Grid code compliance testing of renewables – New requirements and testing experiences

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***Abstract*—This paper describes common practices regarding the application process for grid connection of renewables in view of advanced grid code requirements. The development process of compliance testing guidelines is presented and a detailed example for the technical implementation in a testing laboratory including equipment specifications is given.**

Keywords - grid integration; point of interconnection/ common coupling (POI/ PCC); grid codes; compliance testing; certification; testing infrastructure

I. Introduction

The energy supply in Germany and worldwide is currently undergoing a large transformation process from fossil towards renewable energy with high shares of solar and wind energy. This has led to an enormous rise in the rated power capacity of renewable based generation while the utilization of large conventional power plants is decreasing, especially for Germany not only the utilization is decreasing but also the actual number and capacity of conventional power plants.

A. *Outlook on PV inverter technology*

The focus of new photovoltaic (PV) installations changed during the last years from Europe to the Asia Pacific region. As shown in Fig. 1 both regions reached about 100 GW cumulated installed PV capacity by 2015 [1].

Also the global market outlook for PV installations is very positive. Reasons are ambitious political objectives following the Paris agreement, but even more the fact that the power production costs of PV power plants reached levels competitive to other sources. For large PV power plants average production costs of around 8 €ct/kWh can be reached in Germany today. And costs can get significantly lower in countries more blessed by the sun like India with recent PV tenders resulting in costs around 4.5 €ct/kWh.

India has ambitious objectives for installing renewables energies with PV summing up to 100 GW of which 60% will be central or utility-scale installations. This number reflects also the actual overall market share of central inverters in 2016 with 54%, mostly used in large commercial and utility-scale systems [2]. Although, recently the competition between string and central inverters for medium sized PV power plants seems to be revived [3]. But in larger installations the central inverter is dominating.

For central inverters the development shows increasing rated power with ratings above 2.5 MW per inverter and DC voltages up to 1500 V. In 2017 shipment of around 10 GW of central inverters with 1500 V DC voltage is expected [3]. Even higher DC voltages are sometimes considered, and the possibilities for transformerless, directly MV-grid coupled inverters are investigated on a research level.

The decision on the technical concept of the PV power plant is based on a number of different aspects, like investment costs, efficiency, maintenance and reliability issues, but also the applicable grid code. The selection of the concept, multi-string inverter or central inverter, and topology of the PV farm (collecting grid) influences the behavior of the installation towards the grid at the point of interconnection (PoI) / point of common coupling (PCC). To assess the impact of a PV power plant on the grid the grid operator needs to know the behavior of the full installation.

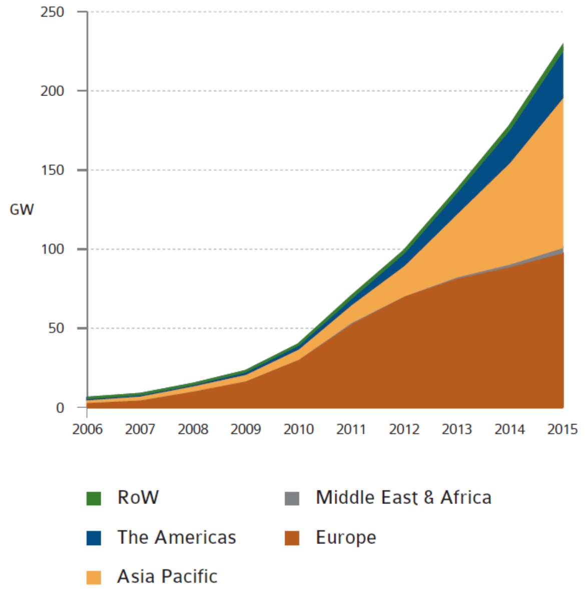

Figure 1. Evolution of regional PV installations (GW) [1]

Due to the growing share of renewables in the power generation mix, it becomes more important, that all renewable generation technologies contribute to power system stability by having the ability to provide system services (e.g. active power response, reactive power provision) during normal operation and to “ride through” short grid faults (e.g. voltage dips).

Following these trends, the paper first describes the process of the technical investigations for interconnection of e.g. a PV power plant. And second, details and experiences are given regarding grid code compliance testing focusing on large central inverters.

II. Application Process for Interconnection of Renewables

The procedure for assessing the technical aspects for interconnection of renewables is usually defined by law or in a similar regulation. These regulations refer to technical requirements specified in grid codes. Compliance to grid code requirements is documented e.g. by successful tests against reproducible test cases. The latter are often done as type tests and supervised by accredited certification bodies. Examples are given in Table I.

Besides the technical aspects the regulatory frame, like deadlines, cost allocation and fees, have to be respected also.

When the grid operator is approached for the interconnection of a new generator / power plant to the grid, he has to consider

a) electrical characteristics of the local PoI / PCC where the power plant will be coupled to the grid (e.g. voltage rise, voltage quality (harmonics, flicker, etc.), detection of unintentional islanding)

b) conditions for the operation of the grid area used for the evacuation of the power (e.g. overload, protection coordination)

c) system wide aspects (e.g. frequency regulation, dynamic voltage support (fault ride through)). (These aspects are part of the System Ancillary Services.)

In the following the application and approval process is detailed from a technical point of view using the German Renewable Energy Act [4], the MV grid code [5] and the testing and certification guideline [6] as an example (see also flow chart in Fig. 2).

TABLE I. Levels of Interconnection Requirements with Examples of Issuing Organizations and Documents

Level	Example California	Example Germany
Law or Regulation	e.g. Rule 21	e.g. Renewable Energy Act (EEG)
by government or regulatory authority		
Grid Code or Standards	e.g. IEEE 1547	e.g. VDE-AR-4120/ -4110/ -4105
by stakeholder associations or standardization committees		
Testing Guidelines	e.g. UL 1741	e.g. FGW TR 3
by working groups of technical specialists like certifying bodies or testing laboratories		

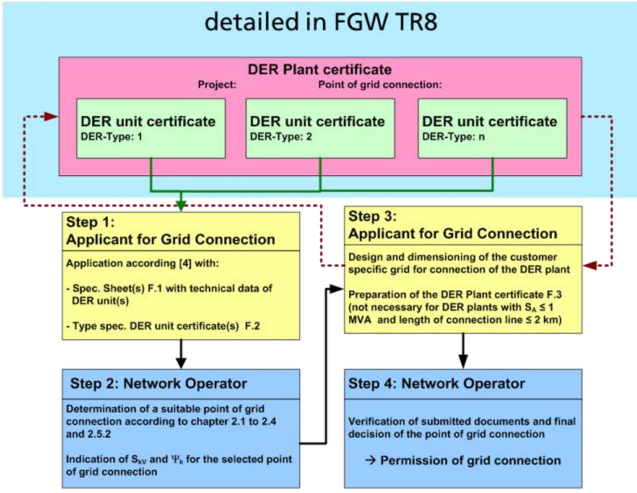

Figure 2. Approval procedure acc. to German MV-Grid Code [5]

Upon receiving a request (application) for grid connection the grid operator firstly defines the location of the interconnection to the grid and proposes the PCC. The applicant provides information concerning the planned type/s of single generator/s and rated power of the plant.

In this stage the focus is on secure grid operation of the grid area with the main aspects load flow / overload and network protection. For the decision on the PCC the sum of the total costs of the connection from the installation to the grid and the costs for possibly necessary grid extension measures (e.g. for mitigation of line congestion) have to be minimized. Direct connection costs will be allocated to the applicant. Grid extension costs have to be borne by the grid operator. (Only, if the grid extension costs are deemed as unreasonably high, the grid operator can deny the request for interconnection. The grid extension cost should not be more than 25% of the total costs of the renewable installation.)

After defining the location of the PCC the installation will be designed in detail and a validated plant model has to be provided for further investigations.

A. *Excursus on Unit and Plant Certification and Modelling*

The German grid code for MV connected distributed energy resources (DER) [5] distinguishes between the single DER unit and the DER plant (in German “EZE – Erzeugungseinheit” and “EZA – Erzeugungsanlage”).

A DER unit is a single device for power generation (e.g. the part of a PV plant, which is connected to only one inverter). The device has to comply with the requirements defined in the grid code. The behavior relevant for the assessment of the PCC and for the system wide aspects are tested in a laboratory according to test cases and the requirements for the test set-up described in the testing guideline. Additionally, a generic model of the DER unit has to be developed and validated with the measurement results of the laboratory tests (the requirements are given in [8]). An accredited, independent third party, the certification body, supervises the process and confirms the grid code compliance of the DER unit by issuing a certificate [6]. The process is summarized in the flow chart of Fig. 3.

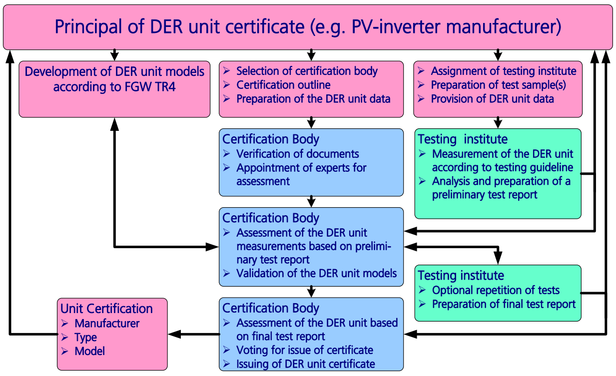

Figure 3. Procedure for issuing a generating unit / DER unit certificate

A DER plant is a farm or cluster with at least one but normally multiple DER units (EZEs) including all equipment necessary for grid connected operation of the DER plant like farm cabling, substation, transformer, farm controller and other power conditioning devices such as filters etc. Based on the DER unit certificate/s (which also comprise/s the unit model/s) a generating plant certificate can be issued. As a pre-condition for this, sufficient information describing the generating plant (e.g. technical data of the park-internal power lines and other equipment such as power transformers and park controllers) has to be delivered to the certification body and to the entity authorized to build the simulation model of the plant, if this is not done by the manufacturer.

B. *New Grid Code Requirements in India*

With more and more renewables installed at all levels of the electricity grid the requirements for generators have to cover aspects of system operation, stability, and security. Consequently grid codes for connection of renewables / DER have been updated continuously worldwide. In Europe a new set of grid codes was recently elaborated (for detailed information see [9]) as well as in Germany with new requirements (new grid code at HV level [10], new draft versions for MV [11] and LV [12]).

In India the situation regarding solar and wind power is similar. At the end of the year 2016 the Indian CEA (Central Electricity Authority) drafted a second amendment to the technical standards for connectivity to the grid [13] including various changes and new requirements.

The changes and new requirements [13] proposed as an update to the Indian grid code comprise

- Under-voltage-ride-through (UVRT) capabilities introduced for solar and adapted for wind power systems
- Introduction of frequency response, Over-voltage-ride-through (OVRT) capability, voltage control and short circuit ratio
- Specification of ramp rates
- Changed reactive power capabilities and harmonic emission limits.

In the following section background information on grid code compliance testing and certification is given and detailed, using the examples of UVRT and interface protection.

III. Grid Codes and Compliance Test Procedures

National and international compliance testing procedures are continuously developed and updated, to verify the actual behavior of the generating systems. This is done by working groups and described in international standards and/or technical guidelines. These working groups usually involve grid operators, regulators / authorities, manufacturers, testing institutes and research facilities in order to allow a high level of practical applicability. The test procedures may also be complemented by a certification process. As described above, the German grid codes describe a certification process which comprises compliance testing for single generating units (i.e. type testing of a generator) and modelling of both the generating unit and the whole generating plant (e.g. wind park). In the German case, three independent parties take part in the certification process; manufacturer, testing institute (accredited acc. to ISO/IEC 17025) and certification body (accr. acc. to ISO/IEC 17065).

Compliance test procedures shall guarantee comparability and reproducibility of the test results, i.e. test results of different test institutes shall be comparable and it shall be possible to reproduce test results (using the same test sample and applying the same test conditions). Establishment of a quality measurement system and possibly the requirement of accreditation often are a pre-requisite to achieve these conditions, but most important is a clear definition of the tests which are to be performed. Therefore compliance test procedures (testing guidelines) have to define the following:

- Test setup
- Measurement system and conditions
- Method of testing and test plan (including operating conditions of the EUT)
- Evaluation process
- Test report

Definitions on the test setup comprise requirements on the different possible test setups (field measurement or test bay) and also on the measurement locations (metering points) and quantities (e.g. AC / DC voltages and currents, wind speed, torque / polar wheel angle). Field measurements are done with the equipment under test (EUT) connected to the public grid, while during tests in a test bay the EUT may be connected to the public grid (see Fig. 4) or to a grid simulator. The testing guideline may give requirements on the used grid simulator and, in the case of testing a photovoltaic (PV) inverter, also on the DC source used to emulate the generation of the PV modules.

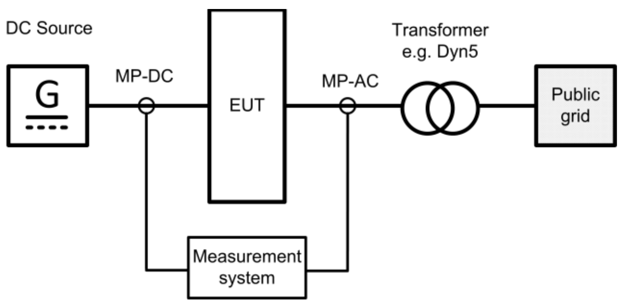

Figure 4. Exemplary test setup of a test bay for testing a PV inverter connected to the public grid, with "MP" = metering points. (Note: Instead of transformer and public grid a grid simulator may be applied.)

The bullet point measurement system and conditions involves requirements like e.g. minimum sampling rate applied at the measurement device, maximum permissible measurement uncertainties or measurement requirements for 0.2-s or 10-min RMS values. For instance, the German technical guideline FGW TR3 [7] requires a sampling rate for voltage and current measurement of at least 3 kHz for steady-state tests (i.e. active / reactive power provision, flicker, interface protection and start-up), 20 kHz for measurement of harmonics and 10 kHz for transient tests, i.e. fault ride through (FRT).

The most extensive part which has to be described in compliance test procedures is the part dealing with the method of testing and the test plan. First the aim of the test has to be explained; usually it is directly linked to a requirement given in a grid code or technical standard. Then the method of testing has to be detailed by stating the different operating points at which the EUT has to be operated during the specific test. Set point values (e.g. for active or reactive power) or characteristics (e.g. for Q(V), cosphi(P) or P(f)) which have to be sent or implemented to the EUT have to be prescribed. Furthermore requirements on the connection to the public grid (e.g. transformer tap position) or on the operation of the grid simulator (e.g. settings for voltage and frequency) have to be given. The sequence of operating points during the test and necessary repetitions of this sequence under different conditions usually can be summarized in a test plan. The challenge in writing a testing guideline is to require a minimum necessary number of operating points and/or test sequences which is needed in order to receive a meaningful and preferably universally valid test result. Most often it is not reasonable to perform tests for all possible operating points of a requirement characteristic. Therefore testing guidelines usually require a set of test points which also comprises worst case (i.e. maximum stress) conditions for the EUT's hardware and control respectively (e.g. thermal impact of maximum operating currents). Examples for the choice of these test points will be given in the subsections below.

Another part which has to be defined in testing guidelines is the evaluation process of the measurement data. It has to be stated which quantities shall be considered for interpretation of the tests and how this data shall be processed and provided, i.e. analyses of average, RMS, peak or fast (sample) values. Data may also have to be processed for dissemination to a certification body accompanying the tests. The prescribed evaluation process also has to define tolerances which have to be considered for reaching set point values; these may include stationary tolerances for e.g. 0.2-s frequency measurements as well as transient tolerances for e.g. build-up and settling time during FRT.

Finally testing guidelines have to state which data has to be provided in the test report. This may include for instance information on the test setup/s, the measurement system and conditions, data of calibration certificates and a consideration of measurement uncertainties, the test results as well as a manufacturer's declaration of the tested EUT.

In the following, testing requirements given in the German guideline FGW TR3 [7] are exemplarily described for selected generator functionalities.

A. Fault Ride Through

Fault ride through (FRT) describes the capability of electrical generators to continue operation during transient events like voltage sags (short-term under voltages) or voltage swells / surges (short-term over voltages) outside of the voltage range for normal grid operation. The capability is requested for events lasting between a few tens of milliseconds to a few seconds depending on the voltage change. In addition to the capability of just "riding through the fault" certain grid codes and interconnection standards request a defined electrical behavior of the generators during and right after the fault. The following two FRT capabilities are discriminated:

- Under-Voltage-Ride-Through (UVRT) capability
- Over-Voltage-Ride-Through (OVRT) capability

As an example, Fig. 5 shows UVRT and OVRT voltage-time characteristics for MV connected generators as specified in South African [14], Italian [15] and German Grid Codes [5]. The UVRT capability is related e.g. to distant network faults or faults in neighboring lines. Generators should stay connected for voltages above the UVRT boundaries. The OVRT capability is requested following e.g. switching operations, see the two upper boundaries in the same figure.

In addition to the characteristics shown in the diagram the German draft MV grid code VDE-AR-N 4110 [11] also requires OVRT capabilities, these are 120% Uc for 5 s and 115% Uc for 60 s; presumably the grid code will get into force beginning of 2018.

For HV connected generating plants in Germany there are already OVRT requirements since 2015 [10]; these are 130% Uc for 0.1 s and 125% Uc for 60 s.

Regarding UVRT capability, the special dynamic behavior requested for generators during and right after voltage dips / faults may include the following:

- Minimization of reactive power consumption (lagging power factor) during faults
- Capability of injecting reactive power into the grid in order to support grid voltage (over-excited operation)
- Return to post-fault values of active and reactive power within a specified time-span

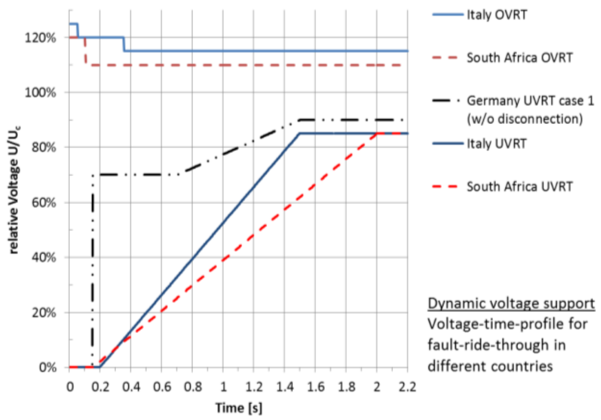

Figure 5. Selected UVRT and OVRT requirements at MV level

For MV connected equipment in Germany requirements for UVRT are given in the BDEW MV guideline [5]. For testing of the UVRT capability BDEW MV refers to FGW TR3 [7]. The major requirements given in FGW TR3 are detailed in the following:

The test objective is to verify the generator's capability to detect voltage dips and "ride through" these dips without damage. Furthermore the dynamic behavior of the generator during and also right after the fault is tested by measuring its current contribution. The test shall be used for validation of the generator model (see [8]) within the certification process (see [6]) and for testing of the generator's control and hardware components.

Compliance testing can either be performed in the field or in a test bed (e.g. by applying a grid simulator with a highly dynamic performance). For testing of PV inverters in a test bed, the utilization of a DC source for emulation of the PV modules is allowed (technical requirements on the DC source are also given by the guideline). In the testing suitable equipment to generate voltage dips has to be used; the guideline provides an example for the test equipment which is also given in IEC 61400-21 [16], see Fig. 6.

Two groups of manually adjustable air-core coils ("Z1" and "Z2") are connected in series and form a voltage divider. At one side of this voltage divider the public grid is connected and at the other side two- and three-phase faults are configured (in the figure this is at the bottom side of "Z2"). The tested generator is connected in the middle of the voltage divider (between "Z1" and "Z2"). By automatically controlled manipulation of the switches (circuit breakers) "S1" and "S2" voltage dips are produced by applying short-term short circuits. The depth of the voltage dips depends on the ratio of Z1/Z2, which is adjustable and has to be pre-configured. The initial state of the switches prior to an UVRT test is: "S1" closed and "S2" open ("by-pass mode" of the UVRT test equipment). A UVRT test sequence consists of the following switching actions:

- opening of "S1", closure of "S2"
- opening of "S2", closure of "S1"

The impact on the public grid is limited by means of the decoupling air-core coil "Z1" (proper sizing of "Z1" and "Z2" is essential). At the measuring points "MP1" to "MP3" (see Fig. 6) suitable measurement equipment has to be installed and measuring data are to be recorded with a sufficiently high sampling rate of at least 10 kHz.

Tests have to be performed for five different levels of voltage dips (see Table II) and for both two-phase and three-phase faults. Moreover, there are two ranges of active power for the tests: part load (0.1 … 0.5 of nominal power, Pn) and full load (> 0.9 Pn, for test bays: 0.98 … 1.02 Pn).

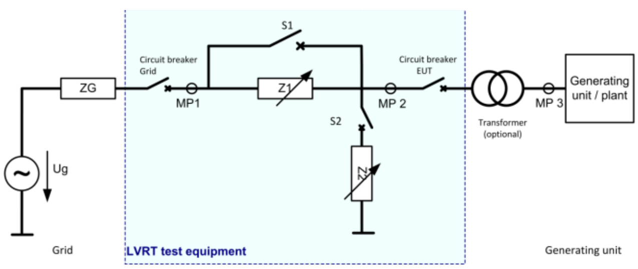

Figure 6. UVRT test equipm. acc. to IEC 61400-21 [16], FGW TR3 [7]

TABLE II. UVRT TESTS FOR "TYPE 2" GENERATING UNITS, ACCORDING TO BDEW MV [5], FGW TR3 [7]

Test number	Ratio of fault voltage to initial voltage (U/U_0)	Fault duration (ms)
1	≤≤ 0.05	≥ 150
2	0.20 … 0.25	≥ 550
2a (alternatively to test no. 2)	0.30 … 0.35	≥ 675
3	0.45 … 0.55	≥ 950
4	0.70 … 0.80	≥ 1400
5	0.90 … 0.95	≥ 10 s

The technical guideline also defines different ranges of reactive power for the UVRT tests. The generating unit has to be operated with a reactive power value in the range of 0 … 0.10 Q/Pn leading or lagging prior to the voltage dip. For test no. 3 additional tests with a reactive power value > 0.10 Q/Pn lagging and for test no. 4 additional tests with a reactive power value > 0.10 Q/Pn leading and lagging have to be performed.

During the voltage dip the tested generator has to supply a reactive current I_R according to a preset k-factor, i.e. $k = (I_R/I_n)/(\Delta U/U_n)$, with nominal current I_n, voltage change $\Delta U = U - U_0$, pre-fault voltage U_0 and nominal voltage U_n. The k-factor is set to a value of 2; in addition a few selected tests have to be carried out with a differing value of the k-factor; e.g.: k = 0, 3 and/or 4.

After fault clearance (after the voltage dip) the generating unit has to return to its pre-fault operating values of active and reactive power within a specified time.

As required in the guideline, two consecutive tests have to be successfully completed for each of the voltage drop tests described above.

For test evaluation the dynamic behavior of the generating unit during the voltage dip and after fault clearance is analyzed. At the time of fault occurrence (beginning of the voltage dip) the generating unit has to quickly provide a reactive current I_R defined by the k-factor as described above. In order to evaluate how fast this current can be provided the technical guideline introduces two parameters, these are the build-up time and the settling times. The build-up time is defined as the instance of time after fault occurrence at which the value of I_R firstly reaches / exceeds the lower limit of the tolerance band for the desired value (set point) of I_R. The settling time is defined as the instance of time after fault occurrence at which the value of I_R leaves the tolerance band for the set point value of I_R for the last time. The required value of I_R and its tolerance band vary depending on k-factor and voltage depths (ratio of fault voltage to initial voltage).

A requirement for the values of post-fault active and reactive power is defined, too. Therefore, the measurement data 2 s prior to fault occurrence and 5 s after fault recovery is evaluated more in detail with special regard to the values of active and reactive power.

All test results have to be provided in a test report for assessment by the certification body. Additionally, measurement data has to be provided for model validation.

B. Interface Protection (Protective disconnection functions for grid and system protection)

For MV connected equipment in Germany requirements for protective disconnection functions are given in BDEW MV [5]. Concerning the test procedure BDEW MV refers to FGW TR3 [7]. Some special requirements given in FGW TR3 are detailed in the following:

Whilst the tests for under- and overfrequency protection are performed for all three phases at the same time, for under- and overvoltage protection FGW TR3 [7] requires individual tests for each of the measured voltages (only for HV connected appliances additionally also symmetrical tests have to be performed). The term "measured voltage" here refers to phase-to-neutral and phase-to-phase voltages respectively, according to the applied type of implementation.

For all protective disconnection functions tests have to be performed for both the maximum and the minimum values of the setting ranges of threshold values and release times respectively.

For instance, the undervoltage protection stage 1 has to be tested individually for each measured voltage

- with the threshold value set to the minimum possible voltage value (within the setting range) and the release time set to the minimum possible time and
- with the threshold value set to the maximum possible voltage value and the release time set to the maximum possible time.

Tests regarding accuracy of the threshold value are performed by applying either a stepped or a pulsed ramp. For instance, for testing the undervoltage protection stage 1 with a stepped ramp the test is started with a voltage value of set threshold value plus 2 % of the nominal voltage Vn. Then the voltage is reduced in steps of 0.5 %Vn, with a step duration of at least 150 % of the set release time and a minimum step duration of 100 ms. According to the related certification guideline FGW TR8 [6] disconnection must occur in the range of threshold value ±1 %Vn. For under- and overfrequency protection the tests are started at a frequency value of set threshold value plus/minus 0.2 Hz and the applied step width is 0.05 Hz. Disconnection must occur in the range of threshold value ±0.1 Hz.

Tests regarding accuracy of the release time are performed by applying a voltage / frequency jump passing by the threshold value. For instance, for testing the release time of the undervoltage protection stage 1 the test is started with a voltage value of set threshold value plus 2 %Vn. Then the voltage jumps to a voltage value of set threshold value minus 2 %Vn. For under- and overfrequency protection the tests are started at nominal frequency. Then the frequency jumps to a frequency value of set threshold value plus/minus 1 Hz.

For under- and overvoltage protection according to [7] also tests regarding the resetting / disengaging ratio are required. For instance, for testing the undervoltage protection stage 1 the threshold value is set to 80 % Vn and the release time to a value between 1 and 1.5 s. The test is started with a voltage value of 102% of the set threshold value. Then the voltage jumps to a voltage value of 98% of the set threshold value for a duration of 500 ms. After this the voltage returns to 102% of the set threshold value. After 5 s the voltage jumps again to 98% of the set threshold value and remains at this value until the release signal for disconnection is generated by the protective disconnection function. If this test is passed (no tripping / disconnection at the first jump, but tripping at the second jump), the tolerance limit of 1.02 (requested by FGW TR8 [6]) is kept.

IV. Test Infrastructure and Testing Experiences

In this section the requirements on a laboratory unit for grid code compliance testing, i.e. certification and reference tests, are outlined and some experiences gained during laboratory operation are presented.

Here certification and reference tests concern mainly the grid interface of single generators and storage systems connected to LV or MV networks but may also be extended to other equipment, e.g. voltage regulators, active filters or reclosers. The tests consist in verifying whether the equipment or system meets the local or international standard related to the performance of electrical parameters in steady state or dynamic conditions. In Fig. 7 main building blocks of a testing laboratory and their conceptual arrangement are shown.

Steady-state tests (like e.g. testing of active power control, reactive power control, connection conditions) can be tested with the equipment under test (EUT) connected to the public grid or to the electronic grid (network) simulator.
As a standard electronic grid simulator may not allow for manipulation of the voltage independently for each phase, testing of grid protection of large inverters, which are designed for connection to the medium voltage network and equipped with test signal terminals, could be done by means of a signal generator in order to perform functional tests of protection equipment of generating units/plants.

Depending on the EUT and the specific test requirements alternatively the steady-state tests may also be performed completely without an electronic grid simulator, just using the access to the public grid and a signal generator. Testing of P(f), Q(V), connection conditions and frequency protection may be performed by changing the values of rated voltage / rated frequency implemented to the EUT. A test signal generator is used for testing of phase-selective voltage protection and may also support testing of the aforementioned functions (feeding the input signals of the controls with virtual test signals for voltage / frequency). This approach may be of interest especially for field testing or testing of very large units.

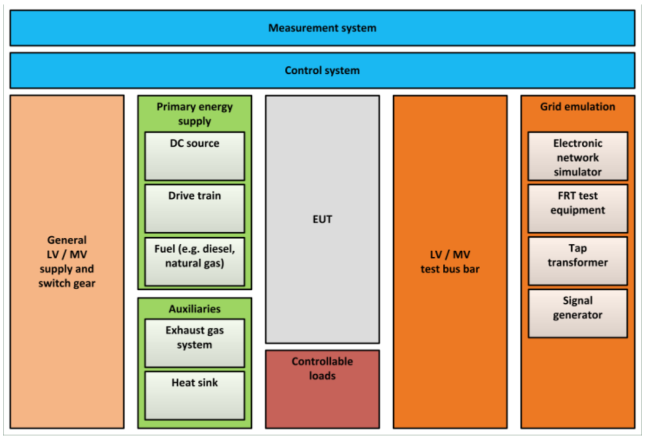

Figure 7. Testing laboratory building blocks and conceptual arrangement

Due to the highly dynamic requirements for FRT tests (UVRT and OVRT) such tests cannot be performed with the standard grid simulator. Therefore the EUT is connected to the public grid via a tap transformer and the FRT test equipment (compare Fig. 6). Grid simulators showing a highly dynamic performance are very costly and are only available for small EUT at affordable cost.

Special tests like testing of anti-islanding protection or insensibility to automatic re-closure out of phase (e.g. 90 or 180 degree) can be done using controllable RLC-loads (resonant circuit). Additional equipment like transformers with differing vector groups may be necessary in order to provide voltages with different phases for the re-closure test under out-of-phase-conditions.

A. Laboratory Infrastructure – Example Fraunhofer IWES

For grid code compliance testing, suitable testing equipment has to be applied. Fraunhofer IWES operates a testing laboratory for PV inverters of up to 3 MW. In this section the laboratory is briefly described. Specific challenges in testing central inverters for utility-scale PV installations are discussed in the subsequent paragraph.

At SysTec ("Test centre 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 [17].

The main infrastructure of the developing and testing laboratory for grid integration comprises:

- LV grid simulator 1 MVA, 100–900 V @ 650 A (100–450 V @ 1300 A), frequency range 45–65 Hz
- programmable DC source 3 MW, 100–1000 V_{DC} @ 3000 A_{DC}, (or with partly parallel connection: 100–±1000 V_{DC} @ 1300 $A_{DC,}$ with grounded midpoint)
- MV (medium-voltage, 20 kV) / LV (low-voltage) tap transformer 1.25 MVA, 254–690 V
- programmable LV RLC loads: 600 kW, 600 kvar (inductive), 600 kvar (capacitive)
- mobile 20 kV UVRT test container, up to 6 MVA

The dynamic requirements are tested by using a mobile UVRT test 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 of the infrastructure is given in [18] and [19].

B. Specific Challenges

Challenges for testing laboratories regarding utility-scale PV installations are, for instance, related to loss-of-mains (LOM) detection, coverage of large power ranges, and non-standardized voltage levels. In the following a description of selected challenges is given based on experience gained at Fraunhofer IWES. First some general challenges are described, next challenges specific to testing of particular capabilities are considered.

The main challenge originates from the large variety of PV inverters with their different technical specifications, such as rated power, rated AC voltage and current, DC voltage and current operating ranges, MPP voltage range.

As "power park voltages" can differ from common LV distribution grid voltages, non-standardized AC voltages in the range of typically 300 V to 690 V may occur. Therefore, the AC grid simulator and the MV/LV tap transformer respectively have to allow for operation over a wide operating range for both voltages and currents. Low AC voltages may pose an extra challenge, since the resultant high AC currents necessitate high efforts in cabling.

The DC source has to cover a wide operating range of DC voltages and currents. The rated power of the EUT has to be matched taking into account the MPP voltage range of the inverter and the coverage of conversion losses. Preferably, tests shall 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 V to 1000 V, but also maximum MPP voltages of 1500 V and above do exist. Covering these wide operating ranges poses a big challenge to the dimensioning of the DC source. As described above, in the SysTec testing laboratory this challenge is solved by series and/or parallel operation of single units of the DC source. Furthermore, the designated PV module grounding scheme has to be considered.

The requirements for AC interconnection depend on the topology of the tested PV inverter. High phase to ground voltages may require a galvanic separation, as the AC grid simulator and the MV/LV tap transformer respectively may not be able to withstand the stresses caused.

Testing of active and reactive power provision by set-point control requires measurement of the command signal sent to the EUT. Appropriate measures have to be taken for measuring of the command signal, which may be of different type (e.g. analogue signal, binary coding given by a programmable logic controller, RS232, RJ45 etc.).

If the capability of grid protection is included in the control of the PV inverter, the testing of protection functions with an automatic relay test system may require test terminals. For EUTs not offering this possibility other means to connect the automatic relay test system have to be provided.

When testing the insensitivity to automatic re-closure with phase shift, adjusting the load bank and thus minimizing the current through the breaker proves to be very challenging; small load increments are needed.

Testing of the capability of Q(V) control is only possible by means of grid 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, which (in general) is the intended effect of the Q(V) capability. The AC grid simulator has to compensate this effect on the AC voltage. Manual corrections carried out by the test engineer may be necessary and may have to be repeated for some or all of the test points. This correlation/ interdependency makes the testing more difficult and tolerance violations during transition times have to be avoided.

Regarding UVRT, in general, voltage dips applied to the EUT can be produced at the medium voltage (MV) or at the low voltage (LV) level. Fraunhofer IWES has testing facilities for both producing voltage dips at the MV level (with the mobile 20 kV UVRT test equipment described in paragraph IV.A) and for producing voltage dips on the LV level (with a highly dynamic 90-kVA AC grid simulator). Both approaches inherit their special challenges.

Challenges faced during testing of UVRT at MV level:

- Due to its electromagnetic nature (inrush), the utilization of the MV/LV tap transformer is very demanding on the performance of the inverter. But this leads to very realistic test conditions.
- The grid impedance seen by the PV inverter during the test is heavily enlarged by the decoupling impedance of the presented medium-voltage UVRT test equipment, which may lead to stability problems in the operation of the inverter.

Challenges faced during testing of UVRT at LV level:

- Testing of UVRT at LV level with an AC grid simulator does not at all reproduce the effect of an MV/LV transformer.
- Due to the usually lower rated power of the AC grid simulator the tests are limited to smaller inverters.

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

V. Conclusions and Outlook

With more and more renewables installed at all levels of the electricity grid the requirements for generators have to cover aspects of system operation, stability, and security.

The rated power of central inverters for utility-scale PV installations depends on technical developments with changing economic and regulatory boundaries. Moreover, new requirements of grid codes and standards on conformance testing may require modified or additional tests. Therefore test conditions have to be adaptable and additional equipment may be required.

For these reasons laboratory infrastructure for testing of utility-scale PV inverters has to be very flexible and should be based on a modular design concept allowing for future extension.

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