Hardware-in-the-loop Testing of Wind Turbine Nacelles for Electrical Certification on a Dynamometer Test Rig

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Abstract.
This paper presents the design and implementation of a hardware-in-the-loop testing framework, for electrical certification of wind turbine nacelles on a dynamometer test rig. This is to enable a realistic test environment in the laboratory, comparable to that in the field. Assessment of electrical properties of wind turbines are usually executed in the field for the complete prototype, however, in the laboratory, missing system components have to be emulated and the effect of test rig’s own actuators are to be attenuated. Therefore, implementation of an adequate real-time wind turbine simulation tool, an efficient control system for the test rig drive train, and a real-time automation system are considered and presented here. Furthermore, execution of type certification experiments according to national and international guidelines is described here and illustrative measurements are provided. The measurements in this case are obtained at Dynamic Nacelle Laboratory, while testing with the Enercon E-115 E2 turbine. The results achieved demonstrate successful test execution in the laboratory and declare the advantage of test rigs.

1. Introduction
Dynamometer ground test stands contribute to technology development and system validation in the wind energy industry and provide an efficient platform for certification of complete wind energy converter (WEC) nacelles, as well as system components. These facilities are an alternative to field tests, offering adjustable and reproducible test conditions in the laboratory. Hereby effective test methods are developed and implemented, leading to a reduction of the costs as well as the time to market. Meanwhile, there are a few nacelle test rigs operative worldwide, being distinguished by the power level and system capabilities. In fact, each test rig has a unique attribute perceiving its main product, varying from performance tests up to experiments under transient conditions. The Dynamic Nacelle Laboratory (DyNaLab) incorporates a full-scale nacelle test rig developed by Fraunhofer IWES in Bremerhaven, Germany [1]. The comprehensive design of the test rig enables not only the emulation of test conditions similar to the field, but also provides the chance for additional experiments not applicable during field tests. Overall, a wide range of mechanical and electrical experiments are offered with respect to national and international guidelines, supported with the extensive measurement and data acquisition systems required.

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Since inauguration of DyNaLab in 2015, seven specimen from the onshore as well as offshore sector in the range of 2.5 to 9 MW have been subject to extensive experiments at IWES. This shows how beneficial test rigs are for manufacturers, but also demonstrates that the test methods incorporated are mature and examined based on the long term gained knowledge and experience. However, comparison of test results with measurements obtained in the field is considered as a necessary intermediate step, in order to evaluate the validity and therefore further increase the acceptance among certification authorities. This is the main topic of the project CertBench, considering electrical type certification of WEC nacelles with respect to national and international guidelines [2][3][4][5]. This project is a collaboration with the Center for Wind Power Drives (CWD) at RWTH University and Enercon, in form of a consortium including also FGH and UL as certification and measurement bodies, respectively. In this context, the Enercon E-115 E2 WEC (Fig.1c) has been subject to electrical type tests on both test rigs at IWES and CWD and the measurements are substantially evaluated in comparison with field measurements.

In this context, this paper presents the development of a novel Hardware-in-the-loop (HiL) test framework based on the standard and technical guidelines, for valid type certification of commercial WECs on nacelle test rigs. This includes real-time implementation of a fully coupled aero-servo-elastic simulation tool incorporated to emulate missing WEC components in the laboratory. Furthermore, control system design for test rig drive train operation with a high dynamic performance is illustrated, enabling a realistic mutual interaction of a virtual rotor with the nacelle. In addition, realization of a real-time automation system, as well as system integration is presented here, all supporting valid execution of grid events in the laboratory. This paper provides measurement results from the test campaign with the Enercon E-115 E2, and demonstrates for the first time a validation of the HiL test framework. This is done by a comparison with field measurements. Here are also practical aspects and requirements for system operation described based on the experience. Moreover, the advantage of type certification on dynamometer test rigs is elaborated.

Among other publications from pioneer institutions in this field, HiL testing of WECs for the purpose of controller validation and electrical testing at CWD are presented in [6] and [7], respectively. Furthermore, HiL testing of utility-scale WECs at the National Renewable Energy Laboratory (NREL) and Clemson University is reported in [8]. Moreover, implementation of a reduced order WEC simulation tool and test rig control design for HiL operation is presented in [9]. In addition, a comparison between FRT containers and the grid simulator at DyNaLab in terms of impedance behavior during unsymmetric faults is presented in [10].

The Enercon E-115 E2 subject to experiments is a type 4 and gearless WEC, incorporating a full-converter enabling variable speed operation. In this case, the hub is directly connected to the rotor of a high-pole field excited ring generator. The full-scale power converter consists of a rectifier, a direct current link and multiple inverters, the number of which depend on the nominal active power output and the required reactive power capability. The electrical performance on

Figure 1: (a) and (b) Test rig motors and drive train, (c) Enercon E-115 E2 at DyNaLab.
the grid is hence defined by the inverters and the associated FACTS control system, regulating the output current to the grid. This WEC has a rated power of 3200 kW and has already passed field measurements for its certification. This allows direct comparison of the results determined on the test rig with the available field data. Consequently, validation of the test method becomes possible.

DyNaLab provides the platform for testing WECs up to 9 MW. The test rig drive train (TRDT) together with the hydraulic load application system (LAS) enable reproduction of rotor torque, as well as the corresponding forces and non-torque loads in an overall six degrees of freedom (DOF) (Fig.1b). Primary movers of the TRDT are two synchronous direct-drive motors that apply torque up to 8.6 MNm at low speeds with a nominal value of 11 rpm (Fig.1a). Furthermore, the LAS is capable of applying forces up to 2 MN and bending moments as high as 20 MNm. In addition, a medium voltage grid simulator (MVGS) is utilized, capable of symmetric and asymmetric faults, as well as overvoltage and frequency change. Various grid conditions are feasible by setting the impedance accordingly. In this way, the device under test (DUT) is supplied by the MVGS and decoupled from the public grid, therefore, grid compliance testing can be accomplished independently. The MVGS is based on the ACS6000 converter technology of ABB, having a short circuit capacity of 44 MVA.

2. Objective
Measurement and assessment of electrical properties of WECs is typically accomplished in the field for a complete prototype. However, similar experiments in the laboratory are executed only on the complete WEC power train. Therefore, in order to enable normal operation of DUT in the laboratory and to obtain a realistic test environment comparable to the field, HiL test methods are required. This includes first of all the emulation of a turbulent inflow and missing components such as rotor blades, pitch system and the tower, denoted by mechanical HiL. And on the other hand, execution of valid grid events in terms of voltage dips and emulation of grid impedance at the point of common coupling (PCC) is required, indicated by power HiL. From this perspective, a DUT is the intersection of mechanical and power HiL systems in the laboratory. Hence, for valid measurement results, a mutual interaction between rotor side dynamics and grid side events is to be realized. The focus of this paper is the design and implementation of the mechanical HiL system as introduced in the following.

3. Methodology
Based on the previously introduced purpose and the defined objective, a novel HiL test framework is designed and implemented at DyNaLab. This framework is consistent with WEC operation and provides a high-fidelity and an adequate modularity in the support of type certification of commercial WECs according to the standard. A simplified schematic of this solution is illustrated in Fig.2, including three main components, namely, virtual rotor emulation, real-time automation system and HiL controller. Further details on these subsystems are provided in the following subsections. The real-time simulation tool provides the corresponding rotor response as set-points for test rig operation, based on the input wind field, pitch, and an actual measurement feedback from the hardware. Furthermore, it enables normal DUT operation by calculating the required rotor side measures expected by the DUT controller. In this respect, the automation system handles the data flow and provides subsystems with the required sensor, actuator and status signals. The automation system incorporates real-time capable field-bus interfaces and therefore enhances system controllability, by realizing short cycle times and low communication jitter. In this context, the HiL controller has the duty to follow and maintain the desired operating point at the DUT main bearing (flange), during static as well as dynamic conditions. This includes rotor side dynamics as well as those induced due to grid transient events, both influencing system response simultaneously.
3.1. Virtual rotor emulation

The real-time virtual rotor model is based on the fully coupled aero-elastic code MoWiT, developed at Fraunhofer IWES [11]. MoWiT takes into account the flexibility of rotor, tower and drive train, as well as transient aerodynamic effects and turbulent 3D wind fields according to the standard [12]. It has been continuously verified in comparison with other WEC load calculation tools such as DNV GL Bladed or OpenFAST. The code utilizes modal reduced elastic beam models for the structural representation of rotor blades and tower. For aerodynamic calculations, the blade element momentum (BEM) theory is implemented including correction models for the tower shadow, dynamic inflow and dynamic stall, among others. For the turbulent inflow, 3D wind fields generated with Bladed or Turbsim can be used as an input to the simulation, as well as gust models or uniform wind scenarios.

It is the real-time capability and adjustability of MoWiT that makes it a well suited tool for HiL test applications. The modular structure of MoWiT allows an interchange between submodels of varying complexity in a systematic manner. Furthermore, it allows the selection of turbulent wind fields with different wind speeds and turbulence during runtime, so that various tests can be executed without any simulation restart being necessary. In case of a required constant wind inflow for a test, the turbulence can be simply deactivated online.

For the introduced application in this paper, a MoWiT model of the Enercon E-115.E2 is derived based on the provided Bladed reference model and verified accordingly. This model is consequently prepared for real-time simulation and finally executed on an OPAL-RT OP5600 real-time machine. The OPAL RT-LAB client provides an interface for integrating models from Matlab/Simulink. By including the MoWiT model as an S-Function into Simulink, this interface is used to run MoWiT models on the OPAL hardware with hard real-time conditions. Moreover, for an enhancement of the real-time simulation capability, a model reduction regarding discretization of aerodynamic calculations is performed. Thereafter, a comparison with the detailed reference model is made for verification purposes. The latter two topics are further elaborated in the following.

For the determination of structural loads, load calculation softwares such as Bladed, OpenFAST or MoWiT, require computation times that are in the order of real-time, but can be significantly slower depending on the physical models and the depth of detail. Such offline simulations are typically conducted with a time step of about 10 ms. To achieve short latencies in data processing for optimized test rig operation, a higher sampling rate of 200 Hz is set as the
aim for this test campaign. Furthermore, in order to maintain an adequate safety margin for the CPU load and to prevent overruns, it is also specified that during test execution this margin must not exceed 75%. To fulfill these requirements, several approaches are investigated and evaluated in order to accelerate model computation [13].

For model reduction, in order to maintain the dynamic eigen behaviour of the reference model, the number of eigen modes used is not modified. Furthermore, the original grid size of the turbulent wind files is not changed, since its influence on the computational effort is observed to be low. In this case, a reduction of a wind field with $24 \times 24$ grid points down to $16 \times 16$, resulted in only 5% decrease of the overall computation time (Fig.3a). However, it is observed that reducing the number of aerodynamic BEM calculations per rotor blade has the most considerable impact on computational performance. This is illustrated in Fig.3b, demonstrating the mentioned influence to be approximately linear. Since the reference model was based on 8 Bladed airfoil sets, the aerodynamic BEM calculations per rotor blade are reduced from 37 to 8 for the real-time MoWiT model. Despite this simplification, simulation results indicate a good agreement for the rotor rotational speed and torque in comparison with the detailed reference model. Verification of the detailed MoWiT model in comparison with the Bladed reference model is performed with load cases of increasing complexity, to allow for a step-by-step comparison and to trace possible deviations of different submodels and methods. In a first step, dead load cases are compared to verify masses and static loads of the structure. In the second step, a modal analysis is carried out and the resulting eigen frequencies and mode shapes are compared. Finally, the dynamic system behaviour is compared in time-domain incorporating the WEC controller, both with rigid and flexible structural components as well as deterministic and turbulent wind inputs.

![Figure 3: Influence of (a) wind field resolution and (b) the number of aerodynamic calculations per blade on computation time](image)

(a) Wind field resolution
(b) Aerodynamic runtime

![Figure 4: Comparison of simulation results for Bladed reference model, MoWiT reference model and reduced MoWiT real-time model](image)

(a) Wind Speed
(b) Rotor Speed
(c) Rotor Torque
It is observed that for constant wind load cases at different wind speeds along the power curve, the differences in both rotor rotational speed and torque were well below 1% for most partial loading wind speeds. There are only two minor exceptions noticed. First, at cut-in wind speed where a maximum deviation of $-6.8\%$ occurred in the rotor torque. Second, a 3.6\% deviation in the rotor torque at 9 m/s wind speed. Load cases with a turbulent wind input show similarly good agreement. Overall, the agreement between the reduced MoWiT model used for HiL testing and the Bladed reference model is demonstrated to be in the order of other code-to-code comparisons performed for load calculation softwares, as described e.g. in [14]. An example time series with turbulent wind input is shown in Fig.4, which displays good accordance between the reduced real-time MoWiT model and the reference Bladed model.

For the test campaign at DyNaLab, 330 turbulent 3D wind fields mostly with a length of 600 s are created with 7 different turbulence seeds for each mean wind speed, in order to execute electrical tests according to guidelines [4][5]. All wind fields are created with the Kaimal turbulence model for wind class I A according to the standard [12]. Furthermore, during this test campaign, the WEC drive train including hub and generator inertias were part of the simulation model, such that a full aerelastic WEC simulation was used to compute setpoints for test rig operation. This is because of the limitation on model separation due to the direct drive WEC. In this case, the HiL controller is to ensure synchronised operation of the hardware with the simulation. Moreover, the feedback mechanical torque to the model is obtained indirectly, as it is calculated based on the electrical power at PCC and the rotational speed, while considering a power-loss model.

3.2. HiL Controller

For the described HiL framework, a model-based driving torque control is designed and implemented to fullfill the objective described in section 2 and 3. The latter introduces high performance requirements in terms of reference following and disturbance rejection as the control objective. This is to assure complete emulation of rotor characteristics and the corresponding dynamics induced by the turbulent inflow during static as well as transient conditions. Furthermore, a TRDT operation has to be guaranteed in conformity with electrical test procedures. It is due to the execution of grid events such as voltage dips or frequency change, that disturbance is excited from the DUT side in form of a rapid change in the active power. During these events, due to the small inertia of TRDT in comparison to that of a WEC rotor, control with high dynamics is necessary in order to minimize the influence of TRDT itself and accomplish rotor emulation completely. The implemented controller is based on the introduced structure in [15] and is refered to as the HiL controller.

The control objective introduced above is to be fulfilled in the presence of model parameter uncertainty, while concentrating on the closed-loop system response in the frequency domain. Therefore, a H-$\infty$ robust controller is designed and implemented here incorporating the mixed sensitivity approach [16]. Moreover, for an estimation of the unmeasured output and state-variables, a discrete time-varying Kalman filter is implemented. The possibility for torque measurement in the multi MNm range is limited and therefore, Kalman filter provides the chance for control with a minimal sensor system in the presence of measurement noise. The HiL control is finally designed in discrete time using MATLAB and implemented in the Simulink Motor Control (SMC) environment of the ABB real-time Power Electronic Controller (PEC), and executed with a sample time of 250 $\mu$s. Fig.5 illustrates block diagram of the closed-loop system. The actuating variable here is $m_a$, designating the total air-gap torque of the motors, whereas $m_g$ indicates that of the DUT generator, acting as a disturbance. In this configuration, torsional torque at the flange is the output variable denoted by $m_{fl}$. Furthermore, $p$ designates the active power and $\omega$ assigns angular velocity. The superscripts $^*$ and $\hat{}$ indicate a set-point and an estimation of the corresponding measure, respectively.
For control design, consider the plant state-space model given in Eq.1, where \( A \) designates the system matrix, \( B, E, C \) are input and output vectors, and \( X \) indicates the corresponding state-variable vector. For \( \mathcal{H}_\infty \) control synthesis, the plant is augmented by incorporating additional sensitivity transfer functions. These weighting functions introduce costs on attributes of the closed-loop system response in frequency domain. Eq.2 illustrates the state-space representation for the augmented plant \( \mathbf{P} \), with the corresponding variables as defined for Eq.1 and designated with the subscript \( a \). In addition, \( U \) represents the manipulating input vector and \( D_a \) is the feed-through matrix. Moreover, the exogenous input vector is denoted by \( W \), while \( Z \) specifies the vector of penalty function. Output vector of the augmented system is indicated by \( Y \).

\[
\begin{align*}
\dot{X}(t) &= AX(t) + Bm_a(t) + Em_g(t) \\
m_a(t) &= CX(t).
\end{align*}
\tag{1}
\]

Subsequently, for control design, an optimization problem is defined as \( \text{min } \| T(\mathbf{P}, \mathbf{K}) \|_\infty \), considering infinity-norm of the target transfer function \( T(s) \). In this regard, the system equation from Eq.2 is reformulated as in Eq.3 and therefore the target transfer function from \( W \) to \( Z \) is obtained as given in Eq.4. \( P_{ij} \) here are the corresponding transfer functions of the augmented plant. The optimization problem here is to shape the sensitivity and complementary sensitivity functions, as well as the actuating variable response. Consequently, the controller is obtained by solving the optimization problem using linear matrix inequalities (LMI) using the MATLAB robust control toolbox.

\[
\begin{pmatrix}
Z(s) \\
Y(s)
\end{pmatrix} = \begin{pmatrix}
P_{11}(s) & P_{12}(s) \\
P_{21}(s) & P_{22}(s)
\end{pmatrix} \begin{pmatrix}
W(s) \\
U(s)
\end{pmatrix}.
\tag{3}
\]

The utilized control system here is well consistent with the requirements in practice, since the sensor-less approach enables control with minimal measurements, including only the speed and input electrical torque signals. Furthermore, this approach is compatible with normal DUT operation, since it is still the DUT controller that governs system operation by controlling the speed, and the HiL controller follows and maintains the commanded rotor torque through the TRDT delivered at the flange. In fact, the flange torque is a control variable in this approach and what finally matters is the delivered power to the grid at PCC, which has to be preserved in accordance with the WEC power curve. The torque control approach here, enables a high dynamic performance since no additional control loops incompatible with the normal DUT operation is present. However, a calibrated torque measurement with real-time access for control purpose is not available as mentioned earlier and therefore, accurate measurements are reduced.
to the rotational speed and the electrical power at PCC. In fact, torque calculation based on the mentioned measurements, or by using electrical machine models, and incorporating efficiency factors introduces uncertainties to the closed-loop calculations. Although this is as low as 1 to 2% of the nominal torque, it can cause minimal deviations in the speed. In order to avoid this and to ensure an accurate operating point, the speed difference (ω_fl − ω_a) is used to modify the final torque setpoint (m_f^*) in a feed-forward manner with a proportional gain.

3.3. Automation System

The test rig automation system integrates the real-time model (section 3.1) and the HiL controller (section 3.2) into the test procedure by realizing the interfaces for data handling and system operation. It handles the interface between WEC controller and the virtual model, by exchanging the required actual measurements and control commands. In this way, the WEC controller operates the same interface signals as in the field and thus no adaptation of the controller code is necessary, which is a prerequisite to fulfill realistic test requirements. In order to meet hard real-time requirements, the Ethernet-based field-bus system EtherCAT in combination with Beckhoff PLC technology is used at DyNaLab as an integrated solution. Fig.6 illustrates the implemented automation structure and the data flow among relevant subsystems. In the following, a brief introduction to interfaces and the test automation framework is provided.

On the OPAL-RT side a cycle time of 5 ms is used for model calculations and on the Beckhoff PLC 1 ms is chosen for the communication task. Here, the OPAL-RT EtherCAT slave device is realized with a Hilscher board, which is in the present configuration not capable of using distributed clocks (DC) functionality for an exact synchronisation with the master device. In this case the lower cycle time of the PLC communication task helps to keep the transmission delay small.

The flange set point from the virtual model is forwarded from the test rig PLC to ABBs drive train controller also using the EtherCAT protocol. ABBs EtherCAT slave device, realized by a HMS Anybus gateway, is likewise not synchronised with the master device using DC. However, in the worst case scenario the transmission time to the Simulink Motor Control is 2 ms and totally sufficient for the present control purpose.

For the communication with the DUT a special bridge terminal from Beckhoff is used (EL6692) to couple two EtherCAT strands with different masters. The cycle time from both strands is equal to 1 ms and the data flow is synchronised with the DC functionality in the range of nanoseconds.

Figure 6: Automation structure
The EtherCAT device on the DUT side serves as a gateway to the host bus system of the WEC, which clocks with a ten times slower cycle time (10 ms). Thus, the faster communication cycle enables a smaller transmission delay. A tailor-made framework automates the test execution in order to ensure exact reproducibility of test conditions considered as an important requirement. With a predefined profile, set points to MoWiT model (e.g. wind field selection) and to the MVGS (e.g. voltage drop level and duration) are commanded by reading out profile information in real-time and a transmission with a minimum delay time. Restarting of the wind field and triggering of the measurement systems can be adjusted in the millisecond range, in order to enable reproduction of test conditions at the exact desired operating points, and to enhance comparability.

4. Experiments and Results
During the test campaign, complete electrical tests according to national and international technical guidelines are executed [4][5]. Among those are, namely, power quality evaluation (e.g. flicker and harmonics), over- and under-voltage-ride-through, reactive power capability, active power control, frequency change and synthetic inertia. In this section, measurement results from the last three mentioned test cases are selected for further illustrations. This is due to the observed high dynamic requirement that these introduce for test rig HiL operation. Furthermore, an attractive advantage of type certification on nacelle test rigs is elaborated here for the case of frequency change and synthetic inertia.

Fig. 7 illustrates measurements from an active power control test with a constant input wind field. Here is the average hub wind speed varied from 3 to 14 m/s in a stepwise manner, while holding constant for 100 seconds at each step. This test is executed for commissioning and fine tuning of the HiL control system, in order to verify the steady-state accuracy and valid operation of the HiL set-up. Here are the pitch and power measurements as well as the speed to be verified in accordance with the wind speed. The provided measurements here demonstrate accurate steady-state operating points adjusted with respect to the DUT power curve.
In Fig. 8 measurement results during grid frequency increase are provided. This test evaluates the grid support capability of WECs in case of a change in the grid frequency. During such an event as specified in the standard, WECs have to react to frequency change by modifying the active power in a proportional manner and within the required response time. The measurements provided here are obtained with an input turbulent wind field having an average speed of 14 m/s (Fig. 8a). As demonstrated by the measurements, it is the Power Frequency Control (PFC) from Enercon that reacts to the frequency increase by an immediate reduction in the DUT active power through the electrical drive train (Fig. 8b). From the test rig point of view, it is observed here that despite the active power drop, the HiL setup follows and maintains the demanded torque immediately and therefore no undesired change in the speed behaviour is observed (Fig. 8c). The resulting step in the active power in this case experiences a high rate of change and by considering the fact that the generator torque acts as a disturbance for HiL control, it is obvious that this test introduces the highest requirement on test rig operation among all experiments for this type of a DUT.

Similar to the previously described experiment, the test Synthetic Inertia is also executed in order to examine the DUT performance in case of a grid frequency drop as specified in the guideline [5]. Fig. 9 illustrates the corresponding measurements during partial as well as nominal load conditions. Here are measurements for a constant wind input provided, having a value of 8 m/s for the case in Fig. 9a, and 15 m/s for the case in Fig. 9b and 9c. The course of the grid frequency realised by the MVGS on the test rig is implied to be identical to the variation observed in the field by Enercon. During this experiment, it is the implemented inertia emulation (IE) functionality of PFC that temporarily increases the active power. For this, grid frequency is continuously measured by the DUT controller and the implemented IE reacts to a frequency drop according to a pre-defined and parameterizable characteristic. Similar to the previously introduced test, measurement results here demonstrate a valid test execution enabled by the high dynamic response of the HiL setup on the test rig.

Figure 9: Laboratory measurement results for the test Synthetic Inertia.

Figure 10: Field measurement results for the test Synthetic Inertia.
It must be mentioned here that activating the PFC or IE functionality of the Enercon E-115 E2 WEC involves also the action of several downstream controllers [17] [18]. Here, the PFC has the duty to define an active power reference which is used to control the generator excitation and the inverter injection (power control). In parallel, the rotational speed is also controlled by actuating the blade pitch angle. Furthermore, the power increase with IE is achieved mostly with the generator excitation control.

For a validation of the HiL test setup, comparable field measurements for the test Synthetic Inertia are given in Fig.10. The comparison here with field measurements demonstrates the efficient performance of the HiL setup in the laboratory, capable of the high gradients demanded for power and torque steps. Furthermore, this example test case for a frequency variation event reveals the advantage of the HiL setup on test rigs since influencing the grid frequency in the field is not possible. In fact, for test execution in the field, the WEC controller is fed with an artificial frequency measurement signal. This indicates the benefit of test rigs in this regard, where real frequency response of the WEC can be validated. In this context, grid operators assess the aggregated response of all WECs on a farm level and not the individual reactions. Therefore, the advantage of testing under constant wind conditions on the test rig is of great benefit. Because in this way, an indication of the cumulative response can be obtained for IE being triggered over a wide geographical area, where local wind turbulence effects are attenuated due to the aggregation. Assessing such a performance in the field involves testing on the farm level and therefore acquire a significant effort in contrast to test benches [19] [20].

5. Conclusion
Wind turbine nacelle test rigs provide the chance for an adjustable and reproducible test conditions in the laboratory, since on the one hand rotor torque and loads are applied by electrical machines and a load application system. And on the other hand, voltage supply for the specimen is provided by a grid simulator, enabling electrical test execution independent from the public grid, based on the national and international standards. There are a few nacelle test rigs worldwide developed by pioneer institutions in this field, each having an individual attribute and test purposes. However, in accordance with the increased penetration of power production using wind energy in the power system, innovative solutions in power conversion are necessary. Here are therefore, novel test infrastructure and methods required, in order to validate the technology, but also to certify in an efficient manner. In this regard, WEC nacelle test rigs have a high potential by incorporating novel hardware-in-the-loop test methods. In this paper, the design and implementation of a novel Hardware-in-the-loop test framework is presented, providing an adequate flexibility for valid execution of electrical certification test procedures in the laboratory. Here in this paper, requirements for system operation on the test rig are introduced according to electrical test procedures. Furthermore, solutions for a virtual rotor emulation and a high dynamic test rig control are provided and described. Moreover, measurement results are provided, demonstrating correct operation of DUT on the test rig, leading to a successful test execution. Furthermore, emulation of rotor characteristics during constant or dynamic load operation is completely accomplished in the laboratory. In addition, the complete HiL setup is validated, by a comparison of test results with field measurements. Furthermore, an important benefit of benefit of test rig systems is elaborated for tests with an alternating grid frequency under deterministic conditions.

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