Utility-scale PV installations and their challenges in grid-code compliance testing

PV inverter testing | The market outlook for utility-scale PV installations is very positive. These PV plants have the capability of supporting grid operation, and the ability to do this is being increasingly required in grid codes. Testing the capabilities of very large PV inverters, however, is demanding for laboratories. Gunter Arnold, Diana Craciun, Wolfram Heckmann and Nils Schäfer from Fraunhofer IWES discuss current developments and resulting challenges and address the gaps and diversity in testing guidelines and standardisation

At the beginning of 2013 the European PV industry tried out two scenarios in its outlook on the market development of ground-mounted, utility-scale PV plants: 1) business as usual, with a little more than 10GW installed globally; and 2) policy driven, with about 18GW [1]. But for 2013, even the policy-driven scenario estimate worked out to be too conservative: by the end of 2013, the globally installed utility-scale PV added up to more than 21GW. In particular, the installations in 2013 by the USA with 2.8GW, China with 1.6GW, India with 0.7GW and the UK with 0.4GW drove this development [2].

The installed capacity of utility-scale PV plants is envisaged to double within the next five years according to the business-as-usual scenario of the EPIA [1], and a strong increase in utility-scale PV installations worldwide (Fig. 1) is predicted in market outlooks. There is a global market for very large PV inverters, but there are associated local grid-code requirements. Testing laboratories are thus doubly challenged – by inverters with increasing rated power and by diverse testing guidelines. Grid-code requirements and the resulting challenges for testing laboratories are examined in this article.

Grid-code developments and testing guidelines

With more and more PV installed at all levels of the electricity grid, the requirements for generators have to cover various aspects of system stability, operation and security. These entail the support of remote-controlled network operation activities, such as feed-in management or power curtailment, as well of dynamic behaviour in the case of network faults. Accordingly, the scope of the testing has to be broadened.

Grid-code comparison

Advanced inverter functionalities required by grid codes are related to frequency and voltage support. But the focus in this paper is on functionalities supporting the secure grid operation at the point of connection to the grid, especially static voltage support/reactive power provision and dynamic voltage support/fault-ride-through (FRT) capabilities. With distributed generation (DG) providing active power depending on the actual frequency, and reactive power depending on the local voltage, the loss-of-mains (LOM)/anti-islanding detection is gaining importance. LOM testing is therefore considered here as well.

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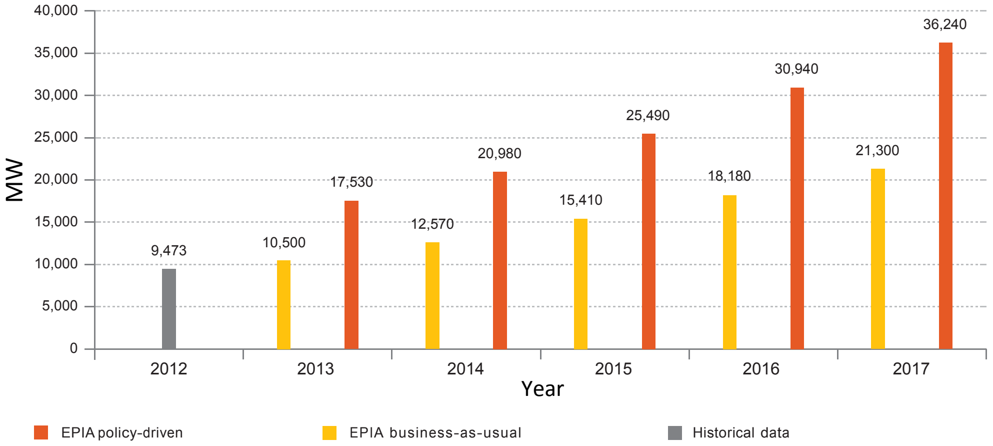


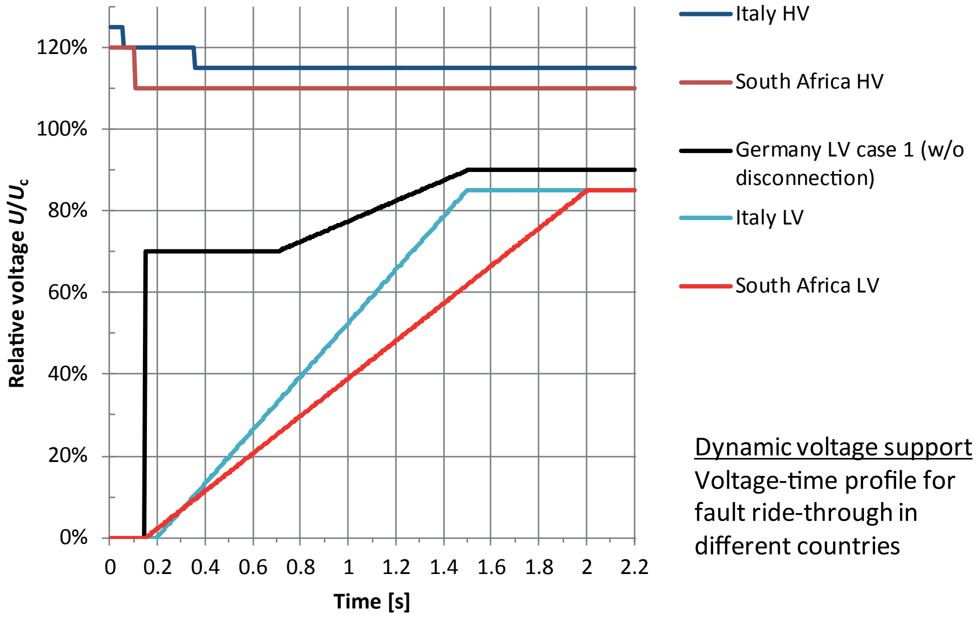
Figure 1. Global utility-scale PV development scenarios up to 2017.
Source: EPIA [1]

For static voltage support, the DG installations have to provide inductive or capacitive reactive power. There are three approaches:

- **Reactive power (Q) control:** fixed or scheduled Q value or remote controllable, over a certain threshold, independent of the active power (P) production.
- **Power factor (cosφ) control:** fixed cosφ or dependent on the actual P production.
- **Voltage (U) control:** Q or cosφ dependent on the actual voltage at the connection point.

Specific requirements for Germany, Italy and South Africa are summarised in Table 1.

Dynamic voltage support is requested



Dynamic voltage support
Voltage-time profile for fault ride-through in different countries

▲**Figure 2. FRT: high voltage (HV) and low voltage (LV) vs. time profile used in Germany [3], Italy [4] and South Africa [5].**

where the share of DG becomes big enough to cause stability problems or to amplify the consequences of a fault in the network when it is operated solely within the usual voltage band of ±10–15% of the agreed service voltage U_c. There are two modes of FRT requirements. The low-voltage (LV) ride-through mode is related, for example, to distant network faults or to faults in neighbouring lines; DG should stay connected for voltages above the LV boundaries, shown in Fig. 2. The high-voltage (HV) mode can occur, for example, following switching operations – see the two upper boundaries in the same figure.

Besides being requested to stay connected, the distributed energy resource (DER) can be additionally asked to actively support the voltage by a feed-in of reactive current. This is described, for example, in the German grid code and shown in Fig. 3; DER should be able to provide reactive current within the area between the two boundaries.

In the context of DG, a main concern for network operators has always been 'unintentional islanding' – i.e. the balancing of loads and generation regarding active and reactive power in a separated, no longer remote-controllable grid area. One of the issues is safety, for maintenance teams and in terms of the functionality of network protection schemes; another is linked with the question of re-synchronisation. For these reasons reliable LOM detection is mandatory.

It is important to note that grid codes also look at the possibility of intentional islanding related to the security of supply or black-start procedures. In ENTSO-E [7] the capability to take part in isolated network operation is defined for type C generators. The detection of the change from an interconnected system to an island operation should not rely solely on the network operator's switchgear position signals, but should also be implemented at the generator level.

Comparison of specifications for LOM and FRT requirements

Specifications given in different grid codes, standards or testing guidelines may vary. Some types of capability may be demanded only in a particular grid code, or different grid codes may specify the same type of capability differently. This section presents a more detailed description of some of these capabilities, while also looking at existing differences in the specifications.

LOM detection

The application of LOM detection for DG plants is often considered by utilities because of its high importance for the safety of personnel. Grid codes therefore typically require a type of LOM detection to be implemented in the DG–grid interface, but the type and degree to which it is applied are usually not further specified. In EN 62116:2011 [8] a test procedure of islanding prevention measures for utility-interconnected PV inverters is described using an adjustable RLC load connected in parallel to the AC source/the public grid at the AC side of the inverter. To prepare the testing, the RLC load is configured to form a resonant circuit with the PV inverter (Fig. 4). With the inverter operating and the RLC load balanced to the generated power, the utility-disconnect switch is opened and the run-on time is measured. The test has to be repeated by adjusting the RLC load according to different classes of load imbalances, which are given as a percentage value of the output power of the PV inverter (first class: 0%, 5% and 10%; second class: 1%, 2%, … 5%).

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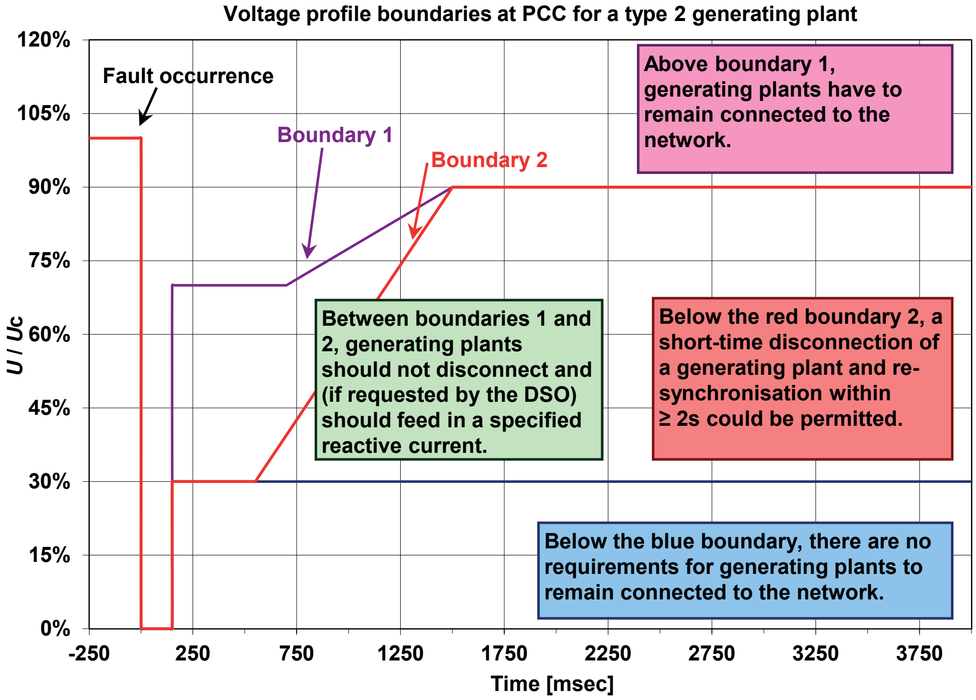
▼**Table 1. Reactive power provision according to the grid codes in Germany [3], Italy [4] and South Africa [5].**

Reactive power provision	Germany	Italy	South Africa (category B)
Operating range	From cosφ = 0.95 under-excited to cosφ = 0.95 over-excited	Up to full semicircle, depending on P_{rated}	From cosφ = 0.975 under-excited to cosφ = 0.975 over-excited
Operating requirements	Fixed set point or scheduled set points or remote controllable	Fixed set point or scheduled set points or remote controllable	Remote controllable or droop controlled
Set point types	cosφ, cosφ(P), Q, Q(U)	cosφ, cosφ(P), Q, Q(U)	Q, Q(U), cosφ(U)
Response time span	< 10s for cosφ(P), between 10 and 60s for Q(U), < 60s for remote control	< 10s (for remote control too)	< 30s for remote control

Usually the run-on time has to be less than 2s.

LOM detection testing is one example in which testing procedures for small-scale PV inverters are extended to utility scale. Testing of LOM detection involves adjusting the RLC load according to different classes of load imbalances, which are given as a percentage value of the output power. For central inverters with a rated power range of several hundred kilowatts, the given specification for the load imbalance as a percentage value of the output power may lead to very large steps between testing points.


Voltage profile boundaries at PCC for a type 2 generating plant

Above boundary 1, generating plants have to remain connected to the network.

Between boundaries 1 and 2, generating plants should not disconnect and (if requested by the DSO) should feed in a specified reactive current.

Below the red boundary 2, a short-time disconnection of a generating plant and re-synchronisation within ≥ 2s could be permitted.

Below the blue boundary, there are no requirements for generating plants to remain connected to the network.

Type 2 generating plant = non-directly coupled synchronous generator, e.g inverter coupled
PCC = point of common coupling (between generating installation and public grid)
DSO = distribution system operator

▲**Figure 3. FRT requirements in Germany, with reactive current provision [6].**

Dynamic voltage support/FRT

Different requirements exist for the capability of LV-FRT. All the requirements comprise specifications on the type of fault which is applied to the equipment under test (EUT). For instance, both FGW TR3 [6] (Germany) and CEI 0-16 [4] (Italy) specify symmetrical and unsymmetrical (two-phase) faults at voltage drops of 5%, 25%, 50% and 75% U/U_c. For the voltage dip of 5% U/U_c, the fault durations differ (FGW TR3: 150ms; CEI 0-16: 200ms).

Further requirements imposed on the behaviour of the EUT differ from standard to standard and can be described by introducing three time segments: the times before, during and after the fault. The condition of the EUT before the fault is described in the same way in both documents (10–30% P_{rated} for partial-load tests, and at least 90% P_{rated} for full-load tests), whereas FGW TR3 Rev. 23 requires that tests be carried out in test stands with 100% P_{rated} for full-load tests.

For the time during the fault, according to FGW TR3 the EUT has to prove its ability to actively support the grid voltage by feed-in of reactive current following a predefined value, called the 'k' factor. According to CEI 0-16, the only

Figure 4. Configurable RLC loads (3 × 200kW/kvar each) at Fraunhofer IWES SysTec.

Credit: Fraunhofer IWES, Beushausen

Credit: Fraunhofer IWES, Prall

requirement is to stay connected for the duration of the specified dips.

For the time after the fault, active and reactive power supplied by the EUT must return to their corresponding pre-fault values within 5s, according to FGW TR3. In contrast, CEI 0-16 specifies a time of 400ms.

Laboratory experience

Fraunhofer IWES operates a testing laboratory for PV inverters of up to 3MW. In this section the laboratory is briefly described, and specific challenges in testing central inverters for utility-scale PV installations are discussed.

SysTec – testing laboratory for grid integration

At its SysTec test centre (Fig. 5) for smart grids and electromobility, Fraunhofer IWES is developing and testing new equipment and operation strategies for smart low- and medium-voltage grids. In addition, investigations regarding grid integration and grid connection of electric vehicles, as well as of PV systems, wind energy plants, and storage and hybrid systems, are carried out under realistic conditions on site [10].

The main equipment of the testing laboratory for grid integration comprises:

- LV network simulator 1MVA, 100–900V @ 650A (100–450V @ 1300A), frequency range 45–65Hz
- programmable DC source, 3MW @ 1000V (DC)
- MV (medium-voltage) / LV (low-voltage) tap transformer 1.25MVA, 254–690V
- programmable LV RLC loads: 600kW, 600kvar (ind.), 600kvar (cap.)
- mobile 20kV LV-FRT unit up to 6MVA

The dynamic requirements are tested by using a mobile LV-FRT container, which is connected in series between the DER unit (EUT) and the public MV network and generates network faults (voltage dips) at the MV level. Both three-phase faults and two-phase faults can be simulated. A more detailed description is given in Schäfer et al. [11] and Geibel et al. [12].

Specific challenges

Challenges for testing laboratories regarding utility-scale PV installations are related to, for instance, LOM detection, the coverage of large power ranges, and non-standardised voltage levels. On the basis of experience gained at Fraunhofer IWES [13], a description of selected challenges is presented next.

Figure 5. Fraunhofer IWES SysTec test centre: the testing shed, a test track for inductive charging, and an adjacent commercial PV installation (22MW).

The main complication originates from the wide variety of PV inverters with specific electrical data: the wide operating ranges of rated AC and DC voltages, as well as of maximum power point (MPP) voltages, in addition to the increasing rated power, are all challenging.

- Non-standardised AC voltages may occur, as individual 'power park voltages' can differ from common LV distribution grid voltages; therefore, the AC network simulator and the corresponding MV/LV tap transformer have to allow operation over a wide operating range in terms of both voltages and currents. Low AC voltages may pose an extra challenge, since the resultant high AC currents necessitate significant efforts with regard to cabling.
- The DC source has to cover a wide operating range of DC voltages and related currents. Tests should be possible over the full MPP voltage range of the tested PV inverter, but at

- least for the maximum and minimum MPP voltage. Typically, MPP voltages range from 600 to 1000V, but higher MPP voltages do exist. Covering these wide operating conditions poses a big challenge to the dimensioning of the DC source. At the SysTec testing laboratory, the answer to this challenge is a series operation of single units of the DC source.
- The requirements for the AC interconnection depend on the topology of the tested PV inverter. High phase-to-ground voltages may require a galvanic separation, as the AC network simulator and the corresponding MV/LV tap transformer may not be able to withstand the stresses caused.
- Testing of the capability of *Q*(*U*) control is possible only with network simulators and can be very challenging for the equipment. The abruptly activated under-excited/over-excited operation of the EUT may have an impact on the AC voltage at the terminals of the EUT; this effect on the AC voltage must be compensated by the AC network simulator.

> "A laboratory infrastructure for testing utility-scale PV inverters must be very flexible and should be based on a modular design concept that will allow future extension"

Regarding LV-FRT, in general the voltage dips applied to the EUT can be produced at the MV or LV level. Fraunhofer IWES has testing facilities for both, generating voltage dips at the MV level (using a mobile 20kV LV-FRT unit) and at the LV level (using a highly dynamic 90kVA AC network simulator). Both approaches possess advantages and drawbacks.

Testing at the MV level features very realistic test conditions but gives rise to some challenges:

- Because of its electromagnetic nature (inrush current), the use of the MV/LV tap transformer is very demanding on the performance of the inverter.
- The grid impedance seen by the PV inverter during the test is significantly increased by the decoupling impedance of the medium-voltage LV-FRT unit, which may lead to stability problems in inverter operation.

Challenges faced during LV-FRT testing at the LV level are:

- The testing at this level with an AC grid simulator does not reproduce the effect of an MV/LV transformer at all.
- Owing to the usually lower rated power of the AC grid simulator, the tests are limited to smaller inverters.

In general, highly dynamic AC network simulators, suitable for testing LV-FRT, are not currently available for testing very large central inverters. Affordable AC network simulators with higher power ratings usually do not allow the voltage drop/rise times specified for LV-FRT testing or asymmetrical faults. With a medium-voltage LV-FRT unit, however, realistic LV-FRT testing of large inverters with a rated power of several hundred kVA to a few MVA can be performed at affordable cost.

Outlook

The active participation of DER installations in regular network operation will increase. Advanced functionalities are defined in the grid codes and will be demanded by the network operators. For testing these functionalities a systems approach needs to be developed, comprising the communication path, the response of the device and the possible mutual interaction of diverse demands. For these reasons, a laboratory infrastructure for testing utility-scale PV inverters must be very flexible and should be based on a modular design concept that will allow future extension. ■

Acknowledgement

The authors would like to thank the German Federal Ministry for the Environment for funding the DEA-Stabil project (FKZ 0325585A), which supported this work. The authors are solely responsible for the content of this article.

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