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Opportunities and Challenges of Advanced Testing Approaches for Multi-Megawatt Wind Turbines

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ABSTRACT To safely integrate large numbers of wind turbines into the electric power grid, turbines must demonstrate compliance with grid codes and technical guidelines through rigorous testing. Such tests are traditionally performed using prototype turbines on designated measurement sites. So-called field tests offer little flexibility and repeatability, as factors such as wind and grid conditions cannot be adjusted at will. Recently, specialized laboratory test facilities were established to augment or completely replace conventional field tests. These facilities need to constantly grow in size, power, and functionality to keep up with wind turbine trends, while new and increasingly complex grid requirements necessitate more advanced testing methodologies. This paper presents four testing concepts and how they can be further integrated into the development and certification process of wind turbines using the laboratories of Fraunhofer IWES as an example. In particular, turbine, nacelle, subsystem, and component testing are reviewed and their advantages and anticipated challenges for evaluating grid code compliance are highlighted. Experiences gained over the past decade from testing wind turbines and constructing experimental testing facilities are shared, including key data and capabilities of the developed test benches. The authors expect the presented approach to be used for validating simulation models that can be embedded into larger interaction and stability studies of wind farms at a later stage. Such an integrated testing approach may lead to quicker and more flexible design and optimization of new generations of wind turbines, effectively increasing the speed of grid integration and ensuring safe and reliable grid operation.

INDEX TERMS Electrical certification, grid compliance, grid simulator, model validation, power hardware-in-the-loop, real-time simulation, test bench, wind turbine testing.

I. INTRODUCTION

In the continued efforts to effectively decarbonize the global energy sector and to promote energy security and independence in the face of recent geopolitical events, demand for renewable energy generation has grown rapidly [1]. The growth of renewable energy demand is expected to further increase in the foreseeable future to meet net-zero emission goals and to limit the temperature increase due to climate change to 1.5 °C above pre-industrial levels as stipulated in the Paris Agreement of 2015 [2]. To satisfy this growing demand, manufacturers together with suppliers and network operators must greatly expand the production and integration of new renewable power plants. For this, strict national and international rules and technical guidelines regarding power quality and grid support must be proven [3], [4], [5], [6]. The related verification of grid code compliance is done via extensive test campaigns covering all aspects of relevant regulations and grid codes. In future, further tests will be added to prove that renewable generation plants can fulfill functions currently performed by conventional power plants [7].

Traditionally, grid code compliance of wind turbines has been tested and evaluated using prototype turbines on special test sites, oftentimes referred to as field testing. This approach has been comprehensively standardized and is widely accepted as state-of-the-art, allowing manufacturers, grid operators, and certification authorities to accept and trust the test results [8], [9], [10]. Considering the sheer amount of power plants that need testing, validation, and certification in upcoming years, however, certain disadvantages of field testing come to light. Most notably, a suitable test site needs to be found and a fully functioning prototype wind turbine must be installed. Favorable wind conditions are furthermore required to test the turbine in all required operating points, routinely making test campaigns a tedious endeavor. Additional difficulties arise due to uncontrollable grid characteristics and the limited application possibilities of traditional field test facilities, such as the exclusive simulation of under- or over-voltage events. In this regard, certain grid code requirements cannot be validated using field testing in general; others only virtually by simulating specific test cases [11].

In the last decade, laboratory test benches have been established as a viable alternative to field testing to replace some or all of the validation tests otherwise conducted on test sites [12], [13], [14], [15], [16]. The laboratory setting enables manufacturers, researches, and certification authorities to perform tests and measurements in a controlled environment, free of the reliance on test site availability, wind conditions, and other external influences. While not yet completed, efforts are being made to describe and fully standardize different test bench setups and their capabilities in order to build confidence in the test bench methods and results. In the meantime, some test benches have already proven that validation and certification of a wind turbine's grid code compliance can be done based entirely on test bench results [17]. Challenges remain, however, due to the increasing size and power rating of new wind turbine generations reaching 15 MW and above, featuring operating voltages of up to 66 kV while even 132 kV is being discussed for offshore applications [18]. Furthermore, future grid compliance tests will include new wind turbine behavior such as grid forming and black start capability, for which no standardized test methodology exists today. To continue testing wind turbine on laboratory test benches, they must keep up in terms of power, voltage, and test capabilities while at the same time, new test and validation methodologies need to be developed and agreed upon [16].

The Fraunhofer Institute for Wind Energy Systems IWES in Bremerhaven, Germany, has developed several large-scale laboratory test benches for multi-megawatt wind turbines throughout the years, cf. Fig. 1. This paper describes the approach that has been taken aiming to support the wind turbine development process with test capabilities and validation of electrical characteristics during different phases of the wind turbine development. In addition to the corresponding test concept and a description of the hardware setup, special features of the test systems are discussed and the challenges associated with the test approach are summarized.

The paper is structured as follows: Section II gives an overview of the current state-of-the-art in wind turbine testing and validation. Section III describes how testing is nowadays conventionally done on the system and subsystem level. In Section IV, a new approach to field testing using a fully programmable grid simulator is explained. Section V then explains testing electrical properties of wind turbines on the component level. Finally, Section VI concludes this paper and gives an outlook on future challenges regarding multi-megawatt wind turbine testing.

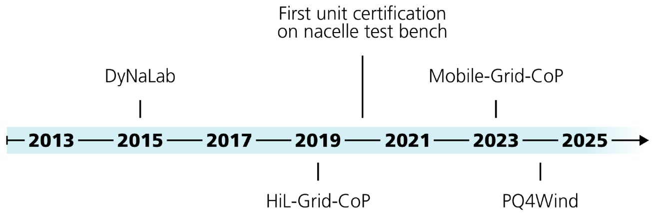


FIGURE 1. Timeline and milestones of test benches developed by and installed at Fraunhofer IWES for electrical testing purposes of wind turbines.

II. BACKGROUND ON WIND TURBINE TESTING

To ensure safe and reliable operation of the power grid, system operators specify technical requirements for power generation units. Compliance with these requirements must be verified by grid code compliance tests in order to protect the grid from adverse effects and interference caused by the power plants. All relevant electrical characteristics that contribute to the grid's power quality are evaluated during these tests [16]. In addition to verifying grid compliance of individual units, it is particularly important to validate simulation models which are required at several points for integration. On the one hand, these allow development activities to be carried out in parallel, such as the development of turbines and the grid connection for a wind farm, and on the other hand, they are increasingly required by grid operators to enable large-scale system studies.

A. VERIFICATION AND VALIDATION STRATEGY

The validation and verification process, as well as the testing activities derived from it, require a financial investment in the low double-digit percentage range of the total costs for developing a new turbine [15]. It is a difficult task to find a compromise between the benefits of testing during development, the testing required to verify grid compliance and the associated costs. Although every manufacturer pursues a different strategy, it is closely aligned with the development and grid integration process of the turbine. The V-model, as depicted in Fig. 2, can be utilized to guide or organize the required validation, verification, and testing activities. The left side of the V-model involves the decomposition of the product, starting from top-level system requirements and progressing to component and controller requirements. Fraunhofer IWES proposes a testing approach that directly follows the development stages of the V-model. The idea is to provide a suitable infrastructure at each level of the development and the derivation and establishment of new testing and validation

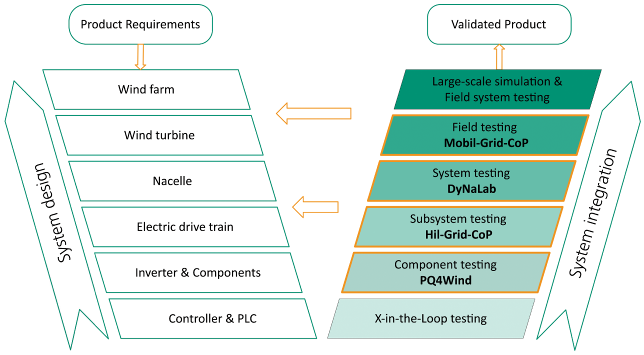


FIGURE 2. Wind turbine development process and proposed testing approach according to V-model.

TABLE 1. Overview of Nacelle Test Benches Around the World

Facility	Country	Conv. power$^{\diamond}$	Mech. power	Reference
CENER	Spain	36 MVA	8 MW	[25]
Clemson	USA	20 MVA	15.7 MW	[26]
		no info	30 MW	[27]*
CWD	Germany	21 MVA	4 MW	[17]
GNTP	Korea	no info	35 MW	[28]*
IWES	Germany	44 MVA	10 MW	[14]
LORC	Denmark	21 MVA	14 MW	[29]
NREL	USA	80 MVA	5 MW	[30]
OREC	UK	18 MVA	15 MW	[31]

*In planning or not yet fully commissioned by the time of writing.
$^{\diamond}$Installed converter power for grid emulation.

methods [15], [16]. The rest of this paper examines specific test concepts and test facilities based on this V-model.

B. PROCEDURES FOR WIND TURBINE TESTING

Test and measurement procedures for wind turbines have been standardized on national and international level, e.g., in the IEC 61400-21-1, IEC 61400-21-4, IEEE 2800-2022, or the German FGW TR3 [3], [8], [9], [10]. In some countries such as Germany, test results and validated electrical models of the turbine must additionally be reviewed by independent certification authorities. On the basis of accredited test reports, the authorities review the test procedures, check for compliance with the relevant technical guidelines and grid codes. Using the measurement data, the electrical models of the turbine are checked in verification and validation simulations and finally issue a certificate for the wind turbine. In particular, the tests required by the technical standards typically include – but are not limited to – the following areas: Power quality aspects, steady-state operation, active and reactive power control, reaction to frequency variations, dynamic performance in the event of faults, and disconnection from the grid, see e.g., [16] for more details.

The requirements for model validation of wind turbine and wind power plant models (fundamental frequency) can be based in particular on the international standard IEC 61400-27-2, taking into account the requirements for generic models from the IEC 61400-27-1 standard [19], [20]. For the validation of wind turbines, the dynamic response to fault ride-through and control should be shown. The dynamic response to active power control and reactive power control should be presented for wind power plants [20].

C. STATE-OF-THE-ART TESTING APPROACH

Conventionally, grid compliance is tested and evaluated directly in field by means of measurement campaigns on prototypes. These turbines are usually fully commissioned, with the auxiliary units and software being adjusted and tested together. The first tests are carried out step by step in partial load operation while the plant is monitored manually around the clock. This phase is referred to as *run-in* and is used for tuning and initial commissioning tests. After successful commissioning, the wind turbine is released to operate at full load and in unmanned mode. This is typically followed by more advanced tests, including fault-ride-through (FRT) tests for evaluating the dynamic performance.

For the longest time, the only option to perform such tests was to use FRT containers representing switchable inductive voltage dividers. This test approach has the advantage of being comparatively easy to use, but requires manual adjustment each time the simulated under- or over-voltages, or the fault scenarios are to be changed. For testing frequency changes, the turbine control has to be re-parameterized to simulate supposed changes in the grid. Such restrictions make the approach inflexible and significantly limit its applicability for testing future requirements.

In addition, field testing for verification and validation is carried out very late in the development process, even after commissioning. This comes with significant disadvantages. Discovering errors late may result in higher costs and longer project timelines for subsequent developments. Given these challenges, approaches that speed up the entire verification and validation process or enable testing at lower test levels are highly attractive to the industry, which is one of the reasons why Hardware-in-the-Loop (HIL) testing laboratories have become increasingly popular and nowadays are also considered state-of-the-art for testing [21], [22], [23], [24].

III. NACELLE AND ELECTRIC SUBSYSTEM TESTING

As described in the previous section, grid compliance of wind turbines was for a long time mainly verified by field measurements using FRT containers, while in the meantime, test benches for testing complete nacelles or turbine subsystems have become established [16], [32]. The test benches usually consist of a mechanical unit for powering the drive train and a power converter system on the electrical side. This converter system is used for emulating virtual networks with predefined parameters or dynamical grid events. Table 1 lists some of largest nacelle test benches worldwide and gives an overview of their electrical and mechanical test capabilities by means of installed converter power for grid emulation and power of the

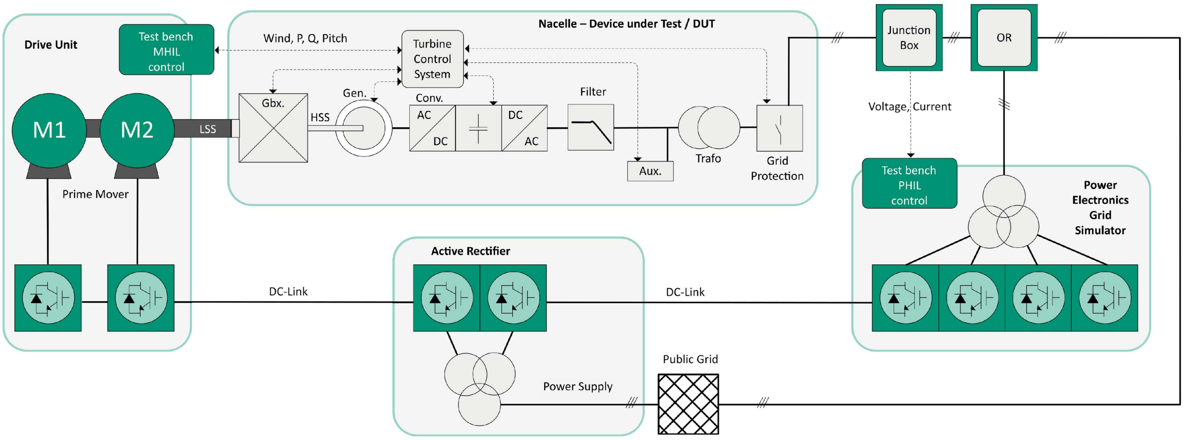


FIGURE 3. DyNalab test bench concept, consisting of a mechanical HIL system for driving the generator shaft and simulating loads, and an electrical HIL system for emulating a virtual power grid.

prime mover on the mechanical side. At Fraunhofer IWES, the testing of entire nacelles is provided by the Dynamic Nacelle Testing Laboratory (DyNaLab) in Bremerhaven, Germany.

A. NACELLE TESTING AT THE DYNALAB

To enable nacelle testing in a 1:1 scale, Fraunhofer IWES built the DyNaLab in 2015 and has so far successfully performed 8 measurement campaigns with different customers. Fig. 3 illustrates the simplified test bench concept, which is discussed more in detail in the following.

1) MECHANICAL HARDWARE AND CONTROL SETUP

The mechanical part of the test facility consists of two series-connected, controllable prime movers, M1 and M2, with a combined power of 10 MW and 150% overloading capacity, coupled to the gearbox of the DUT via a low-speed shaft (LSS). The nominal rotational speed of the shaft is 11 rpm at 8.6 MN m. The drive system without DUT provides an air-gap torque with a control bandwidth of approx. 40 Hz [33]. To replicate realistic operation and load conditions, shear and lateral forces of up to 2 MN as well as bending moments of up to 20 MN m can be applied to the drive train by a so-called parasitic load application system, shown in the picture of the laboratory hall in Fig. 4. The forces are calculated by a virtual wind turbine model running on a dedicated Opal RT real-time simulator with 5 ms time step. The model combines physical real-time models for aerodynamics, structural dynamics, and hydrodynamics for defined wind fields compliant to IEC wind classes including constant and turbulent wind conditions. Typical wind speeds range e.g., from 4 m/s to 15 m/s on average and require dynamic load variations of the rotor within ±5% at up to 10 Hz. The turbine model is based on a validated customer model, which is, after implementation in the Modelica library for Wind Turbines (MoWiT), verified and optimized for real-time simulations in a HIL environment [34], [35]. This model transmits and receives information from the customer's turbine controller and is also used to provide the torque set points for emulating the rotor characteristics via a mechanical HIL (MHIL) controller, running on an ABB motor control unit with 250 μs sampling time. As the complete drive unit and torque measurements in the meganewton-meter range are associated with considerable uncertainties, an H-infinity controller with Kalman filter for estimating non-measurable variables is used for mechanical emulation, achieving a closed-loop torque bandwidth of up to 30 Hz [33].

FIGURE 4. Picture of the nacelle test bench hall, converter system, and filter bank at DyNaLab in Bremerhaven.

2) ELECTRICAL HARDWARE AND CONTROL SETUP

The inverter units used for powering the prime movers are connected to a DC-link which is supplied by two 9 MVA active rectifier units. The same DC-link is used as voltage source for four ABB ACS 6000 3-level neutral point clamped (NPC) medium voltage inverter units with IGCT technology. These units represent the basis of the 44 MVA power electronics grid simulator (PEGS) [36]. For each phase, the four units are interconnected in a H-bridge configuration via a single-phase multi-winding step-up transformer. The low- and high-voltage sides of the transformers are designed to have two windings per phase on two outer main limbs and one middle limb for flux optimization, allowing to generate a controllable 9-level sinusoidal voltage at the output of the grid emulator [37]. This topology has the major advantage that it can be used to emulate symmetrical and asymmetrical grid conditions at different output voltage levels without interactions of the phases and, in addition, results in a low physical input-impedance of the grid simulator [12].

There exist nominal step-up transformer tappings, which are primarily used to emulate a virtual grid with fixed parameters, whereas dynamic tappings can be used for dynamic tests as UVRT and OVRT tests. Hereby, the normal voltage range is between 60% and 110% of the given voltage levels. Depending on the tapping, the transformer base power, S_b, is between 8.3 MVA and 15 MVA, and the short-circuit voltage, u_k, lies in the range of 1.6% and 6%. At the 20 kV voltage level, for instance, this results in a virtual short circuit power of $S_b/u_k \approx 152MVA$. To further improve the voltage quality at the point of common coupling (PCC), an additional ohmic-capacitve (RC) output filter bank is installed between PEGS and DUT, see Fig. 4. Since the transformer and AC output filter can be adapted to various output voltage levels, the setup offers a high flexibility to meet customer requirements.

ABB's low-level control enables dynamic voltage phasor referencing and guarantees a stable operation at transients. Using a voltage slew rate, SR, of max. $20f_0$ p.u./s guarantees that, e.g., a voltage at 50 Hz can be changed from 0 to 1 p.u. within 1 m/s, required by typical standards [9], [10]. On the other hand, the grid simulator is able to generate sinusoidal small-signal oscillations with amplitude $\hat{V}_r$ (in p.u.) and max. frequency $f_r = SR/(2\pi\hat{V}_r)$ without being limited by the slew rate, characterizing its dynamic performance [38]. This allows the grid emulator to be used as a power interface in a PHIL environment with voltage-type interface, coupling the hardware with the software side of the test bench. Connecting conventional grid-feeding turbines, the PEGS is thus operated as a voltage source, where the measured currents at the PCC are fed back to a virtual grid model. As the focus of most tests is on the emulation of large-signal faults at the fundamental frequency, resonance filters are used to extract phasor data and computation is performed on a Beckhoff PLC with 200 μs sampling time using stationary network expressions [24], [37]. The basic principle of the implemented interface is therefore equivalent to known voltage-type PHIL interfaces with stabilizing low-pass filters in the feedback path, compare e.g., to [39]. Table 2 lists the main hardware data and electrical control properties of the DyNaLab.

B. SUBSYSTEM TESTING ON THE HIL-GRID-COP TEST BENCH

Although the testing of nacelles using test benches as the DyNaLab has clear advantages over conventional field tests with

TABLE 2. Technical Data of the DyNaLab PEGS

Description	Key data
Installed converter power	44 MVA
Nominal voltage levels	10 kV, 20 kV, 36 kV
Dynamic voltage levels	13 kV, 26 kV, 46.8 kV
Nominal frequency range	45 Hz to 65 Hz
Topology	9-level NPC
Switching frequency	2.8 kHz to 4.6 kHz (3.4 kHz nominal)
Voltage THD	$< 5\%$ @ nominal operation
UVRT capabilities	$0.6V_{\mathrm{nom}} \geq V \geq 0.2V_{\mathrm{nom}}$ for a couple of minutes $0.2V_{\mathrm{nom}} \geq V \geq 0V_{\mathrm{nom}}$ for 3 s
OVRT capabilities	$1.1V_{\mathrm{nom}} \leq V \leq 1.5V_{\mathrm{nom}}$ for a few seconds
Voltage slew rate	± 1 p.u./ms 50 Hz
Frequency slew rate	± 20 Hz/s
Phase jumps	0 deg to 180 deg within 4 ms

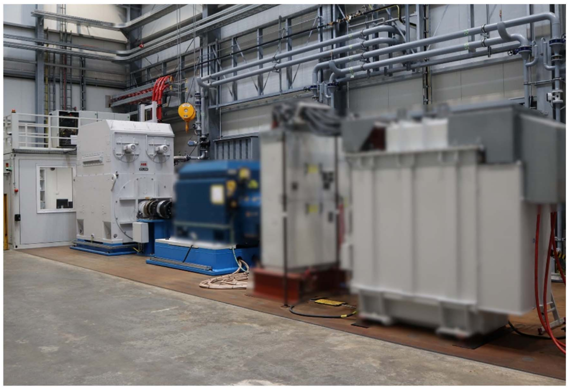


FIGURE 5. Picture of the HiL-Grid-CoP test bench for performing electrical subsystem tests of high-speed generator-inverter systems.

FRT containers, the preparation of a measurement campaign represents a major effort and is still time consuming [15]. While electrical integration is usually straightforward, delivery and mechanical installation needs more complex logistics and coupling the wind turbine's drivetrain to the mechanical part of the test bench often requires adapters that are custom-made for each turbine type. Additionally, time for integration and commissioning of customer interfaces and disassembly must be taken into account.

In order to further reduce development and test cycles, Fraunhofer IWES together with Nordex Energy SE & Co. KG and Vestas Wind Systems A/S have developed and validated new test methods as part of the Hardware-in-the-loop Grid Compliance Test Bench (HiL-GridCoP) project [24], [40]. The constructed test bench aims to perform electrical certification of wind turbines by testing a reduced system consisting of the generator, the converter and the transformer as well as the turbine's control system.

Fig. 5 shows a picture of the test bench setup. Compared to the DyNaLab or other nacelle test benches, all mechanical components before the generator are emulated on real-time simulators. The high-speed shaft (HSS) of the generator is driven by an asynchronous prime mover with 9 MW rated power, 86kNm rated torque, and a rotational speed between 1000 rpm and 2200 rpm at full power. By gradually reducing the torque, the prime mover can be operated at rotational speeds of up to 2400 rpm in the field-weakening range, whereby an additional power reserve of 50% enables a further boost at all operating points for 10 min. Unlike the DyNaLab motors, the air-gap torque of the drive system without connected DUT has a control bandwidth of approx. 70 Hz. These properties make HiL-GridCoP particularly suitable for testing of type III wind turbines equipped with doubly-fed induction generators (DFIGs). During development and construction, care was taken to ensure that the first eigenmode of the test bench is at a high frequency and well separated from the eigenfrequencies of typical turbines, lying in the range of e.g., 1 Hz to 2 Hz. In this regard, the MHIL control fulfills two tasks. First, a cascaded speed-torque controller imposes the natural frequencies of the turbine on the shaft using a simplified virtual spring-mass-damper model for reference generation. Second, the MHIL control damps the eigenfrequencies of the test bench via a state-space controller in modal space, see [40] for more details. On the electrical side, the PEGS of the DyNaLab described in the previous section is used for the emulation of virtual grids or fault conditions [24].

C. CAPABILITIES AND EXPERIMENTAL RESULTS

Nacelle laboratories or test benches for testing subsystems such as HiL-Grid-CoP are now state-of-the-art for grid compliance testing of wind turbines [8], [10]. Compared to tests in the free field, these offer the clear advantage of being able to simulate almost any weather and wind conditions, and the tests are not dependent on local grid connection conditions. In addition, typical balanced and unbalanced grid faults can be flexibly simulated according to the customer's requirements, and frequency changes can also be studied. As measurement and validation campaigns have demonstrated, developed HIL concepts as well as the test methods can be applied to common turbines, such as variable speed wind turbines [17]. In [24], [41] it was shown that the behavior of wind turbines on the test bench is practically equivalent to the behavior in the free field in terms of the properties to be investigated, forming the basis for electrical certification according to e.g., the IEC 61400-21-1 or the German FGW TR3 [8], [10]. In this context, Fig. 6 shows an exemplary comparison between the measurement results of a multi-megawatt type III wind turbine with an FRT container and on the HiL-Grid-CoP test bench in case of an asymmetric under-voltage event.

D. EXPERIENCES AND CURRENT TEST BENCH LIMITATIONS

Although the developed testing concepts are now well established and defined in standards, nacelle test benches are increasingly reaching their limits and also have disadvantages. On the one hand, this is due to the growing size of the systems and the increasing power and voltage classes, and on the other hand to the limits of the hardware and software components currently used in the test benches.

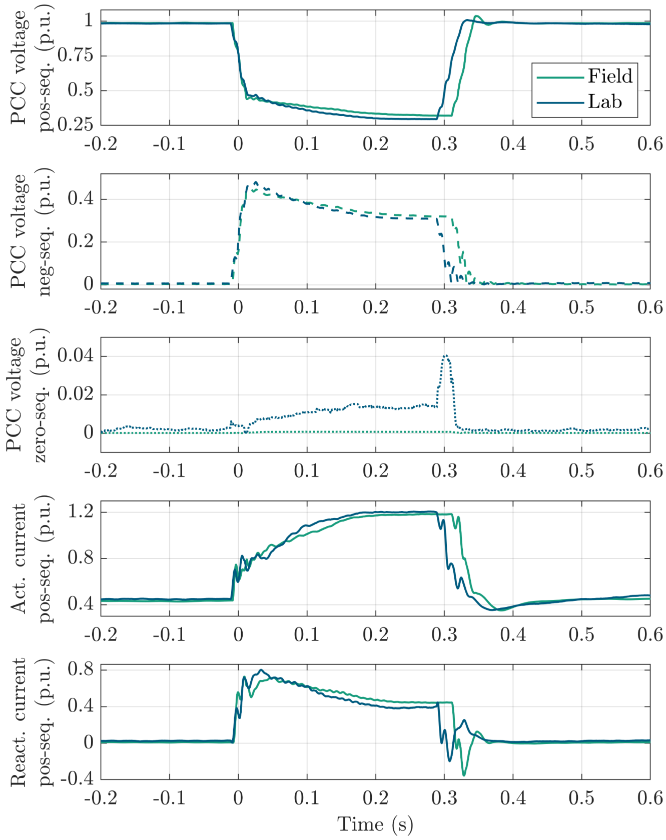


FIGURE 6. Comparison of the measurement results of a type III wind turbine tested with an FRT container and on the HiL-Grid-CoP test bench for minimal system tests [24].

1) SOFTWARE LIMITATIONS

Many grid simulators in the multi-megawatt range only offer the possibility of specifying voltage references in the form of phasors instead of instantaneous values, see e.g., [13], [24], [38]. Although more detailed simulations with high sampling rates are carried out on connected real-time systems, filtering must usually be performed to extract the required phasor quantities, which limits the bandwidth of the PHIL simulation. This is also the case with the grid simulator of the DyNaLab or HiL-Grid-CoP, restricting their application in emulating virtual impedances mainly to the fundamental component.

In addition, closed-loop voltage control is often omitted and the simulators are operated in open-loop, which means that inaccuracies such as unmodeled time delays or the impedance of the step-up transformers at the output of the inverter units have a direct influence on the virtual impedance to be simulated. This may worsen the accuracy of the simulation [24]. For this reason, a precise knowledge of each test bench component is essential to compensate for unwanted effects, which can be complicated by operating point-dependent non-linearities of the components. But even if an exact compensation is possible, a realistic fault emulation can be challenging in certain scenarios, such as when emulating a real short circuit with zero residual PCC voltage. In this case, the inverter is usually forced to stop modulation and the DUT current causes an unwanted voltage drop across the output transformer, which would not be present in field.

2) HARDWARE LIMITATIONS

Besides the limited over-current capability, the test benchs' step-up transformers have turned out to be one of the most significant hardware limitation in performing dynamic tests with power electronics-based grid simulations [12], [24]. Taking, for instance, an abrupt voltage sag or recovery as in the case of an UVRT or OVRT defined in the standards, see e.g., [8], [10], a fast change in magnetization is often required. For unfavorable initial conditions, this can lead to saturation or even tripping of the test bench's inverter system. Therefore, modern grid simulators usually have a lower-level magnetization control that ensures that the flux of the test bench step-up transformer tracks its sinusoidal reference by superimposing a DC component to the output voltage [38], [42]. As illustrated in Fig. 6, this control action can be observed as a zero-sequence component in the emulated PCC voltage, which also affects the transformer of a connected DUT. If the superimposed control action is not limited to a low, single-digit percentage range, the residual flux of the DUT transformer may be damped, resulting in less demanding inrush currents during fault clearance and facilitating stable operation during FRTs or phase jumps. This property may prevent identical test conditions on test benches and in the free field, but can be minimized by an intelligent flux control and a high flux reserve of the step-up transformer on the test bench side [42].

IV. WIND TURBINE TESTING

In contrast to testing wind turbines on test benches, there is still the option of performing full-scale tests directly in the field. These types of tests will probably remain necessary to complement test bench measurements or to perform worst-case tests on real turbines to verify the overall system dynamics and electrical-mechanical interaction [43]. But considering recent developments, there is currently no suitable test facility for the 66 kV voltage level of modern offshore wind turbines which, in addition to classic UVRT and OVRT tests, can also test future requirements such as black start capability or grid-forming properties and validate models for system studies.

A. WIND TURBINE TESTING WITH MOBIL-GRID-COP

In order to also be able to offer tests at this level of the V-model, Fraunhofer IWES, together with ABB Switzerland, and ABB Poland has developed a new approach for field tests of generation units up to 20 MW using a mobile grid simulator in the so-called Mobil-Grid-CoP project [44]. Similar to the test concept of other test benches, Mobil-Grid-CoP aims to emulate a virtual grid in a PHIL environment, but is to be connected directly between the PCC and the DUT at the test site. The test location could be at the manufacturer's site, at an existing test bench, or in the free field.

TABLE 3. Technical Data of Mobil-Grid-CoP

Description	Key data	
	14MVA	28MVA
Nominal voltage levels	10 kV, 20 kV, 33 kV	20 kV, 39 kV, 66 kV
Dynamic voltage levels	12.75 kV, 25.5 kV, 42.1 kV	25.5 kV, 42.1 kV, 84.2 kV
Topology	9-level NPC	17-level NPC
Switching frequency	3 kHz to 6 kHz	6 kHz to 12 kHz
Nominal frequency range	40 Hz to 70 Hz	
Power overload capacity	200% for 10 s; 250% for 0.3 s	
Voltage THD	< 1% @ nominal operation	
UVRT capabilities	$V_{\text{nom}} \geq V \geq 0V_{\text{nom}}$ continuous	
OVRT capabilities	$V_{\text{nom}} \leq V \leq 1.2V_{\text{nom}}$ continuous $1.2V_{\text{nom}} < V \leq 1.5V_{\text{nom}}$ several seconds	
Voltage slew rate	±1 p.u./ms @ nominal taps ±0.5 p.u./ms @ dynamic taps	
Frequency slew rate	±4 Hz/ms	
Phase jumps	0 deg to 180 deg withing 2 ms	
Supported control modes	voltage control and current control	

1) HARDWARE SETUP

From a hardware perspective, Mobil-Grid-CoP consists of two identical strings of 14 MVA, which can be combined to one grid simulator of 28 MVA. Both units basically have the same structure as the grid simulator shown Fig. 3, but using ABB's latest ACS6080 converter platform in a H-bridge configuration, interconnected via three single-phase step-up transformers with $u_k \approx 10\%$. On the input side, the units of Mobil-Grid-CoP have two transformers and two active rectifier units for charging the DC link. As with other converter approaches, the grid simulator is equipped with an AC output filter to ensure high quality of the output voltage at the DUT terminals. By interleaving both strings and synchronizing the modulators, the phase-to-phase output voltage levels are increased from 17 at 14 MVA to 33 in the 28 MVA configuration, which further improves the quality of the emulated voltage. The new test facility has a short-circuit power of 80 MVA and is designed for DUTs with 20 MW nominal power, operated at 10 kV, 20 kV, 33 kV, 66 kV with 50 Hz or 60 Hz. Table 3 summarizes the main hardware properties and capabilities of the developed setup.

The mobile grid simulator will be used primarily as a PHIL power interface in the free field or as an extension of the test infrastructure at DyNaLab in Bremerhaven. Therefore, Mobil-Grid-CoP is designed for flexible use and will be set up and stored exclusively outdoors, which requires a particularly weather-resistant, shockproof and robust design. For this reason, the main electrical components, i.e., the converters, the filters, but also auxiliary and cooling systems as well

FIGURE 7. Aerial picture showing the layout of the mobile grid simulator, Mobil-Grid-CoP.

as protective equipment, are housed in commercial shipping containers, as illustrated in Fig. 7. The transformers use environmental friendly oil and are placed in tubs, preventing oil or glycol from leaking out in the event of a damage. To ensure safe cabling of the components and routing of the cooling pipes, a cable tray is also installed around the system in the field. In total, Mobil-Grid-CoP has a footprint of 41 m × 41 m.

2) COMMUNICATION CONCEPT

Additional improvement is achieved by the implemented communication concept and the low latencies between voltage referencing and the modulator as well as the acquisition of the measurements and the real-time simulators used to run a virtual network, see [44] for more details. Besides commanding phasor references to the modulator, the grid simulator also allows instantaneous voltage references to be provided via a fast communication channel. This is a significant improvement over the limits of most test benches discussed in Section III-D. In addition, the ability to connect several external real-time simulators provides the basis for more advanced and complex PHIL simulations. Further, Mobil-Grid-CoP implements a current control loop so that the mobile PHIL power interface can either be operated as a voltage or current source in grid-forming or grid-feeding mode. Selected voltage harmonics with frequencies of up to 2.5 kHz can be injected, which, along with the other functionalities, is particularly interesting when it comes to proving advanced requirements as defined in [5].

3) CAPABILITIES AND POSSIBLE HARDWARE EXTENSIONS

At the time of writing, Mobil-Grid-CoP is under construction with planned commissioning by the beginning of 2024. First simulation results have already been published in [44] and are very convincing. Due to the interleaved converter concept and underlying modulation scheme in the 28 MVA combined mode, the grid simulator generates an output voltage with 17-level, resulting in a low harmonic distortion. Fig. 8 exemplary shows the expected steady-state behavior. The implemented concept is scalable and can be extended

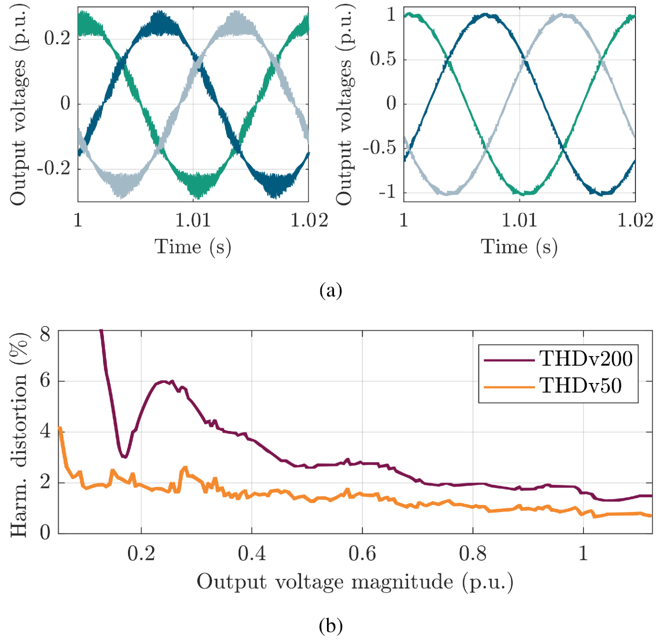


FIGURE 8. Expected steady-state output voltage quality of Mobil-Grid-CoP at different operating points in terms of its three-phase output voltage (a) and voltage spectrum (b) [44].

by additional converter units, further improving the power capability and quality. In addition, the test facility may also be upgraded by adding equipment to damp power oscillations for testing single-phase equipment, e.g., used in traction systems operated at 15 kV and 16.7 Hz, or by filters for testing DC equipment up to 10 MW at 4.5 kV_{DC}.

B. CHALLENGES AND LIMITATIONS OF WIND TURBINE TESTING

Even though many findings throughout grid compliance testing have been considered in design, as e.g., the need of a fast voltage referencing channel or the use of a higher flux reserve of the output transformers, it can be expected that Mobil-Grid-CoP still shows some software and hardware limitations.

A crucial aspect, for instance, is the proper selection and design of a PHIL interface algorithm on the connected real-time simulator. While latencies and therefore delays in the system have been minimized, it remains a challenge to deal with turbines with unknown characteristics. Since the input impedances of the connected DUTs are typically not available, approaches such as the damping impedance method (DIM), which are particularly known for their good coupling properties [39], cannot be implemented. To still ensure a stable closed-loop for various DUTs and any operating points, sufficient damping is required in critical frequency ranges, usually realized by the use of low-pass filters, as in the case of the DyNaLab PEGS. But then again a trade-off must be found between the system's stability properties and PHIL accuracy. Although there are a large number of interface approaches in the literature, see e.g. [39], the question of the most suitable

PHIL interface for future test scenarios has not yet been finally clarified.

Possible hardware limitations will probably become noticeable in very demanding dynamic tests. The simulation results from [44], for example, show some expected disturbing effects on the emulated PCC voltage in the case of an immediate reversal of the output voltages due to a phase jump of 180deg within 2 ms. Based on the experiences gained, it can be assumed that there will be a certain limitation due to the step-up transformer on the output side for any grid simulator based on NPC technology, see also [42]. A possible solution is offered by simulators that use modular multilevel converters (MMCs), where the arm inductance can be gradually reduced as the number of modules increases [12].

V. COMPONENT LEVEL CONVERTER TESTING

Component level testing focuses on developing, optimizing, and validating individual key components rather than an entire system at once. It covers various components, such as converters, controllers, and auxiliary systems [9]. This section concentrates on testing power electronic frequency converters of modern type III and type IV wind turbines, that act as the power interface between the generator and grid. As the frequency converter fully or partially decouples the wind turbine generator from the grid, it largely determines the turbine's electric grid behavior and is thus paramount regarding grid code compliance as well as upcoming topics such as impedance shaping, resonance behavior, or grid forming functionality. Testing converters is done on controllable laboratory test benches, where the test bench equipment replaces the required systems surrounding the DUT.

A. ADVANTAGES OF CONVERTER TESTING

Testing the power electronic frequency converter as an isolated component allows for drawing conclusions about its individual contribution to the wind turbine's grid behavior without other systems or external factors influencing the results. This cannot only help validate the converter's characteristic behavior but also to understand the nature and origin of technical issues during development in the otherwise more convoluted wind turbine system. Hardware, software, and control performance can be examined separately from a specific wind turbine, generator, or transformer. Independent testing allows performing functional validation of converter characteristics early in its development process. In contrast to system or subsystem level tests with larger assemblies of the wind turbine, component level test benches require only the component in question to be developed to a degree in which testing becomes reasonable. Testing and model validation can thus be utilized flexibly and can begin earlier, even if the turbine development is not finished entirely.

This flexibility extends to the test bench itself. As component level test benches for converters tend to be physically smaller than their system level counterparts and require less infrastructure, researchers, manufacturers, and suppliers can more easily set up specialized laboratory environments. The size advantage makes testing more cost-effective as tests can be run in quicker succession with less organizational and logistical effort and easier technical integration. And while physically smaller, newer converter test bench equipment still supports converters up to double digit multi-megawatt power figures due to the availability of modern power electronics and advanced control techniques [45], [46].

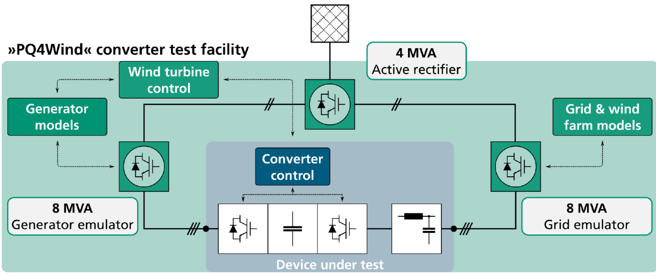


FIGURE 9. Schematic setup of the converter test bench [45].

B. CONVERTER TESTING ON THE PQ4WIND TEST BENCH

Fraunhofer IWES is constructing a new high power converter test facility in the course of the research project PQ4Wind, designed for multi-megawatt wind turbine frequency converters. Purpose of the test bench is to examine the electrical characteristics of power electronic converter systems in a wide frequency region ranging from 0 Hz (DC) up to 10 kHz. The project aims provide a test facility to precisely determine the impedance and power quality of wind turbine converters, to validate EMT and harmonic simulation models, to examine grid forming functionality, and to take further steps towards component level validation and certification of wind turbines [45].

1) TEST BENCH SETUP

The facility uses a power hardware-in-the-loop setup providing a fully programmable high-performance test environment for power converters. It supports most common frequency converters found in modern wind turbines, mainly low-voltage converters in the single-digit megawatt range. The test bench virtually replaces the electrical and mechanical systems of a wind turbine typically surrounding the frequency converter, i.e., the electric turbine generator as well as the aerolastic (MoWiT) model on one side and the utility grid on the other. Turbine, generator and grid are replaced using real-time simulations and two power electronic emulators acting as the power interface between simulation and DUT. Besides the converter itself, no other wind turbine components need to be physically present. Fig. 9 and Fig. 10 show the general structure and a picture of the test bench, respectively, and Table 4 summarizes some of its electrical key parameters.

The test bench consists of three functional units: machine emulator, grid emulator, and grid-connected active front-end. All units share a common DC bus, which the active front-end supplies with power from the utility grid. The machine emulator draws power from the DC bus to provide a controlled

FIGURE 10. Converter cabinets of the PQ4Wind test bench containing a total of 20 MW installed converter power for emulation.

TABLE 4. Technical Data of the Converter Test Bench

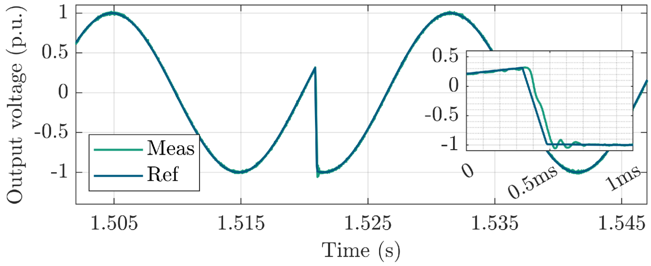
Description	Key data
Rated power	8 MVA per emulator at 690 V
Topology	17-level interleaved NPC
Max. supported voltage	AC mode: 1300 V_{RMS}
	DC mode: 1500 V_{DC}
Max. supported current	AC mode: 7000 A_{RMS}
	DC mode: 7500 A_{DC}
System configuration	AC mode: 1...6-phase
	DC mode: unipolar, bipolar
Switching frequency	128 kHz
Supported control modes	Closed-loop voltage control,
	closed-loop current control
Voltage THD	$\ll 1\,\%$ @ 690 V_{RMS}, 50 Hz
Harmonic injection	1 Hz up to 10 kHz
Impedance emulation	0 Hz to > 2.5 kHz

generator current to the DUT's machine side terminals. The DUT converts the power it receives and feeds it into an artificial power grid provided by the grid emulator, which then supplies the shared DC bus with the power from the DUT. The test bench aims to maintain a circular power flow to minimize power usage from the utility grid. Each emulator consists of two 4 MW power modules. All four power modules are identical in both hardware and software, and can be configured and controlled independently, allowing them to be used individually or together as a pair. Each power module internally consists of eight 500 kVA inverters, where each inverter comprises of a three-phase three-level neutral point clamped half bridge and its associated driver and control circuitry. The half bridges use conventional silicon-based IGBTs with 16 kHz switching frequency. All inverters are connected in parallel via coupling inductors, resulting in an interleaved multi-branch multi-level topology with 17 discrete output voltage levels. The parallel connection enables high output currents, as each branch conducts only about one eighth of the total output current [47]. Interleaved switching of the inverter branches using synchronized phase-shifted PWM carrier signals amounts to a high effective switching frequency of $8 \cdot 16 = 128$ kHz at the power modules' output terminals. While the emulators are primarily meant to examine AC-to-AC wind turbine converters, they are also capable of supplying DC quantities, enabling testing of other power electronic equipment such as battery inverters or hydrogen electrolysis rectifiers. AC, DC, or combined AC/DC operation can be enabled by independently configuring the power modules and whether they act as a power source or power sink.

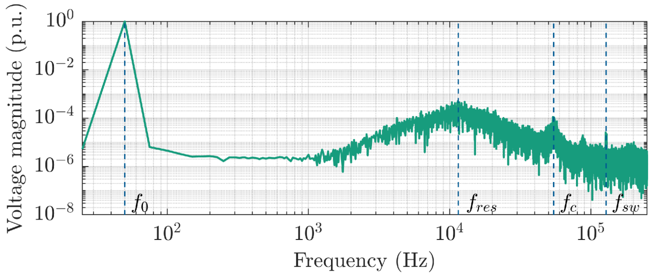
The test bench emulators are physically coupled to the DUT via inductive components. Between grid emulator and DUT, transformers provide galvanic isolation, suppress circular currents in the installation and act as the coupling interface. Though not primarily designed as step-up transformers, they feature additional taps to increase the maximum emulator output voltage to $1300V_{\mathrm{RMS}}$ at the DUT's terminals. On the machine side, variable inductors are used as the interface between emulator and DUT. The inductors can be set to different values between 0 μH (fully bypassed) and 100 μH. The inductance not only physically couples the emulator to the DUT, but can also function as the emulated generator's leakage inductance or part thereof to help with emulation. The maximum inductance value of 100 μH was chosen to be similar in value to the leakage inductance of common wind turbine generators.

2) CONTROL CONCEPT AND PERFORMANCE

Due to lack of mechanical interface components, the test bench relies on power electronic emulation at the DUT's machine and grid side terminals. Considering the project goals to study wind turbine converters at frequencies up to 10 kHz, the test bench must not exhibit any inherent behavior that might interfere with the DUT in this frequency range. Special care was therefore taken to design the emulators' hardware and software such that they operate in a frequency region well above the typical wind turbine converter. As the emulators' behavior heavily depends on their control performance, higher order state-space controllers with sub-10 μs latency and advanced active harmonic damping were chosen. The set points for the controllers are calculated by means of virtual EMT simulation models on Plexim RT Box 2 real-time simulators, which provide independent instantaneous voltage or current references at microsecond intervals. Communication is handled by a custom optical high-speed interface based on the Xilinx Aurora 64b/66b interface standard. Combined with the high effective switching frequency of 128 kHz, the control system prevents unintentional interaction between emulators and DUT. Fig. 11 demonstrates the preliminary control performance during an emulated phase jump event in a no-load scenario and the voltage quality in steady-state. The zoomed in event in Fig. 11(a) illustrates the instantaneous voltage control accuracy with a round-trip delay of approx. 30 μs, while Fig. 11(b) highlights the output voltage spectrum with marked fundamental frequency, f_0, filter resonance frequency, f_{res}, controller bandwidth, f_c, and switching frequency, f_{sw}.



(a)



(b)

FIGURE 11. Preliminary no-load control performance (a) and steady-state voltage spectrum (b) at one phase of the emulators' output terminals during commissioning.

C. CHALLENGES OF CONVERTER TESTING

While system level laboratory test benches have largely been accepted as viable alternative to field tests and have been shown to allow certification solely based on test bench results [17], [37], the role of component test benches in the certification process of wind turbines is not yet clearly defined [9], [11]. Though first attempts have been made to standardize their setup and functionality, broader questions still need answering, notably the validity and comparability of results. To prove their accuracy and show that all relevant effects and behaviors are correctly replicated on the test bench, one approach would be to repeat some tests using regular field measurements against which the results can be validated. Means of confirming the accuracy of test bench results and demonstrating that all relevant effects and behaviors are correctly replicated through accessible, objective measures need to be openly discussed and standardized. Open loop playback simulations of real events from the field can perhaps be one solution for validating test bench results. Other outstanding issues include how to deal with test bench results that deviate from field measurements but that are not wrong per se [11] and how to validate test bench results that cannot be replicated in the field.

Besides regulatory and methodological challenges, technical hurdles remain to be solved as well; some more general, others specific to each converter test bench. Due to lack of comprehensive standardization [9], technical capabilities can vary greatly from one test bench to the next and might include signal emulation, static load, protection and functionality tests, or even complex dynamic PHIL emulation. Since wind turbine frequency converters exhibit electrical characteristics up into the multi-digit Kilohertz range, dynamic PHIL emulation in particular requires test bench equipment that functions in a high frequency region so not to interfere with the DUT. PHIL emulation also necessitates a suitable interfacing algorithm connecting real-time simulation and physical hardware that needs to be both accurate and stable in the frequency range of interest [39]. This equally applies to the test bench controls, that need to operate safely and accurately during dynamic load changes and despite the diversity of converters that might be tested. Additionally, when testing wind turbine converters on a test bench relying on PHIL emulation, multiple simulation domains, i.e., electrical, mechanical and aerodynamic simulations models need to be coupled in real-time to precisely capture and replicate all relevant dynamics of the wind turbine and the power grid. Additional difficulty arises as models running with different time steps and on different simulation platforms need to be coupled to act as one contiguous simulation.

VI. CONCLUSION AND OUTLOOK

Nacelle and subsystem test benches for validating a wind turbine's grid code compliance have matured and are widely accepted as a viable alternative to field measurements on designated test sites. Hardware limitations remain however, be it limited power reserves of the test bench converters, finite flux reserve of the step-up transformers, or narrow control performance. Due to the rapid development of larger wind turbines with steadily growing power output and increasing cost pressure, it is unclear if state-of-the-art testing concepts and existing laboratory infrastructure will be a sustainable path forward.

Besides established testing methods, this paper presented two new approaches according to the V development model, extending the currently available laboratory infrastructure at Fraunhofer IWES. Mobil-Grid-CoP is specifically designed for testing complete wind turbines in the field with voltage levels up to 66 kV, while the PQ4Wind test bench is designed for testing the high frequency performance of individual components such as the turbine's main frequency converter up to 10 kHz. Both concepts are suitable for conventional grid compliance tests and aim to enable the testing of new functions that are increasingly finding their way into standards, such as grid-forming, islanding, or black-start capability. Table 5 summarizes the key aspects of the presented testing methods.

Considering the top level of the V-model, i.e., the testing of large wind farms, it becomes clear that even with more advanced hardware testing approaches, tests in a 1:1 scale is difficult or even impossible due to location, cost, physical size, and power constraints. In addition, such tests are no longer about performing plain grid compliance or system tests, but rather more complex interaction and stability analyses. Relevant studies to date have therefore been based primarily on analytical considerations, tests of scaled down replicas or offline simulations with more or less validated models. Model

TABLE 5. Summary of Technical Capabilities and Challenges of the Four Presented Testing Approaches for Wind Turbine Testing

Turbine testing
✓ mobile application and flexible testing options ✓ better scalability than test benches in halls ✓ mechanical and electrical interaction tests ✓ derivation of valid models of the overall system ✗ dependent on test site availability and wind conditions ✗ increased installation effort in the field ✗ contribution of individual components not visible
Nacelle testing
✓ less integration effort than in the free field ✓ mechanical and electrical tests ✓ simulation of arbitrary wind and grid conditions ✗ few large nacelle test benches available ✗ power rating of turbines is increasingly outgrowing test benches
Subsystem testing
✓ further reduction of effort for preparing measurement campaigns ✓ simple replacement of sub-components ✗ mechanical interactions must be accurately emulated
Component-level testing
✓ scalable in power and voltage ✓ flexible emulation of components and test scenarios ✓ no influence of other components during validation ✓ lowest effort and costs for preparing measurement campaigns ✓ early optimization possible during the development process ✗ complex emulation of missing components ✗ role in current certification process unclear ✗ accuracy and range of validity of test bench results not yet clear

validation at different levels of the V-model and the determination of validity ranges will therefore remain an essential and increasingly important aspect in the future.

To bridge the gap between system tests and offline simulation studies, Fraunhofer IWES is also working on the combination of more complex tests on system, subsystem or component test benches with large-scale real-time simulation of wind farms and the utility grid, referred to as *scenario-based testing*. Apart from the question of suitable hardware for simulating hundreds of pre-validated EMT turbine models in real-time, the main open points are the easy-to-handle and error-free integration of different models and platforms via appropriate and standardized interfaces.

REFERENCES

[1] J. Lee and F. Zhao, "GWEC Global Wind Report 2022," Global Wind Energy Council (GWEC), Brussels, Belgium, Apr. 2022.

[2] United Nations Framework Convention on Climate Change (UNFCCC), "The Paris Agreement," Dec. 2015. Accessed: Aug. 7, 2023. [Online]. Available: https://unfccc.int/sites/default/files/english_paris_agreement.pdf

[3] *IEEE Standard for Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with the Associated Transmission Electrical Power Systems*, IEEE Standard 2800-2022, 2022.

[4] Verband der Elektrotechnik Elektronik Informationstechnik e.V., "VDE-AR-N 4110 Anwendungsregel: 2023-09 - Technische Regeln für den Anschluss von Kundenanlagen an das Mittelspannungsnetz und deren Betrieb (TAR Mittelspannung)," VDE VERLAG GmbH, Berlin, Sep. 2023.

[5] Verband der Elektrotechnik Elektronik Informationstechnik e.V., "VDE-AR-N 4131 Anwendungsregel: 2019-03 - Technische Regeln für den Anschluss von HGÜ-Systemen und über HGÜ-Systeme angeschlossene Erzeugungsanlagen (TAR HG)," VDE VERLAG GmbH, Berlin, Mar. 2019.

[6] The European Commission, "Commission regulation (EU) 2016/631 of 14 April 2016 establishing a network code on requirements for grid connection of generators," Apr. 2016. Accessed: Aug. 7, 2023. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32016R0631&from=IT

[7] Australian Energy Market Operator Limited (AEMO), "Power System requirements - reference paper," Jul. 2020. Accessed: Aug. 7, 2023. [Online]. Available: https://www.aemo.com.au/-/media/files/electricity/nem/security_and_reliability/power-system-requirements.pdf

[8] *Wind energy Generation Systems - Part 21-1: Measurement and Assessment of Electrical Characteristics - Wind Turbines*, IEC Standard 61400-21-1, International Electrotechnical Commission, Geneva, Switzerland, 2019.

[9] *Wind Energy Generation Systems - Part 21-4: Measurement and Assessment of Electrical Characteristics - Wind Turbine Components and Subsystems*, IEC Standard 61400-21-4, International Electrotechnical Commission, Geneva, Switzerland, 2022.

[10] FGW e.V. – Fördergesellschaft Windenergie und andere Dezentrale Energien, "TR3 - Bestimmung der elektrischen Eigenschaften von Erzeugungseinheiten und -anlagen, Speicher sowie für deren Komponenten am Mittel-, Hoch- und Höchstspannungsnetz," Technische Richtlinien für Erzeugungseinheiten und -anlagen, Berlin, Apr. 26, 2022.

[11] O. Curran, G. M. Gomes Guerreiro, S. Azarian, F. Martin, and T. Dreyer, "WTG manufacturer's experience with subsystem and component validation for wind turbines," in *Proc. IEEE 21st Wind Sol. Integration Workshop*, 2022, pp. 458–465.

[12] Z. Li et al., "Medium-voltage megawatt power-electronic-based grid emulators: Testing capability requirements and dynamics challenges — A review," *IEEE J. Emerg. Sel. Topics Power Electron.*, early access, Apr. 2023, doi: 10.1109/JESTPE.2023.3268449.

[13] P. Koralewicz, V. Gevorgian, and R. Wallen, "Multi-megawatt-Scale power-hardware-in-the-loop interface for testing ancillary grid services by converter-coupled generation," in *Proc. IEEE 18th Workshop Control Model. Power Electron.*, 2017, pp. 1–8.

[14] T. Jersch, "LVRT Tesing on DyNaLab—Electrical certification of Windturbines on Test Benches?," in *Proc. 1st Int. Workshop Grid Simulator Testing Wind Turbine Drivetrains*, 2013, pp. 72–77.

[15] J. Wenske et al., *Wind Turbine System Design. Volume 1: Nacelles, Drivetrains and Verification*. London, U.K.: IET Digital Library, 2022, doi: 10.1049/PBPO142F.

[16] J. Wenske et al., *Wind Turbine System Design. Volume 2: Electrical Systems, Grid Integration, Control and Monitoring*. London, U.K.: IET Digital Library, 2023, doi: 10.1049/PBPO142G.

[17] A. Frehn, S. Azarian, G. Quistorf, S. Adloff, F. Santjer, and A. Monti, "First comparison of the electrical properties of two grid emulators for UVRT test against field measurement," *Forschung im Ingenieurwesen*, vol. 85, no. 2, pp. 373–384, Apr. 2021, doi: 10.1007/s10010–021-00476-9.

[18] The Carbon Trust, Unlocking the next generation of offshore wind: Step change to 132 kV array systems, Jun. 2022. Accessed: Aug. 18, 2023. [Online], Available: https://www.carbontrust.com/our-work-and-impact/guides-reports-and-tools

[19] *Wind Energy Generation Systems - Part 27-1: Electrical Simulation Models – Generic Models*, IEC Standard 61400-27-1, International Electrotechnical Commission, Geneva, Switzerland, 2020.

[20] *Wind Energy Generation Systems - Part 27-2: Electrical Simulation Models – Model Validation*, IEC Standard 61400-27-2, International Electrotechnical Commission, Geneva, Switzerland, 2020.

[21] T. Jersch, C. Mehler, and M. Neshati, "Overview of actual development and discussions of electrical certification of wind turbines on test benches," in *Proc. 16th Int. Wind Int. Workshop*, 2017.

[22] U. Jassmann, "Hardware-in-the-loop wind turbine system test benches and their usage for controller validation," Ph.D. dissertation, RWTH Aachen University, Aachen, Germany, 2018.

[23] K. Ma, J. Wang, X. Cai, and F. Blaabjerg, "AC grid emulations for advanced testing of grid-connected converters - an overview," *IEEE Trans. Power Electron.*, vol. 36, no. 2, pp. 1626–1645, Feb. 2021, doi: 10.1109/TPEL.2020.3011176.

[24] F. Hans et al., "Towards full electrical certification of wind turbines on test benches - experiences gained from the HiL-GridCoP project," in *Proc. 21st Wind Sol. Int. Workshop*, 2022, pp. 122–129, doi: 10.1049/icp.2022.2746.

[25] CENER, Powertrain test laboratories and electrical testing, Jan. 2018. Accessed: Aug. 18, 2023. [Online], Available: https://www.cener.com/en/wind-turbine-test-laboratory-lea/powertrain-test-laboratories-and-electrical-testing

[26] Clemson University, Dominion energy innovation center, 2024. Accessed: Feb. 20, 2024. [Online], Available: https://www.clemson.edu/innovation-campuses/charleston/energy/index.html

[27] G. Ozkan, "30 MW test bench," in *Proc. 6th Int. Workshop Grid Simulator Testing Energy Syst. Wind Turbine Drivetrains*, 2022. Accessed: May 25, 2023. [Online]. Available: https://www.nrel.gov/grid/workshop-grid-simulator-2022.html

[28] F. Renger and J. Reicherter, "Multi-motor drive technology in the multi-meganewtonmeter-range," in *Proc. Conf. Wind Power Drives Drivetrain Syst. Eng. Conf.*, 2023, pp. 89–99.

[29] L. S. Rasmussen, "33 kV–21 MVA grid emulator for wind turbine testing," in *Proc. 6th Int. Workshop Grid Simulator Testing Energy Syst. Wind Turbine Drivetrains*, Nov. 2022. Accessed: May 25, 2023. [Online]. Available: https://www.nrel.gov/grid/workshop-grid-simulator-2022.html

[30] V. Gevorgian, "High power testing at NREL. overview of values and opportunities," in *Proc. IEEE 8th Workshop Electron. Grid*, 2023.

[31] ORE Catapult, eGrid project, Jun. 2018. Accessed: Aug. 18, 2023. [Online], Available: https://ore.catapult.org.uk/stories/egrid

[32] M. O. Siddiqui, P. R. Feja, P. Borowski, H. Kyling, A. R. Nejad, and J. Wenske, "Wind turbine nacelle testing: State-of-the-art and development trends," *Renewable Sustain. Energy Rev.*, vol. 188, Sep. 2023, Art. no. 113767, doi: 10.1016/j.rser.2023.113767.

[33] M. Neshati and J. Wenske, "Dynamometer test rig drive train control with a high dynamic performance: Measurements and experiences," *IFAC-PapersOnLine*, vol. 53, no. 2, pp. 12663–12668, 2020, doi: 10.1016/j.ifacol.2020.12.1846.

[34] M. L. Huhn and W. Popko, "Best practice for verification of wind turbine numerical models," *J. Phys., Conf. Ser.*, vol. 1618, no. 5, 2020, Art. no. 052026, doi: 10.1088/1742-6596/1618/5/052026.

[35] M. Leimeister, A. Kolios, and M. Collu, "Development and verification of an aero-hydro-servo-elastic coupled model of dynamics for FOWT, based on the MoWiT library," *Energies*, vol. 13, no. 8, Apr. 2020, Art. no. 1974, doi: 10.3390/en13081974.

[36] M. Miskiewicz et al., "ABB's ACS6000 power electronic grid simulator, PEGS, tests medium voltage equipment," *ABB Rev.*, vol. 2, pp. 52–57, 2020.

[37] S. Azarian, T. Jersch, S. Khan, and S. Azarian, "Comparison of impedance behavior of UVRT-Container with medium voltage grid simulator in case of unsymmetrical voltage dip," in *Proc. IEEE Conf. Wind Power Drives*, 2019, pp. 1–12, doi: 10.1109/CWD.2019.8679528.

[38] P. Koralewicz, V. Gevorgian, R. Wallen, W. van der Merwe, and P. Joerg, "Advanced grid simulator for multi-megawatt power converter testing and certification," in *Proc. IEEE Energy Convers. Congr. Expo.*, 2016, pp. 1–8, doi: 10.1109/ECCE.2016.7854830.

[39] G. F. Lauss, M. O. Faruque, K. Schoder, C. Dufour, A. Viehweider, and J. Langston, "Characteristics and design of power hardware-in-the-loop simulations for electrical power systems," *IEEE Trans. Ind. Electron.*, vol. 63, no. 1, pp. 406–417, Jan. 2016, doi: 10.1109/TIE.2015.2464308.

[40] G. Curioni et al., "HiL-Grid-CoP: Electrical type testing of wind turbines on the minimum system using a test rig," in *Proc. Conf. Wind Power Drives*, 2023, pp. 140–147.

[41] T. Siepker et al., "Comparison of under-voltage-ride-through measurements between field tests and DyNaLab grid simulator tests of the siemens gamesa D8 direct-dirve wind turbine," in *Proc. 18th Int. Wind Int. Workshop*, 2019.

[42] Z. Li, F. Zhao, F. Hans, S. Munk-Nielsen, and X. Wang, "Adaptive anti-saturation control design of transformers in converter-based grid emulators," *Authorea Preprints*, early access, Dec. 2023, doi: 10.36227/techrxiv.170317597.77165320/v1.

[43] B. Nouri, Ö. Göksu, V. Gevorgian, and P. E. Sørensen, "Generic characterization of electrical test benches for AC-and HVDC-connected wind power plants," *Wind Energy Sci.*, vol. 5, no. 2, pp. 561–575, May 2020, doi: 10.5194/wes-5–561-2020.

[44] F. Hans et al., "Mobil-Grid-CoP – a new approach for grid compliance testing of multimegawatt wind turbines in field," in *Proc. IEEE 22th Wind Sol. Integration Workshop*, 2023, pp. 50–57.

[45] P. Borowski, G. Quistorf, and T. Jersch, "PQ4Wind - a novel test bench for component-level wind turbine converter testing," in *Proc. IEEE 21st Wind Sol. Integration Workshop*, 2022, pp. 466–472.

[46] M. Neshati et al., "Grid connection testing of wind energy converters with medium voltage generators and grid emulators on a multi-megawatt power hardware-in-the-loop test rig," in *Proc. 22th Wind Sol. Int. Workshop*, 2023, pp. 451–460.

[47] M. Fischer, D. Erthle, P. Ziegler, J. Ruthardt, and J. Roth-Stielow, "Comparison of two power electronic topologies for power hardware in the loop machine emulaton," in *Proc. IEEE Appl. Power Electron. Conf. Expo.*, 2020, pp. 2950–2954.