DTU Library

Advancements on Grid Compliance in Wind Power: Component & Subsystem Testing, Software-/Hardware-in-the-loop, and Digital Twins

Guerreiro, Gabriel Miguel Gomes; Martin, Frank; Dreyer, Thomas; Yang, Guangya; Andresen, Björn

Published in:
IEEE Access

Link to article, DOI:
10.1109/ACCESS.2024.3366091

Publication date:
2024

Document Version
Publisher's PDF, also known as Version of record

IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 30 January 2024, accepted 9 February 2024, date of publication 13 February 2024, date of current version 23 February 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3366091

PERSPECTIVE

Advancements on Grid Compliance in Wind Power: Component & Subsystem Testing, Software-/Hardware-in-the-Loop, and Digital Twins

GABRIEL MIGUEL GOMES GUERREIRO [1,2], (Member, IEEE), FRANK MARTIN [1], THOMAS DREYER [1,3], GUANGYA YANG [2], (Senior Member, IEEE), AND BJÖRN ANDRESEN [4]

[1]Siemens Gamesa Renewable Energy, 2800 Kongens Lyngby, Denmark
[2]Department of Wind and Energy Systems, Technical University of Denmark, 2800 Kongens Lyngby, Denmark
[3]Siemens Gamesa Renewable Energy, 20097 Hamburg, Germany
[4]Electrical Energy Technology Section, Aarhus University, 8000 Aarhus, Denmark

Corresponding author: Gabriel Miguel Gomes Guerreiro (gabriel.gomes@siemensgamesa.com)

This work was supported by the Siemens Gamesa Renewable Energy (SGRE), Working Group 21 (WG21) under IEC TC88 and Innovative Tools for Cyber-Physical Energy Systems (InnoCyPES), where one of the co-authors funded by the European Union's Horizon 2020 Research and Innovation Programme under the Marie Sklodowska Curie under Grant 956433.

ABSTRACT The rapid expansion of wind power needs increased efforts in establishing rules for connecting wind power plants (WPPs) through grid codes and standards. This makes grid compliance testing and model validation more complex for wind turbine generator (WTG) manufacturers and WPP developers. This paper explores various challenges and solutions within the wind industry concerning grid compliance and the integration of large-scale WPPs. Traditionally, WTG original equipment manufacturers (OEMs) conduct grid compliance tests on full-scale prototype turbines, while WPP developers predominantly engage in studies for new WPPs based on offline EMT and RMS simulations. Up to this point, these approaches have sufficed to ensure grid compliance for WTGs and WPPs. However, as the wind sector progresses, new testing methods are required to meet the growing WT capacity, WPP complexity, and deployment pace, aiming to achieve society's sustainability targets. The industry is actively exploring methodologies that address these challenges by testing new turbine subsystems and components at the development level, employing software-/hardware-in-the-loop real-time simulation for WTG/WPP interoperability assessment, and ensuring control and protection performance verification during design and operation. Additionally, digital twin approaches are being considered, encompassing the entire development and operation chain for grid compliance and connection aspects. Ultimately, this paper presents a fresh overview of these strategies, outlining definitions and the pros/cons for the stakeholders involved in the process.

INDEX TERMS Wind power, grid compliance, component and subsystem testing, SiL/HiL, digital twins.

I. INTRODUCTION

The rapid growth of wind power, particularly large-scale offshore wind power plants connected through long AC cables or HVDC to shore, is creating challenges for transmission system operators (TSOs) who must establish frameworks and rules for the connection of wind power plants (WPPs) through grid codes and modeling requirements [1], [2]. In addition, the industry is also realizing the need to establish additional regulations for deploying ancillary services from renewable sources (e.g. grid forming capabilities including inertia, islanding, black-start, etc), further increasing the complexity of the design and operation of future power systems. As a result, testing and validation become more complex for wind turbine generator (WTG) manufacturers and WPP developers.

The associate editor coordinating the review of this manuscript and approving it for publication was Yifan Zhou.

Many of the challenges outlined above are tackled by various task forces through the establishment of standards, working groups (WGs), and grid code activities. Concerning grid compliance, the wind industry relies on many initiatives, all focused on ensuring the reliable integration of WTG and WPPs into the grid. A comprehensive overview of pertinent standards and WGs about grid compliance is presented in Table (1). Certain task forces adopt a wind-centric approach, as seen in IEC 61400-21/27 series, FGW, and CIGRE WGs, while others take a more generic stance, focusing on Inverter-Based Resources (IBRs) or Converter-Based Resources (CBRs), as evidenced in IEEE standards, CENELEC, select IEC standards, and NERC guidelines. As the industry has evolved, many countries now enforce concrete regulations for such equipment [3], [4], [5].

From the standpoint of wind turbine development, OEMs have refined testing methodologies through extensive field tests, with the majority of grid compliance tests now conducted on full-scale prototype turbines in the field [4], [6], [7]. As turbines grow larger to decrease the Levelized Cost of Energy (LCOE) and overall wind power plant costs, these tests may extend over longer durations due to the availability of suitable test equipment and site impediments arising from increasing sizes, as observed in Fig. 1. The challenges intensify due to expanding testing scopes and vulnerability to on-site weather conditions, leading to protracted test campaigns. Additionally, limitations in current testing equipment and site constraints mean that some grid compliance features cannot be tested by manufacturers, introducing uncertainties regarding turbine behavior under specific grid conditions [8].

Ensuring the stability and compliance of WPPs with grid codes involves developers obtaining validated models from equipment manufacturers and conducting thorough validation at the plant level before, during, and after commissioning. Pre-commissioning studies must typically precede any physical equipment installation, ensuring no compliance issues arise due to hardware or software characteristics. The growing diversity of grid codes, coupled with increasingly complex requirements in new markets, challenges the performance verification of WPPs. Developers are compelled to initiate studies earlier, placing pressure on manufacturers to deliver highly accurate and validated models at an early stage of the design of new equipment. During commissioning, tests and procedures specified in standards and grid codes are employed to verify the plant's grid compliance.

In this context, efforts are underway to improve and speed up the processes of testing, validation, and verification of grid compliance at both the WTG and WPP levels [8], [9], [10], [11], [12], [13], [14], [15], [16], [17]. Recently released or in-progress standards, such as "IEC CD 61400-21-4: Wind turbine components and subsystems," "IEC TS 61400-21-5: Configuration, functional specification, and validation of hardware-in-the-loop test bench for wind power plants," "IEEE P2800.2: Recommended Practice for Test and Verification Procedures for Inverter-based Resources (IBRs) Interconnecting with Bulk Power System," among others, define crucial strategies for testing and validating WTG and WPPs concerning grid compliance and connection requirements.

In addition to the design and commissioning of WTGs and WPPs, operational challenges also arise. Approximately 30-34% of the levelized cost of electricity in wind power is believed to originate from Operation and Maintenance (O&M), with catastrophic O&M events not even factored in yet according to NREL [18]. Despite best efforts, there is currently no comprehensive data available regarding the impact of grid integration aspects on O&M. Nevertheless, historical incidents for example in Hornsea 1 Wind Power Plant [19] and the recent blackout in Brazil [20] have demonstrated that grid integration aspects can profoundly affect the continuity of supply and overall costs. The overall assessment of plant compliance over its lifetime is intricate, given the upgradability of parameters, control software, ever-changing characteristics of the grid, and eventual hardware characteristics of certain equipment changing, as seen in Fig. 1.

This paper presents an overview of three different and complementary strategies that can help stakeholders achieve better results in grid compliance assessment and connection of wind power plants and other IBRs. To the knowledge of the authors, this is the first time that such topics have been discussed in depth with a focus on grid integration aspects of wind power. Part of the paper is based on the extensive ongoing work done by the working group WG21 under IEC TC88. In Section II, an extensive overview and definition of wind turbine component and subsystem testing methodologies and definitions are discussed based on existing standards and industry experience. Section III discusses how real-time hardware- and software-in-the-loop (HiL/SiL) can be used for WPP-level verification to ensure interoperability between different equipment and compliant operation at different lifecycle stages. In Section IV, the Digital Twin paradigm is discussed aiming to leverage models, test benches, historical testing and operational data, and artificial intelligence to aid in the design and operation of wind turbines and power plants. Furthermore, in Section V, discussions are presented regarding the transferability and reliability of the methodologies presented and how acceptance can be further pursued in the community. Finally, an overview of all the methodologies is presented and conclusions are drawn.

II. COMPONENT AND SUBSYSTEM TESTING FOR WIND TURBINE GRID COMPLIANCE ASSESSMENT

The technique of breaking down a system into components or subsystems for more agile and reliable testing has been utilized in many industries that face similar limitations to the wind industry when it comes to ensuring proper testing of their systems. Subsystems of NASA satellites, robots, and vehicles are just a few examples of industries that have implemented this technique to overcome testing challenges [21], [22], [23]. The idea of testing subsystems

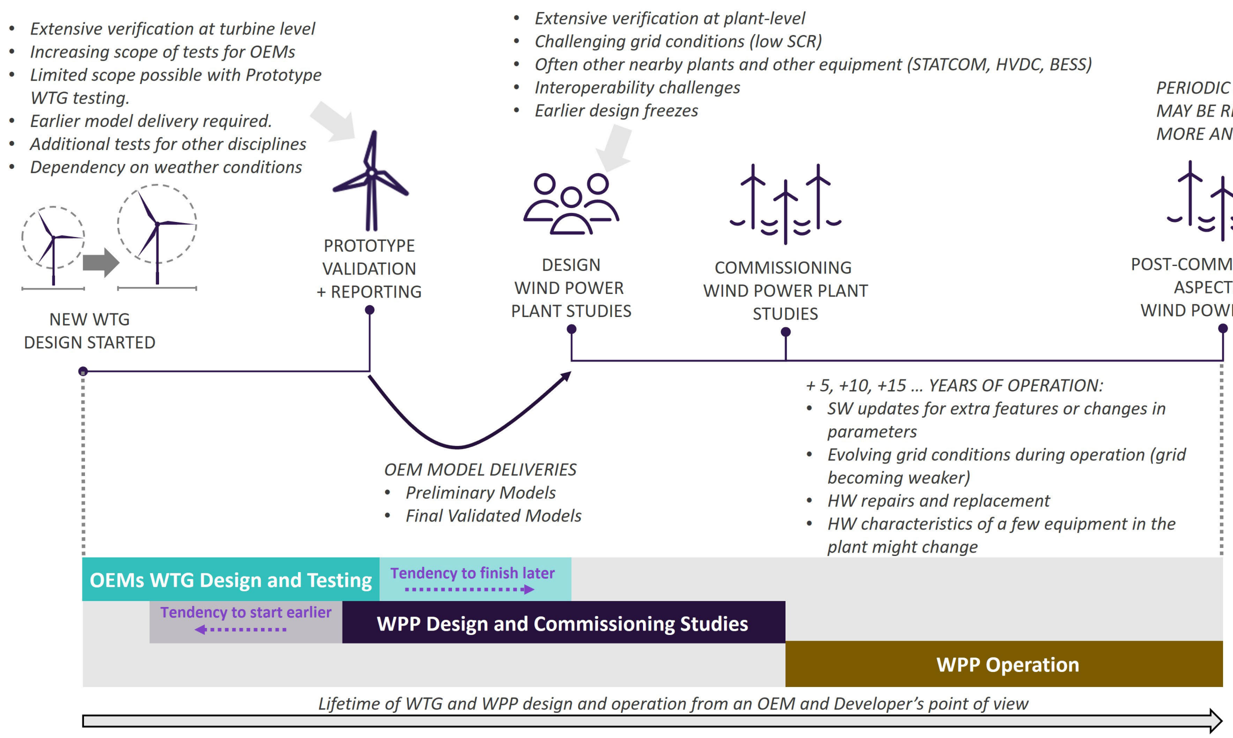


FIGURE 1. **Challenges with Grid Integration of WTGs and WPPs throughout the lifetime.**

is not new to the power system domain and has been widely accepted in other equipment and systems, such as HVDC, Microgrids, and Synchronous machines, due to the infeasibility or impracticality of carrying out field tests on prototype equipment [24], [25]. However, the wind industry has only recently begun exploring standardized and widely accepted testing methods for subsystems and components.

Full-scale prototype turbine field testing has been the primary methodology used for testing and validating wind turbines [6], [7]. However, this approach has limitations when it comes to testing scope, availability of equipment, and weather conditions. These limitations are due to the extensive amount of time required to ensure the proper weather conditions for testing, as well as the requirement for specialized equipment to emulate faults in the grid for Fault-Ride Through (FRT) tests. Furthermore, due to design changes, the replacement of components (RoC) for both software and hardware, can on some occasions generate the need to repeat tests. If tests are only performed at prototype level, the turbine or testing equipment may not be further available, due to a new one being built. Despite its high fidelity, full-scale prototype testing hinders the industry's capability to achieve greater potential in terms of research and development of new turbines, services, and solutions, especially when the industry requires new turbines to be developed and produced faster than ever before.

To overcome these challenges, component, and subsystem (C&S) tests can aid in the overall wind turbine grid compliance testing campaign, making it possible to start tests earlier, allowing models to be validated faster and additional grid compliance features to be verified. Such tests can be carried out on parts of the entire system or at the component level and can represent certain responses or behaviors of the entire system without requiring all the parts to be assembled and present during the test.

Fig. 2 depicts how these tests can contribute to earlier plant-level grid compliance studies, resulting in overall more reliable turbines and plants. The wind industry can learn from other industries that have successfully implemented this technique, and further develop standardized testing methods that are accepted by all stakeholders in the industry.

A. C&S TESTING VIEWED FROM DIFFERENT PERSPECTIVES

The strategy of testing C&S of a wind turbine to obtain an overall performance view for grid compliance purposes can present different pros and cons depending on each stakeholder's perspective. Moving forward, a common agreement can be achieved in many areas such as testing benches, types of subsystems and test plans, and acceptance criteria, among others. Below, a short view of different stakeholder's perspectives is discussed:

- **Original Equipment Manufacturers (OEMs)**: For OEMs, such a strategy can bring many benefits to the development of new turbines, however, in order to achieve that, the industry must agree on the proper strategies for acceptance (e.g. comparison with test fields or other strategies described in subsection E)

TABLE 1. Overview of standards and working groups related to grid compliance and connection aspects of wind power.

Standards	Subdivision or Details	Application Range	Area
IEC 61400-21 series : Measurement and assessment of electrical characteristics	61400-21-1: Wind turbines	Wind Turbine Level	Testing and Grid Compliance Assessment
	61400-21-2: Wind power plants	WPP Level	
	61400-21-3: Wind turbine harmonic model and its application (proposed to be replaced by 27-3)	Wind Turbine Level	Harmonic Testing and Converter Harmonic Model
	IEC CD 61400-21-4: Wind turbine components and subsystems	Wind Turbine Level	Test Bench Validation with all existent and additional Grid Compliance, Stability, and Interoperability testing
	IEC TS 61400-21-5: Configuration, functional specification, and validation of hardware-in-the-loop test bench for wind power plants	WPP Level	
IEC 61400-27 series : Electrical Simulation models	61400-27-1: Generic fundamental frequency models	WT and WPP	Generic Models
	61400-27-2: Validation of fundamental frequency models		Validation of Models (fundamental frequency)
	(New Work Item) 27-3: Structure and validation of multifrequency models		Frequency Domain Models
	(New Work Item) 27-4: Structure and validation of EMT models		EMT Models
Other relevant IEC /IECRE Standards	IEC TR 63411 Grid Connection of Offshore Wind via VSC-HVDC System	WPP and Grid Levels	Requirements
	IEC 62934 : Grid Integration of renewable energy generation - Terms and definitions	WPP and Grid Levels	Terms and definitions
	IEC TS 63102 : Grid code compliance assessment methods for grid connection of Wind and PV power plants	Wind and PV	Grid Compliance Requirements
	IECRE WG-010 - Grid code compliance		
	IECRE OD-501 - Type and Component Certification Scheme	Wind Turbine Level	Testing
	IECRE OD-009 - Power-generating Unit Certification Scheme for Grid Code Compliance	All Types of Generation	Testing and Certification
	IEC 61400-60 Validation of Computational Models	WTG and WPP	Model Validation
IEEE	P2800.1 - Interconnection and Interoperability of Inverter-Based Resources (IBR) Interconnecting with Associated Transmission Electric Power Systems	All IBRs (wind, solar, STATCOM, BESS, etc)	General Guidelines
	Ongoing - P2800.2 –Recommended Practice for Test and Verification Procedures for Inverter-based Resources (IBRs) Interconnecting with Bulk Power Systems		Testing, Model Validation and GC assessment
	IEEE Standard 1547 for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces.		General Guidelines
	IEEE P2882 - Guide for Validation of Software Models of Renewable and Conventional Generators for Power Systems Studies	All Types of Generation	Model Validation
CIGRE	CIGRE JWG A1/C4.52: Wind generators and frequency-active power control of power systems	Wind Turbine Level	
	CIGRE WG C4.49: Multi-frequency stability of converter-based modern power systems	All IBRs (wind, solar, STATCOM, BESS, etc)	Frequency domain stability
FGW (Germany)	FGW TG3 - Determination of the Electrical Characteristics of Power Generating Units and Systems, Storage Systems as well as their Components in Medium-, High- and Extra-High Voltage Grids	All IBRs (wind, solar, STATCOM, BESS, etc)	Electrical Characteristics and Grid Compliance
	FGW TG4 - Demands on Modelling and Validating Simulation Models of the Electrical Characteristics of Power Generating Units and Systems, Storage Systems as well as their Components		Modelling Aspects
CENELEC	CENELEC EN 50549 - 2: Requirements for generating plants to be connected in parallel with distribution networks - Part 2: Connection to a MV distribution network - Generating plants up to and including Type B	WPP Level	Grid Requirements
	CENELEC EN 50549 - 10: Requirements for generating plants to be connected in parallel with distribution networks - Part 10: Tests demonstrating compliance of units	Wind Turbine Level	Testing and Grid Compliance Assessment
NERC - North American Electric Reliability Corporation	NERC - Inverter-Based Resource Performance Working Group (IRPWG)	WPP and Grid Levels	Requirements and Modelling aspects

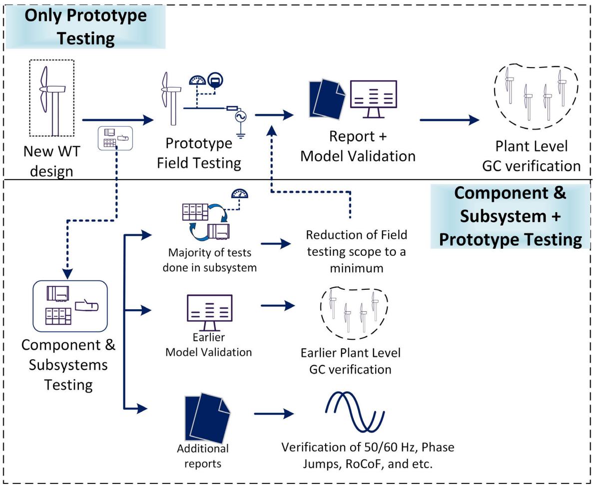


FIGURE 2. Subsystem testing framework, adapted from [8].

of the results so that not many additional procedures and steps are required for new testing campaigns. Component and subsystem testing can, for example, remove dependency on external factors that affect testing and validation and that in many cases can neither be predicted nor controlled, such as wind speed, extreme weather conditions, etc. Furthermore, other tests such as power curve measurements, noise, loads, and many others often must be done on the prototype turbine, and grid compliance-related tests may need to be postponed. Additionally, it can facilitate and speed up the model validation procedures in a way that developers can obtain models with high confidence levels at the early stage of the new wind power plant development process. Finally, subsystem testing can also ensure that other ancillary services and solutions are properly tested in a controllable environment.

- **Wind Power Plant Developers**: From a developer's perspective, other challenges and shortcomings are solved and created by the deployment of such a strategy. First, by being validated against tests in a more flexible environment, models can be more extensively validated against other scenarios and disciplines, ensuring better results at plant-level simulation. Second, due to tests being independent of external factors, highly accurate models can be obtained faster and therefore allow developers to begin plant-level studies earlier in the development process, allowing more time for adjustment of the power plant designs and a more reliable development.
- **TSOs**: From a TSO's perspective, this strategy offers a more reliable grid compliance verification of Wind Turbines and consequently plants, since certain features are verified that otherwise could not be tested in a full-scale prototype turbine. It also offers the possibility of obtaining more accurate models in a quicker time frame for further network studies.

B. TYPES OF TESTS AND TEST BENCHES

The definitions of types of subsystems and tests can aid stakeholders in identifying how to use the strategy to fulfill grid compliance needs. However, although definitions are presented in IEC 61400-21-4 [26] and also in other initiatives in the industry such as FGW Working Group AK KEZ [27], there is still the need for further research and experience in the upcoming years as the definitions are still recent and can evolve with testing technologies. In this section, a general overview of the definitions will be given, although it is recommended a specific search within cited standards and working groups if detailed specifications are required.

1) FUNCTIONALITY TEST

These tests are commonly mistaken for performance tests, however, such tests aim to mainly assess if certain functions or control features of the turbine are working properly and do not necessarily represent the dynamic performance of the turbine regarding those tests. It generally describes the specific behavior of a control strategy or a piece of SW/HW, where some of the capability and performance features of the main turbine subsystems are disregarded. Examples can be commonly found in the literature, where a new control topology is tested on SW or even HW in a real-time digital simulation environment. Such tests can be incorporated at very early stages of the development process of a WTG in order to test the smallest subsystem possible or a core piece of software that will be incorporated into the turbine. In most scenarios, such tests can only be used to validate the functions of a model and will not be used to validate the final models for performance. Nonetheless, functionality tests can be used to facilitate and speed up the development process by identifying early issues with the design of certain equipment or pieces of software before they get incorporated into other parts of the turbine.

2) CAPABILITY TEST

This class of tests is mainly associated with the steady-state operation of a WTG and is generally not influenced by any dynamic behaviors of the mechanical or auxiliary subsystems of the WTG. In this sense, capability tests can incorporate the minimum level of subsystems necessary that can faithfully represent the behavior of a WTG for steady-state grid compliance disciplines. A few examples of these can be power capability curves, voltage and power ranges, harmonics, flicker, etc.

3) PERFORMANCE TEST

Performance tests can be defined by tests that aim to determine the potential of the subsystem to achieve a certain function including all the elements that significantly influence the overall performance of the intended function [26]. These tests are generally more complex than the functionality of certain control functions and are assessed taking into account many different dynamic behaviors of the system. For example, even though the FRT control functionality of the turbine can be assessed only with the control hardware or even the control source code software, the WTG FRT control performance requires that other parts of the turbine's components and subsystems be included in order to account for most of the mechanical, electrical and communication dynamics during the event [26], [27]. Experiences from manufacturers and measurement institutes [9], [10], [12] have shown that it is possible to achieve the equivalent performance of a WTG by using a set of selected components/subsystems of the wind turbine. Thus far, it is a general consensus that nacelle test rigs and some electrical generation test rigs, that have mechanical hardware-in-the-loop (mHiL), can be used for performance tests. However, it can be expected that other configurations in the future will also be found to faithfully represent the system dynamics as the industry acquires more experience with such types of tests.

In Fig. 3, a quick overview of the aforementioned types of tests is coupled to the types of subsystems:

- **Field Test**: This type of testing is the traditional and well-established method of testing wind turbines and WPPs for grid compliance. It is described in different standards and international guidelines as a way of ensuring that turbines can comply with different requirements and also validate the models used for plant-level compliance validation according to IEC 61400-21-1 and IEC 61400-21-2 [28], [29] or other guidelines.
- **Nacelle Test Bench (Type A)**: After full-scale wind turbine grid compliance tests, Nacelle tests are the closest to the full system that can be achievable in a controllable environment for grid compliance testing. They contain the complete electrical system (electrical drive train, converter, transformer, etc), full or partial mechanical drive train, and complete control system. Different manufacturers and research institutes have been experiencing this type of is [9] and [10]. This type of test bench offers a high fidelity and especially overall industry acceptance, however can become quite large in size and overall complexity to realize.
- **Electrical Generation/Drive Train Test Bench (Type B)**: The electrical generation test bench presents a reduced amount of components when compared to the Nacelle test bench, where the mechanical drive train is omitted. A prime mover is connected to the electrical drive train to simulate the torque exerted by the mechanical drive train.
- **Converter Test Benches (Type C)**: These types of test benches include the actual converter hardware with the converter control systems. Typically, if no emulation of the grid is done, such test benches can mostly be used for capability studies on the steady-state as shown in [12]. However, if grid emulators and other novel methodologies are present, these test benches can offer flexibility in terms of implementation, operation, and expansion since the number of components is reduced [11], [16].
- **Component and Other Subsystem Test Benches (Types D and E)**: These types of test benches can include converter control hardware systems, wind turbine auxiliary systems, etc as shown in the experiences by one OEM in [12].

C. NEXT GENERATION TEST BENCHES: USE OF GENERATOR AND GRID EMULATORS

As the number of components in a test bench gets smaller, the probability of using such a setup for performance or capability tests also decreases. This is mainly due to the uncertainties of how representative the behavior is presented by fewer components compared to the full-scale prototype WTG. Next-generation test benches as proposed by [11], [12], [13], [14], [15], [16], and [17] aim to show that test benches with only a few selected components can be used for either component or equipment level validation by leveraging new ways of modeling and emulating missing hardware parts. For equipment-level validation, most grid compliance disciplines including performance tests can be performed. These test benches mainly consist of both the WTG converter and WTG control system, which are connected to separate inverter systems that can emulate either the generator and grid side or only the grid side.

In [13], an overview of Grid Emulators (GEs) is given including a description of ratings, design characteristics, and important considerations for future projects. A novel test bench for component-level certification is presented in [11] where the test bench focuses on examining the electrical behavior of the device under test over a wide range of frequencies, up to the 200th Harmonic. Furthermore, in [14] and [15] strategies utilizing grid emulators are also being explored for static and mobile test rigs.

Lastly, in [16] a novel test-rig is presented where both generator and grid side emulators are present, as illustrated in Fig. 4. The generator side emulator communicates with a real-time simulator of high-fidelity models of the generator and aerodynamic components which include wind field, turbulence, etc. The grid simulator utilizes an inverter-based control of the grid voltage to allow basic (i.e., grid fault ride through) and advanced features such as, dynamic impedance emulation, phase jumps, RoCoF, or harmonic control.

D. NEW ADDITIONAL TESTS

Besides the before-mentioned positive sides of using component, subsystem, and nacelle testing as a feasible alternative for speeding up compliance reporting and model validation, another benefit of testing WTG subsystems in a controllable and grid-isolated environment, especially with a grid emulator. This allows to perform tests under well-defined grid conditions, with varying grid parameters, and with more complex fault conditions to validate the performance of the WTG at different connection types and grid systems.

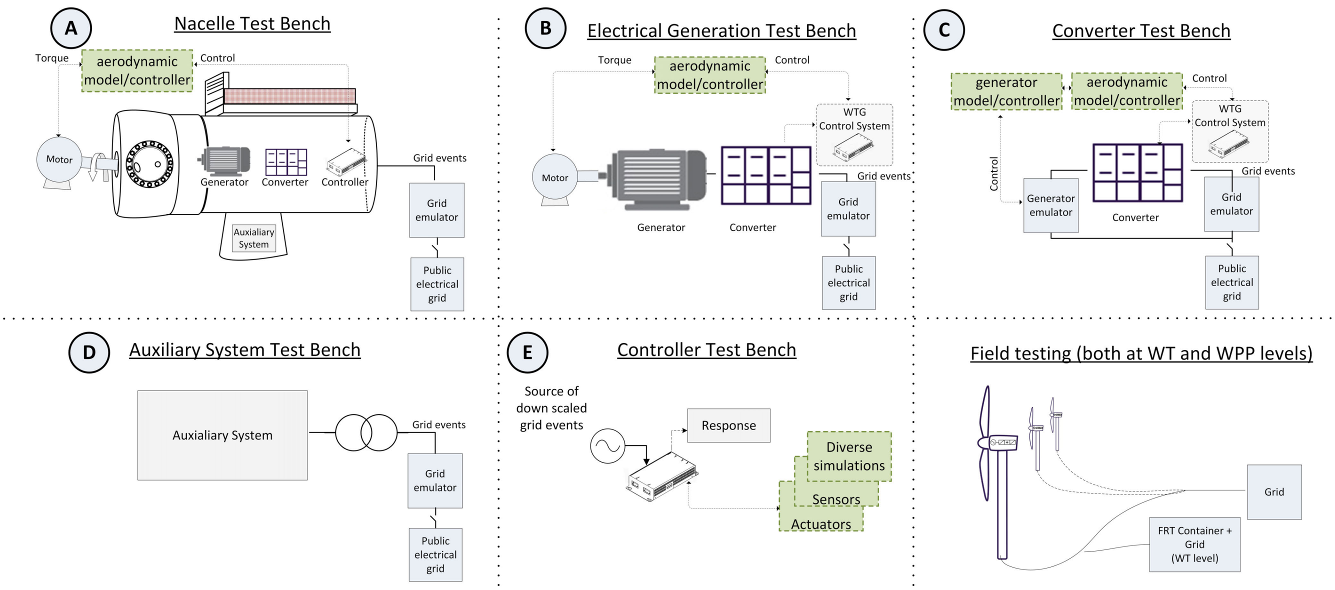


FIGURE 3. **Components & Subsystems definitions adapted from IEC 61400-21-4 [26].**

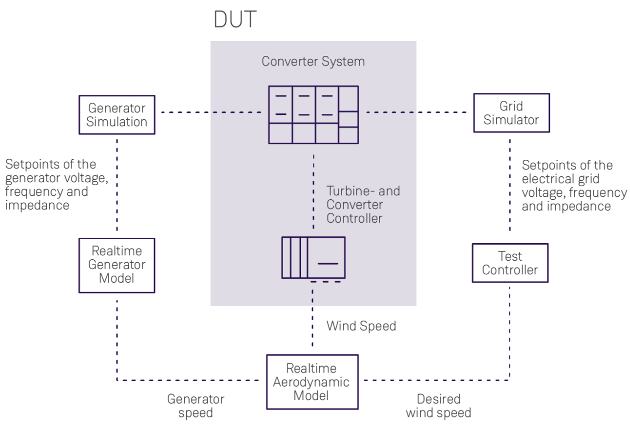


FIGURE 4. **Next generation test benches [12].**

Furthermore, additional tests of the boundaries of the WTG are only possible in a controllable grid system, such as:

- **Voltage and Frequency Capability Tests**: To validate the actual performance of the WTG at the limits of the WTG design and the required operating conditions of the grid system.
- **Harmonic Evaluations**: At-site tests have consistently been heavily influenced by background conditions and have resulted in unreliable harmonic measurements. Testing with a grid emulator allows for harmonic evaluation under ideal conditions, directly applicable to the harmonic model, as defined in, for example, 61400-21-3 [30], and for harmonic stability and resonance analysis as required in relation to the new stability criteria for converter-based generation systems [31].
- **Reactive Power Capability Curves at Different Voltages**: Reactive power capability curves are typically obtained in the field; however, such tests have the limitation of being voltage-dependent and strongly restricted by the connection point at the test site. Therefore, voltage-dependent reactive power capability tests can be conducted with a test rig that is fully decoupled from the public grid.
- **Rate-of-Change-of-Frequency (RoCoF)**: These tests are an integral part of the performance tests of a WTG and WPP and are associated with significant frequency changes that might occur in the grid due to a severe loss of generation or system split.
- **Phase Jumps**: Defined by sudden changes in phase angle during a fault that can cause substantial phase angle displacements. These tests cannot be adequately performed on-site and are additionally required by TSOs to ensure control stability during such events.
- **Ancillary Services**: Grid-forming capabilities, black-start, island operation, etc., can be more easily tested and validated for a wide range of conditions. The use of grid emulators is essential for such complex services.

E. VALIDATION STRATEGIES, TRANSFERABILITY AND MODEL DEVELOPMENT FOR COMPONENT AND SUBSYSTEM TESTING

Although field testing is essential for demonstrating certain functions, capabilities, and performance of wind turbines, components, and subsystem testing can provide a reliable and faster way to assess grid compliance and validate EMT and harmonic models. By using controllable test benches, such type of testing can eliminate external factors and technical limitations for additional tests, enabling more tests with greater diversity. Apart from IEC 61400-21-4 mentioned before, a recently passed operational document "IECRE OD-009 - Power-generating Unit Certification Scheme for Grid

Code Compliance'' can be a useful guide on how to achieve unit certifications using the strategies mentioned above.

Regarding the transferability of results from test benches to be equivalent to tests on the full prototype WTG, the current IEC 61400-21-4 has guidelines. Nacelle Test Benches and Electrical Generation Test Benches (Types A and B) are considered capable of performing all types of tests (i.e. performance, capability, and functionality). Where Type C Converter Test Benches and other types of test benches are currently not considered capable of performing fully equivalent performance tests only. This fact is mainly due to the lack of industry experience with such setups. However, the standard also allows such test benches to be used for demonstrating performance tests if properly compared with the prototype turbine and justified. It can be expected that more experiences will drive further changes in future standards for C&S testing.

As the grid extension and operation all over the world are getting more demanding, the system operators are starting to request validated EMT and harmonic models to be able to investigate and avoid upcoming system challenges e.g. resonance and harmonic stability. C&S testing allows for faster and more accurate procedures to validate models of the WTG components and subsystems, as well as vendor-specific RMS and EMT models. These procedures are mentioned in IEC 61400-21-4 as well as touched upon by different other standards in the IEC 21 and 27 series as well as the ongoing IEEE P2800.2. Furthermore, a new working group from IEC TC88 ''IEC 61400-60 - Validation of computational models'' will work on important aspects of validation procedures for different WTG types.

The results obtained from C&S testing can be used in the future as a basis to validate upcoming tests and validation requirements on EMT and harmonic models, which are currently not standardized. Moreover, these models can be integrated into the HIL system to validate the overall performance of WPP as well as their interoperability. Therefore, there is a strong incentive to transition towards a validation strategy that relies more on subsystem and component testing for the reasons described above. Nonetheless, even though strategies have been written under different frameworks [26], [27], there are still open questions in the industry, for example: Which combination of test setups should be used as part of WTG validation, What is the best role which test bench results play in the overall WTG validation process, How inherent differences between field turbine test setup and test bench can be overcome for validation purposes, among others. By driving more standardization activities and gathering more industry experience, these and other questions will be answered and new potential for testing WTGs in the future will be unlocked.

III. REAL-TIME SIMULATION FOR WIND POWER PLANTS

Real-time simulation (RTS), especially with the use of hardware-in-the-loop (HiL), has become increasingly vital in recent decades as the necessity for thorough verification of control, protection, and communication features has grown across various power system sectors [32]. Specifically, for converter-connected networks, this approach allows for hardware testing and verification at the highest fidelity level through real-time EMT simulation coupled with such hardware. Historically, these simulations primarily served for control and protection hardware verification by component manufacturers or system-level studies like Microgrids, focusing on control, stability performance, or protection studies (e.g., protection for transformers, overhead transmission lines, cables).

In the current wind sector landscape, manufacturers, developers, and other stakeholders conduct the majority of WPP-level simulations in proprietary environments such as PSCAD^{TM}, Power Factory^{TM}, PSSe^{TM}, among others. Due to extensive simulation times resulting from model complexity and computational power limits, especially at the system level, various techniques, such as root mean square (RMS) simulations with higher time steps, omission of communication interfaces and delays, replacement of control &/or protection hardware and software with generic representations, control order-reduction, and equipment simplification, are employed to optimize study time during development and the power plant's lifetime according to application needs. Consequently, the simulated scenarios and behaviors might not fully capture the wind turbine and wind power plant dynamic characteristics during faults and other transient events, making offline simulations the sole reliance, potentially hindering fast decision-making due to their longer processing times.

Challenges also arise in terms of upgradability and interoperability with the use of purely offline simulation tools. Interoperability challenges between different equipment and vendors, considering the connection with HVDC [33], or other active components from various manufacturers (e.g., battery, STATCOM, etc.), can be complex to address using only software offline models. Furthermore, the firmware of the WTG and WPP control may undergo multiple updates during the plant's lifetime to maintain up-to-date functionalities, and constant verification of such updates can be challenging with offline simulation alone.

Wind power plants, being critical infrastructures, demand high security in design and accuracy in the model throughout the operational lifetime. Addressing the standardization of RTS test benches and testing methods for complex systems is crucial, given the growing security requirements, the complexity of WPPs, evolving electric system scenarios, and life cycle operational requirements. This standardization can prove instrumental in resolving the various challenges highlighted earlier.

Currently, working groups, standards, and cooperation projects aim to address and answer a few of these questions related to RTS. CIGRE working group WG C4.56 released the technical brochure ''Electromagnetic transient simulation

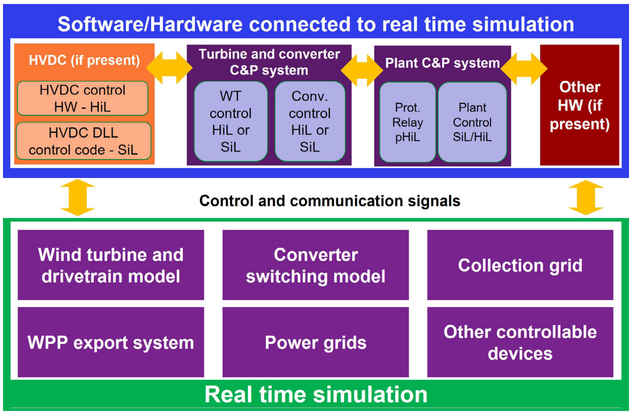


FIGURE 5. Software and Hardware interconnections with real-time simulation environment, adapted from [8].

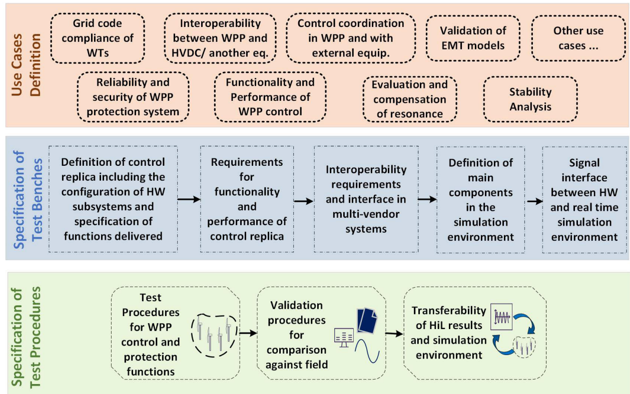


FIGURE 6. Framework for standardization of HiL test benches in WPP simulations, adapted from [8].

models for large-scale system impact studies in power systems having a high penetration of inverter-connected generation" which addressed several aspects of EMT for large systems including RTS [34]. Furthermore, the upcoming standard"IEC TS 61400-21-5: Configuration, functional specification, and validation of hardware-in-the-loop test bench for wind power plants" [35] aims to define uniform specifications of control-hardware-in-the-loop test bench used for testing the integrity and interoperability of large wind power plants connecting with AC or DC grids, applicable both in offshore and onshore contexts. European Union (EU) Horizon Europe project InterOPERA [36], which aims to enable interoperability of multi-vendor multi-terminal HVDC grids that connect large-scale offshore wind power plants to the DC grid.

In Fig. 5, a simple presentation of how Software-and/or Hardware-in-the-loop (SiL/HiL) can be connected to real-time simulation is shown. It can be seen that there are many different control and protection hardware that can be present in a WPP system connected to the grid ranging from the entire turbine and converter control and protection system, the WPP control, HVDC controls in case the WPP is connected in this way, and possibly protection HW for the cable arrays and export cable, among other HW for FACTS devices, etc.

Fig. 6 shows an overview of the definition of RTS test benches, starting from defining use cases or applications to be delivered by the bench, followed by the specification of the test bench in terms of definitions, interface, component, etc., and finally the specification of the test procedures to validate the functionality and transferability of results.

A. TYPES OF REAL-TIME EMT SIMULATION SYSTEMS

Across different guidelines and standards, it is common to see different terminologies that can be often confusing for the reader. Many different equipment can be connected in the loop, and acronyms such as cHiL (control & protection HiL), mHiL (mechanical HiL), and pHiL (power HiL) are used to identify what is included in the test bench, for example, IEC CD 61400-21-4 [26]. Particularly for grid compliance purposes of WPPs and large systems, control & protection hardware-in-the-loop (cHiL) or software-in-the-loop (SiL) are the main types of systems that are tested in the loop with real-time simulators. However, there can be also reasons to include pHiL for larger HW (i.e. converter HW) verification or mHiL for higher fidelity of the models representing the mechanical dynamics.

Other terminologies are constantly emerging in the market, but the ones above are most present in documents and standards, especially related to RTSs. Fig. 7 below is a high-level representation of the different choices one can make for RTS. In the first part, the entire system is represented and then CHiL is shown. The amount of hardware is progressively increased from using only the control hardware to also using electrical power hardware and mechanical hardware. Additionally, one can also connect the Power Plant Controller in Real-Time Systems either in HiL or in SiL. The modeling of the grid can incorporate other types of active devices and their controls, such as HVDC, STATCOM, etc.

B. CONTROL & PROTECTION HARDWARE-IN-THE-LOOP REAL-TIME SIMULATION

Control & Protection cHiL, also commonly known as replicas, can be defined as one or more hardware devices being connected in the loop with a real-time simulator to replicate control and protection functions of the wind turbine, where the simulation signals are fed to the hardware devices, and their responses are fed back to the model running in real-time. The exact definition of the Control Replica is still to be specified by the working group of IEC TS 61400-21-5 and other initiatives, and several definitions regarding configuration, functional specification, and validation of the test bench need to be detailed in the upcoming technical specifications. A Wind Power Plant test bench with cHiL can be composed of WTG converter controls or/and the power plant control.

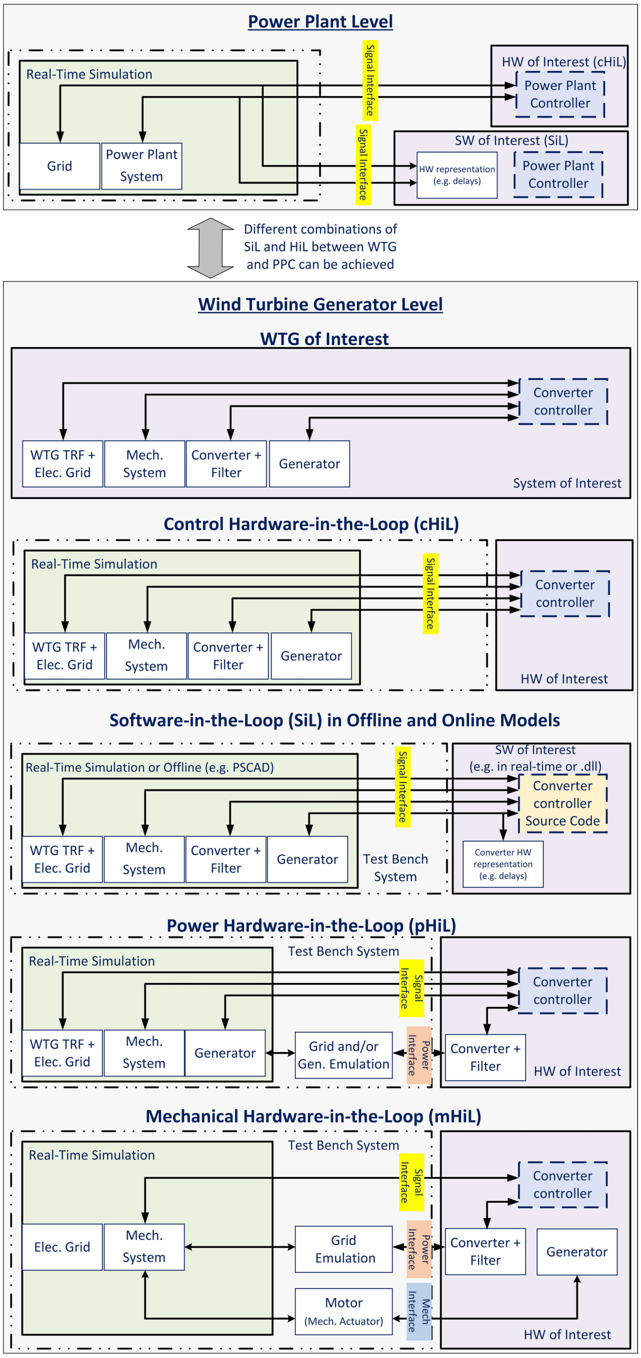


FIGURE 7. Different Types of X-in-the-loop Real-Time Simulation Test Benches for WTG-level and WPP-Level.

C. SOFTWARE-IN-THE-LOOP REAL-TIME SIMULATION

Although HiL testing has been a popular option for verifying the functionality of control systems, software-in-the-loop (SiL) testing is emerging as a viable alternative. SiL testing involves embedding the control system's software in the loop with the real-time simulator rather than using the actual physical proprietary control hardware. While HiL testing has the advantage of testing the control system's hardware and software together, SiL testing has its benefits when it comes to requiring very small to no extra HW apart from the real-time simulator itself. Thus, developing and scaling up large-scale real-time simulation environments becomes simpler and more flexible as the setups can quickly be adapted.

One option for realizing SiL into commercial real-time simulators is using control source codes compiled as black box models and developed using dynamic link libraries (DLLs). A DLL is a collection of small programs that larger programs can load when needed to complete specific tasks. The DLL file contains instructions that help the larger program handle what may not be a core function of the original program. Thus far, a few known experiences in the industry have been performed and are further described in [37] and [38]. However, due to the limitations of DLLs with Windows$^{\text{TM}}$ proprietary software, other solutions are constantly appearing on the market for integrating proprietary control source codes with real-time simulators. These solutions implement different methodologies such as compiling source code into static libraries (*.a) files and using a wrapper code to map inputs/outputs and parameters [39].

The main challenges of SiL testing are integrating proprietary models into real-time simulations in terms of parallel processing and intellectual property protection. Furthermore, accurately modeling the analog and/or digital filters as well as other delays can be a challenge. Although there are some experiences with SiL solutions, the industry still needs to standardize them based on accuracy, functionality, and interfaces.

The next steps for achieving standardization are the definition of testing methods and performance validation of the software on real-time hardware. Additionally, standards also need to address characteristics such as latency/delay and interoperability. Defining these characteristics is crucial to the industry's acceptance and standardization of this type of test bench. Overall, there is a need for a more comprehensive approach to SiL solutions, with a focus on standardization and validation to ensure their reliability and effectiveness.

D. POSSIBLE APPLICATIONS AND FUTURE OUTLOOK

Testing large systems in SiL/HiL real-time test benches will be part of the solutions for the increasing level of complexity and requirements in power systems of the future. The applications shown in Fig. 6 can be utilized for different purposes and at different stages of the life cycle of the WPP:

- **Pre-commissioning Grid Compliance Verification Studies**: SiL and/or HiL can speed up verification in the early studies of a new WPP, contrasting with offline EMT models. It can identify problems and solutions to optimize the existing design, especially in multi-vendor interoperability studies in systems with WPPs in presence of other devices such as HVDC, STATCOMs, synchronous condensers, battery energy storage systems, etc.
- **During Commissioning Grid Compliance Verification and Model Validation**: The same system can be used for model validation and verification during

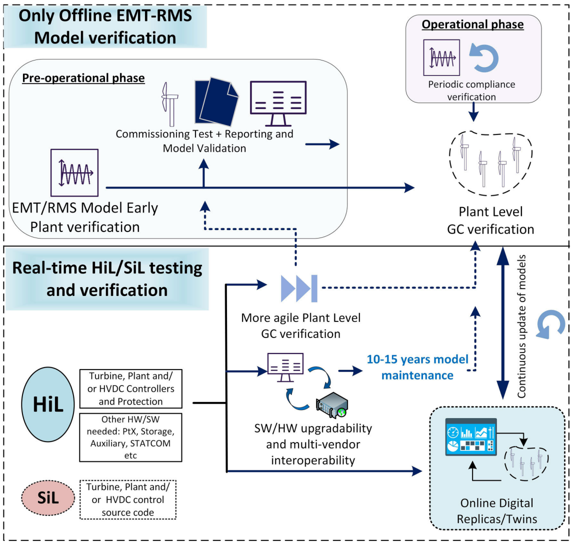


FIGURE 8. Real-Time Simulation solutions for WPPs.

commissioning, comparing, and benchmarking measurements with real-time simulation. The final SiL/HiL model validation can also be performed during this period.

- **Lifetime Assessment and Continuous Model Validation**: These test benches can enhance grid compliance assessments throughout the plant's lifetime. Simulations can be performed faster and more accurately, accounting for updates in the software version and parameters. Additionally, these test benches allow for the use of Digital Twin technologies. Offline EMT models, as shown by [40], can accurately replicate real events on WPPs. Real-time simulation and data feeding to actual hardware and high-fidelity EMT models enable systems for real-time model validation, opening avenues for new applications like real-time stability evaluation, prediction of possible failures, and optimization of operation, among many other use cases.

E. OVERVIEW AND CHALLENGES FOR REAL-TIME SYSTEMS

An overview of RTS solutions for WPP is shown in Fig. 8, where it is possible to observe that can be used to speed up plant-level grid compliance verification, provide better possibilities for upgrading software of the control systems whilst at the same time ensuring interoperability of the multi-vendor simulated system. Finally, it can be seen that such real-time simulators can also be used as digital twins, providing insights and improving decision-making throughout the operational lifetime of the WPP.

Real-time simulation test benches, either by using HiL or SiL, can be a useful tool for ensuring compliance and stability of large systems connected with high shares of converter-connected generation in the future. However, there are still questions and challenges when it comes to standardizing such test benches. In Table (2) below, a few of these challenges and possible solutions through standardization are pointed out.

TABLE 2. High-level challenges in the implementation of RTS test benches [8].

High-Level challenges	Solutions
Aggregation/simplification of components	- Extensive experience already in EMT model can be transferred; - Collection of use cases and customer acceptable accuracy to ensure correct aggregation/simplification;
Upgradability of HW, SW or topology (plant and grid)	- Framework for substitution of digital or physical components; -Periodic benchmarking and adaption of the test benches to allow innovation;
Interoperability requirements between different vendors	- Definition of common time step range where all vendors perform equally; - Definition of maximum latency required by each HW; - Stability analysis with all equipment; - Standardized Control Interfaces;
Simulation and Modeling requirements	- Voltage-Source Model (VSM) or full-switching model approaches; - Definition of model characteristics necessary for each type of study;
Validation Strategies	- Benchmarking WTG model against validated offline EMT models (indirect); - Validation of WPP models against tests during commissioning ; - Validation during operation;

IV. DIGITAL TWINS FOR OPERATIONAL GRID INTEGRATION ASPECTS OF WIND POWER PLANTS

Through the challenges previously presented and rising innovative testing/validation methodologies both at the WTG and WPP levels, new avenues open up for more digitized solutions aiming to assess grid compliance and integration aspects at both WTG and WPP levels. Digitization is at the center of the future energy systems. It is estimated that 90% of the data was created in the last 2 years, according to the International Energy Agency [41]. In light of the extensive amount of data constantly being created and the possibilities of obtaining highly accurate responses in controllable testing environments, the symbiosis between all the data sources is not yet widely explored in this domain. Modern analytical solutions and tools can target problems that are not addressed by the existing tools and provide new possibilities at both the development and operation stages of WTG and WPPs. In this context, a digital twin framework can be able to capture all the existing technologies and create new pathways for optimizing the design and operation of these assets.

Digital Twins (DTs) are digital replicas of an asset that can be used to monitor, predict, or simulate its behavior and performance. The concept of Digital Twins was first developed by NASA and the term was first coined at the beginning of the 2000s by M. Grieves at the University of Michigan [42]. There are many different definitions of Digital Twins which can vary from industry to industry and are especially tied to the complexity and reliability requirements of the systems in place [43], [44]. In the context of power systems, it has been a growing topic of discussion, particularly in transmission and distribution systems [45], [46]. Standards and working groups are also dealing with such a subject such as the ''IEEE Task Force on Digital Twin of Large Scale Power Systems''.

Until now, some research has been done on the topic of DTs of WTGs and WPPs [47], [48], where efficiency and cost-effectiveness in the operation of WTGs and WPPs are improved. However, the focus of applications in the wind energy field is usually not related to grid integration and compliance aspects. Moreover, [49] gives an extended overview of DTs applied to power systems, also considering applications for wind energy. In the context of grid integration, DTs can be used to leverage different data sources and state-of-the-art tools such as historical and current data, RMS and EMT models, highly accurate controllable testing environments, and Artificial Intelligence (AI) models. The DT can present distinct levels of complexity depending on the life cycle stage, application, and set of disciplines that it encompasses. DTs can be used in various stages of the life cycle, from the development to the operational stages. Different modular DTs can be incrementally developed and merged into a more comprehensive representation of the asset. Moreover, as presented in Sections II and III, in power systems and especially for grid compliance and other integration aspects in WTGs and WPPs new concepts for testing and representation are presented. With the symbiosis of hardware and software, a cyber-physical digital twin of the physical object (either the WTG or the WPP) can be represented.

Fig. 9 shows how the different pieces of DTs fit into the physical/digital landscape. The bottom left part shows the scenario where data from the WTG from both the prototype and operational wind power plants are available but not utilized to a large extent. Moving across the x-axis, it is possible to observe that simulation models, component and subsystem testing along with SiL/HiL real-time simulations can leverage the controllable simulation and testing environments to obtain even more knowledge about the desired system. Through the large amounts of data generated in all these environments, it is possible to apply data-driven approaches to speed up analysis and decision-making processes. All of these pieces culminate in the creation of Digital Twins that can assist in grid compliance assessment throughout the entire life-cycle of the assets.

A. DEFINITIONS OF DIFFERENT TYPES OF DIGITAL TWINS - FOCUS ON GRID INTEGRATION

According to recent definitions presented in [47], Digital Twin technology can be split into six different categories of use cases, namely: 0-standalone, 1-descriptive, 2-diagnostic, 3-predictive, 4-prescriptive, and 5-autonomous as shown in Fig.(10). In some other definitions, digital representations are often divided into three different categories: 1-Digital Models, 2-Digital Shadows, and 3-Digital Twins [50]. Such classifications can often be confusing when defining types of models. Therefore, for grid integration aspects where several models are already used, it is favorable to opt for the first definition where use cases are at the center of what the digital twin is used for, instead of classifying it using the second definition.

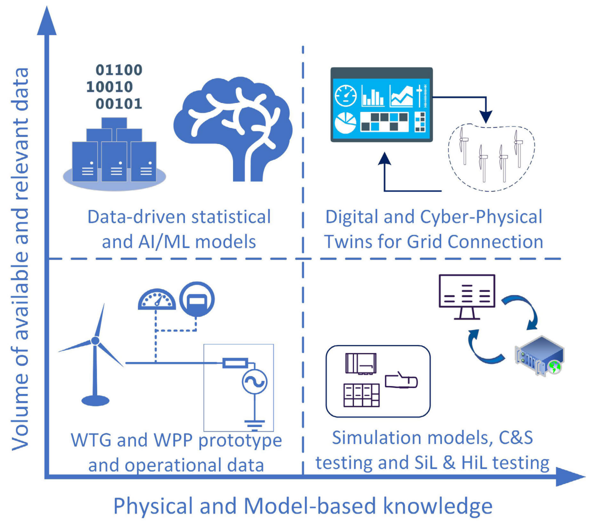


FIGURE 9. Digital Twin summarized framework.

In this context, categories 0 and 1 are well covered by existing models often developed by OEMs and WPP developers for grid compliance and stability evaluation. At early design stages, different models are produced based on prior knowledge and existing experience, without often the presence of actual physical objects. Such models can be for example Electromagnetic Transient models (EMT), Root-Mean Square (RMS), Frequency Domain Models (FDM) often also referred to as small-signal stability models, etc. During later stages of the design, such models can be validated by the OEM through Component & Subsystem and/or actual Prototype Turbine Testing. Upon commissioning and operation of a new WPP, plant models can also be validated for setpoint changes and faults existing in the system. Experiences with validation of EMT models during operation have been recently shown in [40], where such methodologies and procedures are still in the early stages of the industry.

That means that categories 2, 3, 4, and 5 are still not widely applied in grid integration aspects of WTGs and WPPs design and operation, as in other sectors related to mechanical engineering, loads, etc. As the numbers get higher for the DT classification in Fig. 10, the complexity and autonomy of the DT increase. The data flow from the physical object to the digital object becomes more automatic and consequently, the decision-making process as a result of the DT processing becomes more autonomous. As WPPs are critical and complex infrastructures, the autonomous category of DTs is usually very challenging in terms of acceptance. A more realistic view of near-future DTs for WTGs and WPPs is

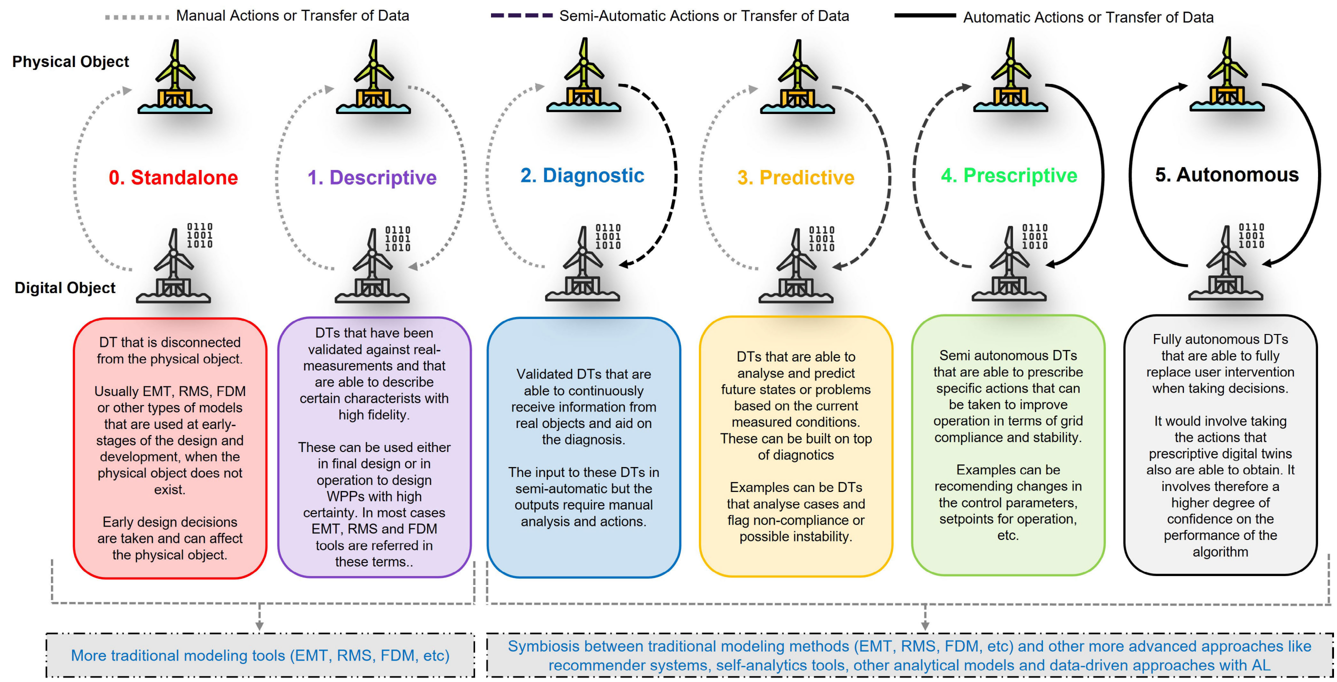


FIGURE 10. Six categories of digital twins based on usability.

category 4 prescriptive DTs where a degree of engineering judgment is embedded into the decision-making process to ensure the reliable operation of DTs.

B. APPLICATIONS FOR GRID INTEGRATION OF WIND POWER PLANTS

In terms of applications, different use cases can be mapped under the overarching Fig. 11. It is possible to observe in the figure that through the design stage, models and data can be used to transfer the knowledge to the operational stages where information can be transferred back to the design and drive changes in SW or HW to optimize the overall grid compliance performance of the turbine. On the different design stages, due to the modular and incremental approach of existing wind turbine families, DTs can also be used to identify trends and patterns from past and current turbine developments, improving the design characteristics of the next generations. During operation, online grid compliance assessment, prediction of evolving grid conditions, etc. The opportunities for Digital Twins present themselves, particularly in closing the gap between design and operation, which is currently not systematically performed in operational plants.

1) IMPROVEMENT OF DESIGN FOR CURRENT AND NEXT WTGS AND WPPS

During design, two types of Digital Twins are applicable. For improvement of design aspects of WTGs and WPPs currently in design, digital models along with C&S and real-time testing can be used to de-risk the design, as presented in Sections II and III, where systematic standardization is also taking place.

Upon the design transition from one turbine type to the next in the same family, often knowledge from the previous products can be used to speed up processes and the design of the next WTG. This aspect is often missed in how Digital Twin frameworks can also aid in the improvement of design for the next generation of equipment. From an OEM point of view, this aspect is particularly valuable and needs to be also mapped into the framework. Improvement of Grid Compliance and Stability aspects of next-generation turbines can be considerably beneficial when correct information is extracted by DTs during operation. Furthermore, not only can software be changed, but hardware can be redesigned if proper insights are given in a timely manner. Some strategies for transferability of results as the one mentioned by IEC 61400-21-4 can serve as a basis for the transferability of the results of operational DTs.

2) IMPROVEMENT OF RELIABILITY DURING OPERATION

Operational aspects are where the Digital Twin paradigm can truly make a difference. During operation, WTGs, produced and tested on a prototype level by the OEM, get operated in different grid and environmental scenarios. It is therefore important to monitor these assets throughout operation to ensure that they remain stable and compliant with local regulations.

On one hand, it is possible to use traditional modeling techniques like EMT, RMS, or FDM models to perform periodic studies and assess different connection aspects. On the other hand, such models are limited in the sense they cannot extract every single information of the assets during operation. Therefore, the analysis can be augmented by more advanced and non-traditional approaches like recommender

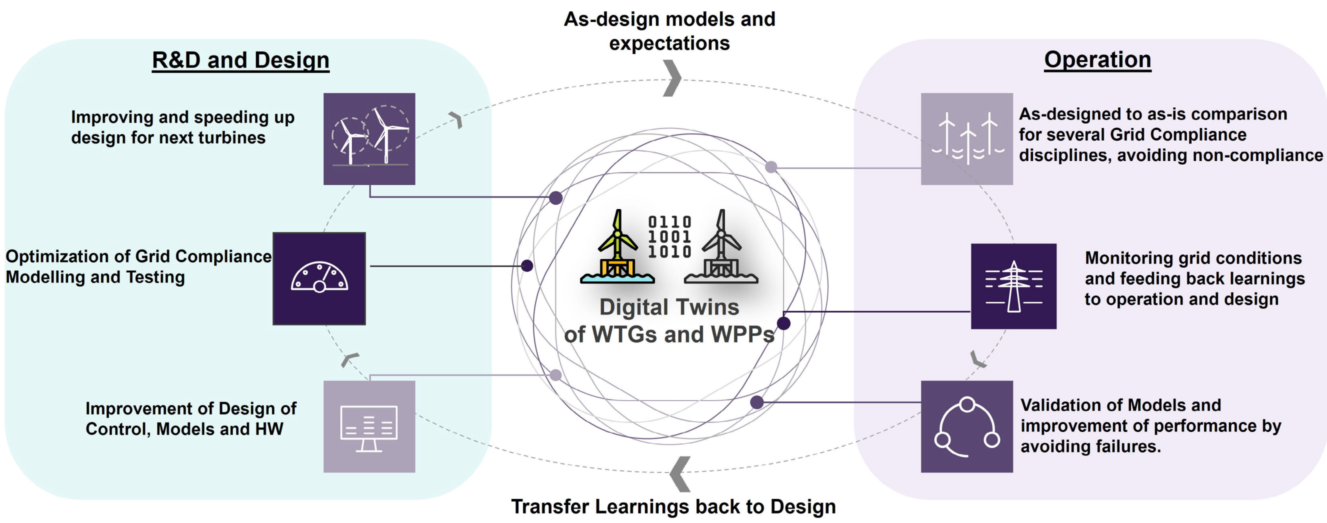


FIGURE 11. Digital Twin use cases for grid compliance and integration aspects.

systems, self-analytics tools, advanced analytical models, and ultimately data-driven approaches.

Examples of that can be:

- **As-designed to as-is comparison**: During design, many tests for different disciplines of grid compliance are performed. Such expectations can be translated in the form of physics-based or data-driven models so that comparisons are performed on an ongoing basis. Any non-compliant scenario can be further analyzed and mitigated accordingly.
- **Monitoring Grid Conditions**: As grid conditions are becoming more challenging with the increasing penetration of converter-based generation, it is of great importance to monitor the grid conditions to avoid maloperation of the WTGs. Different analytical and data-driven approaches can monitor grid conditions to alert and possibly autonomously change control parameters. An example of that could be changing parameters in case the grid gets weaker after a disturbance in the nearby grid.
- **Validation of Models and Improvement of Performance**: Validation of EMT models and other types of models is of special interest during operation, as such models, once validated, can be used for plant-level studies during operation with updated grid conditions provided by the TSO [40]. An example of a successful application of DT could be an automatic flow of information from different sites to validate models, where reports and self-analytics tools are implemented to identify possible mismatches.

C. VALIDATION OF DATA-DRIVEN SOLUTIONS

In the context of DTs, AI and ML models play a vital role, but it is essential to establish benchmarks for their effectiveness. Currently, there is uncertainty about which aspects should be addressed by AI and ML models and how to evaluate their performance. Thus, the key consideration for DT lies in its long-term nature, relying on sustained data acquisition, analytics, observations, and robust operational expertise gained through the application of data-assisted methods.

As WTGs and WPPs are critical infrastructures, the industry is naturally very sensitive in relying on data-driven solutions for decision-making processes. However, such methods can reach results that are unattainable by current modeling techniques used (e.g. EMT, RMS, FDM, and other tools.). Therefore, it is crucial that acceptance in the industry continues to be exercised by the deployment of practical examples of how tools like Machine Learning can be useful in grid integration aspects. It is important to rely always on the physics and explainability of data-driven models [51], [52]. Therefore, constant validation and verification against physics-based models and real measurements are crucial to obtaining performance guarantees and reliability by using data-driven models.

V. FUTURE WORK AND OUTLOOK

As presented in Sections II and III, the wind industry is changing the paradigm of testing and validation of WTGs and WPPs towards a modular approach that is able to faithfully represent the performance characteristics necessary for assessing grid compliance, stability, interoperability, and other grid integration aspects. Furthermore, a new path towards more advanced approaches is described in Section IV, where the Digital Twin paradigm is applied to grid integration aspects, where examples and use cases are defined. Below, some discussions on the future work and future outlook on how these tools can all work together is presented.

A. FUTURE WORK FOR THE INDUSTRY

1) C&S TESTING FOR WTGS

The standardization and acceptance of Component & Subsystem testing are advanced in the wind industry. Therefore, the migration from full prototype WTG to C&S testing

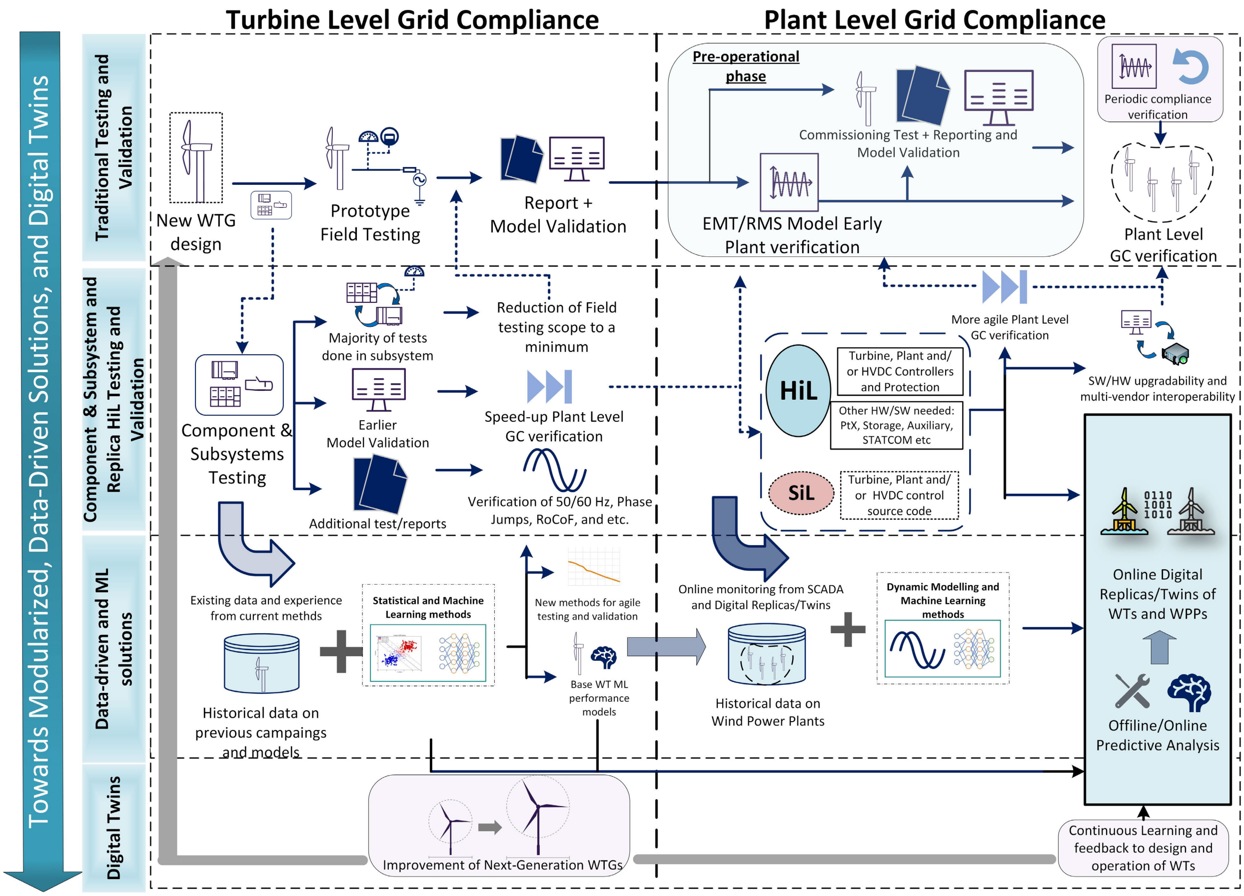


FIGURE 12. Overall framework involving C&S testing, HiL, SiL, and Digital Twins for WT and WPP Grid Compliance Assessment, adapted from [8].

of functionality, capability, and performance of electrical characteristics for WTGs is being adopted by many OEMs and testing institutes. However, the industry still seeks to reduce further the number of components that are deemed necessary for faithfully representing the characteristics when compared to the full prototype WTG. Next-generation test benches with generator and grid emulators have been presented and are currently being commissioned and tested. Nonetheless, additional industrial experiences are desired so that wide acceptance of the performance of these test rigs is achieved.

Particularly, the comparisons against field prototype testing are desired for wide acceptance, but may not always be available or achievable due to inherent changes between the test bench and the turbine on site. Therefore, other indirect transferability strategies are being proposed which involve modeling techniques, etc. Finally, topics such as the transferability of results and conclusions to the next turbine in the WTG family have been discussed by IEC 61400-21-4, but still need to be further matured.

2) RTS SIL AND HIL FOR WIND POWER PLANTS

When it comes to standardization for Real-Time Simulation with Software-/Hardware-in-the-Loop solutions for Wind Power Plants, more experience with such solutions is needed. Particularly, clear definitions of functionality and limitations of each solution must be clearly defined. Projects like InterOPERA and standards like IEC 61400-21-5 are a few of the initiatives that aim to answer some of these questions in the following years. Nonetheless, there are clear needs from the industry, especially in connection with HVDC and other active devices where interoperability must be assessed.

3) FUTURE PERSPECTIVES FOR DIGITAL TWINS

Regarding Digital Twins, the industry is still very immature in the application of such methodologies for improvement of design and operation. This framework can be valuable in uncovering use cases and ways of performing constant validation, verification, and analysis for grid connection that thus far have not been thoroughly explored in the industry. Moving forward, clear use cases and applications need to be defined, where practical experiences are used as a foundation. The authors propose that for future work, the industry can get together to define how such a framework can be done and the benefits of encapsulating several different use cases under the Digital Twin umbrella.

B. OUTLOOK OF SOLUTIONS

In Fig. 12, a general overview containing all the methodologies is presented. In the first row, the traditional methods for grid compliance testing and validation at both the WT and WPP levels are presented. It can be seen that on the second row, the industry is showing the need for faster and more reliable methodologies at both levels and therefore C&S and SiL/HiL RTS test benches are presented as feasible complementary solutions moving forward. Finally, newer elements can be observed in the last row, where a need is mapped for more data-driven solutions leveraging all the knowledge and data constantly produced by all proven traditional methods. In the end, by applying different combinations of such methodologies, results yet unforeseen can be achieved. Furthermore, in order for the strategies to be successful, it is important that the industry comes together in terms of standardization, validation, and acceptance strategies.

VI. CONCLUSION

In conclusion, the paper offers an overview of the hurdles and potential resolutions in speeding up grid integration for wind turbines and wind power plants. The insights presented can also be extended to other renewable generation systems like PV systems, hybrid power plants, Power-to-X systems, or other converter-based generation that also need to be integrated into the system such as HVDC, Battery Storage, STATCOMS, etc. The study underscores the ongoing necessity to consistently review and revise standards and regulations to keep pace with the fast technological advancements in the wind sector.

Testing strategies for components and subsystems are maturing as manufacturers, developers, and TSOs progressively increase the experience and confidence in the precision and applicability of results from such test benches. In parallel, although SiL/HiL RTS test benches are widely employed across various sectors of the power system industry, standardization in the wind sector is still pending concerning validation, transferability, and interoperability strategies. This holds particular significance, given that these test benches, at a system level, typically comprise multi-vendor hardware and software (e.g., Energy Islands, HVDC-connected Offshore WPPs, etc.). For the overall success of current and future strategies, updated model validation requirements will also prove crucial in garnering acceptance and ensuring stable operation under challenging criteria.

Finally, as testing and simulation environments become increasingly flexible and controllable, additional modern paradigms such as Digital Twin leveraging Artificial Intelligence/Machine Learning, self-analytics tools, recommender systems, etc, can be integrated into the future trajectories of the wind industry, with focus on grid integration. This integration can leverage existing tools, vast amounts of data, and industry experience. However, for widespread acceptance across industries, sectors, and countries, further standardization will be imperative in this evolving landscape.

LEGAL DISCLAIMER

Figures and values presented in this paper should not be used to judge the performance of Siemens Gamesa Renewable Energy technology as they are solely presented for demonstration purposes. Any opinions or analyses contained in this paper are the opinions of the authors and are not necessarily the same as those of Siemens Gamesa Renewable Energy.

REFERENCES

[1] S. D. Ahmed, F. S. M. Al-Ismail, M. Shafiullah, F. A. Al-Sulaiman, and I. M. El-Amin, "Grid integration challenges of wind energy: A review," *IEEE Access*, vol. 8, pp. 10857–10878, 2020.

[2] A. Follo, O. Saborío-Romano, E. Tedeschi, and N. A. Cutululis, "Challenges in all-DC offshore wind power plants," *Energies*, vol. 14, no. 19, p. 6057, Sep. 2021.

[3] L. Christensen, I. Srypalle, H. Kocewiak, and F. Santjer, "Overview, status and outline of the new standards series-IEC 61400–21," in *Proc. 14th Wind Integr. Workshop*, 2015.

[4] B. Andresen, P. E. Sørensen, F. Martin, T. Dreyer, K. Ntovolos, H. Kocewiak, and F. B. Nielsen, "IEC TC 88 wind power generation standards in relation to grid conneciton requirements," in *Proc. 18th Wind Integr. Workshop*, 2019.

[5] R. Villena-Ruiz, A. Honrubia-Escribano, F. Jiménez-Buendía, J. L. Sosa-Avendaño, S. Frahmc, P. Gartmann, J. Fortmann, P. E. Sørensen, and E. Gómez-Lázaro, "Extensive model validation for generic IEC 61400–27–1 wind turbine models," *Int. J. Elect. Power Energy Syst.*, vol. 134, Jan. 2022, Art. no. 107331.

[6] P. Ghimire, I. Szczesny, R. Sharma, F. Martin, and P. Mahat, "Use of full-order electro-magnetic transient models for grid compliance assessment of wind turbine—Part 1," in *Proc. 17th Wind Integr. Workshop*, Stockholm, Sweden, 2018.

[7] G. M. G. Guerreiro, R. Sharma, F. Martin, P. Ghimire, and G. Yang, "Concerning short-circuit current contribution challenges of large-scale full-converter based wind power plants," *IEEE Access*, vol. 11, pp. 64141–64159, 2023.

[8] G. M. G. Guerreiro, F. Martin, G. Yang, and B. Andresen, "New pathways to future grid compliance for wind power plants," in *Proc. 21st Wind Sol. Integr. Workshop*, Hague, The Netherlands, Oct. 2022, pp. 115–121. [Online]. Available: https://digital-library.theiet.org/content/conferences/10.1049/icp.2022.2745

[9] U. Jassmann, A. Frehn, H. Röttgers, F. Santjer, C. Mehler, T. Beißel, L. Kaven, D. von den Hoff, R. Frühmann, S. Azarian, M. Neshati, G. Quistorf, A. Zuga, M. Brennecke, T. Jersch, and R. Schelenz, "CertBench: Conclusions from the comparison of certification results derived on system test benches and in the field," *Forschung Ingenieurwesen*, vol. 85, no. 2, pp. 353–371, Jun. 2021.

[10] T. Siepker, T. Dreyer, B. Nedjar, P. Ghimire, F. Martin, S. Azarian, T. Jersch, S. Khan, and G. Quistorf, "Comparison of under-voltage-ride-through measurements between field tests and DyNaLab grid simulator tests of the Siemens Gamesa d8 direct-drive wind turbine," in *Proc. 18th Wind Integr. Workshop*, Dublin, Ireland, Oct. 2019.

[11] P. Borowski, G. Quistorf, and T. Jersch, "PQ4wind—A novel test bench for component-level wind turbine converter testing," in *Proc. 21st Wind Sol. Integr. Workshop (WIW)*, Oct. 2022, pp. 466–472. [Online]. Available: https://digital-library.theiet.org/content/conferences/10.1049/icp.2022.2813

[12] O. Curran, G. M. G. Guerreiro, S. Azarian, F. Martin, and T. Dreyer, "WTG manufacturer's experience with subsystem and component validation for wind turbines," in *Proc. 21st Wind Sol. Integr. Workshop (WIW)*, vol. 2022, Oct. 2022, pp. 458–465. [Online]. Available: https://digital-library.theiet.org/content/conferences/10.1049/icp.2022.2812

[13] Z. Li, X. Wang, F. Zhao, S. Munk-Nielsen, M. Geske, R. Grune, D. B. R. Andersen, and M. G. Rodriguez, "Power-hardware design and topologies of converter-based grid emulators for wind turbines," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 11, no. 5, pp. 5001–5017, Oct. 2023.

[14] F. Hans, G. Curioni, T. Jersch, G. Quistorf, M. Ruben, A. Müller, C. Wessels, C. Fenselau, I. Prima, and J. Lehmann, "Towards full electrical certification of wind turbines on test benches—Experiences gained from the HiL-GridCoP project," in *Proc. 21st Wind Sol. Integr. Workshop (WIW)*, Oct. 2022, pp. 122–129.

[15] F. Hans, G. Quistorf, E. Nippold, T. Jersch, G. Chekavskyy, G. Bujak, P. Sobanski, and J. Eckerle, "Mobil-Grid-CoP—A new approach for grid compliance testing of multimegawatt wind turbines in field," in *Proc. 22nd Wind Sol. Integr. Workshop (WIW)*, Sep. 2023, pp. 50–57.

[16] M. Neshati, S. Azarian, O. Curran, R. R. Pillai, J. Due, E. Guest, N. M. A. Freire, T. Dreyer, and F. Martin, "Grid connection testing of wind energy converters with medium voltage generator- and grid emulation on a multi-megawatt power-hardware-in-the-loop test rig," in *Proc. 22nd Wind Sol. Integr. Workshop (WIW)*, Sep. 2023, pp. 451–460.

[17] V. Gevorgian, P. Koralewicz, S. Shah, W. Yan, R. Wallen, and E. Mendiola, "Testing GFM and GFL inverters operating with synchronous condensers," in *Proc. IEEE Power Energy Soc. Gen. Meeting (PESGM)*, Jul. 2023, pp. 1–5.

[18] T. Stehly, P. Beiter, and P. Duffy, "2019 cost of wind energy review," Nat. Renew. Energy Lab., Golden, CO, USA, Tech. Rep. NREL/TP-5000-78471, Dec, 2019.

[19] CurrentNewsUK. (2020). *Blackout Investigation: What Went Wrong at Hornsea One and Little Barford*. Accessed: Jan. 11, 2024. [Online]. Available: https://www.current-news.co.uk/blackout-investigation-what-went-wrong-at-hornsea-one-and-little-barford/

[20] PledgeTimes. (2023). *ONS Concludes That the Cause of the Blackout Was Failure in Wind and Solar Plants*. Accessed: Jan. 11, 2024. [Online]. Available: https://pledgetimes.com/ons-concludes-that-the-cause-of-the-blackout-was-failure-in-wind-and-solar-plants/

[21] NASA. *NASA SSRI Knowledge Base—Resources for Smallsat Success—Subsystem Testing—Electrical Power*. Accessed: Sep. 5, 2022. [Online]. Available: https://s3vi.ndc.nasa.gov/ssri-kb/topics/50/

[22] D. P. Stoten, J.-Y. Tu, G. Li, and K. Koganezawa, "Robotic subsystem testing using an adaptively controlled dynamically substructured framework," *IFAC Proc. Volumes*, vol. 42, no. 16, pp. 98–103, 2009. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1474667015306194

[23] M. Johnston, E. Leonard, P. Monsere, and M. Riefe, "Vehicle brake performance assessment using subsystem testing and modeling," in *Proc. SAE Tech. Paper Ser.*, Apr. 2005, doi: 10.4271/2005-01-0791.

[24] *Testing and Commissioning of VSC HVDC Systems*, document CIGRE B4.63, 2017.

[25] T. Strasser et al., "Towards holistic power distribution system validation and testing—An overview and discussion of different possibilities," in *Proc. CIGRE*, vol. 134, no. 1, 2016, pp. 71–77.

[26] *IEC CD 61400-21 Wind Energy Generation Systems—Part 21-4: Wind Turbine Components and Subsystems*, document 88/889/CD, 2023.

[27] *Technical Guidelines for Power Generating Units—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—Rev 26*, FGW, Asheville, NC, USA, 2022.

[28] *Wind Energy Generation Systems—Part 21–1: Measurement and Assessment of Electrical Characteristics—Wind Turbines*, document IEC 61400-21, 2019.

[29] *Wind Energy Generation Systems—Part 21–2: Measurement and Assessment of Electrical Characteristics—Wind Power Plants*, document IEC 61400-21, IEC, 2023.

[30] *Wind Energy Generation Systems—Part 21–3: Measurement and Assessment of Electrical Characteristics—Wind Turbine Harmonic Model and its Application*, document IEC 61400-21, 2021.

[31] IEC. *IEC Study Committee SC 8A—Grid Integration of Renewable Energy Generation*. Accessed: Jan. 29, 2024. [Online]. Available: https://www.iec.ch/dyn/www/f?p=103:7:704141841972463::FSP_ORG_ID,FSP_LANG_ID:10072,25

[32] F. Mihalič, M. Truntič, and A. Hren, "Hardware-in-the-loop simulations: A historical overview of engineering challenges," *Electronics*, vol. 11, no. 15, p. 2462, Aug. 2022. [Online]. Available: https://www.mdpi.com/2079-9292/11/15/2462

[33] Ørsted. *Ørsted Announces HVDC Transmission System for Hornsea 3 Offshore Wind Farm*. Accessed: Sep. 13, 2022. [Online]. Available: https://orsted.co.uk/media/newsroom/news/2022/07/hornsea-3-hvdc

[34] *Electromagnetic Transient Simulation Models for Large-scale System Impact Studies in Power Systems Having a High Penetration of Inverter-Connected Generation*, document WG C4.56-TB881, CIGRE, 2022.

[35] *Wind Energy Generation Systems—Part 21-5: Configuration, Functional Specification, and Validation of Hardware-in-the-Loop Test Bench for Wind Power Plants*, document IEC TS 61400-21, IEC, 2024.

[36] *Successful Kick-off of InterOPERA Horizon Europe Offshore Electricity Grids Project*. Accessed: Apr. 12, 2023. [Online]. Available: https://cinea.ec.europa.eu/news-events/news/successful-kick-interopera-horizon-europe-offshore-electricity-grids-project-2023-01-20_en

[37] *Development of a Digital Twin Simulation Wind Turbine and Power Plant Controller Model in RSCAD, Based on Microsoft Windows Dynamic-Link Library Code Integration By Using IntervalZero*. Accessed: Jun. 30, 2022. [Online]. Available: https://knowledge.rtds.com/hc/en-us/articles/5129723975191-EPISODE-3

[38] OPAL-RT. *Massively Accelerate PSCAD Models, Including Manufacturer Real Code Controllers, With HYPERSIM*. Accessed: Jun. 30, 2022. [Online]. Available: https://www.opal-rt.com/learning-journey/

[39] RTDS. *GTSOC V2: Multi-Function Auxiliary Simulation Hardware*. Accessed: Jan. 29, 2024. [Online]. Available: https://knowledge.rtds.com/hc/en-us/articles/7817390306199-GTSOC-V2-Multi-Function-Auxiliary-Simulation-Hardware

[40] G. M. G. Guerreiro, R. Sharma, F. Martin, and G. Yang, "EMT model validation of an offshore wind power plant with SGRE DD wind turbines under real power system events," in *Proc. 22nd Wind Sol. Integr. Workshop (WIW)*, Sep. 2023, pp. 44–49.

[41] IEA. (2017). *Digitalisation and Energy*. Accessed: Sep. 11, 2022. [Online]. Available: https://www.iea.org/reports/digitalisation-and-energy

[42] M. Grieves, "Digital twin: Manufacturing excellence through virtual factory replication," White Paper, 2015.

[43] D. Hartmann, M. Herz, M. Paffrath, J. Rommes, T. Tamarozzi, H. V. der Auweraer, and U. Wever, *12 Model Order Reduction and Digital Twins*. Berlin, Germany: De Gruyter, 2020, pp. 379–430, doi: 10.1515/9783110499001-012.

[44] F. Tao, H. Zhang, A. Liu, and A. Y. C. Nee, "Digital twin in industry: State-of-the-art," *IEEE Trans. Ind. Informat.*, vol. 15, no. 4, pp. 2405–2415, Apr. 2019.

[45] L. Fan, Z. Miao, S. Shah, P. Koralewicz, V. Gevorgian, and J. Fu, "Data-driven dynamic modeling in power systems: A fresh look on inverter-based resource modeling," *IEEE Power Energy Mag.*, vol. 20, no. 3, pp. 64–76, May 2022.

[46] P. Palensky, M. Cvetkovic, D. Gusain, and A. Joseph, "Digital twins and their use in future power systems [version 2; peer review: 2 approved]," *Digit. Twin Open Res. Platform*, vol. 1, no. 4, 2022.

[47] F. Stadtmann et al., "Digital twins in wind energy: Emerging technologies and industry-informed future directions," *IEEE Access*, vol. 11, pp. 110762–110795, 2023.

[48] M. Fahim, V. Sharma, T.-V. Cao, B. Canberk, and T. Q. Duong, "Machine learning-based digital twin for predictive modeling in wind turbines," *IEEE Access*, vol. 10, pp. 14184–14194, 2022.

[49] Z. Song, C. M. Hackl, A. Anand, A. Thommessen, J. Petzschmann, O. Kamel, R. Braunbehrens, A. Kaifel, C. Roos, and S. Hauptmann, "Digital twins for the future power system: An overview and a future perspective," *Sustainability*, vol. 15, no. 6, p. 5259, Mar. 2023. [Online]. Available: https://www.mdpi.com/2071-1050/15/6/5259

[50] A. Fuller, Z. Fan, C. Day, and C. Barlow, "Digital twin: Enabling technologies, challenges and open research," *IEEE Access*, vol. 8, pp. 108952–108971, 2020.

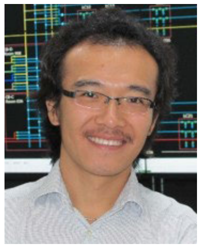
[51] S. Chatzivasileiadis, A. Venzke, J. Stiasny, and G. Misyris, "Machine learning in power systems: Is it time to trust it?" *IEEE Power Energy Mag.*, vol. 20, no. 3, pp. 32–41, May 2022.

[52] J. Wang, P. Pinson, S. Chatzivasileiadis, M. Panteli, G. Strbac, and V. Terzija, "On machine learning-based techniques for future sustainable and resilient energy systems," *IEEE Trans. Sustain. Energy*, vol. 14, no. 2, pp. 1230–1243, Apr. 2023.

GABRIEL MIGUEL GOMES GUERREIRO (Member, IEEE) received the Diploma (Engineering) degree in electrical engineering from the Federal University of Itajubá (UNIFEI), Brazil, in 2016, and the M.Sc. degree in electrical power engineering from the KTH Royal Institute of Technology, Sweden, in 2020. He is currently pursuing the Industrial Ph.D. (Marie Curie) degree with Siemens Gamesa Renewable Energy and the Technical University of Denmark (DTU). He was a Protection & Control Commissioning Engineer in Brazil, between 2017 and 2018, and a Research and Development Protection Engineer with Hitachi Energy, between 2019 and 2021. His Ph.D. degree is funded by the H2020 Program through InnoCyPES MSCA ITN. Since 2022, he has been an active member of IEC TC88 under the 61400-21 series with a special focus on 21-5 for real-time systems. His research interests include modeling in power electronics-dominated power systems, protection, control, power system stability, data-driven methodologies, and machine learning.

FRANK MARTIN received the M.Sc. degree in renewable energies/wind engineering from the University of Kassel, Germany, in 2007. He has been a Senior Key Expert in the grid connection area with Siemens Gamesa Renewable Energy A/S, since 2010. He worked for three years with Germanischer Lloyed Industrial Services as an Expert of grid code compliance and in the area of electrical certification. His research interests include the area of grid codes and requirements for wind turbines and wind power plants, where he supports SGRE's product and technology development. Since 2023, he has been the Chair of IEC TC8 SC8A and is active in international grid code and standardization work.

THOMAS DREYER received the Dipl.-Ing. (FH) degree in electrical engineering (field of study energy technology) from the Kiel University of Applied Science, Germany, in 1999. He has been a Senior Key Expert in the grid connection area with Siemens Gamesa Renewable Energy GmbH & Co. KG, since 2008. From 1999 to 2008, he was a Test Engineer with Windtest Kaiser Wilhelm Koog (now DNV), where he was involved in various tests at wind turbines due to a wide range of interests, such as power curve measurement, wind potential measurements, and site assessments; and later in the area of grid connection and as an Expert in the newly emerging voltage dip test ''LV-FRT'' for assessing the electrical compliance of wind turbines. With this area of expertise, he supports SGRE's product and technology development and is also involved in several national (DKE and FGW) and international (IEC TC 88 and IECRE WG 003) standardization working groups and research projects (e.g., grid-harmony).



GUANGYA YANG (Senior Member, IEEE) received the Ph.D. degree from The University of Queensland, Australia, in 2008. He joined the Technical University of Denmark. From 2020 to 2021, he was a full-time Specialist in electrical design, control, and protection of large offshore wind farms with Ørsted. He is currently an Associate Professor with the Technical University of Denmark. His current research interests include the stability and protection of converter-based power systems, with an emphasis on offshore wind applications. He is the Convener of IEC61400-21-5 on configuration, functional specification, and validation of hardware-in-the-loop test bench for wind power plants. In addition, he is also the Coordinator of the H2020 Marie Curie Innovative Training Network Project Innovative Tools for Cyber-Physical Energy Systems (InnoCyPES) and the Lead Editor of the Power and Energy Society Section in IEEE Access.

BJÖRN ANDRESEN received the B.Sc. (EE) degree in Kiel, Germany, in 1996, the M.Sc. (EE) degree from Aalborg University, Denmark, in 1998, and the E.B.A. degree from the VIA University College, in 2009. He held positions with Vestas Wind Systems, from 1998 to 2003, Gamesa Wind Engineering, from 2003 to 2008, and Siemens Wind Power, from 2008 to 2015. Since March 2015, he has been with Aarhus University as a Professor and the Head of the Electrical Energy Technology Section, focusing on electrical energy transition, renewable power generation, grid integration, power systems, and power quality. He is also involved in various roles, including convening the IEC 61400-21 series, participating in the IEC TC120 for energy storage systems and serving as an Expert Member for the IEC TC 8 for Grid Integration Requirements. Additionally, he leads the Danish Standard subcommittee S508, participates in the ST-Aarhus University Academic Council and serves on the Council for Electricity and Gas Security under the Ministry of Business and Growth. Furthermore, he is an appointed Expert Member of the UN Regarding the Green Energy Transition.