self-discharge. A typical value for the cycle life is 3000-4000 cycles for a daily depth of discharge of 20%.

- In *rod-plate* lead-acid batteries the positive plate is made up of rods with the active mass between them. The plates have a low antimony content. The construction height of the battery is fairly low, so there is almost no stratification of acid. This battery has superior properties for PV applications, but is rather expensive.

One can also distinguish open (vented) and sealed (maintenance-free) lead acid batteries. In order to make lead acid batteries maintenance-free, all or part of the antimony in the plates is replaced by calcium. A calcium alloy with a very low antimony content ($< 1\%$) has a very low self-discharge (approximately 1% per month at 25 °C) and reduces the splitting of water into oxygen and hydrogen. In most maintenance-free lead acid batteries the electrolyte is contained either in a gel between the plates or in a micro-porous separator. Oxygen produced at the positive plate can diffuse through the gel or the micro-porous separator and reach the negative plate, where it reacts with water to form water again. Maintenance-free lead acid batteries frequently used for PV applications are flat-plate batteries with a gel or micro-porous separator and tubular plate batteries with a gel.

## 19.4 Charge controllers

After having discussed different types of batteries and different battery characteristics, it is now time to discuss *charge controllers*, which are used in PV systems that use batteries. As we have seen above, it is very important to charge and discharge batteries at the right voltage and current levels in order to ensure a long battery lifetime. A battery is an electrochemical device that requires a small over-potential to be charged. However, batteries have strict voltage limits, which are necessary for their optimal functioning. Further, the amount of current sent to the battery by the PV array and the current flowing through the battery while being discharged have to be within well-defined limits for proper functioning of the battery. We have seen before that lead-acid batteries suffer from both overcharge and overdischarge. On the other hand, the PV array responds dynamically to ambient conditions like irradiance, temperature and other factors like shading. Thus, directly coupling the battery to the PV array and the loads is detrimental to the battery lifetime.

Therefore a device is needed that controls the currents flowing between the battery, the PV array and the load and that ensures that the electrical parameters present at the battery are kept within the specifications given by the battery manufacturer. These tasks are done by a *charge controller*, that nowadays has several different functionalities, which also depend on the manufacturer. We will discuss the most important functionalities. A schematic of its location in a PV system is shown in Fig. 19.25.

When the sun is shining at peak hours during summer, the generated PV power excesses the load. The excess energy is sent to the battery. When the battery is fully charged, and the PV array is still connected to the battery, the battery might overcharge, which can cause several problems like gas formation, capacity loss or overheating. Here, the charge controller plays a vital role by de-coupling the PV array from the battery. Similarly, during severe winter days at low irradiance, the load exceeds the power generated by the PV array, such that the battery is heavily discharged. Over-discharging the battery has a detrimental effect on the cycle lifetime, as discussed above. The charge controller prevents the

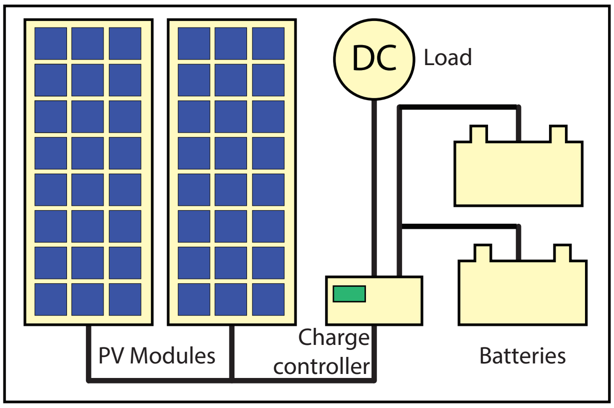


**Figure 19.25:** Illustrating the position of the *charge controller* in a generic PV system with batteries.

battery from being over-discharged by disconnecting the battery from the load.

For optimal performance, the battery voltage has to be within specified limits. The charge controller can help in maintaining an allowed voltage range in order to ensure a healthy operation. Further, the PV array will have its $V_{\text{mpp}}$ at different levels, based on the temperature and irradiance conditions. Some charge controller perform an appropriate voltage regulation to ensure the battery operates in the specified voltage range, while the PV array is operating at the MPP.

However, most simple charge controllers available on the market have no MPP tracker included. In this case the battery will determine the voltage at which the module is operated. In then is important to size the module such that it fits to the battery. For example, for systems that are connected to a 12 V battery often crystalline-silicon panels with 36 cells in series are used, while for 24 V batteries modules with 72 cells connected in series are appropriate.

As we have seen above, certain C-rates are used as battery specifications. The higher the charge/discharge rates, the lower the coulombic efficiency of the battery. The optimal charge rates, as specified by the manufacturer, can be reached by manipulating the current flowing into the battery. A charge controller that contains a proper current regulation is also able to control the C-rates. Finally, the charge controller can impose the limits on the maximal currents flowing into and from the battery.

If no blocking diodes are used, it is even possible that the battery can "load" the PV array, when the PV array is operating at a very low voltage. This means that the battery will impose a forward bias on the PV modules and make them consume the battery power, which leads to heating up the solar cells. Traditionally, blocking diodes are used at the PV panel or string level to prevent this *back discharge* of the battery through the PV array. However, this function is also easily integrated in the charge controller.

We distinguish between *series* and *shunt* controllers, as illustrated in 19.26. In a series controller, overcharging is prevented by disconnecting the PV array until a particular voltage drop is detected, at which point the array is connected to the battery again. On the other hand, in a parallel or shunt controller, overcharging is prevented by short-circuiting the PV

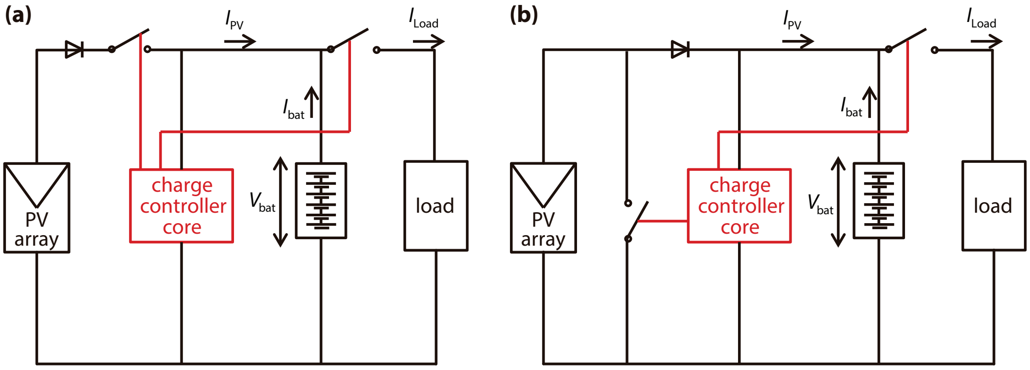


**Figure 19.26:** Basic wiring scheme of (a) a series and (b) a shunt charge controller.

array. This means that the PV modules work under short circuit mode, and that no current flows into the battery. These topologies also ensure over-discharge protection using power switches for the load connection, which are appropriately controlled by the algorithms implemented into the charge controller algorithm.

As we have seen above, temperature plays a crucial role in the functioning of the battery. Not only does temperature affect the lifespan of the battery, but it also changes its electrical parameters significantly. Thus, modern charge controllers have a temperature sensor included, which is attached to the battery back. This sensor allows the charge controller to adjust the electrical parameters of the battery, like the operating voltage, to the temperature. The charge controller thus keeps the operating range of the battery within the optimal range of voltages.

### 19.4.1 Charge controllers for lead acid batteries used for PV applications

The role of the overcharge protection part of controllers will be discussed more in detail now for the case of lead acid batteries. A typical mode of operation of an autonomous PV system is that the battery will be discharged partly during the night and will be charged again during the day. High states of charges will be reached after noon. This implies that the time available subsequently in the afternoon to charge the battery fully is limited or more precisely phrased the time available to convert all the lead sulphate into lead and lead dioxide is limited. This conversion is crucial because if lead sulphate stays too long in the amorphous state it will change into polycrystalline lead sulphate which cannot be changed into lead and lead oxide. In order to convert all the amorphous lead sulphite into lead and lead oxide in the short time available, sufficient overvoltage is required. This voltage, however, is not allowed to be too high for a too long period, otherwise voltage induced corrosion of the plates takes place.

In practise, during charging the batteries, the battery voltage will rise gradually in the course of a day. A good controller will switch off the array current once a certain voltage level is reached and will switch the array on again at a slightly lower voltage. In this way, keeping the voltage within a narrow voltage band close to the gassing voltage, the optimum charge conditions are realised. In controllers with a boost charge facility, the array current is switched off at a relatively high voltage once (a day) and subsequently the voltage is kept within a narrow band as described above. During boost charging the overvoltage is relatively high during a short period of time, accelerating the conversion of lead sulphate into lead and lead oxide. The precise voltage settings are dependent on the specific type of lead acid battery.

In case of lead acid batteries, the deep discharge protection acts on the battery voltage, in general. Because the battery terminal voltage depends both on the actual state of charge and the internal voltage drop caused by the battery current flowing through the internal battery resistance (see section 19.3.2), the controller needs to act on the battery terminal voltage corrected for this internal voltage drop. A deep discharge protection doing so is called to have current compensation. If the voltage drop along the battery cables (and fuses if present) cannot be neglected, separate leads (battery voltage sense lines) are used to measure the actual battery terminal voltage.

## 19.5 Cables

The overall performance of PV systems also is strongly dependent on the correct choice of the cables. We therefore will discuss how to choose suitable cables. But we start our discussion with *color conventions*.

PV systems usually contain DC and AC parts. For correctly installing a PV system, it is important to know the color conventions. For *DC cables*,

- **red** is used for connecting the $+$-contacts of the different system components with each other while
- **black** is used for connecting the $-$-*contacts* and for interconnecting the modules with each other.

For DC string cabling between modules in an array, in many cases black cables are used because of the poor UV stability of coloured cables. Polarity indication is done by the use of dedicated connectors with polarity marking. An example is the famous multi-contact connector, which can be delivered together with the flying cable as one unit.

For *AC wiring*, different colour conventions are used around the world.

- For example, in the *European Union*,
  **blue** is used for neutral,
  **green-yellow** is used for the protective earth and
  **brown** (or another color such as **black** or **grey**) is used for the phase.
- In the *United States* and *Canada*,
  **silver** is used for neutral,
  **green-yellow**, **green** or a **bare** conductor is used for the protective earth
  and **black** (or another color) is used for the *phase*.
- In *India* and *Pakistan*, for example
  **black** is used for *neutral*,
  **green** is used for the protective earth and
  **blue**, **red**, or **yellow** is used for the *phase*.