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TE^4 Technologie-Entwicklung für Erneuerbare Elektrische Energie
(Development of technologies for renewable electric energy)

Feeding into the grid of electric energy from distributed sources of variable power over a DC bus

Abstract

By a Swiss ***patent application*** a new concept of power conditioning for photovoltaic systems and other generators of variable power is proposed, which is based on a DC bus standardized independent of manufacturers.

The patent application has been registered on March 31st 2009 under the No. 516/09 and the title:

"Regelungskonzept für die Netzeinspeisung elektrischer Energie
aus dezentralen, leistungsvariablen Quellen über einen Gleichspannungs-Bus"

(Control concept for the feeding into the grid of electric energy
from distributed sources with variable power over a DC bus)

In ***part 1*** of a detailed ***documentation***, the principles of the concept are described and the application for photovoltaic systems as well as the extension to turbines of variable speed discussed. It is shown which new product lines can be developed on that base.

In ***part 2*** of the documentation, the principal structure of a DC-DC converter is shown that is suitable for the feeding of electric energy from a photovoltaic string to the DC bus. Furthermore, the related specifications of the DC bus are discussed.

Part 3 of the documentation shows the principal structure of a DC-AC inverter that is suitable for the feeding of electric energy from the DC bus to the grid. The related specifications of the DC bus are discussed here, too.

Should the patent actually be granted, I shall offer cost-effective ***non-exclusive licenses*** to interested manufacturers of PV inverters. In any case I shall announce the method to the experts (for the first time at the poster session of the 8th National Photovoltaic Conference, on February 4th/5th 2010 in Winterthur, Switzerland). For establishing a standard independent of manufacturers, my services as a ***neutral expert*** are available on a fee base.

Max Blatter, dipl. El.-Ing. ETH
Version of 2009-11-23

Control concept for the feeding into the grid of electric energy from distributed sources with variable power over a DC bus

Description

The invention relates to the feeding of electric energy from distributed sources with variable power into the public power supply system. These sources can in particular be power generators that are operated from renewable resources, such as photovoltaic generators, wind turbines, water turbines, and the like. The characteristic of the invention is that the feeding into the grid occurs over a DC bus, in which a control concept according to patent claim 1 is used.

In the following, the invention is described by the example of photovoltaics. The statements can be applied in principle to the other mentioned power generators.

According to the state of the art, the energy of the photovoltaic generator is directly fed into the AC grid by one ore more DC-AC inverters. Thereby, either one single so-called central inverter is used, or the photovoltaic generator is split up in several strings with one string inverter each. The disadvantage of the central inverter is that all parts of the photovoltaic generator are run at the same operating point, which may lead to a not optimum utilization of power. The disadvantage of the string inverters is on the other hand, that each of them must contain a complete control unit for the feeding into the grid, which increases the cost of the system.

These disadvantages are avoided by a likewise well known solution. Thereby, the inverter is assembled internally by several DC-DC converters, a DC bus, and one actual DC-AC inverter. This enables the independent operating point control of several photovoltaic strings without the necessity of multiple control units for feeding into the grid. This solution, however, relates to a compact unit, of which the components are not separately accessible to the user and thus can not freely be combined, either.

The purpose of the invention is to perform, in the sense of the last mentioned solution, the operating point control of the photovoltaic string separated form the actual feeding into the grid. Thereby however, the discrete components shall be separated physically, too, and thus be accessible to an easy way of standardization in order to ensure their compatibility independent of manufacturers.

This task is solved by the method according to patent claim 1.

The advantage of the method lies in the flexibility of the system built after it, in which maximum utilization of power and minimum hardware cost are given at the same time.

Fig. 1 shows as an example the principal circuit diagram of a photovoltaic plant working according to the mentioned method. Several photovoltaic strings 1 are each connected over an individual DC-DC converter 2 to a DC bus 3. To the bus is connected a DC-AC inverter 4 with a storage capacitor 4a placed ahead, which feeds the electric energy into the grid 5.

Fig. 2 describes the control concept of the DC-DC converters that are assigned to the photovoltaic strings. Within the control range drawn as a dotted area, the operating point of maximum string power P_{St} is searched. As long as the bus DC voltage U_{DC} does not exceed the nominal value $U_{\mathrm{DC,N}}$, the power can maximally reach the nominal power of the converter, $P_{\mathrm{St,N}}$. If U_{DC} does however exceed the nominal value $U_{\mathrm{DC,N}}$, the power P_{St} will incrementally be limited, until it reaches zero at a defined higher voltage level $U_{\mathrm{DC,M}}$. If the bus DC voltage U_{DC} increases even further, the power P_{St} remains zero.

Fig. 3 shows the control behavior of the DC-AC inverter. As long as the bus DC voltage U_{DC} stays below the nominal value $U_{\mathrm{DC,N}}$, the AC power fed into the grid, P_{Grid}, remains zero. When the nominal voltage $U_{\mathrm{DC,N}}$ is reached, the power is controlled such that the voltage U_{DC} remains constantly at the value of $U_{\mathrm{DC,N}}$. When the delivered power has reached its nominal value $P_{\mathrm{Grid,N}}$ and the photovoltaic strings could together deliver more power, the bus DC voltage U_{DC} will increase above the nominal value $U_{\mathrm{DC,N}}$. The power then remains limited to the nominal value $P_{\mathrm{Grid,N}}$.

In order to make the components compatible independent of manufacturers, important static and dynamic parameter values of the method have to be standardized. Specially, at least the following parameters must be defined:

a) the value and the tolerances of the voltage levels $U_{\mathrm{DC,N}}$ and $U_{\mathrm{DC,M}}$,

b) the size of the storage capacitor in function of the nominal power for which the DC-AC inverter is dimensioned,

c) the dynamic properties (settling times and the like) of the control units of the DC-DC converters and the DC-AC inverter.

Patent claims

1. Method of controlling a system for feeding electric energy from sources of variable power into the grid, **characterized in the way** that one or more DC-DC converters and one DC-AC inverter are connected to a common DC bus, these components detect the actual value of the bus DC voltage and hereby perform their respective control functions autonomously.

2. Method according to claim 1, characterized in the way that the DC-DC converters perform a maximum power control up to a certain value of the bus DC voltage, and that above this voltage a power limitation starts.

3. Method according to claim 1, characterized in the way that the power fed into the grid by the DC-AC inverter is controlled in the range of zero to the nominal value such that the bus DC voltage remains constant.

4. Method according o one of the claims 1 to 3, characterized in the way that the decisive values of the bus DC voltage are standardized such that a compatibility independent of manufacturers is achieved.

5. Method according to one of the claims 1 to 3, characterized in the way that the control dynamic is standardized such that a compatibility independent of manufacturers is achieved.

6. DC-DC converter, characterized in the way that it contains a control unit which is suitable for the application of the method according to one of the claims 1 to 5.

7. DC-AC inverter, characterized in the way that it contains a control unit which is suitable for the application of the method according to one of the claims 1 to 5.

Abstract

The method serves for the feeding into the grid of electric energy form sources of variable power. It uses as the central element a DC bus. The components connected to it detect its voltage and perform based on that their control functions autonomously.

(Fig. 1)

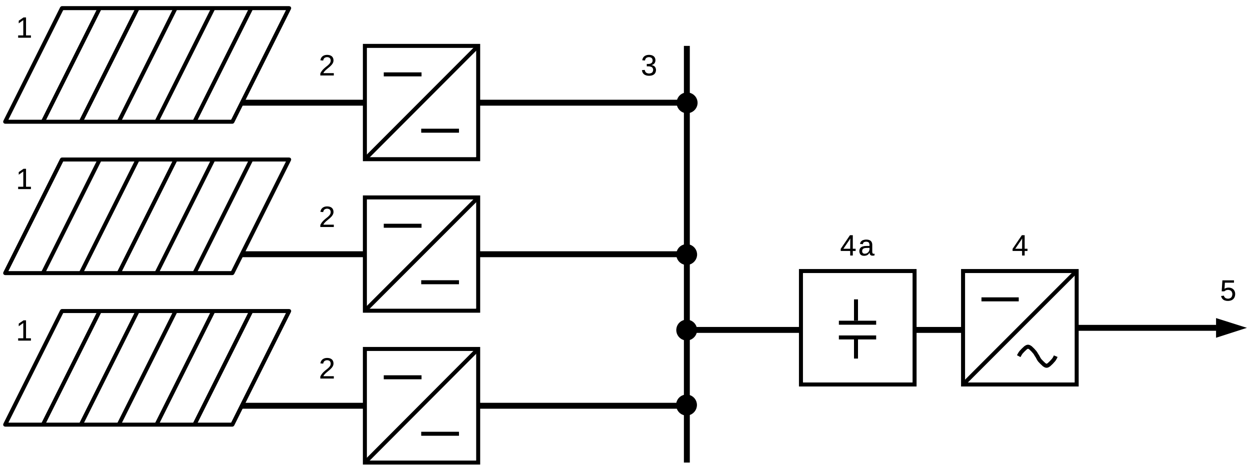

Fig. 1

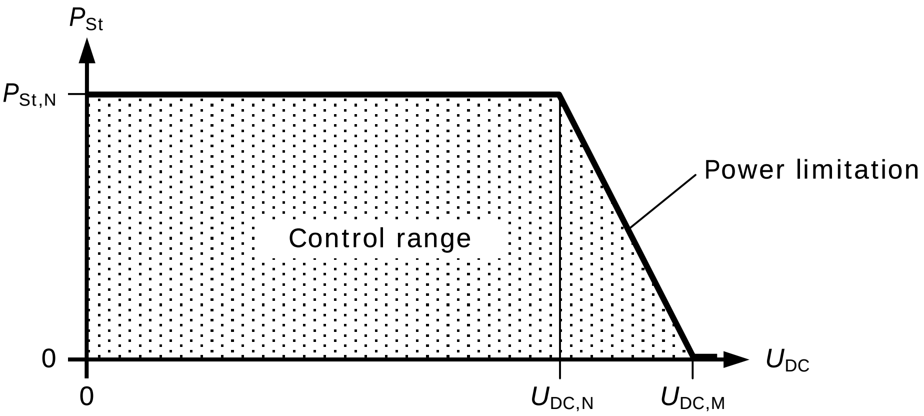

Fig. 2

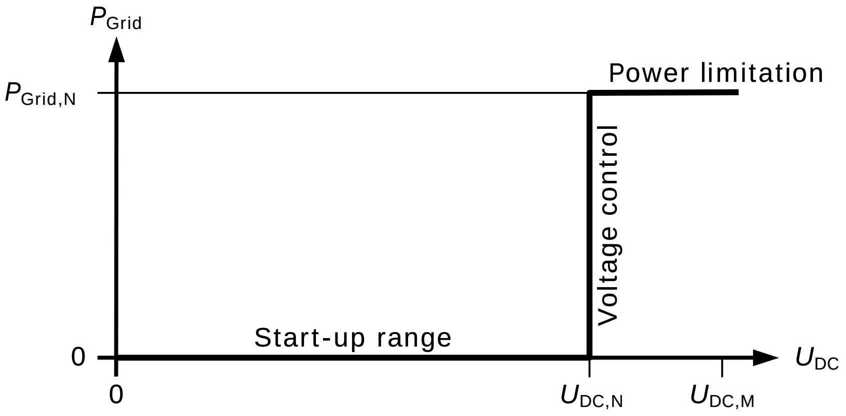

Fig. 3

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Feeding into the grid of electric energy from distributed sources of variable power over a DC bus

Part 1: General concept for photovoltaic systems and small water and wind turbines of variable speed

Max Blatter, dipl. El.-Ing. ETH
created 2009-11-23
last modified 2009-12-22

Content

Abstract

In a Swiss patent application [1], a new concept of power conditioning for photovoltaic (PV) systems and other generators of variable power has been proposed. It is based on a DC bus that shall be standardized independent of manufacturers. In the present documentation, the basic concept is explained and the application on PV systems as well as on turbines of variable speed is discussed. It is shown which new product lines can be developed on this basis.

1. Starting point

Most of the renewable energy resources are characterized by relatively small power flux densities, but extend to large areas. This suggests the use of modular systems for their exploitation: Separate energy production units, the minimum size of which is determined by economy, are assembled to complete systems according to the available space and the desired yield. The total system size is subject to almost no limits.

This is a best proven procedure especially for PV systems. Thereby, units ("strings") of some 1 kilowatt have become a usual size. The power conditioning needed (i.e. the electric adaptation of the energy delivered by the PV strings to the grid) is either done separately for each string by so called string inverters, or the strings are assembled by a parallel connection and the conversion is done in a common central inverter.

The power conditioning must perform two tasks:

- Ensure maximum power output from the PV strings (Maximum Power Point Tracking MPPT),
- Feeding an alternating current into the public grid that is synchronous to the grid voltage and meets the requirements of the electricity supplier.

For the first task an individual MPPT of each string is desirable, whereas for the second task a common central inverter is more economical. These facts suggest the separation of the two functions.

2. Separation of power point control and feeding into the grid

With bigger systems, it may indeed be advantageous to carry out MPPT in a first step by one separate DC-DC converter for each PV string. Their outputs are connected to a DC bus, from which the grid synchronous inversion is done by a central inverter.

If the nominal voltage of this DC bus is standardized, there is the possibility of integrating other power generators (such as modular hydropower systems or small wind turbines) as well. Figure 1 shows the general concept of such a system.

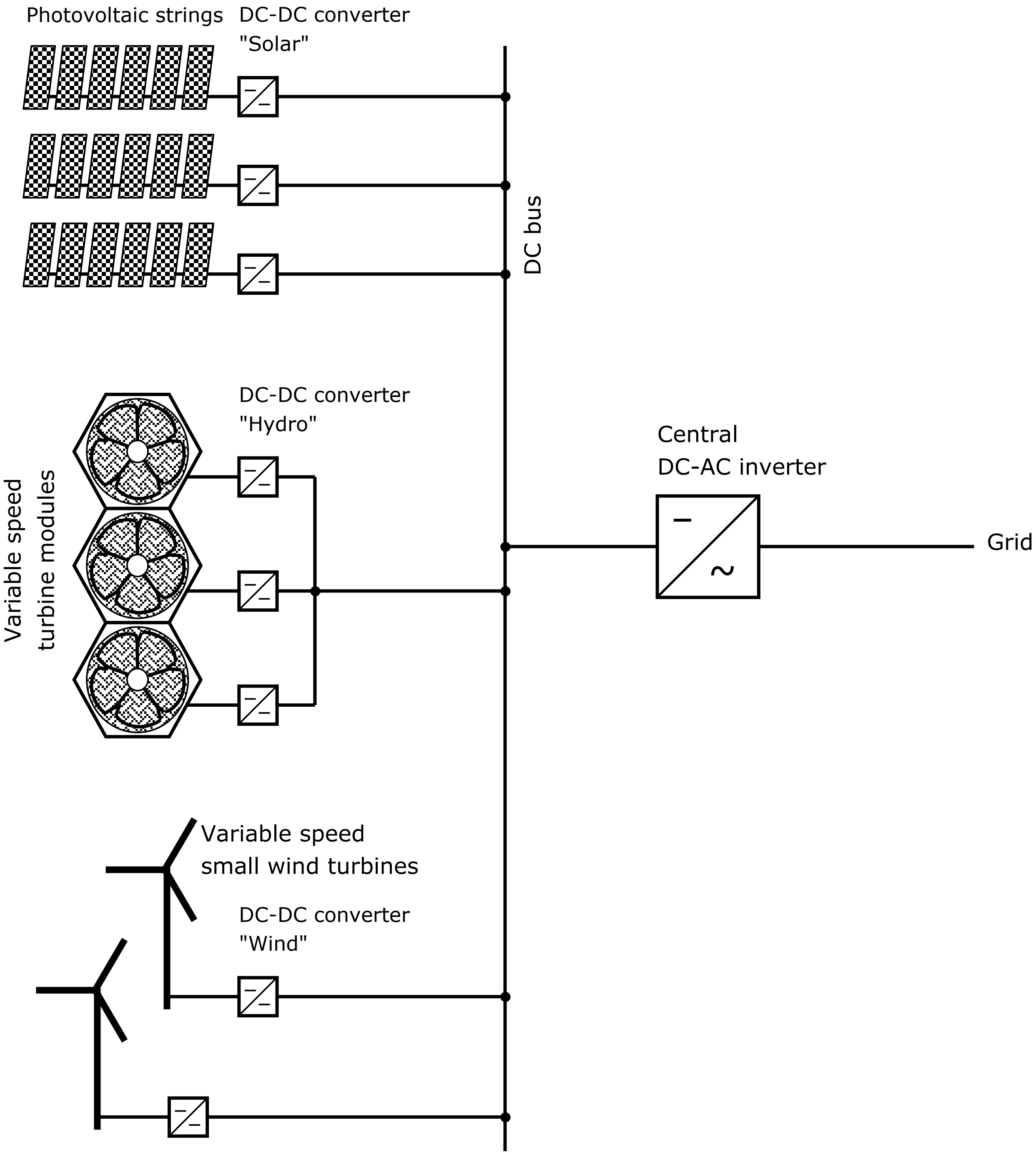


Figure 1:
General concept of a system for distributed production of electric energy

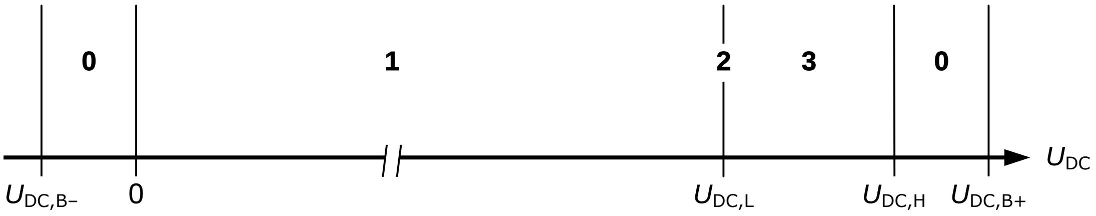
Thus, the DC-DC converters can be adapted and dimensioned specially for the application in the PV, hydro, or wind domain, without the need to consider each time the function of feeding into the grid and the involved prescriptions of the electricity suppliers. The latter is only done by the central inverter that is connected after the DC bus, and that is for its part independent of the power generator's characteristic.

3. Operation concept of the DC bus

As is explained in section 2 and shown in figure 1, there are normally several DC-DC converters connected to the DC bus on the generator side, whereas on the grid side one central inverter passes the power on to the electricity grid. The inverter must take exactly the amount of power from the DC bus that is totally supplied on the generator side. How is the correct operating point found?

Different operating states occur when the system starts up, or when more power is available on the generator side as the inverter is able to process. How are these operating conditions managed?

The requirements of stability, forgivingness, manufacturer-independent compatibility, and simple system design, can hardly be fulfilled by a digital bus system and a central control unit. The various operation conditions shall rather be detected by each involved component in an autonomous way. The information needed shall be extracted from the evaluation of the actual DC bus voltage level. Figure 2 shows the operating ranges defined for this purpose.



1 Start-up range:
DC-DC converter works with activated power point control,
power of DC-AC inverter is zero.

2 Normal operating point:
DC-DC converter works with activated power point control,
power of DC-AC inverter is controlled to constant bus DC voltage $U_{DC,L}$.

3 Limitation range:
Power of DC-DC converter is reduced in function of U_{DC} (down to zero at $U_{DC,H}$),
power of DC-AC inverter is maximum.

0 Operating ranges that occur only when the system is disturbed.

$U_{DC,L}$	Lower operating voltage
$U_{DC,H}$	Higher operating voltage
$U_{DC,B+}$	Absolute limit for overvoltage
$U_{DC,B-}$	Absolute limit for inverse voltage

Figure 2:
Definition of the operating ranges and voltage levels

In figure 3, the control concept is shown as a signal-flow diagram. Both the DC-DC converters on the generator side and the inverter on the grid side are controlled dependent on the U_{DC} voltage such that the operating ranges mentioned before are maintained. This is achieved by suitable control characteristics which are explained in figure 4 and figure 5.

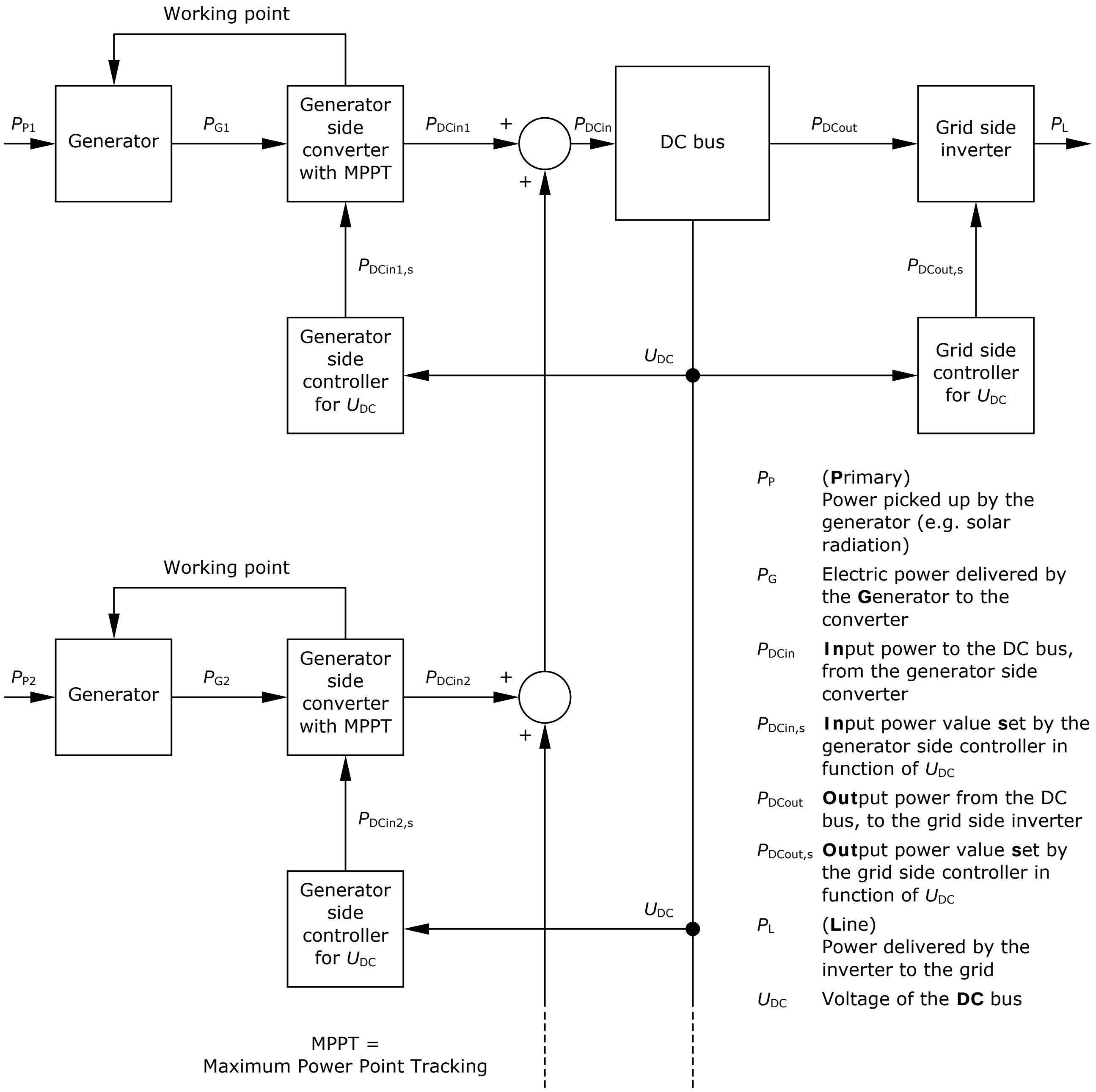


Figure 3:
Signal-flow diagram for the control structure of the DC bus with generator side converters connected ahead and one grid side inverter connected behind

Concrete proposals for the standardization of the voltage levels and the other parameters are presented in [2] und [3].

Figure 4 shows the characteristic of the controller on the generator side. In the range $0 \leq U_{DC} \leq U_{DC,L}$, controlling the DC-DC converter is left to the MPPT controller. Only when U_{DC} exceeds the value $U_{DC,L}$, a power limitation becomes active: The power is reduced linearly with increasing value of U_{DC} until it reaches zero at $U_{DC} = U_{DC,H}$. In this way, U_{DC} can not exceed the higher operating voltage $U_{DC,H}$.

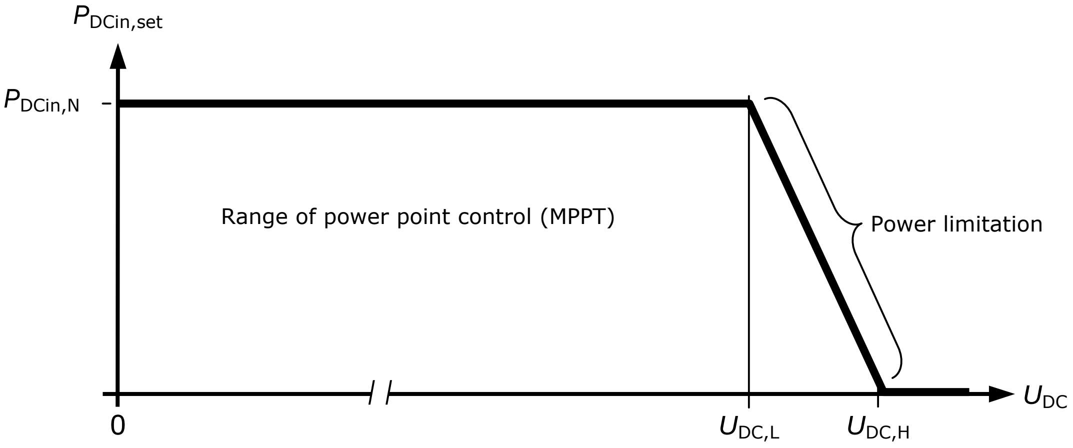


Figure 4:
Power limitation of the DC-DC converters in function of the bus DC voltage

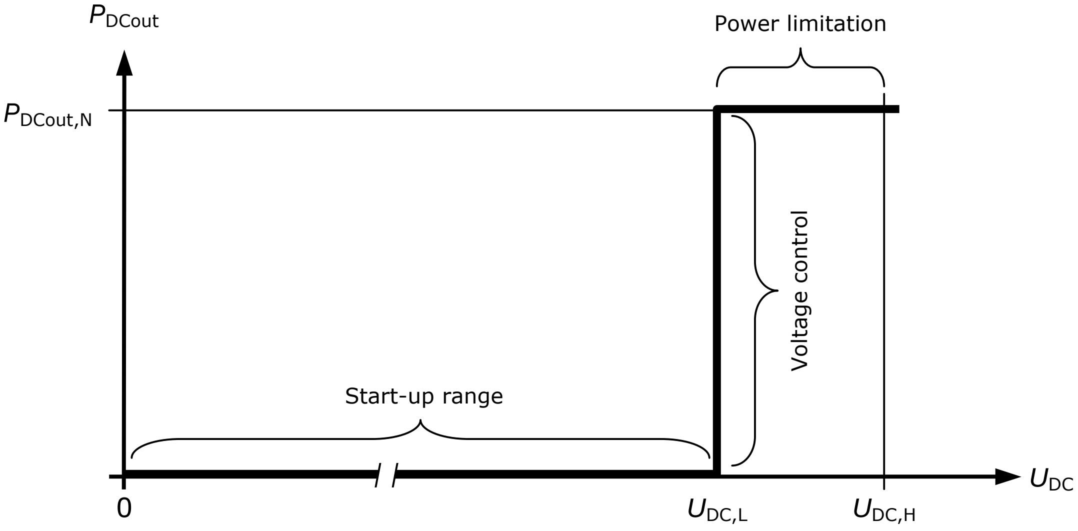


Figure 5:
Voltage control and power limitation of the central inverter in function of the bus DC voltage

In figure 5 , the characteristic of the controller on the grid side is shown. In the voltage range $0 \leq U_{DC} \leq U_{DC,L}$, the power of the inverter is set to zero. As soon as U_{DC} reaches the value $U_{DC,L}$, the power is controlled such that $U_{DC} = U_{DC,L}$ remains constant. At $U_{DC} \geq U_{DC,L}$, the power is limited to its nominal value.

4. *Comparison of the power conditioning concepts*

It is not as if the concept of the DC bus completely replaced the other power conditioning concepts (strings connected in parallel directly to the central inverter, or individual string inverters). Each concept has its pros and cons, and there will for all of them be application domains where they suit best – see table 1.

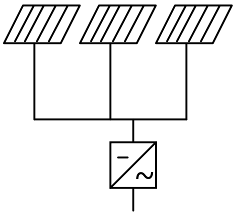
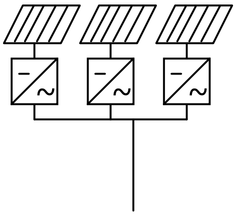
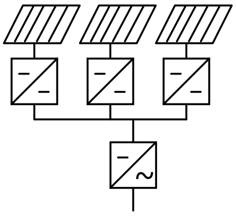
Option	**1**	**2**	**3**
	 Strings connected in parallel to the central inverter	 String inverters	 String DC-DC converters, DC bus and central inverters
Advantages	cost-effective option	individual power point control of the strings, thus optimum efficiency also in the status of partial shading no total breakdown at the failure of an inverter or a photovoltaic string	individual power point control of the strings, thus optimum efficiency also in the status of partial shading no total breakdown at the failure of a photovoltaic string optimum cost/benefit ratio of medium to large systems
Disadvantages	*no* individual power point control of the strings, thus deteriorated efficiency in the status of partial shading total breakdown at the failure of the inverter possibly total breakdown at the failure of a photovoltaic string	not cost-effective at a large number of strings, because each string inverter has its own grid control unit	total breakdown at the failure of the inverter

Table 1:
Characterization of the different options
of power conditioning at photovoltaic systems

5. Proposed development of new product lines

DC-DC converter

DC-DC converters including MPPT should be further developed such that they are suitable for feeding power to the standardized DC bus. A basic concept for that is presented in [2].

The new product lines should cover the following domains:

- short term: string converters for PV application,
- medium term: converters for small wind turbines of variable speed which are equipped with a DC generator or with an alternator and a rectifier,
- long term: converters for water turbine modules of variable speed.

DC-AC inverter

DC-AC inverters have to be developed which can feed power from the standardized DC bus into the grid. It seems possible to adapt existing concepts of central inverters for this purpose with a small effort. A basic concept is presented in [3].

6. Reference publications

[1] Patent application No. 00516/09, "Gleichspannungs-Bus" (DC bus)
Swiss Federal Institute of Intellectual Property, 31st March 2009
German title:
Regelungskonzept für die Netzeinspeisung elektrischer Energie aus dezentralen, leistungsvariablen Quellen über einen Gleichspannungs-Bus.
Non-official translation:
Control concept for the feeding into the grid of electric energy from distributed sources with variable power over a DC bus.

[2] Max Blatter:
Feeding into the grid of electric energy from distributed sources of variable power over a DC bus
Part 2: Concept of a DC-DC converter including maximum power point tracking and DC bus control
Max Blatter, dipl. El.-Ing. ETH, Biel/Bienne, 2009

[3] Max Blatter:
Feeding into the grid of electric energy from distributed sources of variable power over a DC bus
Part 3: Concept of a DC-AC inverter including control for feeding into the grid and DC bus control
Max Blatter, dipl. El.-Ing. ETH, Biel/Bienne, 2009

1. *Annex: Power point control on the generator side*

PV cells, panels, and strings, have a typical and well-known voltage-current characteristic: The power, as the product of these two quantities, has a maximum somewhere between short-circuit and open-circuit point.

Figure 6 illustrates this fact.

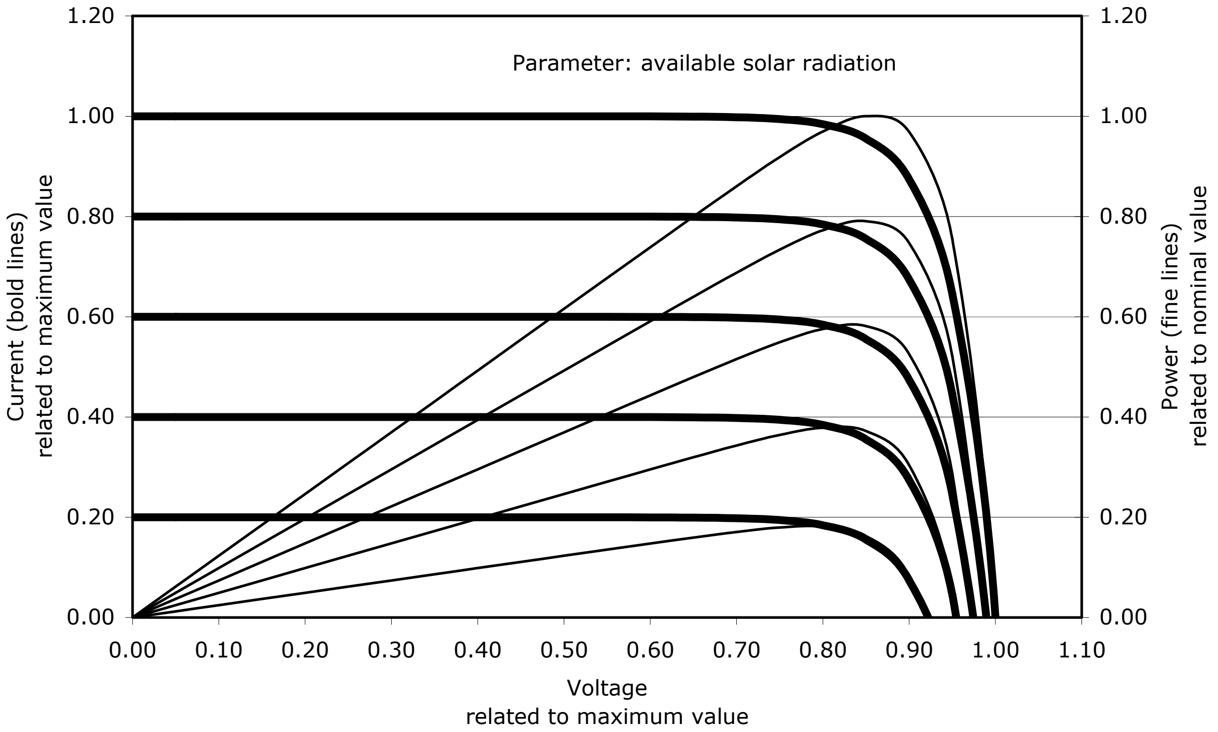


Figure 6:
Voltage-current and voltage-power characteristics
of a typical photovoltaic string

It is the task of the maximum power point tracker to find automatically the operating point where the power reaches its maximum.

A quite similar situation occurs at turbines of variable speed, be it water or wind turbines: Instead of the voltage-current characteristic, the speed-torque characteristic is here involved. Here also, the power has a maximum between stoppage and no-load point, even if the characteristic differs in the details from the voltage-current characteristic of a PV string (figure 7).

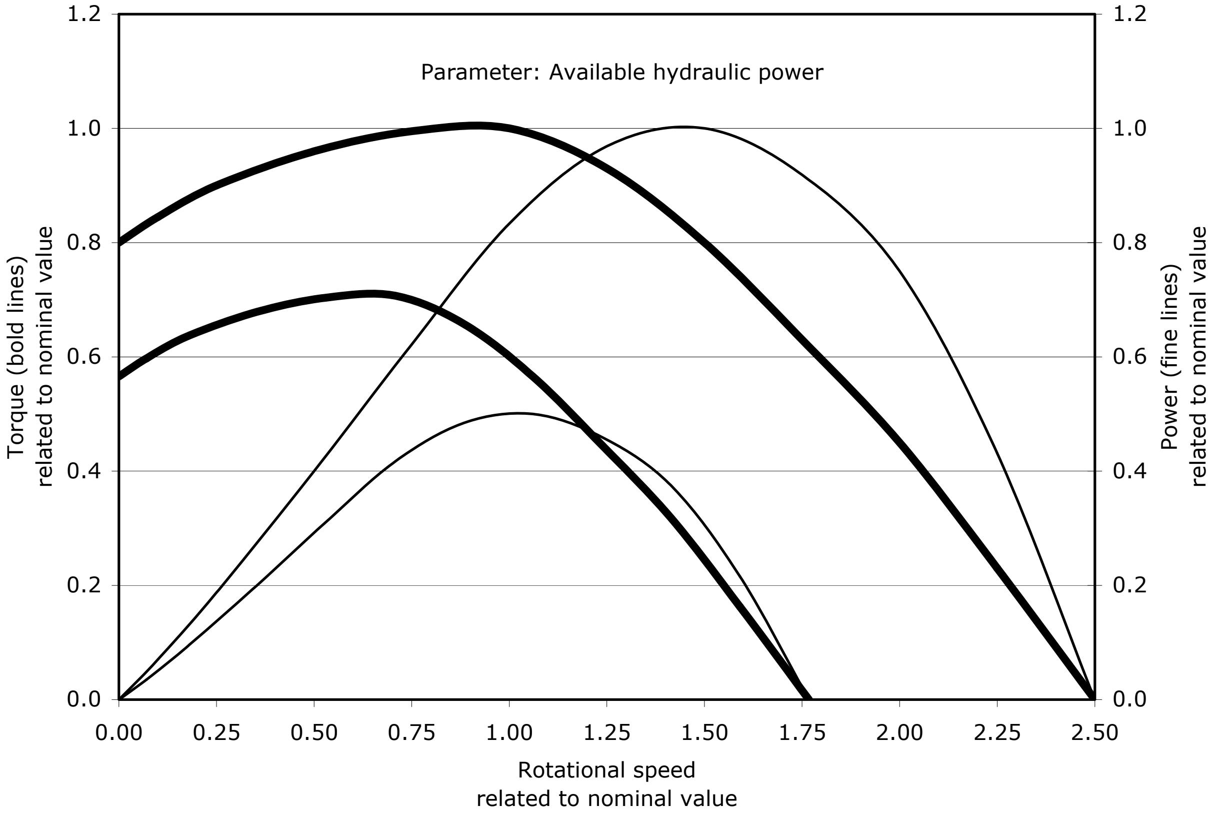


Figure 7:
Speed-torque and speed-power characteristics
of a typical variable speed turbine
(the example shows a Kaplan turbine with non-variable blades)

By the generator, the speed-torque characteristic is transformed into a similar voltage-current characteristic, again. The task of maximum power point tracking remains the same, in analogy to the PV string. It can be solved basically by the same procedures that are known from power conditioning concepts for PV systems. In [2], a particularly proven method is described.

Thus, there lies a great synergy potential in the development of power conditioning units for PV systems on the one hand and for turbines of variable speed on the other hand.

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Feeding into the grid of electric energy from distributed sources of variable power over a DC bus

Part 2: Concept of a DC-DC converter including maximum power point tracking and DC bus control

Max Blatter, dipl. El.-Ing. ETH
created 2009-12-17
last modified 2009-12-21

Content

Abstract

In a Swiss patent application [1], a new concept of power conditioning for photovoltaic (PV) systems and other generators of variable power has been proposed. It is based on a DC bus that shall be standardized independent of manufacturers. In the present document, the principal structure of a DC-DC converter is shown that is suitable for the feeding of electric energy from a PV string to the DC bus. Furthermore, the related specifications of the DC bus are discussed.

1. Introduction

Proceeding from the state-of-the-art power conditioning for PV systems, an innovative concept has been shown in [2]. The idea is to split up the function of maximum power point tracking (MPPT) and the one of feeding into the grid into two separate devices. These are interconnected by a standardized DC bus. – The essential parts of the concept are on hand as a Swiss patent application, too [1].

A very essential point of the concept is that the generator-side DC-DC converter and the grid-side DC-AC inverter operate as fully autonomous devices each. The information on the overall state of the system is thereby derived from the voltage level of the DC bus.

In this document, the basic structure of a generator-side converter is presented, which is designed as a DC-DC converter including MPPT and performing at the same time the control functions required by DC bus operation.

2. Structure of the DC-DC converter

2.1 Overview

Figure 1 shows the overall structure of the DC-DC converter. The power components are indicated by bold lines, the control components by fine lines. – In the following, the general function is described, before the single components are focused in the next sections.

A PV string is indicated as an example of a power generator; however, the same concept can also be used for other DC sources of variable power. The output of the DC-DC converter is connected to the standardized DC bus. The ratio of input and output voltage, $U_{\mathrm{St}}/U_{\mathrm{DC}}$, lies between 0 and 1, which means that a step-up converter is concerned. Thus, the generator voltage can lie in the range of $0 \leq U_{\mathrm{St}} \leq U_{\mathrm{DC}}$.

The converter is controlled on one hand by the MPP tracker. Its input quantities are x_I und x_U as representatives for the generator current I_{St} and the generator voltage U_{St}. The controller influences the transformation ratio y_{nA} such that the generator operates at the maximum power point.

On the other hand, there is a current limiter which sets a maximum value $x_{I\mathrm{max}}$ representing the maximum generator current, dependent on the voltage level U_{DC} or its representative x_{DC}, respectively. A controller then increases the transformation ratio y_{nB} such that the operating point of the generator moves away from the maximum power point towards the open-circuit point.

A pulse generator finally converts the command signal y_{n} into the switching pulses that are needed for the power component of the DC-DC converter.

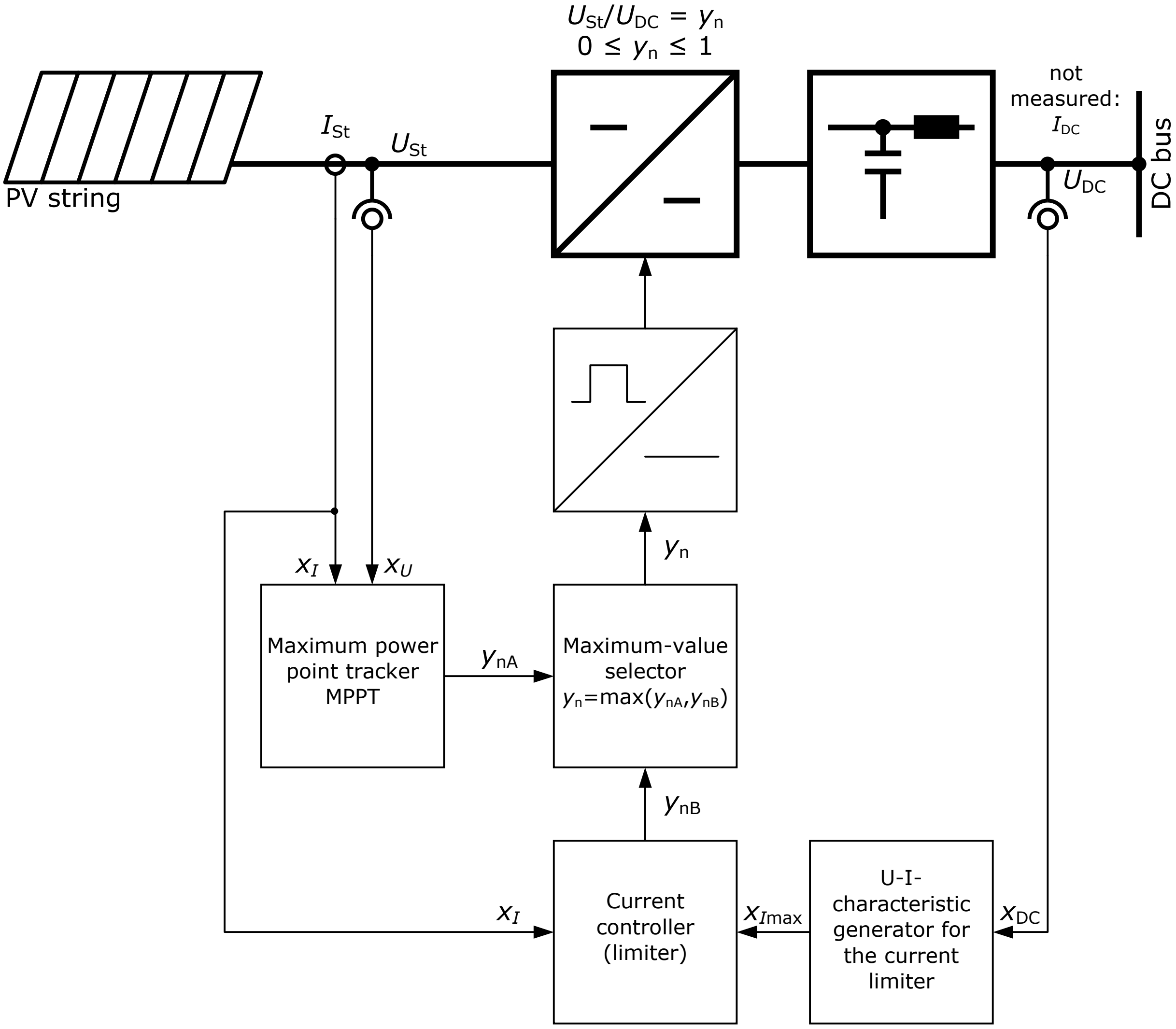


Figure 1: Overall structure

2.2 Power components

2.2.1 DC-DC converter including pulse generator

Figure 2 shows the power component of the DC-DC converter including the pulse generator as a block diagram. As already mentioned, a step-up converter is concerned, which means that its output voltage is higher than its input voltage.

The pulse generator produces a switching signal $s(t)$ by comparison of the command signal y_n with a sawtooth signal. The resulting pulse duty factor T_1/T is equal to y_n. Thus, the input and output voltages and currents of the DC-DC converter have the shapes shown in figure 3.

As the DC bus voltage U_{DC} is given, the input voltage of the converter, U_{St} and thus the operating point of the PV generator are determined by the pulse duty factor, or in other words by the command signal y_n.

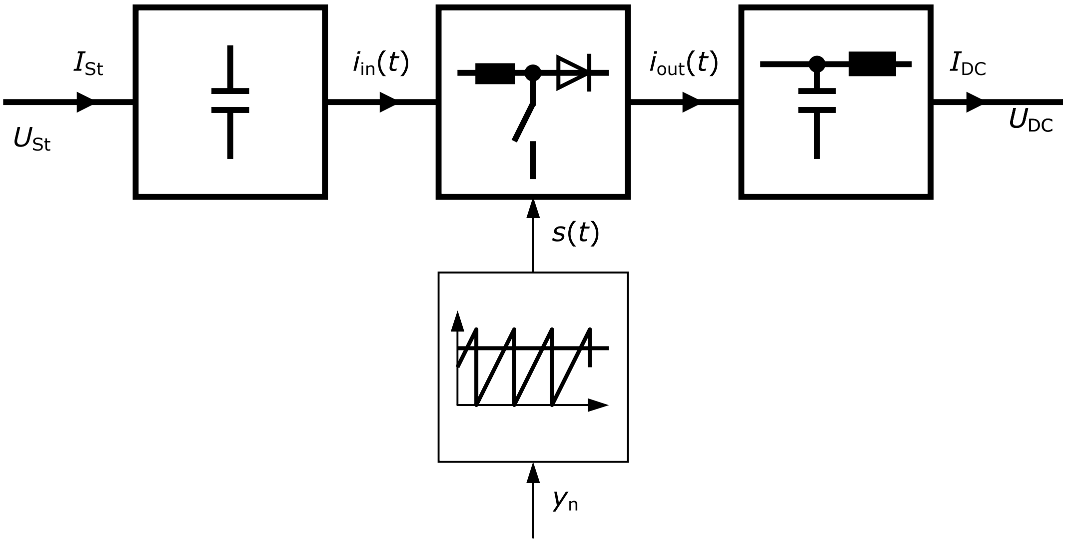


Figure 2: Structure of the step-up DC-DC converter

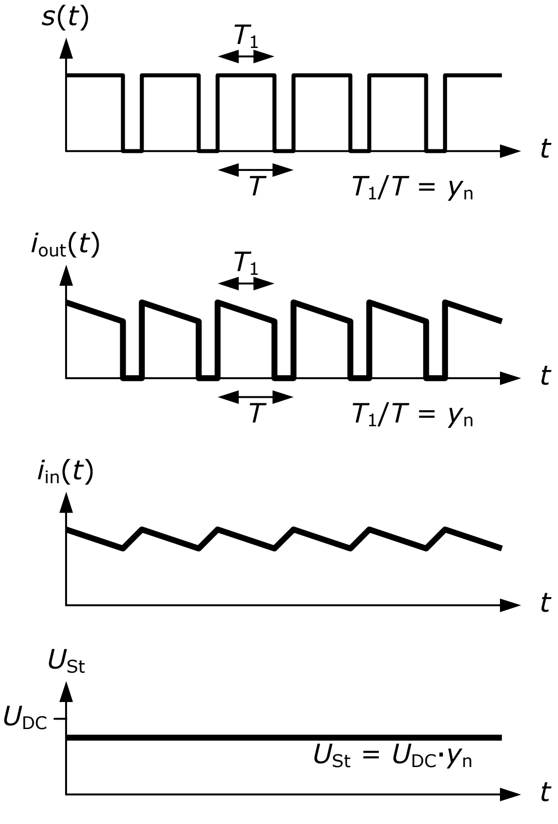


Figure 3: Idealized current and voltage time functions of the step-up DC-DC converter

2.2.2 Transducers

Part of the power components are also the transducers which supply the input quantities of the controllers. Here, transducers for the string voltage U_{St}, the string current I_{St}, and the bus voltage U_{DC} are needed, which convert the measured values to the measurement signals x_U, x_I, and x_{DC}.

2.3 Control components

2.3.1 Maximum power point tracker MPPT

The most central function is MPP tracking, the task of which is to hold the operating point of the PV generator always at the maximum power point.

There have been developed several methods for solving this task which is known in theory as a (one-dimensional) extremal control. One of them is the characteristic-curve method of Böhringer [4] that is described in the following on the basis of figure 4 and figure 5.

Truth table of the logic circuit

	Input		Output	
Quantity	s_U	s_I	s_{Hold}	s_{Dir}
Meaning	$x_U<k\cdot x_U*$	$x_I<k\cdot x_I*$	0: follow U, hold I 1: follow I, hold U	0: $h=+1$ 1: $h=-1$
	0	0	unchanged	unchanged
	1	0	0	0
	0	1	1	1
	1	1	(does not occur)	

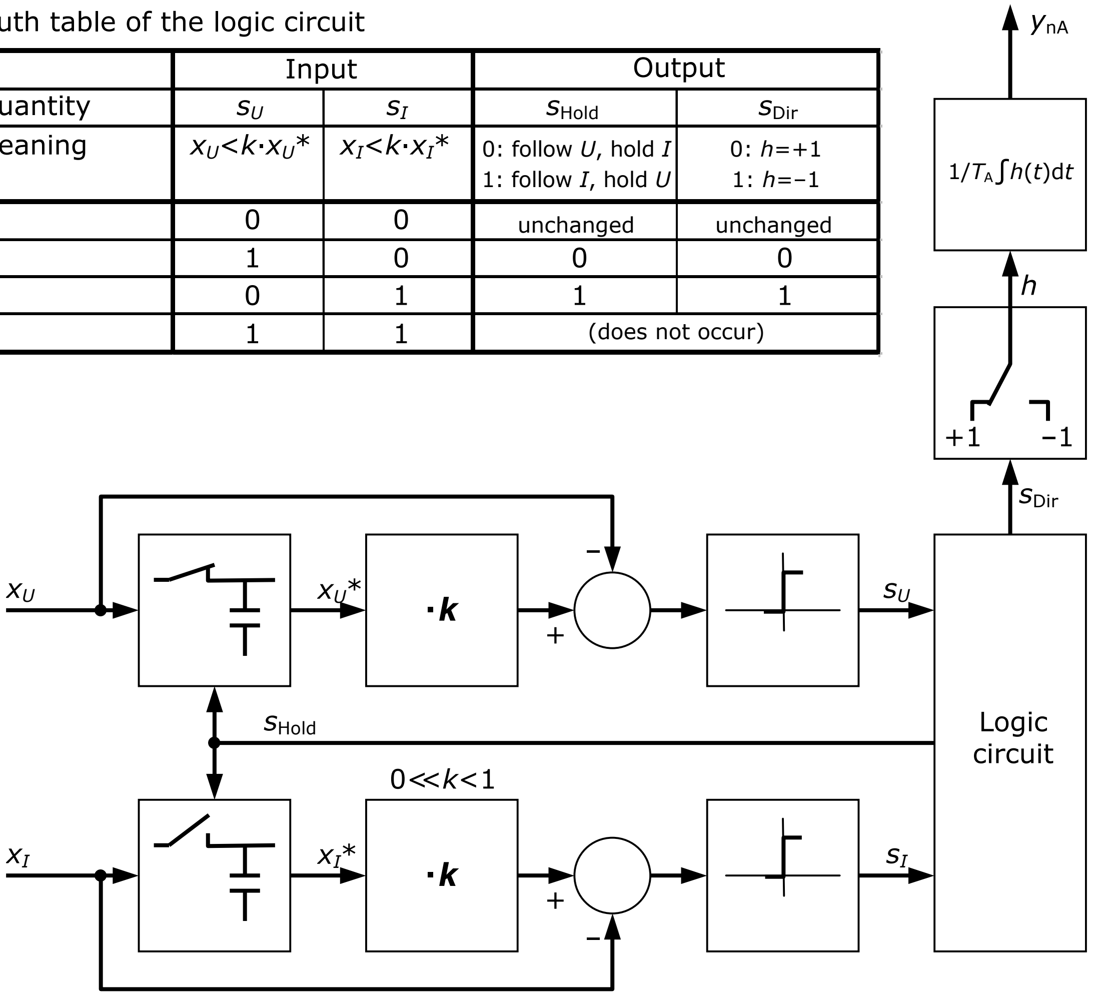


Figure 4: Structure of the MPP tracker operating according to Böhringer's method

Like at most of the know methods, the operation point is moved slightly forth and back in an active oscillating motion. At Böhringer's method, the switching points of this motion are determined as follows: Whenever the motion is switched towards higher string voltages, the actual measurement signal of the current, x_{I1}, is stored. As soon as the current has reached the smaller value corresponding to $k{\cdot}x_{I1}$, the motion is switched towards lower string voltages. In this moment, the actual measurement signal of the voltage, x_{U1}, is stored. As soon as the voltage has reached the smaller value corresponding to $k{\cdot}x_{U1}$, the direction of the motion is again switched over and the cycle is repeated from the beginning.

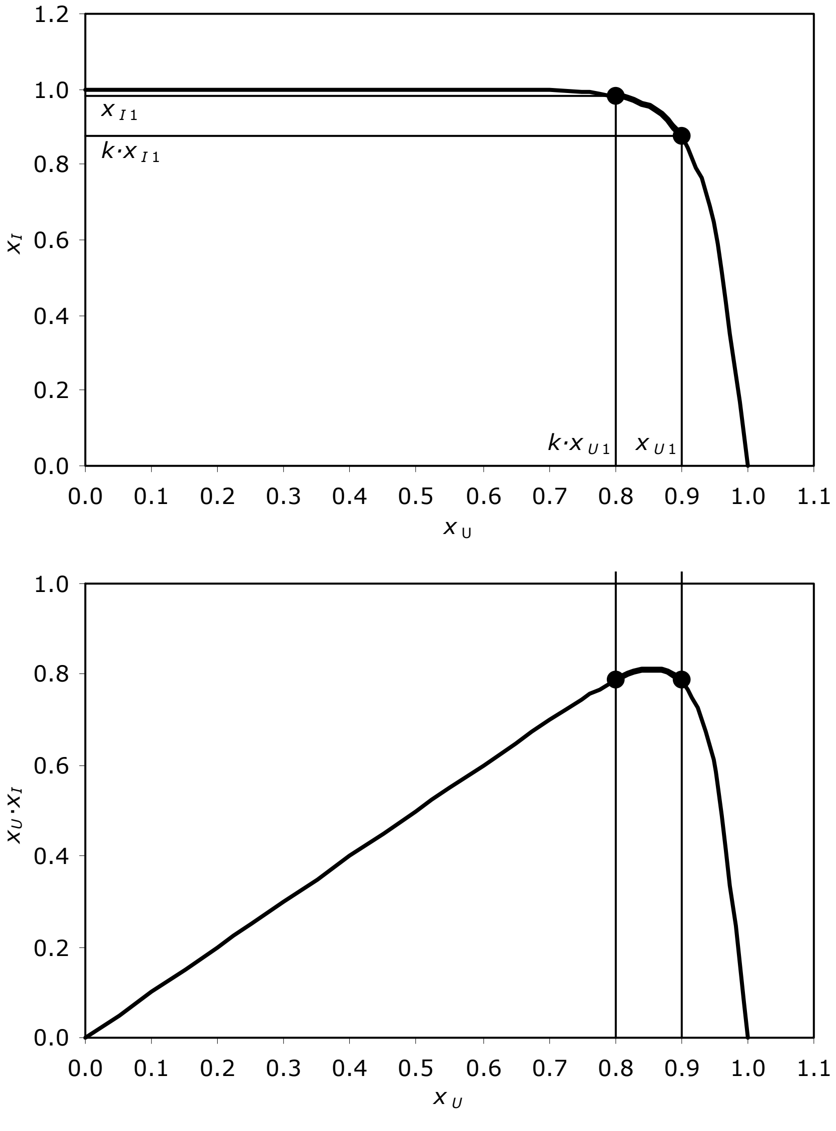


Figure 5: Operating principle of Böhringer's characteristic-curve method

In practice, the range of the oscillating motion will be restricted (e.g. by presetting minimum values $x_{I\text{min}}$ and $x_{U\text{min}}$), in order to avoid a hang-up at the open-circuit or the short-circuit point.

As Böhringer has shown mathematically, the limit cycle includes the point where the product $x_U{\cdot}x_I$ has a maximum (if the characteristic curve meets certain requirements). The factor k ($0<k<1$), common for current and voltage, determines the behavior of the control with regard to a compromise between precision and forgivingness: Thus, the controller works the more precise (and the oscillating motion is the smaller), the closer k comes to unity. However, the danger will then also increase that the controller hangs up at a possibly present side maximum, or that it becomes unstable due to measurement imprecision. – A value of k ≈ 0,95 has been proven as an adequate compromise.

An other essential parameter of the controller is the slope of the ramp generator that produces the command signal y_{nA}, i.e. the gain constant $1/T_{\mathrm{A}}$ of the corresponding integrator. It determines the rapidity of the searching oscillation and should be chosen such that the controller can follow the shift of the maximum power point dependent on weather conditions. The fact has to be considered that dynamic changes of cloudiness can take place in time scales clearly below one minute. – On the other hand, the MPP tracker has to be slower than the control of the DC bus voltage that is achieved by the DC-AC inverter on the grid side. This aspect will be considered in section 3.2.

The special advantages of Böhringer's method are:

- Best possible indifference against variation of the characteristic curve
  (if the factor *k* is chosen adequately);
  thus the method is principally suitable also for the non-monotonic characteristic curves
  of speed variable turbines [2] without further adaptations.
- Easy implementation in different control concepts:
  - Analog control circuit
  - Digital control circuit
  - Software building block

2.3.2 Current limiter

An increasing bus voltage U_{DC} indicates that the total power supplied to the DC bus has exceeded the maximum power of the grid-side DC-AC inverter. In this case, a current limiter becomes active which finally increases the pulse duty factor of the DC-DC converter, such that the operating point of the PV generator moves away from the maximum power point towards the open-circuit point.

2.3.2.1 U_{DC}–I_{St}–characteristic generator

The first component involved in the above mentioned task is the U_{DC}-I_{St}-characteristic generator shown in figure 6, which generates the set value of the maximum string current, $x_{I\mathrm{max}}$. This quantity is determined depending on the bus voltage U_{DC}, or its measurement signal x_{DC} respectively, as follows: As long as U_{DC} does not exceed the fixed lower operating voltage $U_{\mathrm{DC,L}}$, the $x_{I\mathrm{max}}$ quantity remains at the constant value representing the nominal string current, $I_{\mathrm{St,N}}$. When $U_{\mathrm{DC,L}}$ is exceeded, $x_{I\mathrm{max}}$ is reduced linearly until it reaches zero at $U_{\mathrm{DC}} = U_{\mathrm{DC,H}}$.

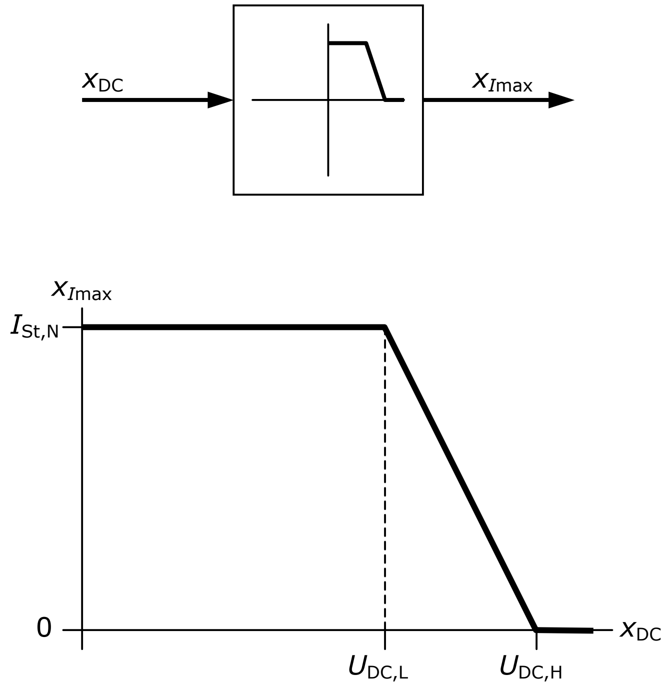


Figure 6: Function of the U_{DC}-I_{St}-characteristic generator

2.3.2.2 Current controller

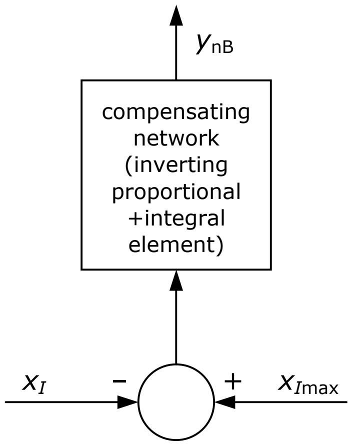


Figure 7: Structure of the current controller

The current controller (figure 7) influences the pulse duty factor via the command signal y_{nB} such that the maximum string current, represented by $x_{I\max}$, is maintained. – Because a decrease of the string current is achieved by an increase of the command signal, the compensating network of the controller must be inverting. Its frequency-response curve has to be dimensioned according to the known theories of control engineering with regard to stability and response time. The latter must be longer than the pulse period T of the DC-DC converter, such that the controller does not respond to the ripple of the string current, $i_{St}(t)$. On the other hand, the response time must be short enough to hold the bus voltage, U_{DC}, in the allowed range also at dynamic changes of the system. This aspect will be considered in section 3.2.

With regard to the dimensioning of the control circuit, the calculation has to take the non-linear U-I-characteristic of the PV generator into account. This means that the circuit parameters are strongly dependent on the operating point. There might be the need of a non-linear control circuit which at a negative control deviation ($x_I > x_{I\mathrm{max}}$) becomes active instantaneously, whereas it is dimensioned according to the usual stability criteria for control deviations near zero.

2.3.2.3 Maximum-value selector

As can be seen in the overall structure diagram (figure 1, p. 4), a maximum-value selector selects the higher of the two command signals y_{nA} und y_{nB}. Thus, the MPP tracker keeps control (command signal y_{nA}), as long the value x_I lies below $x_{I\mathrm{max}}$. Only when x_I reaches or even exceeds $x_{I\mathrm{max}}$, the current limiter becomes active via the command signal y_{nB}.

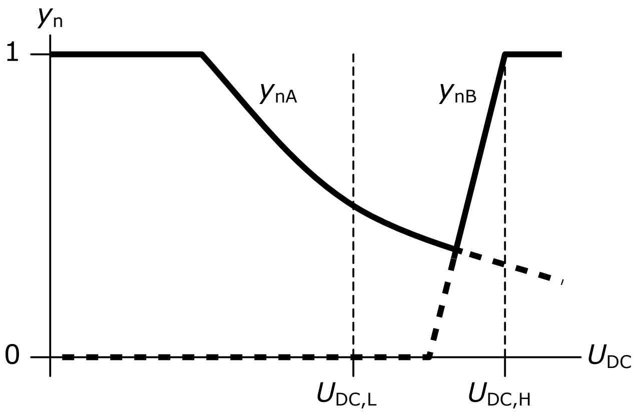


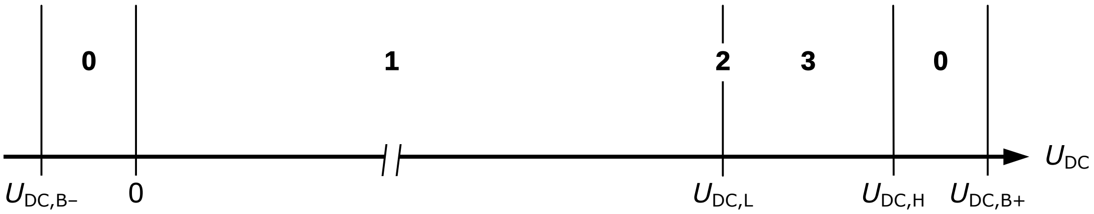
Figure 8: Operating principle of the maximum-value selector

The curves show the qualitative shape of y_{nA} and y_{nB} as functions of U_{DC}. In detail, the shapes depend on the operating point of the PV generator.

3. Standard for the operation of the DC bus

The following statements are meant as a discussion basis for manufacturers that are active in the domain of power conditioning for PV systems.

3.1 Voltage ranges



1 Start-up range
$0 \leq I_{St} \leq I_{St,N}$
determined by the MPP tracker

2 Normal operating point
$0 \leq I_{St} \leq I_{St,N}$
determined by the MPP tracker

3 Limitation range
at $U_{DC} = U_{DC,L}$: $0 \leq I_{St} \leq I_{St,N}$
at $U_{DC} = U_{DC,H}$: $I_{St} = 0$
generally: $0 \leq I_{St} \leq I_{St,N} \cdot [1-(U_{DC}-U_{DC,L})/(U_{DC,H}-U_{DC,L})]$

0 Operating ranges that occur only when the system is disturbed

$U_{DC,L}$ Lower operating voltage

$U_{DC,H}$ Higher operating voltage

$U_{DC,B+}$ Absolute limit for overvoltage

$U_{DC,B-}$ Absolute limit for inverse voltage

Figure 9: Operating ranges defined by the voltage levels of the DC bus

The following voltage levels are put to discussion:

$U_{DC,L}$	= 400 V	This value lies about 13%, or 46 V respectively, above the peak value of a 250 V alternating voltage, which is an advantageous level for the dimensioning of the grid-side DC-AC inverter.
$U_{DC,H}$	= 440 V	This corresponds to a usual nominal value of direct voltages.
$U_{DC,B+}$	= 462 V	The absolute overvoltage limit is chosen 5% above the higher operating voltage. The DC-DC converter has to withstand this voltage continuously; no power must be supplied to the DC bus in this state. Afterwards, the converter must restart automatically. If the limit is exceeded, the converter must disconnect automatically from the DC bus. It must restart only upon manual intervention.
$U_{DC,B-}$	= −22 V	The absolute inverse voltage limit is chosen −5% of the higher operating voltage. The DC-DC converter has to withstand this voltage continuously; afterwards, the converter must restart automatically. If the limit is exceeded, the converter must disconnect automatically from the DC bus. It must restart only upon manual intervention.

3.2 Dynamic behavior

3.2.1 Maximum power point tracking

The MPP tracker should not cause too quick changes of the output current I_{DC}, in order to avoid interferences with the grid frequency and with the control of the grid-side inverter. The following requirements are proposed:

- When put into operation, or after a breakdown, the MPP tracker shall start up from $y_n = 0$, i.e from the short-circuit point. (Reason: Thus, the output current I_{DC} is softly run up; a start-up with $y_n = 1$ and $U_{DC} = 0$ would cause a jump of I_{DC} from zero to the short-circuit-current of the PV string, I_{St}.)
- The MPP tracker shall pass the whole range from $y_n = 0$ ~~bis~~ $y_n = 1$ or reverse not quicker than in 10 s.
- If a MPP tracker performs an oscillation round the maximum power point, its period shall not be shorter than 100 ms.

3.2.2 Current limitation

As explained in section 2.3.2, the current limitation becomes active as soon as the grid-side inverter can no longer lead off the supplied power. Then, the control has to be quick enough to hold the DC bus voltage in the allowed range. Thereby, the capacitance installed at the input of the grid-side inverter can be taken into account.

This leads to the following requirement:

- The current limiter shall be dimensioned for the case that in the beginning 120% of the nominal power are supplied to the DC bus, but only 100% are led off. The bus DC voltage must then increase by no more than 10 V until the control becomes effective. The presence of a parallel capacitance of 1000 µF per kW nominal power may be assumed. This results in a required response time of about 4 ms.

As indicated in section 2.3.2.2, it may be that only a non-linear control meets the requirements of rapidity and stability simultaneously.

3.3 Potential against ground

The concept stipulates that the negative conductor of the DC bus lies at ground potential. This is ensured by the grid-side inverter, in which the corresponding terminal is connected either to the PE or PEN conductor of the grid, or to a separate potential equalization conductor [3]. Thus, no connection to ground is allowed in the power components of the DC-DC converter. The same is valid for the PV generator, unless the DC-DC converter provides galvanic isolation.

3.4 Electromagnetic compatibility

The high-frequency interference currents supplied to the conductors of the DC bus must not exceed the limits given in the European Standard EN61000-6-3 [5].

4. Reference publications

[1] Patent application No. 00516/09, "Gleichspannungs-Bus" (DC bus)
Swiss Federal Institute of Intellectual Property, 31st March 2009
German title:
Regelungskonzept für die Netzeinspeisung elektrischer Energie aus dezentralen, leistungsvariablen Quellen über einen Gleichspannungs-Bus.
Non-official translation:
Control concept for the feeding into the grid of electric energy from distributed sources with variable power over a DC bus.

[2] Max Blatter:
Feeding into the grid of electric energy from distributed sources of variable power over a DC bus
Part 1: General concept for photovoltaic systems and small water and wind turbines of variable speed
Max Blatter, dipl. El.-Ing. ETH, Biel/Bienne, 2009

[3] Max Blatter:
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Part 3: Concept of a DC-AC inverter including control for feeding into the grid and DC bus control
Max Blatter, dipl. El.-Ing. ETH, Biel/Bienne, 2009

[4] (Publication in german)
A. Böhringer:
Die selbsttätige Einstellung der Extremwerte von Funktionen der Form
$z=g(x^a \cdot y)$ nach einem Kennlinienverfahren
In: Regelungstechnik, Jg.17 (1969), Heft 12

[5] European Standard EN61000-6-3:
Electromagnetic compatibility (EMC). Part 6-3: Generic standards – Emission standard for residential, commercial and light-industrial environments
Quoted (in german): Heinrich Häberlin, Photovoltaik. AZ Verlag und VDE Verlag 2007

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TE^4 Technologie-Entwicklung für Erneuerbare Elektrische Energie
(Development of technologies for renewable electric energy)

Feeding into the grid of electric energy from distributed sources of variable power over a DC bus

Part 3: Concept of a DC-AC inverter including control for feeding into the grid and DC bus control

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Content

Abstract

In a Swiss patent application [1], a new concept of power conditioning for photovoltaic (PV) systems and other generators of variable power has been proposed. It is based on a DC bus that shall be standardized independent of manufacturers. In the present document, the principal structure of an inverter is shown that is suitable for the feeding of electric energy from the DC bus to the grid. Furthermore, the related specifications of the DC bus are discussed.

1. Introduction

Proceeding from the state-of-the-art power conditioning for PV systems, an innovative concept has been shown in [2]. The idea is to split up the function of maximum power point tracking (MPPT) and the one of feeding into the grid into two separate devices. These are interconnected by a standardized DC bus. – The essential parts of the concept are on hand as a Swiss patent application, too [1].

A very essential point of the concept is that the generator-side DC-DC converter and the grid-side DC-AC inverter operate as fully autonomous devices each. The information on the overall state of the system is thereby derived from the voltage level of the DC bus.

In this document, the basic structure of a grid-side inverter is presented, which is designed as a DC-AC inverter including grid synchronization and performing at the same time the control functions required by DC bus operation.

2. Structure of the inverter

2.1 Overview

Figure 1 shows the overall structure of the inverter. The power components are indicated by bold lines, the control components by fine lines. – In the following, the general function is described, before the single components are focused in the next sections.

The input side of the inverter is, parallel to a storage capacitor, connected to the DC bus having the voltage U_{DC}. At the output side, the inverter supplies a time-variable voltage $u_{\mathrm{out}}(t)$, the average value of which lies in the range $-U_{\mathrm{DC}} \leq \bar{u}_{\mathrm{out}}(t) \leq U_{\mathrm{DC}}$, according to the pulse duty factor of the inverter. Over an inductive filter, the connection to the grid is made.

A current controller influences the pulse duty factor such that the desired time function of the current supplied to the grid, $i_{\mathrm{Grid}}(t)$, results. For this purpose, a signal $y_{\sim}(t)$ is first generated from the grid voltage $u_{\mathrm{Grid}}(t)$, or its measurement signal $x_u(t)$ respectively, by means of a grid synchronizer. This determines the shape of the set grid current. Its amplitude $y_{\hat{\imath}}$ is given by the power controller. Thus, the power supplied to the grid is set such that the bus DC voltage U_{DC}, represented by its measurement signal x_{DC}, remains constant as long as possible. At the maximum power of the inverter, a limitation occurs finally.

So, the set value of the grid current is given by $y_{\hat{\imath}} \cdot y_{\sim}(t)$. By comparison with the measurement signal $x_i(t)$, $y_{\mathrm{n}}(t)$ is controlled such that the set time-function of the grid current is maintained.

The pulse generator converts the command signal $y_{\mathrm{n}}(t)$, supplied by the controllers, into the switching pulses needed by the power component of the inverter.

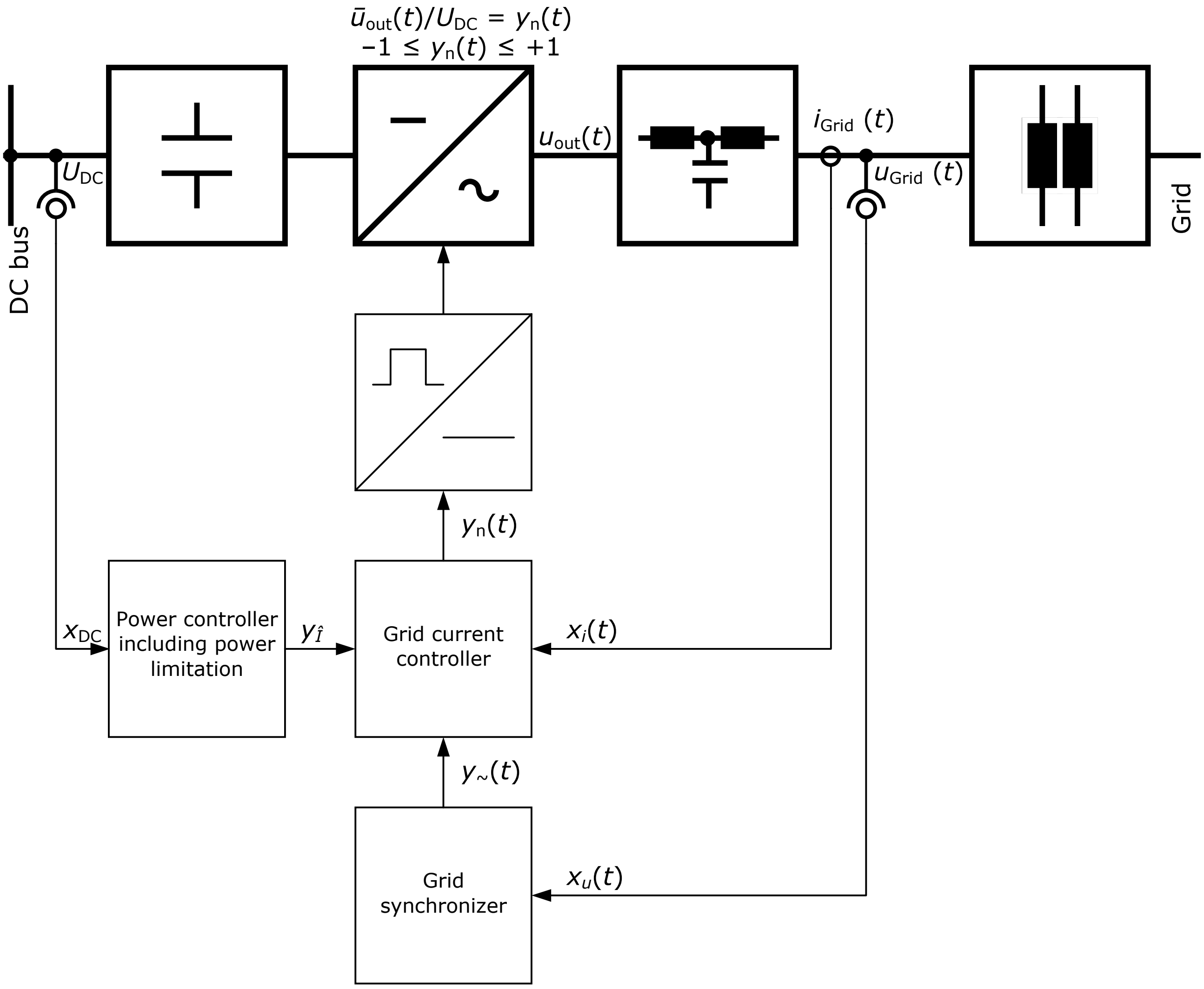


Figure 1: Overall structure

2.2 Power components

2.2.1 Inverter including pulse generator, input capacitor, and output inductor

Figure 2 shows the power components of the inverter, including the pulse generator. It is designed as a pulse-width modulated bridge inverter.

The pulse generator compares the command signal, y_n, with two time-shifted triangular functions, thus supplying the switching signals, $s_1(t)$ and $s_2(t)$, which control the two half-bridges of the inverter. The resulting current and voltage time-functions are shown in figure 3, in the left half for the case $y_\mathrm{n} = +0.5$, in the right half for the case $y_\mathrm{n} = -0.5$.

The average of the output voltage, $\bar{u}_\mathrm{out}(t)$, taken over the pulse period T, follows the command signal y_n. Thus, a sinusoidal shape can be achieved.

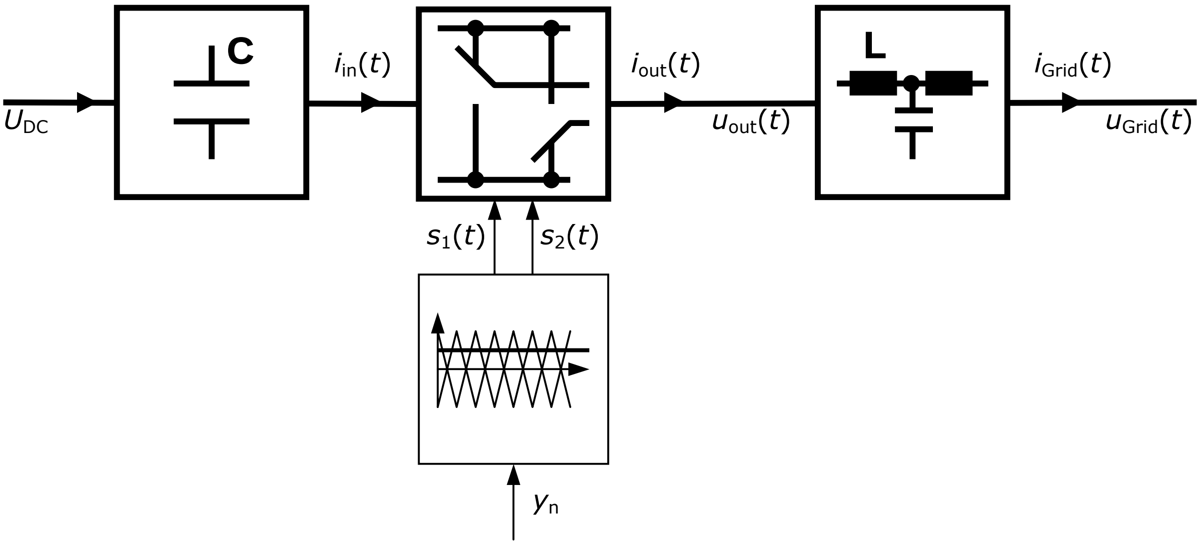


Figure 2: Structure of the pulse-width modulated bridge inverter

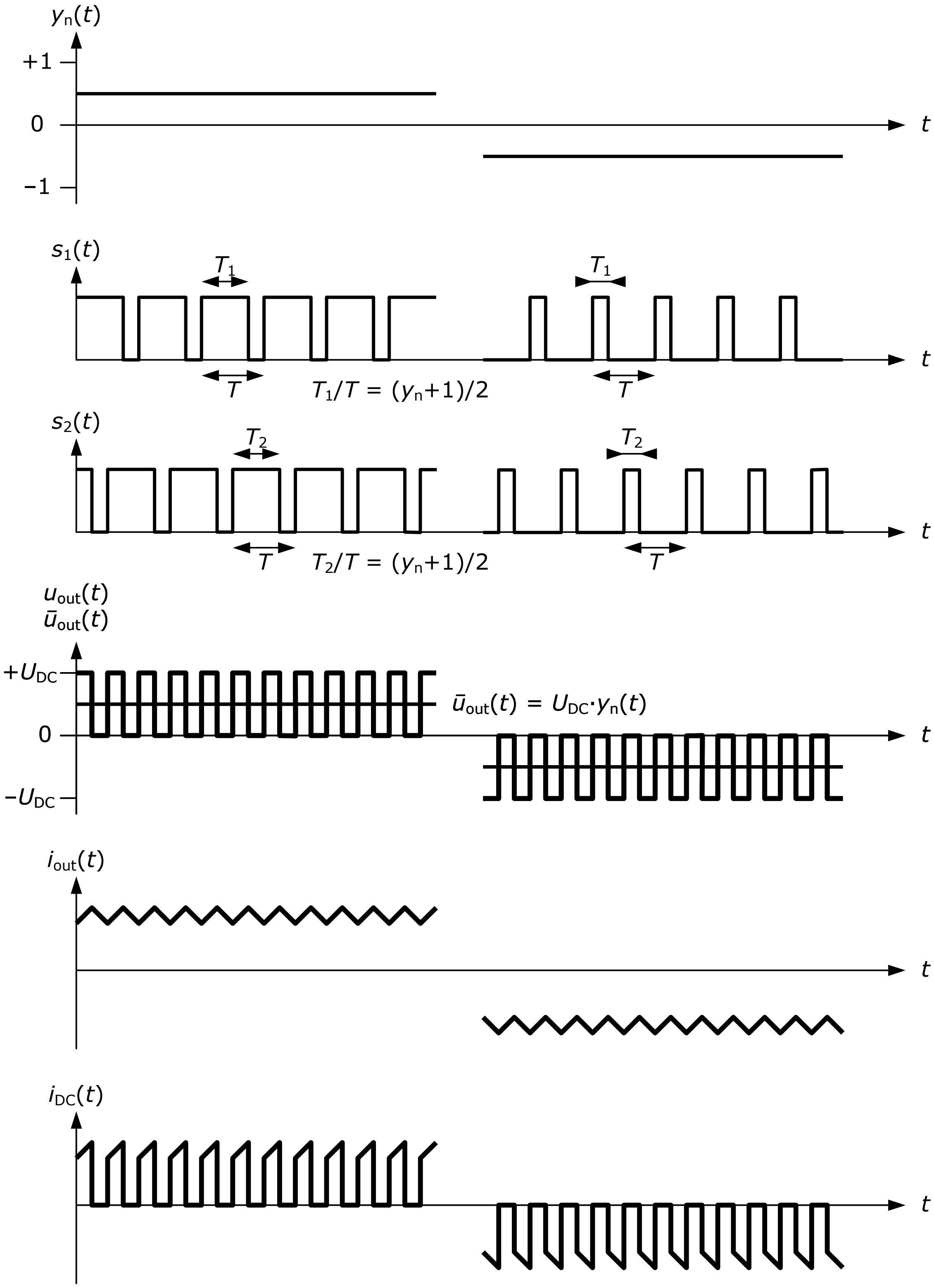


Figure 3: Idealized current and voltage time functions of the pulse-width modulated bridge inverter

2.2.2 Transducers

Part of the power components are also the transducers which supply the input quantities of the controllers. Here, transducers for the grid voltage $u_{\mathrm{Grid}}(t)$, the grid current $i_{\mathrm{Grid}}(t)$, and the bus voltage U_{DC} are needed, which convert the measured values to the measurement signals $x_u(t)$, $x_i(t)$, and x_{DC}.

2.3 Control components

2.3.1 Grid synchronizer

The task of the grid synchronizer is to determine shape and phase position of the set grid current. This is most adequately done by a phase-locked loop (PLL), as shown in figure 4.

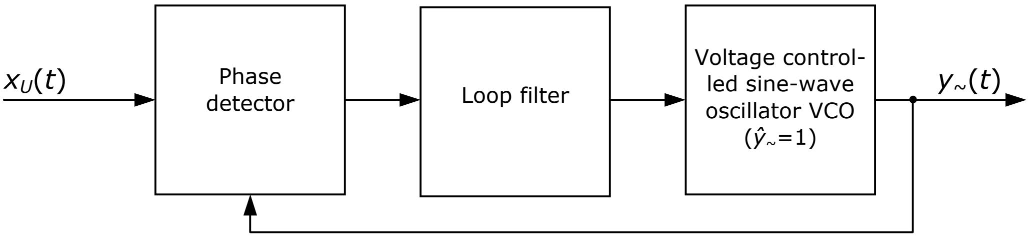


Figure 4: Typical structure of a grid synchronizer operating on the basis of a phase-locked loop (PLL) circuit

Thereby, a voltage controlled oscillator (VCO) generates a sinusoidal signal $y_{\sim}(t)$ of the amplitude $\hat{y}_{\sim}=1$, the frequency of which can be varied within the range of grid frequency. A phase detector compares $y_{\sim}(t)$ with the measurement signal of the grid voltage, $x_U(t)$. It supplies a signal that indicates the phase difference between the two input signals. Over a loop filter, the frequency of the VCO is controlled such that the phase difference becomes zero. – Phase detector and loop filter have to be designed and dimensioned according to the known theories of PLL such that the synchronizer locks in correctly and stays locked at the given grid frequency.

In practice, one will also derive an information on the grid state from the PLL. Thus, the inverter can be disconnected from the grid if a synchronization is not possible e.g. due to a grid breakdown. This is then part of the safety concept demanded by relevant standards and by prescriptions of the electricity suppliers. However, additional monitoring elements are still needed as a rule.

2.3.2 Power controller

In addition to the shape, $y_{\sim}(t)$, the amplitude $y_{\hat{I}}$ of the set grid current has to be determined. This is done by the power controller, the structure of which is shown in figure 5.

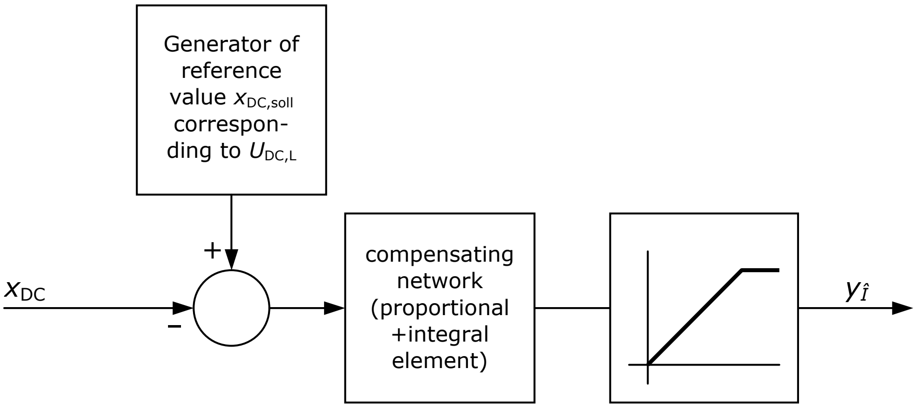


Figure 5: Structure of the power controller

Thereby, the measurement signal x_{DC} is compared with a constant reference value corresponding to the fixed lower operating voltage of the DC bus, $U_{DC,L}$. – The frequency-response curve of the compensating network has to be dimensioned according to the known theories of control engineering with regard to stability and response time. The latter must on one hand be long compared to the grid voltage period, T_{Grid}, because quicker changes of the quantity $y_{\hat{I}}$ would only lead to distortions of the grid current shape. On the other hand, the response time has to be short enough to hold the bus voltage, U_{DC}, sufficiently constant also at dynamic changes of the system. This aspect will be considered in section 3.2. – After the output of the compensating network, the command signal $y_{\hat{I}}$ is limited to a defined maximum value corresponding to the grid current amplitude at nominal power.

2.3.3 Grid current controller

The grid current controller (figure 6) performs at the first place the multiplication $y_{\hat{I}} \cdot y_{\sim}(t)$. The resulting signal corresponds to the set time-function of the grid current. By comparison with the measured time-function, $x_i(t)$, the command signal $y_n(t)$ is generated via the compensating network.

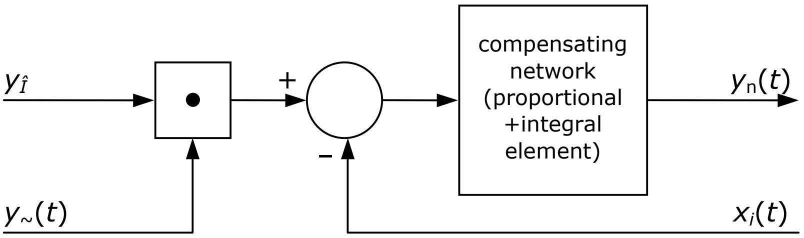


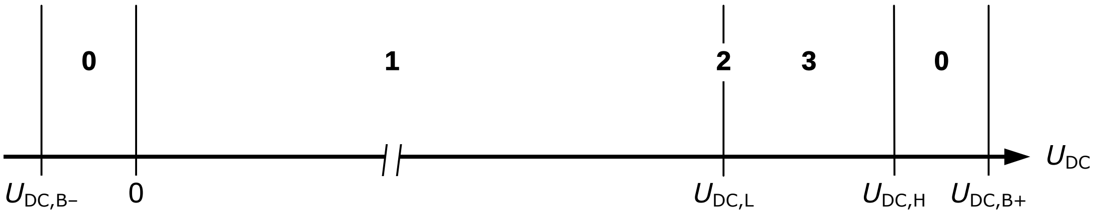
Figure 6: Structure of the grid current controller

The frequency-response curve of the compensating network has to be dimensioned according to the known theories of control engineering with regard to stability and response time. The latter must on one hand be long compared to the pulse period T of the inverter, such that the controller does not respond to the pulse-frequency ripple of the grid current $i_{Grid}(t)$. On the other hand, the response time must be short compared to the grid voltage period T_{Grid}, such that the control is able to track the grid current $i_{Grid}(t)$ accurately to the sinusoidal set value.

3. Standard for the operation of the DC bus

The following statements are meant as a discussion basis for manufacturers that are active in the domain of power conditioning for PV systems.

3.1 Voltage ranges



1 Start-up range
$y_{\hat{I}} = 0$
Power zero

2 Normal operating point
$0 \le y_{\hat{I}} \le 1$
Power controlled to $U_{DC} = U_{DC,L}$

3 Limitation range
$y_{\hat{I}} = 1$
Nominal (maximum) power

0 Operating ranges that occur only when the system is disturbed

$U_{DC,L}$	Lower operating voltage
$U_{DC,H}$	Higher operating voltage
$U_{DC,B+}$	Absolute limit for overvoltage
$U_{DC,B-}$	Absolute limit for inverse voltage

Figure 7: Operating ranges defined by the voltage levels of the DC bus

The following voltage levels are put to discussion:

$U_{DC,L}$	=	400 V	During normal operation, this voltage must be held within a tolerance range of +2,5% / –0 % by the power controller of the inverter.
$U_{DC,H}$	=	440 V	This corresponds to a usual nominal value of direct voltages. The inverter must be able to handle this voltage level continuously.
$U_{DC,B+}$	=	462 V	The absolute overvoltage limit is chosen 5% above the higher operating voltage. The inverter must be able to handle this voltage level during 10 minutes. Afterwards it may switch off but has to withstand the voltage continuously and must restart automatically. If the limit is exceeded, the inverter must disconnect automatically from the grid. It must restart only upon manual intervention.
$U_{DC,B-}$	=	–22 V	The absolute inverse voltage limit is chosen –5% of the higher operating voltage. The inverter has to withstand this voltage continuously; afterwards, it must restart automatically. If the limit is exceeded, the inverter must disconnect automatically from the grid. It must restart only upon manual intervention.

3.2 Dynamic behavior

3.2.1 Parallel capacitor to the DC bus

As part of the inverter, a parallel capacitor is connected to the DC bus which shall buffer a power difference between input and output during some grid voltage periods. Furthermore, it smoothes the ripple of double grid frequency that is caused on the DC bus by one-phase inverters.

The following specification is proposed:

- Related to the nominal power P, a capacitance of C/P = 1000 µF/kW (+20 % / –0 %) shall be provided.

(Considering the input resistance of the inverter at nominal power, $R = U_{DC}^2/P$, a time constant of $R \cdot C$ = 160 ms results.)

3.2.2 Power controller

The power controller has to follow the changes of the power supplied from the DC bus so quickly that the voltage changes over the parallel capacitance do not affect normal operation.

The following specification is proposed:

- If the power supplied on the DC bus changes abruptly from 100 % to 80 % of nominal power, the bus DC voltage must not sag by more than 10 % below the value of $U_{DC,L}$.
- The correction time of the control must not exceed 200 ms.

3.3 Potential against ground

The concept stipulates that the negative conductor of the DC bus lies at ground potential. For this purpose, the corresponding terminal of the inverter must be internally connected either to the grid-side terminal for the PE or PEN conductor (if present), or to a separate potential equalization terminal.

3.4 Electromagnetic compatibility

The high-frequency interference currents supplied to the conductors of the DC bus must not exceed the limits given in the European Standard EN61000-6-3 [4].

4. Reference publications

[1] Patent application No. 00516/09, "Gleichspannungs-Bus" (DC bus)
Swiss Federal Institute of Intellectual Property, 31st March 2009
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[3] Max Blatter:
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Part 2: Concept of a DC-DC converter including maximum power point tracking and DC bus control
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