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WTG Grid Compliance Testing and Validation Part 2: Combined Test Rig- and Prototype WTG-Based Model Validation Proposal

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Abstract

The traditional method for electrical model validation of Wind Turbine Generators (WTG) relies on full-scale field prototype turbine testing. Model validation based on full-scale field testing is, without argument, the most reliable and robust way, but it also presents limitations. Major limitations include the scope of faults, controllability of events, time, and ultimately, cost. There are events such as phase jump, fast frequency change, single-phase-to-ground faults, etc., that would require an advanced test container setup to be performed on full-scale field testing. Furthermore, the availability of the turbine for testing is also heavily dependent on the weather/wind conditions, which can considerably prolong the test campaign. To address these limitations, this paper proposes a strategy, backed by the results from Part 1 of the paper, that utilizes EMT models and test rigs to enhance the testing and validation robustness of a new WTG. The proposed strategy includes three pillars: using EMT models for assessment before testing, conducting test rig testing for grid compliance and model validation, and finally, testing and verification with a reduced scope on the full-scale field turbine. By including additional steps prior to testing on the field prototype WTG, this strategy aims to build a more robust testing and validation strategy for developing better models to be used in studies during the design and operational life cycles of WPPs. The results presented in the paper show that this process can speed up model delivery while improving robustness. The paper further highlights that grid compliance can be tested and validated in different ways, and flexibility on the requirements to Original Equipment Manufacturers (OEMs) shall be present to allow more innovation in the processes while ensuring that model validation and model quality, as the main objective, is maintained.

1 Introduction

The utilization of large-scale wind power plants (WPPs) and other inverter-based resources (IBRs) is projected to experience rapid growth in the coming decades, leading to increased complexity in power system design and operation. While the power industry has historically relied on established metrics and models for stability and fault analysis for over a century [1, 2], the growing prevalence of IBRs necessitates a reevaluation of these approaches. As IBRs become more prevalent, their impact on traditional stability definitions must be acknowledged and factored into power system planning and operation [3]. Consequently, there is now a greater emphasis on the development of advanced modeling tools aimed at ensuring the reliable integration and operation of new assets in the grid.

Traditionally, model validation WTGs is carried out based on full-scale prototype turbine testing. These models can be commonly referred to as "electrical client user models" or "user-defined models," which are handed over by the OEM to developers and other stakeholders performing studies at the plant or system level [4, 5]. This validation process can last for several months or even years, depending on different factors such as weather conditions, external site/equipment availability, and the scope and complexity of grid compliance tests. In the context of grid compliance, such tests are usually required for both certification of the WTG in different grid codes and validation of electrical models. Nonetheless, as turbines get larger and requirements for testing and validation become more stringing and comprehensive, the current methodologies utilized by the wind industry are being challenged, and alternatives are being sought after [5–10].

This paper, based on the detailed methodology and results presented in Part 1 for the Grid-Converter Test Rig (G-CTR), showcases the PSCAD model validation results and presents a validation strategy for utilizing models and test rigs to enhance the testing and validation robustness of a new WTG. Initially, the paper presents past OEM experiences with a testing strategy centered around using only field prototype WTG, which has challenges and limitations. With the increasing confidence levels gained on the performance of test rigs, such as G-CTR, and EMT models with the actual latest converter control software, this paper argues that it is in the best interest to utilize these resources as much as possible to speed up the processes of testing and validation and at the same time improve model quality.

The three pillars of this strategy are presented: 1- EMT Models with the actual latest converter control software are used for thorough assessment prior to testing. 2 – Test rig testing, certification, and model validation; 3 – Final fine-tuning and testing on the field prototype turbine. By including additional steps prior to the testing in the prototype WTG, this strategy aims to build a more robust testing and validation strategy centered around several steps towards achieving better models to be used in studies during the design and operational life cycles of WPPs.

Results for PSCAD model validation in G-CTR are shown, and reflections are made on how this process can speed up model delivery while improving robustness. This process, however, requires extensive knowledge of the limitations and capabilities of the model, the test rig, and the WTG prototype so that explainable results are obtained. In the end, the paper concludes by exploring other alternatives and showcasing that grid compliance can be tested and validated in many different ways, and flexibility on the requirements to OEMs shall be present to allow more innovation in the processes. The industry's potential for researching and developing new turbines, services, and solutions is limited by the requirement for full-scale prototype testing despite its high fidelity.

2 Model Validation and Industry Practices

This section presents a general idea of the industry's current model validation strategies. It also discusses challenges and opportunities for improvement in terms of quality and time/cost related to model validation for a new product. As previously mentioned, full-scale field prototype turbine testing has been the primary methodology for testing and validating wind turbines. However, this approach has limitations and challenges, mainly in two areas: time/cost and quality.

2.1 Improvements of Time and Cost

One of the main drivers for the wind industry nowadays is decreasing the Levelized Cost of Energy (LCOE), which generates the need for faster time-to-market of new products. At the same time, as more stringent requirements are being applied to both OEMs and WPP developers, testing and modeling tend to take longer, creating a paradoxical scenario. As seen in Figure (1), the exponential increase in requirements often can result in a longer time required to validate models. Conversely, due to the growing demand for connection studies of new WPPs, developers and other parties involved in WPP studies tend to require models earlier.

The challenges that can affect the timeline of model deliveries and cost can be divided into four categories:

- **Weather Conditions**: Many tests on a full-scale field WTG require specific weather conditions to be present for an extended amount of time to perform tests at very low wind or particularly at high wind for rated power production. OEMs often experience long waiting periods of days/weeks for suitable weather conditions. Particularly, there are occasions when tests are required to be performed for 10 minutes or longer, and the wind suddenly changes during the test, generating the need for repeating the test.
- **External Equipment and Site Availability**: As turbines get larger and grid requirements get wider, the need for specialized equipment to emulate different grid events is increasing, such as Rate-of-Change-of-Frequency (RoCoF), phase jumps, etc.
- **Updates of Software**: As measurement campaigns tend to last longer, often longer than a year, software upgrades introducing new features may be rolled out. These upgrades, in some instances, may require repeating validation.
- **Validation of Upgraded Designs**: During the design process, new variants of existing WTGs may be done, after the validation of the initial design has been concluded. In this scenario, when the WTG family has already been extensively validated, carrying out a new grid compliance measurement campaign on a new field WTG would require an extensive time before validated models of the turbine variant could be delivered.

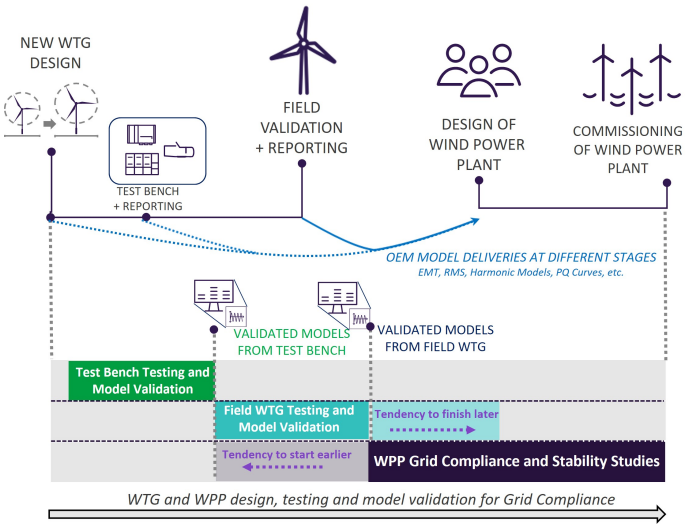


Fig. 1: Challenges during Grid Compliance Model Deliveries.

2.2 Improvements of Quality

As WPPs become larger, high-quality models are essential more than ever to ensure the designs are done properly and that the operation of the plant is reliable and compliant with grid code requirements. Models are continually being requested earlier, sometimes before the validation campaign is completed. In such situations, by validating models earlier, e.g., on the test bench, more realistic and higher-quality studies at the WPP level can be obtained. Furthermore, the test bench offers flexibility on the tests and validation that can be performed, which are otherwise not possible on field testing currently, such as single-phase-to-ground faults (1ph-g), Phase Jumps, RoCoF, etc., ensuring better results at plant-level simulation and thus

increasing model quality. For e.g., as described [4], 1ph-g cannot be done on the field due to safety concerns, and as these are the most common types of faults, it is important to use other methods to validate models against such faults.

Furthermore, improvements in quality may directly impact positively cost and time. Due to the extensive time necessary for testing in the field, models get validated for different grid codes at different times, as required by the projects. Each grid code requires a specific fault-ride-through response and, in some cases, specific tests. It presents a potential risk that the product/model may not necessarily be tested thoroughly considering the scope of tests and parameters required.

3 Proposed Methodology

To overcome the aforementioned challenges, component and subsystem (C&S) tests can aid in the overall wind turbine grid compliance testing campaign, making it possible to start tests earlier, validate models faster, and verify additional grid compliance features. This way, grid code-specific tests and market-specific models can be performed and validated concurrently, allowing for better model quality and robustness. Such tests can be carried out on parts of the entire system or at the component level and can represent certain responses or behaviors of the entire system without requiring all the parts to be assembled and present during the test.

A methodology for testing and validating models is therefore proposed aiming at delivering faster and more robust models to different stakeholders in the industry. The strategy can be seen in Figure (2), whereupon the design of a new WTG, the models from the previously validated turbines, and the knowledge acquired can be leveraged to perform a preliminary model-based assessment. Sequentially, test benches, like the one presented in the next sections, can be used to perform validation following grid code requirements and internal specifications. Finally, the field full-scale prototype WTG can be used for the final validation of internal specifications. In the next subsections, the proposed methodology will be further explained.

3.1 Internal vs External Test Cases

Initially, the definition of two types of tests is proposed. Internal test cases aim to exercise the turbine's capability and limitations. OEMs have the best knowledge of WTG features and limitations, as well as experience with grid code tests. This is used to define suitable internal tests that will comprehensively demonstrate WTG behavior in many different configurations and grid conditions to obtain a thoroughly validated model compared to validation against a single specific grid code.

On the other hand, it is known that certain grid codes and other stakeholders often require specified tests at a specific configuration. In these situations, external test cases are defined according to specifications given by outside stakeholders.

3.2 Three-Step Process

As mentioned, the strategy is built in a three-step process to achieve faster and higher quality models. Below, the three steps are further explained:

- **Preliminary Model-Based Assessment :** At this stage, the latest available model is updated with the specifications of the new WTG, which may not yet be built, and the internal test cases exercising turbine capability are performed. During this process, potential problems can be identified and fixed in software.
- **Test-Bench Testing and Model Validation :** For testing and validation in the test bench, it is proposed that both internal and external test cases are tested. As the setup is fully controllable, tests and debugging can be performed faster; therefore, more tests can be covered. Internal cases exercise turbine capability and are performed first to solve any further problems that the model-based assessment could not address. External test cases are also performed once the model is validated for internal test cases and the model is further validated.
- **Full-Scale Field Testing :** At this final stage, due to the many limitations on site, it is proposed that only internal test cases are performed. Field testing is where all components in a wind turbine will be tested together. Though all grid-related performance is expected to be captured by a test-bench setup, full-scale field testing is still important where other aspects, such as the actual mechanical system and other components of a wind turbine, are tested together with the converter and the electrical system. The objective should be to perform fast yet conclusive internal model validation at the field WTG.

3.3 Transitive Property of Equality

As it will be better described in the next few sections, a direct comparison between a test bench and field may not be the most optimal strategy. First, validation on the proposed test bench and field validation are foreseen to happen at different times, fulfilling one of the primary purposes of earlier model deliveries. Secondly, a test bench (especially with Power Hardware-in-the-loop) will most likely have some different electrical components when compared to field WTG. Nonetheless, the WTG parts deemed important for model validation remain identical and therefore the response in both setups is equally representative of the core WTG behavior.

It is, therefore, proposed that the transitive property of equality (i.e., if A = B and B = C, then A = C) is applied in this context. The variations between field WTG and a test bench are attributed solely to the additional electrical components present and are accurately mapped in the EMT models representing each setup. Therefore, if EMT models match each setup accurately, it can be indirectly proven that the test bench and field are equivalent in relation to the operating conditions and disturbances applied in the test cases. This strategy will be further supported by the results section.

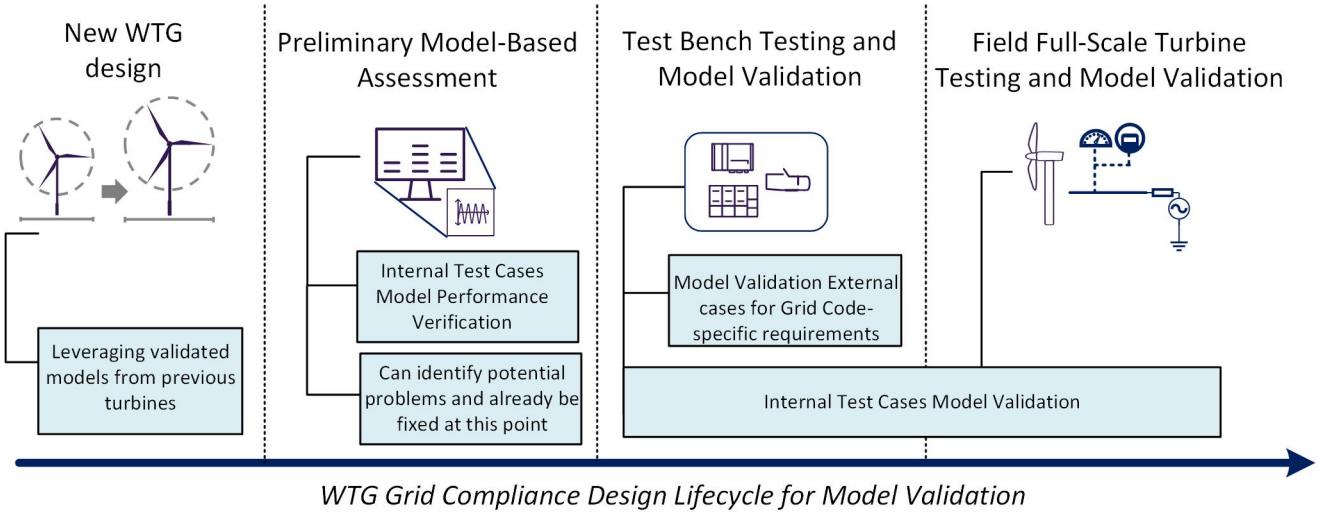


Fig. 2: Overview of Proposed Strategy for Model Validation.

4 Test System and Validation Methodology

In Figure (3), a simplified diagram shows the G-CTR and the full-scale field prototype WTG test systems used for certification and model validation of WTGs. The field prototype WTG is a full-scale one-to-one system equivalent to the actual WTG system. The WTG is connected to the 0.69/66 kV transformer. This transformer is then connected to a 66/33kV transformer connected to the test equipment used for applying faults, known as the Fault Ride-Through (FRT) Container.

The G-CTR is designed to thoroughly test and validate the grid connection characteristics of large-scale wind energy converter units. As seen in Figure (3), the Device Under Test (DUT) comprises the converter modules, converter control, WTG control, reactor, filter, and auxiliary systems optionally. The generator side of the back-to-back converter is connected to a generator emulator, which receives set points from a real-time generator model and a servo-aeroelastic simulation tool. On the net side, the DUT is connected through low-voltage (LV) cables to a transformer, and then connected to the grid emulator. This system operates as a power-hardware-in-the-loop, with power electronic devices emulating the generator and grid sides. These devices are based on ABB's medium voltage drive system, utilizing industry-proven hardware and dedicated real-time control to act as a programmable voltage source. This setup enables the emulation of an electrical machine and the grid with associated disturbances to assess the grid connection properties of the DUT. The grid emulator is equipped with a passive filter to adapt voltage quality and decrease distortions, resulting in good voltage quality and controllability. The electrical system has a closed-loop configuration, supported by the active rectifier unit supplying the DC-link and allowing for bi-directional power flow with a controllable power factor. The grid emulator's impedance control at the fundamental frequency was tuned as described in part 1 of the paper. This way, the G-CTR's response is expected

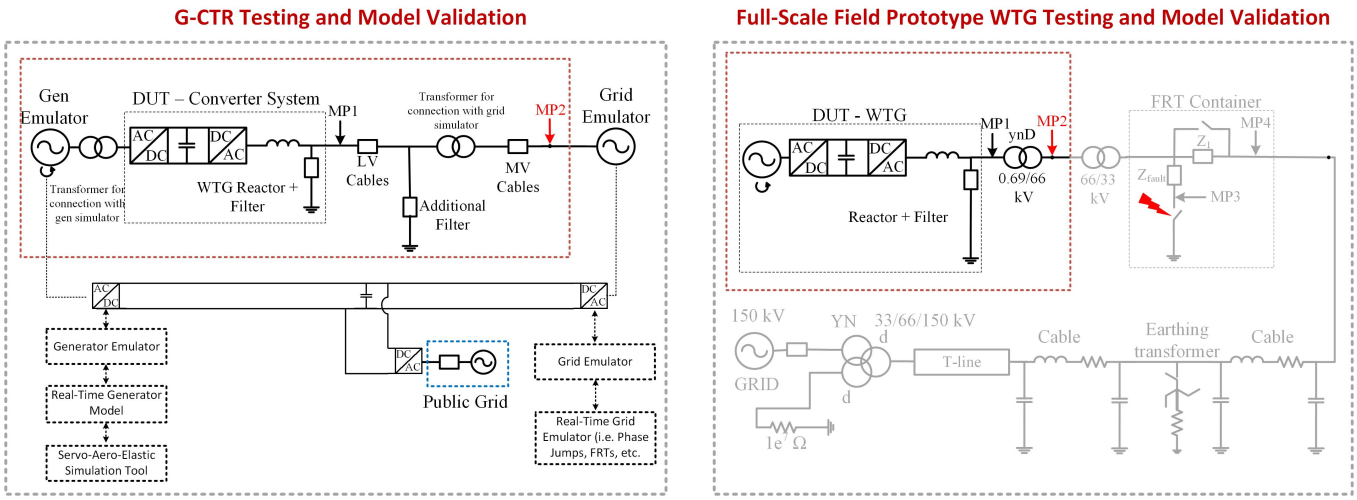


Fig. 3: Overview of G-CTR and Field Full-Scale Prototype Test Systems.

to be similar to the field but some differences are nonetheless expected due to the other components and their frequency-dependent/ non-linear behaviors. For a more detailed description of G-CTR, refer to Part 1 of this paper and [11].

4.1 EMT Model

The WTG EMT model used in this paper was built in PSCAD™. The electrical system comprises a permanent magnet synchronous generator (PMSG) direct drive and a back-to-back full converter (commonly referred to as Type IV WTG) along with a DC link with the chopper, WTG transformer, and measurement ports. The mechanical system of the WTG includes aerodynamic and shaft models. Additionally, the control system incorporates a reduced order WTG level control, encompassing pitch, power, and speed control, and a comprehensive converter control with the actual source code embedded as a *.dll* (dynamic link library). This part is considered the common model core between the two PSCAD models used. One representing G-CTR and the other representing the field.

Besides the core components common to both models, the PSCAD models for G-CTR and full-scale field prototype WTG need to account for the inherit differences in the two setups, particularly on the network side, which can be seen in Figure (3). For G-CTR, the converter system is connected to LV cables, filters, additional transformer (for connection to the grid emulator) and an MV cable where the voltages are recorded for play-back. On the other hand, for field WTG, the DUT is connected to the actual WTG transformer and the voltages at the MV terminal is played-back for model validation. So the two setups are slightly different though the main component which is the back to back converter system within the DUTs remain the same.

4.2 Model Validation Methodology

There are essentially two measurement points (MPs) in each system, MP1 and MP2. MP2 is used for play back the measurements from either the field testing or the test bench into the EMT model, whereas MP1 is used to compare the response and validate the model. The play-back approach is a common approach utilized for model validation and consists of using a voltage source to replicate the on-site voltage by replaying the measured instantaneous voltage signals from the real setup (i.e. the test bench of field WTG). The EMT models will then contain the area highlighted by the dotted red box, including the WTG model and parts of the test setup. As it can be inferred, the two EMT models contain slightly different passive equipment, which naturally introduces minor differences in how the turbine will respond to the fault played back in MP2.

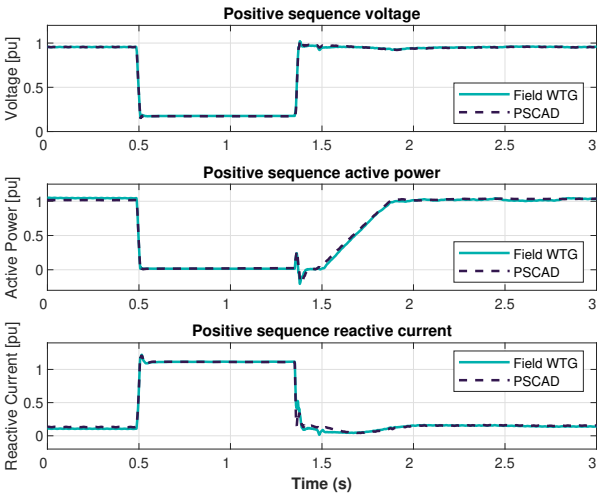
5 Model Validation Results

In this section, the validation results of the PSCAD model and the full-scale field, as well as the PSCAD model and G-CTR, will be shown and discussed. The results for both Field and G-CTR are plotted side-by-side and overlayed with the respective EMT models.

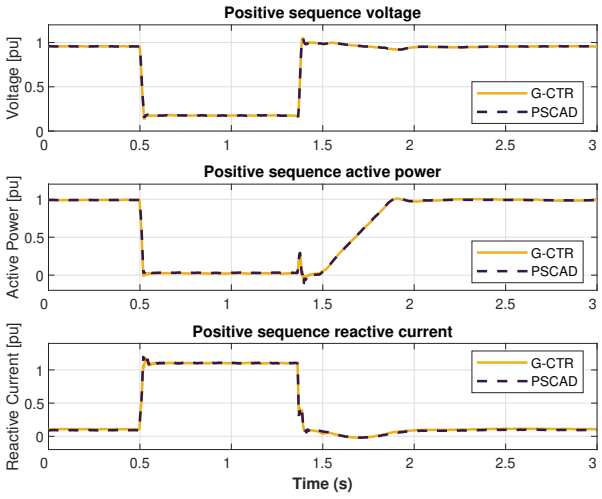
Model validation is not always about achieving perfect match between the model and the site data, but also about understanding the differences and ensuring that the model behaviour is acceptable for the purpose it is built for.

5.1 PSCAD Model vs. Field Prototype WTG

In Figure (4a), the result for a 3ph fault comparison between PSCAD model and field is shown. The overlay of different signals between the model and the field data is good and well within acceptable tolerances both during transients and

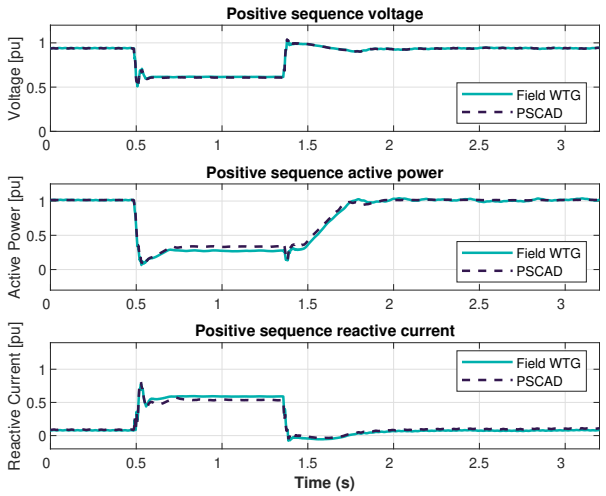


(a) 3ph Fault - PSCAD vs Field

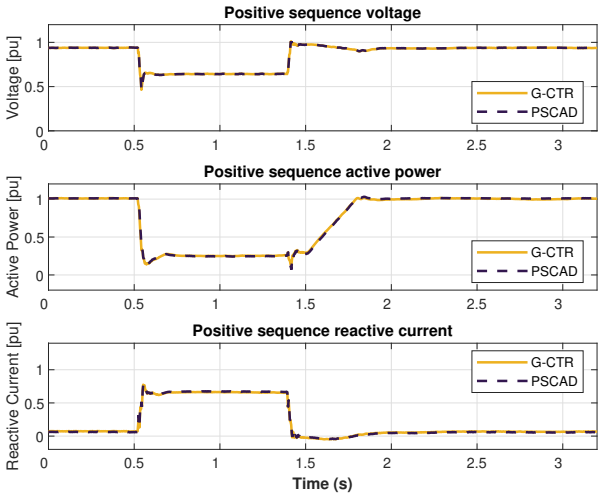


(b) 3ph Fault - PSCAD vs G-CTR

Fig. 4: 3ph Fault comparison between PSCAD model and measurements from both G-CTR and Field WTG for Positive Sequence Voltage and Active Power, and Reactive Current.



(a) 2ph Fault - PSCAD vs Field



(b) 2ph Fault - PSCAD vs G-CTR

Fig. 5: 2ph Fault comparison between PSCAD model and measurements from both G-CTR and Field WTG for Positive Sequence Voltage and Active Power, and Reactive Current.

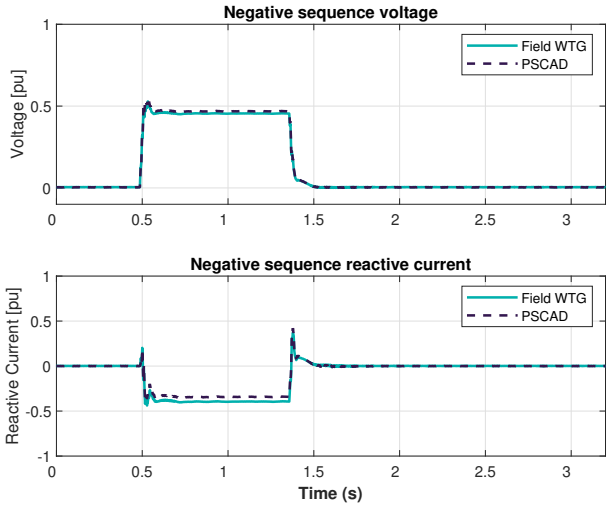
steady state. Minor deviations are present, specifically during the clearing of the fault. These deviations have been traced down to have come from the modeling of the wind turbine transformers where it is challenging to model the transformer transient and saturation behaviour with the highest precision.

Figures (5a) and (6a) show the results for a 2ph fault comparison between PSCAD model and field in both positive and negative sequence domains. The overlay of different signals between the model and field data is well within acceptable tolerances.

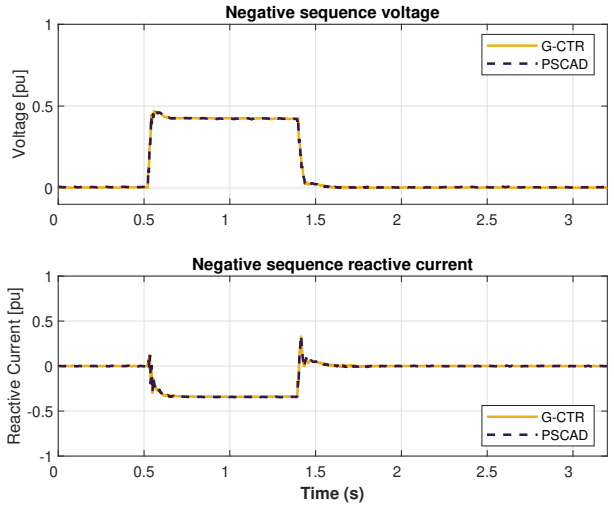
5.2 PSCAD Model vs. G-CTR

Figures (4b), (5b) and (6b) show the same faults now applied in G-CTR and validated against PSCAD model. Similarly to what was presented for comparison between the model and full-scale field test data, it can also be observed that the EMT model results for both faults match well within acceptable tolerances in the case of G-CTR.

The same core wind turbine model used for field validation has also been used for G-CTR validation. The small differences noted in validation between field and model, and G-CTR



(a) 2ph Fault - PSCAD vs Field



(b) 2ph Fault - PSCAD vs G-CTR

Fig. 6: 2ph Fault comparison between PSCAD model and measurements from both G-CTR and Field WTG for Negative Sequence Voltage and Reactive Current.

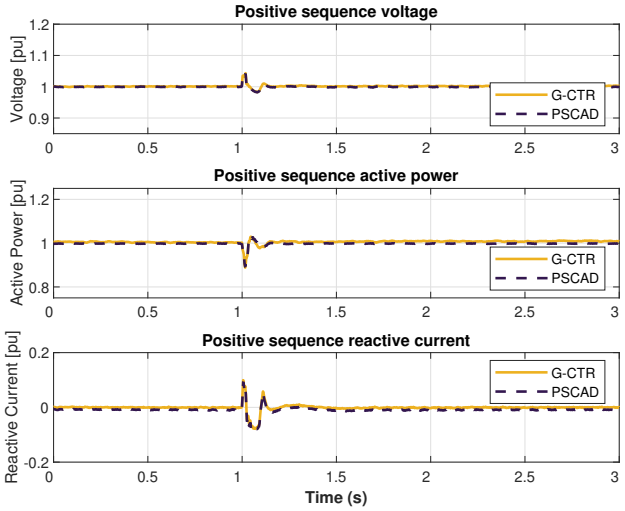


Fig. 7: 15 Degree Phase Jump comparison between PSCAD model and GCTR for Positive Sequence Voltage, Active Power and Reactive Current.

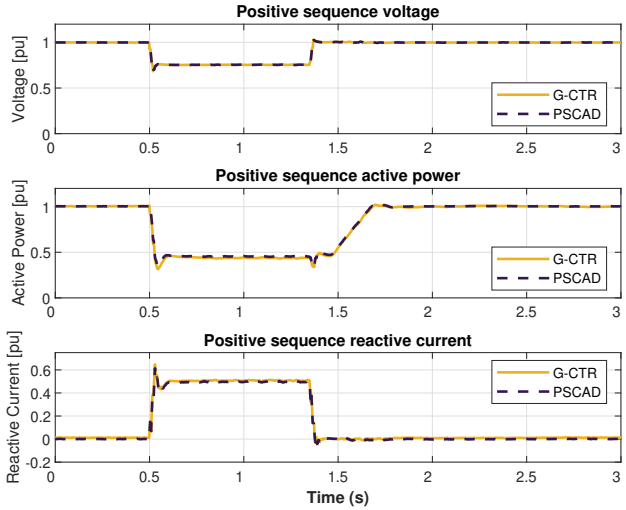


Fig. 8: 1ph Fault comparison between PSCAD model and GCTR for Positive Sequence Voltage, Active Power and Reactive Current.

and model are, therefore, owing to the difference in the external components (as expected) between the two setups. The same core model was successfully validated independently with field, and G-CTR further confirms that the G-CTR setup can serve as a valid substitute for the field turbine in matters related to electrical model validation for grid connection and compliance purposes.

5.3 PSCAD Model vs. G-CTR - Further Tests

As described previously, there is a wide range of tests that are very challenging to be applied in the field of WTGs with the current technology or equipment available, including 1ph-g faults and phase jumps. These events are among the most common to occur in the power system, and validating models for such events is of high importance for grid operators experiencing high IBR penetration. Such tests can be performed in G-CTR and used for model validation. In Figure (7), the results are shown for a phase jump of 15 degrees.

Furthermore, in Figures (8) and (9), results between G-CTR and PSCAD model for a single-phase fault are presented. The results from these different grid events show that the model overlays with the measurements from G-CTR within acceptable tolerances.

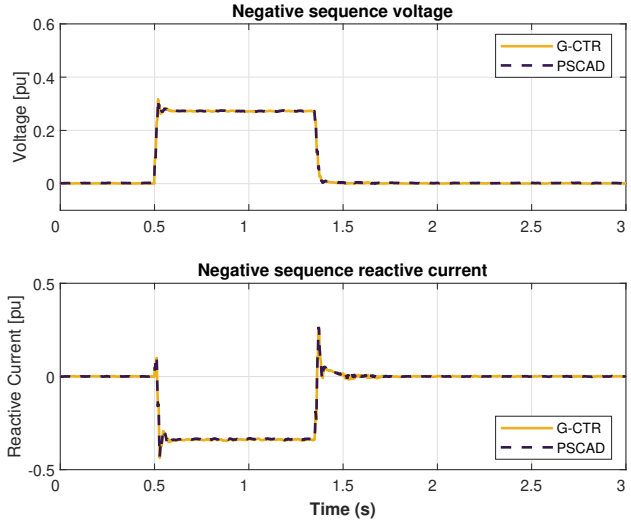


Fig. 9: 1ph Fault comparison between PSCAD model and GCTR for Negative Sequence Voltage and Reactive Current.

6 Conclusion

Backed by the results presented in parts 1 and 2 of this paper, a new strategy described for validating models is presented which will facilitate reliable and timely models for grid integration assessment studies during the design and commissioning of WPPs. The proposed strategy includes three stages: model-based assessment, test-bench testing and validation, full scale field testing and validation.

The extensive experience gathered and results presented in the last few years with G-CTR and other equivalent test-benches have shown that such setups can be relied upon for the majority of grid code and generic model validation purposes. The full-scale field testing and validation can then be utilized for final confirmation with internal test cases designed to test the specific product.

The paper shows that the model validation strategy presented in the paper is viable. Furthermore, model validation for grid events that are generally not possible to be performed in a standard field setup, such as phase jumps and single-phase faults, are also done, and the validation results for those test cases are also presented. The authors would, therefore, like to highlight

that test-bench setups, such as G-CTR, offer wider flexibility to demonstrate compliance and validate models and, most importantly, allow OEMs to offer mature models to their customers without compromising on quality. It must be stressed that the proposed strategy does not cut any corners but utilizes different setups available to enhance model validation.

For future work, the test rig will be expanded, and further validation will be shown for more complex events that cannot be tested in a field WTG.

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

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