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New Pathways to Future Grid Compliance for Wind Power Plants

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Abstract

Over the last decade, the rapid growth of wind power is driving an increase of efforts in defining the frameworks and rules for the connection of wind power plants (WPPs) through the grid codes and standards, making testing/validation more demanding and complex for wind turbine (WT) manufacturers and WPP developers. Traditionally, WT manufacturers carry out grid compliance tests at full-scale prototype turbines whereas WPP developers and Transmission System Operators (TSOs) mainly perform studies for new WPPs based on offline RMS and EMT simulations. Until now, these strategies have been sufficient for ensuring grid compliance of WTs and WPPs, however moving forward the wind sector needs new testing methods to meet the increasing WT capacity, WPP complexity, and deployment pace to achieve society's desired sustainability targets. In this paper, the emerging strategies that target these challenges are presented as: a) subsystems and component testing of WTs specified in IEC 61400-21-4; b) - hardware-in-the-loop (HiL) real time simulation for WT/WPP control and protection appraisals (future 61400-21-5). Finally, a future outlook is given on the importance of addressing model validation and how these strategies can be complemented with other modern analytical tools such as artificial intelligence/machine learning, data-driven dynamic modelling, digital twin technology, and software-in-the-loop (SiL) real time simulation.

1 Introduction

The wind industry is growing rapidly in many different places of the world as a response to the growing concerns of carbon emissions and the race to reach net-zero emissions. Current outlooks predict that in order to reach the target emissions by 2050, wind capacity additions must be around 310 GW onshore and 80 GW offshore annually until 2030 [1]. Although offshore capacity increase is mainly concentrated in Europe and China, other countries and continents have started building their first large-scale offshore wind power plants which will be operational in the coming years.

From a grid compliance perspective, the increasing penetration of wind power, specially large-scale offshore wind power plants connected through long AC or DC cables to shore, is forcing TSOs to define more stringent frameworks and rules for the connection of wind power plants (WPPs), making testing/validation more demanding and complex for manufacturers and developers. In addition to that, the industry is also observing the need to address interoperability between multi-vendor equipment and establish additional frameworks for deployment of ancillary services (e.g. black start, inertia provision, frequency reserves, grid forming capabilities, etc) by such renewable sources, which brings further complexity to future testing and validation strategies of turbines and power plants.

Throughout the last decades, WT manufacturers have matured the turbine testing methodologies through various field tests and currently carry out the majority of grid compliance tests in the field using full-scale prototype turbines tests. As turbines get larger to reduce the Levelized-Cost-of-Energy (LCOE) and overall costs of wind power plants, such tests can last for longer periods due to availability of proper test equipment and test site impediments due to growing sizes. The problems are aggravated by the increasingly testing scopes and susceptibility to weather conditions on site, causing test campaigns to last for long periods. Moreover, due to the current testing equipment and site limitations, certain grid compliance features cannot be tested at all by the manufacturers, resulting in uncertainties regarding the turbine's behaviors under some grid conditions.

From another perspective, to ensure that the WPPs are compliant with the grid codes, wind power plant developers must obtain validated models from equipment manufacturers and carry out extensive validation at the plant level before, during and after the commissioning of such plants. At the pre-commissioning stages, usually such studies must be carried out long before any physical equipment is installed and commissioned on site in order to ensure that no compliance problems will be found due to equipment's hardware or software characteristics. The increasingly diversity of requirements due to new markets combined with the increasingly complex requirements poses challenges to the performance verification of wind power plants and is forcing power plant developers to start studies even earlier, putting pressure on manufacturers to deliver highly accurate and validated models faster. For validation during commissioning, tests and procedures described in standards and grid codes are used to ensure that the plant is grid compliant. Finally, after commissioning and during the operational stages of these plants, periodic studies and assessments of the plant are necessary to ensure continuous compliance and model validation. The overall compliance assessment of plants during their lifetime is very complex and brings many challenges due to upgradability of parameters, SW, and HW.

The wind industry has developed large experience with test bench systems and as a result of the challenging scenarios, innovative alternatives to ensure grid compliance of turbines and wind power plants are currently being explored and standardized to fulfill current and future requirements. This paper presents an overview of the current and future practices in the wind sector for grid compliance assessment. In Section 2, component and subsystem testing for WT grid compliance assessment is explained with a focus on the newly released IEC CD 61400-21-4 Measurement and assessment of electrical characteristics - Wind turbine components and subsystems [2]. Furthermore, in Section 3, HiL test benches are explored through analysis of the current state of the industry and future initiatives such as the upcoming IEC TS 61400-21-5 Measurement and assessment of electrical characteristics - Wind turbine components and subsystems [3]. Finally, in Section 4, an overview of the strategies and future outlook are presented with other modern analytical tools or innovative alternatives such as digital twin technology, artificial intelligence/machine learning and software-in-the-loop (SiL) real time simulation.

2 Component and Subsystem Testing for WT grid compliance assessment

Breaking down a system into subsystems and components for more agile and reliable testing has been a technique used in many industries that face similar limitations as the wind industry when it comes to ensuring proper testing of their systems [4–6]. It is not a new idea in itself even in the power system domain and has been more commonly accepted in other equipment/systems such as HVDC, Microgrids, Synchronous machines in large power plants, etc, due to the infeasibility or impracticality of carrying out full-scale prototype field testing, as mentioned in [7, 8]. In the wind industry, test benches have reached a maturity level which allows for standardization of requirements and test procedures as well as wider acceptance by all stakeholders in the industry.

Full-scale prototype turbine field testing has been until today the main methodology used for testing and validation of wind turbines against the many grid compliance disciplines present in the grid codes, IEC standards [9–14] and other standards. Such field tests offer the highest fidelity possible on testing a wind turbine, once all the components (tower, nacelle, blades, generator, converter, transformer, auxiliary and etc) are in place at the first prototypes. In the field, extensive amount of time goes into ensuring that the proper weather conditions for testing are present, in order to fulfill all the requirements for partial and full load tests. Furthermore, for Fault-Ride Through (FRT) tests, testing containers and other special equipment are required in order to emulate faults in the grid and replicate such scenarios in a safe way for verification of the turbine performance.

Besides offering valuable and trustworthy data about the turbine performance and capability, solely relying on full-scale prototype tests can hinder the capability of the industry to achieve greater potential in terms of research and development of new WTs, services and solutions. As the industry requires new turbines to be developed and produced faster than ever, one of the responses to the growing wind industry and the several challenges pointed out is subsystem and component testing in the form of the forthcoming IEC CD 61400-21-4: Measurement and assessment of electrical characteristics - Wind turbine components and subsystems [2] and other initiatives such as the FGW guideline for component based unit certification [15], ENTSO-E in "General Guidance on compliance verification and use of compliance testing equipment certificates. Such tests are carried out at parts of the entire system or at component level and can represent certain responses or behaviors of the entire system without needing all the parts to be assembled and present during the test. Furthermore, since the tests are performed in controllable environments under several well-defined testing and grid conditions, the uncertainties of the varying nature of the wind and the grid on site are limited.

Figure (1) shows how these tests can aid in the overall wind turbine grid compliance testing and validation campaign. The new turbine development life cycle are nowadays mainly driven by market needs and requirements for larger turbines in order to optimize overall costs. In many cases, the wish is to perform plant level grid compliance verification studies earlier through the use of validated models to account for the growing requirements around many different markets. In the schematic, it can be seen that through subsystem testing, field tests can be reduced to a minimum, models can be validated faster and additional features/reports can be verified, allowing the possibility of earlier plant level grid compliance studies and overall more reliable turbines and plants.

The recently published committee draft (CD) of IEC 61400-21-4, has been developed within the working group WG21 under IEC TC88, which consists of 82 expert members from over 14 countries, representing manufactures, developers, component suppliers, test and certification bodies, system operators, universities, etc. During the development of the standard, the defined test methods have been validated at different nacelle test-bench setups in Denmark, Germany, among other countries, and compared with field measurements to prove the validity of the new guideline [16, 17].

The IEC 61400-21-4, specifies the test procedures and defines an uniform methodology that standardizes measurements, testing and assessment procedures of electrical characteristics of WT components and subsystems as basis for the verification of the electrical capabilities of WTs and WT families. The results of these component and subsystems test can

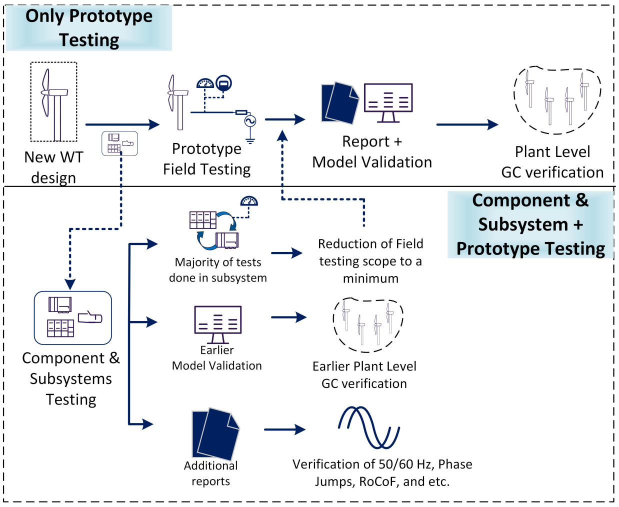

Fig. 1. Component and Subsystem testing benefits.

be used to replace site specific tests as defined in IEC 61400-21-1 and validate detailed simulation models. This technical specification defines overall:

- The minimum test setups in relation to the test & measurements of the electrical capabilities associated to the grid compliance requirements.
- The systems requirements for the test bench to perform these measurements.
- The procedures and related risks for the transferability of test bench components & subsystems test results to Wind turbines and Wind turbines families.
- The documentation and validation requirements for the wind turbine components and subsystems.

In the end the results will be used as basis for the final test of the complete wind power plant as defined in IEC 61400-21-2 and other standards, regulations and system requirements.

2.1 Test system definition, structure and methodology

The technical specification defines the different test systems and the requirements in relation to perform the necessary measurements. The definitions of types of subsystems and types of tests can aid stakeholders into identifying how to use the strategy to fulfill certain grid compliance needs. Existing definitions are mainly presented in [2] and can be split into two categories, types of components/subsystems and types of tests.

There are three main types of tests, initially defined in IEC 61400-21-2 [11], namely functionality, capability, and performance tests and can be seen in Figure (2). Functionality tests can be integrated in the performance tests, however such tests aim to mainly assess if certain features of the turbine are functioning properly and do not necessarily represent the dynamic performance of the turbine regarding some of the tests. It generally describes the specific behavior of a control or protection algorithm/strategy or a piece of SW/HW, where some of the capability and performance features of the main turbine subsystems are disregarded.

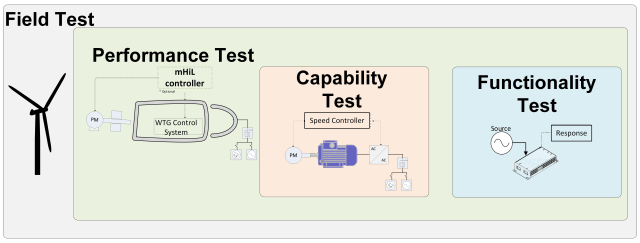

Fig. 2. Overview on different types of tests, adapted from [2].

Capability tests are mainly associated to the steady-state operation of a WT and are generally not influenced by any dynamic behaviors of the mechanical or auxiliary subsystems of the WT. In this sense, capability tests can incorporate the minimum level of subsystems necessary that can faithfully represent the behavior of a WT for steady-state grid compliance disciplines. A few examples of these can be power capability curves, voltage and power ranges, power quality, and etc. Finally, 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.

The types of components/subsystems can be mainly divided into nacelle, electrical generation (generator plus converter), converter, auxiliary and controller test rigs. Within such test rigs, when necessary, it is possible to also include different type of models that replicate and substitute the dynamic behavior of different hardware, such as for example mechanical hardware-in-the-loop that simulate the wind field and dynamic forces on the mechanical drive train (mHiL), generator model, among other options. More detailed definitions and specifications for which tests and grid compliance disciplines that each type of test bench can be used for are found in [2].

2.2 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 WT subsystems in a controllable and grid-isolated environment, specially 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 WT at different connection types and grid systems. Furthermore additional test of the boundaries of the WT are only possible in a controllable grid system, such as:

- **Voltage and frequency capability tests**: to validate the real performance of the WT at the limits of the WT design and the required operating conditions of the grid system.
- **Harmonic evaluations**: at site tests, have always be heavily influenced by the background conditions and been the source of unreliable harmonic measurements. The test with a grid emulator enables the harmonic evaluation under ideal conditions, and can directly be used for the harmonic model, as defined in e.g. the 61400-21-3 [12], and for the harmonic stability and resonance analysis as required in relation to

the new stability criteria's of converter based generation systems [18].

- **Reactive Power Capability Curves at different voltages**: Reactive power capability curves are commonly obtained in the field, however, such tests have the limitation to be voltage dependent and strongly limited by the connection point at the test site. Therefore, voltage dependant reactive power capability tests can be executed with a test rig that is fully decoupled from the public grid.
- **Rate-of-Change-of-Frequency (RoCoF)**: These tests are an essential part of the performance tests of a WT and WPP and are related to large changes in frequency that might occur in the grid due to a severe loss of generation or system split.
- **Phase Jumps**: Phase jumps are defined by sudden changes in phase angle during a fault that can cause large phase angle displacements. These tests cannot be tested on site and need to performed to ensure control stability during such events.
- **Ancillary Services**: Such as grid forming capabilities, black-start, island operation and etc, can be more easily tested and validated for a wide range of conditions.

2.3 Transferability and model development

The component and subsystem test results from the IEC 61400-21-4 and their defined transferability methods permits the transfer of results to the Wind turbine under test and their product families. Furthermore, the results are used as input to the validation of the electrical simulation models as described in IEC 61400-27-2.

As the grid extension and operation all over the world is 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 in relation to e.g. resonance and harmonic stability. The defined tests at 61400-21-4 allows for faster and more accurate procedures to validate models of the WT components and subsystems, as well as vendor specific RMS and EMT models. The results can be used in the future as basis to validate upcoming test and validation requirements on EMT and harmonic models, which are currently not standardized. Finally, these models can be integrated in the HIL-system to validate the overall performance of WPP as well as their interoperability.

3 Hardware-in-the-loop test benches for WPP grid compliance assessment

Real-time hardware-in-the-loop (HiL), especially control hardware in the loop (cHiL), applications became important in the last few decades as the need for proper verification of control, protection, and communication features grew in many different sectors of power systems. Particularly, for converter-connected networks, this approach enables testing of the hardware and allows verification to be performed at the highest fidelity level by the use of real-time EMT simulation coupled to such hardware. These types of simulation, until now, have been mainly used either for the control and protection hardware verification by component manufacturers, or system level studies such as Microgrids focusing on control or stability performance, or protection studies (e.g. protection for transformers, over-head transmission lines, cables).

In the wind sector nowadays, manufacturers, developers and other stakeholders carry out the majority of WPP-level simulations in proprietary simulation environments such as PSCAD, Power Factory, PSSE, among others. Due to the extensive simulation times resulting from the model complexity and computation power limits, particularly at system level, assumption and simplification techniques are adopted to optimize the study time during development and lifetime of the power plant according to the application needs. Techniques can include root mean square (RMS) simulations, use of generic models of wind turbines and plant controls, assumptions such as omission of communication interfaces and delays, among others. As a result, the simulated scenarios and behaviors might not be as realistic as the real system and may not fully capture the wind turbine and wind power plant dynamic characteristics such as during faults and other transient events. Furthermore, by only using offline simulations can hinder the power for fast decision making, as offline simulation take longer to be performed.

Challenges also come on the upgradability and interoperability topics regarding the use of pure offline simulation tools. The interoperability challenges between different equipment and several vendors, considering connection with HVDC [19], or other active components from different manufacturers (e.g. battery, STATCOM, etc), can be complex to address with only software models. Furthermore, the firmware of the WT and WPP control can be updated several times during the lifetime in order to keep the functionalities up to date and constant verification of such updates can be challenging in offline simulation.

Wind power plants, as critical infrastructures, require high security in design and accuracy in model throughout the operational lifetime. Resulting from growing security requirements, complexity of WPPs, increasing electric system scenarios, as well as life cycle operational requirements, there is a need to address standardization of HiL test benches and testing methods for complex systems as it can aid on the solution of all the issues and challenges previously presented.

Currently, several working groups in different standardization bodies and cooperation projects aim to address and answer a few of these questions above. Particularly, the upcoming IEC61400-21-5 aims to define uniform specifications of control-hardware-in-the-loop test bench as shown in Figure (3) used for testing the design integrity and system interoperability for large wind power plants connecting with AC or DC grids, applicable both in offshore and onshore contexts.

3.1 Control replica based Hardware-in-the-Loop for WPP applications

Control replicas can be defined by one or more hardware devices being connected in loop with a real time simulator with the goal of replicating control and protection functions of the

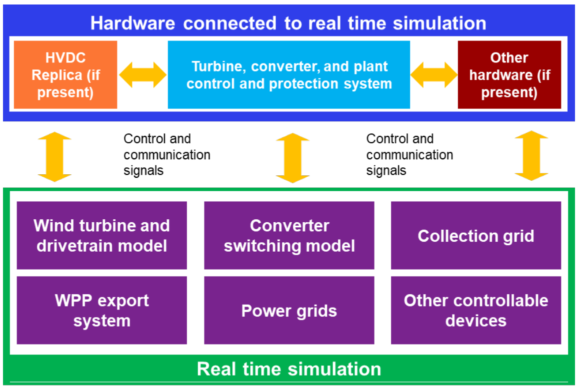

Fig. 3. HiL Applications in the Wind Sector.

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 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.

Many different equipment can be connected in the loop, often acronyms such as cHiL (control & protection HiL), mHiL (mechanical HiL), pHiL (power HiL) are used to identify what is included in the test bench [2]. Particularly for grid compliance purposes for WPP and large systems, control & protection hardware (cHiL) are the main types of hardware 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.

Figure (4) shows an overview of definition of HiL 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 in order to validate the functionality and transferability of results. Furthermore, in Table (1) below, certain challenges and possible solutions through standardization are pointed out and are essential to be targeted.

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;

Table 1. High level challenges in implementation of HiL

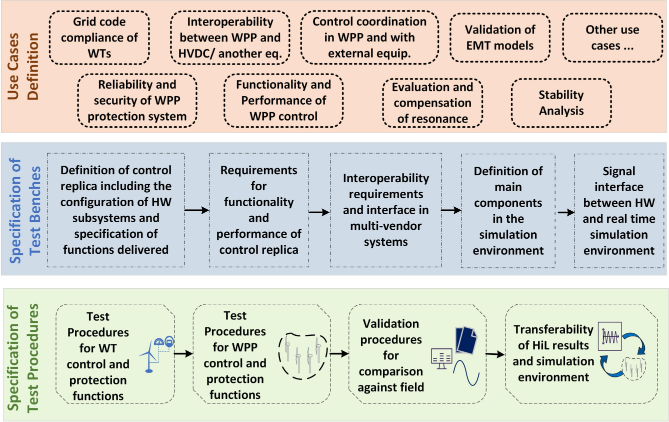

Fig. 4 Framework for standardization of HiL test benches in WPP simulations.

Testing large systems in HiL test benches will be part of the solutions for the increasingly level of complexity and requirements in power systems of the future. The applications shown in Figure (4) can be utilized for different purposes and at different stages of the life cycle of the WPP:

- **Pre-commissioning grid compliance verification studies**: HiL can be used on the early studies of a new WPP as a way to speed-up verification in contrast to offline EMT models and particularly can identify problems and solutions to optimize the existing design. Particularly, multi-vendor interoperability studies are a very important use case at this stage.
- **During commissioning Grid Compliance verification and model validation**: The same system can also be used for model validation and verification during commissioning, by comparing and bench-marking measurements and real-time simulation. During this period, the final HiL model validation can also be performed.
- **Life time assessment and continuous model validation**: Finally, HiL can also enhance the grid compliance assessments during the lifetime of the plant. On one side, it is possible to perform simulations faster and more accurately and account for updates in SW during the life time of the plant. Furthermore, these test benches allow for the use of Digital Twin technologies, by making real-time simulation and data feeding possible to actual HW and high-fidelity models, it is possible to create systems that estimate the next states, predict failures, optimize the operation, among many other use cases.

4 Overview of strategies and future outlook

The two major aforementioned strategies together can yield important results for the upcoming challenges that the wind industry will face. In Figure (5), a general overview with both subsystem & component and HiL test benches strategies is shown. The complementary aspects of the two strategies can be observed, where component & subsystem testing can achieve more reliable and faster WT simulation models and validation

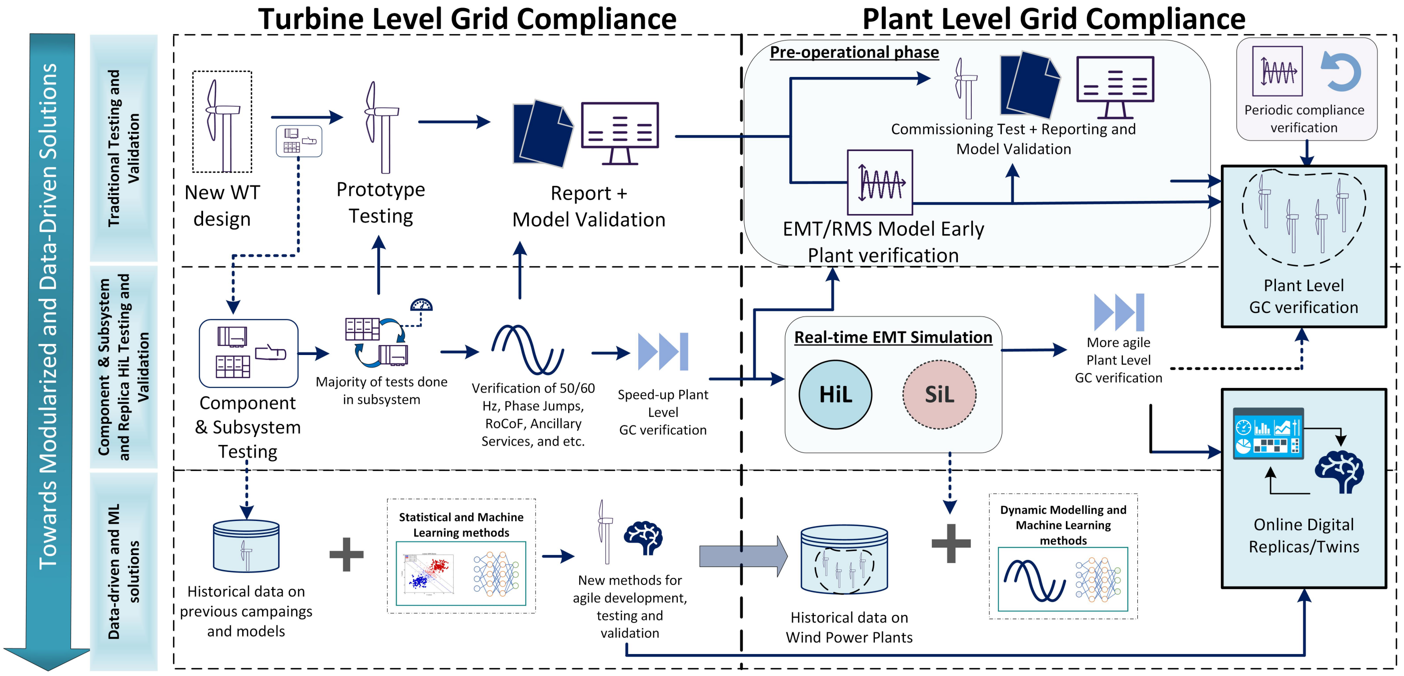

Fig. 5. Framework for future pathwats for Grid Compliance of WTs and WPPs .

and the HiL test benches will then make use of such models to verify system-level compliance in a faster way.

In order for these strategies to be successful, it is imperative that all the industry stakeholders including OEMs, Developers, TSOs, certification bodies, and etc, widely agrees in terms of standardization, validation and acceptance strategies. Moving forward, model validity will also be the major point to archive a stable grid operation under challenging system stability criteria. Therefore, there is a further need for updating standardization activities regarding model validation such as IEC 61400-27 series and other relevant standards, regulations and requirements.

Through the challenges and rising innovative testing/validation methodologies both at WT and WPP level, new avenues open up for more digitised solutions aiming to assess grid compliance at both levels. Digitisation is at the center of the future energy systems and it is estimated that 90% of the data was created in the last 2 years, according to the International Energy Agency [20]. In the light of the extensive amount of data constantly being created and the possibilities of obtaining highly accurate responses on 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 development and operation stages of WT and WPPs by providing for example a) new techniques for early model validation and delivery of new WTs long before any subsystem or prototype is available; b) increasing maintenance and operation of WPPs by providing insights into its performance and capability as well as estimating grid conditions. Below, some examples are described:

- **Machine Learning / Artificial Intelligence models**: The use cases for Machine Learning tools in grid compliance can be divided into two different aspects of the wind turbine life cycle. On the development side, due to the modular and incremental approach of existing wind turbine families, machine learning tools can speed up the testing through identifying trends and patterns from past and current turbine developments, triggering necessary changes on models and parameters on the turbine prior to testing the prototype on site or test-rigs. Moreover, on the operational side, such tools can further be used to deliver insights on the turbine and current grid conditions, identifying potential risks and offering solutions for solving such risk [21].
- **Software-in-the-loop (SiL) real time simulation with Dynamic-link Library (DLL) source codes**: A dynamic link library (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, few experiences running DLLs in real time have been performed and are further described in [22, 23]. It could be seen that positives results could be obtained and a new path for the future can be open for symbiosis between HiL and SiL test benches where some hardware in the bench can be substituted by software. Besides the existing limited number of experiences, software codes need to be standardized based on the accuracy and functionality, then testing methods and performance validation of the software running on a real time hardware can be standardized. Furthermore, latency/delay and interoperability characteristics also need to be defined before this type of test bench becomes standardized in the industry.

- **Digital Twin technology:** Through the symbiosis of subsystem test rigs, full-scale prototype tests, HiL/Sil, historical data, high fidelity validated models, and experience through the application of novel machine learning algorithms and techniques, where such tools can be used during development and operation of the turbines [24, 25].

5 Conclusion

In this paper, an overview of future pathways for grid compliance of wind turbine and wind power plants was described, detailing what are the challenges and possible solutions moving forward. This pathway can also be adapted and used in other renewable generation or systems, e.g PV systems, hybrid power plants, as well as the demand side in relation to new consumer types as Power-to-X (PtX) systems. Therefore, it is important that standards and other regulatory initiatives are constantly revisited and updated in order to support and accommodate the fast-paced technology development in the wind sector.

Subsystem and component testing strategies are becoming more mature as manufacturers, developers, and TSO's are incrementally gaining more experience and confidence on the accuracy and transferability of results from such test benches. On the other hand, although widely used in many different sectors of the power system industry, HiL test benches are yet to be standardized in terms of validation, transferability and interoperability strategies. This is particularly important as such test benches, in a system level, are usually composed by multi-vendor HW and SW (e.g. Energy Islands, HVDC connected Offshore WPPs, etc). For the overall success of current and future strategies, updated model validation requirements will also be crucial for providing acceptance and achieving stable operation under challenging criteria.

Finally, with increasingly flexible and controllable testing and simulation environments, further modern methods such as Digital Twin, Artificial Intelligence/Machine Learning, data-driven dynamic modelling and real time SiL simulation can also be incorporated into the future pathways for the wind industry, leveraging the already existing tools, large amounts of data data and experience gathered by the industry. In this context, further standardization will be necessary to ensure wide acceptance across industries, sectors and countries.

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