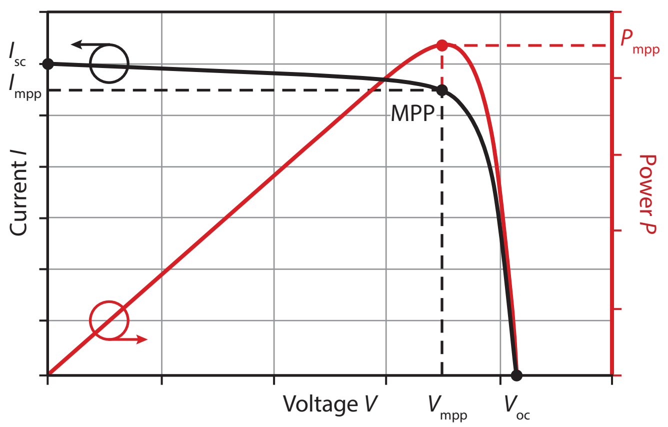

Figure 19.2: A generic *I*-*V* curve and the associated *P*-*V* curve. The maximum power point (MPP) is indicated.

Fixed voltage method

For example, in the *fixed voltage* method (also called *constant voltage method*), the operating voltage of the solar module is adjusted only on a seasonal basis. This model is based on the assumption that for the same level of irradiance higher MPP voltages are expected during winter than during summer. This method is not very accurate; it works best at locations with minimal irradiance fluctuations between different days.

Fractional open circuit voltage method

One of the most common *indirect* MPPT techniques is the *fractional open circuit voltage* method. This method exploits the fact that – in a very good approximation – the V_{mpp} is given by

$$V_{\mathrm{mpp}} = k \cdot V_{\mathrm{oc}}, \tag{19.2}$$

where k is a constant. For crystalline silicon, k usually takes values in between 0.7 and 0.8. In general, k of course is dependent on the type of solar cells.

As changes in the open circuit voltage can be easily tracked, changes in the V_{mpp} can be easily estimated just by multiplying with k. This method thus can be implemented easily. However, there are also certain drawbacks.

First, using a constant factor k only allows to roughly estimate the position of the MPP. Therefore, the operating point usually will not be exactly on the MPP but in its proximity. Secondly, every time the system needs to respond to a change in illumination conditions, the V_{oc} must be measured. For this measurement, the PV module needs to be disconnected from the load for a short while, which will lead to a reduced total output of the PV system. The more often the V_{oc} is determined, the larger the loss in output will be. This drawback can be overcome by slightly modifying the method. For this modification a pilot PV cell is required, which is highly matched with the rest of the cells in the module. The pilot cell receives the same irradiance as the rest of the PV module, and a measurement of the pilot PV cell's V_{oc} also gives an accurate representation of that of the PV module, hence it can

Table 19.1: A summary of the possible options in the P&O algorithm.

Prior Perturbation	Change in Power	Next Perturbation
Positive	Positive	Positive
Positive	Negative	Negative
Negative	Positive	Negative
Negative	Negative	Positive

be used for estimating V_{mpp}. Therefore, the operating point of the module can be adjusted without needing to disconnect the PV module.

19.1.2 Direct MPPT

Now we discuss *direct* MPPT, which is more involved than indirect MPPT, because current, voltage or power measurements are required. Further, the system must response more accurately and faster than in indirect MPPT. We shall look at a couple of the most popular kind of algorithms.

Perturb and observe (P&O) algorithm

The first algorithm that we discuss is the *Perturb and Observe* (P&O) algorithm, which also is known as "hill climbing" algorithm. In this algorithm, a perturbation is provided to the voltage at that the module is currently driven. This perturbation in voltage will lead to a change in the power output. If an increasing voltage leads to an increasing in power, the operating point is at a lower voltage than the MPP, and hence further voltage perturbation towards higher voltages is required to reach the MPP. In contrast, if an increasing voltage leads to a decreasing power, further perturbation towards lower voltages is required in order to reach the MPP. Hence, the algorithm will converge towards the MPP over several perturbations. This principle is summarised in Table 19.1.

A problem with this algorithm is that the operating point is never steady at the MPP but meandering around the MPP. If very small perturbation steps are used around the MPP, this meandering, however, can be minimised. Additionally, the P&O algorithm struggles from rapidly changing illuminations. For example, if the illumination (and hence the irradiance) changes in-between two sampling instants in the process of convergence, then the algorithm essentially fails in its convergence efforts, as illustrated in Fig. 19.3: in the latest perturbation, the algorithm has determined that the MPP lies at a higher voltage than of point B, and hence the next step is a perturbation to converge towards the MPP accordingly. If the illumination was constant, it would end up at C and the algorithm would conclude that the MPP is at still higher voltages, which is correct. However, as the illumination changes rapidly before the next perturbation, the next perturbation shifts the operating point to C′ instead to C, such that

$$P_{\mathrm{C}'} < P_{\mathrm{B}} \tag{19.3}$$

While the MPP still lies to the right of C′, the P&O algorithm thinks that it is on the left of C′ so that it moves to point D′. This wrong assumption is detrimental to the speed of

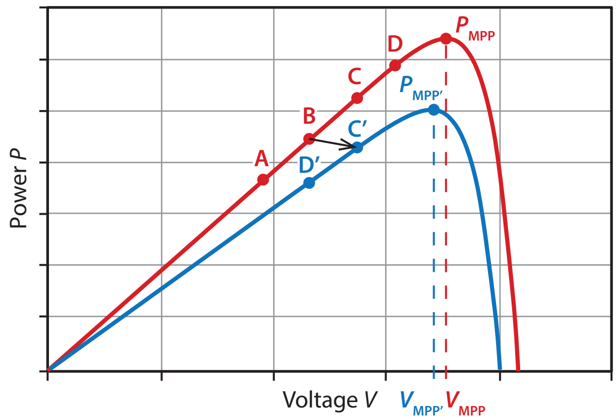

Figure 19.3: The *perturb&observe* algorithm struggles from rapidly changing illumination conditions.

convergence of the P&O algorithm, which is one of the critical figures of merit for MPPT techniques. Thus, drastic changes in weather conditions severely affect the efficacy of the P&O algorithms.

Incremental conductance method

Next, we look at the *Incremental Conductance* Method. The *conductance* G of an electrical component is defined as

$$G = \frac{I}{V} \tag{19.4}$$

At the MPP, the slope of the P-V curve is zero, hence

$$\frac{\mathrm{d}P}{\mathrm{d}V} = 0. \tag{19.5}$$

We can write

$$\frac{\mathrm{d}P}{\mathrm{d}V} = \frac{\mathrm{d}(IV)}{\mathrm{d}V} = I + V\frac{\mathrm{d}I}{\mathrm{d}V}. \tag{19.6}$$

If the sampling steps are small enough, the approximation

$$\frac{\mathrm{d}I}{\mathrm{d}V} \approx \frac{\Delta I}{\Delta V} \tag{19.7}$$

can be used. We call $\Delta I/\Delta V$ the *incremental conductance* and I/V the *constanteneous conductance*. Hence, we have

$$\frac{\Delta I}{\Delta V} = -\frac{I}{V} \quad \text{if} \quad V = V_{\mathrm{mpp}}, \tag{19.8a}$$

$$\frac{\Delta I}{\Delta V} > -\frac{I}{V} \quad \text{if} \quad V < V_{\mathrm{mpp}}, \tag{19.8b}$$

$$\frac{\Delta I}{\Delta V} < -\frac{I}{V} \quad \text{if} \quad V > V_{\mathrm{mpp}}. \tag{19.8c}$$

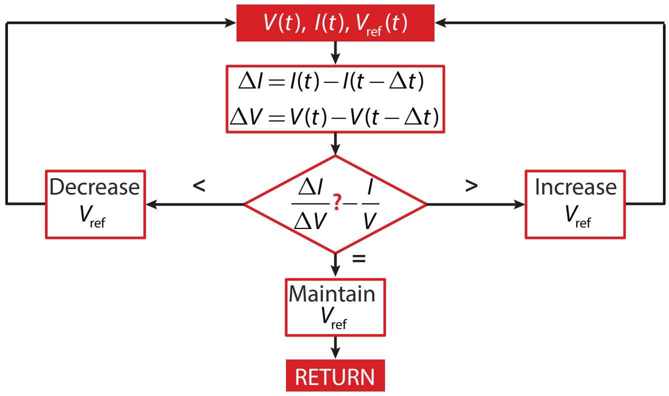

Figure 19.4: A conceptual flowchart of the *incremental conductance* algorithm.

These relationships are exploited by the incremental conductance algorithm.

Figure 19.4 shows a conceptual flowchart. Note that this flowchart is not exhaustive. While both, the instantaneous voltage and current are the observable parameters, the instantaneous voltage is also the controllable parameter. V_{ref} is the voltage value forced on the PV module by the MPPT device. It is the latest approximation of the V_{mpp}. For any change of the operating point, the algorithm compares the instantaneous with the incremental conductance values. If the incremental conductance is larger than the negative of the instantaneous conductance, the current operating point is to the left of the MPP; consequently, V_{ref} must be incremented. In contrast, if the incremental conductance is lower than the negative of the instantaneous conductance, the current operating point is to the left of the MPP and the is consequently decremented. This process is iterated until the incremental conductance is the same as the negative instantaneous conductance, in which case $V_{ref} = V_{mpp}$.

The incremental conductance algorithm can be more efficient than the P&O algorithm as it does not meander around the MPP under steady state conditions. Further, small sampling intervals make it less susceptible to changing illumination conditions. However, under conditions that are strongly varying and under partial shading, the incremental conductance method might also become less efficient. The major drawback of this algorithm is the complexity of its hardware implementation. Not only currents *and* voltages must be measured, but also the instantaneous and incremental conductances must be calculated and compared. How such a hardware design can look like however is beyond the scope of this book.

19.1.3 Some remarks

While a MPPT is used to find the MPP by changing the voltage, it does not perform changes of the operating voltage. This is usually done by a DC-DC converter that will be discussed in section 19.2.2.

In modern PV systems, the MPPT is often implemented within other system components like inverters or charge controllers. The list of techniques presented in this section not

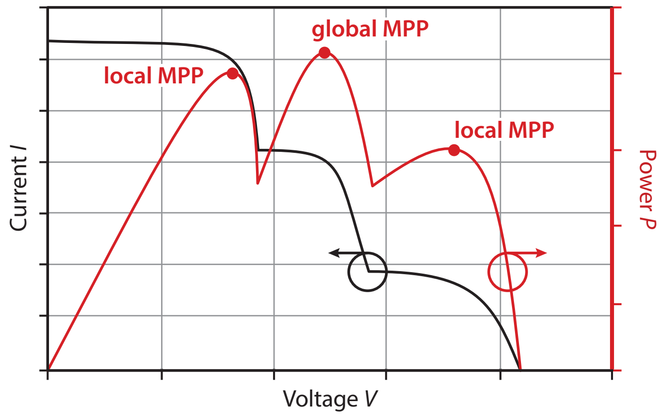

Figure 19.5: The *P*-*V* curve of partially shaded system that exhibits several local maxima.

exhaustive, we just discussed the most common ones. The development of more advanced MPPT techniques is going on rapidly and many scientific papers as well as patents are published in this area. Furthermore, manufacturers usually use proprietary techniques.

Up to now we only looked at situations the total *I*-*V* curve is similar to that of a single cell. Let us now consider a system that is partially shaded, as illustrated in Fig. 19.5. Then, the *P*-*V* curve will have different local maxima. Depending on the used MPPT algorithm, it is not sure at all that the algorithm finds the global maximum. Different companies use proprietary solutions to tackle this issue. Alternatively, each string can be connected to a separate MPPT. Nowadays, inverters are available, which have connections for several strings (usually two).

19.2 Power electronics

A core technology associated with PV systems is the converter, which is based on power electronics. An ideal PV converter should draw the maximum power from the PV panel and supply it to the load side. It is very important to distinguish between inverters in grid-connected systems and in stand-alone systems.

Note that the term *inverter* can have two different meanings: First, it is used for the actual inverter, which is the electronic building block that performs the DC-to-AC inversion, as described in section 19.2.3. Secondly, the term inverter also is used for the total unit produced by manufacturers, that depending on the application may contain an MPP tracker, a DC-DC converter, and/or a DC-AC converter.

In *grid-connected* systems, the inverter is connected directly to the PV array. It converts the DC electricity coming from the PV array into AC electricity. Further, such an inverter usually contains an MPPT system, that we discussed in Section 19.1. As such a inverter is connected to the electricity grid, it must synchronise with the grid, meaning that the phase of the AC signal coming from the inverter is *in phase* with that of the grid. Further, its signal should have minimal harmonic content. Usually, grid-connected inverters cannot