19

Power Conditioning for Photovoltaic Power Systems

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In PV systems, power conditioning units are used to provide a match between the specific characteristics of the PV generator and the connected balance of system (BOS) components. Furthermore, they take over the control of other BOS components, for example, batteries or back-up generators.

In general, the characteristic curve of a PV generator varying with solar radiation and temperature does not match the characteristic curve of the load. In those cases, the power conditioning unit effects a transformation of the load's voltage and current in such a way, that the PV generator is operated at its optimum operation voltage V_{MPP} even under changing boundary conditions.

In the following chapter, the characteristics of the most common power conditioning units – charge controllers, DC/DC converters and inverters – are described.

In almost every stand-alone system, a charge controller is required to optimally operate the storage battery within safe limits as prescribed by the manufacturer.

The matching of PV generator and the load can be achieved by means of DC/DC converters which can be integral part of a charge controller, an inverter or a DC pump, but can also be a separate BOS component.

If in stand-alone systems the load requires an AC voltage, inverters are used to convert the DC power supplied by the PV generator or the storage battery into AC power. Inverters are mandatory in grid-connected PV systems. Here, besides high efficiency, reliability and power quality, safety is an important issue and has to be dealt with.

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19.1 CHARGE CONTROLLERS AND MONITORING SYSTEMS FOR BATTERIES IN PV POWER SYSTEMS

In PV-powered systems, batteries are still the component with the lowest average lifetime. Compared to solar modules, which in principle have an infinite economic lifetime and in many cases offer a guarantee period of 25 years, the lifetime of batteries is much lower. The maximum lifetime found in practice is around 8 to 10 years; in most cases it is in the range of 3 to 6 years and in some cases even lower. The upper limit will be determined by normal ageing; the shorter lifetimes are mostly caused by inappropriate treatment or unsuitable control strategies. This topic is discussed in Chapter 18.

Looking at the battery cost in a typical PV diesel system, one can find that its share of the initial costs is around 15%. Because of repeated replacement of exhausted batteries, this initial share grows to more than 35% or even 50% over the expected 25-year service life of the system. Compared to this, the costs for solar modules and other balance-of-system components become small.

To achieve minimum lifetime costs and satisfying operation of the PV system, equipping the battery with appropriate peripherals is money well spent. Some examples, such as systems to automatically mix the electrolyte to prevent acid stratification or automatic water-topping systems, are explained in Chapter 18. Besides this, the application of appropriate operation modes is a crucial factor.

In this chapter, the technical realisation of the key component, the "charge controller", will be described. Furthermore, a new system to operate long battery strings optimally will be introduced.

19.1.1 Charge Controllers

The fundamental task of a charge controller is to operate the battery within the safe limits defined with respect to overcharging and deep discharging by the battery manufacturer or by the operation mode.

Compared to conventional battery chargers powered by the public grid, the situation is much more complex in PV systems. Here, charging power and energy are limited and depend on the varying insolation and load demand. Well-known charging strategies such as constant-current–constant-voltage charging (CC/CV) or more complex charging strategies, cannot be applied one to one. For example, in PV systems the charging current varies according to the insolation. Nevertheless, the term used is "constant current charging". Also, regular full charging of the battery – which is very important for a long service life – cannot be guaranteed.

Furthermore, very high energy efficiency is crucial for all balance-of-system components in PV systems. Most grid-powered battery chargers offer only unsatisfactory efficiency values.

In the following sections, the fundamental technical concepts of charge controllers [1, 2] as well as the associated control strategies will be explained. In addition, a list of criteria will be given that should be taken into account when developing or selecting charge controllers.

19.1.1.1 Self-regulating PV systems

In small systems, such as house-number illumination or power supplies for measurement systems, a charge controller can be avoided in special cases.

This is, for example, true for NiCd batteries, when the current provided by the PV module is lower than the continuous charging current accepted by the battery. Also, such "self-regulating" systems have been used in the past for systems in the 50-W range such as light buoys.

In these systems illustrated in Figure 19.1, only a series diode is needed to block reverse currents from flowing into the module at night. To prevent overcharging of the battery, specially tailored PV modules with, for example, 30 crystalline-silicon cells will be used for 12-V lead acid batteries. With this low number of cells, the operating point will move into the steeply sloping part of the module's $I-V$ curve when the battery is fully charged.

To make this kind of system operate reliably, the load profile as well as the insolation and temperature at the place of operation must be known accurately. Because cheap and reliable charge controllers are available today in the market, such "self-regulating" systems should be avoided.

In all cases, deep-discharge protection according to Section 19.1.1.6 should be implemented.

19.1.1.2 Linear charge controllers

When PV applications commenced, the well-known principles of conventional linear charge controllers were adapted to photovoltaics. These principles do not take advantage of the special properties of solar cells, for example, that they are infinitely tolerant to short circuits. Therefore, the initial linear charge controllers have been replaced by the switching charge controllers described below.

Meanwhile, novel integrated voltage controllers have appeared in the market, which make the principle of linear charge controllers a reasonable option in the power range up to about 50 W like in Solar Home Systems (SHS).

In a linear charge controller, the charging current will be adjusted by a final controlling element that acts continuously and is located either in series or in parallel with

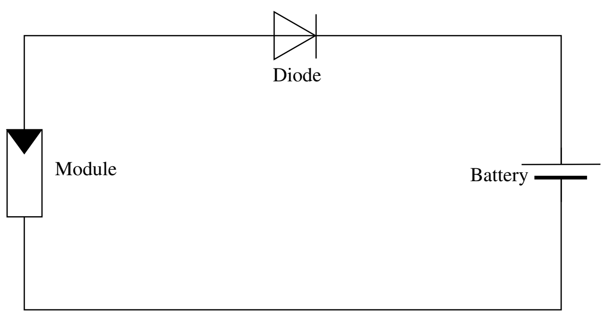

Figure 19.1 "Self-regulating" PV system without a charge controller

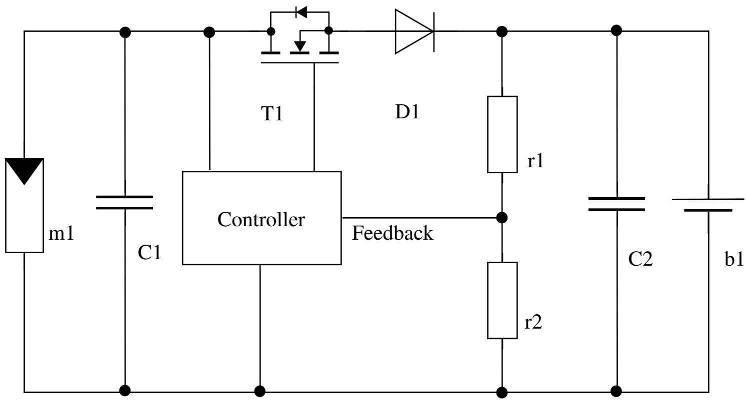

Figure 19.2 Linear charge controller based on the integrated voltage controller MIC 5158 (MICREL) labelled controller with an external power MOS-FET

the solar generator. By driving the controlling element appropriately, the battery voltage can be prevented from exceeding the end-of-charge limit.

Figure 19.2 shows the block circuit diagram of a linear series charge controller. In the constant-current (CC) phase, in which the battery voltage is below the end-of-charge voltage, the control element MOS-FET T1 is fully conducting. The solar generator and the battery are directly coupled via the blocking diode D1. The operating point of the solar generator is determined by the instantaneous insolation and the battery voltage. The power losses inside the control element are almost negligible in this phase. Additional power losses are caused by the voltage drop across the blocking diode D1, which in most cases will be a Shottky diode with a very low forward voltage drop. To minimise the power losses, the blocking diode can be replaced by a second MOS-FET connected back-to-back in series with T1. With such designs, care has to be taken that both MOS-FETs turn off during the night, and that no reverse current flows into the solar generator!

It is important to note that in most cases the energy gained by the reduction of power losses is not relevant for the function of the PV system. In fact, the goal is to reduce the voltage drop across the controller, which finally leads to a saving of one or two solar cells in the module.

As soon as the end-of-charge voltage has been reached, the gate voltage for the MOS-FET T1 will be reduced by the controller. Now, the output voltage is kept constant while the charging current will drop slowly according to the battery's increasing state of charge. In contrast to the first charging phase, now the difference between the solar generator voltage and the battery voltage will occur at the transistor terminals and cause some heat dissipation.

In Figure 19.3, the operating points for three different charging currents are shown as an example. The shaded areas are proportional to the power dissipated in the control element. As can be seen, this power is in the range between approximately one-fourth and one-tenth of the instantaneous maximum power point (MPP) power of the generator. The resulting heat must be dissipated by appropriate heat sinks. This is a clear disadvantage compared to the switching charge controllers described below. On the other hand, there are

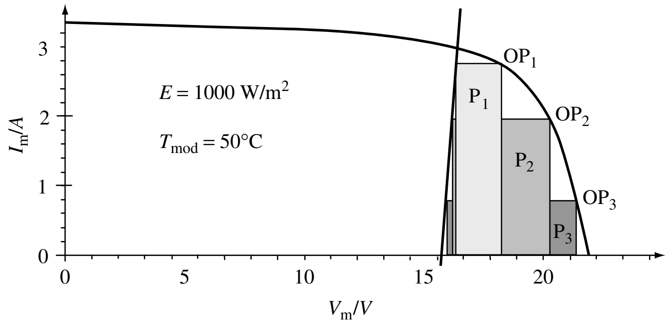

Figure 19.3 $I-V$ curve of a 36-cell PV module and characteristic curve of a 12-V lead acid battery with 3-m input lead (1.5 mm^2 cross-section) for three different charging currents. The shaded areas show the power dissipated in the control element

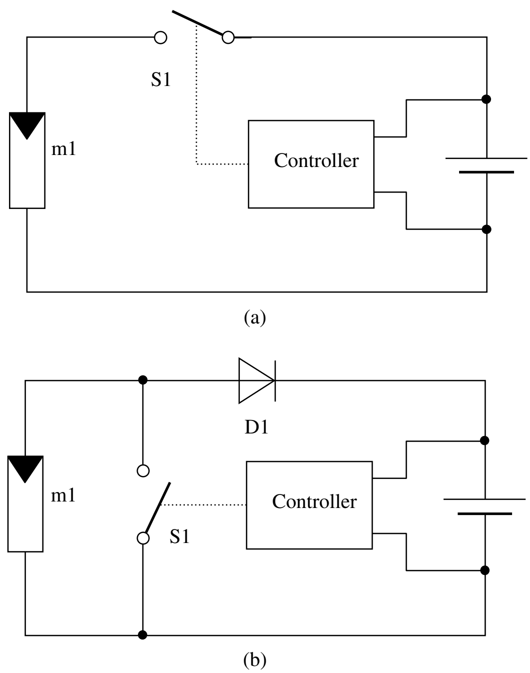

Figure 19.4 Principle of (a) series and (b) shunt controllers

no problems with electromagnetic compatibility (EMC), and the battery will be charged with a life-extending CC without micro-cycles.

19.1.1.3 Switching controllers

The above-mentioned disadvantage of intensive heat dissipation in linear charge controllers can be overcome with switching controllers. In these controllers, the control element is either fully closed (conducting) or fully open (blocking). Under ideal conditions, the power losses are zero in both cases because either voltage or current at the control element is zero.

Once again, it must be pointed out that the additional energy gained in this way is normally not relevant for the functioning of the PV system. By contrast, the reduction of heat generation leads to savings in component costs (heat sinks) and to an increased reliability due to lower component temperatures.

In a series controller as shown in Figure 19.4(a), the charging current will be controlled by an element switched in series with the solar generator.

In early charge controllers, relays were used as switching elements, but today semiconductor switches like MOS-FETs are used in almost every application.

One advantage of the series controllers is that in addition to PV generators, they can be used for other power sources that are not being tolerant to short circuits such as wind turbines. Furthermore, the voltage stress for the switch is lower compared to the shunt controller described below. With a fully charged battery, the solar generator operates in the open-circuit mode. In this operation mode, no module overloading due to partial shading can occur. On the other hand, the solar generator current is fully turned on and off, which can lead to greater EMC problems compared to shunt controllers.

In the past, the series controller was accused of having fundamentally higher losses. This is no longer true since low-resistive semiconductor switching elements have been used – the losses can be even lower than for shunt controllers. Furthermore, some early series controllers did not start with completely flat batteries because they did not have enough energy to activate the series switch. This problem can easily be solved by powering the controller from the PV module instead of from the battery.

A parallel or shunt controller as shown in Figure 19.4(b) makes use of the electrical characteristic of PV modules that they are infinitely tolerant to short circuits.

In the constant-current charging phase, the module current flows through the blocking diode D1 into the battery. When the end-of-charge voltage has been reached, the PV generator is short-circuited by the switch S1. The blocking diode now prevents the reverse current flowing from the battery into the switch. Furthermore, it suppresses the discharging currents into the PV generator during the night.

In contrast to the series controller, this kind of charge controller will also reliably start charging with a fully discharged battery, because the switch can be energised only when the battery is fully charged.

The hybrid charge controller is a modified shunt controller, in which the blocking diode is bypassed by a second transistor in the charging phase. This reduces the power dissipation in the controller, which leads to smaller heat sinks and lower thermal stress. Furthermore, the reduction of the voltage drop supports the use of cost-optimised PV modules with a smaller number of series-connected cells, for example, 30 to 33 crystalline-silicon cells for 12-V systems.

Another variant of the shunt controller is the partial-shunting controller according to Figure 19.5. Here, only some of the series-connected modules are shunted via taps.

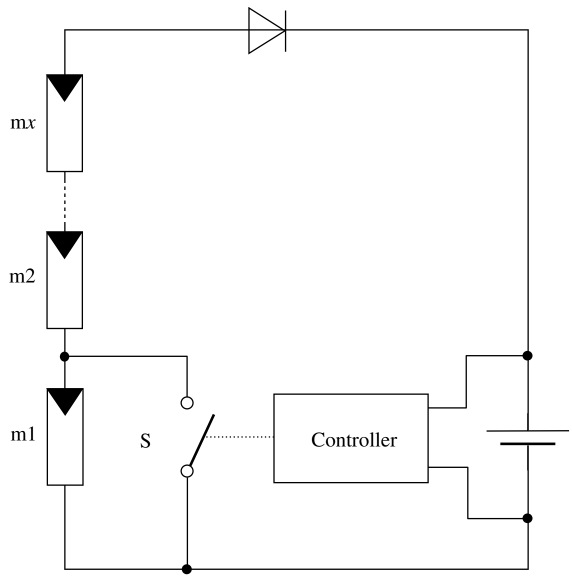

Figure 19.5 Partial-shunting controller for high-voltage systems

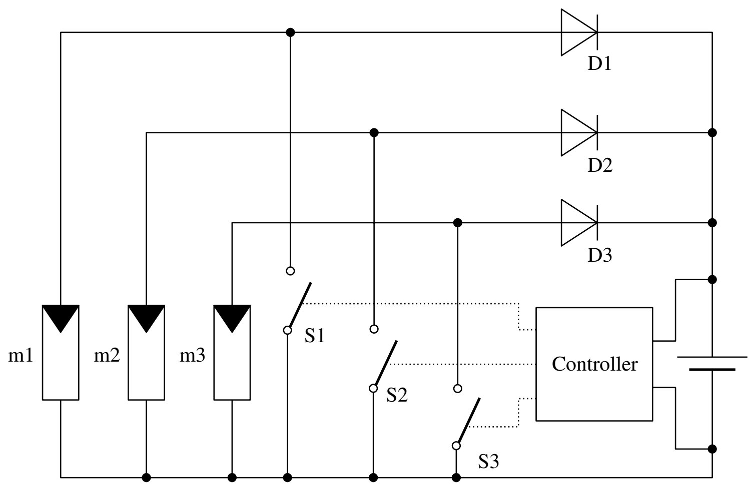

Figure 19.6 Sub-array switching controller for high-power systems

In consequence, the remaining generator voltage is too low to further charge the battery. The advantage of partial shunting is the reduced voltage stress for the switch in high-voltage systems. On the other hand, a tap and additional wiring are needed.

In high-power systems, sub-array switching according to Figure 19.6 is used for charge control. The PV generator is set up as a number of sub-arrays (strings), and each of these strings is connected to the battery via its own control element (e.g. blocking diode and switch).

Two different control strategies are used. The multiple switches can be driven in parallel, turning the full array current on and off in one step. A preferred strategy is to drive the switches in a certain sequence that allows stepwise adjustment of the charging current.

With all of the switching controllers described above, the designer or end user has to be aware that the solar generator is directly coupled with the battery and the load. If the battery connection is interrupted (maintenance work, lead breakage, blowing of the battery fuse etc.), the full open-circuit voltage of the PV generator can be applied to the load and may destroy it! To prevent damage, either the loads must be able to withstand the high voltage or the controller must be designed to avoid voltages higher than the rated output. This can be achieved, for example, by rapid over-voltage detection and load cut-off.

19.1.1.4 Control strategies

When the end-of-charge voltage is reached for the first time, the battery is not yet fully charged. The missing 5 to 10% of charge can be added to the battery by keeping it at the end-of-charge voltage level for a prolonged period. In this constant-voltage (CV) phase, the charging current will slowly decrease. How can such a charging regime be implemented by a series or shunt controller as described above, which can only switch all of the PV generator current on and off? Two techniques are used in practice to approximate the ideal CC/CV charging mode.

In a two-position controller, the charging current is dropped to zero by either opening the series switch or closing the shunt switch as soon as the end-of-charge voltage has been reached. As a result, the battery-terminal voltage decreases. The charging current is enabled again when the battery voltage drops below a threshold that is between 5 and 50 mV/cell lower than the end-of-charge voltage.

This sequence gets repeated periodically and the charging pulses become shorter and shorter, while the intervals in between become longer, as the battery's state of charge increases as shown in Figure 19.7. The average charging current decreases, while the terminal voltage is more or less constant. The period of the cycle described above is

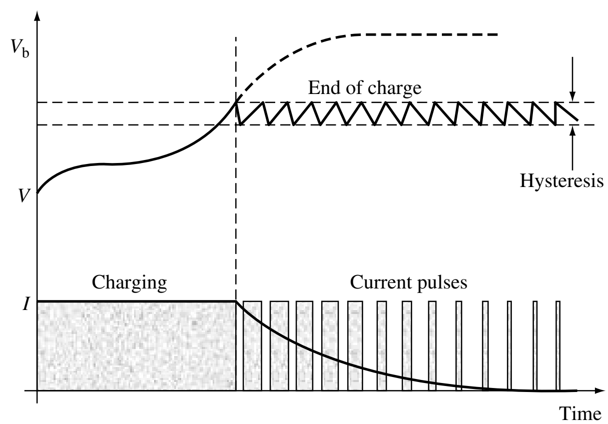

Figure 19.7 Battery voltage and current during charging

not constant and depends on the battery capacity, the state of charge, the charging or discharging current as well as the voltage hysteresis. It can vary from milliseconds to minutes. If mechanical relays are used as switching elements, the period should not be shorter than 1 to 5 min.

The second control regime found in practice is pulse-width modulation (PWM). In principle, it works like the two-step controller described above, but the switching frequency of the control element is fixed and determined by a clock generator. The typical frequency is about 100 Hz. In the CC phase, the switch is permanently closed and the full charging current flows into the battery. When approaching the end-of-charge voltage, the duty cycle (the ratio between the charging time and the cycle period) will be reduced towards zero by the pulse-width modulator. As mentioned above, the average charging current will drop and the battery voltage is kept constant.

One advantage of PWM controllers is that the switching frequency is known and constant. EMC problems can be solved more easily, and also monitoring of the average charging current becomes simpler.

19.1.1.5 Matching DC/DC converter, MPP trackers

Both the battery voltage and the PV generator voltage vary over a wide range during operation due to the changing state of charge and boundary conditions such as temperature and insolation. When directly coupled, this leads to a certain mismatch between the actual and the optimum operation voltage (MPP voltage) of the solar generator and therefore causes energy losses.

The mismatch can be overcome by introducing a matching DC/DC converter (MDC) that de-couples the characteristic curves of the PV generator and the battery. The power stage of these converters corresponds to the well-known topologies such as buck, boost or inverting converters. The control section is specially tailored to the PV conditions and consists of two control loops: one for the input and the other for the output. As long as the end-of-charge voltage has not been reached, the input voltage controller keeps the PV generator voltage at a constant level by appropriate adjustment of the DC/DC converter's switching regime (PWM). The voltage level can either be fixed (CV mode) or can track the actual MPP by an appropriate searching strategy (MPP tracking, MPPT). When the end-of-charge voltage is reached, the output voltage controller takes over and keeps the battery voltage at a constant level. The PV generator's operating point then shifts towards open-circuit conditions.

Numerous strategies and algorithms have been developed to find and track the MPP of a solar generator. They can be grouped into two categories:

- Indirect MPP trackers
  This type of MPP tracker estimates the MPP voltage by means of simple assumptions and measurements.
  Some examples from practice include the following:
  - The operating voltage of the solar generator can be adjusted seasonally. Higher MPP voltages can be expected in winter due to lower cell temperatures and vice versa.
  - The operating voltage can be adjusted according to the module temperature.

- The operating voltage can be derived from the instantaneous open-circuit voltage by multiplication with a constant factor, for example, 0.8 for crystalline silicon solar cells. The open-circuit voltage is measured periodically (e.g. every two seconds) by disconnecting the load for one millisecond.

The advantage of the above-mentioned procedures is simplicity, but they only give an estimate of the optimum operating point. They are not able to adapt to changing solar generator characteristics due to ageing or soiling.

- Direct MPP trackers
In these systems, the optimum operating voltage is derived from measured currents, voltages or the power of the PV generator. Therefore, they are able to react to changes in the generator's performance.
Some examples include the following:
  - Periodic scanning of a part of the $I-V$ curve. Here, the operating voltage of the module is varied within a given voltage window by means of the DC/DC converter. The maximum module power is determined and then the operating voltage is adjusted to the corresponding voltage level. In practice, it is much easier to measure the output current of the DC/DC converter and to maximise it. This leads to the same result as above.
  - "Mountain-climb algorithm". Here, the operating voltage is periodically changed in small steps. The increment can either be constant or can be adapted to the instantaneous operating point as shown in Figure 19.8. If the module's power (and therefore the charging current) increases from one step to the next, the search direction is retained; otherwise it is reversed. In this way, the MPP is found and the operating point oscillates around the actual MPP.

The above-mentioned losses due to mismatch are mostly overestimated. Particularly, if the components are chosen properly (e.g. modules with 30 to 33 cells for 12-V systems), the energy losses are on the order of a few percent when using direct coupling

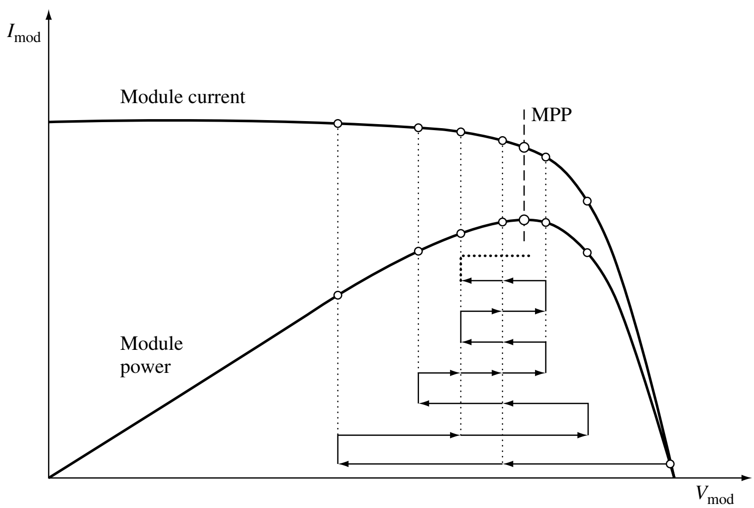

Figure 19.8 Working principle of the "Mountain-climb" MPP-tracking algorithm

instead of ideal matching! Besides this fact, it should be considered whether the additional energy gained by optimum matching is relevant to the function of the system at all. For example, the battery in a typical Solar Home System will be fully charged before noon and the excess solar energy will be dissipated.

In general, caution is indicated if the inventors or the manufacturers claim a tremendous energy gain by the use of MPP trackers!

Nevertheless, there are three advantages in using charge controllers with matching DC/DC converters:

- In the case of long wires from the PV generator to the battery, the generator voltage can be chosen much higher than the battery voltage, resulting in lower currents and therefore lower wiring losses.
- In small applications, the PV module can consist of only a few, large cells instead of numerous small cells connected in series. This reduces production costs, the impact of cell mismatch and the sensitivity to partial shading.
- More complex charging-current profiles can be realised by means of a DC/DC converter.

19.1.1.6 Deep-discharge protection

To achieve a maximum service life, deep discharging of batteries as well as prolonged periods with a low state of charge should be avoided. Therefore, the load has to be disconnected automatically from the battery as soon as the state of charge falls below a certain level. The load should be reconnected to the battery only when a sufficient state of charge has been reached.

Different criteria for detecting the deep-discharge condition have been explained in Chapter 18. In commercial products, the battery voltage will be used as a criterion for load disconnection. As soon as the battery voltage drops below a determined level, the load will be disconnected via a (bi-polar) relay or a semiconductor switch. Also, a control signal can be output to shut down balance-of-system components like inverters.

More complex charge controllers are able to generate a warning signal when the deep-discharge condition is being approached. Also, different loads can be disconnected according to a given priority. Charge controllers including an energy-management systems (EMS) are used to start back-up generators such as diesel or gas generators, depending on the battery's instantaneous state of charge. Additional parameters like load demand, weather conditions and so on can be considered.

There should be an appropriate delay time $t_{\mathrm{d\ off}}$ of 10 to 60 s between the undershooting of the end-of-discharge level and the actual disconnection of the load as shown in Figure 19.9. This ensures that undesirable disconnection of loads with large starting currents, for example, motors, refrigerators, washing machines and so on can be avoided. As the end-of-discharge voltage threshold depends on the instantaneous battery current, some advanced charge controllers offer a current-dependent adaptation of the disconnect threshold.

The ideal solution would be deep-discharge protection based on the actual state of charge of the battery. As systems or algorithms for accurately measuring the state of charge

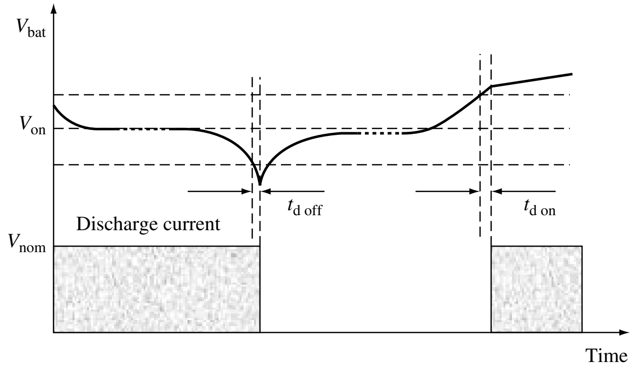

Figure 19.9 Changes in the battery voltage and load current during discharge

under the complex boundary conditions in PV systems are still under development, this type of controller is not yet in the market. For safety reasons, deep-discharge protection systems based on algorithms should be combined with a redundant control system based on simple voltage thresholds as described above!

The voltage threshold for reconnection of the load must be adjusted properly. If it is too low, the battery's open-circuit voltage will overshoot the threshold and the load will be reconnected periodically. In spite of the protection system, the battery will be deeply discharged and damaged. A time delay $t_{d\ on}$ as described above is also appropriate for guaranteeing a minimum state of charge before load reconnection.

In contrast to the end-of-charge threshold, the end-of-discharge threshold should not be temperature-compensated.

19.1.1.7 Monitoring systems and interfaces

Successful functioning of most PV systems strongly depends on the co-operation of the user. Reliable and meaningful information to the user about the current status of the system – the battery in particular – is therefore crucial. It would be ideal to have a "fuel gauge" that enables the system operator to plan the future energy demand. Such systems to monitor the state of charge have been discussed in Chapter 18.

As a minimum, the charge controller should be equipped with a display, for example, a light-emitting diode (LED) that indicates the conditions "Battery can be further discharged (green)" and "Battery is fully discharged (red)". Other conditions like "Battery close to end-of-discharge" can be helpful. Furthermore, an experienced operator can draw a lot of information from a meter showing the battery's voltage and current as shown in Figure 19.10.

All user interfaces should be ergonomic and provide only that information really required by the operator.

Energy-management systems are equipped with (potential free) inputs and outputs to communicate with external components, for example, to remotely start a diesel generator. In addition, standard interfaces such as RS 232, RS 485 or CAN-Bus can be integrated

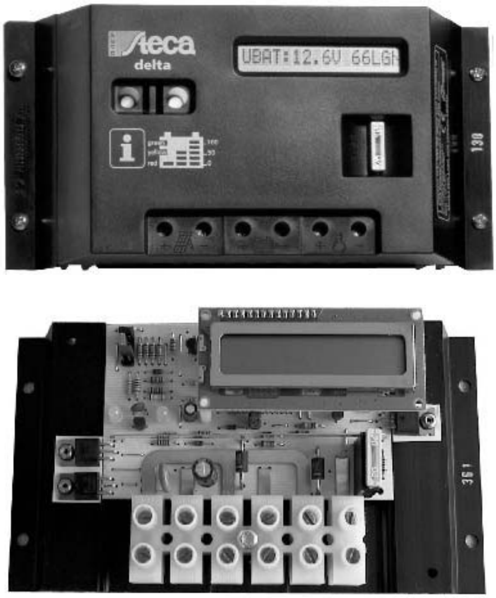

Figure 19.10 Charge controller with integrated voltage and current meter (Courtesy: STECA Solarelektronik, Germany)

to parameterise the controller, to read out the status of the system or to download operation data from the built-in data logger. Another feature is to communicate with external balance-of-system components via power line transmission.

In Solar Home Systems, the charge controller can act as an energy meter or can be used to automatically debit energy costs from a pre-paid card.

19.1.1.8 Design criteria and appraisal factors for charge controllers

The following summary of requirements is intended to support a designer or a purchaser of a charge controller. Which of these requirements must be met has to be decided specifically for each individual application.

The values of voltage thresholds and so on are related to lead acid batteries.

1. Charging phase.

- The end-of-charge voltage threshold should be adjustable according to the battery in use (2.3–2.5 V/cell at 25°C). To prevent extreme misadjustment, the setting range should not extend beyond these limits.
- The end-of-charge voltage can automatically be adapted to the system voltage (e.g. 12 V or 24 V).
- If the battery temperature is expected to deviate more than ±10°C from the average temperature under operation, the end-of-charge voltage should have a temperature compensation (approximately −4 to −6 mV/K per cell). If the temperature deviation is smaller, temperature compensation is not mandatory and the threshold should be set

according to the average battery temperature. Fail-safe behaviour is crucial in case of a temperature-monitoring malfunction, for example, due to broken sensor wires.

- The thresholds must be stable over temperature and time.
- If relays are used as control elements, the minimum switching period should be 1 to 5 min.
- The charge controller should be able to charge totally flat batteries. As a minimum requirement, charging should start from a cell voltage of 1.5 V.
- The battery voltage can be monitored by separate sensor wires. This is recommended if the battery wiring is long and of low cross-section. Fail-safe behaviour is crucial in case of broken sensor wires.
- The charge controller should be able to automatically perform gassing charging or equilibration charging according to the manufacturer's recommendations.
- It must be possible to prevent gassing charging in case of valve-regulated batteries (Gel- or AGM-VRLA batteries).
- The output voltage must be limited to safe values in the case of system operation without a battery, for example, due to unintended disconnection of the battery, wire breakage or blowing of the battery's fuse.

2. *Deep-discharge protection*.

- Deep-discharge protection is mandatory for a long service life. Only when the function of the system is more important than the battery life (e.g. in SOS telephones), deep-discharge protection can be omitted.
- The threshold voltages should be adjustable in a range of 1.5 to 2.0 V/cell. The adjustment range should not extend beyond this range to prevent extremely incorrect settings.
- The threshold should not be temperature-compensated.
- The threshold must be stable over temperature and time.
- The threshold can automatically adapt to the instantaneous battery current.
- The threshold can be based on the battery's actual state of charge.
- A time delay of 10 to 60 s should be implemented between undershooting of the threshold and the actual load disconnection.
- A warning signal can be given out when the deep-discharge condition is approached, for example, switch on a yellow LED 30 min before load disconnection at full load.
- Load disconnection can be performed according to load priorities.
- After load disconnection, only minimum current ($<I_{10.000}$) should be drawn from the battery. This can be achieved by appropriate design, for example, displaying of the current system status only on demand.
- The threshold for load reconnection should be relatively high, for example, >2.1 V/cell.
- A time delay of 10 to 60 s should be implemented between overshooting of the reconnection voltage threshold and the actual reconnection of the load.

3. *Efficiency*.

- The parasitic consumption of the charge controller should be less than 0.2% of the PV generator's power, for example, <8 mA in a 12-V/50-W controller.

- The voltage drop measured between the PV input terminal and the battery terminal should be less than 4% at full charging current, for example, approximately 0.5 V in a 12-V system.
- The voltage drop measured between the battery terminal and the load terminal should be less than 4% at full load current, for example, approximately 0.5 V in a 12-V system.
- The above-mentioned figures lead to an efficiency of >96% under rated charging as well as discharging conditions.

4. *Safety aspects and compliance to codes*.

- The charge controller must be protected against the reverse polarity of the input voltage and the battery voltage, for example, by a combination of fuses and diodes. Also, interchange of the inputs and outputs must not lead to damage.
- The charge controller must permanently withstand the maximum possible open-circuit voltage of the PV generator. This occurs at maximum insolation and minimum module temperature.
- Inputs and outputs must be protected against transient over-voltages by appropriate voltage arresters, for example, varistors.
- The charge controller must be designed according to the ambient temperatures at the usage site.
- The housing for the charge controller must withstand the environmental stress at the usage site, for example, protection level IP 00 inside a control cabinet, or IP 65 for outdoor applications.
- The electronic components should be protected by lacquer or encapsulation.
- The terminals should be generously dimensioned and robust. Cage clamps are a preferred solution.
- The charge controller must comply with relevant codes concerning electric safety and electromagnetic compatibility (EMC). It must have a Communautés Européennes (CE) label.

19.1.2 Charge Equaliser for Long Battery Strings

19.1.2.1 Introduction

All electrochemical storage systems react sensitively to operating states that do not conform to their specifications, such as overcharging, deep discharge or reversed polarity. The general observations are that the lifetime is shortened, the storage capacity and the efficiency are diminished and more maintenance is required. Further, detrimental conditions can arise with some batteries, for example, lithium-ion batteries, which lead to destruction or even explosion.

Thus, the manufacturers specify the allowable charging and discharging voltages, currents and also temperatures very precisely for individual cells – for the voltages, tolerances on the order of 1% are no exception.

However, on proceeding from the individual cell to series connection of several cells or groups of cells, which are usually needed, a well-known phenomenon is observed: in all applications, from laptops through PV systems and electric vehicles to un-interruptible power supplies and grid back-up systems, each individual cell in the series connection behaves differently. This individualisation results from differences in cell capacity, self-discharge rate, charging factor and so on. They are determined by production conditions, ageing and temperature and cannot be avoided on principle.

Conventional charge controllers are not able to recognise this variation in the behaviour of the cells, so that the undesirable operating conditions listed above arise. In practice, it is evident that the "weakest link in the chain" determines the quality of the whole string, and that the deviating performance of a single cell can lead to a chain reaction.

The problem of increasing divergence in individual cell properties within a battery has been known since the beginning of battery technology, so that over the years a number of different procedures to solve the problem have been developed. Most of them are based on the dissipation of the surplus energy of fully charged cells in a bypass element. This approach is not suitable for applications in which highest efficiency is crucial, such as PV systems. Furthermore, it is effective only with a fully charged battery – it has no impact when the battery is being discharged.

On the basis of experience with numerous PV systems, active, non-dissipative charge-equalising systems have been developed. In contrast to conventional dissipative systems, here the surplus energy from cells having a higher state of charge is redistributed among the remaining cells. As indicated in Figure 19.11, this redistribution occurs not only during or at the end of charging but also constantly during discharging.

As a result, cells with a lower capacity are supported by the other cells during discharge. Their relative state of charge decreases evenly with that of the cells with higher capacity. In this way, the entire available capacity of all cells can be used. During charging, some of the charging current is redistributed from weaker cells to stronger ones, so that these are charged with a higher current, resulting in faster charging.

The energy redistribution also allows cells with larger capacity tolerances to be connected together in series. Costly selection of matched cells during battery construction can thus be avoided. In extreme cases, it is even possible to sustain operation with a mixture of new cells and old cells after the replacement of defective cells. Additionally,

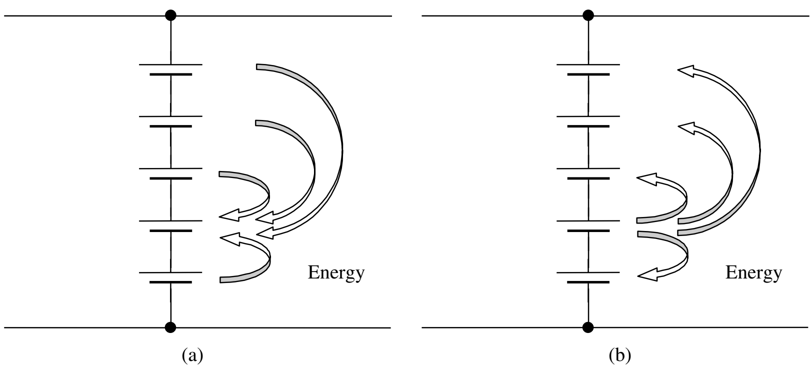

Figure 19.11 (a) Support for a weak cell during discharge by redistribution of energy from stronger cells. (b) Protection against overcharging

it has been shown that the energy efficiency can increase as overcharging or reverse charging is prevented.

19.1.2.2 The T-CHEQ principle

Several different procedures for active charge equalisation were developed and publicised under the name “CHarge EQualizer” (CHEQ) [1].

The “T-CHEQ” principle is based on a multiple-gate forward converter as shown in Figure 19.12. It can be used over a wide power range, but is particularly suited to higher power values. Here, the cells are coupled magnetically via coils, which are wound around a common core. The coils are periodically connected to the single cells with alternating polarity via semiconductor switches. As the same voltage is induced in all the coils due to the tight coupling, an equalising current automatically flows into or out of the cells if there is any deviation from the average cell voltage. It is advantageous that all cells can be treated simultaneously. Furthermore, this device can be extended to a battery charger by feeding energy into an additional coil wound around the core.

19.1.2.3 Operating experience

The working principle of active charge equalisation has been proven in numerous laboratory tests and pilot installations.

A typical charging cycle from a long-term test with a T-CHEQ system is shown in Figure 19.13. The battery was charged according to a CC/CV charging profile with a

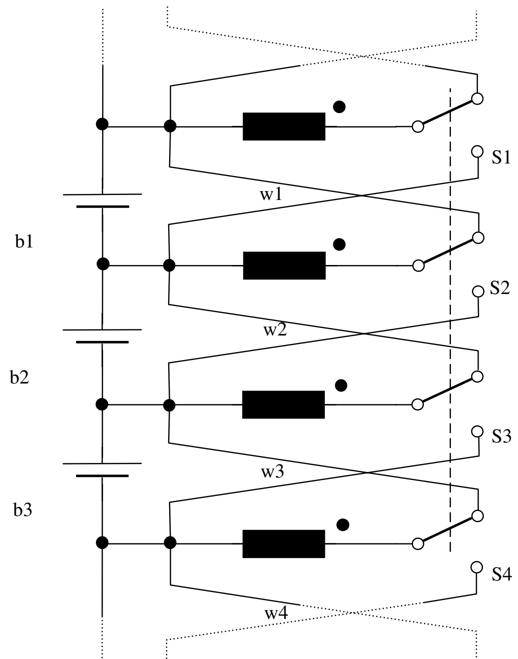

Figure 19.12 CHarge EQualizer with transformer coupling (T-CHEQ)

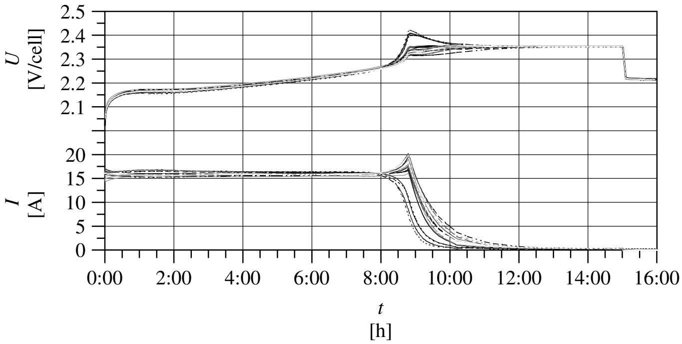

Figure 19.13 Voltages and currents of 16 series-connected cells during charging with an activated T-CHEQ

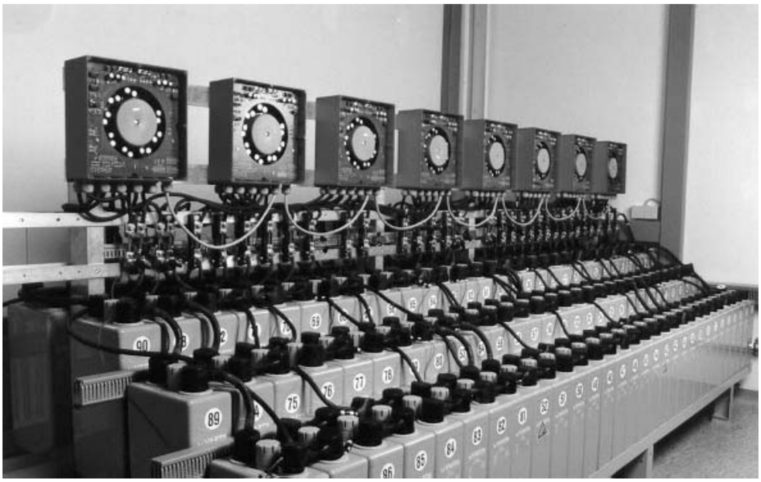

Figure 19.14 Experimental set-up with a 342-V/200-Ah sealed lead acid battery with eight cascaded T-CHEQs

charging current of 16 A and an end-of-charge voltage of 2.35 V/cell. The upper curves in Figure 19.13 show the 16 individual cell voltages and the lower curves show the corresponding cell currents. The cells with a lower capacity are the first to be fully charged – their voltage increases above the average voltage. As a result, the T-CHEQ draws some of the charging current from these cells and directs it to the cells with a lower state of charge. After 9 h, some cells are effectively charged only with 5 to 10 A, whereas the charging current for others is around 20 A. At the end of the charging phase, the T-CHEQ achieves a convergence of all the cell voltages and all the cells are fully charged.

Investigations of a 342-V/200-Ah sealed lead acid battery (VRLA, Gel-type) with eight cascaded T-CHEQs (Figure 19.14) show that such high system voltages can be operated without any difficulties. This type of battery is very sensitive to overcharging due to its demobilised electrolyte.

19.2 INVERTERS

19.2.1 General Characteristics of PV Inverters

Since the production cost of PV electricity is several times more expensive than conventional electric energy, conversion efficiency becomes predominant to the economics of the total PV system. As a consequence extremely high efficiency not only in the nominal power range but also under a part-load condition is a requirement for PV inverters in grid-connected as well as in stand-alone systems. Since some characteristics of both types of applications are different, they will be highlighted separately in the following chapter.

19.2.2 Inverters for Grid-connected Systems

This configuration consists mainly of the following components: the PV generator, the inverter, the safety devices and, in many cases, the electric meter as shown in Figure 19.15.

The actual power fed into the grid can be estimated by multiplying the actual power of the PV generator with the actual efficiency of the inverter if we neglect the losses in the safety device and in the meter. More important is the energy produced by the system after a certain period of time, for example, after one year of operation. In this case the mean efficiency of the inverter taking into account all load conditions throughout the year becomes important. As a first step the inverter must allow the PV generator to operate in the MPP by adjusting the corresponding operation voltage as shown in Figure 19.16.

Many inverters adjust this operation voltage continuously to the actual MPP. This operation is called maximum power point tracking (MPPT). The method most commonly used to perform the MPPT is to change the actual input voltage in such a way that maximum power is obtained (Figure 19.8). The effect of continuous MPPT is often overestimated. Simulation has shown that for grid-connected PV systems, CV operation leads only to losses between 1 and 2% when properly adjusted [1, 2].

For optimum use of the PV energy, MPPT and CV operation can be seen as equivalent. As a matter of their operation principle, single-phase inverters, which are most common in small-scale PV systems ($P \leq 5\ \mathrm{kW_P}$), lead to deviations from the MPP due to DC ripple, which is explained as follows: when injecting AC power into the grid, the feed-in current should be in phase with the grid's voltage, which means that the power factor equals one as shown in Figure 19.17.

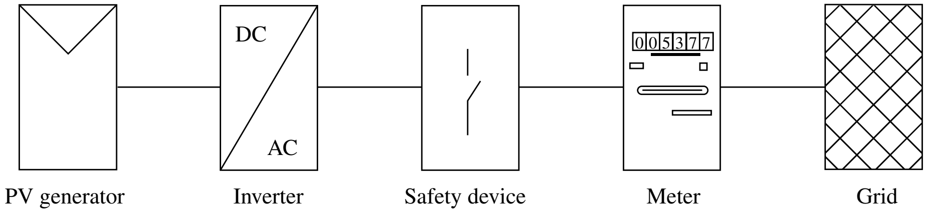

Figure 19.15 General structure of a grid-connected PV system

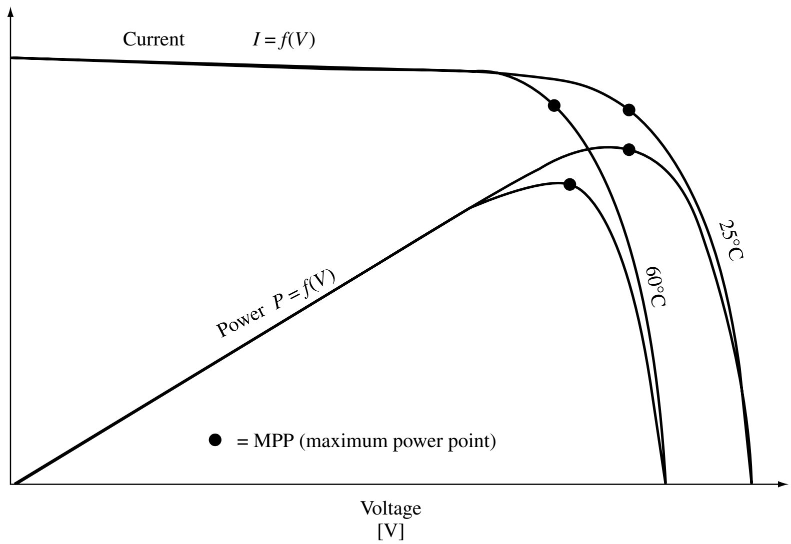

Figure 19.16 Maximum power point (MPP) for different module temperatures

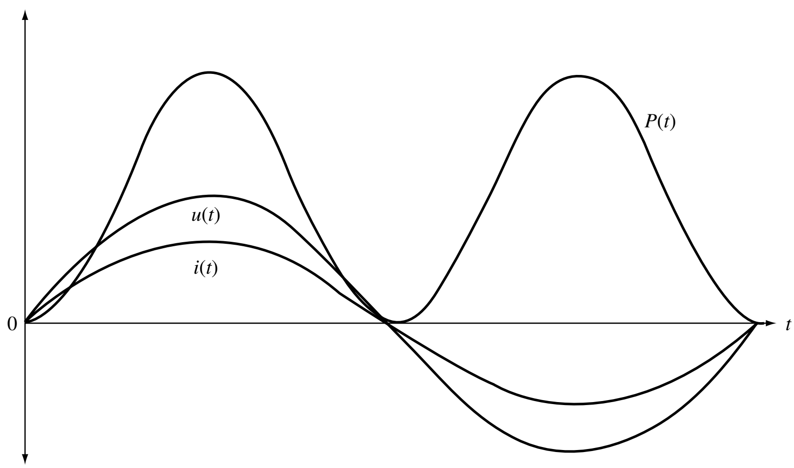

Figure 19.17 Pulsewise injection of power into single-phase grids needs energy storage

As a consequence, the actual power injected into the grid becomes

$$\begin{aligned} P(t) &= u(t) \cdot i(t) \\ &= u_o \cdot \sin(\omega t) \cdot i_o \cdot \sin(\omega t) \\ &= u_o \cdot i_o \cdot \sin^2(\omega t) \\ &= ui[1 + \sin(2\omega t)] \end{aligned}$$

These power pulses with a frequency of 100 Hz are also shown in Figure 19.17. Since the PV generator provides continuous and quasi-constant power and since power injection

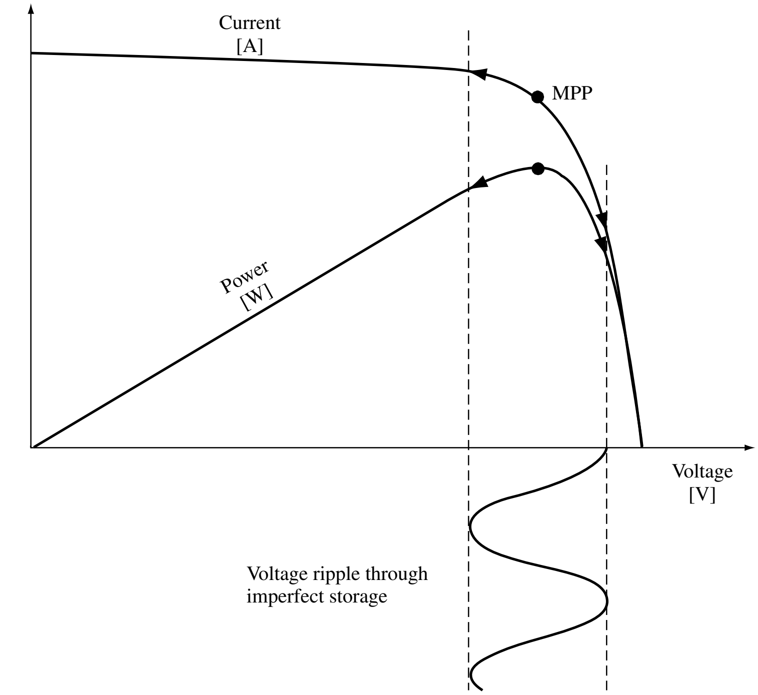

Figure 19.18 Deviations from the MPP through DC voltage ripple caused by the working principle of single-phase inverters

into the grid is pulsewise, each single-phase inverter needs a storage element that can be realised either using a capacitor or an inductor [3]. Since for economic reasons these storage elements must be limited, a voltage ripple can be found with all single-phase inverters at the DC side. This ripple forces the PV generator to deviate from the MPP as shown in Figure 19.18.

Well-designed single-phase inverters show DC voltage ripple with a negligible influence on MPP deviations. It should be noted at this point that three-phase inverters inject a continuous power into the grid, which eliminates the need for this kind of storage.

19.2.3 Inverters for Stand-alone Operation

Typical inverters for this type are often supplied by batteries. They have to provide constant voltage and frequency to the loads irrespective of the actual load profile. In case of reactive loads they have to provide and to absorb reactive power.

In hybrid PV systems, they should be able to operate in a bi-directional mode. This means that they should be able to recharge the battery in case of surplus power at the AC side.

Basically, both inverter types for a grid-connected and stand-alone operation have very similar hardware elements with respect to power electronics. Differences are found in inverter control.

19.2.4 Inverter Principles

19.2.4.1 General aspects

Basically, inverters convert direct current (DC) into alternating current (AC) by inversion of the DC polarity in the rhythm of the desired AC frequency (Figure 19.19). The symbol used to describe an inverter is shown in Figure 19.20.

19.2.4.2 Square-wave-type inverters

A simple version of such an inverter is shown in Figure 19.21.

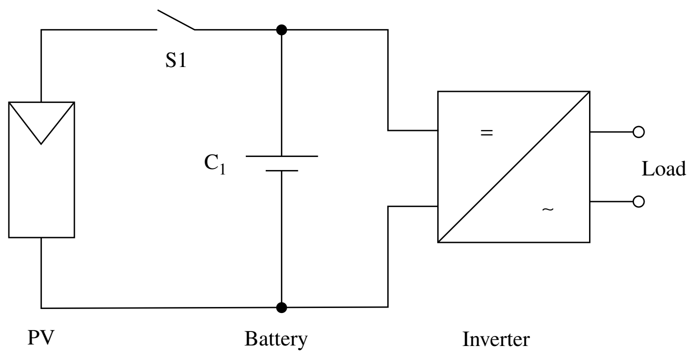

Figure 19.19 Typical configuration for stand-alone AC power supply systems

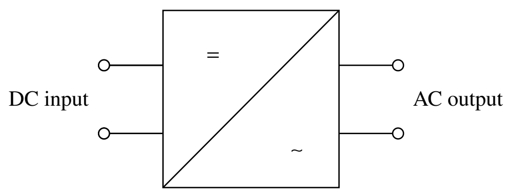

Figure 19.20 Symbol used to describe inverters

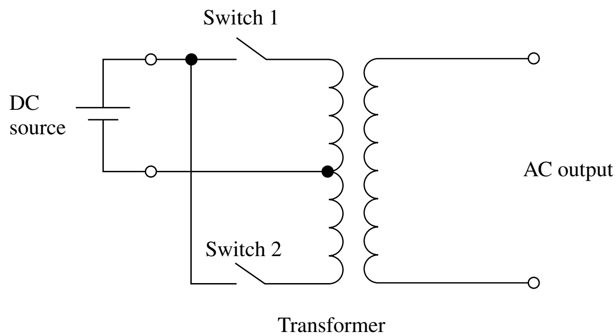

Figure 19.21 Layout of a simple inverter with square-wave AC output

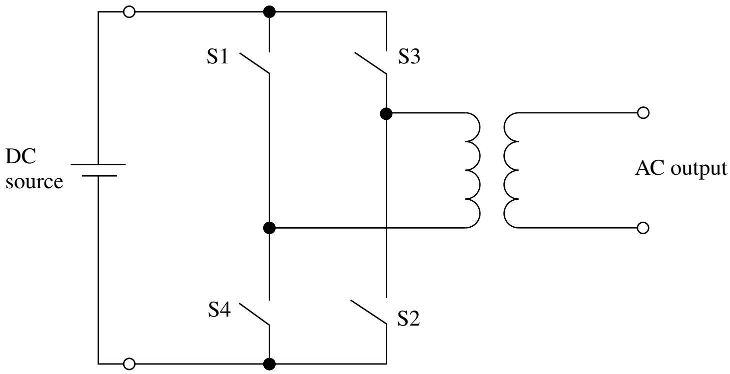

Figure 19.22 H-bridge-type inverter

AC at the primary windings of the transformer is produced by alternatively closing the switches 1 and 2. If switch 1 is closed, switch 2 is open and vice versa. The resulting AC output voltage is of the square-wave type, which may be used for resistive-type loads such as incandescent light bulbs and so on. The two primary windings of the transformer can be reduced to one if two more switches are used as shown in Figure 19.22.

In this configuration, the switches are opened and closed pairwise in such a way that the groups S1 and S2 and the groups S3 and S4 open and close alternately. At the output of the H-bridge formed by the switches S1 through S4, AC is already available. The transformer is only necessary in case of a voltage transformation.

19.2.4.3 Inverters with sinusoidal AC output

Since many consumers and the public grid operate on the basis of sinusoidal voltage, high-quality inverters should also be able to provide this type of AC output. This voltage form can be produced by voltage-transformation principles. Two of the most common transformation principles, namely, the step-down and the step-up converter and a combination of both will be highlighted as well as a digital synthesis one.

19.2.4.3.1 Step-down converter (Buck converter)

With the help of these converters, the input DC voltage, which is, for example, generated by the PV generator (V_{PV}) as represented in Figure 19.23, can be stepped down.

If the switch S_1 is turned on at t_0, the diode D is reverse-biased and a circuit current arises (Figure 19.24). The current ($= i_L$) does not increase immediately but rather rises with a rate imposed by the inductor L:

$$\frac{di_L}{dt} = \frac{V_{PV} - V_{load}}{L}$$

Meanwhile, the inductor stores energy in a magnetic form. If S_1 is turned off after $t = t_1$, the load is separated from the supplied system. The current is, however, maintained by the stored energy in the inductor L and flows through the freewheeling

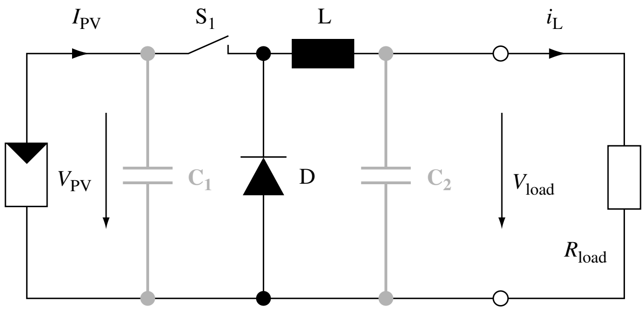

Figure 19.23 Equivalent circuit diagram of a step-down converter

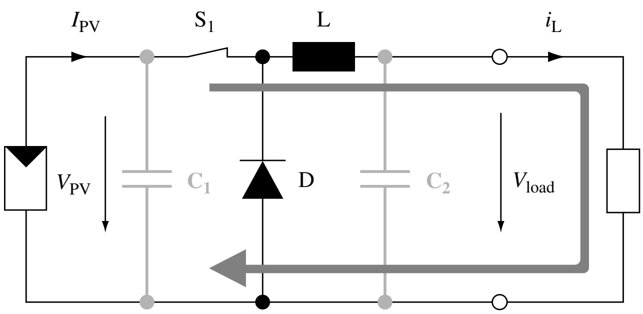

Figure 19.24 Step-down converter during "on" state

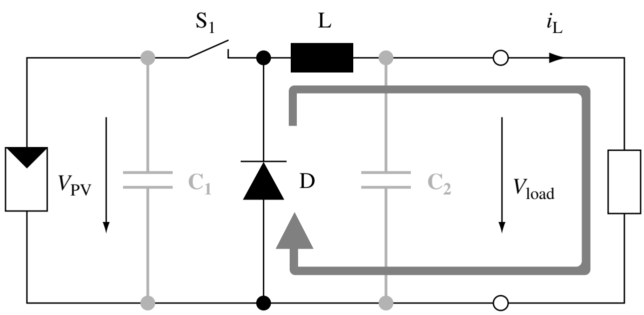

Figure 19.25 Step-down converter during "off" state

diode instead (Figure 19.25). Neglecting the voltage drop across the diode, the current falls down, however, due to the following equation:

$$\frac{di_L}{dt} = -\frac{V_{load}}{L}$$

The capacitor C_1 is used to support the supply voltage (V_{PV}). In principle, S_1 is turned on and off with a switching frequency (i.e. with "t_{on}" and "t_{off}"). With regard to Ohm's law, the behaviour of the load voltage can be obtained from the load current ($= i_L$).

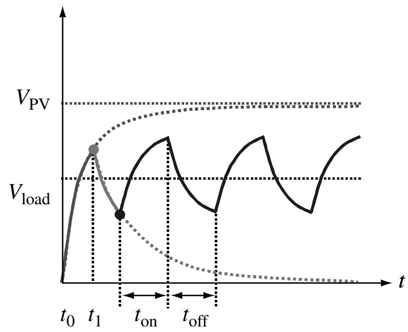

Figure 19.26 Behaviour of the load voltage of a step-down converter

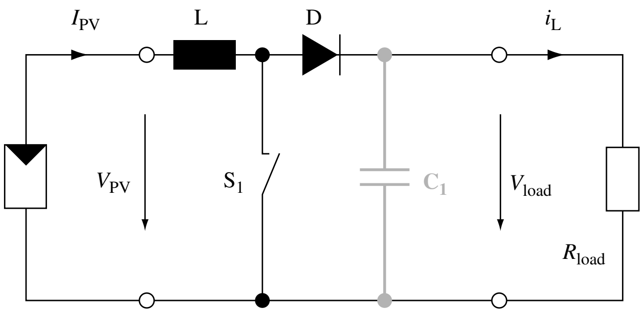

Figure 19.27 Equivalent circuit diagram of a step-up converter

As shown in Figure 19.26, the resulting load voltage obviously has a ripple, which can be smoothed by the additional capacitor C_2. Anyway, its average value (V_{load}) is lower than V_{PV}. In case the switching frequency is increased, for example, up to the kilohertz range, then the necessary inductance can be reduced considerably.

The resulting voltage transformation can be described by the relation of the switching time as follows:

$$\frac{V_{load}}{V_{PV}} = \frac{t_{on}}{t_{off} + t_{on}}$$

19.2.4.3.2 Step-up converter (Boost converter)

By rearrangement of the components of the step-down converter, a step-up converter can be obtained (Figure 19.27). Contrarily, here V_{PV} is stepped up. At a steady state as S_1 is still "off", V_{load} is equal to the V_{PV}, neglecting the voltage across diode.

As shown in Figure 19.28, during "on" state, without C_1 the load voltage drops immediately to zero. The circuit current ($= i_L$) flows through the inductor L and S_1 and rises according to the following equation:

$$\frac{di_L}{dt} = \frac{V_{PV}}{L}$$

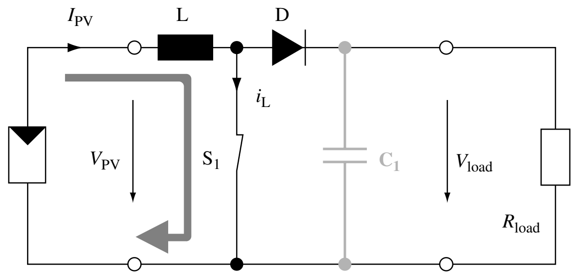

Figure 19.28 Step-up converter during "on" state

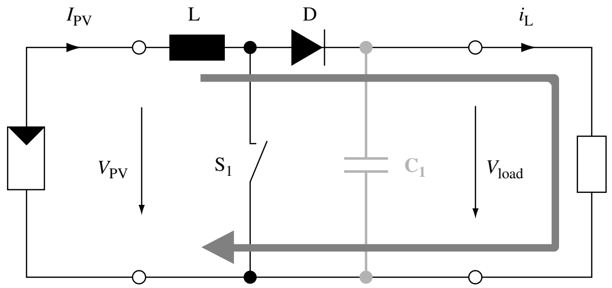

Figure 19.29 Step-up converter during "off" state

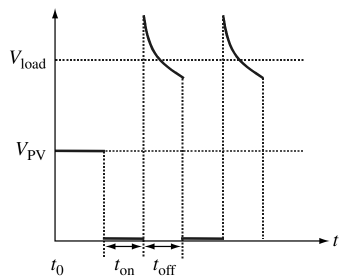

Figure 19.30 Behaviour of the load voltage of a step-up converter

After S_1 is switched off (Figure 19.29), the induced voltage in the inductor adds itself to V_{PV}, which then lies across the load. i_L flows through the inductor and further to the load. Thereby, it falls down gradually because $V_{load} > V_{PV}$:

$$\frac{di_L}{dt} = \frac{V_{PV} - V_{load}}{L}$$

The proceeding of the load voltage is illustrated in Figure 19.30. The diode D protects against a short circuit (i.e. discharge) of the charged capacitor C_1, which is assumed to be so big that it can smooth the load voltage completely.

The resulting voltage transformation then becomes

$$\frac{V_{\text{load}}}{V_{\text{PV}}} = \frac{t_{\text{off}} + t_{\text{on}}}{t_{\text{off}}}$$

19.2.4.3.3 Step-down/step-up converter (Buck/Boost or inverting converter)

This circuit (Figure 19.31) enables both step down and step up of a DC voltage. During the "on" state, the energy given by the source (PV generator, in this case) is stored in the inductor L (Figure 19.32). The stored energy in the inductor L is then delivered to R_{load} during the "off" state (Figure 19.33). With the help of the diode D, the current flows through the inductor L only in one direction during both "on" and "off" states. As a result, V_{load} obviously has an opposite polarity to V_{PV}. Therefore, the circuit is also called an inverting converter. Equations describing the proceeding of the circuit currents can be derived in the same way to both converters mentioned before and will not be done here. As stated earlier, the capacitor C_1 supports the supply voltage V_{PV} and C_2 smoothes V_{load}. In conclusion, the amplitude of V_{load} can be either lower or higher than V_{PV} depending on the adjusted t_{on} and consequently t_{off} [4]:

$$\frac{V_{\text{load}}}{V_{\text{PV}}} = \frac{t_{\text{on}}}{t_{\text{off}}}$$

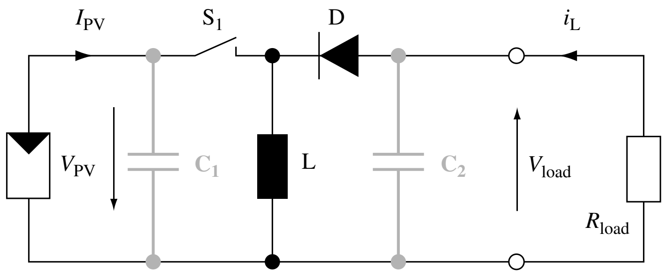

Figure 19.31 Equivalent circuit diagram of a step-down/step-up converter

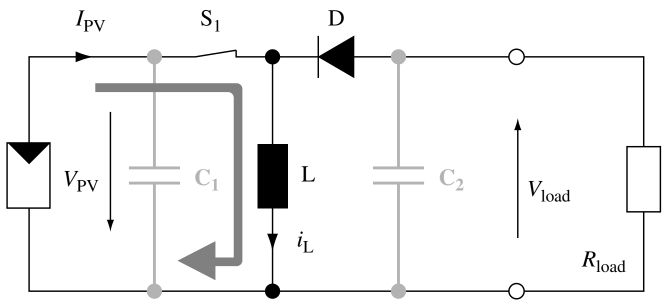

Figure 19.32 Step-down/step-up converter during "on" state

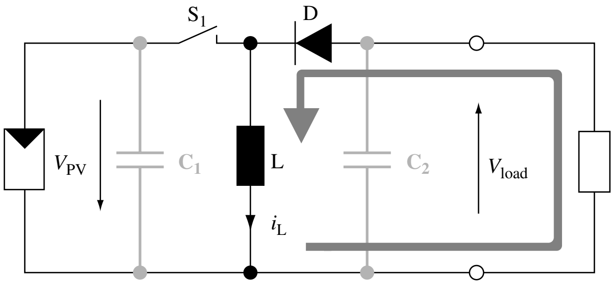

Figure 19.33 Step-down/step-up converter during "off" state

19.2.4.3.4 Combination of a step-down converter with an inverter

The combination of a step-down converter with a voltage inversion is shown in Figure 19.34. It should be noted that in this configuration the voltage of the DC input sources must always be equal to or bigger than the AC peak voltage.

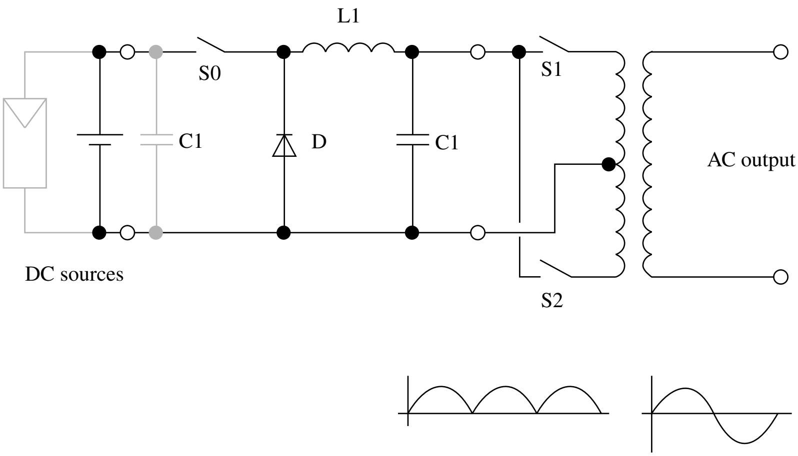

Figure 19.34 The combination of a step-down converter with inverters allows to produce sine-shaped AC output voltage. Wave shapes correspond to the voltage at the terminals over them

19.2.4.3.5 Voltage shaping by digital synthesis

In a further concept, the step-down converter can be replaced by digital synthesis as shown in Figure 19.34. In this concept, the desired voltage is obtained by binary addition of individual voltage sources [5–7]. Depending on the sum of these sources, the sine-shape can be approximated.

When using 5 sources, 32 voltage steps according to 2^5 adjustable levels can be obtained as shown in Figure 19.35. The resulting total harmonic distortion (THD)[1] can be kept well below 5%.

[1] Definition of THD: sum of the amplitudes of all harmonic frequencies compared to the amplitude of the fundamental signal (the 50- or 60-Hz frequency).

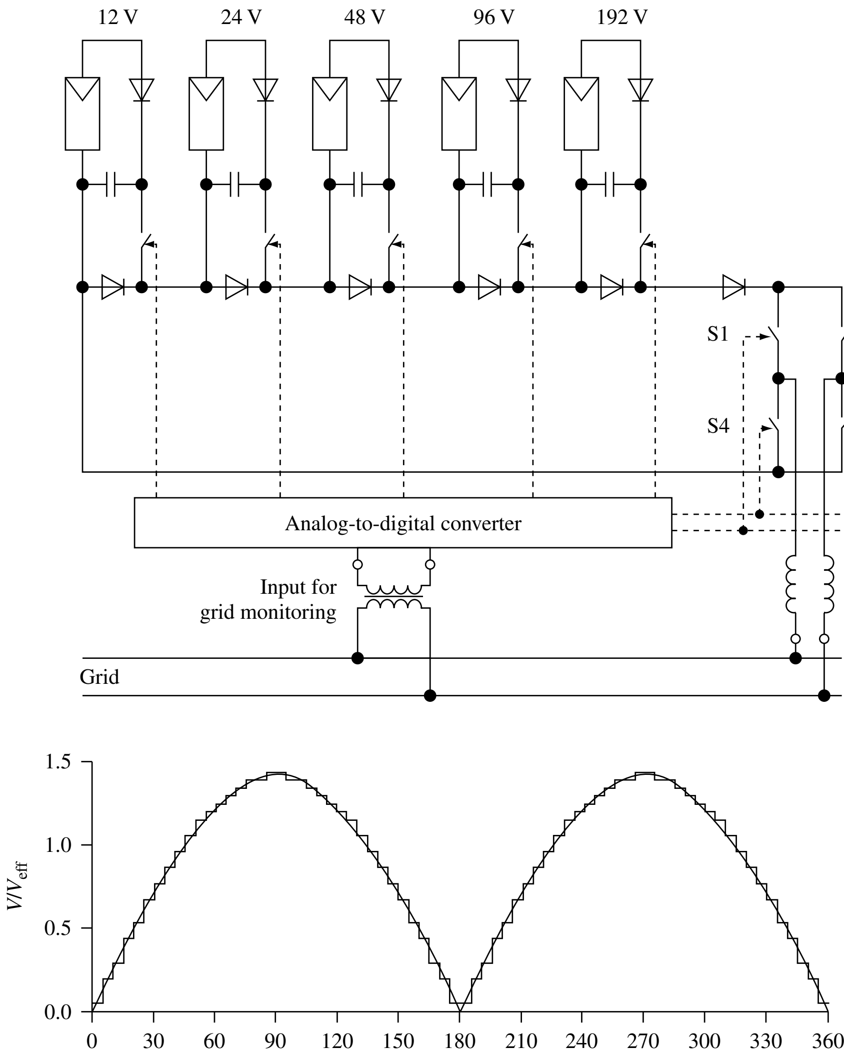

Figure 19.35 Digital waveform synthesis inverter

This concept provides extremely high efficiency since no induction coils or other magnetic elements are required (see Figure 19.35). One disadvantage that can be seen in the use of multiple voltage sources is the increase in cabling needs between the PV generator and the inverter.

In this concept the switches (transistors) S1 through S4 are needed to invert every second sine half-wave to arrive at AC. If using voltage sources with such voltages that they can sum up with the peak voltage of the desired AC output as

$$\sum_{i=1}^{n} V_i = 1.1\sqrt{2}V_{\mathrm{AC}} = 358 \text{ Volts} \quad \text{for 230 V AC (+10\% tolerance)}$$

no transformer is needed, which increases the efficiency of this concept further, especially under part-load conditions.

19.2.4.3.6 Integration of the step-down principle into the inverting process

The four switches of the H-type bridge itself can also be used to form the desired sine-shape of the AC output. In this case a choke has to be inserted between the bridge and the AC output as shown in Figure 19.36. As has been shown in the concepts before, the switches S1 and S2 and therefore S3 and S4 act synchronously, but their switching frequency becomes very much higher than the desired AC output frequency that is called the fundamental frequency. During the first half-period of the fundamental frequency (10 ms for 50 Hz), the switches S1 and S2 change their on and off state in such a way that the relation t_{on}/t becomes proportional to the actual desired voltage similar to the step-down converter principle shown in Figure 19.23. In fact, the step-down converter principle has been extended to work under both positive and negative polarities.

The configuration shown in Figure 19.36 has become popular since only a very few components are needed, resulting in high efficiency and low cost. One possible disadvantage of this concept is the high DC input voltage necessary for proper working, for example, 358 V DC for 230 V at the AC side. Adding a transformer between the load and the inverter's output allows reducing the DC input voltage according to its transformation ratio. This combination can be found in many products that are in the market today. Compared to the transformer-less version, separation of the potential between source and load becomes feasible. Reduced efficiency and increased investment costs are the consequences, however.

The concept shown in Figure 19.36 allows further operation in a reversed power flow. This situation may occur for inverters in the stand-alone mode if the load is of a reactive type or if surplus power from the AC side is used to charge the battery. In both cases, the variable AC voltage must be transformed to the DC voltage level, which is always higher than any value of the AC voltage as shown in Figure 19.37. By combining S2 and D3 in Figure 19.36, a complete step-up converter can be realised for the positive part of the AC voltage. For the negative part, the combination of S1 and D4 forms the step-up converter for inverse power flow.

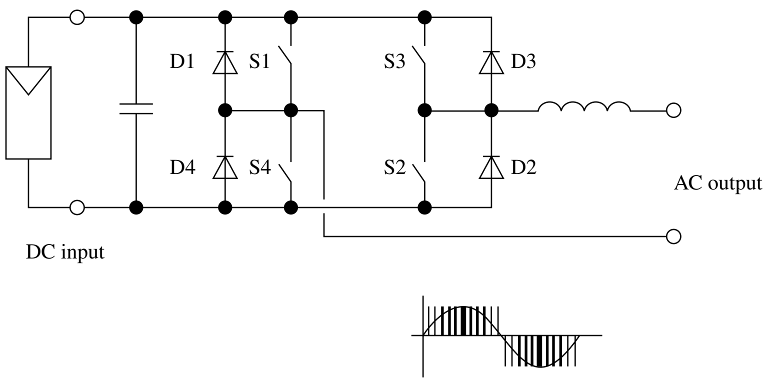

Figure 19.36 Pulse-width modulated (7-phase chopping) H-type bridge inverter

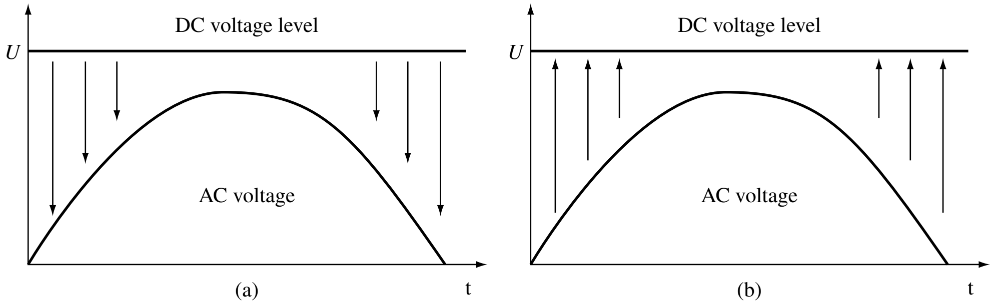

Figure 19.37 (a) Step-down conversion in the forward power-flow mode. (b) Step-up conversion in the reverse power-flow mode

19.2.4.3.7 Bi-directional step-up/step-down conversion

The concept described above allows reversed power flow only in cases in which the DC voltage level is always higher than the peak voltage of the AC side, which means that $U_{DC} \geq 358$ V for 230 V AC. However, there are two possibilities to lower the DC voltage level, that is, to install a transformer at the AC side or to install a bi-directional DC-DC converter at the DC side. Since a conventional step-down converter, as was described earlier, is not able to act as a step-up converter in the reversed power-flow mode, either two converters in anti-parallel mode or a different conversion concept would be necessary. One topology developed by Cuk [8] in 1977, which is able to fulfil these requirements, is given in Figure 19.38.

This conversion principle is in fact able to perform step-up as well as step-down conversion in both directions. The relation between the input voltage U_1 and the output voltage U_2 becomes:

$$U_2 = U_1 \cdot \frac{t_{on}}{(t_{off} + t_{on}) \cdot \left(1 - \dfrac{t_{on}}{(t_{off} - t_{on})}\right)}$$

Switches S1 and S2 operate complementarily, for example, if S1 is on, S2 is off and vice versa.

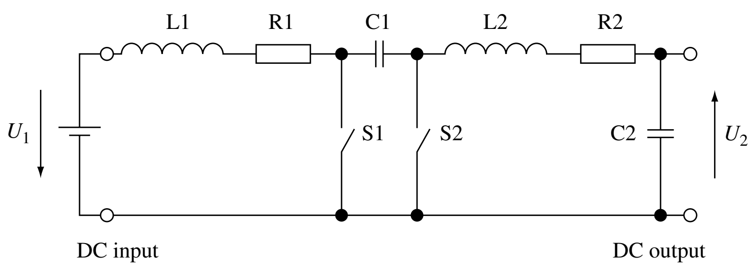

Figure 19.38 Bi-directional Cuk converter

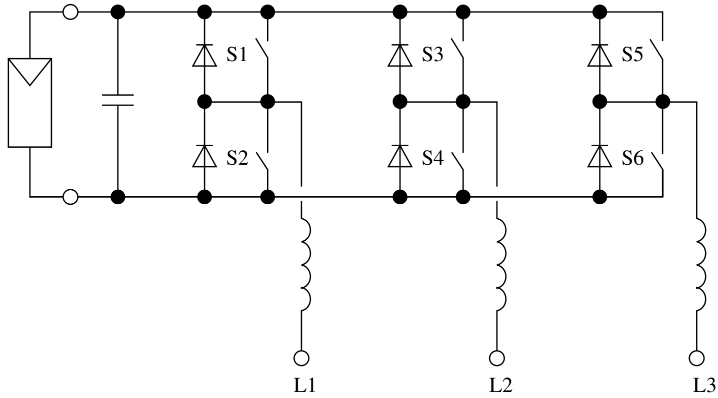

Figure 19.39 Three-phase PWM inverter

19.2.4.3.8 Three-phase configuration

The configuration shown in Figure 19.36 is also very well suited to be expanded into a three-phase version as given in Figure 19.39 [4].

This type of inverter is normally suited to a power range above 5 kW. Connection efforts at the AC side are somewhat higher since three terminals have to be dealt with. The most striking advantage of a three-phase concept can be seen in the fact that the power output and, thus, the power input are absolutely constant. As a consequence, no storage capacitor at the DC input side is needed.

This concept can also be combined with a three-phase transformer in a way as has been described earlier.

This inverter type is most commonly used in PV pumping systems. In contrast to most other applications, PV pump inverters operate with variable frequency and voltage at the AC output side. As an example, a typical characteristic of a centrifugal pump system is given in Figure 19.40.

The figure shows the pump head as a function of mass flow. The parameters are pump speed equivalent to the frequency and system efficiency.

Since the sinusoidal shape is obtained by a step-down process, as was described earlier, lowering of the AC voltage can be easily performed by the same configuration. In addition, MPP tracking can easily be performed by adjusting the frequency and proportionally the AC voltage in such a way that the PV generator can provide maximum power. In Figure 19.41, a typical PV pump system configuration is shown.

19.2.4.3.9 High-frequency concepts

If electric isolation between DC input and AC output is requested and if the bulky 50-Hz transformer should be avoided, high-frequency (HF) transformer concepts may be used. Three topologies using HF concepts will be described in this section.

In the first concept, the configuration as described in Figure 19.34 is used to operate with a high frequency (some 100 kHz) using an HF transformer. The HF square-wave

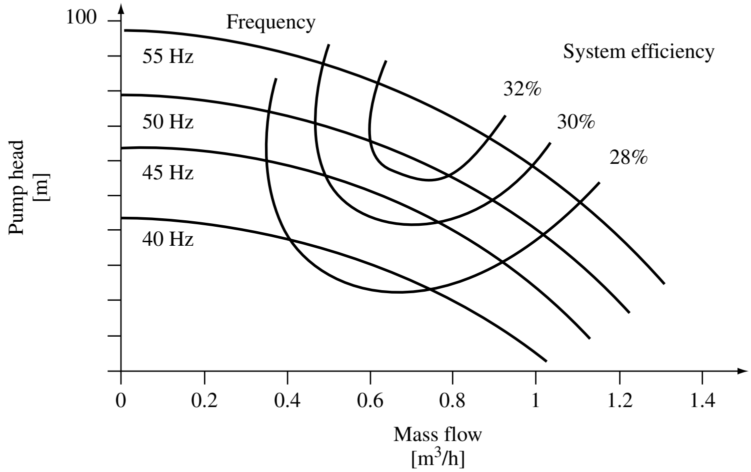

Figure 19.40 Characteristic of a centrifugal pump system

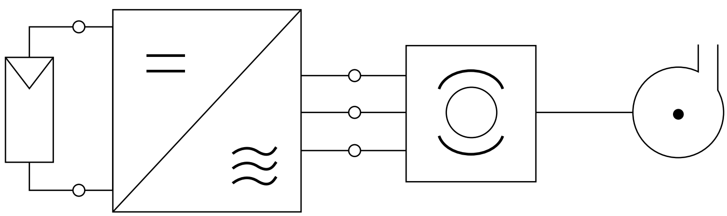

Figure 19.41 Typical layout of an AC PV pumping system

AC output is then rectified as shown in Figure 19.42, providing the desired DC voltage necessary for PWM inversion according to the H-type Bridge explained in Figure 19.36.

Compared to the low-frequency concepts, it becomes obvious that the savings using the HF transformer are widely being compensated by extra components. This might be one of the reasons HF concepts have not widely been used in inverters offered to the market so far.

When operating the high-frequency concept, as described in Figure 19.42, in the PWM mode, in which the desired low frequency is used for modulation, a PWM series of unipolar half-waves result after the rectifier at the secondary windings of the HF transformer. By means of the combination of L and C_2, a unipolar series of sine-shaped half-waves result, which are finally inverted with the H-type bridge as described in Figure 19.43. The 100-Hz pulsewise power injection requests an adequate storage element, which is realized by means of the capacitor C_1. It should be noted that this storage function is realized with C_2 in the topology presented previously in Figure 19.42.

Finally, an HF concept is presented in which AC is directly produced at the secondary side of the HF transformer. In this case, the non-controlled rectifier shown in

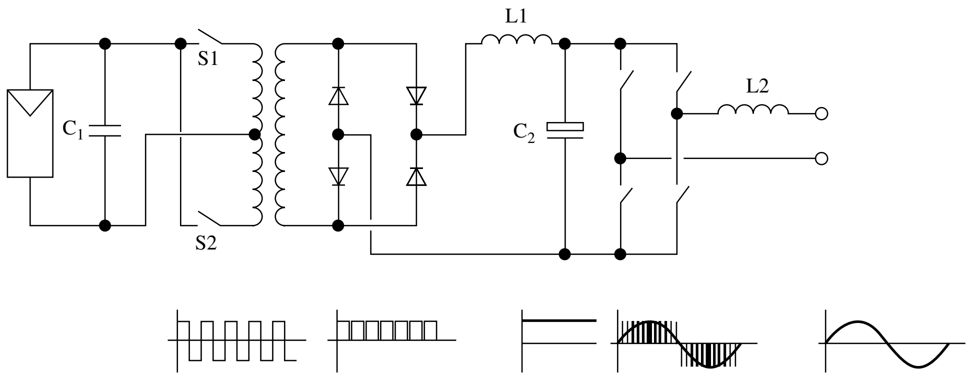

Figure 19.42 HF transformer combined with PWM H-type bridge inverter

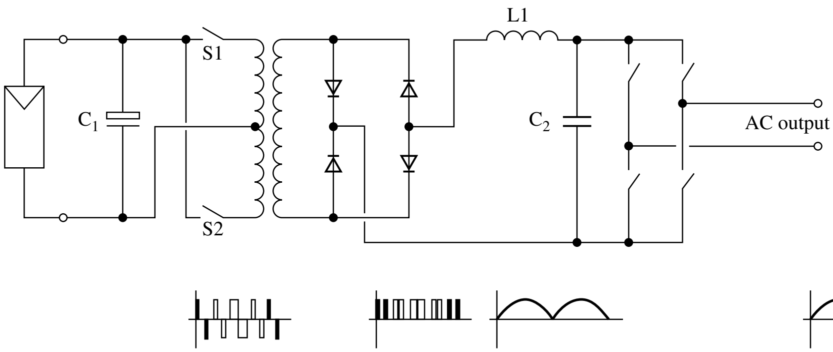

Figure 19.43 HF transformer combined with PWM high-frequency generator at the input side and a low-frequency H-type bridge at the output side

Figure 19.43 has been replaced by active switches combining the functions of rectification and inversion. This configuration is shown in Figure 19.44. It should be noted that in this case, the switches in the H-type bridge have to be operated in the rhythm of the high frequency in contrast to the configuration according to the topology shown in Figure 19.43. Since transistors switched with higher frequencies have higher losses as well as higher investment costs, the benefit of saving the passive rectifier used in the concept given in Figure 19.43 might be compensated by these facts to a certain extent.

19.2.5 Power Quality of Inverters

When dealing with power quality, a distinction has to be made between stand-alone and grid-connected applications.

In a stand-alone operation, the output waveform becomes important for many applications. Square-wave inverters, according to the working principle shown in Figure 19.21 or Figure 19.22, may be used to power resistive-type loads such as light bulbs or similar objects. When feeding power to reactive-type loads such as motors, proper operation

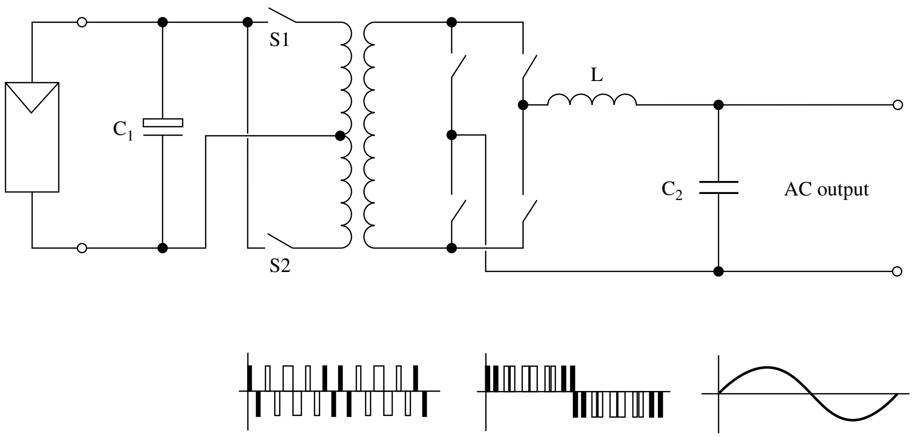

Figure 19.44 Direct AC synthesis at the secondary winding of the HF transformer. The PWM high-frequency signal is inverted in the low-frequency rhythm and smoothed by means of L and C_2. C_1 is needed to store the input energy in the rhythm, which equals twice the low frequency

might become difficult and losses inside the load created by the square-wave character of the supply might occur [9]. For these load-types, ideal sinusoidal voltage supply would be best. In reality, a compromise between this ideal voltage that results in high expenses and a lower quality for cheaper investments must be found.

The deviation from the ideal sinusoidal voltage is normally described as total harmonic distortion (THD). THD is usually defined as the ratio of the square root of the sum of the squares of the rms values of the harmonics to the rms value of the fundamental. This ratio is usually converted to percent or decibels (dB). As an example, the third harmonic and their influence on the shape of the fundamental waveform are given in Figure 19.45.

For high-quality power supply, the THD of the output voltage should be less than 5%, which corresponds with the quality of the public grid.

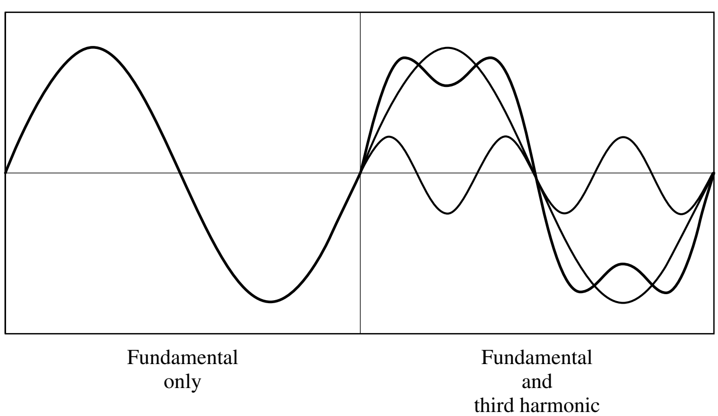

Figure 19.45 Influence of harmonics on the waveform

As a second and very important power-quality element for stand-alone applications, the ability to provide and to absorb reactive power should be mentioned. Typical loads requesting reactive power are electric motors. Under these load conditions, the load current is no longer in phase with the voltage as shown in Figure 19.46.

Proper handling of reactive power is only possible with appropriate topologies as have been described and presented in Figures 19.36 and 19.37. In some inverter designs, handling of reactive power is limited depending on the load type. In this case, the acceptable power factor, which corresponds with the cosine of the phase-angle difference between voltage and current, is defined and the maximum power of the inverter is given in kilovolt amperes (kVA) instead of kilowatts (kW). The energy of the reactive power, which is to be absorbed and afterwards re-injected into the load, is normally stored in capacitors of appropriate size.

If all the elements in the inverter allow for reverse power flow, a bi-directional inverter is obtained, which can be used to charge the battery, when surplus power at the AC side is available. The combination of a Cuk converter shown in Figure 19.38 with a H-type bridge given in Figure 19.22 allows for such a concept.

Finally, stand-alone inverters should also be able to blow fuses in cases in which a short current occurs in loads. This requirement is perfectly fulfilled with only a few inverters. The reason can be seen in the high current needed to blow fuses. Depending on the reaction time, this current can be as high as five times the nominal one as shown in Figure 19.47.

Some inverters produce this high current by reducing the AC output voltage significantly. The resulting flicker observed for loads not to be separated by the fuse in question may be accepted in most cases.

Since the output voltage of grid-connected inverters has to correspond with the grid's voltage, the quality of the current that is to be injected into the grid becomes important. Under ideal circumstances, this current should be in phase with the grid's voltage (power factor = 1). The deviation from this power factor becomes therefore important for the description of the power quality. All modern transistor-based inverters have a power factor near unity at nominal load, with a tendency towards smaller values under part load (Figure 19.48).

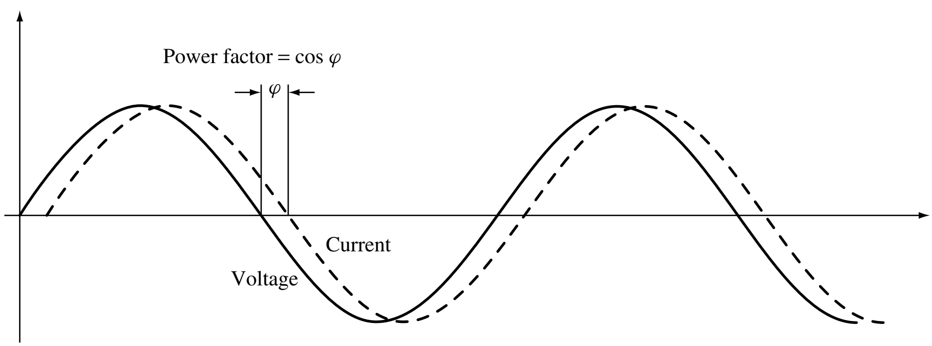

Figure 19.46 Power factors $\neq 1$ produced by reactive (inductive or capacitive) loads

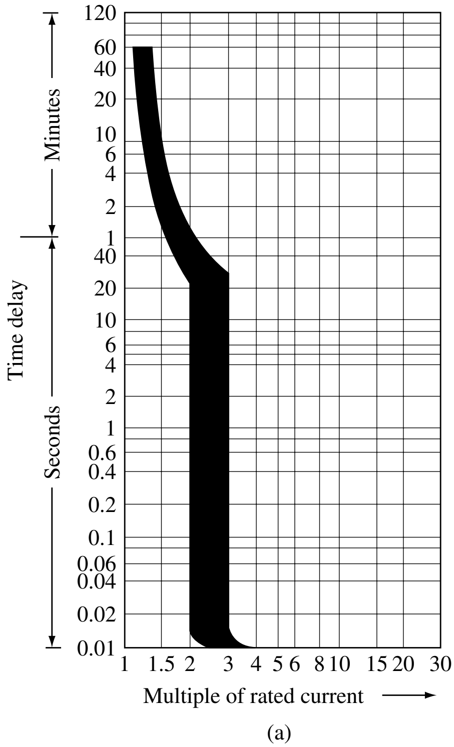

Figure 19.47 Current–time diagram for different fuse types: (a) characteristic left and (b) characteristic right (DIN EN 60898, DIN EN 62019)

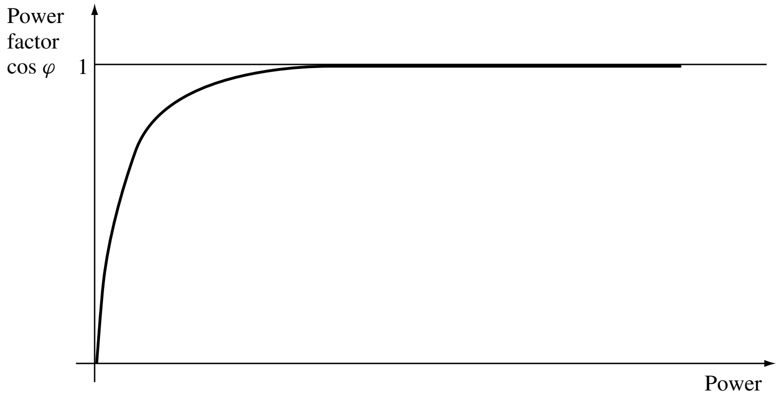

Figure 19.48 Power factor as a function of the output power of a typical grid-connected inverter

For grid-connected inverters' the THD of the current injected into the grid is used to describe the inverters' quality. The THD of the injected current, which is defined in the same way as was done for the voltage. A high-quality grid-connected inverter shows a THD in the current that is below 5%.

19.2.6 Active Quality Control in the Grid

Since the power factor in modern grid-connected inverters can be adjusted by internal control, this kind of inverters can be used to compensate reactive power flow in the grid, which otherwise must be performed by extra compensation units such as inductors or capacitors. This ability can either be fixed to a constant value or, in case of an appropriate communication system, be controlled by the grid operator according to the actual needs.

As a further means of power quality improvement, high-quality inverters are able to compensate deviations in the sinusoidal voltage of the grid. As shown in Figure 19.49, the inverter injects surplus power into the grid to compensate for the actual deficit in the voltage.

In a later stage of PV use, inverters will have to prevent grid overloading. Grid-connected inverters can easily handle this kind of power control by changing the DC input voltage from the MPP in such a way that the PV generator reduces power production to the desired level. This request may come in a situation in which several hundreds of megawatts of PV power are fed into a local system. To allow for such ability, the grid operator must be able to communicate with these inverters.

As a consequence, it can be stated that high-quality inverters will be able to improve the power quality in the grid by adjusting the power factor, by reducing the THD and by stabilising power flow through power control. To realise these functions, appropriate control and the availability of a communication element becomes necessary. A few inverters in the market already show these features today.

19.2.7 Safety Aspects with Grid-connected Inverters

An important issue for grid-connected systems is associated with islanding protection. Islanding may occur, if a part of the local grid is switched off, for example, for maintenance reasons and if the injected power is equal to the actual load in the separated part of the grid. This situation is shown in Figure 19.50.

The situation described above becomes very unlikely since not only the effective power but the reactive power as well must be equal between production and consumption.

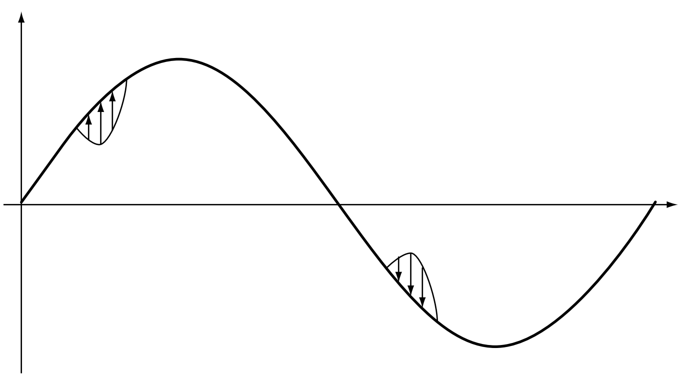

Figure 19.49 Inverter injects surplus power

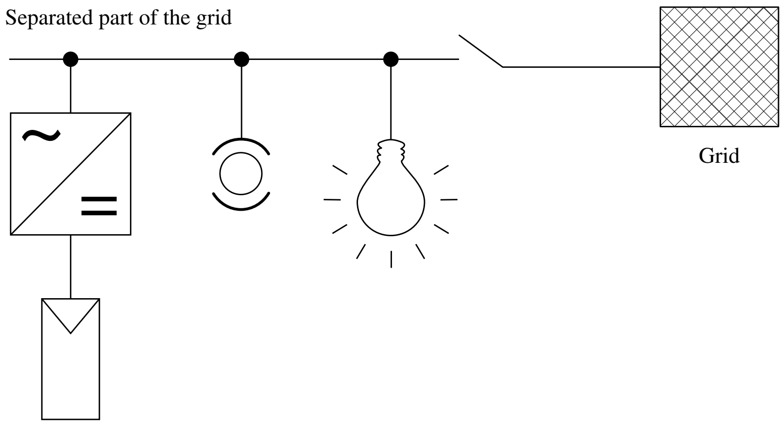

Figure 19.50 After switch-off, the separated part of the grid may continue operation, if the injected power by the PV system equals the actual load

As a first measure, frequency and voltage monitoring will identify by far most situations in grids turned off since the smallest deviations in production or in consumption will lead to changes in frequency or voltage or in both of them. The experience with big wind farms has shown that limitation of voltage or frequency may lead to undesired results, however.

In case of heavy loads on the grid, both the voltage and the frequency may fall below the set point. In this situation, cut-off of power sources takes place when they would be needed urgently to support the grid. As a further method to identify islanding conditions, monitoring of the grid's impedance is being performed by injecting power peaks, which do not correspond with the fundamental frequency (50 or 60 Hz), by the inverter into the grid and by monitoring this influence on the grids voltage shape. This method is currently accepted by German safety code.

This code, which applies to grid-connected single-phase PV systems smaller than 5 kW, requests a separation from the grid, if the impedance of the grid exceeds 1.75 ohms or if a jump in the impedance $\geq$0.5 ohms occurs. Reconnection to the grid is allowed for grid impedance smaller than 1.25 ohms. There are two independent monitoring and switching systems that have been requested. One of the two systems must act on a mechanical switch, for example, a relay, while for the second system, the semiconductors of the inverter output bridge are accepted. Figure 19.51 explains this configuration.

In addition to the monitoring of the grid impedance, frequency deviations above $\pm$0.2 Hz or voltage differences bigger than -15 or $+10\%$ must lead to a separation of the grid as well. The safety protection device can either be integrated into the inverter or installed separately between the inverter and the grid. The latter may be used preferably in combination with small-scale inverters, for example, module-integrated ones. In these cases, the investment cost for integrating the unit in each of the small inverters with a power of not more than a few hundred watts may not be economic. In case of a separate installation, one supervision unit could be used to protect several small module-integrated inverters. As an alternative, also accepted as a safety device, voltage monitoring of all three phases of the grid, which lead to a separation, if one of the three phases becomes

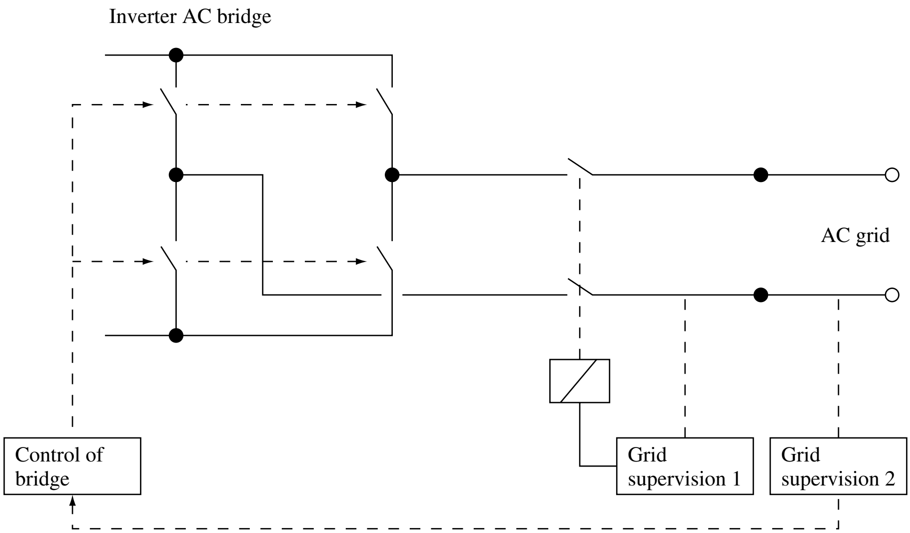

Figure 19.51 Two independent grid-supervision units for safety against islanding (DIN VDE 0126)

zero, can be used in Germany. In case of a single-phase grid, as is the case in many rural areas of the world, this method cannot be applied, however.

There is a limitation to be expected, if a big number of inverters are monitoring the grid in this way. In this case, interference between the different inverters may lead to unspecific interpretation of the grid's response. It might become necessary therefore to equip all inverters with communication capabilities. This feature would allow switching off all relevant inverters by the grid operator if needed. As a further benefit, power-quality improvements controlled by the grid operator will become feasible as well.

19.3 ACKNOWLEDGEMENT

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