TechnologyCompendium 3.4

PV Grid Integration

Backgrounds, requirements, and SMA solutions

4th revised edition, last revised: May 2012

CONTENT

Note: Current information on this topic can be found on the Internet at **www.SMA-Solar.com/gridintegration**

Introduction

The subject of grid integration coupled with renewable power generation is playing an increasingly important role. The powerful growth in Germany's photovoltaic capacity is attracting considerable attention – and rightfully so: According to data by the Federal Network Agency, a total of nearly 25 gigawatts of PV power has already been installed in the grid since the end of 2011. The PV plants consequently supply more than 16 large nuclear power plants under ideal irradiation conditions. The optimum integration of this decentralized and variable power generation capacity into the existing distribution grid (designed for unidirectional flows of power) is as crucial as it is pressing for that very reason.

Inverters as grid managers

For a long time, PV plants were only considered "negative consumers" with a pure active power supply. However, photovoltaics has increasingly been integrated into the grid regulations since 2009. For example, various system requirements for larger plants, which are ultimately targeted at improving the way decentralized power generation plants are integrated into the grids, are set out in art. 6 of the Renewable Energy Sources Act (EEG)[1] and the medium voltage directive[2] of the German Association of Energy and Water Industries (BDEW).

On January 1, 2012, fundamental new connection regulations according to which small and medium-sized PV plants are also required to provide system services now came into effect for the low-voltage

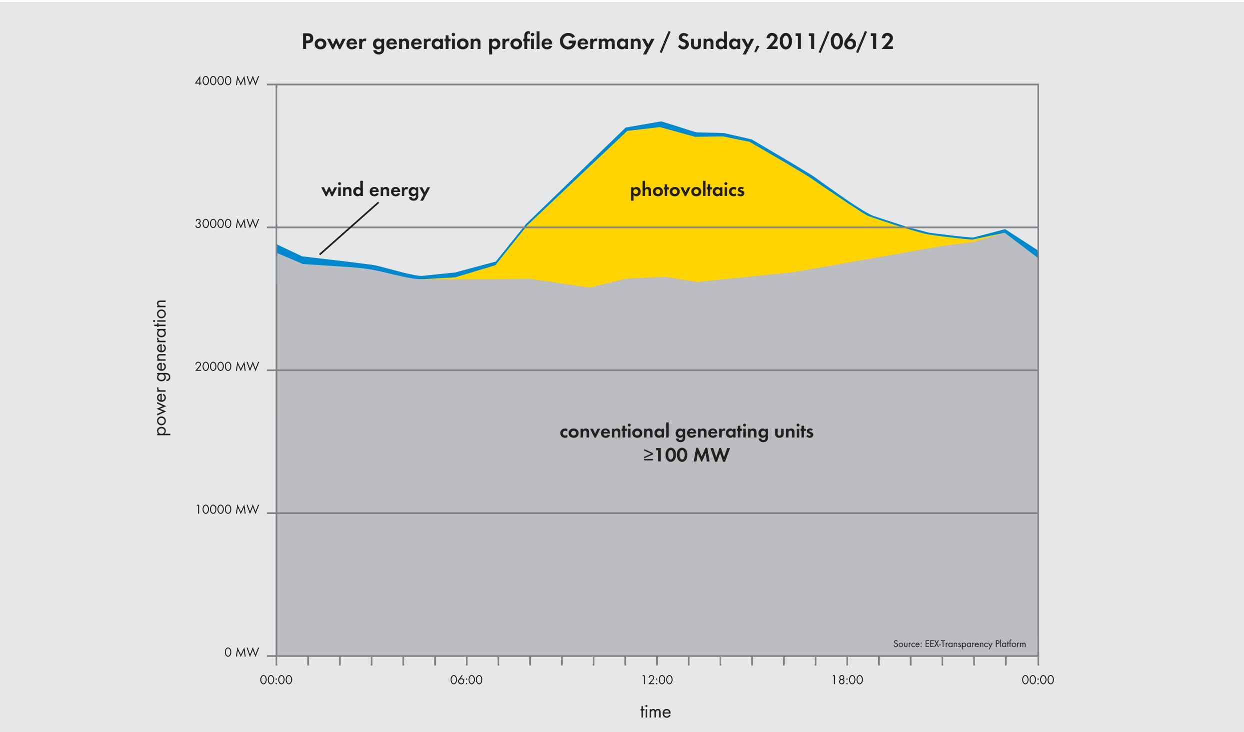

Fig. 1: Solar power can already entirely cover the noon-time peak in the German power distribution grid on sunny days

grid with the VDE 4105 code of practice[3], which after all receives around 85 percent of the PV power available in Germany. Being the market and technology leader in the field of PV system engineering, SMA has been very committed to the subject of grid integration from the very beginning by participating in the relevant committees and working groups, on the one hand, and by undertaking massive development efforts, on the other hand. With success: SMA inverters were among the first to achieve full compliance with the requirements of art. 6 of the Renewable Energy Sources Act (EEG) 2009 and the progressively adopted medium-voltage directive – including the additionally required communication technology. SMA will also offer suitable product solutions for the new VDE code of practice in due time.

The future starts now

There are already progressive approaches for the optimum grid integration of renewable power generation capacity that go beyond both directives: Comprehensive energy management at the household level, the incorporation of solar radiation forecasts, and the use of local storage systems are paving the way to the intelligent grid, the "smart grid". SMA is also committed to this field – with the development of the innovative Sunny Home Manager, the collaboration with PV forecast services, or the advancement of the proven Sunny Backup system for a grid-connected storage solution.

Whether it is coming from the European Photovoltaic Industry Association (EPIA)[4], the expert advisory board of the German federal government, or from the government in its own national action plan for renewable energy: Virtually all experts foresee a permanent increase in the share of solar power in Europe's energy mix. In addition to reducing energy production costs further, the optimum grid integration of photovoltaics is therefore of vital importance. As flexible, power electronic control elements, inverters are excellent at dealing with the system management tasks associated with this.

[1] Renewable Energy Sources Act (EEG)

[2] Directive of the German Association of Energy and Water Industries (BDEW) for the connection and parallel operation of power generation plants in the medium-voltage grid

[3] VDE-AR-N 4105: Generators connected to the low-voltage distribution network – Technical requirements for the connection to and parallel operation with low-voltage distribution networks

[4] European Photovoltaic Industry Association

1. The general conditions in Germany

1.1 The grid structure

Up until now, the respectively applicable regulations for connecting decentralized electricity generators to the grid have focused on the design of the power distribution grid, which is characterized by several voltage levels arranged in a hierarchy. The voltage level that the respective power generation plant feeds electricity into is generally the decisive factor; extra-high, high, medium, and low voltage levels are distinguished in that context.

The extra-high-voltage grid operates with 220 to 380 kV and is used for long distance transmission as well as the connection to the international power distribution grid. Energy is transferred regionally via the high-voltage grid operating with a voltage ranging from 60 to 110 kV. Large wind farms and large-scale PV plants also feed in power at this grid level.

The voltage in the medium-voltage grid is between 6 and 30 kV; the energy here is supplied to large consumers as well as transformer stations in the low-voltage grid. Municipal combined heat and power plants with cogeneration of heat and power, larger PV plants, and individual wind power plants feed the generated energy into the power distribution grid at the medium-voltage level.

Finally, the voltage in the low-voltage grid is 400 V (three-phase) or 230 V (single-phase). This grid handles the distribution of the energy to the end consumer; however, the lion's share of the PV plants installed in Germany also feed in their energy at this voltage level.

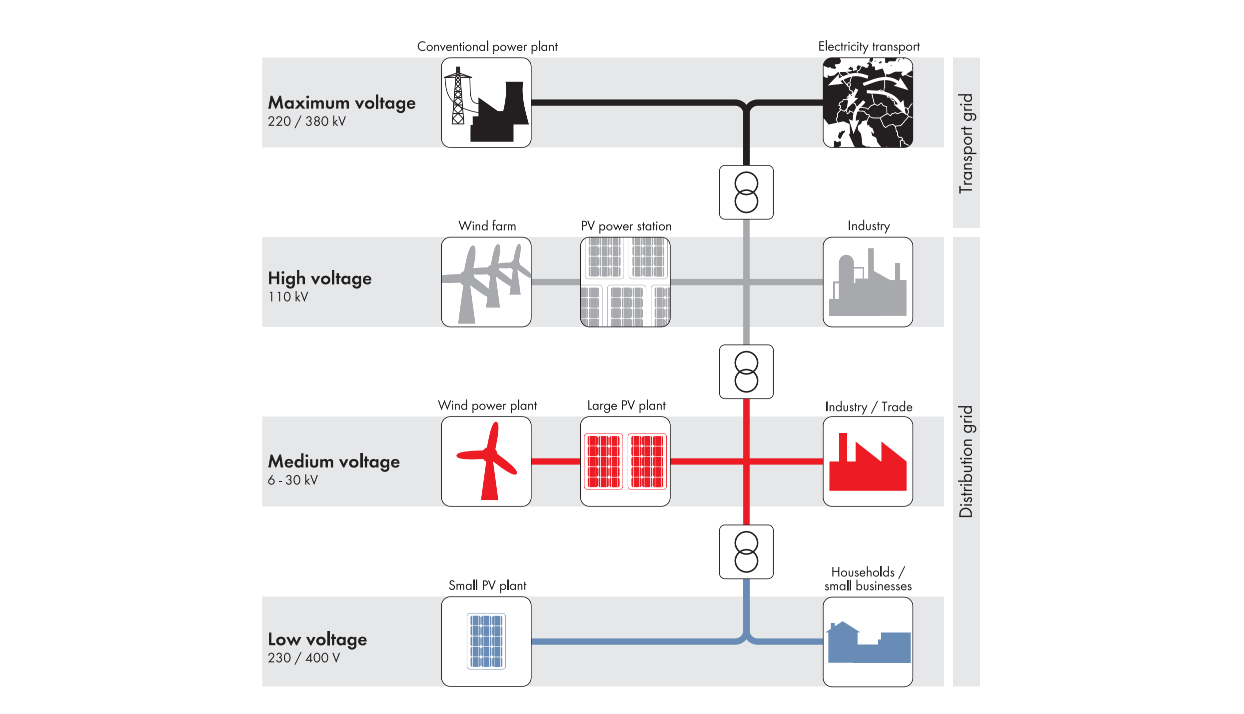

Fig. 2: The voltage levels in the German power distribution grid

1.2 Guidelines, rules and laws

Currently, there are three directives in Germany that establish requirements for PV plants in terms of grid integration:

The BDEW medium voltage directive
The BDEW medium voltage directive has been in place since January 1, 2009, and is for all power generation plants that feed in on the medium-voltage level (with the exception of plants with a capacity of less than 100 kW nominal power. They are governed by the VDE code of practice).

The VDE code of practice
The VDE 4105 code of practice has been in place since August 1, 2011, and binding since January 1, 2012, and affects all PV plants that feed in to the low-voltage grid, which means the vast majority of them.

The Renewable Energy Sources Act (EEG) 2012
The Renewable Energy Sources Act has laid down the requirements in terms of grid integration since 2009. The version passed on January 1, 2012, greatly expands on these requirements once again.

The transmission code governs the access to the high-voltage connections. Several requirements were adopted from it and incorporated in the medium-voltage directive; however, it will soon be replaced by a corresponding VDE code of practice. The first draft is expected to be released for commenting prior to the summer recess in 2012. It will likely be published at the end of 2012 or slightly later, depending on the number of objections raised.

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<tr><td>01/01/2009</td><td colspan="3">Feed-in management
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Fig. 3: Chronological sequence of the requirements for the BDEW medium voltage directive

2. The BDEW medium voltage directive

Since January 1, 2009, the revised medium voltage directive has been in effect for all power generation plants that feed at the medium voltage level into the power distribution grid – i.e., typically for plants with approximately 200 kW of power and more. The revised version was formulated by the German Association of Energy and Water Industries (BDEW). However, the network technology / network operation forum (FNN) newly created in 2008 – a committee of the VDE that also includes representatives of PV system technology manufacturers – was responsible for the final version. Its requirements may be divided into four stages, which successively came into effect.

2.1 Participation in feed-in management

If a section of the relevant medium-voltage grid or higher level transmission grid is temporarily overloaded, the distribution grid operator should be able to remotely limit the power of decentralized power generation plants in increments of no more than 10 percent of P_{nom}. To do this, the operator generally sends a ripple control signal that is processed accordingly and must be implemented as limitation of the fed-in active power (typically 60, 30 or zero percent of the rated power). The respectively required limitation must be implemented by the inverter within 60 seconds.

Note: The EEG has also called for participation in the feed-in management in art. 6 since January 1, 2009. The requirements are in many respects very similar to those of the medium voltage directive. However, the grid level into which the plant feeds is not definitive in the Renewable Energy Sources Act, but rather its nominal or installed power.

2.2 Active power reduction in case of overfrequency

The frequency in alternating current grids is kept constant within strict limits, in Europe at exactly 50 Hz. If more energy is taken from the grid than is fed in by the generators, the frequency will drop – it will rise in case of an energy surplus. Up to now, PV inverters had to disconnect from the grid immediately upon the power frequency exiting the permitted range of 47.5 to 50.2 Hz. Since the sudden disconnection of large PV power generation capacities always has a negative effect on the grid stability, the medium-voltage directive now demands frequency-dependent power regulation in the inverter: The devices should reduce their current power with a gradient of 40 percent per Hertz from 50.2 through 51.5 Hz and only disconnect from the grid above 51.5 Hz. The disconnection limit in case of underfrequency remains unchanged at 47.5 Hz.

Note: If the frequency drops again prior to reaching the disconnection limit, curtailing may still not be canceled in accordance with the characteristic curve. The inverter may only revert to feeding in at the maximum possible power if the frequency has dropped below 50.05 Hz (so-called drag pointer function). In addition, decentralized power generation plants may only increase their power slowly with a gradient of no more than ten percent of P_{nom} per minute after a complete disconnection in order to simplify the start-up of the grid by the grid operators after interference.

2.3 Provision of reactive power

The voltage must be kept within defined limits on all grid levels – especially in the distribution grid. However, voltage increases may occur there due to the increasing (active power) feed-in on the low and medium voltage levels, which make the connection of additional power generation plants more difficult or impossible. Furthermore, existing phase shifts and/or reactive power percentages in the grid reduce its transmission capacity and increase the accumulated transmission losses. The typical causes of phase shifts are transformers, large motors, or longer cable routes.

Inverters with reactive power capability can help to compensate the reactive power balance in the grid or keep the voltage stable at the grid connection point in order to ensure the voltage quality stipulated in EN 50160 in that manner. Consequently, the medium-voltage directive requires power generation plants to be able to supply or absorb both active and reactive power (leading or lagging phase shift). The grid operator may demand a displacement power factor cos(φ) of between 0.95 and 1 with three variations for the definition of the target value being available to that end:

1. The grid operator specifies fixed target values that the plant operator is required to set.

2. Various reactive power values are set on the basis of an agreed upon time schedule or specified via supervisory control signal by a central control center of the grid operator.

3. The reactive power percentage is regulated via a characteristic curve – depending on the grid voltage measured at the connection point or the ratio of the currently supplied active power and the nominal power of the inverter. The latter variation is frequently used when the PV plant strongly influences the voltage at the connection point. In that context, the voltage is supported at low output power levels while it is reduced at high output power levels in order to relieve the connection point. The grid operator provides the respective characteristic curve.

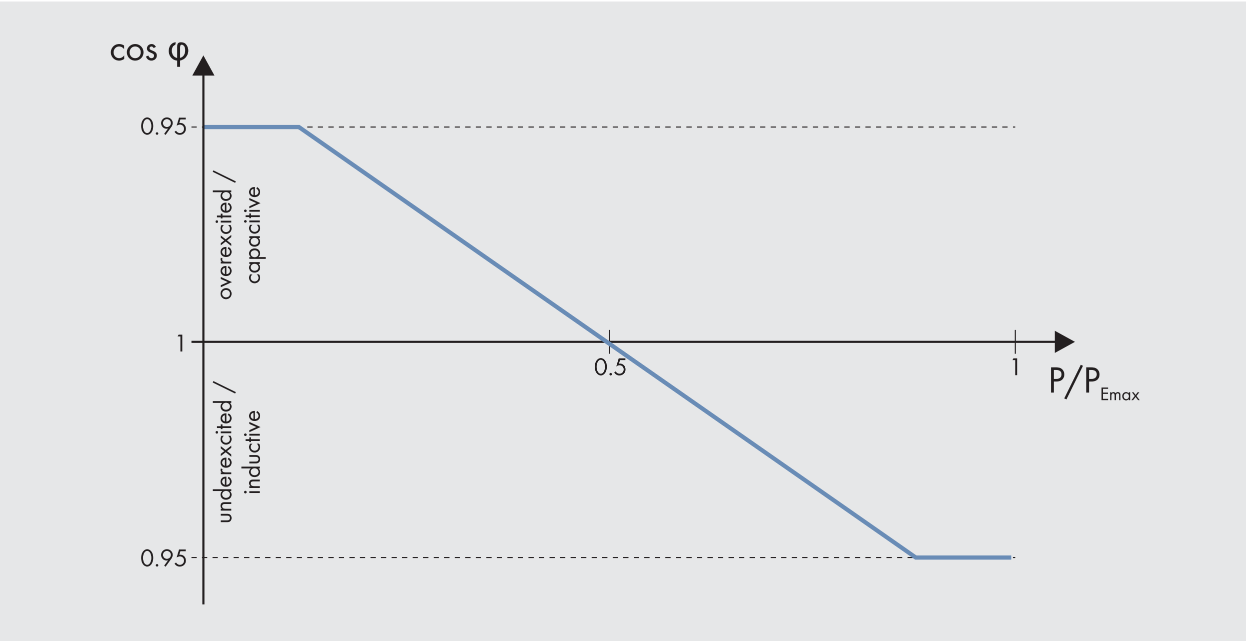


Fig. 4: Among others, the reactive power may be regulated as a function of the supplied active power

2.4 Dynamic grid support

In the past, local power generation plants had to disconnect from the grid immediately, even in case of brief drops in the grid voltage. However, this requirement has become problematic in light of today's significant power generation capacity, as even brief system incidents that are generally easy to manage could result in the sudden disconnection of larger power generation capacities under certain circumstances, resulting in an energy imbalance of the grid.

The revised medium-voltage directive now requires PV inverters to support the grid in case of an incident by "riding through" voltage drops of up to several seconds and then resuming normal feed-in immediately afterwards (so-called low-voltage ride-through, or LVRT). The inverter behaves passively throughout the course of the error in the limited version. The device also needs to feed reactive power into the power distribution grid during a voltage drop in the complete version of the LVRT, as it has been required since April 1, 2011. As a result, they contribute to the resolution of the incident and help to trigger the grid protection devices.

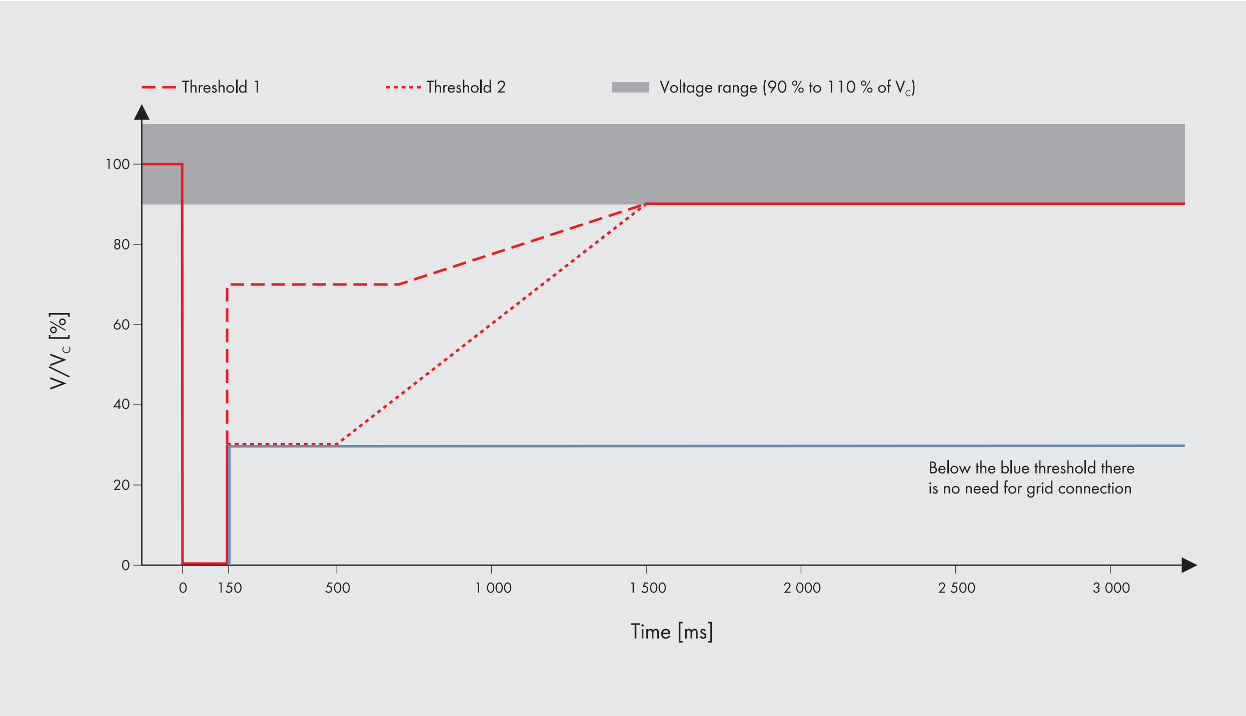


Fig. 5: The dynamic grid support requirements in detail

2.5 Equipment and plant certification

A unit certificate confirming conformity with all requirements of the medium voltage directive has become mandatory for each generation unit (i.e., each inverter type) at the same time as the dynamic grid support capability. The manufacturer receives this certificate following comprehensive testing of the respective device by specially authorized testing institutes. A simulation model, which may be used to simulate the behavior of the inverter in the event of an error, is also part of the respective certificate. In addition, the date of commissioning is decisive for the certification obligation.

If the total apparent power of a larger PV plant exceeds 1 MVA or the connection line to the grid is longer than two kilometers, the entire plant must also be certified. The so-called plant certificate is based on calculations and simulations utilizing a grid model and the respective unit models The settings of the protective devices and power generation plant parameters are defined here in order to facilitate compliance with the individual specifications of the grid operator. The plant certificate is required for the grid connection permit. It has the character of an individual agreement that must be negotiated separately as part of the feed-in agreement with the respective grid operator.

2.6 SMA product solutions

Being a pioneer in the field of grid integration, SMA offers a complete product range for the implementation of larger PV plants complying with the requirements of the medium voltage directive: PV inverters with the prescribed unit certificate confirming their conformity with the regulations have been available for both centralized and decentralized plant concepts since April 2011 In addition, SMA also has a wide range of product and system solutions available for the necessary communication tasks, which also fulfils individual requirements.

SMA Utility Grade is an integrated concept that bundles SMA system engineering and services to enable successful power plant projects. All products and services that have this label meet the high and complex requirements demanded of modern, competitive PV power plants. In addition to unit certificates for all Utility Grade inverters, SMA also offers support for simulated inspections of the grid connection. An example is the calculation of the PQ diagram of the entire PV plant taking into consideration the topology and plant’s own electric equipment.

If there are characteristics available for the connected grid, it is also possible to perform dynamic simulations based on inverter models developed by SMA. When using the inverter models in your own studies, SMA also offers support in performing them.

UTILITY
GRADE

2.6.1 Centralized plant concepts

The inverters of the Sunny Central CP production series already fulfilled all requirements of the medium voltage directive including full dynamic grid support upon their market introduction.

Their enclosure suitable for outdoor use renders the need for a heavy concrete station obsolete. In addition, their power characteristics match the temperature-dependent behavior of PV modules in an ideal manner: The compact devices deliver a full 10 percent more than the specified nominal power during continuous operation at outdoor temperatures up to 25 °C; the nominal power only marks the actual limit at 50 °C. Accordingly, a Sunny Central 800CP can deliver 880 kVA of apparent power at 25 °C which still yields 836 kW of active power, even with a displacement power factor of 0.95.

Due to these and other characteristics that all contribute to the reduction of the system costs, the Sunny Central CP was the winner of the Intersolar Award in 2010. The prescribed unit certificates are available for all power variations (500, 630, 720, 760, and 800 kVA); as a result, maximum planning reliability is achieved.

2.6.2 Decentralized plant concepts

Decentralized large-scale PV plants may easily and flexibly be implemented with the three-phase feeding in Sunny Tripower. This device was recognized with the Innovation Award by the PV symposium Bad Staffelstein in 2010 and also fulfills all requirements of the medium voltage directive, in addition to VDE 4105 code of practice.

So far, the Sunny Tripower is available in six power variations, which may be combined in an arbitrary manner. And with the exception of the 8 kVA model, all include the corresponding unit certificates. The Sunny Tripower 20000TL High Efficiency with 20 kVA nominal power, available since the beginning of 2012, offers a maximum conversion efficiency rate of 99.15 percent by concentrating on the essentials and being the first to use silicon carbide switches in a series-produced inverter. The inverter is ideally suited for high-efficiency medium to large-scale PV plants because the specific price has also been reduced.

Bestseller with power reserves: Sunny Central 800CP

World champion in efficiency: Sunny Tripower 20000TLHE

2.6.3 Remote power limitation

Since the beginning of 2009, SMA has offered the Power Reducer Box for remote power limitation required by both the medium voltage directive and art. 6 of the Renewable Energy Sources Act (EEG). The device provides the communication interface between the grid operator and the plant. A radio ripple control receiver is typically used for the target value transmission. It receives the specifications of the grid operator, for instance via longwave radio (similar to the DCF77 time signal), and makes them available via four relay contacts.

The SMA Power Reducer Box converts the incoming signal into a control command for the Sunny WebBox, which in turn communicates with the inverters. In the process, each switching procedure is logged both in the Power Reducer Box and in the Sunny WebBox – as a result, this data may be accessed via the Sunny Portal from anywhere in the world.

2.6.4 Remotely controlled reactive power setpoint and reactive power control

As an alternative to the active power specifications, the Power Reducer Box is also able to process target values for the reactive power or the displacement power factor cos(φ) and consequently facilitates the variable specification of the reactive power by the grid operator. The control of the reactive power as a function of the voltage at the grid connection point or other, more complex control tasks may be implemented by means of a flexibly programmable logic controller or the SMA Power Plant Controller. It can actively control both centralized and decentralized large-scale plants (one or several Sunny WebBoxes may be required in the latter situation).

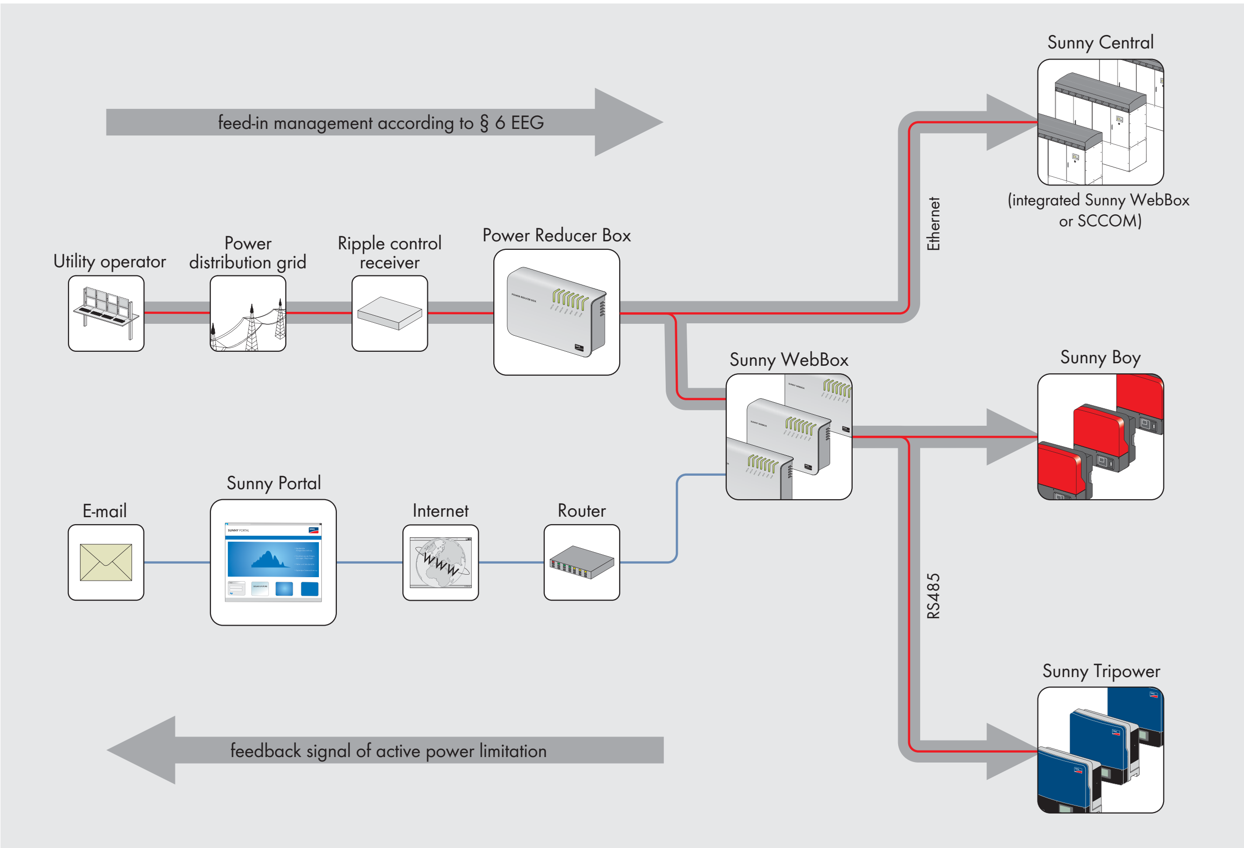


Fig. 6: Remote power limitation with the SMA Power Reducer Box

3. The VDE 4105 code of practice

The VDE-AR-N 4105, often also referred to as "low voltage directive," is the amended version of the VDEW guideline "Generators connected to the low-voltage distribution network" following thorough revision by the network technology / network operation forum in the VDE. It came into effect on August 1, 2011, and is binding for all new PV plants starting on January 1, 2012. Being the leading manufacturer of PV inverters, SMA also participated in the revision of the code of practice within the framework of the FNN.

The requirements are in many respects very similar to those of the medium voltage directive: On the one hand, the aim is to support the voltage and avoid extension measures by providing reactive power. On the other hand, the goal is to achieve a gradual reduction of the PV plant power while the power frequency rises. Background: In 2009, the PV power installed in the German low-voltage grid already exceeded the European spinning reserve, which meant that the disconnection conditions previously applicable to grid-connected PV plants in the low-voltage grid were no longer viable. Another focus is on the topic of "three-phase feed-in"; the connection criteria and targets for symmetry and unbalanced load are defined more clearly here than in the past.

Note: VDE-AR-N 4105 is also binding for power generation plants on the medium voltage level, providing their nominal power is less than 100 kVA.

3.1 Basic requirements

The requirements of the VDE code of practice are manifold, although some are only valid for certain applications or upwards of a certain plant power. For this reason, the following is a list of the basic requirements with which each inverter and each PV plant are required to comply.

3.1.1 Active power reduction in case of overfrequency

This directive has no impact on planning a PV plant and the consequences for the respective yields are negligible. However, it is extremely important for grid safety. The problem: According to the previous connection regulations, PV plants had to disconnect from the grid instantly when the power frequency was too high. However, the simultaneous disconnection of the now installed PV power in the German low-voltage grid could lead to instabilities in the European power distribution grid (see "The 50.2 Hz problem").

For this reason, PV plants should not disconnect immediately when the power frequency is too high, but first reduce their power on an infinitely adjustable scale. The permissible frequency band will be expanded to a range from 47.5 to 51.5 Hz accordingly. The current feed-in power must be reduced by 40 percent/Hz. The plant needs to be disconnected only if 51.5 Hz is attained. According to this characteristic curve, the curtailing percentage is always based on the current power when the 50.2 Hz mark is exceeded. If the irradiation conditions improve in the meantime, the inverter may only increase its power with a defined slope to the new, non-throttled maximum value upon dropping below the curtailing limit. The increase in power may take several minutes.

Note: This point is practically identical with the corresponding requirement of the medium voltage directive. The only difference: While inverters may only cancel curtailing at the medium voltage level again upon the frequency dropping below 50.05 Hz, the VDE code of practice stipulates "operating" according to the characteristic curve.

Retrofitting requirements

Many of the existing plants pose a difficulty in terms of the 50.2 Hz issue. They were initially parameterized by disconnection criteria that were once valid but not advantageous in terms of technology. For this reason, one key solution approach is to gradually retrofit or modify these existing plants, in addi-

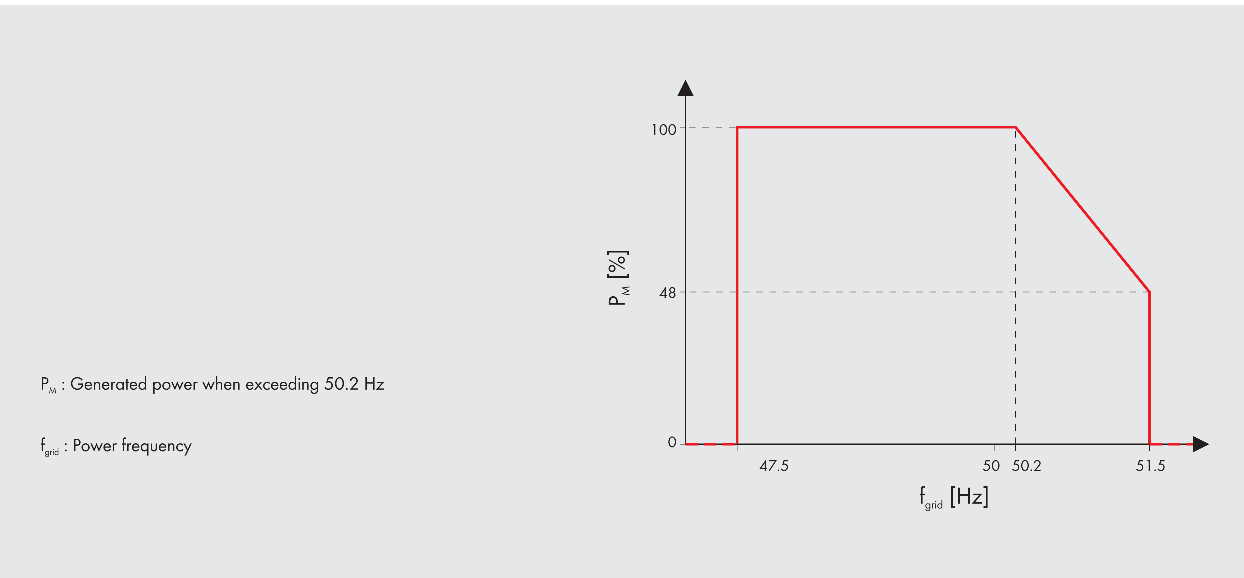


Fig. 7: The frequency/active power characteristic curve in accordance with the VDE code of practice: The power is limited from 50.2 Hz.

tion to the transition of the connection regulations for new plants. However, it is not clear when the retrofitting needs to start and be completed. Yet, the costs will be split between the EEG payment provisions and the grid feed payment as adopted in the EEG amendment by the Bundestag on March 29, 2012.

It is expected that a regulation "to ensure the technological system stability and safety" will be passed sometime in 2012, regulating all requirements and possible sanctions for plant operators. It is already clear that the retrofitting requirement affects all PV plants that were connected after August 30, 2005, and exceed a capacity of 10 kWp. Similar to retrofitting in the 50.2 Hz transition regulation, either the existing characteristic curve function is activated or the disconnection limit of 50.2 Hz is set to a higher value. It may be necessary to update the firmware of some older inverter types in order to use the characteristic curve function from the BDEW medium voltage directive. SMA will prepare a technical description on the details for the retrofitting work for all device types that are affected in good time.

3.1.2 Connection criteria and permissible unbalanced load

The connection criteria have become clearer as far as the maximum unbalanced load is concerned: a general limit of 4.6 kVA per phase applies and the previous option of feeding in up to 110 percent of this power as a single phase has been dropped. Hence, a maximum plant power of 13.8 kVA results when using single-phase, uncoupled inverters (3 x 4.6 kVA) only. Therefore, at least the proportion of the power exceeding 13.8 kVA must be designed with three-phase or communicatively coupled single-phase inverters in larger plants. Conversely, larger three-phase plants may also be supplemented with single-phase and non-coupled devices as long as their aggregate power of 4.6 kVA per phase is not exceeded. For the Sunny Mini Central production series, SMA provides for this coupling with the Power Balancer function. This ensures that if even if a device fails, no incorrect unbalanced load may occur in this case either.

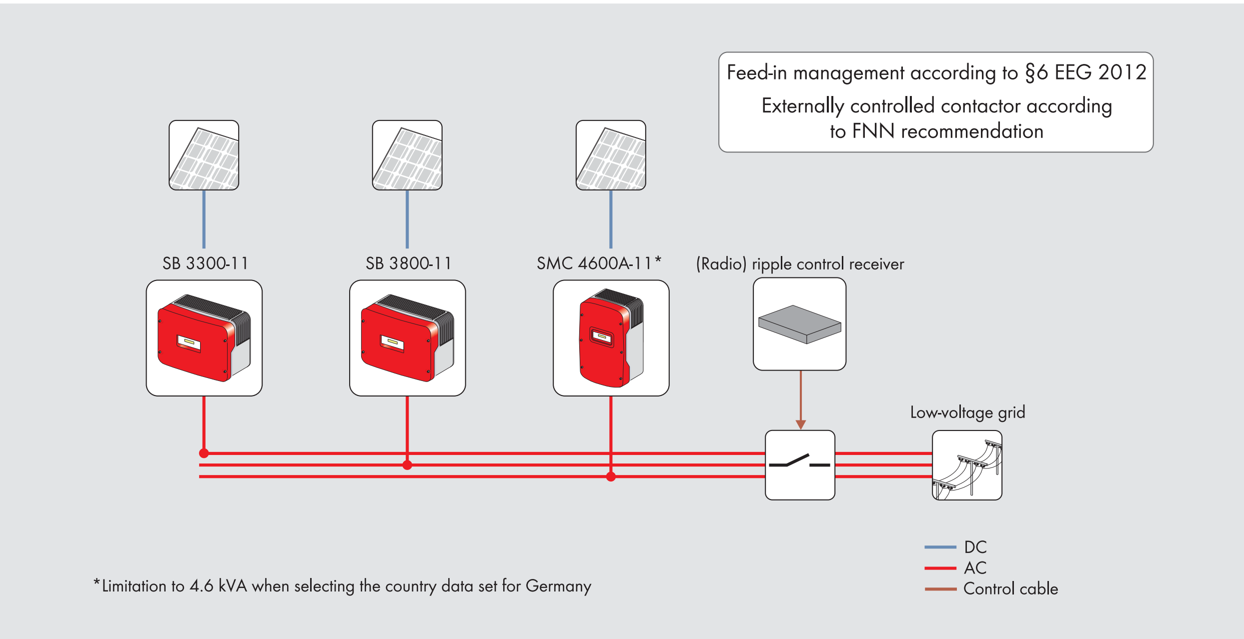


Fig. 8: The VDE code of practice allows a maximum of 4.6 kVA of apparent power from single-phase inverters per phase

3.1.3 Grid and plant protection

An additional new requirement concerns grid and plant protection (short: G/P protection), i.e., the protective device that monitors all relevant grid parameters and disconnects the plant from the grid, if necessary. A freely accessible disconnection point for plants with more than 30 kVA of apparent power is no longer required, but more extensive grid monitoring including the power frequency and single error safety is stipulated in return.

Plants with less than 30 kVA of apparent power may still be operated with G/P protection integrated in the inverter. The higher requirements that apply here, including the fail-safe protected switch device, have already been met by SMA inverters for a long time. If all inverters include separate stand-alone grid detection with grid disconnection via the tie breaker integrated in the device, separate stand-alone grid detection may be omitted in the central G/P protection. This solution is a considerable cost-saver and is possible with all SMA inverters.

Set values for the G/P protection:

Deactivation limits:

Voltage drop protection (U <)	< 184 V
Voltage increase protection (U >)	> 253 V
Voltage increase protection (U >>)	> 264.5 V
Frequency drop protection (f <)	< 47.5 Hz
Frequency increase protection (f >)	> 51.5 Hz

Reconnection limits:

Voltage greater than 195.5 V and less than 253 V
Frequency greater than 47.5 Hz and less than 50.05 Hz

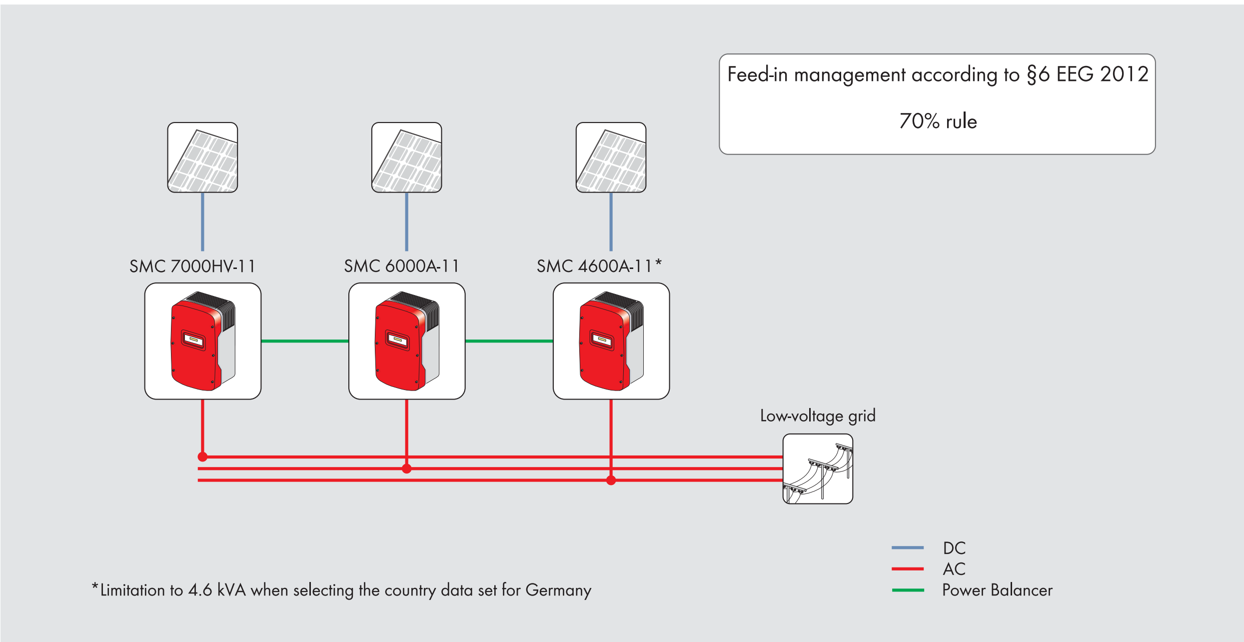


Fig. 9: Another option includes the communication-based coupling of three single-phase Sunny Mini Central inverters

3.2 Supplementary requirements

The following requirements of the code of practice are only valid for a certain plant power. The three-phase feed-in connection criteria and specifications are considered a special situation. The topic has already been addressed in the basic requirements due to the modified unbalanced load and the new approach. The topic will be addressed here again because the specifications also contain an indirect power limit.

3.2.1 Provision of reactive power

Far more PV plants can utilize the existing infrastructure of the low-voltage grid by means of inverters with reactive power capability; as a result, the supply of reactive power is also now required on this voltage level. Background: The feed-in of active power into the low-voltage grid with its predominantly ohmic properties generally results in an increase of the voltage at the feed-in point. In the case of long network feeder, an additional aspect is that the voltage must already be set higher on the transformer side in order to ensure that the lower voltage threshold of 207 V is still maintained at the consumer.

If active power is to be fed in on the side of the consumer now without absorbing power of a similar magnitude at the same time, the upper voltage limit may be exceeded at the feed-in point (fig. 10). However, inverters may lower the voltage at the grid connection point by simultaneously consuming lagging reactive power. Consequently, the code

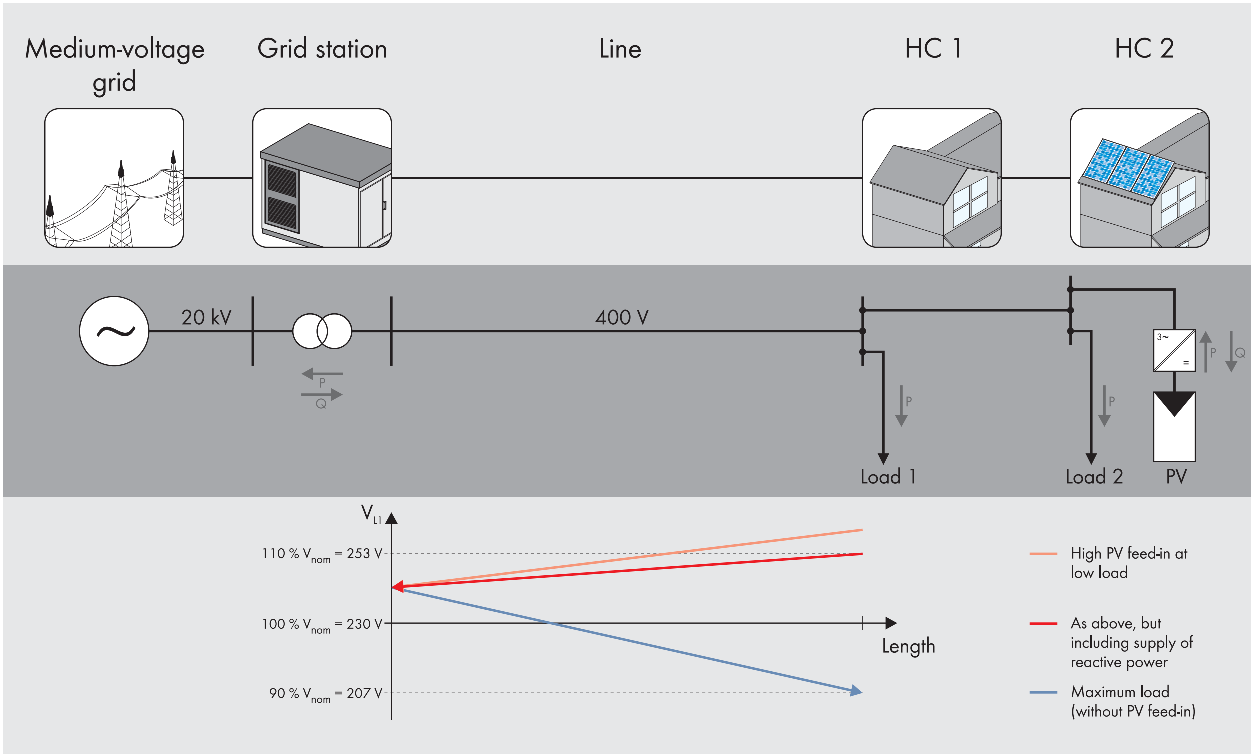


Fig. 10: The required voltage setting may cause the maximum voltage to be exceeded at the feed-in point. The solution: lagging reactive power

of practice requires the capability of the inverters to feed in with displacement power factors up to $0.95_{lagging/leading}$ from an apparent plant power of 3.68 kVA If the plant power exceeds 13.8 kVA, even displacement power factors up to 0.9 must be supported.

Important: The present plant power is included when expanding or retrofitting existing plants. As a result, limiting values that are based on the new total power apply to the newly added plant section. However, contrary to the medium voltage directive, the VDE code of practice forgoes requiring the remote, variable cos(φ) specification. The respective target value is either specified as a fixed value or results from the currently supplied active power as detailed in a standardized characteristic (fig. 11): The respective inverter must feed in without phase shift up to half its nominal power of active power. After that, it is to be steadily increased until it operates at full nominal power with the maximum displacement power factor (underexcited) valid for the respective plant. This standard characteristic curve should already be preset in the delivery state of the devices.

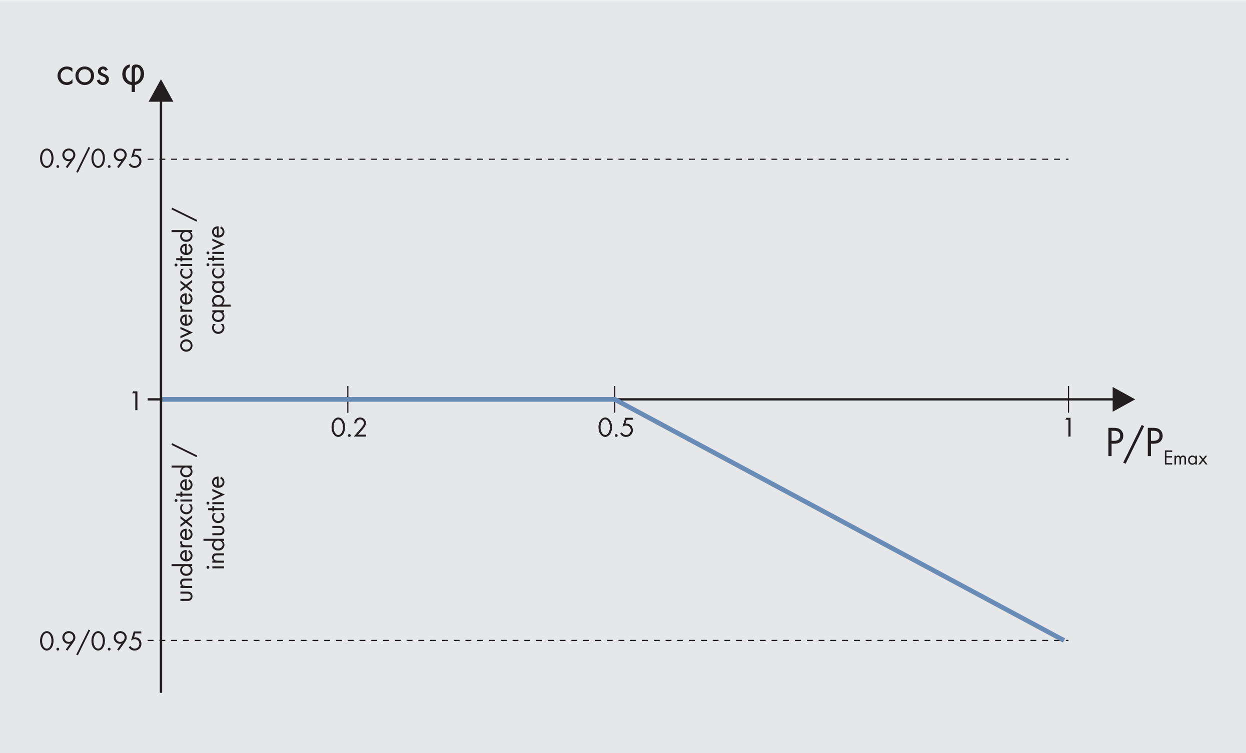


Fig. 11: Power generation units must absorb lagging reactive power above 50 percent of their nominal power in order to reduce the voltage

3.2.2 Three-phase feed-in

The code of practice aims to achieve the goal of actively balancing the voltage in the low-voltage grid by having larger plants feed into the grid as symmetrically as possible. However, there are not any special regulations for plants exceeding 13.8 kVA; the unbalanced load of 4.6 kVA per phase applies independent of the power, even in case of an error.

Yet the unbalanced load limit means that at least a portion of the plant power exceeding the 13.8 kVA needs to feed in using three-phase voltage. In addition to deploying three-phase inverters, there is also another solution in the communication-based coupling of single-phase inverters into three-phase feed-in units, such as the ones SMA offers with its Power Balancer for the Sunny Mini Central production series. With this option, if one device fails, the other devices are also disconnected so that no significant unbalanced load can occur (see also section 3.1.2).

3.2.3 Remote power limitation

The distribution grid operator should also be able to remotely limit the power of PV plants in increments of no more than 10 percent of P_{nom} in the low-voltage grid (in that context, proven increments are 60, 30, or zero percent of the nominal power). Among others, conceivable reasons for a power limitation include the operation of emergency generating units, a short term overload of the superordinate medium-voltage or transmission grid, or a system-endangering frequency increase. This requirement of the code of practice applies to all plants with more than 100 kW of power and is otherwise comparable to that in the medium voltage directive.

Note: According to art. 6 of the Renewable Energy Sources Act (EEG) 2012, the feed-in management will also apply to plants with a nominal power of less than 100 kWp (see also section 4).

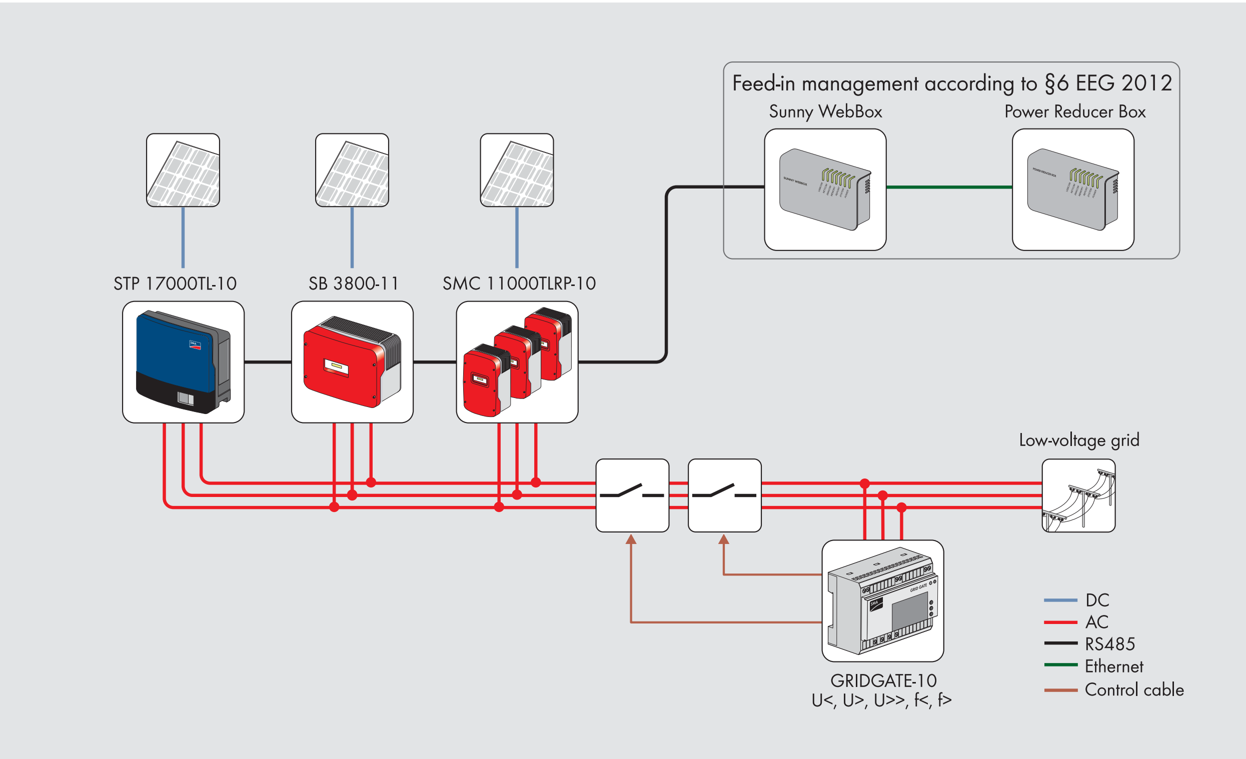


Fig. 12: Single-phase inverters can only be designed with a maximum of 4.6 kVA of total apparent power per phase in accordance with AR 4105

3.3 SMA product solutions

SMA provides PV inverters that conform to the requirements of the new code of practice in terms of all relevant power ranges. In addition, SMA offers communication solutions for the participation in the feed-in management and grid and plant protection conforming to AR 4105 (SMA Grid Gate). The table below provides a product overview. In addition, an overview poster that gives an example of two plant configurations for five different power classes each is available at SMA. They comply with the requirements of the VDE code of practice and the Renewable Energy Sources Act 2012.

Product identification	**S_{max} [kVA]**	**Fulfillment of the basic requirements**	**Reactive power-capable** (Use for plants > 3.68 kVA)	**Use for plants > 13.8 kVA**
SB 1200/1700/2500/3000	1.2/ 1.7/ 2.5/ 3	✓	–	–
SB 1300/1600TL-10	1.3/ 1.6	✓	–	–
SB 2100TL	2.1	✓	–	–
SB 2000/2500/3000HF-30	2/ 2.5/ 3	✓	–	–
SB 2500/3000TLST-21[3)]	2.5/ 3	✓	✓	–[2)]
SB 3300-11/3800-11	3.6/ 3.8	✓	✓	–[2)]
SB 3000/3600/4000/5000TL-21[3)]	3/ 3.68 / 4/ 4.6[1)]	✓	✓	–[2)]
SMC 4600A-11	4.6[1)]	✓	✓	With communicative coupling
SMC 5000/6000A-11	5.5/ 6	✓	✓	With communicative coupling
SMC 7000HV-11	7	✓	✓	With communicative coupling
SMC 9000/10000/11000TLRP-10	9/ 10/ 11	✓	✓	With communicative coupling
STP 8/10/12/15/17000TL-10[3)]	8/ 10/ 12/ 15/ 17	✓	✓	✓
STP 15000/20000TLEE-10[3)]	15/ 20	✓	✓	✓
STP 15000/20000TLHE-10[3)]	15/ 20	✓	✓	✓
Feed-in management:	Power Control Module, Sunny WebBox and Power Reducer Box			
Grid and plant protection:	SMA Grid Gate			

1) Limitation to 4.6 kVA when selecting the country data record for Germany only
2) Deployable while observing the 4.6 kVA unbalanced load limit
3) Compatible with the Power Control Module

4. The Renewable Energy Sources Act (EEG)

The Renewable Energy Sources Act (EEG) as amended mid-2011 and valid from the beginning of 2012 also includes new requirements regarding the grid integration of PV plants. It now stipulates unequivocally that plants with more than 100 kW peak power must participate in feed-in management and, at the same time, extends this demand to smaller plants – albeit in somewhat less stringent form: for instance, there is no longer any obligation to let the distribution grid operator retrieve the current actual power of the plant. Furthermore, operators of PV plants with less than 30 kWp of power may skip installing the device for remote power limitation if they accept a general limitation of feed-in power to 70 percent of the installed generator power in return.

As for the obligation to retrofit, both power categories also differ: plants between 30 and 100 kWp are to be retrofitted by the end of 2013, if they were commissioned after December 31, 2008. There is no obligation to retrofit plants with less than 30 kWp.

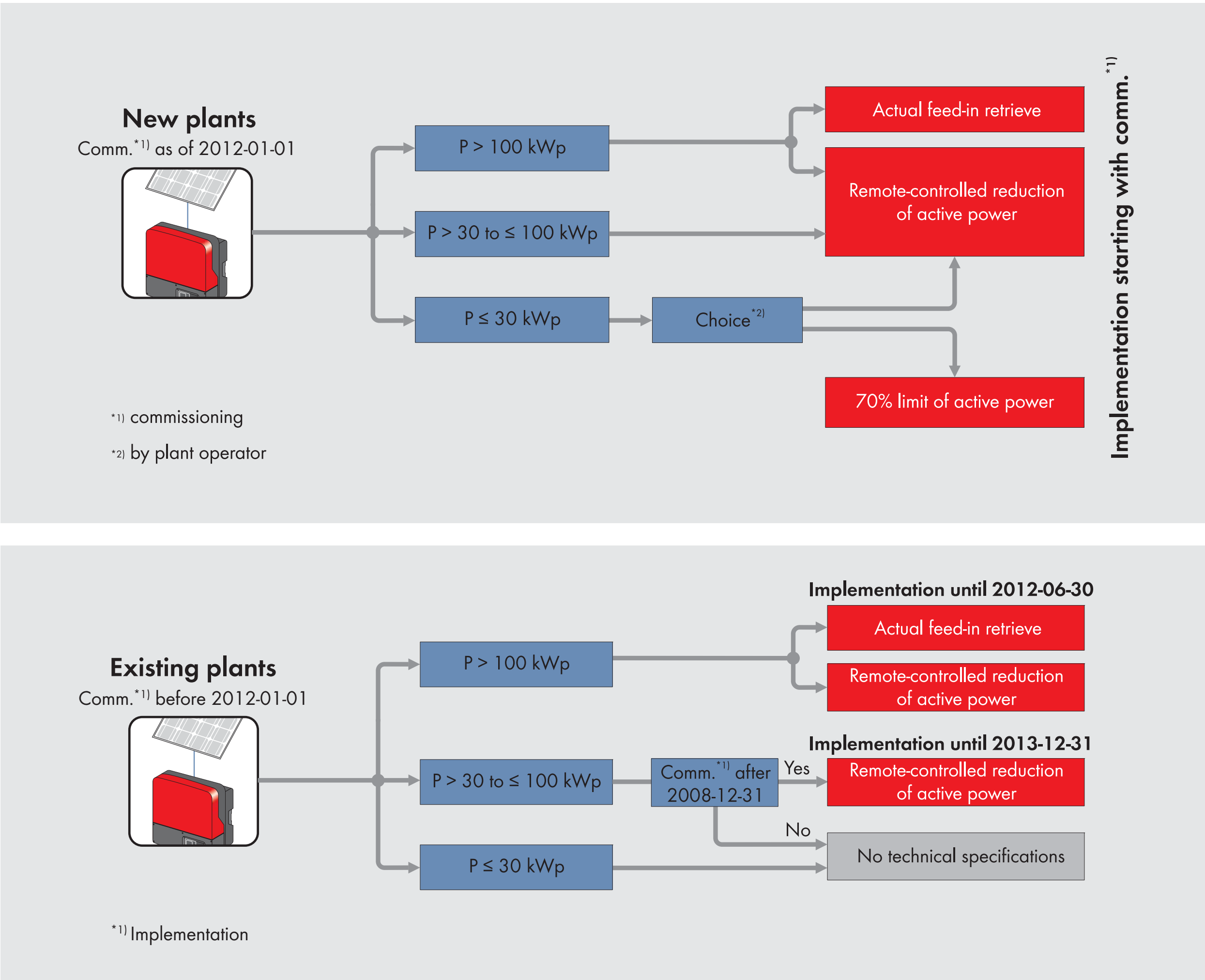


Fig. 13: Requirements of the EEG 2012 on the participation of new and existing PV plants in feed-in management

4.1 FNN recommendation and EEG transition period for simplified feed-in management

The practical introduction of the simplified feed-in management for smaller PV plants before the beginning of the year has proved to be difficult, since many grid operators still do not have the necessary control technology. Since according to art. 11 of the EEG in PV plants ≤ 100 kWp, feed-in management measures are implemented as a second-tier option (first, conventional generators are curtailed, then EEG generators > 100 kWp, and only then PV plants ≤ 100 kWp), it is unlikely that specific curtailing will take place in the coming years.

For this reason, the FNN published a recommendation in agreement with the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety in December 2011. This body recommends the installation of an externally controlled relay or contactor, and if necessary a (radio) ripple control receiver (fig. 14) as a compromise. This equipment enables the remote curtailing of plant power to 0 percent as soon as the distribution grid operator himself has the relevant control technology at his disposal. The Federal Ministry for the Environment, Nature Conservation and Nuclear Safety and the Federal Ministry of Economics and Technology published an application note on December 21, 2011.

Furthermore, the Bundestag agreed on a transitional period for PV plants ≤ 100 kWp in terms of participation in the feed-in management as part of the recent EEG amendment on March 29, 2012. All plants commissioned in 2012 are required to be capable of remotely limiting the active power starting on January 1, 2013. The version with the limitation to 70 percent for plants up to 30 kWp will only be relevant as of this date.

Compared to the possible yield losses incurred by capping feed-in capacity at 70 percent of generator nominal power, the installation of an additional contactor (and ripple control receiver, if required) is usually the cheaper option. Furthermore, SMA is working on an inverter-integrated solution for active power limitation.

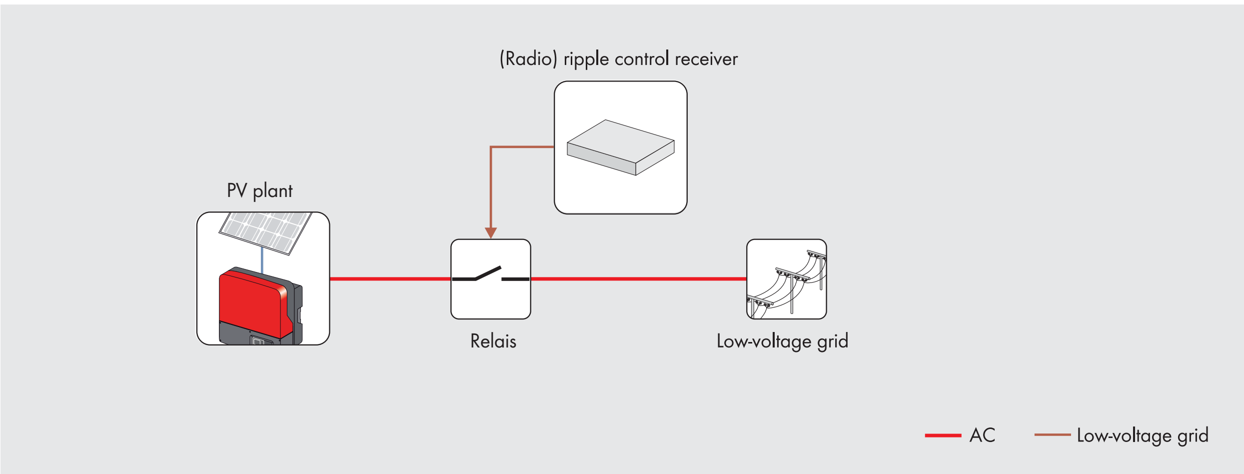


Fig. 14: Remote controlled disconnection: The FNN recommendation for simplified feed-in management for PV plants ≤ 100 kWp

4.2 Design according to the 70 percent option

The application of the 70 percent option is only advantageous if the maximum expected feed-in capacity on the grid-connection point is substantially less than the generator nominal power. Typical situations include a heavy shading of the modules, substantial self-consumption at the same time as the generation maximum or east/west-facing PV arrays because the maximum power of the substrings will never occur simultaneously. SMA's design program, Sunny Design, can take this into account when sizing the inverters from version 2.20 and later. SMA will provide information on any new inverter-integrated solutions or solutions in conjunction with the Sunny Home Manager in due time.

Note: The potential yield losses increase disproportionately as the size of the inverter becomes smaller. If intermediate sizes are yielded by the design when applying the 70 percent option, it is often not cost-effective to choose the next smaller device version. Normally, you should choose the next larger inverter and limit it based on the corresponding parameterization to the precisely required power value.

4.3 Retrofitting older PV plants

Based on today's perspective, the required retrofitting of older PV plants is not a problem. The appropriate technology is available for plant and distribution grid operators for plants with more than 100 kWp, meaning that retrofitting work could be completed by mid-2012 without any difficulties. For this reason, SMA has offered the Power Reducer Box since the beginning of 2009 as a solution for remote power limitation.

PV plants between 30 and 100 kWp can be retrofitted in accordance with the FNN recommendation. However, we expect to encounter more technically demanding solutions for the feed-in management before the retrofitting deadline at the end of 2013.

5. PV grid integration outside Germany

The optimum grid integration of PV plants is also of great interest to many committees, authorities, and institutions outside Germany. A first draft of the European Network of Transmission System Operators for Electricity (ENTSO-E) for a corresponding European directive is available on the European level.

The new CEI 0-21 standard governing the connection of power generation and consumption plants in the low-voltage grid was published in Italy in December 2011. The corresponding transition regulations were established by the AEEG 084-12 from March 8, 2012. Two annexes to the Italian Grid Code call for new PV plants to have the frequency-dependent active power limitation on all voltage levels and for the expansion of the frequency band for existing medium-voltage plants. The CEI 0-21 is just the first step in the direction of an optimized grid integration of PV plants. The standard CEI 0-16 for plants on the medium voltage level is expected to be revised shortly as well. Due to royal decree RD 1565/2010, dynamic grid support is already mandatory for all PV plants exceeding two megawatts in Spain today, even retroactively for existing plants with a certain transitional period.

Regulations comparable to those of the medium voltage directive of the German Association of Energy and Water Industries (BDEW) are also being discussed and demanded in the United States and Canada, e.g., by the North American Electric Reliability Corporation (NERC), the Institute of Electrical and Electronics Engineers (IEEE), and other institutions, as well as grid operators.

6. Background information: reactive power

As it happens, the ability to provide reactive power is just one of many requirements of the new directives for improved grid integration. However, the topic of reactive power is predestined to lead to misunderstandings with regard to the physical principles, the technical correlations, and last but not least, the effects on the plant planning. Against this backdrop, since 2009, SMA has offered informational material that explains the technical background of reactive power provision and the impact on plant planning using example calculations.

6.1 What is reactive power?

The correlations are still simple in terms of direct current: The product of voltage and current is referred to as power; the unit of power is the watt. However, matters are more complex for alternating current: The intensity and direction of current and voltage change here at regular intervals. Both exhibit a sinusoidal curve with a frequency of 50 Hertz* in the power distribution grid. The product of the pulsating current and the pulsating voltage consequently specifies a pulsating power.

However, the alternating current power can assume differing forms – depending on whether current and voltage are phase-shifted or not. Without a phase shift (current and voltage reach their maximum and minimum values at the same time), the power oscillates between zero and the positive maximum value. This consequently results in a positive power

*Also 60 Hertz in certain countries

value in the temporal average; only active power is generated (fig. 15). In contrast, the power assumes alternating positive and negative values during a phase-shift of 90 degrees or ¼ period (maximum current at zero voltage). The temporal average is consequently zero; this is known as reactive power, which effectively "shuttles back and forth" in the lines (fig. 16). During smaller phase shifts, the power fluctuation is only pushed slightly below the zero line; a mixture of reactive and active power results in this case.

The following generally applies: Only active power is actually usable power. It may be used to power machines, operate electric heaters, or make lamps glow. The matters are different for reactive power: It cannot be consumed and consequently cannot perform electrical work. Instead, it simply shuttles back and forth in the power distribution grid and consequently burdens it further.

The sum of active and reactive power is the so-called apparent power. It is to be noted in this context that they are not added "normally," but geometrically: Active and reactive power form the catheti of a right-angled triangle; the hypotenuse corresponds to the apparent power. In other words, 5 kW of active power and 3 kvar of reactive power result in just 5.8 kVA of apparent power. However, all components of an alternating current circuit must be designed for the resulting apparent power on principle (also refer to 6.3).

As the phase shift can occur in two directions, there are also two types of reactive power: lagging and leading. A consumer will absorb reactive power or behave in a lagging manner if the current phase follows the voltage phase – it will behave in a leading manner or supply reactive power in the opposite case. If a generator produces reactive power, it is also referred to as overexcited operation (or under-excited operation in the case of reactive power absorption).

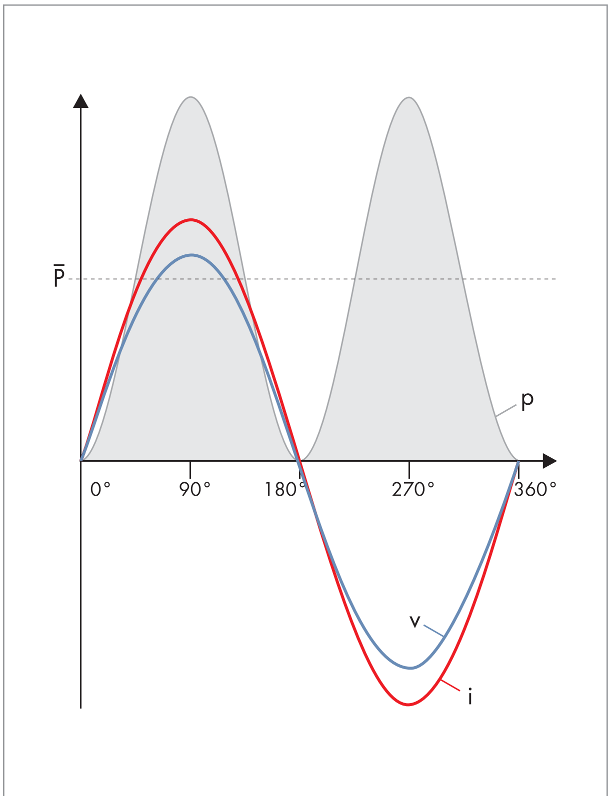


Fig. 15: Fluctuating, but always positive power – pure active power – results when the current i and the voltage v are in phase

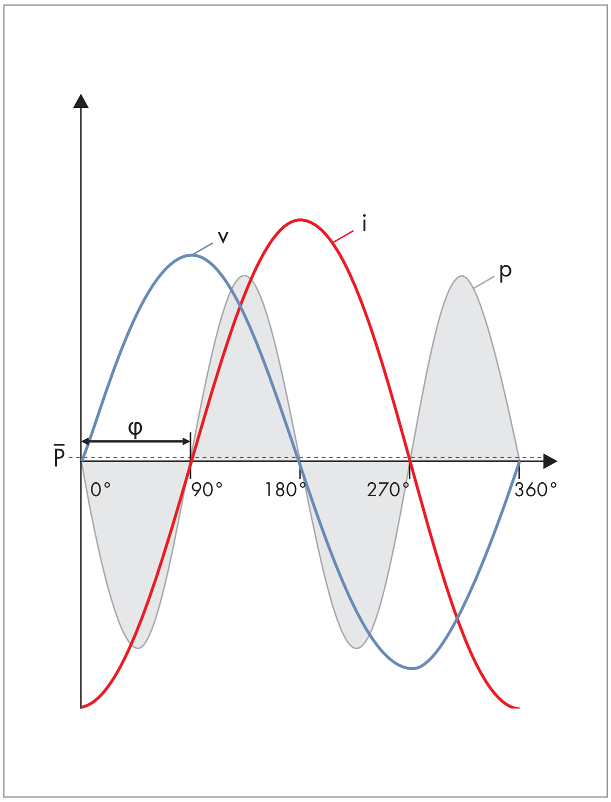


Fig. 16: The average value of the power is zero – pure reactive power – in case of a phase shift of 90 degrees between i and v

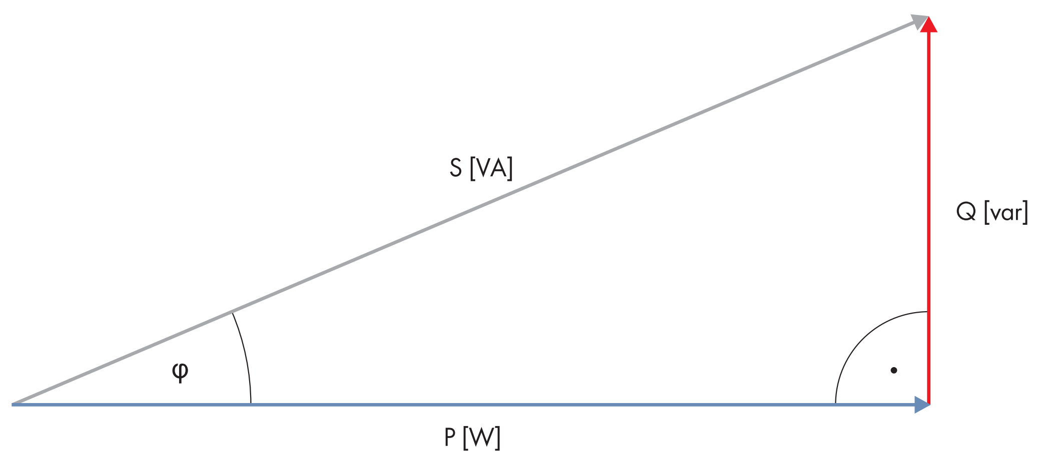
The phase shift is specified in angular degrees (a periodic cycle of the sine wave corresponds to 360 degrees); the phase angle is identified by the Greek letter φ (pronounced "phi"). The direction of the shift is designated by the suffix "leading" or "lagging."

However, the displacement power factor cos(φ) is used for calculations most of the time due to the fact that this results in a very simple correlation between active and apparent power: A value of 0.95 means that 95 percent of the apparent power is usable as active power – the remainder "comprises" reactive power.

It results from geometric subtraction and consequently does not amount to about five, but rather approximately 31 percent of the apparent power in this case (see example calculation). Viewed from the opposite side, the apparent power is about 5.26 percent greater than the given active power at a cos(φ) of 0.95 (apparent power = active power divided by displacement power factor, ref. example calculation).

FORMULAS AND VARIABLES

Identification	Symbol	Unit
Apparent power	S	[VA]
Active power	P	[W]
Reactive power	Q	[var]
Displacement power factor	$\cos(\varphi)_{\text{leading / lagging}}$	Factor without unit



$S^2 = P^2 + Q^2$ (Pythagorean theorem for right-angled triangles)

$$S = \sqrt{P^2 + Q^2} \qquad S = \frac{P}{\cos(\varphi)} \qquad P = S \cdot \cos(\varphi) \qquad Q = \sqrt{S^2 - P^2}$$

EXAMPLE CALCULATION

40 Sunny Tripower 15000TL inverters feed into the grid with a displacement power factor of 1 and a total active power of 600 kW. As an alternative, grid feed-in should take place with a displacement power factor of 0.95. Which apparent, active, and reactive power results? Are the available inverters sufficient?

The available active power P is 600 kW.

The following applies to the apparent power S: $S = \frac{P}{\cos(\varphi)}$ i.e., $S = \frac{600}{0.95} = 631.57$ kVA

The following applies to the reactive power Q: $Q = \sqrt{S^2 - P^2}$ i.e., $Q = \sqrt{631^2 - 600^2}$ i.e., $Q = 197.2$ kvar

Result

Due to the phase shift with a displacement power factor of 0.95, the inverters must provide additional 197.2 kvar of reactive power in addition to the 600 kW of active power. The geometric total indicates an apparent power of 631.6 kVA. The inverters and the downstream grid infrastructure must be designed for this apparent power. 631.6 kVA of inverter power are consequently required to operate at the same PV generator – e.g., 42 Sunny Tripower 15000TL inverters (or 37 STP 17000TL inverters as an alternative if this is more favorable in terms of the module configuration).

Information

When planning with a reactive power supply, the power of the PV generator must be evenly distributed to the now greater number of inverters. The power of inverters with reactive power capability is generally to be regarded as apparent power and must always be indicated in VA in that context. Active and apparent power have the same value in case of a displacement power factor cos(φ) = 1 only, resulting in the power of devices without reactive power capability being indicated in watt as has been customary up to now.

6.2 How is reactive power created?

Just as active power develops at ohmic resistances, reactive power is generated by reactive impedances – the so-called reactances. All types of coils (inductances) and capacitors (capacities) act as reactive impedances: While they have no (coil) or an infinitely large resistance (capacitor) in the direct current circuit, they cause a phase shift in one or the other direction and consequently lagging or leading reactive power in the alternating current circuit. Decisive for the use in the alternating current grid is that practically all electronic components – regardless of their primary function – act as leading or lagging reactances. For example, long cables behave like capacitors (leading reactances) due to the conductors being in close proximity to one another while the coils built into transformers or electric motors act as lagging reactances. Even high voltage overhead lines may be imagined as extremely long-stretched coils with just one winding – and they actually do cause a lagging phase shift.

Conclusion: It is nearly impossible to keep the voltage and current in phase at every point of an alternating current grid. The more or less strong phase shift corresponds to a certain amount of reactive power that constantly oscillates in the grid.

REACTIVE IMPEDANCES (REACTANCES)

Capacitor (capacity)

A capacitor constitutes a real interruption in the direct current circuit – i.e., an infinitely large resistance. However, the electrical charges only oscillate back and forth in the case of alternating current. A capacitor is consequently charged and discharged again in an alternating manner in the alternating current circuit. The voltage between the capacitor poles builds up during the charging process and reaches its maximum when the capacitor is completely charged and the current flow has come to a standstill. The behaviors are reversed during the discharge process: The current is at its greatest upon the capacitor being completely discharged.

Result: A capacitor in the alternating current circuit delays the voltage as opposed to the current. Or the other way round: It ensures that the current precedes the voltage and consequently acts as leading reactive impedance.

Coil (inductance)

A coil conducts direct current like a normal wire. A respective time delay in the current flow, which is caused by the build-up and the drop of the magnetic field, only occurs during the activation and deactivation. Every change in the current direction results in these delays in alternating current conditions.

Result: A coil delays the current flow as opposed to the voltage and consequently acts as lagging reactive impedance.

6.3 What are the effects on the distribution grid?

In short: Reactive power subjects the grid and the entire grid infrastructure to a load without contributing to the energy transmission. In contrast to active power which is "consumed" as usable power, i.e., transformed into motion, light, or heat, reactive power at first provides no visible use in the grid. Nevertheless, all lines, switches, transformers, and other components must take the additional reactive power into consideration. Specifically: They need to be designed for the apparent power, i.e., the geometric total of effective and reactive power. In addition, the ohmic losses during the energy transmission occur as a function of apparent power; any additional reactive power consequently causes bigger transmission losses. (Mnemonic: Reactive currents also cause active losses!)

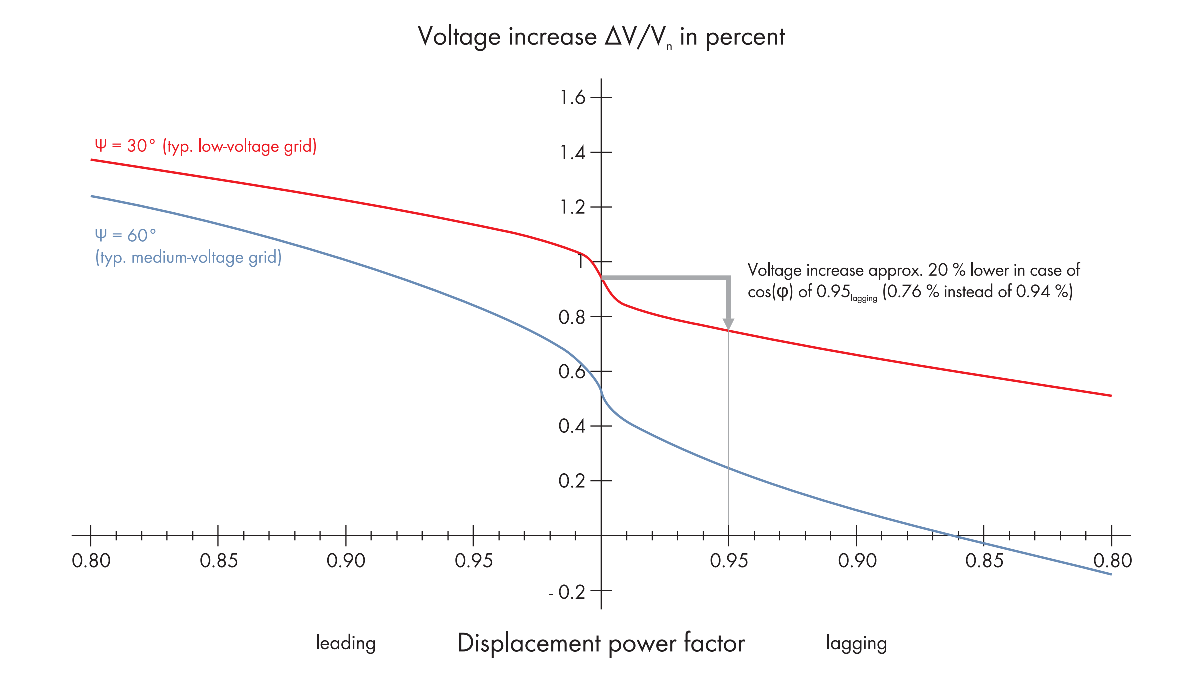
The opposite applies: If one compensates the unavoidable phase shifts in the grid and at the consumers, one will also lower the transmission losses. In addition, the grid will only be subjected to the active power load anymore – the released line resources could consequently be used for the transmission of additional active power.

However, reactive power (i.e., the deliberate shifting of the phases) can also be used to control the line voltage as a leading or lagging phase shift increases or lowers the voltage in the grid. In other words: Just as feeding in or consuming active power affects the frequency, the provision or absorption of reactive power will affect the voltage – though depending on the design of the respective grid level (e.g., cable or overhead line). The monitoring and control of the phase shift is consequently also of extraordinary importance for the grid control.

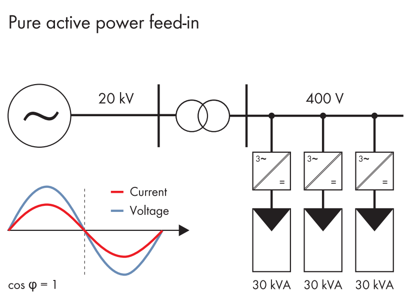
MORE PV POWER INTO THE GRID VIA INVERTERS WITH REACTIVE POWER CAPABILITY

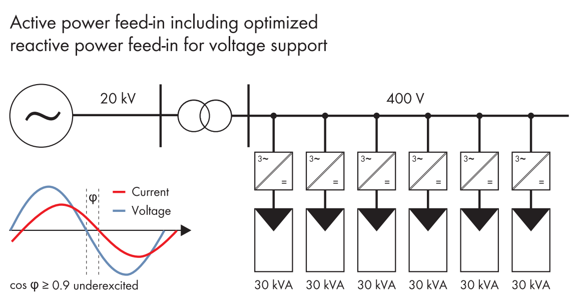
The voltage-lowering effect of reactive power depends on the design of the respective grid level (overhead line or underground cable, cable design): For example, the German high and extra-high-voltage grid is almost exclusively characterized by reactive impedance due to the large proportion of overhead lines and the big line distances, while the (ohmic) active resistance has a more significant share at the medium and low voltage level.

Therefore, the supply of reactive power has significantly less effects on the voltage at the lower grid levels than in the high-voltage grid. Instead, the supply of active power also causes a noticeable increase of the voltage here. This is exactly why the provision of reactive power should also become mandatory on the low voltage grid starting from a plant power of 3.68 kVA: While the voltage-regulating effect is comparably small, compensation of the voltage increase caused by active power is still essential.



Example 1: Given a grid impedance angle of 30 degrees (typical low-voltage grid), the voltage increase from feeding-in 27 kW of PV power with a displacement power factor of $0.95_{lagging}$ may be reduced by almost 20 percent (from 0.94 percent to 0.76 percent)





Example 2: Twice as many PV inverters may be operated when feeding in with a displacement power factor of $0.9_{lagging}$. This results in a maximum active power of 163 kW, instead of 90 kW without reactive power – an increase of approximately 80 percent

6.4 How is reactive power supplied in the grid?

Synchronous generators used in large power plants are able to make both lagging as well as leading reactive power available via the corresponding control of the exciting current. Due to the many overhead lines and transformers for the various voltage levels, the power distribution grid exhibits a lagging inductive reactance overall. In addition, a majority of the consumers also causes a lagging phase shift. In large power plants, a leading phase shift is fed in during power generation in order to counter this and raise the resulting drop in voltage again.

6.5 What does the reactive power supply cost?

The cost greatly varies from case to case: For example, a radio ripple control receiver will be used, even in large PV plants, only if the grid operator wants to remotely control the reactive power supply on short notice. An SMA Power Reducer Box is also needed in that case. If stabilization of the desired reactive power is also required at the grid-connection point, a PLC-based control solution, such as the SMA Power Plant Controller, is needed. Inverters with reactive power capability do not incur any additional costs because this functionality is available in virtually all SMA devices as standard due to the relevant connection directives.

Besides that, the changed dimensioning of the inverters has an effect on the total costs of the plant: Either more or more powerful inverters are necessary in order to facilitate feeding in the entire active power of the PV generator with phase shift. However, this makes up less than one percent of the plant costs for a required displacement power factor of 0.95.

6.6 How does plant planning change if reactive power is required by the grid operator?

It goes without saying that the provision of reactive power must be considered when designing the PV plant. The desired or required displacement power factor plays the decisive role in that context: It determines the amount of apparent power and consequently the required inverter power. Given a cos(φ) of 0.95, approximately 33 percent of additional reactive power results; this equals an apparent power of approximately 105 percent of the active power provided by the PV generator in the geometric total. Consequently, an inverter with at least 105 kVA of nominal apparent power will be required to feed in 100 kW of active power with this phase shift (also refer to the example calculation in 6.1).

The active power absorbed by the inverter will be fully preserved in the process. The respective reactive power also occurs in the inverter, which is why it needs to be dimensioned larger accordingly.

If this is not the case, the active power offered cannot be absorbed in full. Less available active power consequently results from the given apparent power of the inverter and the desired displacement power factor. Version 1.5 and later of the free SMA planning software "Sunny Design" may be used to calculate all possibilities for the reactive power supply.

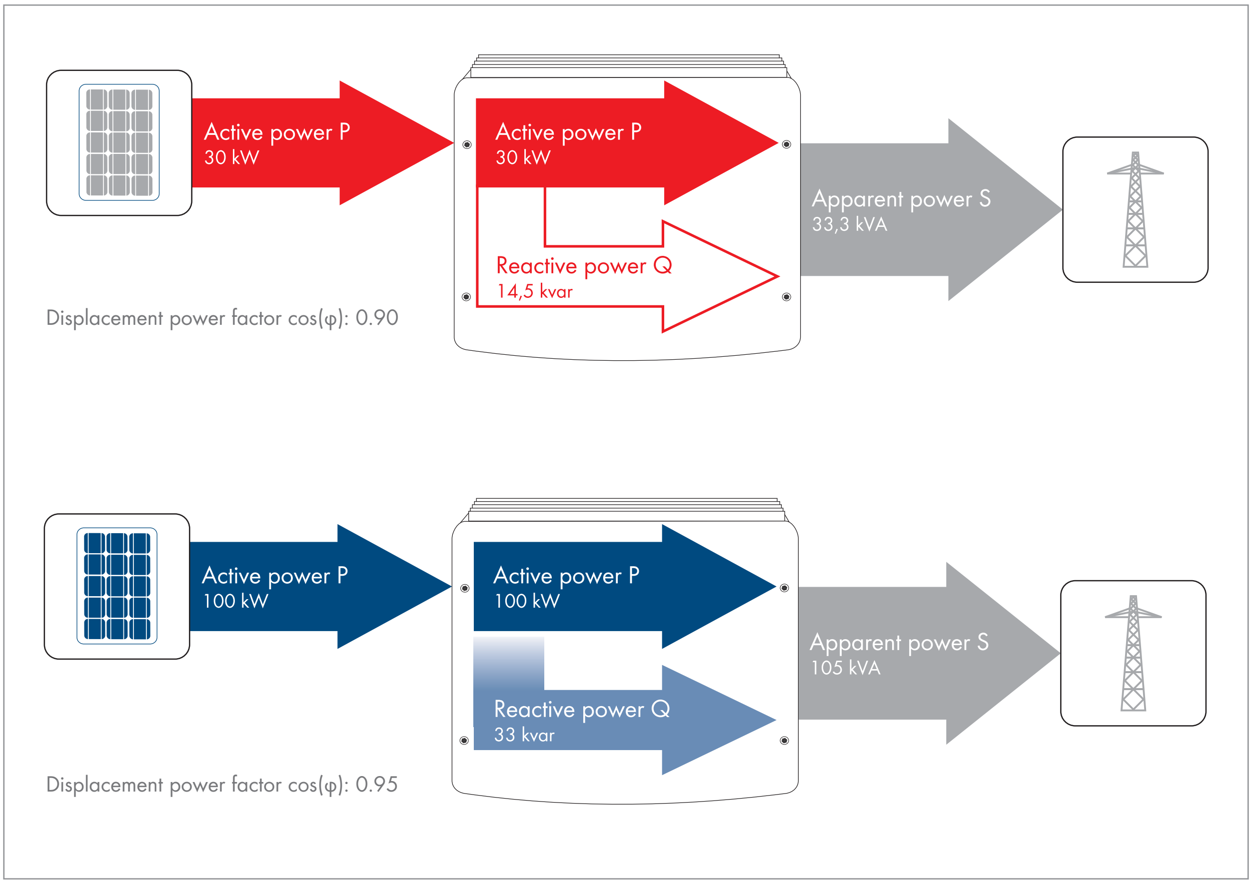


Fig. 17: The active power of the PV generator is maintained in full; however, the inverter must be dimensioned to the larger apparent power

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