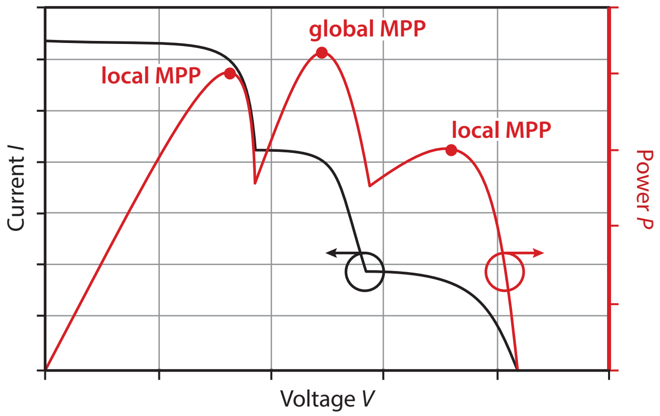

Figure 19.5: The *P*-*V* curve of partially shaded system that exhibits several local maxima.

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

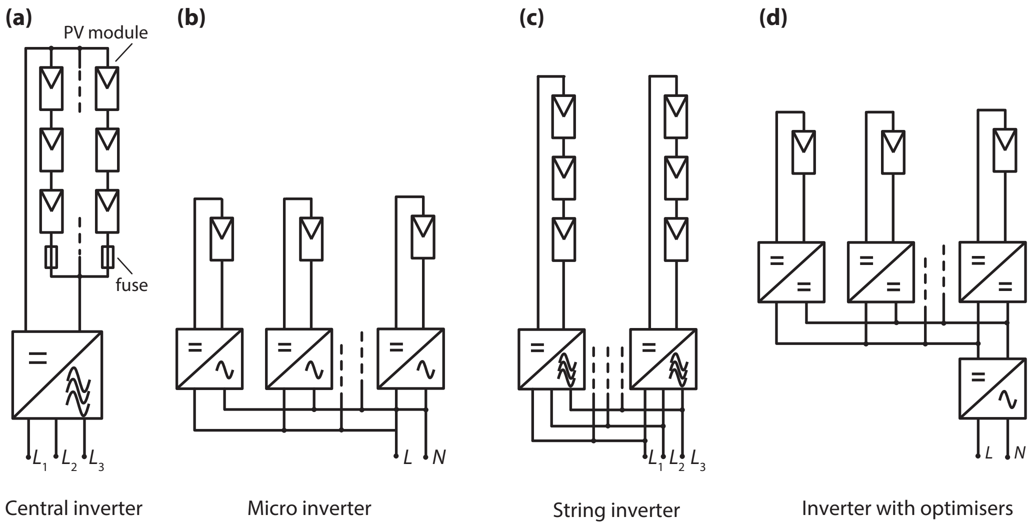

Figure 19.6: Different system architectures employed in PV systems.

act autonomously, but are switched off when the electricity grid is down. This is to prevent *islanding*, which we discuss in Subsection 19.2.4.

Inverters used in *stand-alone* systems usually are connected to the batteries. As PV array is connected to the battery via a charge controller, such an inverter does not require an MPP tracker or a DC-DC converter. Often, these inverters are especially designed for the use with batteries and prevent them from being discharged too far, which would be detrimental to the battery lifetime as discussed in Section 19.3. Sometimes, these inverters also can be used to charge the batteries, for example if a AC generator is connected to the AC side of the inverter. In that case, the inverter also functions as an *AC-DC converter*. As such an inverter is not connected the electricity grid, it must control the AC voltage and frequency.

In this section a short review of different topologies often associated with PV systems is given. The semiconductor switches in the following are assumed to be ideal.

19.2.1 System architecture

Before digging into details about different converter topologies used for power conversion in PV systems, a general overview of different system architecture will be presented. The system architecture determines how PV modules are interconnected and how the interface with the grid is established. Which of these system architectures will be employed in a particular PV plant depends on many factors such as environment of the plant (whether the plant is situated in an urban environment or at an open area), scalability, costs etc. In Figure 19.6 an overview of different system architectures is given. The main advantages and disadvantages of the different architectures are discussed below.

In general solar inverters should fulfil the following *requirements* [149]:

- Inverters should be highly efficient because the owner of the solar system requires the absolute maximum possible generated energy to be delivered to the grid/load.

- Special demands regarding the potential between solar generator and earth (depending on the solar module type); see potential-induced degradation in Section 19.2.4.
- Special safety features like active islanding detection capability; see Section 19.2.4.
- Low limits for harmonics of the line currents. This requirement is enforced by law in most countries since the harmonic limits of both sources and loads connected to the grid are regulated.
- Special demands on *electromagnetic interference* (EMI), which are regulated by law in most countries. The goal of these minimise the unwanted influence of EMI on other equipment in the vicinity or connected to the same supply. Think for example of the influence of a mobile phone on an old radio.
- Also the effect of electromagnetic fields to people must be taken into account; the maximally allowed field strength emitted from the inverter is regulated in many countries.
- In many instances the solar system is to be installed outdoors and inverters should adhere to certain specification regarding temperature and humidity conditions, *e.g.* IP 54.
- Design for high ambient temperatures.
- Designed for 10-25 years operation under harsh environmental conditions.
- Silent operation (no audible noise).
- Often, the possibility to monitor the PV system is required by the user.

We have to distinguish between *single-phase* and *three-phase inverters*. For low powers, as they are common in small residential PV systems, single-phase inverters are used. They are connected to one phase of the grid. For higher powers, three-phase inverters are used that are connected to all phases of the grid. If a high power would be delivered to one phase, the currents flowing across the three phases would become very asymmetric leading to several problems in the electricity grid.

Central inverters

This is the simplest architecture employed in PV systems. Here, PV modules are connected in strings leading to an increased system voltage. Many strings are then connected in parallel forming a PV array, which is connected to one central inverter. The inverter performs maximum power point tracking and power conversion as shown in Fig. 19.6 (a), where a system with a three-phase inverter is depicted. This configuration is mostly employed in very-large scale PV power plants, with central inverter usually being DC to three phase [150]. In case where more than one string are connected in parallel and significant differences in the irradiance from string to string are expected, blocking diodes are required to prevent current circulation inside strings.

Many different inverter topologies are utilised as a three phase inverter. Sometimes they are organised as a single DC to three phase unit but sometimes as a three separate DC-to-AC single phase units working with a phase displacement of 120 degrees each. Having all the PV modules connected in a single array in such a centralised configuration offers the lowest specific cost (cost per kW_p of installed power). Since central inverters only use a few components, they are very reliable what makes them the preferred option in large scale PV power plants.

In spite of their simplicity and low specific cost, central inverter systems suffer from the following disadvantages:

1. Due to the layout of the system, a large amount of power is carried over considerable distances using DC wiring. This can cause safety issues because fault DC currents are difficult to interrupt. Special precaution measures must to be taken such as thicker insulation on the DC cabling and special circuit breakers, which can increase the costs.
2. All strings operate at the same maximum power point, which leads to mismatch losses in the modules. This is significant disadvantage. Mismatch losses increase even more with ageing and with partial shading of sections of the array. Mismatch between the different strings may significantly reduce the overall system output.
3. Low flexibility and expandability of the system. Due to the high ratings a system is normally designed as one unit and hence difficult to extend. In other words the system design is not very flexible.
4. Power losses in the string diodes (if any), which are put in series with each string to prevent current circulation inside strings.

Micro inverters

A very different architecture is that of the *micro inverters*, as shown in 19.6 (b). These inverters operate directly at one or several PV modules and have power ratings of several hundreds of watts. Because of the low voltage rating of the PV module, these inverters require often require a two stage power conversion. In a first stage, the DC voltage is boosted to the required value while it is inverted to AC in the second stage. Often, a high frequency transformer is incorporated providing full galvanic isolation, which enhances the system flexibility even further. These inverters are usually placed close to the PV panels, sometimes they are also directly integrated in the PV panels (so called 'AC PV panels'). One of the most distinguishing features of this system is the "plug and play" characteristic, which allows to build a complete (and readily expandable) PV system at a low investment cost. Another advantage of these inverters is minimisation of the mismatch losses that can occur because of non-optimal MPPT.

All these advantages come at certain expenses. Because these inverters are be mounted on a PV module, they must operate in harsh environment such as high temperature and large daily and seasonal temperature variations. Further, these inverters often accept only a very narrow range of input voltages. Therefore it is not possible to use bypass diodes within the modules that bypass one- or two-third of the module. Another disadvantage is that the PV module voltage is much below the output AC voltage, therefore the DC-DC conversion has to boost the voltage a lot. This has a detrimental effect on the inverter efficiency. Also, the specific costs are the highest of all the inverter topologies. Many topologies for micro inverters have been proposed, with some of them being already implemented in commercially available inverters by various companies.

String Inverters

String inverters, as illustrated in 19.6 (c), combine the advantages of central and module integrated inverter concepts with little tradeoffs. A number of PV modules that are connected in series form a PV string with a power rating of up to 5-6 kWp in 1-phase configurations and up to 20-30 kWp in 3-phase configuration.

The open circuit voltages are up to 1 kV, which already makes one disadvantage of this topology apparent: these high DC voltage requires special consideration, similarly as this already was the case for the central inverter architecture. Here, this issue is even more important because string inverters are usually being installed in households or on office buildings, without designated support structure or increased safety requirements. The protection of the system also requires special consideration, with emphasis on proper DC cabling.

Although partial shading of the string will influence the overall efficiency of the system, each string can independently be operated at its MPP, if each string has its own MPPT. Also, because no strings are connected in parallel, there is no need for series diodes as in the case of PV arrays with many parallel strings. This reduces losses associated with these diodes. However, it still is a risk that within a string hot-spot occurs because of unequal current and power sharing inside the string.

Central inverter with optimisers

This architecture is a hybrid between a central inverter and micro inverters. An optimiser box is attached to every module, which contains a MPP tracker and a DC-DC converter as illustrated in Figure 19.6 (d). The optimiser boxes of all the modules are connected in series to each other and to the central inverter. The inverter can accept input voltages within a certain range – if the voltage is outside this range, the current is altered such that the voltage is inside the acceptable range again. As a consequence, the output voltage of the optimisers is determined by the input power from the PV module and the current that is enforced by the inverter.

The main advantage of this architecture is that every module can operate at its MPP. This is not only important for shading of single modules, but also because of the fact that no two modules are the same. Another advantage of this architecture is that all the optimisers can operate at voltages close to the voltage of the PV module. Therefore, the DC-DC conversion is very efficient. Further, the optimisers consume only very little power, so there are no problems with heating up, in contrast to what we have seen with micro inverters.

Team Concept

Aside of the four system architecture already described, many other concepts are also discussed in literature. However, these concepts are less widely utilised than the ones already presented. One of the alternative concepts is so called *team concept*, which combines the string technology with the master-slave concept. A combination of several string inverters working with the team concept is shown in Figure 19.7. At very low irradiation the complete PV array is connected to a single inverter. This reduces the overall losses as any power electronic converter is designed such that it has maximum efficiency near full load. With increasing solar radiation more inverters are being connected dividing the PV array

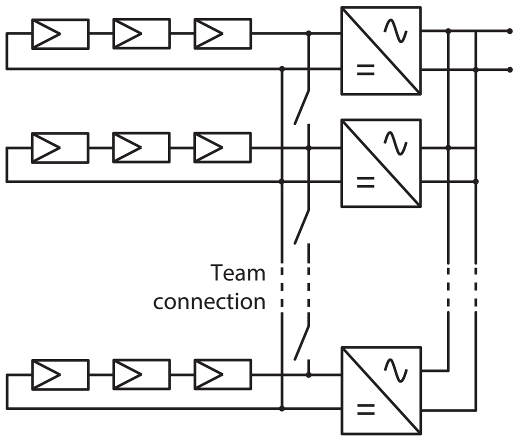

Figure 19.7: The team concept of inverters.

into smaller units until every string inverter operates close to its rated power. In this mode every string operates independently with its own MPP tracker. At low solar radiation the inverters are controlled in a master-slave fashion.

In literature many other concepts can be found. For further reading on this subject, we refer for example to Ref. [151].

19.2.2 DC-DC converters

DC-DC converters fulfil multiple purposes. In an inverter, DC power is transformed into AC power. The DC input voltage of the inverter often is constant while the output voltage of the modules at MPP is not. Therefore a DC-DC converter is used to transform the variable voltage from the panels into a constant voltage used by the DC-AC inverter. Additionally, as already stated in section 19.1, the MPP tracker controls the operating point of the modules, but it cannot set it. This also is done by the DC-DC converter. Further, in a stand-alone system the MPP voltage of the modules might differ from that required by the batteries and the load. Also here, a DC-DC converter is useful and hence applied in some high-end charge controllers. Three topologies are used for DC-DC converters: *buck*, *boost*, and *buck-boost* converters. They are described below.

Step-Down (Buck) Converter

Figure 19.8 (a) illustrates the simplest version of a buck DC-DC converter. The unfiltered output voltage waveform of such a converter operated with pulse-width modulation (PWM) is shown in Fig. 19.8 (b). If the switch is *on*, the input voltage V_d is applied to the load. When the switch is *off*, the voltage across the load is zero. From the figure we see that the average DC output voltage is denoted as V_o. From the unfiltered voltage, the average output voltage is given as

$$V_o = \frac{1}{T_s}\int_0^{T_s} v_o(t)\,\mathrm{d}t = \frac{1}{T_s}\left(t_{\mathrm{on}}V_d + t_{\mathrm{off}}\cdot 0\right) = \frac{t_{\mathrm{on}}}{T_s}V_d. \tag{19.9}$$