Performance of Test Bench Testing for the Evaluation of Grid Compliance of Wind and Solar Generating Units

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Executive summary

In this paper, an investigation of the topic of test bench testing of wind and solar stations is performed. The aim is to review the currently available types of test benches and identify the extent to which measurements under controlled conditions can be used for the certification of the generating units instead of actual field measurements, which has been the standard practice up to now. The advantages and restrictions are discussed, and specific proposals for the establishment of optimal certification procedures are formulated.

Introduction

The current state of grid compliance testing of wind turbines (WTs) and solar inverters is to perform the tests in the field, with only some components — such as the grid protection devices — being tested at laboratory facilities. Solar inverters are often tested at test benches in which the solar panel is emulated by a direct current (DC) source.

Field testing provides the advantage of examining the behavior of the complete system in actual environmental and grid conditions. The use of test bench facilities is generally convenient for manufacturers during the development of new prototypes. Test bench facilities give the possibility of performing special tests, not limited to the electrical characteristics, for the investigation and optimization of the performance of WT or solar inverter components in a controlled and systemic manner.

Furthermore, testing under controllable conditions is helpful for the validation of the simulation models and offers the chance for deploying relevant R&D activities. Especially for the evaluation of grid compliance, a consensus is growing that electrical characteristics relevant to the provision of ancillary services, such as voltage dependency of reactive power or set-point active/reactive power control, can be sufficiently tested on a test bench level. But for demonstrating the fault ride through (FRT) capability or power quality (PQ) performance, many open technical issues must still be addressed and discussed in order to establish a standardized and universally accepted procedure.

Main concerns that must be investigated include:

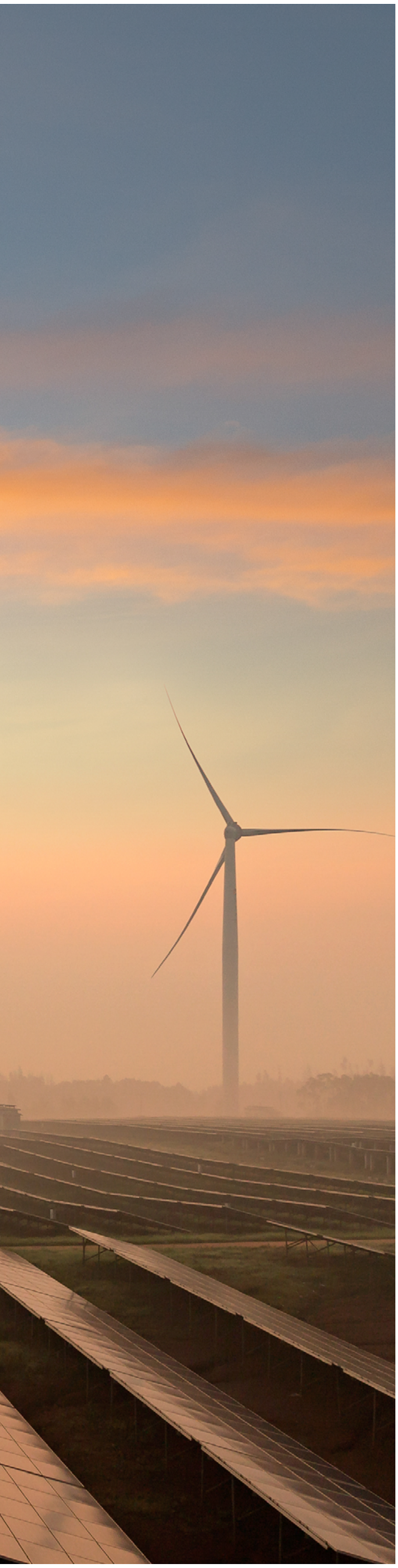
- Which electrical characteristic parameters can be reliably tested at a test bench and which cannot?
- Which tests must be performed in the field?
- How does the test bench characteristics influence the performance of the tested units?
- How can we draw conclusions for the performance of the complete unit based on the subsystem or component testing?

Driven by such concerns, IEC has recently launched a dedicated working group (WG) aimed at the thorough technical investigation of the topic, in order to define the relevant requirements to be included in a separate international procedure for the measurement and assessment of wind turbine components and subsystems (future IEC 61400-21-4[1]). Further research work on this topic is ongoing in Germany in the context of the project CertBench,[2] where UL is member of the Consortium, in which the comparison of measurement results taken at the test bench with electrical properties determined during field measurements is being performed.

Taking the above into account, the aim of this paper is to answer the open questions regarding the use of test bench facilities for the testing of grid compliance of power generating units (mainly wind and solar stations), in order to provide a necessary technical background to be considered for the grid compliance evaluation. The work consists of the following main parts:

- Description of the international experience and review of worldwide standardization activities in test bench testing
- Classification of test benches in terms of complexity, e.g., constant or varying torque, rotor modeling, inverter only without rotating machine etc., and proposals for options that can actually be applied from a practical perspective
- Proposal for the range of validity of the tests at a test bench
- Proposal for the field and test bench testing for the main electrical characteristics

Regarding the structure of the paper, in Section II the current status and progress in the topic of test bench testing is done. Section III includes a technical discussion about the classification of test benches with regard to their testing scale level, e.g., full-scale nacelle testing, components testing, etc. In Section IV, the expected differences between the field testing and test bench testing for the main electrical characteristics are presented and discussed, while the conclusions of the present work are summarized in Section V.



International experience in test bench testing

The evaluation of grid code compliance of power generating units (PGUs), especially for WTs, is traditionally based on actual field measurements on the full-scale prototypes. The relevant test results are used afterward for direct comparison with the grid code limits as well as for the validation of simulation models by the manufacturers and the certification bodies. For these purposes, specific standards and guidelines have been developed. IEC 61400-225 refers to the general certification requirements for WTs and is used by all certification bodies in the global wind market. In this standard, requirements for the electrical performance certification is also included, but at a quite limited extent. It is mainly up to the certification bodies to define further rules depending on the requirements of the specific grid code under investigation. In some countries, more detailed guidelines for certification have been developed, like the FGW TR8 in Germany.[9]

Simulation of the behavior of the PGUs and the validation of the constructed models play an important role in this certification process because they provide the possibility to examine the PGU performance under predefined conditions that are different from the actual conditions during field measurements. For WTs, this topic is addressed by IEC 61400-27-1[6], which specifies dynamic simulation models for generic wind turbine topologies, concepts and configurations existing in the market with the aim to study the electrical characteristics of WTs at the connection terminals. WT modeling as well as modeling of other PGUs is also covered in FGW TR4,[8] which is applicable in the German market. Especially for WT model validation, this topic is also covered in IEC 61400-27-1 and expected to be included in a separate standard (IEC 61400-27-2) in the near future.[7]

In an environment of increasing certification needs (model validation at various conditions, diversity of the requirements of grid codes, etc.), the possibility of electrical characteristic testing at test benches has become the focus of certifying bodies and manufacturers for a more thorough investigation of PGU performance. Testing on a test bench system may provide the advantage of examining PGU response under predefined and controllable conditions but, in parallel, requires that the real test conditions and the behavior of the PGU can be represented with sufficient accuracy. These points are considered in the recent editions of the relevant standards in which the test bench testing option is introduced.

In the recently published new IEC 61400-21-1,[3] the concept of subsystem and component testing in WTs is introduced in a systematic way and different system levels are defined. The idea is that for some electrical characteristics, such as the grid protection, it will be sufficient if the complete testing is on the component level, i.e., the protection device, rather than on the WT level. Besides, further subsystem tests are also defined on optional basis, if certain conditions are met, with the aim to assist for a more detailed assessment of simulation models and grid code compliance. In FGW TR3,[4] a definition of test bench requirements is provided in Annex D. The use of test bench tests, instead of measurements in the field, is acceptable only if the PGU response is equivalent to measurements in the field or if it is modeled for use on free field-testing equipment. In any case, advance agreement with the certification body is mandatory. In order to strengthen the validity of the tests, specific requirements on the test bench specifications for WTs, solar units and combustion engines are also provided, as will be explained in Section III. Apart from these two testing standards, R&D activities for investigating the topic of test bench testing are ongoing in some countries, like project CertBench.

A new work item proposal has been submitted and approved by the IEC Technical Committee 88 to harmonize the requirements and specify a uniform test procedure for test benches on a global basis. The new work item supports the development of a relevant technical specification of the measurement and assessment of electrical characteristics of WT components and subsystems[1]. The following are to be included in the final document:

- Definitions of test benches — subsystems and description of the necessary interfaces
- Definitions of system requirements for the test bench to perform these measurements, e.g., harmonic distortion, short circuit power, etc.
- Test and measurement procedures of electrical characteristics of components and subsystems, in relation to grid compliance requirements
- Procedures for the transferability of the component and subsystem test results, measured at the test bench, to WT product families
- Documentation requirements and validation procedures of components, subsystems and complete WTs

Particular aspects under investigation under this IEC

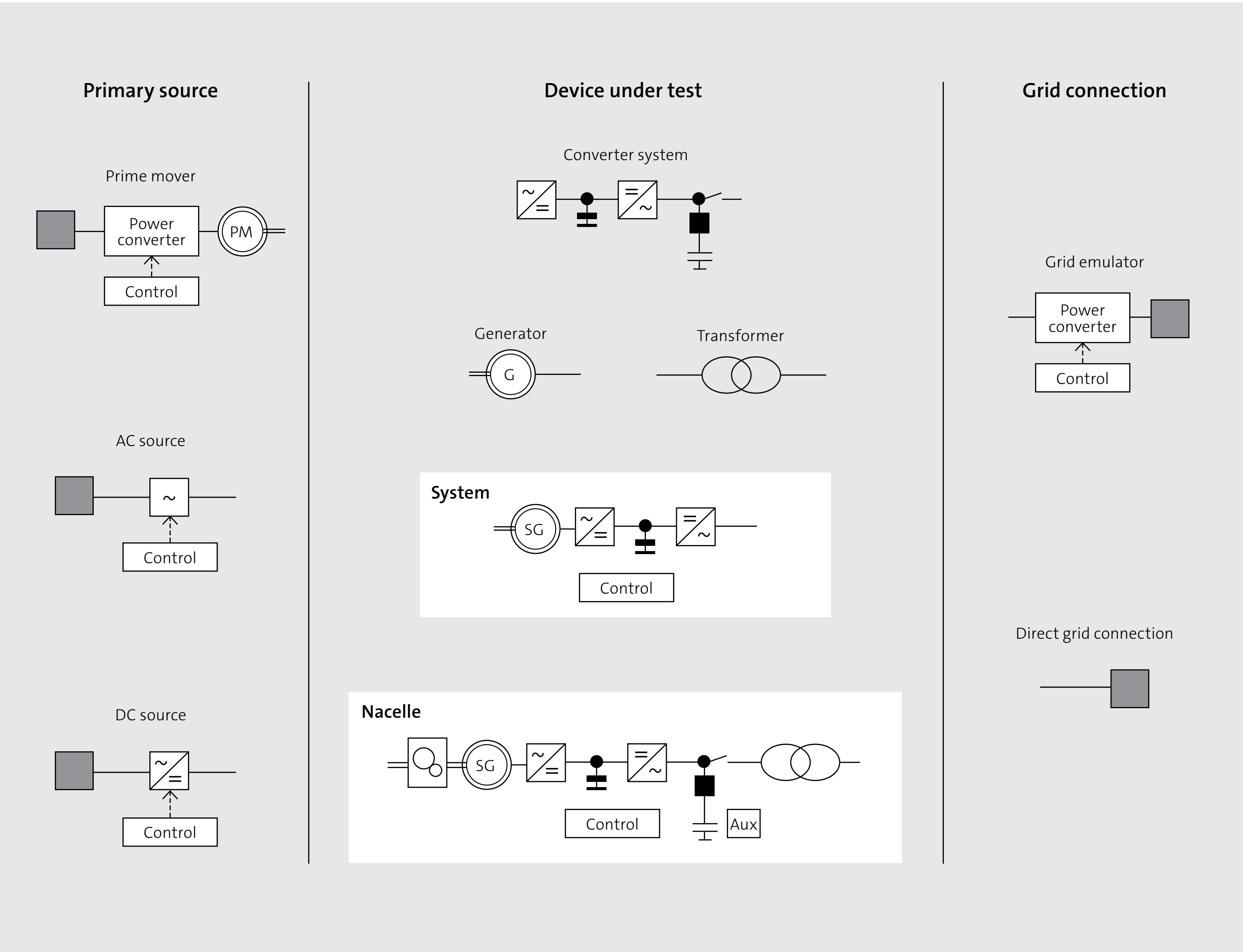


Fig. 2: Variants of test bench types.

Classification of test benches

Following the increasing interest for test bench testing, certain test bench facilities are being developed by private companies or research and development institutes worldwide. The fundamental requirement for the development of a suitable test bench system must be capable of emulating a grid that fulfills the PQ limits imposed by the relevant local or international standards. According to FGW TR3, a test bench test can include four different areas:

- Power source (simulation of the primary energy source)
- Power output (simulation of the grid and grid dynamics)
- Tested component of the device under test (DUT)
- Each of these categories must meet certain requirements.

In Fig. 1, a simplified schematic diagram of a test bench layout for the case of WT or solar units is shown. However, a test bench can be constructed with several levels of complexity. A mapping of the available global test and demonstration facilities is included in.[11]

Test benches may be classified according to specific criteria of the test bench and of the DUT. Generally, the DUT may comprise:

- Components, like the generator, the converter, the control or the transformer
- Systems, like the generator in combination with the converter and the control system
- Nacelle, where the complete electrical system including the control is included

The test bench itself can have different complexity and different control strategies:

- The source, simulating the primary energy, can be a prime mover or an AC or a DC-source (for the inverter).
- The prime mover can have constant speed or torque or can simulate the wind speed and rotor behavior including the eigenfrequencies of the WT and of the tower by fluctuating speed and torque.
- The DUT can either be connected to the real grid (at low voltage or medium/high voltage level) or to a (converter based) grid emulator.

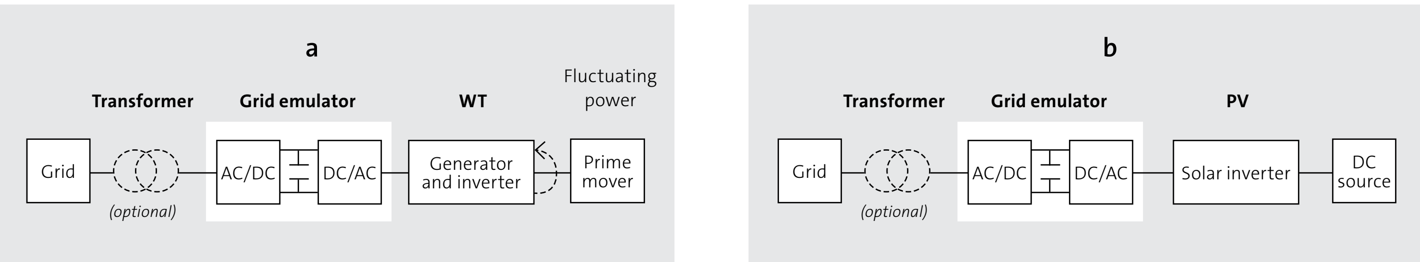


Fig. 1: Example of a test facility with an inverter-based grid emulator for wind turbines (a) and for solar (b)

In Fig. 2, an overview of possible variants of test benches and of the DUT is given. From the test bench side, the primary source replaces the wind speed and the rotor for a WT, or it replaces the solar panel. The primary source can either be a prime mover or an AC or a DC source, depending on the DUT type. The grid connection can be done either directly to the public grid of the test bench site or by a grid emulator, where possibly the voltage, the frequency and the output impedance are adjustable. The DUT can either be a component (like the converter, the generator or the transformer) or it can be a system or the whole nacelle of a WT. The system consists of two or more components, generally including the control of the system. One example for such a system is the generator, the converter, the filters and the complete control of this system. The nacelle is also a system, but one in which all the components of the nacelle of the wind turbine are included. Only the rotor and the wind speed are emulated by the prime mover.

However, for running the DUT at a test bench. defining the interfaces between the primary source, the DUT and the grid emulation is important. In real operation, the DUT may have sensors and actuators that are not available at the test bench, e.g., the pitch system of the rotor blades. But, their influence should be considered at the test bench operation.

Testing of electrical characteristics

Considering the different types of test benches described in the previous section, the applicability and limitations of test bench testing of electrical characteristics (power quality, steady state operation, control, dynamic performance and disconnection from the grid) are given below.

A. Flicker measurements

Flicker emission levels of inverted-based PGU technologies are generally of minor significance with regard to the compliance with the grid code limits. However, as the flicker-related frequencies — which are mainly lying in the sub-synchronous frequency range — are still present in the PGUs, flicker testing remains mandatory in all testing standards. In addition, flicker disturbance is still potentially high in case of directly connected synchronous and asynchronous generators used, for example, for combined heat and power units (CHPs) or for small RES installations.

For testing the flicker emission, the required test level depends on the type of the DUT. In case of WTs, flicker shall be tested in the free field (full-scale tests), so that the influence of the aerodynamic part is thoroughly incorporated. Further test bench measurements can also be performed to serve as a basis for the development and testing of flicker mitigation mechanisms through the control of the tested unit. Test bench tests may be also performed as a supplement to full-scale testing, for example for the evaluation of switching operations if a new inverter is used. For solar inverter testing, as the change in the input DC-source power level can be directly adjusted, it is acceptable to perform tests at test bench, still in the complete power range but with smaller number of data required to be recorded, as described in the FGW TR3.[4] Similar conditions may apply also for CHPs.

B. Harmonic measurements

As the main source of harmonics in modern power systems are considered to be the PGU power converters, performing harmonic measurements on a test bench level is generally acceptable, focusing on the performance of the inverter at different operating levels and ignoring the rest PGU subsystem. Especially for WTs, an important issue for consideration is the harmonic behavior of the doubly fed asynchronous generators (DFAG) used for many WT models. In DFAG WTs, the low frequency components change continuously with the rotational speed of the generator and significantly influence actual harmonic emission. To address this feature accurately at a test bench facility, the combine generator-inverter system must be tested at various operating ranges as shown in Fig. 1(a). Another question for investigation is how to measure the total harmonic emission of a unit consisting of multiple inverters.

On the other hand, our experience shows that measured harmonic currents are strongly influenced by background voltage harmonic distortion, resonances of the grid impedances and other disturbances in the grid at the point of connection. This means that the measured harmonic values to be included in the relevant test reports are not always representative of the actual harmonic emissions of the tested units but contain components that are attributed to the grid influence where the WT or PV inverter either acts as a passive consumer of harmonics coming from the grid or actively improves the harmonic voltages. This issue is still a major topic for investigation for the harmonic measurements at test benches where the use of an inverter-based simulator results in a considerable background harmonic distortion that often coincides with the switching frequencies of the DUT inverter. In Fig. 3, an example of the influence of the harmonic distortion of a grid emulator on the actual harmonic performance of the DUT is shown. After changing the switching frequency of the grid emulator, the measured current harmonics of the DUT were significantly different. This fact reveals the need for a more systematic methodology to be followed for the harmonic test bench testing. The grid emulator to be used shall at least meet some minimum requirements regarding the total harmonic distortion and probably for some critical individual harmonics, while the methodologies for the determination of the grid influence included in FGW-TR3 and in the new IEC 61400-21-1 standard shall be also exploited to derive unbiased results.

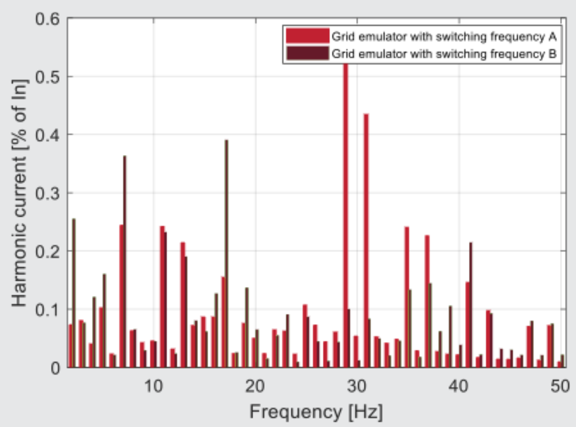


Figure 3: Comparative harmonic measurement results perfomed at a PGU at a test bench with inverter-based grid emulator. The two tests were performed with different switch frequency settings of the grid emulator.

C. Steady state operation

This group of electrical characteristics mainly consists of measurements of maximum active power, and reactive power capability, as defined in IEC 61400-21-1. For WTs, the maximum active power and the reactive power at Q=0 (nominal operational mode) can be calculated from the same data set collected for flicker measurements. Thus, additional tests at a test bench are not necessary.

For the reactive power capability and voltage dependency of a PQ diagram, it is possible to perform the tests at a test bench on a subsystem level. The reactive power behavior of a WT is mainly affected by the converter system, the generator, any filter and auxiliaries, and the control. It is important that at least these components will be tested for reactive power behavior as a system at the test bench. Generally, the reactive power capability and behavior is dependent on the actual voltage. The grid emulator allows the voltage for the DUT to vary. Thus, it is possible to test and measure the reactive power for the whole voltage range of the DUT, often from 85% to 110% of nominal voltage.

D. Control performance

As the main control functions in the PGUs are taken over by the inverters' controllers, testing control performance on subsystem level is possible. However, since the rotor dynamics and the response of the complete mechanical system plays an important role in WTs, active power set point and ramp rate limitation control are still suggested by IEC 61400-21-1 to be performed in free field. Testing of these two parameters at a subsystem level can be accepted only if certain conditions are fulfilled.
For testing of reactive power control on test benches, the requirements as described in subsection C for steady state operation must be fulfilled. In case of Q(U) functionality, the grid emulator gives advantages for testing of the whole voltage range, but an adequate (grid) impedance of the emulator should be included to perform tests for real grid situations.

For frequency control, the grid emulator allows a real change in frequency, not only for the control, but also for the complete drive train and the converter system.
The same is valid also for synthetic inertia control.
However, for the prime mover of the test bench, it must be considered that the rotational speed of the rotor of the WT will be decreased during the test according to the real dynamic behavior of the rotor. Also, following this, the power output of the prime mover must decrease for lower rotational speeds.

E. Dynamic behavior

For the performance of FRT capability tests, specific requirements for the performance of the grid emulator are set by IEC 61400-21-1 and FGW TR3 standards. For WTs, full-scale, free field testing following IEC 61400-21-1 is recommended because the reactance of the complete system in the grid faults needs to be thoroughly examined. The rotor of the WT influences the dynamic behavior of the WT during the grid faults as well as the whole drivetrain. However, sometimes small auxiliary components are not prepared for FRT and cause the WT during grid faults to trip. Thus, such small auxiliaries must also be included in the tests. On the other hand, some additional tests with different settings, for example, reactive power or current during the fault, may be performed at test benches.

For PGU inverters, the use of a grid emulator at a test bench is acceptable, as the inverter control is the main component involved in fulfilling the relevant requirements.

F. Summary

In general, the electrical behavior of PV inverters can be tested at test benches, where the primary source is emulated by a DC source representing the behavior of the solar panel. The DC voltage shall have the voltage level and range of the real PV installation. The tests can be performed either where the PV inverter is directly connected to the grid or by a grid emulator.

From the actual experience and the discussions in several working groups for WTs, the following suggestions in Table 1 may give an overview of the test levels and requirements for the testing of the electrical characteristics.

Table 1 – Suggested levels for the testing of electrical characteristics of wind turbines

Category	No.	Parameter	Suggestion
Power quality	1	Flicker in continuous operation	Testing in free field only
	2	Flicker in switching	
	3	Harmonics	Can be tested at test benches, but the harmonic voltage emission and the impedance of the grid emulator must be considered.
Steady safe	4	Maximum active power	Testing in free field only
	5	Reactive power at Q=0	Will generally be tested in combination with flicker in continuous operation.
	6	Maximum reactive power (over/under excited)	Can be tested at test benches, but all components of the WT affecting reactive power must be included in the tests.
	7	Voltage dependency of PQ diagram	Can be tested at test benches. The grid emulator allows a wide variety of the voltage.
	8	Unbalance factor	Will generally be tested in combination with flicker in continuous operation but can also be tested at test benches. In case of the use of a grid emulator, the voltage unbalance and the (grid) impedance of the emulator should be considered.
Control performance	9	Active power set point control	Due to the influence of the rotor and of the drive train of the WT, it is suggested to do the tests at free field.
	10	Active power ramp rate limitation	
	11	Frequency control	Can be tested at test benches.
	12	Synthetic inertia	Can be tested at test benches, but the prime mover must emulate the behavior of a real rotor of the WT.
	13	Reactive power control	Can be tested at test benches. The grid emulator allows a wide variety of the voltage.
FRT	14	FRT capability	Full scale, free field testing is suggested, because the complete WT with all components must be tested. Some additional tests with different settings, e.g., reactive power/ currents, may be performed at test benches.
Disconnection from grid	15	Grid protection	Can be tested on test benches on component level.
	16	Reconnection time	Can be tested at test benches, as long as the same environmental conditions are maintained.
	17	Rate of change of frequency	Can be tested on test benches on component level.

G. Competencies of the testing laboratories

To ensure transparency and traceability of the certification tests, the tests and measurements described in the previous paragraphs must be performed by measuring institutes accredited for the relevant services according to ISO/IEC 17025.[15] The measurement equipment shall meet the accuracy requirements of IEC 61400-21-1.[3] All currents and voltages must be recorded with a sampling rate ≥4 kHz for flicker and switching, ≥10 kHz for FRT testing and ≥20 kHz for harmonics.

Summary and conclusion

This paper includes a technical approach on test bench testing of PGUs, including wind turbines and photovoltaics, with the aim to recognize the additional capabilities and constraints compared to the standard on-site full-scale testing procedures.

The main conclusion is that test bench testing can be used for the grid compliance testing of PV inverters and single electrical generators as soon as specific requirements for the formulation of the background grid, the DC power source and the emulation of grid faults are fulfilled. For WTs, several tests relevant to the performance of the WT controller and protection system can be also performed at a test bench, but for flicker and FRT, the full-scale testing is recommended. In these cases, additional test bench tests can be performed if necessary, for model validation purposes or for the further investigation of alternative control parameters. In all cases, the general principle is that if a test can be performed on-site, it should.

It is believed that the content of this paper will help with the clarification of certain open questions and concerns regarding test bench testing and contribute to the establishment of a common understanding among all involved parties (manufacturers, grid operators, regulatory authorities, certification bodies, etc.) regarding the acceptable options for grid compliance testing of PGUs.

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Endnotes

1. IEC 61400-21-4 Wind energy generation systems – Part 21-4: Measurement and assessment of electrical characteristics – Wind turbine components and subsystems, Technical Specification under development within IEC-TC88 Working Group (2019).

2. CertBench – "Systematic validation of system test benches based on the type testing of wind turbines," Project funded by the German Federal Ministry of Economic Affairs and Energy, June 2017 – Nov, 2019.

3. IEC 61400-21-1 Wind energy generation systems – Part 21-1: Measurement and assessment of electrical characteristics – Wind turbines, Ed.1, May 2019.

4. FGW e.V., Technical Guidelines for Power Generating Units and Systems - Part 3 (TG3), "Determination of the electrical characteristics of power generating units and systems, storage systems as well for their components in medium-, high- and extra-high voltage grids," Revision 25, 01.09.2018.

5. IEC 61400-22 Wind turbines – Part 22: Part 22: Conformity testing and certification, Ed.1, May 2010.

6. IEC 61400-27-1, Wind turbines – Part 27-1: Electrical simulation models – Wind turbines, Ed.1, Feb, 2015.

7. IEC 61400-27-2: Wind energy generation systems – Part 27-2 Electrical simulation models – Model validation, under development (2019)

8. FGW e.V., Technical Guidelines - Part 4, "Demands on modelling and validating simulation models of the electrical characteristics of power generating units and systems, storage systems as well as their components," Revision 9, 01.02.2019.

9. FGW e.V., Technical Guidelines - Part 8, "Certification of the electrical characteristics of power generating units, systems and storage systems as well as their components on the grid," Revision 9, 01.02.2019.

10. Jens Fortmann, Nicholas Miller, Yuriy Kazachkov, John Bech, Björn Andresen, Pouyan Pourbeik, Poul Ejnar Sørensen, "Wind Plant Models in IEC 61400-27-2 and WECC - latest developments in international standards on wind turbine and wind plant modeling," 14th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, Brussels, Belgium, Oct. 2015.

11. Megavind Report, "Test and Demonstration Facilities for Wind Energy Needed to Promote a Competitive Wind Industry in Denmark," Jan. 2016.

12. Australian Energy Market Operator (AEMO), "R2 Testing Guideline," 2013.

13. Commission Regulation (EU) 2016/631 of 14 April 2016, "Establishing a network code on requirements for grid connection of generators."

14. AEE, "Procedure for verification validation and certification of the requirements of the P.O. 12.3 on the response of wind farms and photovoltaic farms in the event of voltage dips," Version 9, 2011.

15. ISO/IEC 17025, "General requirements for the competence of testing and calibration laboratories."

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