

Responses to the interactive comment on “Proposal for Generic Characterization of Electrical Test Benches for AC- and HVDC-Connected Wind Power Plants” by Behnam Nouri et al.

Responses to the referee: Prof. Ola Carlson

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(Comments received and published: 3 January 2020)

Comments reply by authors:

We are pleased to get your precious comments and elaborate on our paper by considering them. We appreciate your considerations and time regarding the paper. The following revision have been prepared according to the comments:

1. Referee’s comment: “May I also suggest that the author make a suggestion of which work is most important for the future operation of the power system and why.”

Author’s response:

This Comment is very close to the first comment from BJÖRN ANDRESEN as well that is “1. Add a little bit more explanation on “Why” you mean the proposed new tests are necessary from the system perspective - system impact. (Black start, Grid forming, etc.)”. Regarding to the referees comments, we have revised paragraphs in the Introduction, section 5.2 and Conclusion as follows:

Author’s changes:

- The paragraph revised in the Introduction, lines 41-49:

“Primarily, power quality and transient performance during faults have been essential aspects, which needed to be tested and verified. However, by increasing trends towards 100% VRG-based grids, the VRGs are required to be developed and featured by advanced capabilities to ensure the robustness and reliability of such grids. In this way, the state-of-the-art Wind Turbines (WTs) are under development to be upgraded to more advanced features such as grid-forming, black start, and frequency support capabilities. These new features would necessitate test and assessment standards in the near future (Langstadtler et al. (2015); Asmine et al. (2017); Gevorgian et al. (2016)). Besides, by increasing wind power installations, the requirements and appropriate test methods are required to study the rising challenges such as harmonic

resonances and control interactions of WPPs in connection to different types of AC and HVDC transmission systems according to Hertem et al. (2016), Zeni et al. (2016) and Buchhagen et al. (2015).”

- The paragraph added to the section 5.2 Additional Proposed Open-Loop Tests, lines 427-429:

“In this section, the additional open-loop tests to the IEC 61400-21-1 standard regarding WT capabilities are proposed, as it is presented in Figure 4. The higher importance of the WT capability tests is because the wind turbine manufacturers are developing their products with advanced features that are required to be verified following the appropriate test standards and regulations. Therefore, it is urgent to foresee the near future needs in the standards.”

- The paragraph added to the Conclusion, lines 530-533:

“Primarily, the focus of IEC standard tests had been on the compliance test of WT capabilities through predefined open-loop tests. The new features of modern WTs, such as grid-forming, system restoration, black start, harmonic rejection, and frequency support capabilities, have been introduced by manufacturers to support renewable energy dominated power grids. These new features necessitate new or reformed test standards in the near future.”

2. Referee’s comment: “The references are well covering the subject, the author may consider including the work by Mebtu Beza and Massimo Bongiorno, “Identification of resonance interactions in offshore-wind farms connected to the main grid by MMC-based HVDC system” International Journal of Electrical Power and Energy Systems, p. 101-113, <https://doi.org/10.1016/j.ijepes.2019.04.004>, in line 230 of the paper.”

Author’s response:

Thanks for the recommended useful reference.

Authors revision:

The paper has been referred in line 254 and is added to the references as 43th reference.

3. Referee’s comment: “And paper: Selam Chernet, Mebtu Bihonegn Beza, Massimo Bongiorno, “Investigation of subsynchronous control interaction in DFIG-based wind farms connected to a series compensated transmission line” International Journal of Electrical Power and Energy Systems, p. 765-774 <https://doi.org/10.1016/j.ijepes.2018.09.005>, in line 255 of the paper.”

Author's response:

Thanks for the recommended useful reference. This paper is a very good example regarding the influences of the grid characteristics on wind turbines. We decided to review and use this paper in the sub-section "4.1.1 Grid Impedance"

Authors revision:

In the sub-section "4.1.1 Grid Impedance", the new paragraph has been added along with the suggested paper as 44th reference, lines 255-258 as follows:

"In a synchronous-generator-based grid, large electrical loads facilitate the grid stability during dynamics and resonances. However, in such grids, the sub-synchronous control interactions between WTs and series compensated transmission lines, which is investigated in Chernet and et al. (2019), are still a serious concern. The impedance of the test bench would be arranged as such to study the sub-synchronous control interaction as well."

4. Referee's comment: "The abbreviations in formula 4 is not clearly written in the text, see line 261-2."

Author's response:

We appreciate your precise attention to the paper.

Authors revision:

We changed the abbreviation from "TSI" to " E_{Ti} " which makes more sense for the total rotational inertia of the system in MW-s, that is the energy metrics.

5. Referee's comment: "In line 487 PV should be PEV."

Author's response:

We appreciate your helpful comments. We corrected the typo.

Finally, we would like to appreciate the precious comments from the referee again. We hope to succeed in understanding the comments and revising the paper on a satisfactory level.

Responses to the interactive comment on “Proposal for Generic Characterization of Electrical Test Benches for AC- and HVDC-Connected Wind Power Plants” by Behnam Nouri et al.

Responses to the referee: Prof. Björn Andresen

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(Comments received and published: 9 January 2020)

Comments reply by authors:

We are delighted to receive your precious comments and elaborate on our paper by considering them. We are thankful for your precise considerations and time regarding our paper. The following revision has been done according to the comments:

1. Referee’s comment: “Add a little bit more explanation on “Why” you mean the proposed new tests are necessary from the system perspective - system impact. (Black start, Grid forming, etc.)”

Author’s response:

As it was mentioned before, this comment is close to the first comment of Prof. Ola Carlson. The reason for the new tests from the system perspective would be new features and new challenges regarding renewable energy dominated power grids. The renewables should be developed robust and reliable to achieve 100% green power system. New features of wind turbines are meant to facilitate these goals. Accordingly, Abstract, Introduction and Conclusion are revised as follows:

Author’s changes:

- A sentence has been added to the Abstract to convey the importance of WT capabilities from the system perspective, lines 4-6:

“Besides, the modern wind turbines have been featured by new capabilities, such as grid-forming, black start, harmonic rejection and frequency support, **to increase the robustness and reliability of renewable-energy-based grids.** Furthermore, the increasing challenges, such as

harmonic resonances and grid interactions, **are compromising wind energy integration into power systems.**”

- The paragraph revised in the Introduction, lines 41-50: (VRG: Variable Renewable Generation)

“Primarily, power quality and transient performance during faults have been essential aspects, which needed to be tested and verified. However, by increasing trends towards 100% VRG-based grids, the VRGs are required to be developed and featured by advanced capabilities to ensure the robustness and reliability of such grids. In this way, the state-of-the-art Wind Turbines (WTs) are under development to be upgraded to more advanced features such as grid-forming, black start, and frequency support capabilities. These new features would necessitate test and assessment standards in the near future (Langstadtler et al. (2015); Asmine et al. (2017); Gevorgian et al. (2016)). Besides, by increasing wind power installations, the requirements and appropriate test methods are required to study the rising challenges such as harmonic resonances and control interactions of WPPs in connection to different types of AC and HVDC transmission systems according to Hertem et al. (2016), Zeni et al. (2016) and Buchhagen et al. (2015). Thus, it is essential to adapt or define new regulations, standards, and compliance test methods to analyse the developments and issues regarding wind energy.”

- The paragraph added to the Conclusion, lines 531-533:

“The new features of modern WTs, such as grid-forming, system restoration, black start, harmonic rejection, and frequency support capabilities, have been introduced by manufacturers **to support renewable energy dominated power grids.** These new features necessitate new or reformed test standards in the near future.”

2. Referee’s comment: “It would be nice to elaborate a little bit more on the transferability and assessment procedures from the proposed test bench results to Wind power plant operation, e.g. by validation of simulation models. (As the title suggest to validate the characteristics of Wind power plants), as well as the limits for the test bench tests – can anything be validated on the converter based test bench.”

Authors response:

This is a very good idea to mention to the transferability and model validation applications as well as the limits of converter based test benches. Therefore, maybe it would be useful to mention that the validation of simulation models can be performed for WT models as well as WPP aggregated models.

Author’s changes:

- To elaborate on Simulation Model Validation, the reference 18 as “CIGRE Technical Brochures: Network modelling for harmonic studies, JWG C4/B4.38, Reference no. 766, 2019” has been added and referred in Introduction line 52.

“To date, several standards and recommendations such as IEC, IEEE, DNV GL, and CIGRE have been published for design, simulation, operation, and test of electrical aspects of WTs (IEC 61400-21-1 (2019); IEEE Std 1094-1991 (1991); DNVGL-ST-0076 (2015) and CIGRE TB766 (2019)).

- To elaborate on importance of tests and their application in Simulation Model Validation for WTs and WPPs, the following sentences have been added in subsection “2.1.1 Electrical test levels”, lines 132-135:

“The test results concern wind farm developers and system operators in terms of WPP model validation and grid connection compliance, and WT manufacturers in terms of WT design and simulation model validations. This way, the results of tests are considered to be transferable and useful for the assessment of WTs as well as WPPs and developed simulation models (Ausin et al. (2008); Zeni et al. (2016); Koralewicz et al. (2017)).

- To mention the limits of tests and application of tests for model validation the following sentences have been added to section “5.3 Proposed Closed-Loop Tests”, lines 474-476:

“It is evident that it is not feasible to simulate all different aspects of a real power system for a WT or WPP; however it is possible to assess part of most critical conditions in a test environment and validate the simulation models (Ausin et al. (2008); Zeni et al. (2016)).”

- In addition, the section “5.4 discussion” has been added to the paper to discuss and summarize the propose test options, limits and application of tests regarding model validation and design validation, lines 519-523:

“The proposed test structure covers the needs of industry and research and development studies regarding the compliance test of WTs and assessment of WPPs. Furthermore, some parts of the tests, such as harmonic rejection, transient performance, power quality, and control performance, would be useful for the design validation of WT and its sub-systems as well. On the other hand, both groups of tests would be helpful to validate simulation models in WPP as well as WT levels. Therefore, the tests on the DUT can be performed as such that the results to be transferable for higher levels including WT and WPP levels.”

- In this regard, the following sentences have been added to the Conclusion as well, lines 542-543:

“Although it is not feasible to simulate all different aspects of a real power system; however, it is possible to assess part of the most critical conditions in a test environment and validate the simulation models for WTs and WPPs.”

3. Referee’s comment: “It would be beneficial for the reader and understanding of the article if you could distinguish between tests, which are necessary for the design of the Wind turbine and components (Design validation) as well as tests necessary for the grid connection and interaction with the grid. E.g. will the test of harmonic background (chapter 4.1.4) / harmonic injection be relevant to validate the design of the components (design validation), as well as potential tests for new features / harmonic filtering and last but not least harmonic stability analysis. You should consider maybe to separate the tests into – design validation of the wind turbines and components, and test necessary for the grid operation under various grid conditions.”

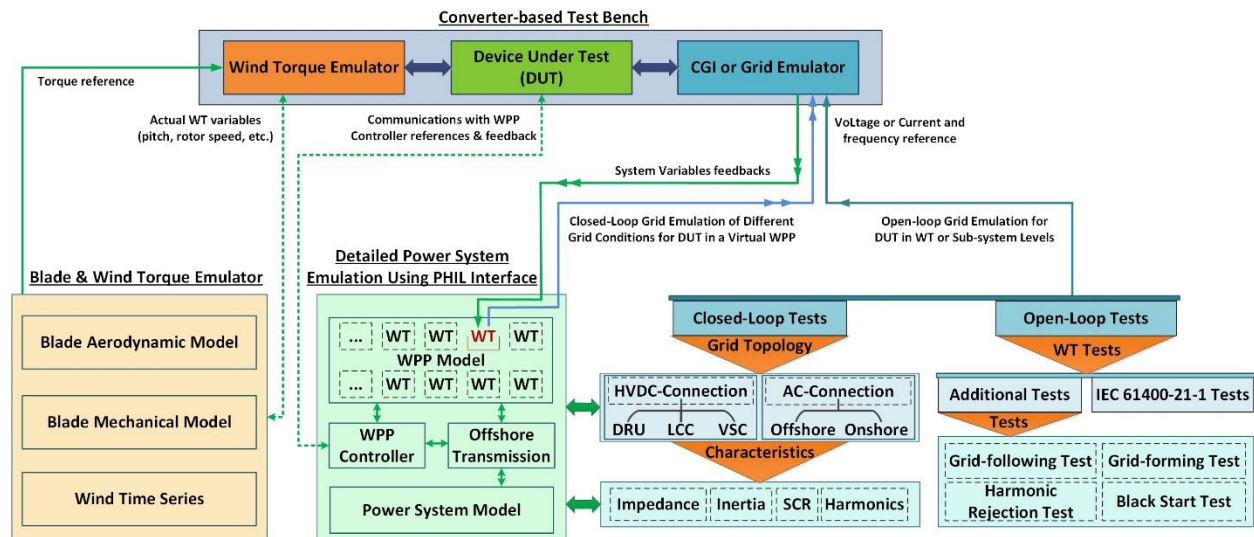
Authors response:

According to this comment, we restructured the test proposals into two divisions: First group is open-loop tests, which include the available and futuristic capability tests that are developed for WTs. Open-loop tests would be implemented by predefined references and waveforms for the converters of the grid emulator. Second group is closed-loop tests, which includes electrical characteristics of different grids and evaluates grid interactions with WTs and WPPs. The closed-loop tests would be performed by PHIL interface.

Also, this comment raises an interesting discussion that what is the most purpose of the test standards? According to the IEC 61400-21-1 and 21-4 standards. The grid connection compliance is the main scope of these standards, which the main concern of TSOs and WPP developers. Besides, some of the tests would be applicable for design validation as well, which concerns WT and component manufacturers. Therefore, we would suggest mentioning that parts of the tests can be used for design validation of WT, components and control systems.

Author’s changes:

- The new structure of Figure 4 is illustrated below:



- The explanation of the revised test structure in the Abstract has been changed to the following sentences, lines 7-13:

“This paper proposes a generic test structure within two main groups, including open-loop and closed-loop tests. The open-loop tests include the IEC 61400-21-1 standard tests as well as the additional proposed test options for the new capabilities of wind turbines, which replicate grid connection compliance tests using open-loop references for the grid emulator. Besides, the closed-loop tests evaluate the device under test as part of a virtual wind power plant and perform real-time simulations considering the grid dynamics. The closed-loop tests concern grid connection typologies consisting of AC and HVDC, as well as different electrical characteristics, including impedance, short circuit ratio, inertia, and background harmonics.”

- To elaborate on Electrical Design and Validation, the 16th reference as “IEEE Std 1094-1991: IEEE Recommended Practice for the Electrical Design and Operation of Windfarm Generating Stations, 1991” and the 17th reference as “DNVGL-ST-0076: Design of electrical installations for wind turbines, 2015” have been added to the Introduction, line 52:

“To date, several standards and recommendations such as IEC, IEEE, DNV GL, and CIGRE have been published **for design, simulation, operation, and test** of electrical aspects of WTs (IEC 61400-21-1 (2019);IEEE Std 1094-1991 (1991);DNVGL-ST-0076 (2015) and CIGRE TB766 (2019)).”

- To elaborate on importance of tests for different industrial partners, the following sentences have been added in subsection “2.1.1 Electrical test levels”, lines 132-135:

“The test results concern **wind farm developers and system operators** in terms of WPP model validation and grid connection compliance, and **WT manufacturers in terms of WT design and simulation model validations**. This way, the results of tests are considered to be transferable and useful for the assessment of WTs as well as WPPs and developed simulation models (Ausin et al. (2008); Zeni et al. (2016); Koralewicz et al. (2017)).”

- In addition, the section “5.4 discussion” has been added to the paper to discuss and summarize the propose test options, limits and application of tests regarding model validation and design validation, lines 520-521:

“Furthermore, some parts of the tests, such as harmonic rejection, transient performance, power quality, and control performance, would be useful for the design validation of WT and its sub-systems as well.”

4. Referee's comment: "Some more specific comments:

Chapter 5.1.5 better use the wording: "Grid Protection test" not disconnection test. Figure 3. – Use bigger symbols for the Drive motor / generator Figure 2 - Add description of the filter."

Authors response:

We appreciate your precise attention and considerations regarding the content of the paper.

Author's changes:

The above mentioned comments have been applied on the paper. Figure 2 has been revised. Also, the figure description has been added to the section "2. Grid Connection Compliance Tests" as well, lines 68-72:

"As shown in Figure 2-a, the AC-connected offshore WPP connects to the main onshore grid through high voltage submarine cables and transformers. The shunt inductors are required to dampen the possible over-voltage phenomena caused by the capacitive effect of the AC cables. The typical structure of an HVDC-connected offshore WPP is illustrated in Figure 2-b, which consists of HVDC transmission cables, transformers, AC/DC converters, and harmonic filters of the converters."

Finally, we would like to appreciate your precious and helpful comments on the paper. We are sure that considering these comments would add value to the paper and make it more useful.

Responses to the interactive comment on “Proposal for Generic Characterization of Electrical Test Benches for AC- and HVDC-Connected Wind Power Plants” by Behnam Nouri et al.

Responses to the referee: Dr. Torben Jersch

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(Comments received and published: 17 January 2020)

Comments reply by authors:

We are delighted to receive your valuable comments, and elaborate and correct our paper by considering them. We are thankful for your precise considerations and time regarding our paper. The following revision has been prepared according to the comments:

1. Referee’s comment: “1. For me there is missing a discussion about the dynamic change of impedances, this occurs often by changing the grids topologies and with special regard during UVRT testing with standard inductive voltage dividers.”

Author’s response:

We would add this comment to the section “4.1.1 Grid Impedance” as an affecting factor in WT dynamic response. Also, it would be valuable to mention this issue for voltage divider-based test equipment in the Introduction.

Author’s changes:

- To mention the disadvantage of voltage divider regarding uncontrollable impedance dynamics, the following sentence has been changed in lines 38-40:

“However, it has certain fundamental limitations, such as dependence on a stronger point of interconnections, **uncontrollable dynamic change of impedance during test**, and inability to replicate any evolving grid characteristics..”

- The following sentences have been added to the section “4.1.1 Grid Impedance” to mention the dynamic impedance issue, lines 259-261:

“The controllable dynamic impedance emulation is another advantage of the converter-based CGI, in comparison to the voltage divider test equipment shown in Figure 1, which imposes fewer uncertainties regarding equivalent impedance to the point of connection of DUT.”

2. Referee's comment: "2. According to the wind torque emulator chapter: The intended use is emulating the wind turbine behavior combined with HiL simulations of the entire wind turbine, as mentioned it can be done either in torque controlled or speed controlled mode. "The motor drive system is used to simulate wind profiles to the shaft of ET's generator" –this is inaccurate. Further information: Neshati, Mohsen, et al. "Hardware-in-the-loop drive train control for realistic emulation of rotor torque in a full-scale wind turbine nacelle test rig." 2016 European Control Conference (ECC). IEEE, 2016."

Authors response:

Thanks for your precise consideration of the content. We reviewed the suggested reference and use of it in our paper as a reference and correcting the content accordingly, would improve our grasp on the wind torque part of the test bench.

Author's changes:

- The recommended paper has been added to this paper as 40th reference.
- The following sentences have been added to the section "3.3 Wind Torque Emulator", lines 223-227 as follows:

"The wind torque emulator is a prime mover system consisting of a drive converter connected to an AC or DC motor. This way, the characteristics of the missing WT rotor in the laboratory environment would be recreated. This objective is necessary for hardware-in-the-loop (HiL) testing of DUTs, especially for the tests, such as LVRT capability test, in which a realistic emulation of rotor torque for the DUT's main shaft is required. This requirement implies an accurate emulation of steady-state and dynamic torque characteristics of the rotor including the rotor inertia and its eigen-frequencies as studied in Neshati (2016)."

3. Referee's comment: "Specific Comments: Figure 3: Naming the grid connected converters as DC Grid Emulator is very unusual, Active front end (AFE) or active rectifier unit (ARU) would be more common"

Authors response:

The idea of using the word "DC grid emulator" was because there is a potential in the converter-based test benches to be controlled as an HVDC converter. This opportunity would make it possible to perform different grid topology tests. In an HVDC system the utility grid connected converter is responsible for "DC grid regulation". However, still, we can change the name to "active rectifier unit (ARU)".

Author's changes:

The name "DC grid emulator" is changed to "**Active Rectifier Unit (ARU)**" in section "3.2 Grid Emulator" as well as Figure 3.

4. Referee's comment: "Line 151: please correct to Fraunhofer IWES, Fraunhofer Institute for Wind Energy Systems Table 1: IWES CGI rating 15 MVA, Wind emulator rating 10 MW - Wind Emulator rating seems to be the motoring power, therefore the unit should be MW."

Authors response:

Thanks for the precise attention. The Table 1 and name of institution "Fraunhofer IWES" have been corrected according to the comments.

5. Referee's comment: "Line 202-203: the drive system is not capable of providing mechanical loads."

Authors response:

Our perception of "mechanical load" was the same as "mechanical torque". To avoid possible miss-understandings, the phrase "mechanical load" has been removed from the section "3.3 Wind Torque Emulator". Thanks for the comment.

Finally, we would like to appreciate your considerations and detailed comments. We hope to revise the paper as such to include all of your valuable comments.

Generic Characterization of Electrical Test Benches for AC- and HVDC-Connected Wind Power Plants

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Abstract. The electrical test and assessment of wind turbines are going hand in hand with standards and network connection requirements. In this paper, the generic structure of advanced electrical test benches, including grid emulator or controllable grid interface, wind torque emulator and device under test, has been proposed to harmonize state-of-the-art test sites. Besides, the modern wind turbines have been featured by new capabilities, such as grid-forming, black start, harmonic rejection and frequency support, to increase the robustness and reliability of renewable-energy-based grids. Furthermore, the increasing challenges, such as harmonic resonances and grid interactions, are compromising wind energy integration into power systems. Therefore, it is necessary to develop new and revised test standards and regulations. This paper proposes a generic test structure within two main groups, including open-loop and closed-loop tests. The open-loop tests include the IEC 61400-21-1 standard tests as well as the additional proposed test options for the new capabilities of wind turbines, which replicate grid connection compliance tests using open-loop references for the grid emulator. Besides, the closed-loop tests evaluate the device under test as part of a virtual wind power plant and perform real-time simulations considering the grid dynamics. The closed-loop tests concern grid connection typologies consisting of AC and HVDC, as well as different electrical characteristics, including impedance, short circuit ratio, inertia, and background harmonics. The proposed tests can be implemented using the available advanced test benches by adjusting their control systems. The characteristics of a real power system can be emulated by a grid emulator coupled with real-time digital simulator systems through a high bandwidth power-hardware-in-the-loop interface.

1 Introduction

Wind energy has been one of the most promising renewable energy sources used worldwide, mostly located onshore. Besides, a better quality of the wind resource and larger suitable areas in the sea have made offshore installations a considerable choice for Wind Power Plants (WPPs). To date, the total installed capacity has reached 592 GW with 23 GW share of offshore in 2018. The new total installations would continue with more than 55 GW each year by 2023 (GWEC (2018); Wind Europe (2018)).

The increasing installed capacity of Variable Renewable Generation (VRG) has concerned power system operators in terms of stability and reliability of the overall power system. Consequently, new interconnection requirements, standards, and market mechanisms are evolving in various parts of the world for VRGs, including wind power, to provide various types of essential reliability services to the grid – the role that has been typically reserved for conventional generation (NERC, 2015). Further-

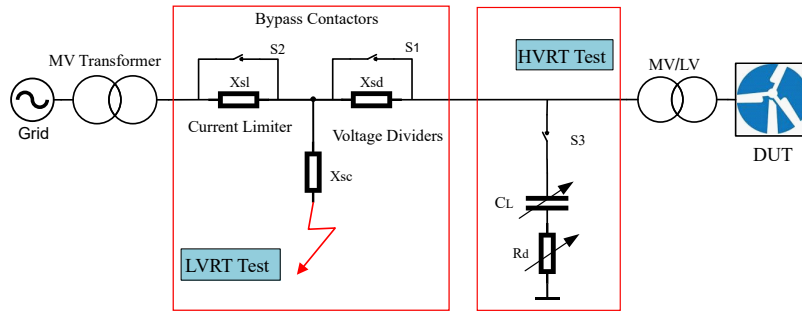


Figure 1. The basic structure of impedance-based topology for LVRT and HVRT capabilities tests (Ausin et al. (2008); Langstadtler et al. (2015)).

25 more, the industry has focused on collaborations and harmonization to achieve the technical and economic benefits of a uniform technology and market, especially in Europe (IRENA (2018); Sørensen et al. (2019)). In this way, for instance, the European Commission has regulated international requirements for AC- and HVDC-connected power-generating modules as well as HVDC systems (Commission Regulation 631 (2016); Commission Regulation 1447 (2016)). Consequently, compliance test standards are needed to ensure the power quality and performance of VRGs, especially WPPs.

30 Compliance test methods are in line with relevant network codes and standards. Furthermore, wind technology has been matured by research, development, and demonstrations in industrial test sites and laboratories. Figure 1 illustrates the basic compliance test equipment, which had been proposed for Low Voltage Ride-Through (LVRT) capability test in Ausin et al. (2008) and is addressed as an example in IEC 61400-21-1 (2019). Recently, this structure has been adapted for High Voltage Ride-Through (HVRT) capability test as well (Langstadtler et al., 2015). In this topology, the voltage divider impedances (X_{sd} and X_{sc}) are used for the LVRT test of the device under test (DUT). Also, the parallel capacitors (C_L) in series with damping resistors (R_d) are used for the HVRT test. X_{sl} is used to limit the effect of tests on the utility grid by limiting the current flow from the utility grid during the test. The test apparatus structure shown in Figure 1 had proven to be a useful tool in the early stages of grid integration research and criticizing of utility-scale wind power. However, it has certain fundamental limitations, such as dependence on a stronger point of interconnections, uncontrollable dynamic change of impedance during test, and inability to replicate any evolving grid characteristics.

40 Primarily, power quality and transient performance during faults have been essential aspects, which needed to be tested and verified. However, by increasing trends towards 100% VRG-based grids, the VRGs are required to be developed and featured by advanced capabilities to ensure the robustness and reliability of such grids. In this way, the state-of-the-art Wind Turbines (WTs) are under development to be upgraded to more advanced features such as grid-forming, black start, and frequency support capabilities. These new features would necessitate test and assessment standards in the near future (Langstadtler et al. (2015); Asmine et al. (2017); Gevorgian et al. (2016)). Besides, by increasing wind power installations, the requirements and appropriate test methods are required to study the rising challenges such as harmonic resonances and control interactions

of WPPs in connection to different types of AC and HVDC transmission systems according to Hertem et al. (2016), Zeni et al. (2016) and Buchhagen et al. (2015). Thus, it is essential to adapt or define new regulations, standards, and compliance test methods to analyse the developments and issues regarding wind energy. To date, several standards and recommendations such as IEC, IEEE, DNV GL, and CIGRE have been published for design, simulation, operation, and test of electrical aspects of WTs (IEC 61400-21-1 (2019); IEEE Std 1094-1991 (1991); DNVGL-ST-0076 (2015); CIGRE TB 766 (2019)). The IEC standards as the leading international standards for the test and assessment of wind turbines have been reviewed in this paper.

In this paper, the authors aim to extend the state-of-the-art developments in wind energy towards harmonized test methods and propose additional test options to the standard tests to extend the applications of advanced industrial test benches in terms of research and development studies. In part 2, grid connection compliance tests, including typical grid connection topologies, IEC standards, and electrical test levels, have been introduced. Part 3 overviews the state-of-the-art industrial test benches and illustrates the generic structure of converter-based test equipment. In part 4, the electrical characteristics of different grids to be emulated in a test site have been studied and proposed. Finally, part 5 proposes the generic structure of test options consisting of the recommended tests in IEC standard as well as proposed additional test options for open-loop tests as well as closed-loop tests for WTs and WPPs.

2 Grid Connection Compliance Tests

The integration of wind energy into the power system has been one of the main challenges for the development of WPPs. The wind power can be transmitted either through AC or HVDC transmission systems to the main AC grids. Besides, there is an increasing trend to develop WPPs in offshore areas because of the higher power capacity of offshore winds and limited onshore sites (Wind Europe (2018); (Cutululis, 2018); (Kalair, 2016)). According to the European Wind Energy Association (EWEA) (Pierria et al., 2017), potentially, the European offshore wind power can supply Europe seven times more than its demand. Figure 2 illustrates a typical structure for AC and HVDC connections of offshore WPPs. As shown in Figure 2-a, the AC-connected offshore WPP connects to the main onshore grid through high voltage submarine cables and transformers. The shunt inductors are required to dampen the possible over-voltage phenomena caused by the capacitive effect of the AC cables. The typical structure of an HVDC-connected offshore WPP is illustrated in Figure 2-b, which consists of HVDC transmission cables, transformers, AC/DC converters, and harmonic filters of the converters. HVDC connection has economic advantages for long distances, especially in case of offshore WPPs (Hertem et al. (2016); Cutululis (2018); Kalair (2016)). Hence, the recent interests in wind energy are focused on offshore WPPs, and HVDC systems are required due to distances from the main AC grids. The collector system voltages in AC- and HVDC-connected WPPs are typically 33 kV and 34.5 kV in Europe and the U.S., respectively. Recently, several 66 kV collector systems in offshore WPPs have been demonstrated. Therefore, 66 kV seems to be a general trend in collector system design in the offshore wind industry (Wiser et al., 2018).

The development process of grid connection requirements -or network codes- and compliance test methods occurred by the maturation of wind energy technology. Besides, the industry is currently interested in the technical and economic benefits of international collaborations (Wind Europe (2018); NERC (2015)). Therefore, harmonized regulations and standards are in

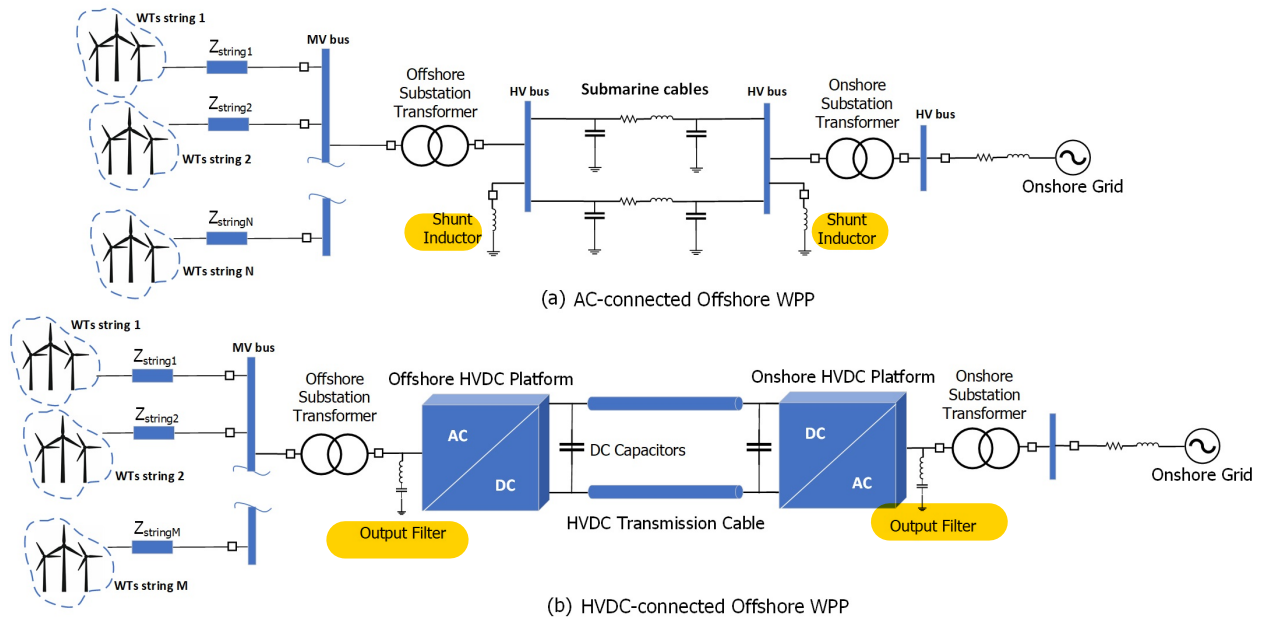


Figure 2. Typical structure of AC (a) and HVDC (b) connected offshore WPPs (Cutululis (2018); Kalair (2016)).

progress for design and performance assessment of WTs as well as WPPs. The development of European network codes and IEC standards are some of the best harmonization practices.

In European network codes, the requirements have been regulated for AC-connected offshore and onshore as well as HVDC-connected Power-Generating Modules (PGM) (Commission Regulation 631 (2016); Commission Regulation 1447 (2016)).

85 According to (Nouri et al., 2019), the requirements for AC-connected offshore and onshore PGMs are mostly similar, while relatively different operation ranges and conditions have been considered for AC- and HVDC-connected PGMs. The AC and HVDC transmission systems impose different electrical characteristics on WPPs. Consequently, different control schemes and design considerations have been used for WTs and WPPs. Therefore in this paper, the authors propose to define a group of grid interaction tests considering the AC and HVDC connections for WTs using a converter-based test bench and emulate different

90 grid characteristics for DUT. Although, reflecting all aspects of different grids is challenging, but at the same time, essential to assess the performance of WTs in a more realistic environment. Network code compliance tests and standards are critical factors in preserving the reliability and stability of WPPs. Thus, in the next section, IEC standards, as the leading international standards for test and assessment of wind turbines capabilities, have been reviewed.

2.1 IEC Standards for Assessment of Wind Energy

95 In 1988, Technical Committee 88 (TC88) of the IEC began its efforts to organize international standards for wind turbines as 61400 series. TC88 consists of several working groups, projects, and maintenance teams to develop and issue standards, technical reports, and specifications (Andresen et al., 2019). Initially, TC88 focused on power performance (i.e., power curve)

tests and structural and mechanical design. The works on electrical tests started in 1997 as IEC 61400-21 series by the working group WG21.

100 The second edition of IEC 61400-21 was published in 2008 to cover the definition and specifications for measurement and assessment of power quality characteristics for wind turbines. Currently, IEC TC88 WG21 is working on four new documents for the IEC 61400-21 series, where the title is changed from power quality characteristics to electrical characteristics appreciating that not only power quality characteristics are included (Andresen et al., 2019). To date, there is no IEC standard for testing the electrical characteristics of WPPs, but only for testing single WTs. Regarding the grid connection compliance assessment, 105 the evaluation of performance and quality of WPPs is based on measurements, simulations, and model validation tests (Ausin et al. (2008); Asmine et al. (2017); Andresen et al. (2019)).

Recently, IEC 61400-21-1 is published and replaced the second edition of 61400-21. IEC 61400-21-1 specifies test methods for electrical characteristics of wind turbines (IEC 61400-21-1, 2019). Also, IEC 61400-21-2 specifies test methods for electrical characteristics of WPPs (Andresen et al., 2019). Concerning the growing issues regarding harmonics in WPPs, IEC 61400-21-3 aims to focus on harmonic modeling as a technical report. The IEC TR 61400-21-3 provides a starting point for the required frequency-domain modeling of wind turbines (IEC TR 61400-21-3, 2019). Furthermore, the IEC 61400-21-4 recommends a technical specification for component and subsystem tests (Andresen et al., 2019). IEC 61400-21-1 and 21-3 are 110 61400-21-3 aims to focus on harmonic modeling as a technical report. The IEC TR 61400-21-3 provides a starting point for the required frequency-domain modeling of wind turbines (IEC TR 61400-21-3, 2019). Furthermore, the IEC 61400-21-4 recommends a technical specification for component and subsystem tests (Andresen et al., 2019). IEC 61400-21-1 and 21-3 are published in 2019, while 61400-21-2 and -21-4 may be published in 2021.

Besides, the IEC 61400-27 series specifies standard dynamic electrical simulation models for wind power generation. The 115 first edition of IEC 61400-27-1, published in 2015, specifies generic models and validation procedures for wind turbine models. Furthermore, the next edition is under development to expand the scope towards WPPs models in addition to the WTs models (Sørensen, 2019). The next edition consists of two parts: IEC 61400-27-1 specifying generic models for both WTs and WPPs, and 61400-27-2 specifying validation procedures.

2.1.1 Electrical test levels

120 According to the IEC-61400-21-1 (IEC 61400-21-1, 2019), the electrical characteristics to be simulated and validated for wind turbines consist of five different categories as power quality aspects, steady-state operation, control performance, transient performance or fault ride-through capability, and grid protection. The electrical characteristics of WTs can be measured and tested at different levels. The test levels consist of component test level (such as capacitors and switches), subsystem test level (such as nacelle and converter), field measurement at wind turbine level (or type test), and field test or measurement at WPP 125 level (IEC 61400-21-1, 2019). WT level tests can also be split into two subcategories: (a) testing of the full drive-train connected to low voltage test bench; (b) testing of the full drive-train connected to medium voltage test bench via WT's transformer with a full set of protection and switchgear (Koralewicz et al., 2017). The second option is closer to reality since it includes impacts of transformer impedance and configuration and protection settings on transient performance. In IEC 61400-21-1 (2019), an overview of the required and optional test levels for different test and measurement requirements is provided.

130 Nowadays, to have a flexible and economical solution for grid connection compliance tests and model validations, the trend is to perform tests at lower levels, such as WT and subsystem levels. The tests for WT and subsystem levels are mostly

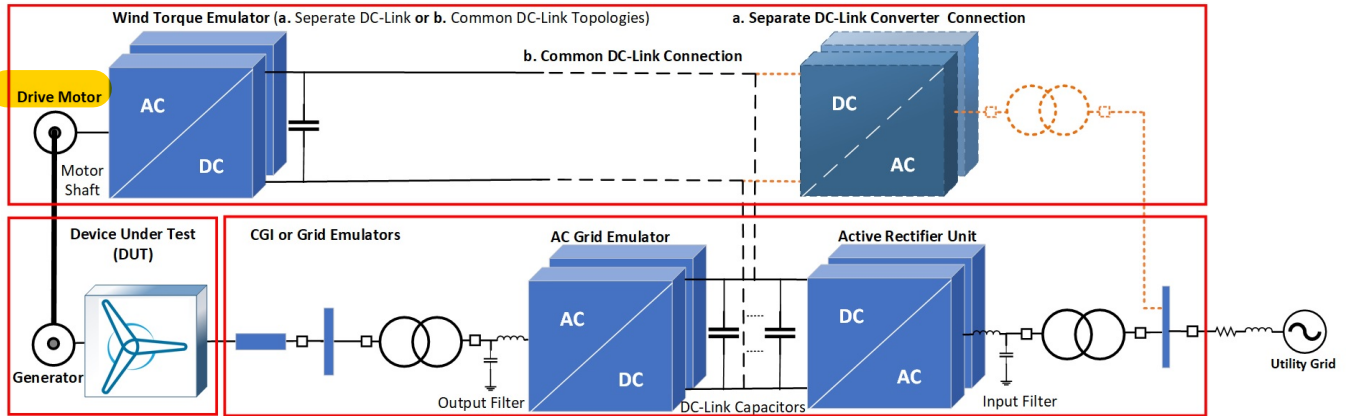


Figure 3. Proposed generic schematic diagram of a converter-based test bench.

implemented in a research and development environment or test sites. The test results concern wind farm developers and system operators in terms of WPP model validation and grid connection compliance, and WT manufacturers in terms of WT design and simulation model validations. This way, the results of tests are considered to be transferable and useful for the assessment of WTs as well as WPPs and developed simulation models (Ausin et al. (2008); Zeni et al. (2016); Koralewicz et al. (2017)). However, in some cases performing field tests and measurements are still necessary as reported in (Asmine et al., 2017). Accordingly, the Hydro-Québec TransÉnergie experience (Asmine et al., 2017) regarding the inertial response has shown that an adequate evaluation of the inertial response cannot be performed accurately at WT level and should include an evaluation performed at the WPP level. As another example, the power quality assessment of WPPs is either assessed using scaling rules of WT test results or accomplished by the assessment of online measurement data. The online monitoring is achieved during the first year of operation of the WPP (Asmine et al., 2017). The owners of power plants should secure that their connection to the local grid does not cause voltage distortion or fluctuation more than an acceptable range. However, the increasing challenges, such as harmonic resonances, grid interactions, and voltage and frequency stability issues, have proven the need for more extended analysis and assessment of WPPs. In this regard, the generic converter-based test bench and possible test and assessment solutions for WTs as well as WPPs are proposed in the next sections.

3 Generic Converter-Based Test Bench

Different electrical test benches as Controllable Grid Interfaces (CGI) have been reported for grid dynamics emulation in Ausin et al. (2008), Gevorgian et al. (2016), Espinoza et al. (2019), Espinoza et al. (2015), and Yang et al. (2012). The impedance-based test equipment in Figure 1 is only intended for the fault ride-through capability tests. A more advanced and flexible topology is a full-power converter-based CGI Yang et al. (2012), which is shown in Figure 3. This topology has been used in the latest industrial test benches and is studied in the next sections of this paper.

In MEGAVIND (2016), a mapping of global test and demonstration facilities serving the wind industry in Europe and the U.S. is presented by topics and locations. Accordingly, most of the latest industrial test benches are based on power electronic converters. The popularity of the converter-based test benches is because of enhanced control and test opportunities for both electrical and mechanical aspects of WTs. Converter-based test equipment provides emulation of unlimited test scenarios applicable to power systems of various sizes (sizeable interconnected power grids, island systems, or mini-grids) operating at both 50 Hz or 60 Hz, with full controllability over strength, imbalances and harmonic content of emulated grids. The generic schematic diagram of a converter-based test rig is shown in Figure 3. Generally, an industrial test bench for wind energy consists of three main parts: Device Under Test (DUT), wind torque emulator, and grid emulator or CGI. In Figure 3, the DUT is a WT nacelle. The CGI can also be used for testing of complete WTs in which case the wind torque emulator in Figure 3 is not required.

In Table 1, the specifications for some of remarkable advanced test sites are illustrated. As it is presented in Figure 3, the application of multilevel drive converter modules in parallel connections is a typical topology to establish a medium power and medium voltage source as grid and wind torque emulators (Averous et al. (2017); Gevorgian (2018); Jersch (2018); Rasmussen (2015) and Tuten (2016)). The multilevel converters, such as Three-Level Neutral Point Clamped (3L-NPC) and H-bridge topologies, are developed to achieve higher efficiency and lower harmonic distortion rather than conventional two-level converters and reduce the size of harmonic filtering and undesired interference.

According to the Table 1, a group of test benches such as available test setups in NREL (National Renewable Energy Laboratory, USA), Fraunhofer IWES (Fraunhofer Institute for Wind Energy Systems, Germany) and CENER (National Renewable Energy Centre, Spain), have used three-level NPC drive converters developed by ABB company. The ABB drive converters

Table 1. Comparison of different concepts applied in industrial test benches.

Test Centre	CGI rating	Short circuit capacity	Torque Emulator rating	Converters Type	*N (ARU)	**M (AGE)	Converter Control	RTDS
LORC	15 MVA	30 MVA	13 MW	3-level NPC GE (IGBT)	2	2	AVC	no
Aachen	3.5 MVA	7.5 MVA	4 MW	3-level NPC GE (IGBT)	1	1	AVC	yes
NREL	7 MVA	40 MVA	5 MW	3-level NPC ABB (IGCT)	1	4	DTC	yes
F. IWES	15 MVA	44 MVA	10 MW	3-level NPC ABB (IGCT)	2	3	DTC	yes
CENER	9 MVA	18 MVA	9 MW	3-level NPC ABB (IGCT)	1	2	DTC	yes
Clemson	15 MVA	20 MVA	7.5 and 15 MW	H-bridges TECO- Westinghouse (IGBT)	2	2	AVC	yes

*N(ARU): Number of ARU modules, **M(AGE): Number of AC Grid Emulator modules.

are controlled by Direct Torque Control (DTC) method with Integrated Gate-Commutated Thyristor (IGCT) switches (ABB, 2018). On the other hand, in the second group, such as LORC (Lindø Offshore Renewables Center, Denmark) and Aachen (RWTH Aachen University, Germany), the converters are three-level NPC developed by GE company (General Electric). GE's medium power drive converters are controlled by Advanced Vector Control (AVC) using Insulated Gate Bipolar Transistor (IGBT) switches (GE, 2018). Besides, different types of converters would be utilized in a test site. For instance, the drivetrain test facility at Clemson University is established using multilevel H-bridge drive converters developed by TECO-Westinghouse company (Tuten, 2016). Each converter developer utilizes different components, control methods, and interface algorithms. However, all of the test benches should be able to perform tests according to the standards and research objectives, and minimize the effect of non-ideal emulation of a real test environment for DUT. In most of the test sites, a Real-Time Digital Simulation (RTDS) system is used to get to a dynamic online model of the grid as well as the overall system. The main limitation of converter topology shown in Figure 3, as well as any converter-based test rigs, is limited over-current capability. This constraint can be addressed by over-sizing the MVA rating of the test side converter similar to what was done in NREL's CGI (7 MVA continuous power rating but capable of operating at 40 MVA short circuit capacity during 2 seconds (Gevorgian, 2018)) as given in Table 1. Over-sizing of converters for this purpose is costly but is necessary for LVRT testing of Doubly-Fed Induction Generator (DFIG) type WT, which can produce higher levels of short circuit current contribution.

The establishment of test equipment would be based on different criteria, objectives, and motivations. The majority of companies have plans to develop their sites as such to be able to test a wide range of WTs, including medium power to higher power ratings, that are mostly for offshore applications. According to GE (2018), the new trends in the development of grid simulators are as follow:

- Higher power ratings: up to 24MW rating and 80MVA short circuit power.
- Grid impedance emulation: virtual impedance emulation using the converters control system.
- Higher bandwidth for harmonic injections: up to 25th or 50th or even 100th harmonics injection for stability tests.
- Extension of use for component and sub-system tests. Also, mobility of equipment to test installed DUTs in the field.

The three main parts of the generic converter-based test rig, which is shown in Figure 3, are introduced as follows.

3.1 Device Under Test

Device Under Test (DUT) can be one or more numbers of a whole WT or its sub-systems such as a nacelle consisting of converters and generator, or only converters of a WT. Nowadays, WTs are mainly full-converter or DFIG types in new developed WPPs. The main objective of test facilities is to perform compliance electrical and mechanical tests in the WT and sub-system test levels on DUT. Test results are used to evaluate the behavior of DUT during dynamic and steady-state operations according to the test standards.

3.2 Grid Emulator

The grid emulator or CGI consists of two back-to-back converter units to emulate a real grid characteristics for DUT, as it is shown in Figure 3. The first converter unit is connected to the utility grid through a transformer, which is called as "Active Rectifier Unit (ARU)". Generally, the control objective for the ARU is to regulate the DC-link voltage in a reference value within an acceptable deviation range. The reference value for DC-link depends on the type and objectives of the test. Thus, the ARU should perform as a current source to exchange active and reactive power between the DC-link capacitors and the utility grid.

The second converter unit is connected to the DUT through a transformer, which is called as "AC Grid Emulator". The controller of the AC grid emulator is designed to emulate a realistic grid dynamic and steady-state behavior. Besides, to have an acceptable range of total harmonic distortion and to prevent unwanted harmonics and noise interference in the setup, appropriate passive filters on both sides of the converters have been considered. Also, in some cases, active filtering methods are implemented by additional control strategies such as selective harmonic elimination and interleaved harmonic elimination methods, to decrease the need for the large passive filters (Gevorgian et al. (2016) and Averous et al. (2017)). High power and short circuit capacity are achieved by parallel connection of converters in each converter unit as indicated by $N(\text{ARU})$ and $M(\text{AGE})$ in Table 1. Thus, by this structure, the power flow in the CGI is controlled. Meanwhile, the assessment of DUT behavior would be accomplished by online simulations, measurements, and data analysis.

3.3 Wind Torque Emulator

Assessment of electro-mechanical interactions of WTs can be achieved by using the wind torque emulator part in the test bench. As it is shown in Figure 3, the wind torque emulator would be connected directly to the DC-link of CGI as a common DC-link, or have a separate converter unit connected to the utility grid. Separate DC-link for the wind torque emulator enables an independent control system and reduces the side-effects of power electronic converters on each other such as harmonics interference, DC-link voltage deviations, and control interactions.

The wind torque emulator is a prime mover system consisting of a drive converter connected to an AC or DC motor. This way, the characteristics of the missing WT rotor in the laboratory environment would be recreated. This objective is necessary for hardware-in-the-loop (HiL) testing of DUTs, especially for the tests, such as LVRT capability test, in which a realistic emulation of rotor torque for the DUT's main shaft is required. This requirement implies an accurate emulation of steady-state and dynamic torque characteristics of the rotor including the rotor inertia and its eigen-frequencies as studied in Neshati (2016). The drive system converts the electrical power to the mechanical power for the shaft of the generators. On the other hand, the generators convert the mechanical power to the electrical power in connection to the CGI. In this way, the power flow circulates through the utility grid, wind torque emulator, and grid emulator. The first constraint of this power circulation is the manageable power loss. Also, the second constraint for the power flow is during the LVRT capability test. During voltage sag emulation by the AC grid emulator for the DUT, the ARU has to provide the active power to the wind power emulator. Thus, the maximum required power flow and power losses during tests should be considered in the cooling system design.

4 Test Bench Characteristics

235 The advanced specification of converter-based test equipment not only makes it possible to perform grid connection compliance tests, but also gives the opportunity to analyze, understand, and predict possible challenges facing wind energy technology, and even further to develop solutions and perform validation tests. In this section, electrical characteristics of the emulated grid by an advanced test bench have been studied.

4.1 Emulated Grid Characteristics

240 The characteristics of a real power system that test article is exposed to at its Point of Common Coupling (PCC) can be emulated by CGI coupled with RTDS through high-bandwidth Power-Hardware-in-the-Loop (PHIL) interface. This way, the grid emulator can replicate all characteristics of PCC for testing DUT. The AC grid emulation can provide flexible options regarding the electrical characteristics of power grids, including impedance, short circuit ratio, inertia, and background noise.

4.1.1 Grid Impedance

245 One of the main differences between AC and HVDC connections is the structure of equivalent grid impedance as shown in Figure 2. Especially in AC-connected offshore WPPs with long AC export submarine cables, the grid impedance is high and frequency-dependent, which can create resonances and instability (Kocewiak et al., 2013). Also, in the case of onshore AC connections, the main issue would be considerably high grid impedance for remote WPPs. Typically, for AC offshore connections, the grid impedance would be considered capacitive, while for AC onshore connections, it would be high inductive
250 impedance. Besides, regarding HVDC-connected offshore WPPs, the equivalent resistance of the grid impedance is low. Thus, the natural resonance damping capability in such grids is low, and the converters of WTs are prone to interact with the converters of the HVDC system. Therefore, the harmonic stability of an HVDC connection is very vulnerable. The interactions among grid impedance, converters' controllers, and passive filters can cause instability and resonance problems in a WPP as well as HVDC station (Buchhagen et al. (2015); Kocewiak et al. (2013); Sowa et al. (2019) and Beza and Bongiorno (2019)).

255 In a synchronous-generator-based grid, large electrical loads facilitate the grid stability during dynamics and resonances. However, in such grids, the sub-synchronous control interactions between WTs and series compensated transmission lines, which is investigated in Chernet and et al. (2019), are still a serious concern. The impedance of the test bench would be arranged as such to study the sub-synchronous control interaction as well. Therefore, it is essential to consider the emulation of grid impedance characteristics in the test environment and test results. The controllable dynamic impedance emulation is
260 another advantage of the converter-based CGI, in comparison to the voltage divider test equipment shown in Figure 1, which imposes fewer uncertainties regarding equivalent impedance to the point of connection of DUT.

4.1.2 Short Circuit Ratio

As the AC system impedance increases, the voltage magnitude of the AC system becomes even more sensitive to the power variations at the PCC. This dependency is usually determined by the Short-Circuit Ratio (SCR), which is a ratio of the short-

265 circuit capacity (S_{sc}) versus the rated power of the AC grid at PCC (P_{npcc}) as illustrated in equations (1) and (2) (IEEE Std. 1204, 1997).

$$S_{sc} = \frac{V_{pcc}^2}{Z_{grid}} \quad (1)$$

Where Z_{grid} is the equivalent impedance of the grid and V_{pcc} is the nominal phase-to-phase voltage at PCC.

$$SCR = \frac{S_{sc}}{P_{npcc}} \quad (2)$$

270 The investigations in Fan and Miao (2018) have shown that a weak grid interconnection of an AC-connected WPP (e. g., ERCOT, USA) can lead to poorly damped or undamped voltage oscillations. The SCR evaluation for an HVDC-connected AC grid is defined as an Effective Short Circuit Ratio (ESCR). ESCR is the ratio of the short-circuit power of the AC grid along with HVDC converter filters and capacitor banks ($S_{(AC+HVDC)}$) to the rated power of the HVDC link (P_{HVDC}), as presented in equation (3). Typical weak HVDC-connections have ESCR less than 2.5 (Yogarathinam et al., 2017).

$$275 \quad ESCR = \frac{S_{(AC+HVDC)}}{P_{HVDC}} \quad (3)$$

The HVDC transmission limitations imposed by AC system strength, AC grid impedance characteristics and converter Phase-Locked Loop (PLL) parameters have been investigated in Zhou et al. (2014). These studies have concluded that the operation of the HVDC converter is greatly affected by the angle of the AC grid impedance. As the impedance becomes more resistive, the minimum required SCR for the rectification side converter of the HVDC system increases; In contrast, it decreases
280 at the inverting side converter. Also, the results have proven that the gains of the PLL, significantly affect the operation of the HVDC converter, particularly at low ESCRs (less than 1.3). In the case of stronger AC networks, the converters' control systems operate well as long as the PLL gain is preserved adequately large to achieve a satisfactory damping coefficient (Zhou et al., 2014).

The converter-based test bench has a similar structure to an HVDC connection system with two back-to-back converters.
285 Thus it can be used to emulate an HVDC system with different ESCRs for DUT. These emulations would be implemented by adjusting the control system, modular selection of the CGI converters and reconfiguration of output filter components, especially in a test setup consisting of an RTDS system.

4.1.3 Grid Inertia

The grid inertia is another important criterion for evaluation of grid strength. The effective inertia constant (H_{dc}) for an HVDC-
290 connected AC grid is defined as the ratio of the total rotational inertia of the AC system (E_{TI}) in MW-s to the MW rating of the HVDC link, which is illustrated in equation (4).

$$H_{dc} = \frac{E_{TI}}{P_{HVDC}} \quad (4)$$

H_{dc} is less than 2.0 for weak grids (Yogarathinam et al., 2017). In an HVDC-connected offshore WPP, there is no rotating mass. Therefore the inertia is zero. The test bench converters can be considered as an HVDC system connection for DUT. In this

295 way, by **adjusting** the CGI control system, it is possible to emulate different inertia ranges to evaluate the control performance of WTs.

4.1.4 Background Harmonics

The background noise and harmonics are high-frequency content in the grid voltage as part of harmonic sources. By increasing converter-based installations, the harmonic injection and interactions have concerned the power system operators and WPP
300 developers. The possible harmonic challenges can be studied in two main categories as follows:

– Harmonic emission sources: Non-ideal power sources and non-linear loads generate harmonics. The harmonic emission is a power quality issue and **would be assessed** by measurements **data analysis** (Sørensen et al., 2007). From power quality point of view, the harmonic emission is important because of power loss, system operation interference, and **effect on** overall cost. The assessment of emission limits for the connection of distorting installations at medium and higher voltage
305 levels is recommended in IEC 61000-3-6 technical report. The emission limits depend upon the **consented** power of the connected power plant and the system characteristics (Joseph et al., 2012).

– Harmonic stability issues: Primarily, harmonic stability problems are significant in the case of fully renewable-based power grids; since converters mostly dominate such grids. Therefore, HVDC-connected offshore WPPs are the main subject of harmonics and resonance studies. As an example, BorWin1, which is the first offshore HVDC station and is
310 developed to transmit wind energy from BARD offshore WPP to the onshore grid in Germany (Buchhagen et al., 2015). So far several serious problems such as outages of the HVDC station, severe harmonic distortion, and resonances in the offshore grids, have been reported because of harmonic interactions among active components such as power converters, and passive components such as filters and grid impedance (Buchhagen et al. (2015); Kocewiak et al. (2013); Bradt et al. (2011)). Besides, it is crucial **to consider** that the current limit recommendations in the standards do not apply to
315 harmonic currents that are absorbed by the WPPs from the background harmonic source of the grid. Therefore, series and parallel resonances from the capacitive collector cable can easily occur in the WPP, by absorbing more harmonic current than **determined in** the standards (Kocewiak et al. (2017); Preciado et al. (2015)). One of the promising study proposals for the harmonic stability of converter-based power systems is impedance-based analysis (Sun, 2011).

According to Bradt et al. (2011), in the case of harmonic studies, the utility grid is characterized by two groups of parameters:
320 The first category is the background voltage distortion present at the PCC without connection of the WPP. The second category is the driving-point impedance of the grid at harmonic frequencies, which consists of transmission system harmonic impedance and reactive compensation equipment equivalent impedance. The harmonic content of the synchronous generator-based grids would contain low order harmonics due to non-linear loads. While a converter-based grid mainly would have high order harmonics generated by high-frequency switching concepts of the power converters. Therefore, it is essential to emulate **more**
325 **realistic grid** background harmonics using test equipment and evaluate the performance of DUT with the presence of the grid harmonics. However, high order harmonic injection would need high bandwidth in the output transformer of the AC grid emulator and the measurement instruments.

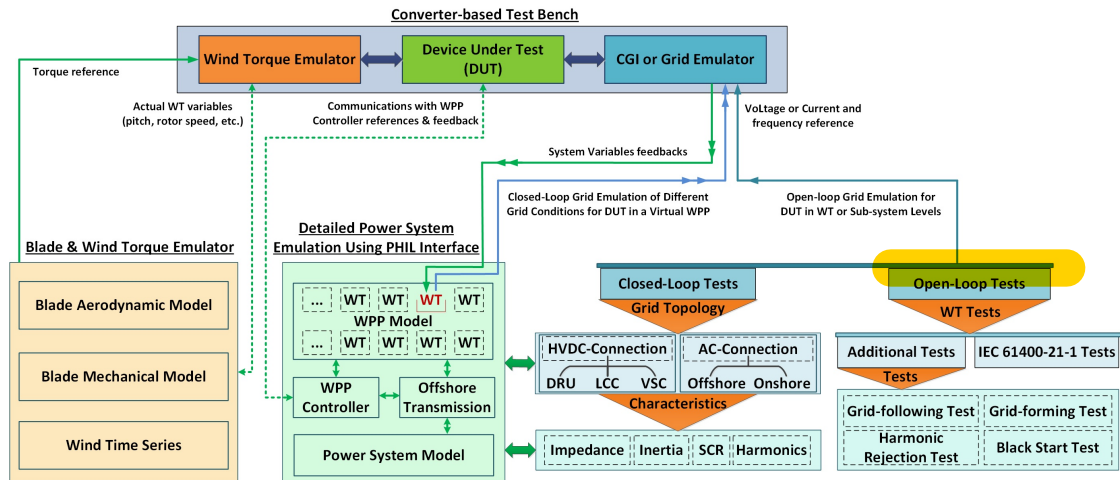


Figure 4. Proposed test structure for converter-based test benches.

4.2 Utility Grid Effects on a Test Bench

The interconnection of the grid emulating CGI and the utility grid depends on their characteristics. If the utility grid had low SCR, then the CGI connection to the utility grid would be very similar to an HVDC connection to a weak AC grid. According to Durrant et al. (2003), using current vector control for converters, only 0.4 per-unit (pu) power transmission can be obtained for DC-link, where only in one of AC sides of the CGI (DUT or utility grid sides), the SCR is 1 pu. However, by using more efficient control methods or increasing DC-link capacitance, it can be increased to higher than 0.8 pu (Zhang and Harnefors, 2011). Also, the connection of CGI to the utility grid should comply with the local grid connection requirements regarding power quality aspects. Therefore, it is vital to consider the local grid characteristics and connection requirements in design and control strategies for the test bench.

5 Proposed Test Options for Advanced Test Benches

In general, control of a WPP is managed by two control levels: WPP control level, and WT control level. The control system of a controllable grid interface (CGI) can be designed considering objectives of tests, specification of DUT and research and development studies. The test of DUT should be performed as such to ensure that the emulators would not affect the test results. In Figure 4, the proposed test structure for advanced test benches is illustrated. Depending on the test modes and study objectives, the reference values for the controllers of the test bench converters would be prepared using either Power-Hardware-in-the-Loop (PHiL) interface or real-time system model calculations (Koralewicz et al. (2017); Averous et al. (2017)). The electrical test options consist of two main groups including open-loop and closed-loop tests. The open-loop tests include the capability evaluation tests in WT and sub-system levels and recreate the grid events according to predefined references and waveforms for the CGI converters. The open-loop tests consist of IEC 61400-21-1 standard compliance tests and additional

proposed tests including grid-following, grid-forming, blackstart, and harmonic rejection capability tests. The second group of tests are proposed for validation of grid interactions in a system level including different grid connection topologies and characteristics. The closed-loop tests would analyze the behavior of DUT in connection to a virtual WPP by online simulation of a detailed power system.

Besides, the blade and wind torque control unit for wind torque emulator would be necessary in the case of WT's nacelle tests. Typically, the nacelle of WT contains gearbox, generator, converters, and output transformer. Since the mechanical parameters vary slower than electrical parameters, the speed or torque references can be defined as set-points in short-term studies for electrical tests. However, for long-term studies, the aerodynamics, pitch control, and mechanical torque could be considered in control of the wind torque emulator (Neshati, 2016). According to Figure 4, the torque or speed references for the drive system can be derived from real-time calculations based on blade aerodynamics and mechanical models, and wind speed time series. The control methods for converter-based CGI have been discussed in Gevorgian et al. (2016), Zeni et al. (2016), Espinoza et al. (2019), Espinoza et al. (2015) and Neshati (2016). In the following sections the IEC 61400-21-1 standard tests and additional proposed open-loop tests for WT capabilities as well as the proposed closed-loop tests are introduced.

5.1 IEC 61400-21-1 Standard Open-Loop Tests

Nowadays, most of the industrial test benches have been focused on performing the grid connection compliance tests, which are recommended in IEC 61400-21 standard. Therefore, in this section, the electrical characteristics to be simulated and validated for wind turbines are studied according to the IEC-61400-21-1 standard (IEC 61400-21-1, 2019).

5.1.1 Power quality aspects

The power quality tests consist of measurement of harmonic emissions and flicker tests. Flicker addresses the voltage fluctuations imposed by WTs under continuous and switching operation conditions. Mainly, the flicker effect is considerable for the first generation of WTs without power converters, which were widely connected to distribution power systems in the previous millennium. The harmonic emission consists of current harmonics, inter-harmonics (non-integer multiples of the fundamental frequency), and higher frequency components during continuous operation.

The power quality of the emulated AC grid can be arranged based on the emulation type, including HVDC or AC connection. Accordingly, the power quality aspects can be emulated for DUT. The flicker can be generated by adding a low-frequency component to the fundamental frequency of reference signals for the AC grid emulator unit. In addition, to study the harmonic interactions of WTs in a WPP, the harmonic injection tests have been considered in several test sites (Gevorgian et al. (2016); Sun et al. (2019)). Depending on the converter switching frequency of the AC grid emulator, output filter, and transformers' bandwidth, part of low order harmonics can be injected to the connection point of DUT. To date, there is no dedicated standard or regulation for harmonic interaction studies.

5.1.2 Steady-state operation test

The steady-state operation test evaluates the active power (P) production against wind speed, maximum power, and reactive power (Q) capability of DUT. These characteristics aim to validate the power-speed and P-Q curves. The test procedure and
380 necessary measurements have been recommended in IEC 61400-21-1 (2019).

5.1.3 Control performance test

Active and reactive power related controls by WT can be divided into two major categories: WT level control and WPP level control. Control performance testing of each of these categories requires special technique. The methods discussed in this section are related to the WT level control. In this way, control performance refers to the ability of a WT in terms of active
385 and reactive power control and grid frequency support. The assessment of power control performance is verified by set-point tracking speed and steady-state error of the control system. Also, the grid frequency support includes the active power reduction as a function of the grid over-frequency conditions. Providing additional active power during under frequency events is another grid frequency supporting feature, which should be evaluated through the relevant tests.

5.1.4 Transient performance test

The transient performance or Fault-Ride Through (FRT) capability consists of Low Voltage Ride-Through (LVRT) and High Voltage Ride-Through (HVRT) capabilities. Within the last decade, several serious WT tripping incidents have been reported in different countries such as Germany, China, and the UK due to voltage dips (under-voltage) and swells (over-voltage). Voltage transients have led to cascaded system trips, over-voltage excursion in transmission systems, and serious frequency deviations in power grids (Langstadtler et al. (2015); Wiser et al. (2018); Zhang et al. (2016)). Also, the measurements on real WPPs have
395 shown that during HVDC converter blocking, the voltage at the WT terminals may increase by 30%, and even it can spike up to 2.0 pu by other transient processes (Erlich, 2016). These incidents have indicated the necessity of HVRT and LVRT capabilities for WTs. Consequently, by facing similar problems, some countries, such as Germany, Denmark, Spain, the USA, Italy, and Australia, have adapted the national network codes for both HVRT and LVRT capabilities. Accordingly, the FRT capability demands the WTs to tolerate a specified range of high- or low-voltage events for certain periods.

400 The compliance tests can be implemented by giving open-loop voltage reference values for the AC grid emulator as a voltage-time profile according to the network codes. In the case of the LVRT capability test, the Active Rectifier Unit (ARU) would decrease the DC-link voltage to achieve an efficient modulation index and less voltage stress on switches and filters of the AC grid emulator. However, this is not possible in cases that wind torque emulator is connected directly to the ARU.

So far, the solutions for the HVRT capability test using full-converters have been either utilization of step-up tap transformers
405 or over-designing of the converters to be able to generate the required over-voltage range. In the case of converters over-design, the ARU should increase the DC-link voltage to make the over-voltage emulation possible for the AC grid emulator. However, using a step-up tap transformer, the nominal output voltage of the converters would be set as such to generate the maximum over-voltage at the output terminal of the transformer, which is connected to DUT.

One of the critical specifications of a test setup for FRT tests is the Rate of Change of Voltage (RoCoV) during the emulation
410 of voltage dynamics for DUT. The AC side converter should be able to simulate over-voltage or under-voltage events very fast.
This is one of the main advantages of converter-based CGIs that can emulate 100% voltage changes within less than 1 cycle of
the fundamental frequency of the grid. The fastness of a converter depends on ESCR, DC-link capacitors, short circuit current
capability of the AC grid emulator, control system, and overall system delays.

Furthermore, one of the recent studies in dynamic performance is the response of WTs against unbalanced faults. The
415 unbalanced voltage deviations can be performed by setting positive and negative sequences in the voltage references and
control loops for the AC grid emulator. The emulation of faults with zero-sequence voltage by CGI is challenging. However,
this type of fault emulation is not necessary because of the transformers and three-wire structure of WTs. In such structures,
the zero-sequence does not propagate to the WTs. However, the objective of tests with zero-sequence voltage would be the
assessment of a four-wire sub-system with grounded wire.

420 5.1.5 Grid protection test

Grid protection tests refers to the disconnection and re-connection functions of a grid-connected WT following its different
protection schemes. Protection schemes for disconnection from the grid operate during extreme amplitude changes or the rate
of changes in voltage and frequency of the grid. The relevant test procedure to the protection schemes evaluation is provided
in IEC 61400-21-1 (2019).

425 5.2 Additional Proposed Open-Loop Tests

In this section, the additional open-loop tests to the IEC 61400-21-1 standard regarding WT capabilities are proposed, as it
is presented in Figure 4. The higher importance of the WT capability tests is because the wind turbine manufacturers are
developing their products with advanced features that are required to be verified following the appropriate test standards and
regulations. Therefore, it is urgent to foresee the near future needs in the standards. Besides, the grid connection compliance
430 tests would be used for design validation of wind turbines or their subsystems as well.

5.2.1 Grid-following capability test

The electrical characteristics, which are considered in the IEC 61400-21-1 standard, only concern the performance of DUT in
grid-following mode. In this way, the WTs are considered as current sources that follow the frequency and voltage references of
the connected grid. Therefore, the grid-following capability of DUT addresses the control performance test, which is done for
435 the nacelle of WTs in industrial test benches. However, this test is applicable in WT and WPP levels using the PHIL interface,
as well.

5.2.2 Grid-forming capability test

Recently, the grid protection ability of WTs has been extended to a new capability, called "grid-forming capability". WTs with grid-forming capability can perform as a voltage source to form a local AC network during disconnection from the main power grid and supply local loads. Some manufacturers have designed a new generation of WTs with more flexible features such as the grid-forming capability to enhance the stability and reliability of converter-based power generation and the interconnected power systems. According to the grid connection requirements, WTs are allowed to disconnect from the AC grid during very severe voltage or frequency deviations out of their tolerable ranges. However, grid-forming WTs can support local loads and increase the reliability of WPPs (Tijdink et al., 2017).

Test bench converters can simulate fault occurrence conditions for DUT to evaluate the grid-forming capability of such WTs. During the grid-forming operation of DUT, the CGI should perform as a current source converter and active load for the DUT. This study case would be more challenging when the WTs are meant to be used in an HVDC-connected offshore WPP in which there is no considerable local load for the offshore WPP. In all cases, the grid-forming capability is a temporary operation mode, which would be followed by reconnection to the grid and resuming the normal operation.

5.2.3 System restoration and black start capability test

Following a partial or complete shutdown, it is crucial to restore the defected network and stabilize the overall power system. System restoration is the capability of reconnection of WTs to the grid after an incidental disconnection caused by a network disturbance. According to European network codes (Commission Regulation 631, 2016), the system restoration requirements consist of black start, island operation, and quick re-synchronization capabilities. State-of-the-art WTs can be equipped with functions such that they can start and run without the need for external auxiliary power supplies (Jain et al., 2018). Black start capability is one of the advanced features of WTs, which helps fast and environmentally friendly power system restoration. The black start would be essential for the start-up of a power generation unit or restart after shutting down due to faults. In a WPP, after the system shuts down, part of WTs with black start capability should be energized by an internal storage system. Then, the energized WTs should be able to energize the rest of WTs by producing wind power over time (Tijdink et al. (2017) and Jain et al. (2018)). A similar process has been described for the black start of converters of an HVDC station (Commission Regulation 631, 2016). The performance of DUT during system restoration conditions can be studied using advanced converter-based test benches.

5.2.4 Harmonic rejection test

The harmonic stability and harmonic interactions of wind turbine control systems can be studied by injecting harmonic voltages and currents to the wind turbine terminals using the test bench converters. This way the harmonic rejection capability and durability of WTs and their control system can be evaluated. The experimental verification of the impedance-based stability analysis method for harmonic resonance phenomena is presented in Sun et al. (2019). Besides, in the modern test setups, harmonic injection ability is considered as an advantage using CGI converters or additional equipment (Averous et al. (2017);

470 Gevorgian (2018); Jersch (2018); Rasmussen (2015)). Accordingly, converters' response to the specifically injected harmonics would help to analyse harmonic interactions with wind turbine control system.

5.3 Proposed Closed-Loop Tests

475 In this section, the closed-loop tests are proposed concerning the grid integration challenges of WPPs, such as HVDC system interaction, weak grid conditions, sub-synchronous, and harmonic resonances. Different grid topologies and characteristics are considered in the proposed test options to emulate a more realistic grid connection for DUT. It is evident that it is not feasible to simulate all different aspects of a real power system for a WT or WPP; however it is possible to assess part of most critical conditions in a test environment and validate the simulation models (Ausin et al. (2008); Zeni et al. (2016)).

5.3.1 Detailed power system emulation

480 The IEC 61400-21-1 standard considers the tests for a single WT, or it's sub-systems, which can be performed by CGI converters. However, these tests do not address the electrical power grid interconnection issues, such as converter interactions in the WPP level, grid characteristics influences, renewable power generation integration, and power system stability issues. Detailed power system emulation can be performed through a Power-Hardware-in-the-Loop (PHiL) interface. According to Figure 4, the voltage, current, and frequency references for the CGI converters can be extracted from the overall system model, including WPP, transmission system, and power system models. The CGI would emulate the characteristics of the AC grid for DUT in its connection point to the simulation model. The detailed power system emulation using the PHiL interface would be an effective option to perform several tests on the WPP level and analyze the behavior of DUT in extensive system conditions.

5.3.2 SCR and inertia emulation test

490 SCR of the interconnected AC grid has an essential impact on the behavior of WTs. Emulation of a variable SCR and X/R ratio allows studying the control system and stability of WTs. The number of converter modules and DC-link capacitors modifies the rating power and ESCR of the AC grid emulator. Besides, the software options for variable ESCR are considering a virtual impedance and current and power limits in the control loops of converters. In Wang (2015), the virtual impedance control method for a converter has been studied in detail. Accordingly, the virtual impedance controller behaves as a series-connected impedance at the output of a voltage source converter, which can be implemented using the RTDS system.

495 The magnitude of feasible inertial response by WT generator and related stability implications would be highly dependent on the location of the WPP in the power grid and SCR of PCC. The grid emulator would allow exploring these limits using the RTDS system and relevant control schemes for the CGI converters. Therefore, it is possible to emulate all inertia range from the conventional generation ($H_{dc}=14s$) down to HVDC-connected offshore grids ($H_{dc}=0s$) in a test environment to assess the performance of WTs. In Zhu (2013), the inertia emulation control method using converters of an HVDC system is proposed. It is shown that the inertia of a voltage source converter depends on the number of capacitors, DC-link voltage, and output frequency. Therefore, these options can be used for inertia emulation by CGI.

500 5.3.3 Different grid connection test

As it is described in section 4, AC and HVDC transmission systems impose different electrical characteristics and control schemes on WPPs. The converter-based CGIs allow emulating these differences in a test environment for the DUT. The control and operation system of an HVDC system depends on the structure of the HVDC converters as well. Typically, there are three topologies for the HVDC converters illustrated in Figure 4-b: Line Commutated Converters (LCC-HVDC), Voltage Source
505 Converters (VSC-HVDC), and Diode Rectifier Units (DRU-HVDC) Göksu et al. (2017). The CGI converters have IGBT or IGCT switches in reversed-parallel connection with diodes. The converter switching method can be adjusted to perform switching based on the type of emulated HVDC topology.

The DRU-HVDC system is a cost-effective option to be used in offshore wind power transmission. To replicate a DRU-HVDC, all of the test-side converter switches should be turned off, and the remaining diodes can operate as a DRU converter.
510 On the other side, the ARU should perform DC voltage regulation. The control methods for DRU-HVDC connected offshore WPPs have been studied in Göksu et al. (2017).

5.4 Discussion

The test structure for converter-based test equipment is proposed and studied in two main groups, including open-loop and closed-loop tests. The demand for open-loop tests is urgent due to developments in the WT design and manufacturing process.
515 As it is discussed through this section, the state-of-the-art test benches are adjustable to perform tests regarding the new capabilities of WTs, mainly by new control schemes for the converters of the test bench. Besides, the use of RTDS systems for online simulations and high-speed communications in the test bench would make it feasible to implement the closed-loop tests. This way, the increasing challenges regarding operation and control of WPPs can be simulated in a test environment. The proposed test structure covers the needs of industry and research and development studies regarding the compliance test of
520 WTs and assessment of WPPs. Furthermore, some parts of the tests, such as harmonic rejection, transient performance, power quality, and control performance, would be useful for the design validation of WT and its sub-systems as well. On the other hand, both groups of tests would be helpful to validate simulation models in WPP as well as WT levels. Therefore, the tests on the DUT can be performed as such that the results to be transferable for higher levels including WT and WPP levels.

The future works would involve in implementation of the proposed additional test options and measurement data analysis.
525 The authors aim to propose and evaluate new test methods using available advanced test benches to increase their beneficial applications and reduce the necessity of field tests, which are difficult and costly.

6 Conclusions

In this paper, the generic topology of industrial test benches has been proposed. According to the structure of available industrial test benches, there is a strong potential for general harmonized topology and methods for test and assessment of WTs
530 and WPPs. Primarily, the focus of IEC standard tests had been on the compliance test of WT capabilities through predefined

open-loop tests. The new features of modern WTs, such as grid-forming, system restoration, black start, harmonic rejection, and frequency support capabilities, have been introduced by manufacturers to support renewable energy dominated power grids. These new features necessitate new or reformed test standards in the near future. Therefore, the appropriate additional test options for newly developed capabilities are proposed. Besides, increasing challenges in wind energy integration, such as control interactions, harmonic resonances, and grid characteristics influences, have compromised the renewable generation based power grids. In this regard, the closed-loop test options for the grid interaction tests concerning different grid characteristics and topologies are proposed. The electrical characteristics of different grids consist of impedance, inertia, and SCR. In addition, the grid topologies include AC and HVDC transmission systems, as well as different HVDC converter types. By real-time simulation of the detailed power grid, the wind integration challenges can be emulated in WT and WPP levels.

Most of the available advanced test sites are developed based on full-converters. Therefore, the characteristics of a real power system can be emulated by the grid emulator coupled with RTDS systems through a high-bandwidth PHiL interface. Although it is not feasible to simulate all different aspects of a real power system; however, it is possible to assess part of the most critical conditions in a test environment and validate the simulation models for WTs and WPPs. Besides, part of the proposed tests would be applicable for the design validation of WTs or their subsystems. This way, the possibility of research, development, and demonstration studies on wind turbines and wind power plants would increase.

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