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Grid connection requirements and test procedures: Experiences in the certification process of PV inverters

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ABSTRACT

The new German BDEW MV guideline demands static and dynamic functionalities from distributed energy resource (DER) units in order to support network operation and stability. Initial indications show that, in general, photovoltaic (PV) inverters are able to fulfil both the static and the dynamic requirements. Besides the new requirements of the guideline, an extensive certification process for DER units and plants has also been introduced. During initial certification processes, a significant need for PV-specific test procedures and test equipment has been determined. This article describes the developments within this area from the perspective of a measurement institute.

Introduction

The strong increase in installed distributed energy resources (DERs) has a major influence on network behaviour. By the end of 2010, more than 55GW of renewable generation had been installed in Germany, of which 17.3GW fell upon PV. At the end of 2009, more than 23% of all PV systems with an installed capacity of 2279MW were connected to medium- and high-voltage grids [1]. The share of 'large' PV systems above 100kW rated power is showing a strong increasing trend.

Due to the large growth in the numbers of DER units, the adaptation of interconnection requirements has been under discussion, at the national and international level, between network operators, manufacturers, DER plant operators and research institutes. A paradigm change of the role of DER units is occurring. Commonly, in the past, DER units were not permitted to take an active role, but nowadays all DER technologies are asked to support the network in terms of static and dynamic issues [2].

In Germany, since January 2009 the new BDEW guideline [3] for interconnection of DER units to the MV network has been in force. From the beginning of August 2011, advanced interconnection requirements for the LV networks also come into operation.

In addition to the release of the new BDEW MV guideline, a certification process for all kinds of DER units and plants has been introduced. This procedure is already familiar for wind turbines, but had to be extended to all other DER technologies with all the

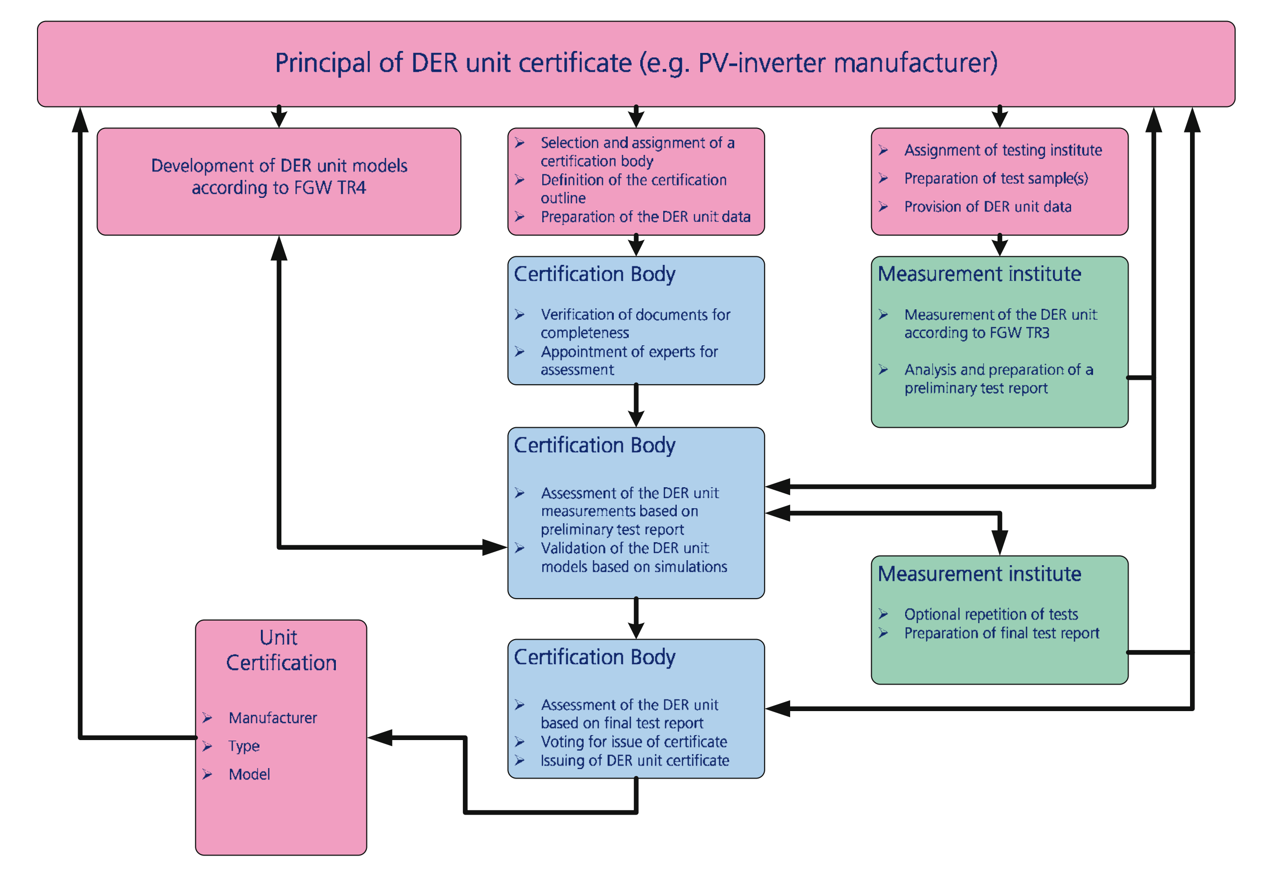

Figure 1. Flow chart of the process of unit certification.

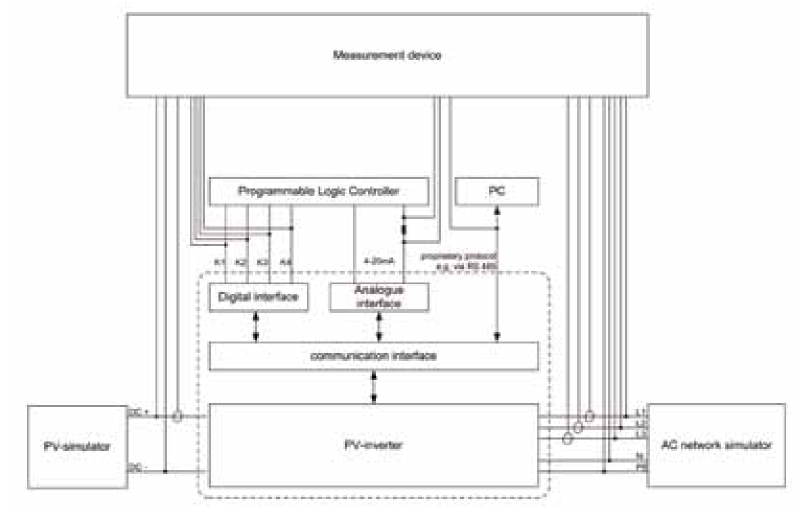

Figure 2. General measurement set-up of a PV inverter for measurements according to FGW TR3.

associated implications. This has resulted in several temporary regulations since, on the one hand, the development of the new inverter functionalities required a lot of time and resources from the manufacturers and, on the other hand, adapting the existing certification guidelines of wind turbines to other DER units with different primary energy sources posed a challenge.

This article concentrates on testing issues arising within the certification process. A short overview of the general certification procedure is given first, followed by a description of new test procedures especially developed for PV inverters. Additionally, requirements for testing PV inverters regarding laboratory infrastructure are discussed. The new functionalities of the BDEW MV guideline are explained by presenting measurements achieved during certification processes carried out by Fraunhofer IWES.

Procedure of unit certification according to FGW TR8

As evidence of compliance with the new BDEW MV guideline, it is mandatory to obtain unit and plant certificates. Therefore the procedure of certification according to FGW TR8 will be briefly described as follows.

Since January 1st 2009, the grid-conformance behaviour of distributed generating systems (such as a solar or wind farm) connected to the public MV network must be validated by a so-called unit certificate. Additionally, for plants above 1MVA rated power, a plant certificate based on the unit certificate is required. The temporary regulation allowed PV units to delay the fulfilment of the static requirements stated in the BDEW MV guideline until July 1st 2010, and of the dynamic requirements until April 1st 2011.

By nature, the principal of the unit certificate (typically the manufacturer of the DER unit) plays a decisive role within the certification process. Fig. 1 shows the significant steps of the procedure and the participants – the manufacturer, the certification body and the measurement institute. For achieving conformance with the BDEW MV guideline, measurements according to FGW TR3 [4] and validation of simulation models according to FGW TR4 [5] have to be carried out. Based on these results a certification body is allowed to issue a unit certificate guaranteeing that the requirements of FGW TR8 [6] have been fulfilled.

Laboratory infrastructure for measurements according to FGW TR3

General measurement set-up for a PV inverter

Fig. 2 shows a general set-up of a PV inverter for taking measurements according to FGW TR3. Besides the acquisition of voltages and currents on the DC and AC sides of the PV inverter inputs and outputs, the set points supplied to the communication interface of the PV inverter have to be recorded synchronously. Since several kinds of set point signals are commonly used – e.g. RS 485 (for internal farm communication), digital signals from a ripple control receiver or analogue signals – the measurement equipment should provide various flexible inputs for the acquisition of set point signals.

Usually, RS 485 signals are generated via manufacturer-specific software commands and sent from the PC to the PV inverter. If digital or analogue interfaces are used, the set point signals can be easily generated in the laboratory via a programmable logic controller (PLC).

Requirements for the DC source

Using a PV generator is not mandatory for the supply of the PV inverter at the DC terminals, since FGW TR3 states that module-independent tests are sufficient for the determination of the behaviour on the AC side. Instead of a PV generator, it is possible to use a variable DC voltage source which fulfils the requirements of Annex E of FGW TR3 regarding power and voltage range, control mode and dynamics. This simplification is especially meaningful with regard to high-power applications, since a real PV generation in this power range proves to be quite costly. For testing string inverters, the use of PV simulators is quite common. This ensures that the characteristic curve of a PV array is provided to the PV inverter, even during transient events such as radiation changes or network faults.

Requirements for the AC network simulator

If the power rating of the DER unit is of the order of a few kilowatts, it makes sense to use a network simulator for the measurements instead of connecting the DER unit to the public network. This procedure offers advantages, especially for the test of power quality parameters and of low-voltage ride-through (LVRT). Of course, the network simulator has to fulfil certain requirements in order to achieve a behaviour comparable to a public network. A basic requirement is that each phase of the simulator be controlled independently in amplitude and phase angle; controlling the frequency should also be possible. Furthermore, the usage of a physical impedance network for emulation of a network connection point with certain parameters – short-circuit power S_k and network impedance angle ψ_k – is mandatory.

For DER units with power ratings up to 90kVA, the laboratory at Fraunhofer IWES offers a network simulator with the aforementioned requirements. This 4-quadrant AC network simulator, consisting of linear amplifiers, provides the possibility of reproducing any desired network behaviour.

Test infrastructure for high-power applications

For economic reasons, it is nearly impossible to provide such high-class test equipment for DER units with higher power ratings. A balance has to be struck as to which kind of test infrastructure is used for certain power levels. It is obvious that a general solution cannot be given. However, Fraunhofer IWES has set up a reference laboratory for testing DER units in the higher power range; the developed concept is shown in Fig. 3 and will be briefly described below. The reference lab is integrated within the new test centre IWES-SysTec of Fraunhofer IWES for Smart Grids and Electro mobility (see Fig. 4).

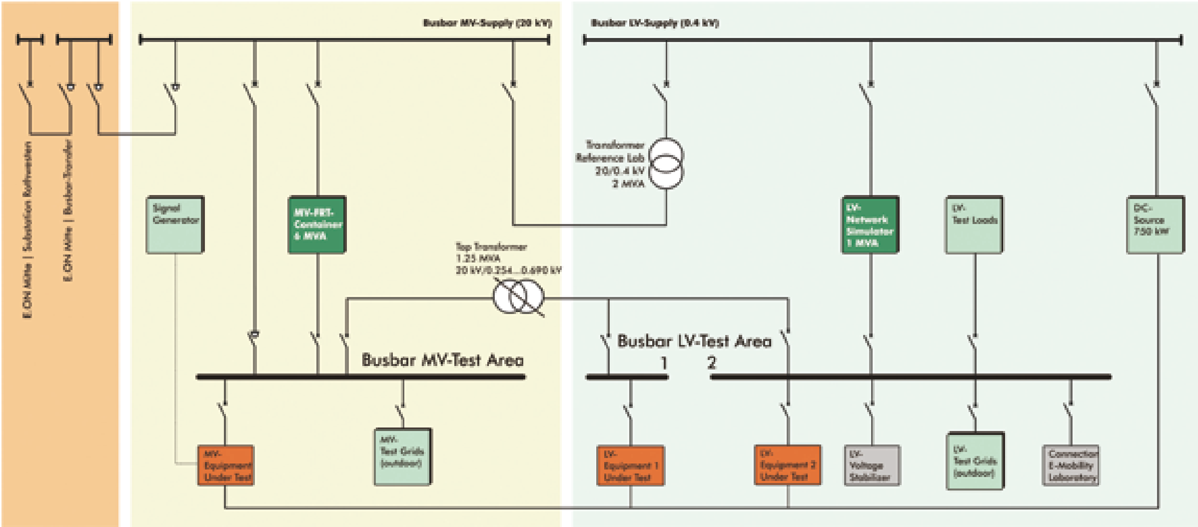

Figure 3. Schematic of the new reference laboratory of Fraunhofer IWES at IWES-SysTec for testing DER units in the higher power range.

Source: Fraunhofer IWES, Frank Hellwig

Figure 4. IWES-SysTec: new test centre of Fraunhofer IWES for Smart Grids and Electromobility.

The IWES reference lab offers the possibility of testing DER units rated up to 1.25MVA on an LV level and up to 6MVA on an MV level. The testing possibilities are not limited to PV inverters; moreover, new network elements such as voltage stabilizers or controllable transformers can be integrated as equipment under test into the reference lab.

> "The IWES reference lab offers the possibility of testing DER units rated up to 1.25MVA on an LV level and up to 6MVA on an MV level."

Different test beds on the LV and MV levels for static and dynamic requirements have been developed and set up. At the LV level, the static requirements are covered by using an LV network simulator with a nominal apparent power of 1MVA. At the MV level, for testing static requirements, a signal generator is connected to the secondary systems (controller, protection, etc.) of the DER unit. The dynamic requirements are tested by using a so-called

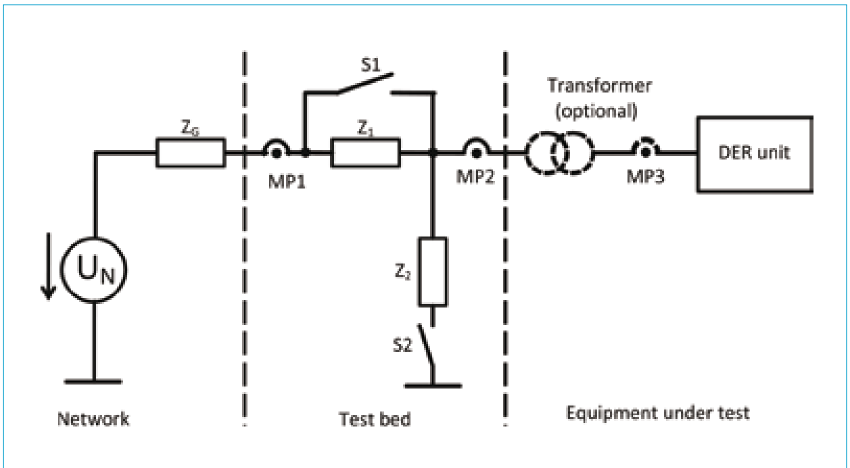

Figure 5. Simplified schematic of the LVRT container according to FGW TR3.

Nominal network voltage Rated power of the EUT	10/20kV 0.25–6MVA
Short-circuit power of the connection point	80–350MVA
Ambient temperature	–25 to +60°C
Operating temperature	0 to +50°C
Humidity	≤ 70% average per day
Test bed assembly	40-foot Maritime High Cube container

Table 1. Technical details of the mobile LVRT container developed by Fraunhofer IWES.

LVRT container. This mobile container is connected in series between the DER unit and the public MV network and generates network faults on the MV level without disturbing the public network. The simplified schematic of the developed system is shown in Fig. 5 and technical details are given in Table 1. For DER units with LV outputs, a step transformer with a wide voltage range (from 254V to 690V) is used for connecting these units to the LVRT container.

Development of PV-inverter-specific test procedures

As a basis for obtaining the unit certificate, measurements have to be carried out in order to prove compliance with the BDEW MV guideline. The measurement institute has to be accredited according to DIN EN ISO/IEC 17025. The applied test procedures are described in FGW TR3 and, although they were originally developed for wind turbines, nowadays all kinds of DER units (wind, photovoltaic and biomass) have to be tested according to these procedures. Therefore a combination of adapted existing test procedures and newly developed procedures for each kind of primary energy source has to be used. The reasons for this are that primary energy sources (sun, wind, etc.) behave differently, and the units to be certified have widely varying power ratings, ranging from a few kilowatts (e.g. string inverters) to several megawatts (e.g. central inverters).

Several committees within the FGW association are responsible for the adaptation and development of the PV-inverter-specific test procedures. Through the collaboration of certification bodies, measurement institutes and manufacturers, achieving a target-oriented approach for modification of the FGW guidelines should be ensured. In particular, during the first certification processes for PV inverters, a lack of clarity in existing test procedures was identified and brought to the attention of the corresponding committees. As a result of this, several new test procedures for PV systems were created.

Test procedure for LVRT

According to IEC 61400-21 [5], LVRT tests have to be carried out by generating network faults at the MV level, but these test procedures are not meaningful for PV inverters with low-power ratings (≤ 100kW). Therefore FGW TR3 also allows testing LVRT behaviour by providing network faults at the LV level (according to Annex F.2). However, it must be ensured that the faults have the same behaviour as if they were generated at the MV level. The vector group of the MV/LV transformer has to be considered, especially for unbalanced faults. Fig. 6 shows the difference during the fault for a Dd and a Dy transformer.

If LVRT tests are conducted with a network simulator, it must be possible to control the voltage amplitude and the phase angle of each line independently, with very high slew rates (> 30V/µs for the network simulator used). In order to provide realistic network conditions, a physical impedance network for setting up the short-circuit power and the network impedance angle

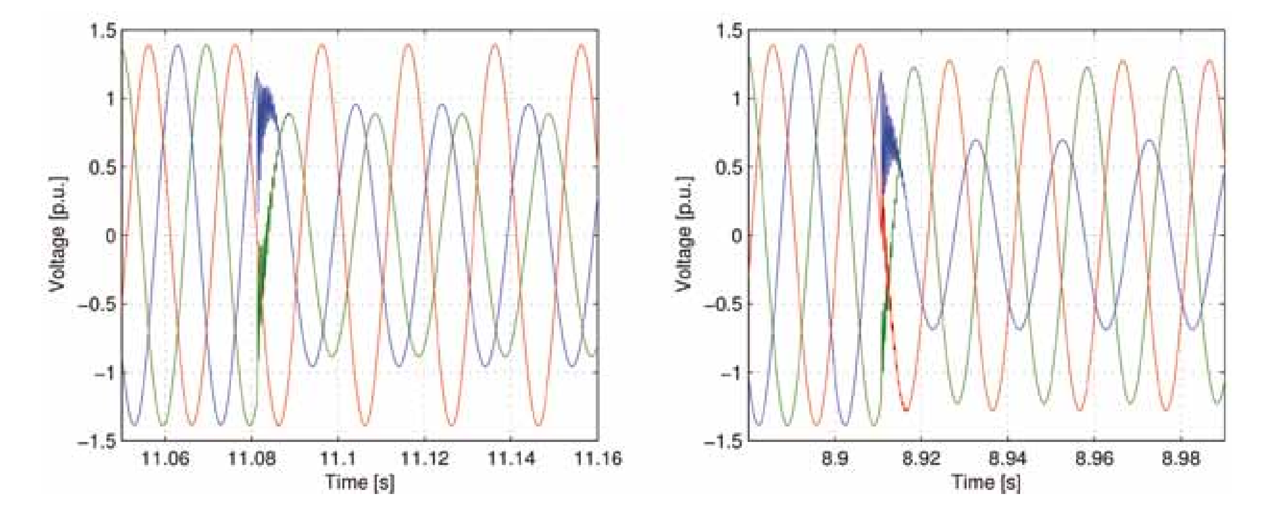

Figure 6. Measured voltages during unbalanced faults. Left: Dd MV/LV transformer. Right: Dy MV/LV transformer.

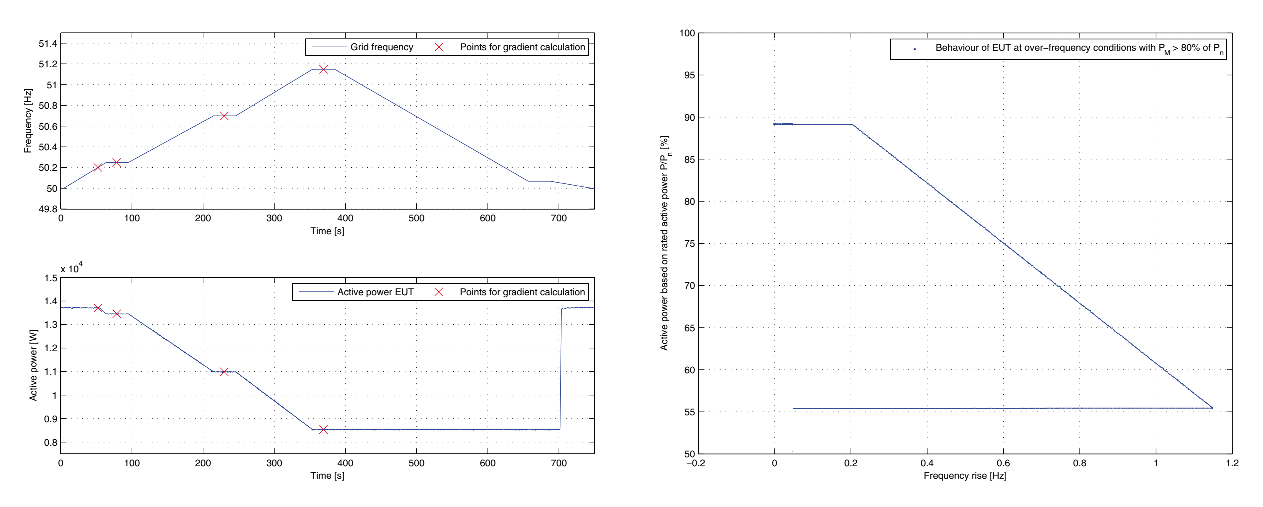

Figure 7. Measurement results for active power reduction corresponding to the over-frequency behaviour of the STP15000TL string inverter.

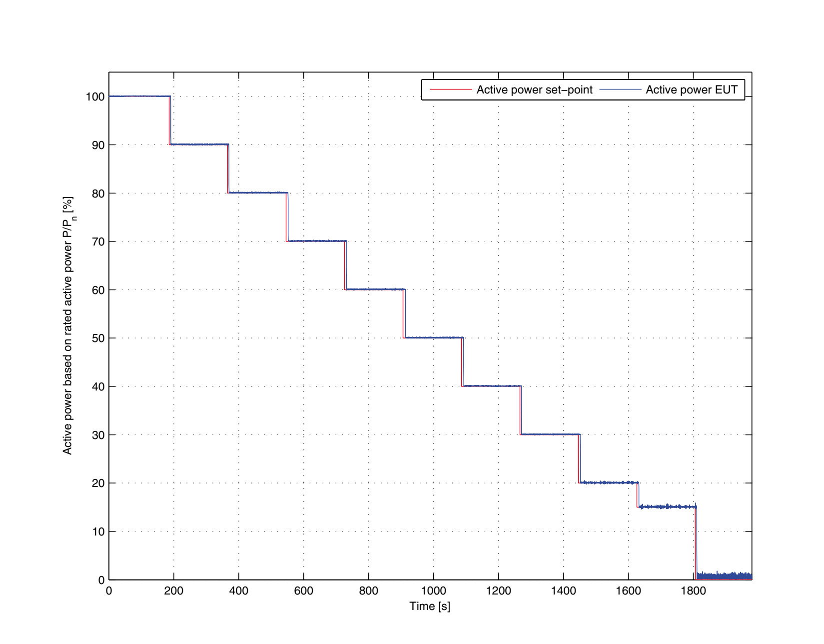

Figure 8. Measurement results for the STP15000TL string inverter with active power reduction by the network operator.

is used. Besides the network impedance, the impedance of the transformer and the cables of the DER unit should be taken into account in the impedance calculation.

Confirmation of electrical properties of PV inverters according to German BDEW MV guideline

In the BDEW MV guideline, several requirements concerning static and dynamic behaviour of DER units are described. They can broadly be grouped as follows:

- Active power provision, including set point control and power reduction in an over-frequency condition
- Reactive power provision by set point or characteristic curve (Q(U), cosφ(P))
- Power quality issues such as switching operations, flicker, harmonics, interharmonics and higher frequency components

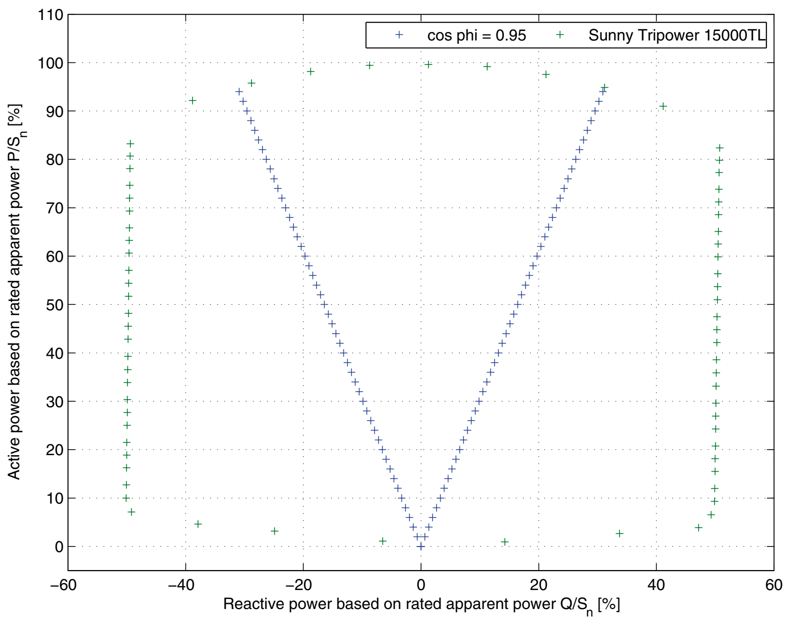

Figure 9. Measured reactive power capability of the STP15000TL string inverter.

- Grid protection
- Connection conditions
- Response to voltage drops (LVRT)

The most important new functionalities concerning grid integration issues, namely active power and reactive power provisions as well as LVRT, are described below. The mode of action of these functionalities is clarified by presenting the measurement results obtained at the Fraunhofer IWES laboratory for the certification process of the SMA Solar Technology string inverter Sunny Tripower STP15000TL.

Active power

The new functions for active power control enable the DER unit to reduce the actual power output in case of network congestion. This power reduction is either done locally, and automatically if there is an over-frequency situation in the network, or done remotely by the network operator.

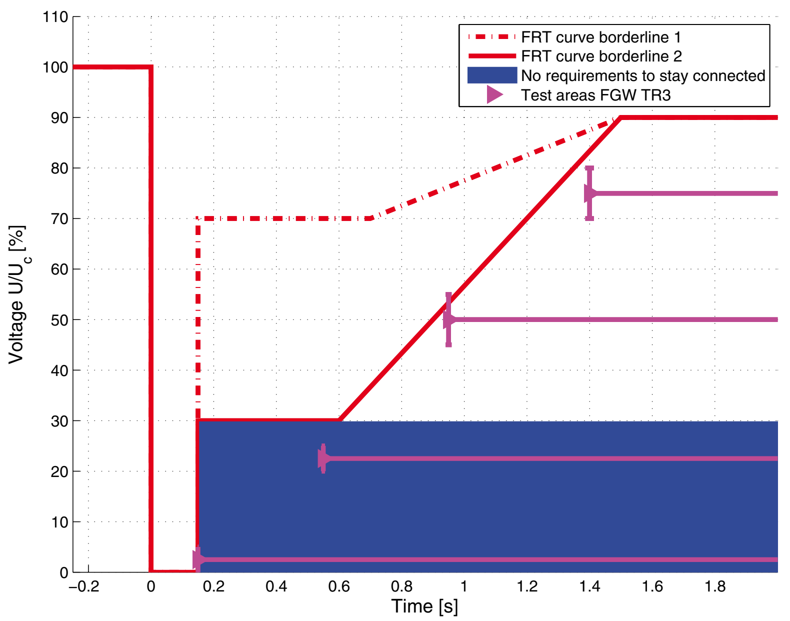

Figure 10. German LVRT curve for type 2 generators, according to [3] and FGW TR3 test areas.

Power reduction in an over-frequency condition

A surplus of power generation capacity in the network leads to a frequency rise. If frequency control of the network is no longer capable of keeping the frequency within acceptable limits, DER units can support the network by reducing active power injection. The BDEW MV guideline asks for an active power reduction of 40% per Hz, starting at 50.2Hz, but an increase of active power injection is allowed when the frequency falls below 50.05Hz.

To comply with FGW TR3, six different specified frequency points in the range 50.00–51.20Hz have to be set for testing purposes, and the active power reduction of the inverter is evaluated for these points. Using a network simulator for the tests offers the advantage of being able to continuously vary the grid frequency. The frequency profile used at Fraunhofer IWES for testing the DER units is shown in Fig. 7 (left). In accordance with FGW TR3, when a specified frequency point is reached, the frequency is held constant for at least 30s. Between these specified points, the frequency is changed at a rate of 0.225Hz/min. The power reduction behaviour as a function of frequency is then determined from the measurement data, based on average values over 200ms, and shown in Fig. 7 (right).

Power reduction by the network operator

In contrast to the autonomous reduction of active power in over-frequency conditions, power reduction by the network operator occurs remotely and is selective. The network operator is allowed to reduce the active power injection of DER plants in order to secure network operation in the event of, for example, network transmission capacity shortages or overloading of network equipment.

The DER units must be able to reduce the active power output to set points given as percentages of the rated active power, the most common values being 100%, 60%, 30% and 0%. However, according to FGW TR3, different steps of active power must be tested. The set points and measurement results for the STP15000TL string inverter are given in Fig. 8.

Besides the set point accuracy, the response time of the unit has to be measured. The response time – defined as the time taken until the active power enters and stays within the tolerance band around the set point – should not exceed 1 minute. This time range is considered to cover the whole communication line, beginning from the receipt of the set point signal at the plant controller up until the alignment of the reduced active power output at the DER unit. Experiences with different kinds of PV inverters have shown that this requirement can be met quite readily and is not difficult to implement in the software of the inverter.

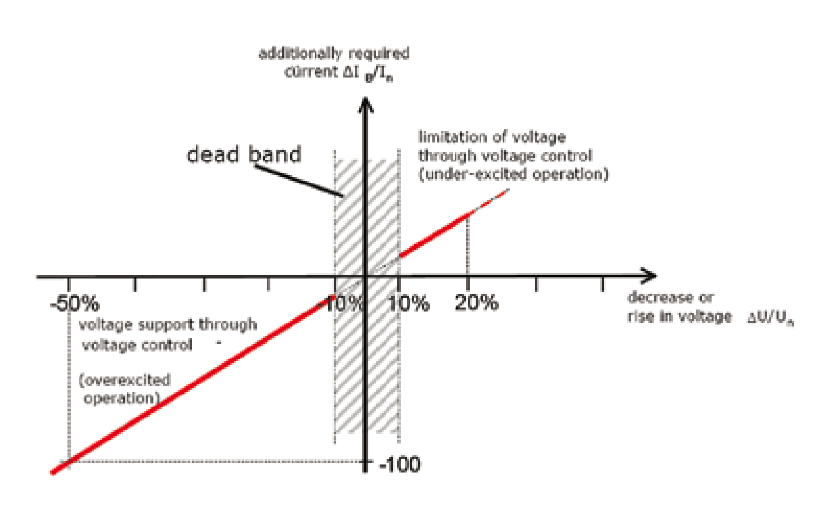

Figure 11. Reactive current injection from DER units during balanced network faults, according to [7].

Reactive power

Nowadays, because of the rising deployment of DER units, voltage control is becoming an important issue. In the past, DER units did not inherently provide reactive power, but with extended reactive power control functionalities, they are now able to support the network and thereby increase the capacity of their integration into the network.

The BDEW MV guideline demands a power factor of 0.95, leading and lagging at the point of common coupling (PCC). In order to fulfil this requirement, inverters should be capable of delivering a power factor lower than 0.95, since the reactive power demand of internal network equipment, such as cables and transformers, must also be considered.

The limiting factor for reactive power provision of inverters is the current-carrying capacity of semiconductors. An over-dimensioning of the inverter is necessary if a simultaneous injection of reactive power at rated active power is desired. Otherwise, the maximal active power injection has to be limited.

To determine the reactive power capability, at least three 1-minute average values based on 200ms average values have to be recorded for every 10% power band, i.e. 0–10%, 10–20%, and so on. This ensures that the reactive power behaviour of the inverter over the whole active power range is known. Fig. 9 shows the reactive power capability of the measured PV inverter. As it can be seen from the image, the PV inverter fulfills the requirement of a power factor of 0.95 from the BDEW MV guideline.

> "During the certification, it is necessary to determine: 1) the accuracy of the set point alignment and 2) the time duration for the set point adjustment."

Besides the functionality of pure reactive power provision, the network operator has the possibility of providing a set point according to the actual system needs. The BDEW MV guideline allows several possibilities:

- Fixed power factor cosφ
- Fixed reactive power in Mvar

- Characteristic curves:
  - Power factor and active power cosφ(P)
  - Reactive power and voltage Q(U)

During the certification, it is necessary to determine: 1) the accuracy of the set point alignment and 2) the time duration for the set point adjustment. Clearly, if an inverter provides several interfaces for receiving set points, all of them are to be tested. At the moment, the characteristic curve test is not mandatory for unit certification, but has to be considered for plant certification.

Measurement results of dynamic requirements - LVRT

Network faults cause voltage dips, the magnitudes of which depend on the distance to the fault location and the network topology and parameters. In the past, because of grid protection settings, DER units had to disconnect from the network very quickly in the event of under-voltage conditions. Due to the rising number of DER units, transmission network operators are particularly afraid of a sudden loss of a large number of distributed generating capacities. Therefore, DER units should technically be able to ride through faults in order to continue active power injection immediately after a fault clearance. Fig. 10 shows the LVRT curve according to the BDEW MV guideline and the test areas of FGW TR3 used for the measurements of the DER unit.

Voltage support through reactive current

A further requirement of DER units is voltage support during network faults. Depending on the magnitude of the voltage dip and the k-factor characteristic (Fig. 11), an additional reactive current has to be injected by the DER unit, and this must be least its rated current. In the calculation of the reactive current set point, reactive power injection and voltage deviations before the fault have to be taken into account.

The influence of the injected reactive current on the network voltage is shown in Fig. 12. Here, the same voltage dip is applied to the PV inverter by a network simulator with a physical impedance network, but different settings of the k-factor are used. During the first voltage dip, the k-factor is 0, which means that the PV inverter simply rides through the fault but does not inject any reactive current. For the second voltage dip, the k-factor is set to 2, which leads to a reactive current injection in the range of the nominal current of the PV inverter, at a voltage drop of about 50% of the nominal voltage. The rise of the measured voltage in the grid simulator can be clearly seen.

During the procedure of taking measurements for certification, LVRT tests have to be performed using different parameters and the results evaluated. Adjustable parameters, according to FGW TR3, are the type of fault (balanced and unbalanced), the active power injection before the fault (10–30% and > 90%) and the k-factor. A sampling rate of at least 5kHz is required for the transient measurements. Furthermore, it has to be ensured that the length of time recording before and after the fault is sufficiently long to determine all necessary parameters, e.g. the voltage and current before the fault,

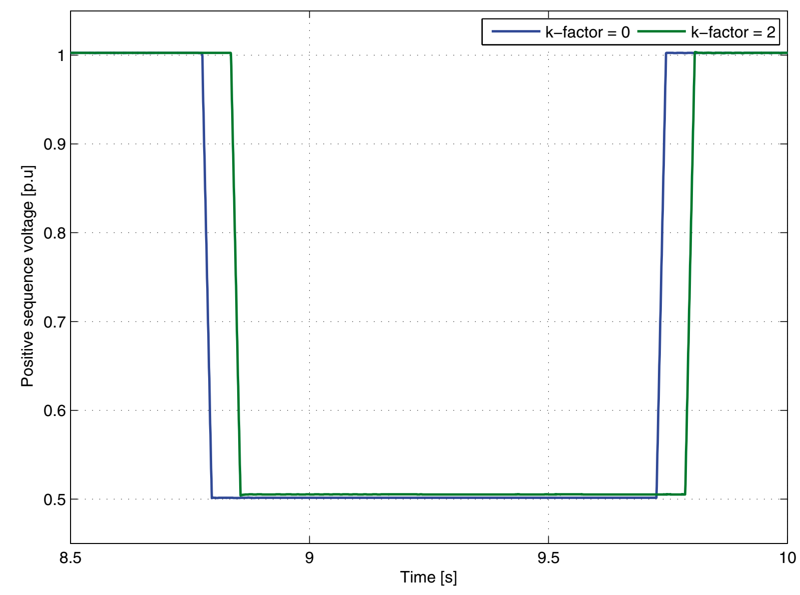

Figure 12. Influence of reactive current injection during network faults. The same voltage dip is applied to the PV-inverter (STP15000TL) in both cases.

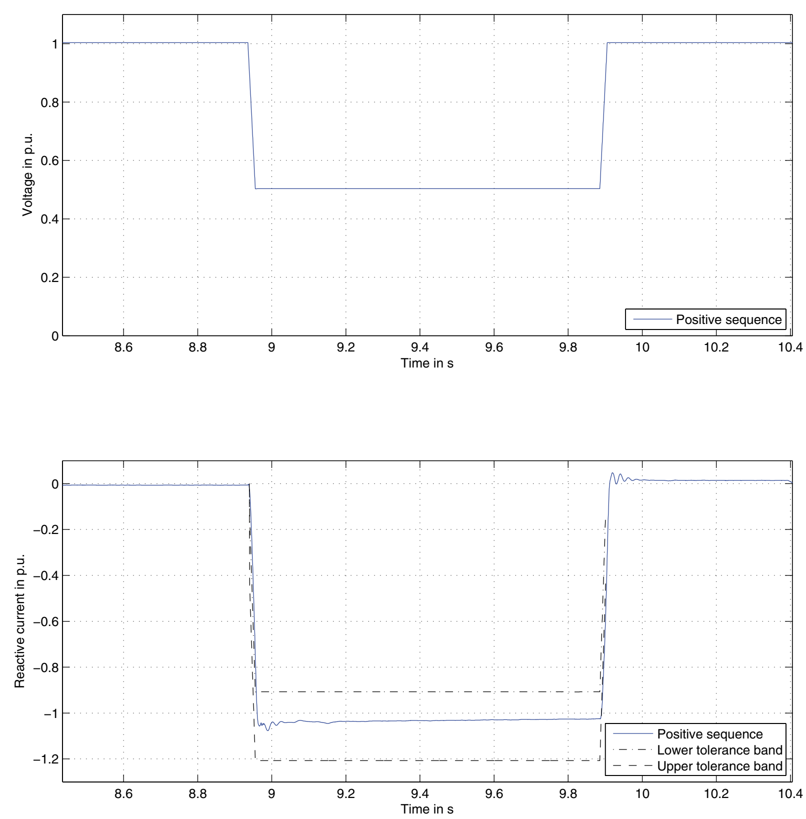

Figure 13. Measurement results for the STP 15000TL, when a balanced voltage dip to 50% of the nominal voltage U_n is applied.

which are used to calculate the reactive current set point, and the active power behaviour after the fault clearance.

Different parameters characterizing the behaviour of the DER unit during the fault have to be calculated from the transient recordings and documented in the test report, e.g. half- and full-period RMS and peak values of the short-circuit current contribution at different points in time during the fault; the time to reach 90% of the active power before the fault occurred; and the determination of the k-factor and the control response time. Observations from different measurement campaigns have indicated that the requirement of achieving a control response time of 20ms according to TC2007 [7] is the most challenging.

Fig. 13 shows a typical measurement of the reactive current injection during a fault, using the STP 15000TL. The reactive current injection of the PV inverter starts very quickly and stays within the tolerance band of –10% and +20% of the rated current around the reactive current set point. The control response time requirement is also satisfied because of the fast reaction of the inverter.

Conclusions and outlook

Initial tests have revealed that PV inverters are generally capable of satisfying the static as well as the dynamic functionality requirements of the new German BDEW MV guideline, in terms of supporting network operation and stability. The extensive certification process for DER units and plants that has been introduced, in addition to the new guideline, has highlighted a particular need for PV-specific test procedures and test equipment. Therefore it has been necessary to develop specific features, such as laboratory infrastructure and test procedures, required for the confirmation of the electrical properties of PV inverters, according to the test guideline FGW TR3. This guideline, developed primarily for wind turbines, has been successfully adaptated for PV inverters during the last two years.

With particular regard to LVRT tests at the LV level, Fraunhofer IWES has been able to develop, validate and successfully apply a new method of testing, using a network simulator with a physical impedance network, for several certification procedures. However, it is recognized that there is a lack of laboratory capacity, not only for testing but also for the development and validation of new test procedures. This is particularly true for high-power applications and so, in September 2011, Fraunhofer IWES set up a reference laboratory for inverters rated up to 6MVA, to support future development in the field of PV inverters.

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Gunter Arnold has been a member of the Electricity Distribution Networks Group at Fraunhofer IWES since 2008. His main research topics focus on power plant features of PV inverters and testing procedures for grid integration of DER generators, as well as power quality characteristics of DER plants. Gunter has a diploma degree in electrical engineering from the Technical University of Darmstadt and received his Ph.D. from Kassel University in 2004.

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