Renewable Electric Energy Systems EE—546

Photovoltaic System Technology

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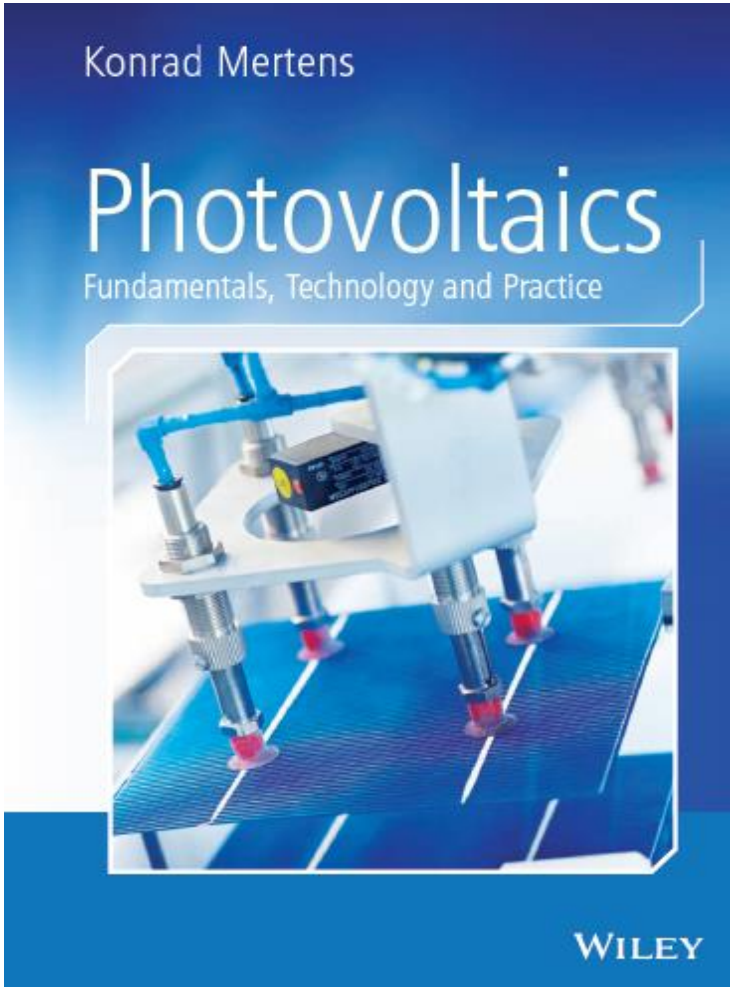
Slides are prepared from:—Chapter 7



Konrad Mertens—Photovoltaics Fundamentals Technology and Practice

Photovoltaic System Technology:

DC/DC Converters,

MPP-Tracking,

Grid-Connected Systems,

Structure of Inverters,

Efficiency of Inverters,

Requirements of Grid connection,

Stand-Alone Systems,

Batteries,

Charge Controllers.

7.1 Solar Generator and Load

7.1.1 Resistive Load

The load easiest to study is an **ohmic resistance**. In the I/V characteristic curve it is described as a linear equation:

$$I = \frac{1}{R} \cdot V \tag{7.1}$$

Figure 7.1 shows the case of a direct connection of an ohmic load to a solar module. If the solar generator is operated at 1000 W/m2, then the operating point 1 is near the MPP1 of the module. If the irradiance falls to half, then a new operating point 2 is adjusted that is, however, far away from the actual optimum MPP2. In this case the solar module can **only** contribute **a portion** of the actually available **power** to the load. It is therefore desirable to **decouple** the voltage at the solar generator from the voltage at the load. For this purpose we use an electronic **DC/DC converter**.

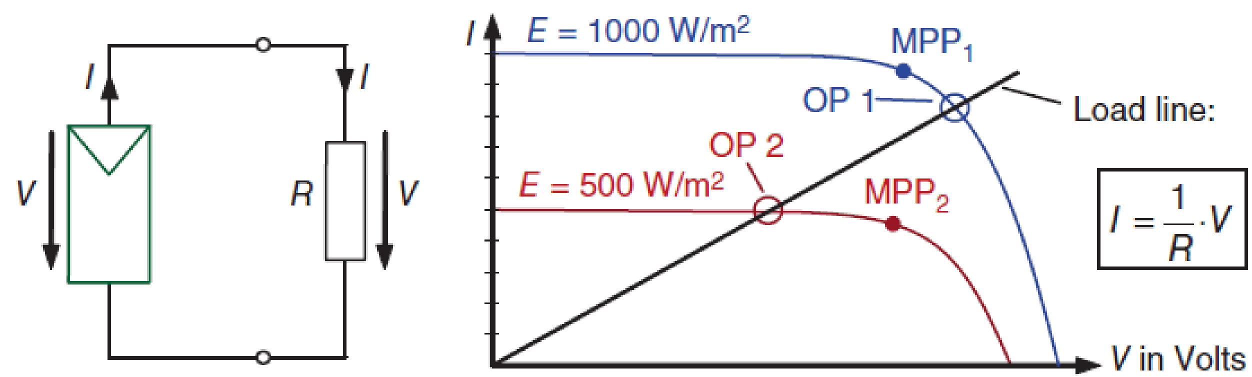


Figure 7.1 Operation of an ohmic load at a solar module: In the case of half the Sun's irradiance ($E = 500\ \mathrm{W/m^2}$), the operating point (OP 2) is far away from MPP_2

DC/DC Converters

A **DC/DC converter** converts an input voltage $V1$ into an output voltage $V2$. The result of this is that the **voltage** at the solar module can be selected almost **independently** of the voltage at the load.

In the case of an ideal converter with an efficiency of 100% the input and output power are the same:

$$P_1 = V_1 \cdot I_1 = V_2 \cdot I_2 = P_2 \qquad (7.2)$$

But power been delivered depends on the amount of Irradiance available.

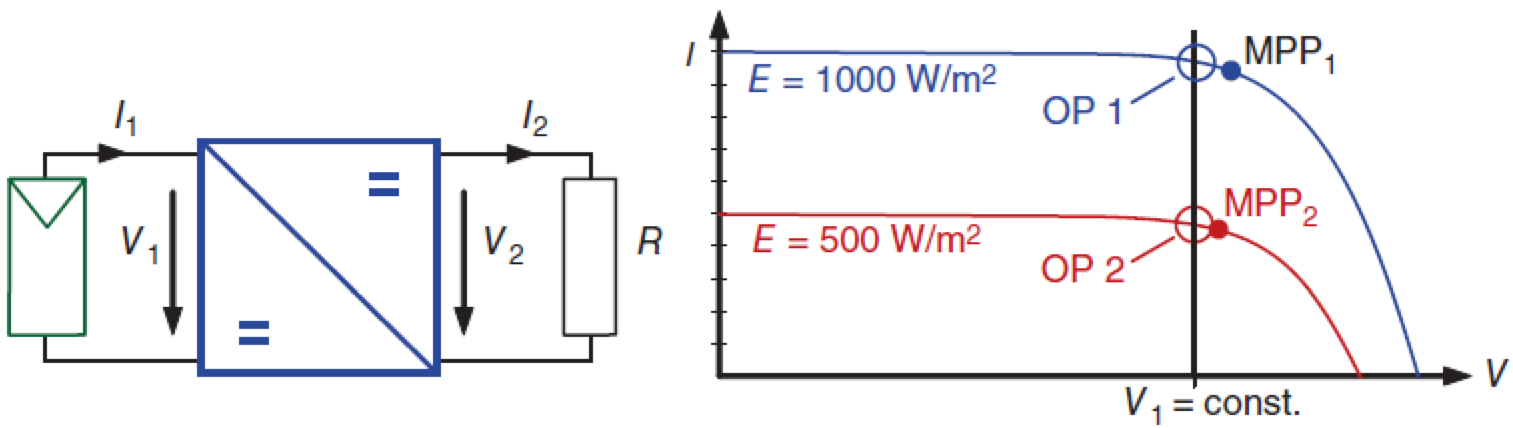


Figure 7.2 Application of a DC/DC converter: The voltage at the solar generator can be selected independently of that at the load; for example, it can be left constant

DC/DC Converters

An important purpose of using **DC/DC converters is to bring the operating point of solar** module very close to the MPP.

$$P_1 = V_1 \cdot I_1 = V_2 \cdot I_2 = P_2 \tag{7.2}$$

But power been delivered depends on the amount of Irradiance available.

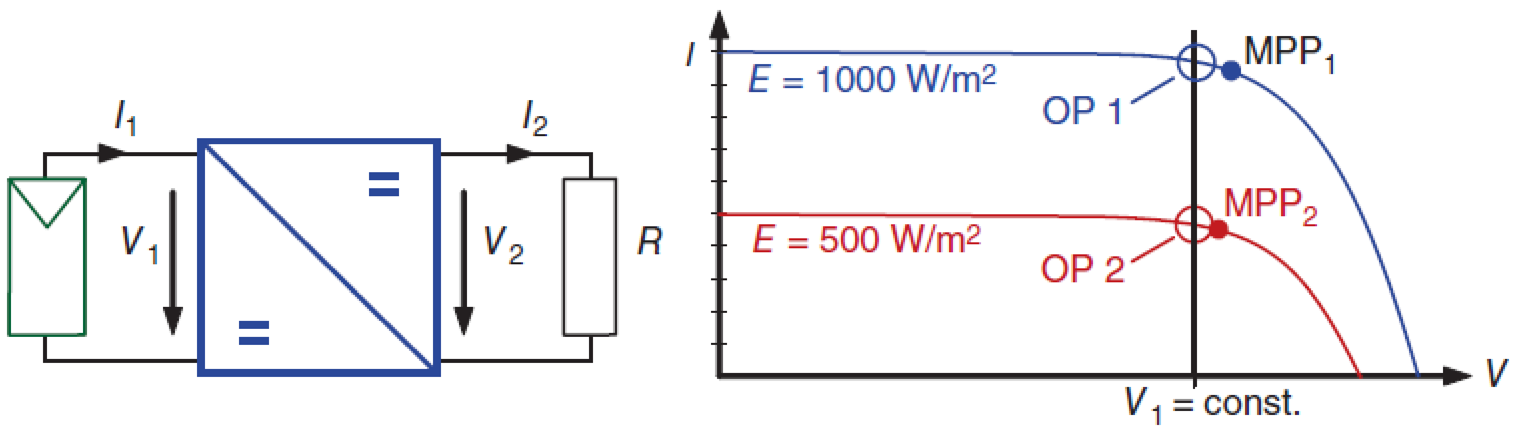


Figure 7.2 Application of a DC/DC converter: The voltage at the solar generator can be selected independently of that at the load; for example, it can be left constant

7.1.2.2 Buck Converter

Modules are often connected in series in order to obtain a high voltage. If this voltage is to be reduced then a **buck converter** (**step-down converter**) is used.

The result is a pulsed voltage $\boldsymbol{v_2(t)}$ at the output that has a mean value of:

$$\overline{v}_2 = \frac{T_{\mathrm{On}}}{T} \cdot a \cdot V_1$$

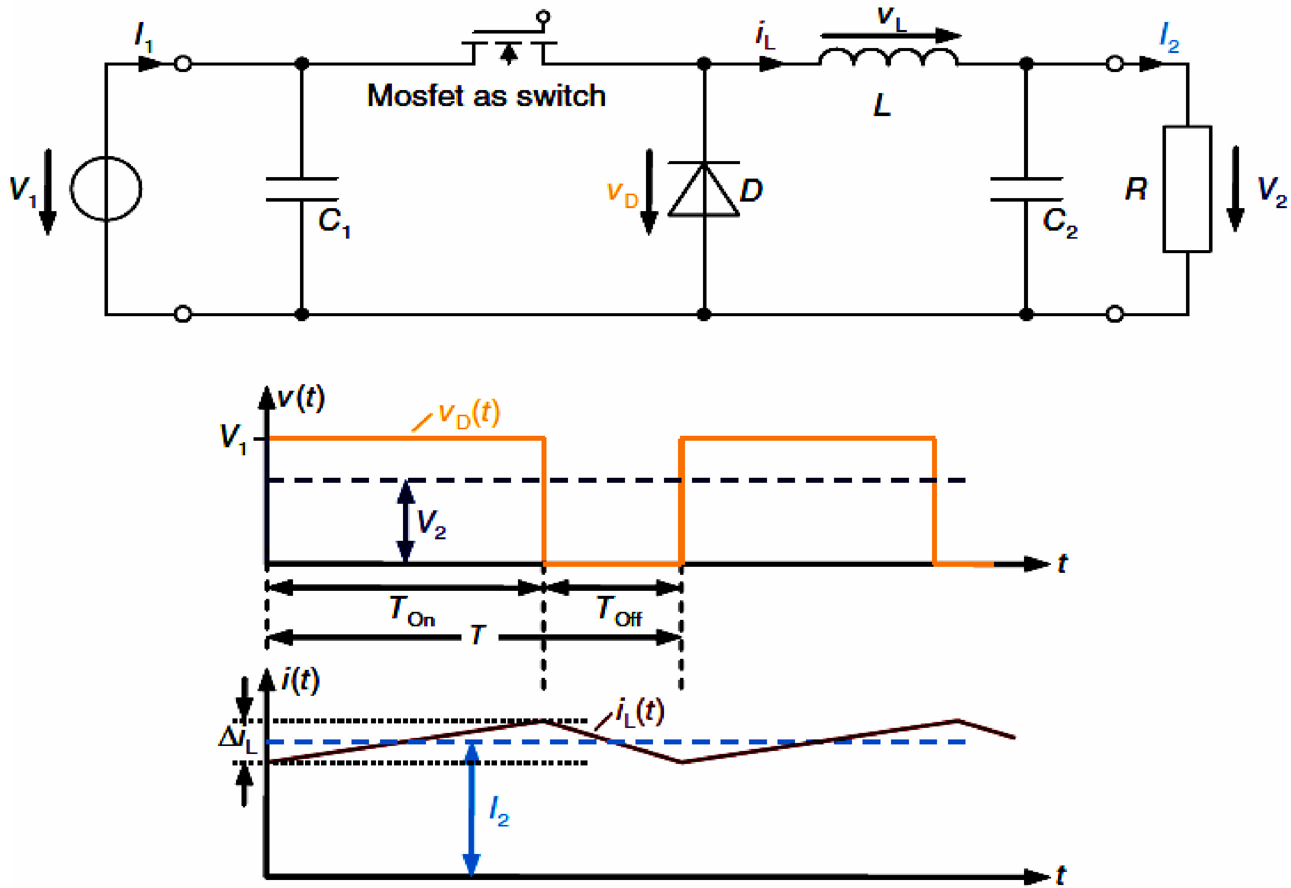
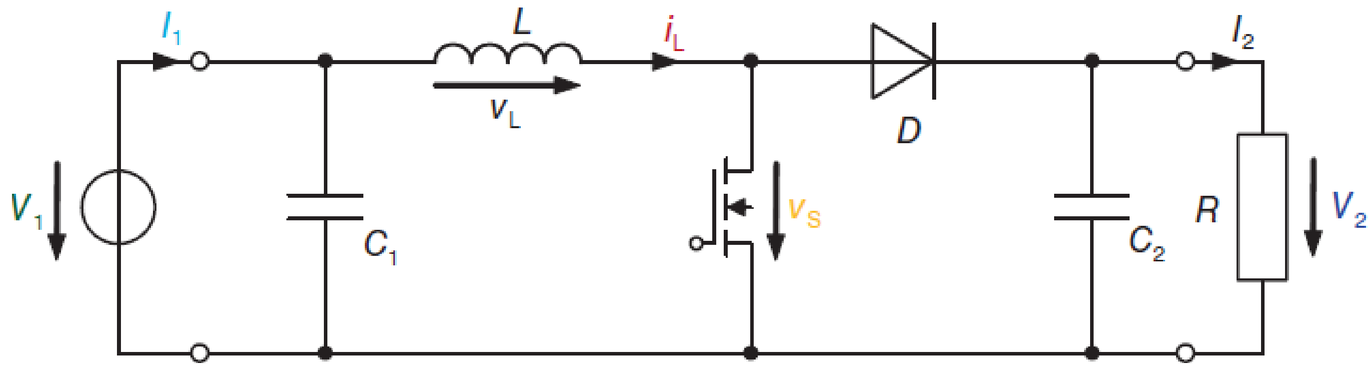


Figure 7.4 Circuit as well as current and voltage curves of the buck converter [91]

7.1.2.3 Boost Converter

It is often necessary to convert a small solar generator voltage into a higher voltage, for example, in order to feed into the public grid. In this case use is made of a **boost converter** (**step-up converter**).



$$V_2 = \frac{T}{T_{\text{Off}}} \cdot V_1 = \frac{T}{T - T_{\text{On}}} \cdot V_1$$

$$= \frac{1}{1 - T_{\text{On}}/T} \cdot V_1$$

$$= \frac{1}{1-a} \cdot V_1 \qquad (7.16)$$

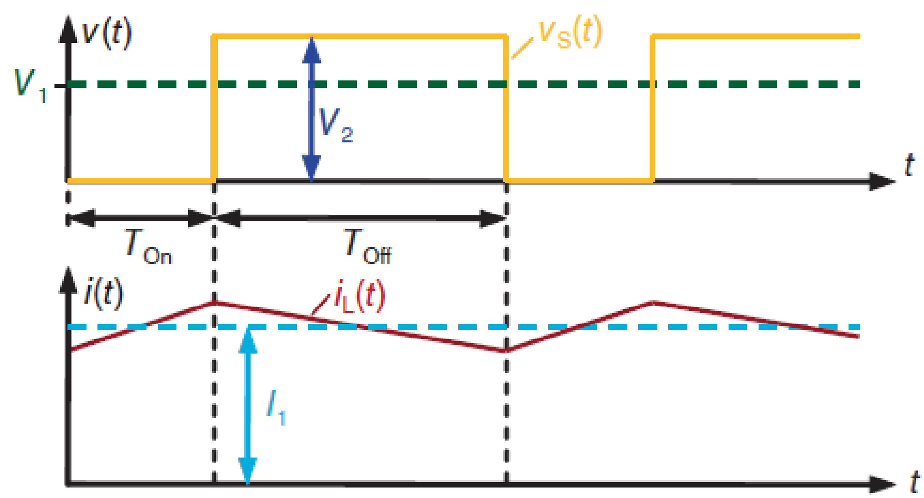


Figure 7.5 Connecting a boost converter with current and voltage progressions [91].

7.1.3 MPP-Tracker—Example 1

DC/DC converter can be used for MPP tracking (MPP control), Figure 7.6 shows the basic principle.

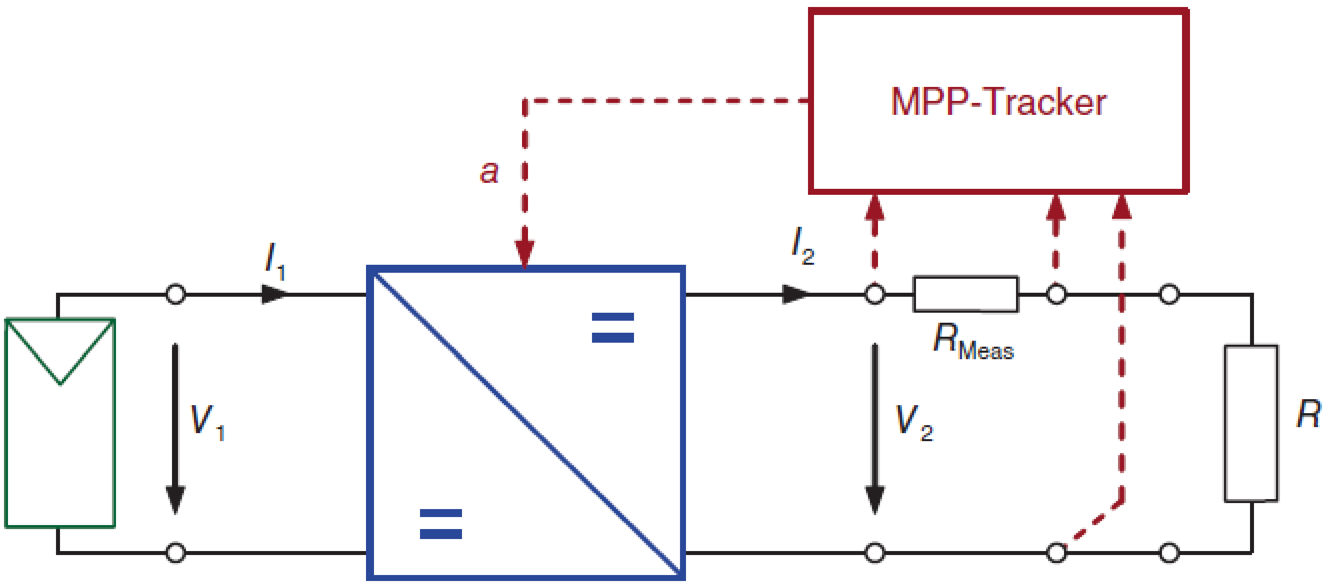
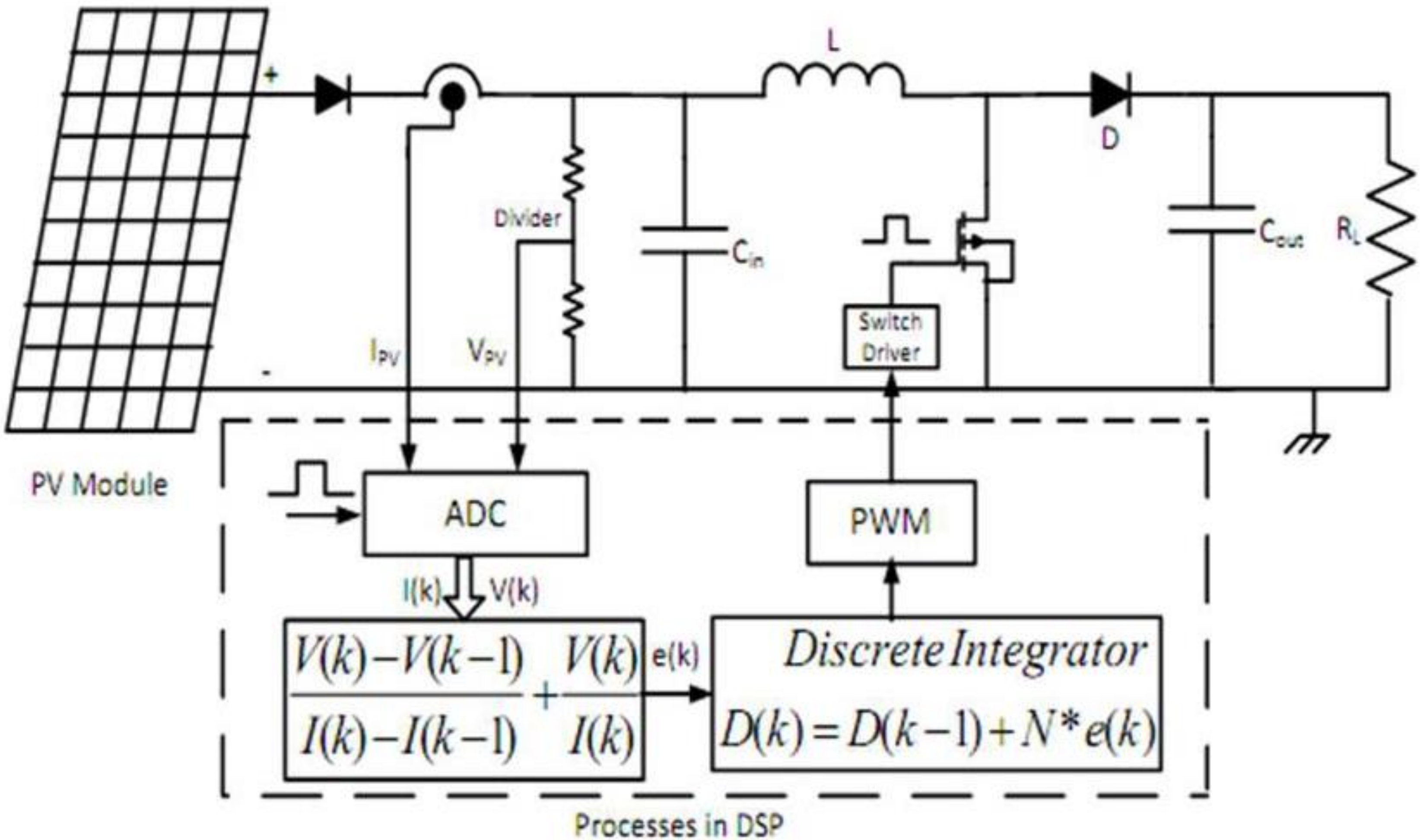


Figure 7.6 Principle of MPP tracking: The output power is maximized by measuring the current and voltage with the simultaneous variation of the duty factor

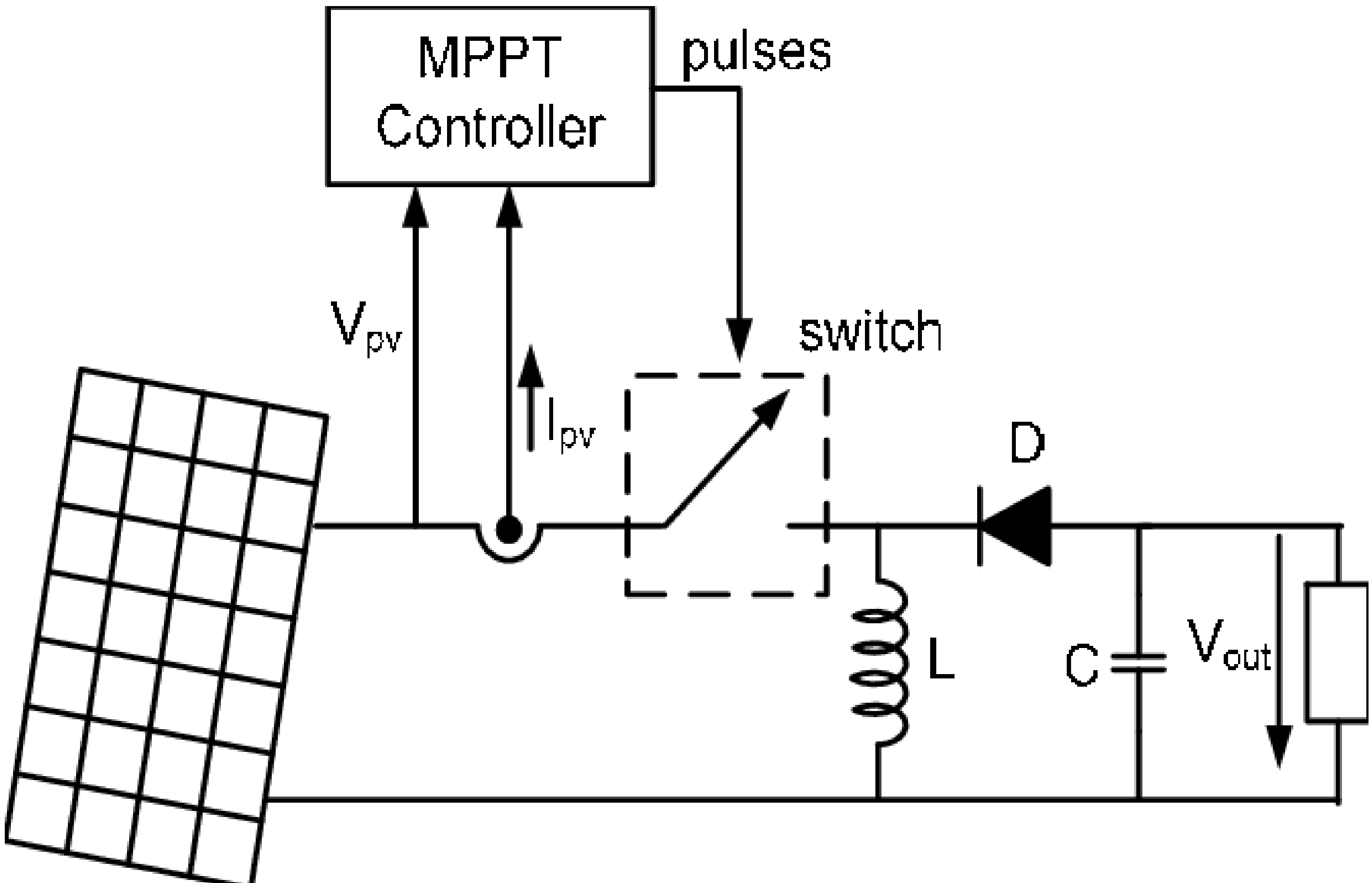
7.1.3 MPP-Tracker—Example 2

DC/DC converter can be used for MPP tracking (MPP control), Figure 7.6 shows the basic principle.



7.1.3 MPP-Tracker—Example 3

DC/DC converter can be used for MPP tracking (MPP control), Figure 7.6 shows the basic principle.



MPP-Tracker—P&O Algorithm

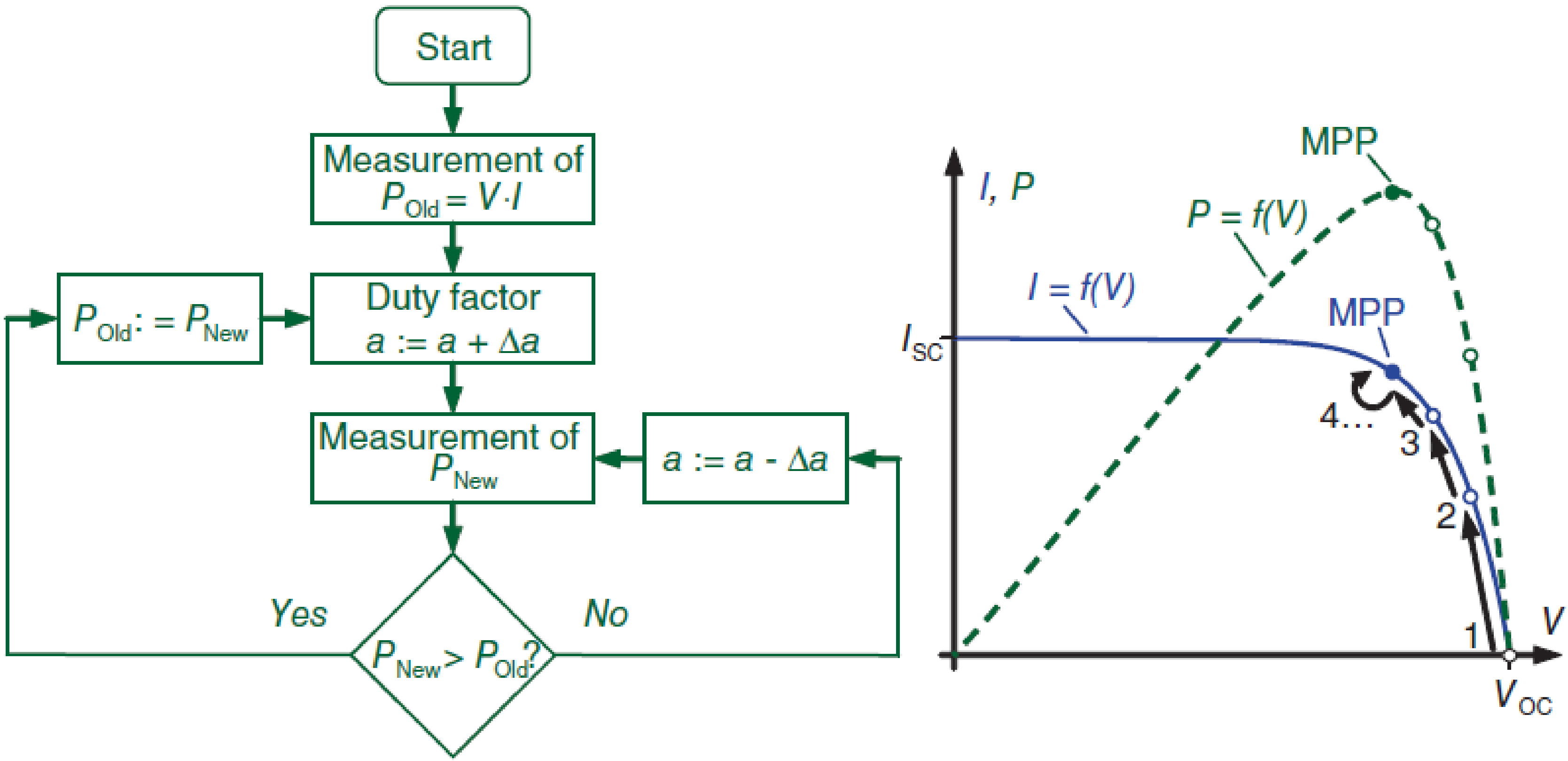
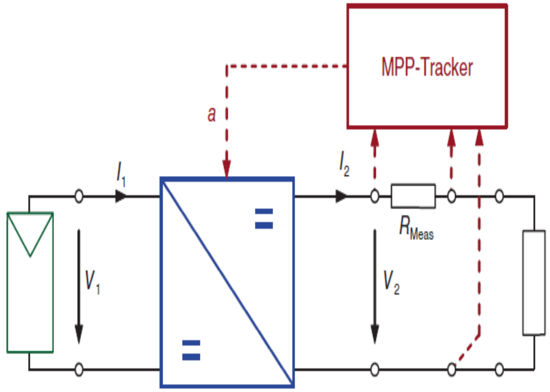


Figure 7.7 Algorithm of the *Perturb and Observe* method: Starting from the open circuit point the duty cycle is changed, the new power is determined and the duty cycle is further optimized depending on the result until finally the MPP is reached

Perturb and Observe metho



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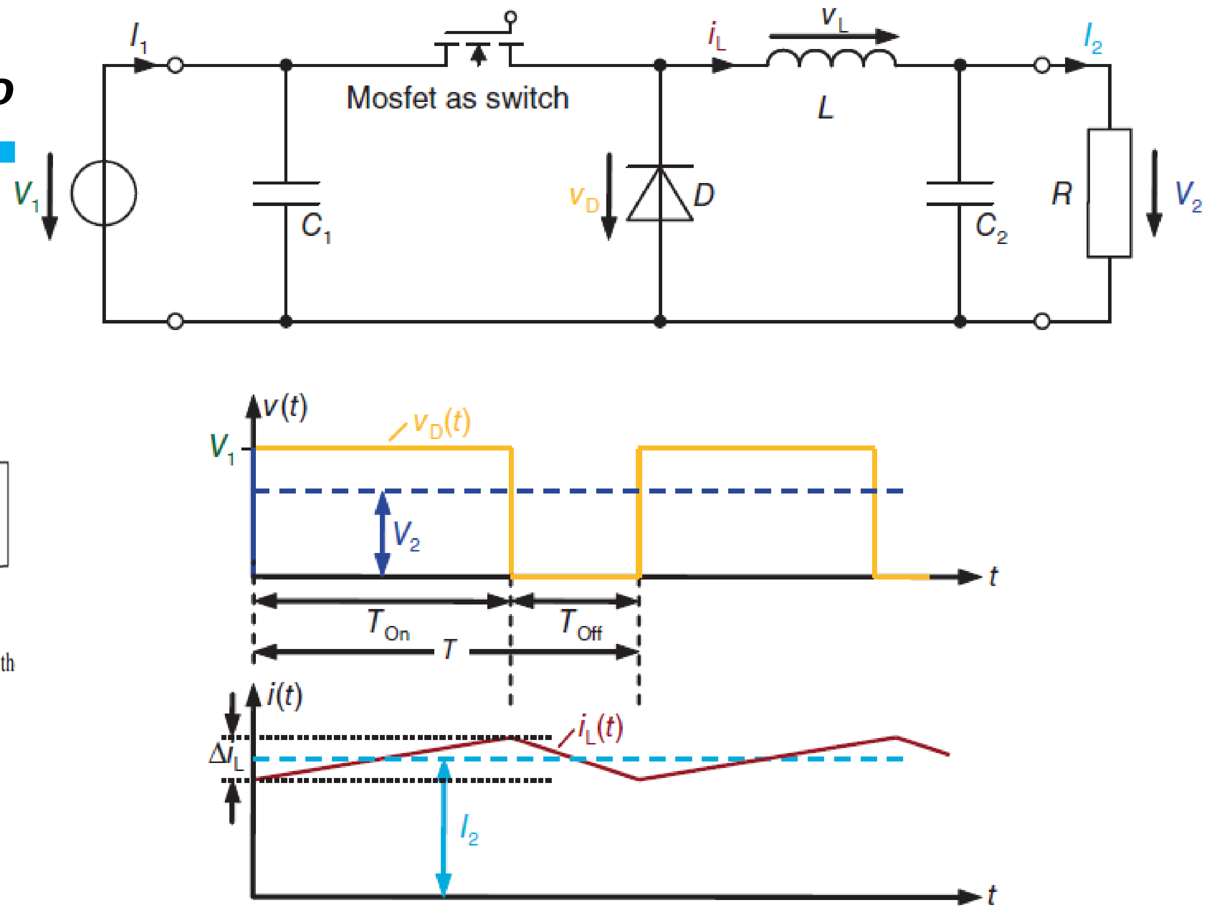


Figure 7.4 Circuit as well as current and voltage curves of the buck converter [91]

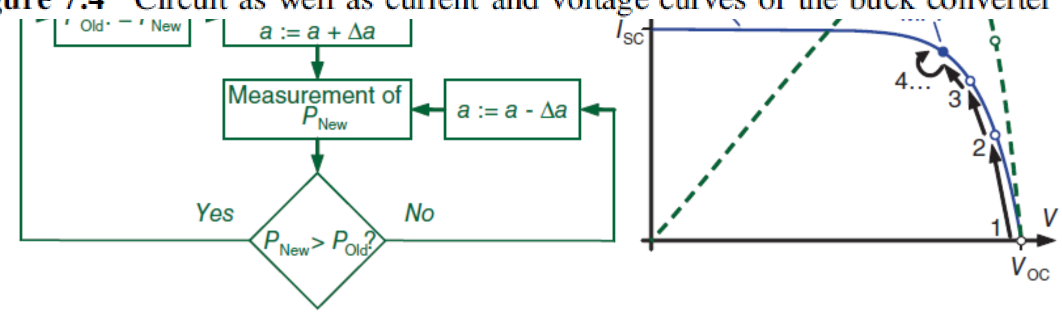


Figure 7.7 Algorithm of the *Perturb and Observe* method: Starting from the open circuit point the duty cycle is changed, the new power is determined and the duty cycle is further optimized depending on the result until finally the MPP is reached.

7.2 Grid-Connected Systems

7.2.1 Feed-In Variations

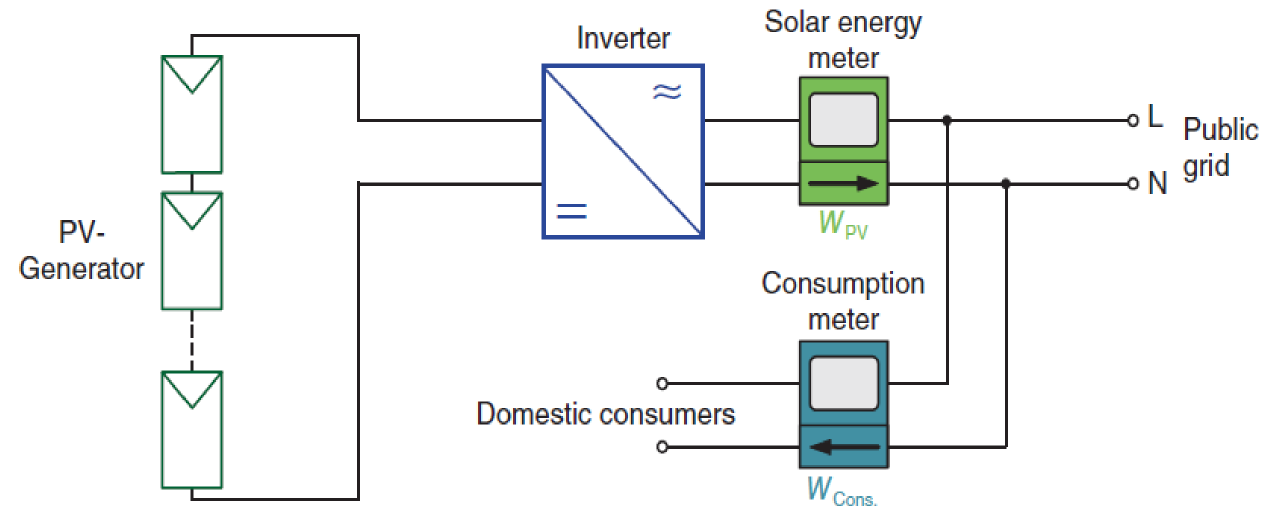


Figure 7.8 Classic connection of a photovoltaic installation to the public grid: The whole of the solar power is fed into the public grid via a feed-in meter whilst the domestic use is separately measured by means of a consumption meter

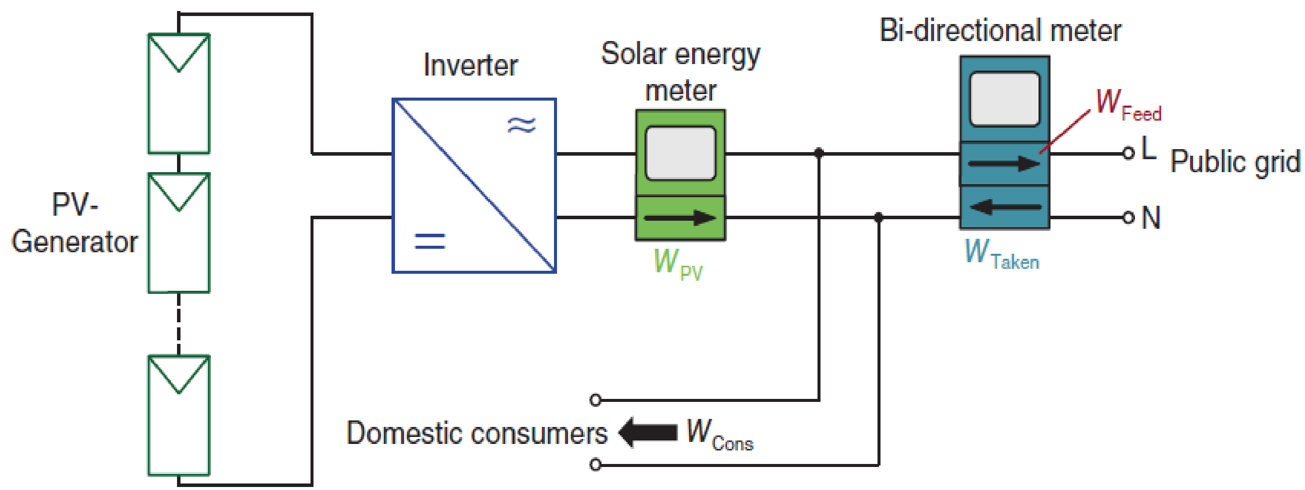
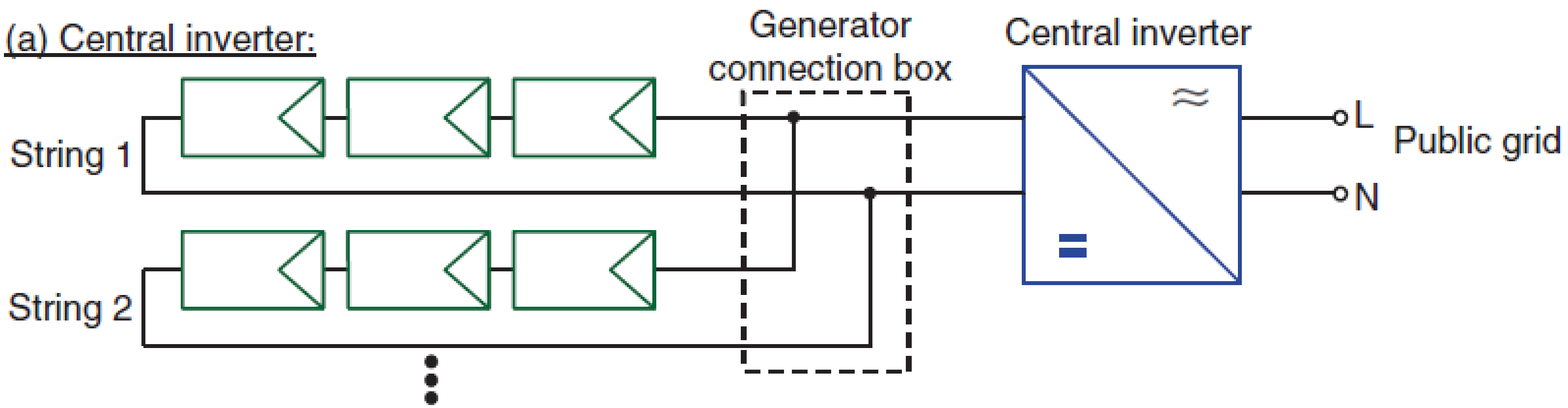


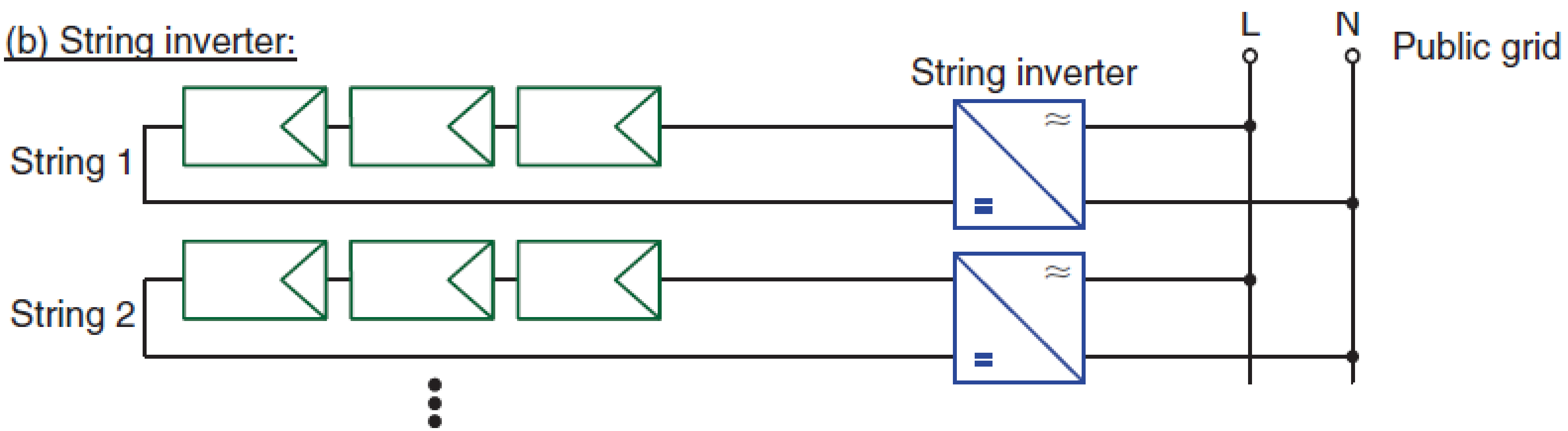
Figure 7.9 Use of bi-directional meter for separated acquisition of the fed-in and the energy taken from the grid. The solar energy meter is installed additionally if the overall generated solar energy is also to be measured

7.2.2 Installation Concepts

(a) Central inverter:



(b) String inverter:



7.2.2 Installation Concepts

(c) Module-integrated inverter:

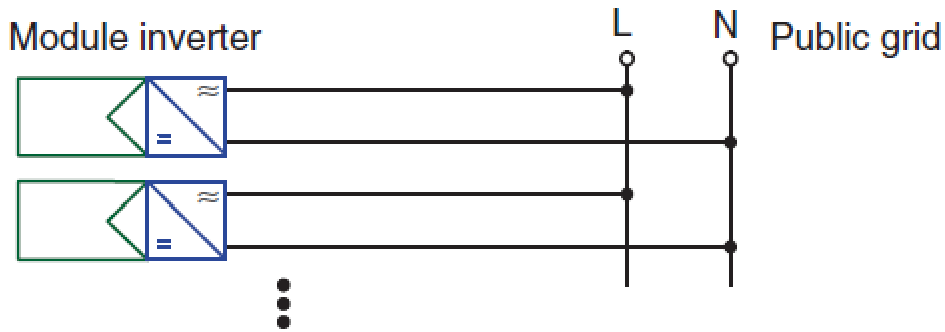


Figure 7.10 Variations of the arrangement of photovoltaic systems connected to the grid

7.2.3 Structure of Inverters

7.2.3.1 Tasks of the Inverter

We will now list the most important tasks of the inverter of a PV plant connected to the grid.

- Converting direct current into a sinusoidal-form alternating current
- Achieving a high degree of efficiency (>95%)
- Feeding the current synchronously with the grid frequency
- MPP tracking
- Monitoring the grid for voltage, frequency and grid impedance in order to prevent an inadvertent stand-alone operation
- Measures for personnel protection:
- Preparation of actual condition data of the plant (power, current, voltage, error codes) via an external data interface.

7.2.3.2 Line-Commutated and Self-Commutated Inverter

The **classic inverter** makes use of **thyristors** as switching elements. These have the disadvantage that they **cannot be turned off** by means of the control electrodes. In order to block them one must wait for the next zero pass of the mains voltage.

For this reason, this type of inverter is called a **line-commutated inverter**. The thyristors can only be switched on and off once per period, leading to a rectangular form of current flow. In order to fulfill the requirements of **electromagnetic compatibility** (EMC), the current must be smoothed by means of additional filters.

We obtain far fewer harmonics with **self-commutated inverters**. This switching principle is now standard for devices up to 100 kW as a series of suitable **components** that **can be switched off** are available: **GTOs** (Gate Turn Off thyristor), **IGBT**s (Insulated Gate Bipolar Transistor) and **power MOSFETs**. These permit quick on and off switching (e.g., 20 kHz) and thus a piece-by-piece copy of a sinusoidal current flow (see Figure 7.12). Therefore, we will consider only the self-commutated inverters.

7.2.3.3 Inverters without Transformers

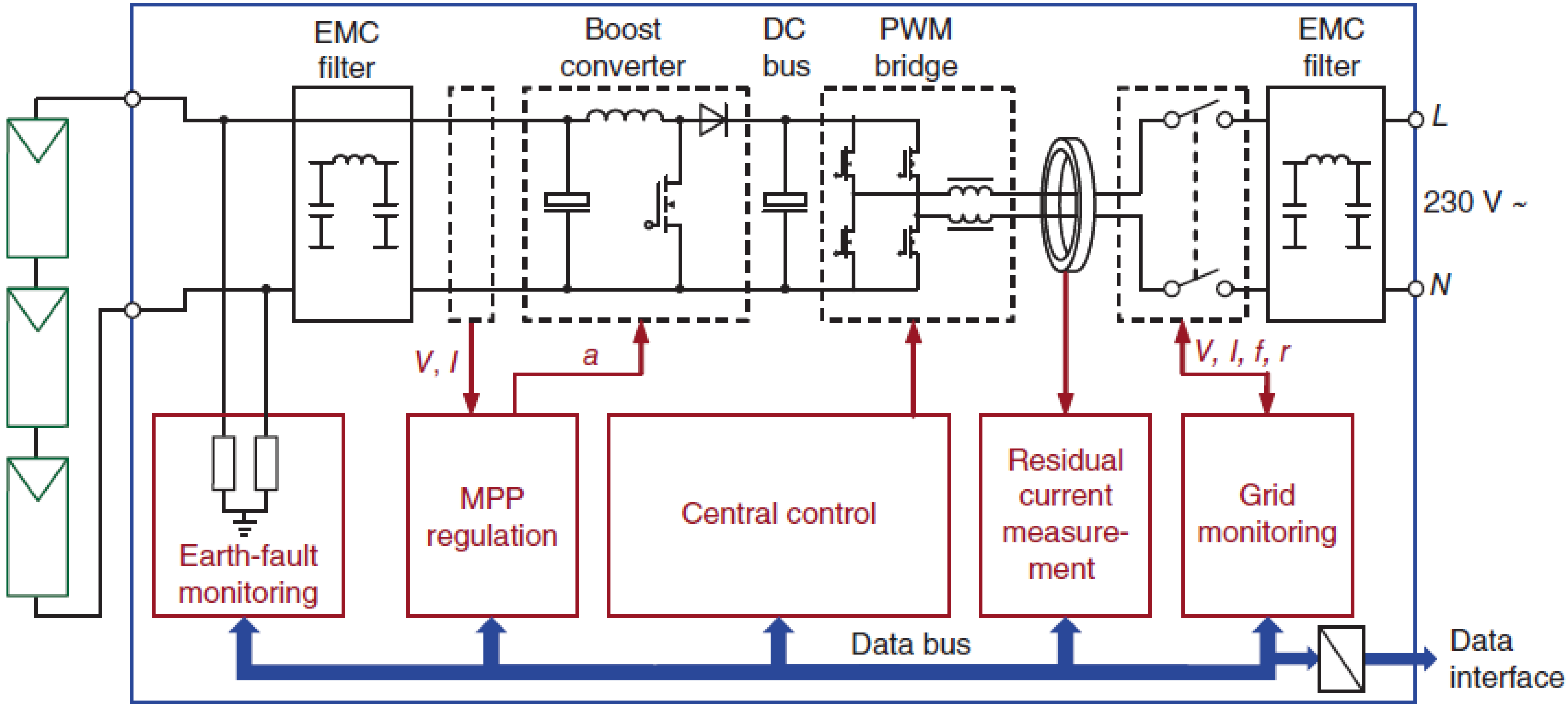


Figure 7.11 Overall arrangement of an inverter without transformer: Besides the actual grid feed-in it must fulfill a number of other functions such as MPP tracking, residual current measurement and grid monitoring

7.2.3.4 Inverters with Mains Transformer

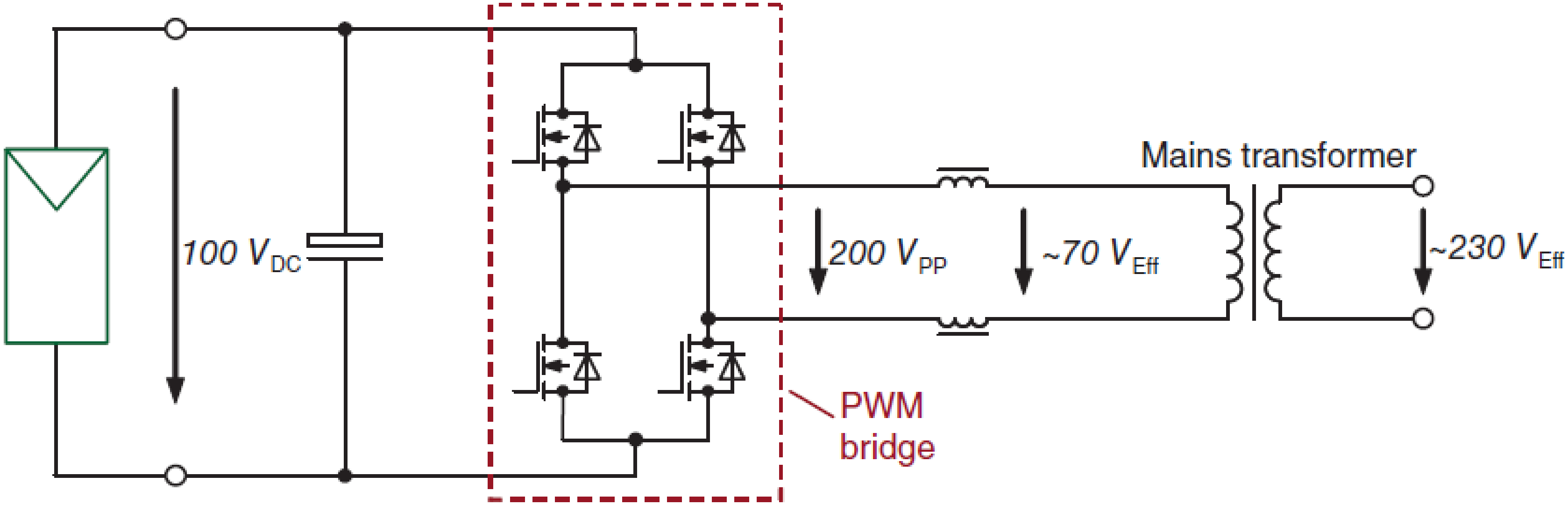


Figure 7.13 Principle of the inverter with mains transformer: The voltage signal received from the PWM bridge is converted to the desired mains voltage by the transformer

7.3 Stand-Alone Systems

Photovoltaic stand-alone systems are typically used when there is no electric grid or the costs for connecting to a grid are too high.

7.3.1 Principle of the Structure

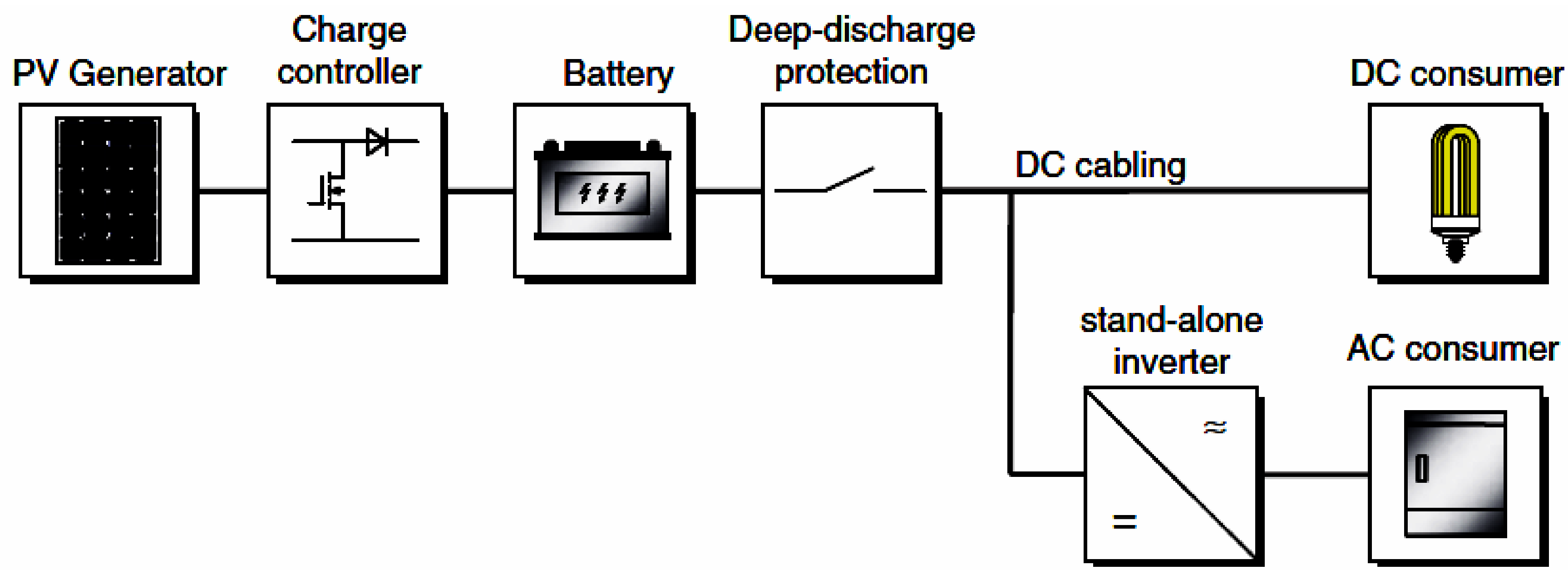


Figure 7.25 Principle of the arrangement of a photovoltaic stand-alone system: The battery fed by the module over a charge controller makes the power available for the DC consumer. An additional stand-alone inverter is provided in the case of AC consumers (e.g., refrigerator)

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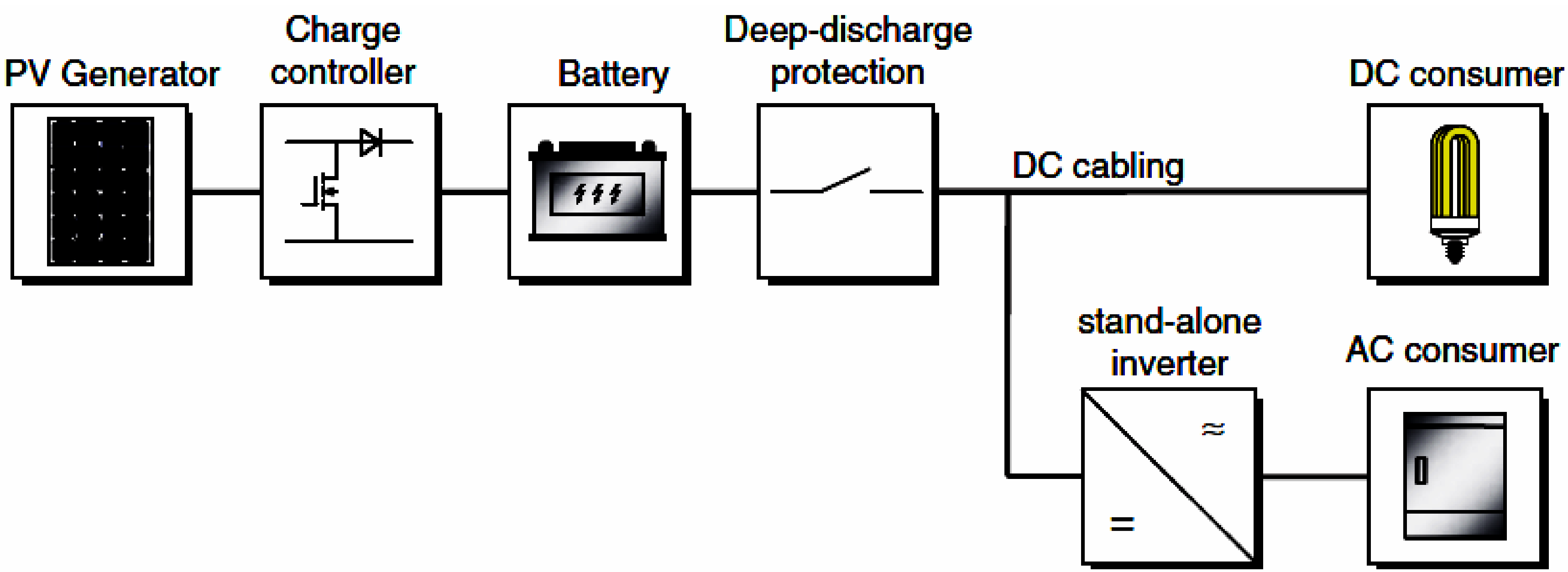

Figure 7.25 Principle of the arrangement of a photovoltaic stand-alone system: The battery fed by the module over a charge controller makes the power available for the DC consumer. An additional stand-alone inverter is provided in the case of AC consumers (e.g., refrigerator)

7.3 Stand-Alone Systems

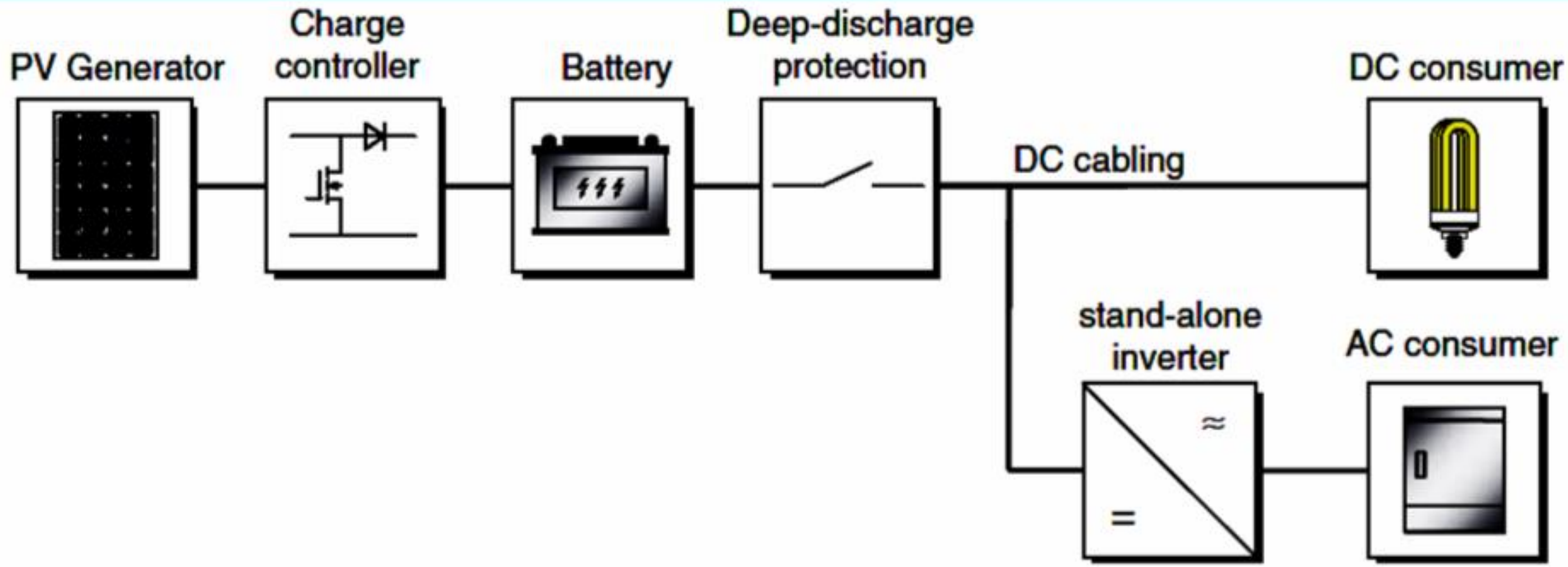

Figure 7.25 Principle of the arrangement of a photovoltaic stand-alone system: The battery fed by the module over a charge controller makes the power available for the DC consumer. An additional stand-alone inverter is provided in the case of AC consumers (e.g., refrigerator)

A **lead battery is used to store charge**. Battery is protected from overloading by a **charge controller**. Damage to the battery is prevented by means of a special **deep-discharge protection** in which the load is uncoupled in case the voltage falls below a critical level. **DC loads**, for instance, are energy saving **lamps, or water pumps**. For AC loads, an additional **stand-alone inverter** must be provided.

7.3.2 Batteries

Various types of batteries are can be used for storing electrical energy. Lead batteries, nickel metal hydrite batteries, lithium-ion batteries, lithium-polymer batteries, and so on.

7.3.2.1 Principle of the Lead-Acid Battery

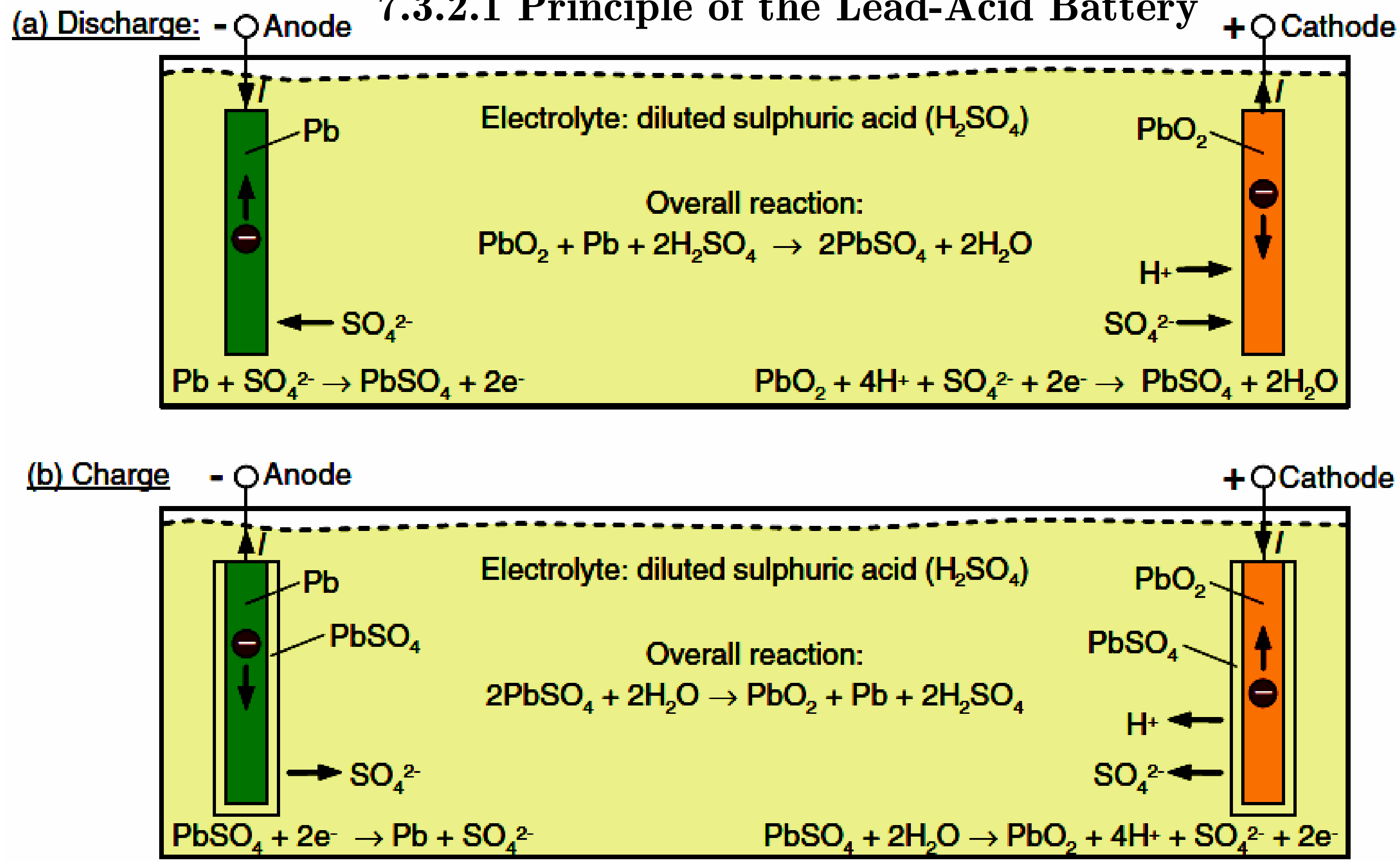

Figure 7.26 Principle structure of a lead-acid battery: When discharging, a layer of lead sulfate ($PbSO_4$) forms at both electrodes, that is decomposed again during charging

What is Depth of Discharge and how does it affect a battery?

When a battery is discharged, the amount of energy taken out will determine the depth at which it was discharged. For example if you have a 100 amp hour battery and use 50 amp hours you have discharged the battery 50% which means the depth of discharge is 50%. If you took the same battery and discharged it only 20 amp hours or 20% of the battery, your depth of discharge will be 20%. This is an important number to keep in mind, because depending on which type of battery you are using, the number of cycles will be vary based on your depth of discharge.

Most lead acid batteries experience significantly reduced cycle life if they are discharged more than 50%, which can result in less than 300 total cycles.

7.3.2.4 Voltage Progression

The nominal voltage of an individual battery cell is 2.0 V. Series connection of six individual cells is normal so that, depending on the charge condition, there is a **battery voltage of 12.0–12.7V**. Figure 7.30 shows at the left the progression of the voltage in the **discharge** of the battery: Starting from the open circuit voltage, the voltage is reduced up to the **end-of-charge voltage of 10.8V**. If current continues to be drawn off it will reach deep-discharge that can damage the battery.

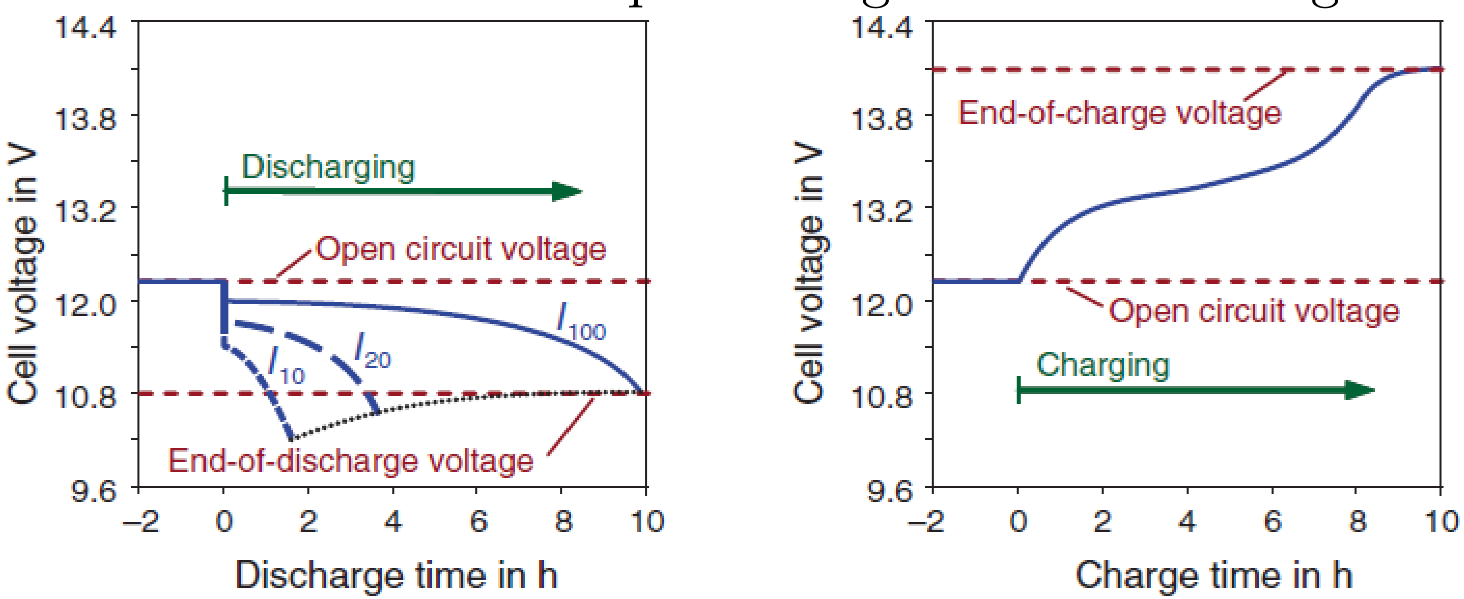

Figure 7.30 Progression of voltage of a 12 V battery when discharging and charging: The lower permissible limit is the end-of-discharge voltage whereas the upper permissible limit is the end-of-charge voltage [104]

7.3.3 Charge Controllers

Tasks of the charge controller include:

- **Overload protection**
- **Deep-discharge protection**
- **Prevention of unwanted discharging**
- **State-of-charge monitoring**
- **Adjusting to battery technology (electrolyte/gel)**
- **Voltage conversion (possibly)**
- **MPP tracking (possibly)**

7.3.3.1 Series Controller

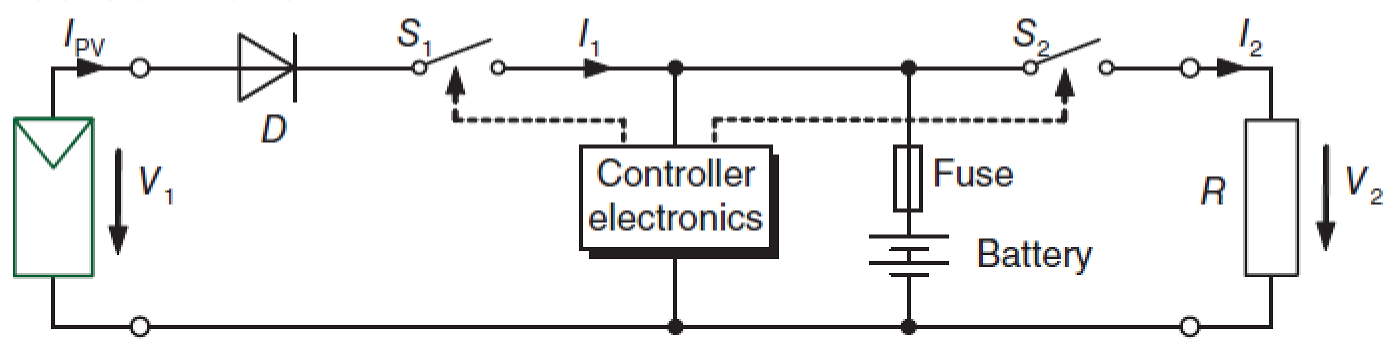

Figure 7.31 Principle of a series charge controller: Switch S_1 interrupts the charge current when reaching the end-of-charge voltage; switch S_2 serves for the deep-discharge protection of the battery

7.3.3.2 Shunt Controller

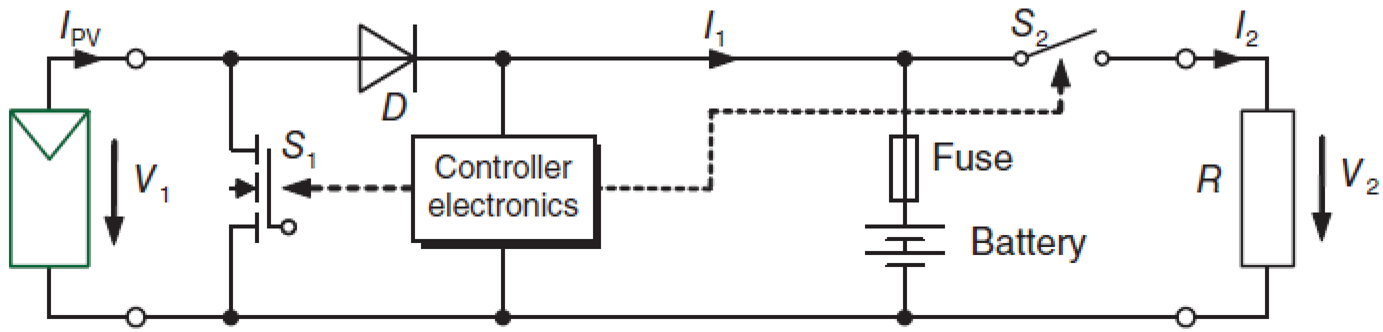

Figure 7.32 Principle of the shunt controller: If the charge current is to be interrupted then the transistor S_1 short circuits the solar generator

7.3.3.3 MPP Controller

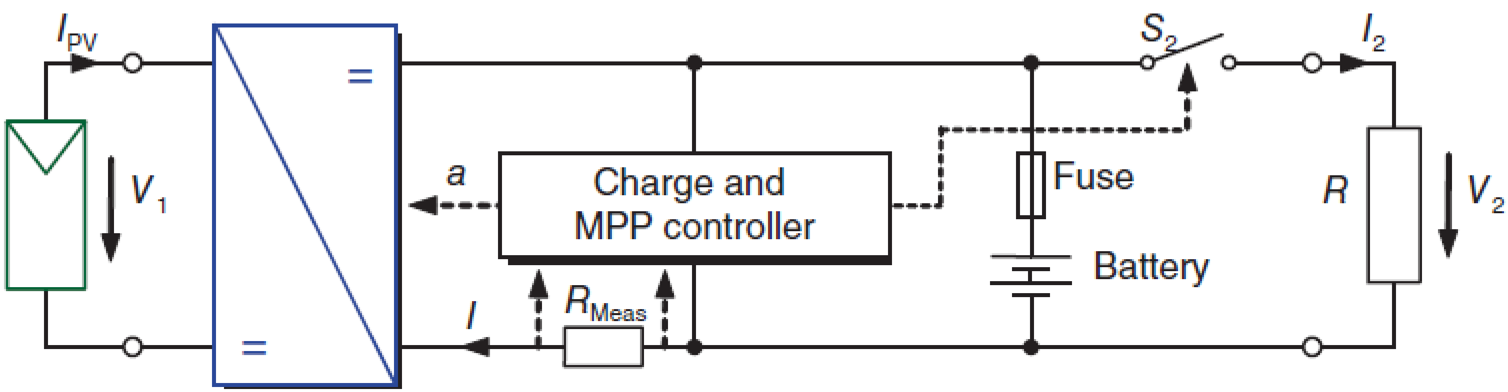

Figure 7.33 Principle of a charge controller with MPP controller: The voltage of the DC/DC converter is varied by varying the duty factor a and thus the MPP of the solar generator is reached

End of Solar Energy—Semiconductor Part 4
Course Work