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CHINA ELECTRIC POWER RESEARCH INSTITUTE

7th International Workshop on Grid Simulator Testing of Energy Systems and Wind Turbine Drivetrains

The Use of Grid Simulators in CEPRI and the Development of 25MW Drivetrain Test Bench

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Contents

China Electric Power Research Institute (CEPRI)

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- A research institute directly under the State Grid Corporation of China (SGCC).
- 4 Chinese national key laboratories and 18 research departments, including the departments of power system, high voltage, renewable energy, energy storage, AI in power system, etc.

- Founded in 1951
- 2739 employees
- Beijing, Shanghai, Nanjing, Wuhan, Fuzhou…
- 2 academicians of Chinese Academy of Sciences
- 3 academicians of Chinese Academy of Engineering
- 10 national laboratories
- 11 provincial and ministerial laboratories
- 19 SGCC laboratories

Department of Renewable Energy Research

- Focus on the prediction, schedule/dispatch, control and test of renewable power generation.
- Research resources and wind power test bases include National key laboratory of renewable energy grid-integration, Zhangbei wind power test base, National offshore wind power test and research base (under construction), etc.

HiL simulation systems, Beijing

Zhangbei wind power test base, Hebei

National offshore wind power test and research base, Fujian
(Completion expected by end 2024)

Contents

Grid Simulators in Use

- IGBT-based grid simulators rated at 2MVA~10MVA (mostly mobile 6MVA and 10MVA), with parallel operation capability. Mainly used in wind turbine grid adaptability tests and fault ride-through tests.
- IGCT-based 90MVA grid simulator developed for the 25MW drivetrain test bench.

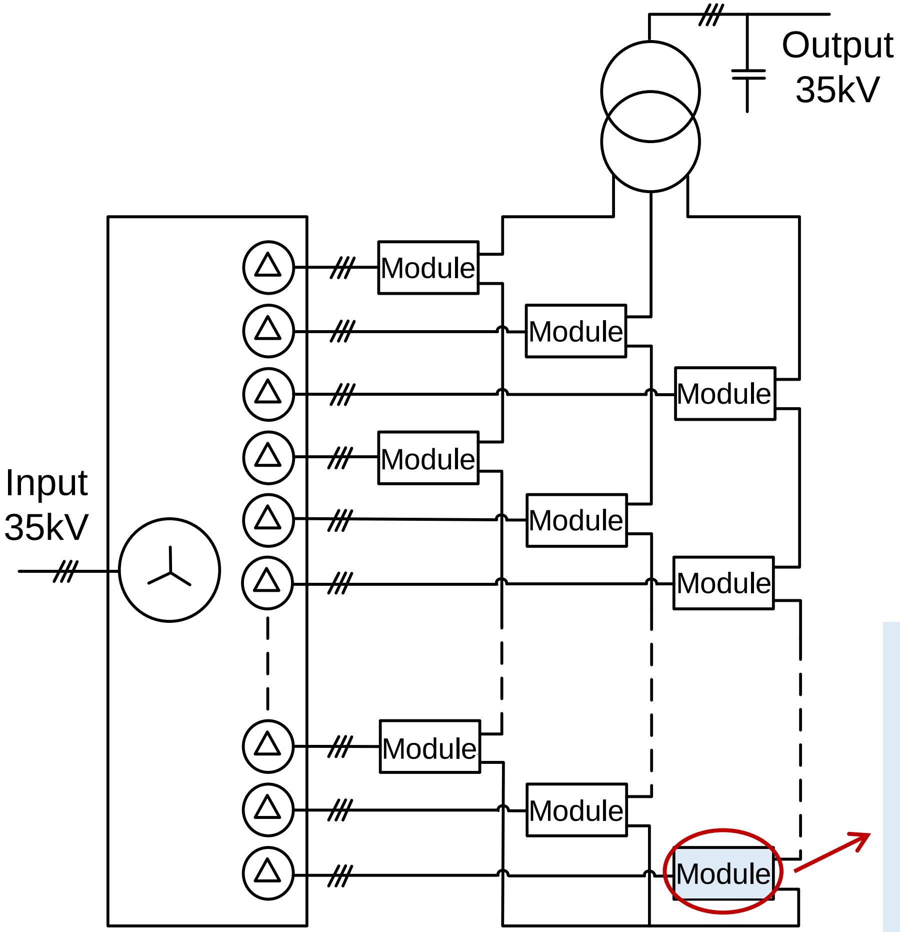
Tests using mobile grid simulators

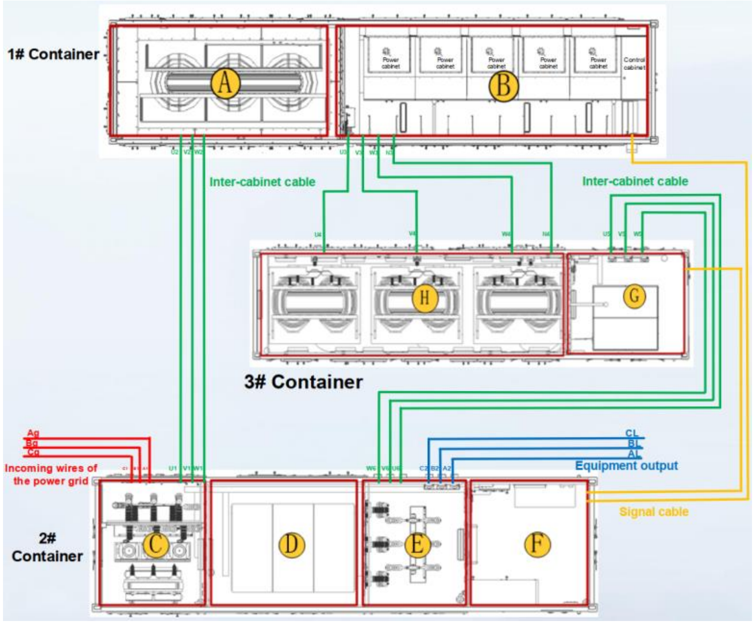
Large capacity grid simulator for the test bench

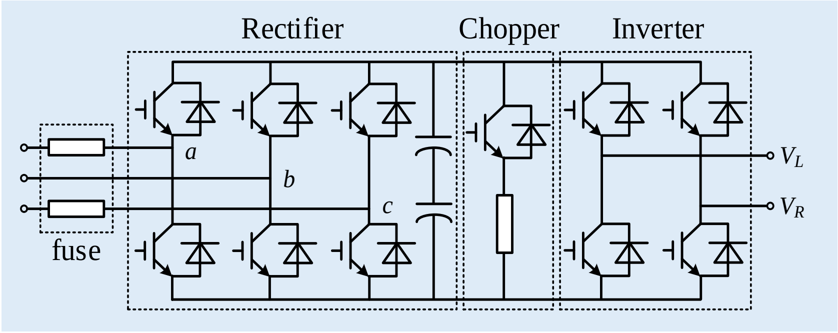
Grid Simulators in Use

6MVA~10MVA Grid Simulators

- Input: three-phase voltage source rectifiers connected to a multi-winding transformer.
- Output: cascading of H-bridge modules at each phase.







Specifications of grid simulators

Specifications	Values
Nominal voltage	35kV line-to-line
Power factor	-0.9 ~ 0.9
Voltage range	0 ~ 140%
Frequency range	45Hz ~ 66Hz
Voltage unbalance	0 ~ 10%
Voltage flicker Pst	0 ~ 10
Overload capability	110%: 1min 135%: protection
Harmonic voltage output capability	2^{nd}~7^{th} ≤ 6%/10% 8^{th}~25^{th} ≤ 3%/5%

Grid Simulator Tests in China

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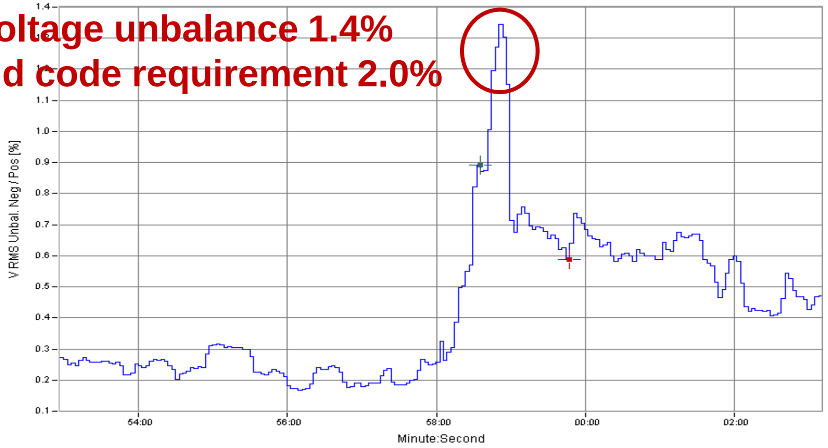
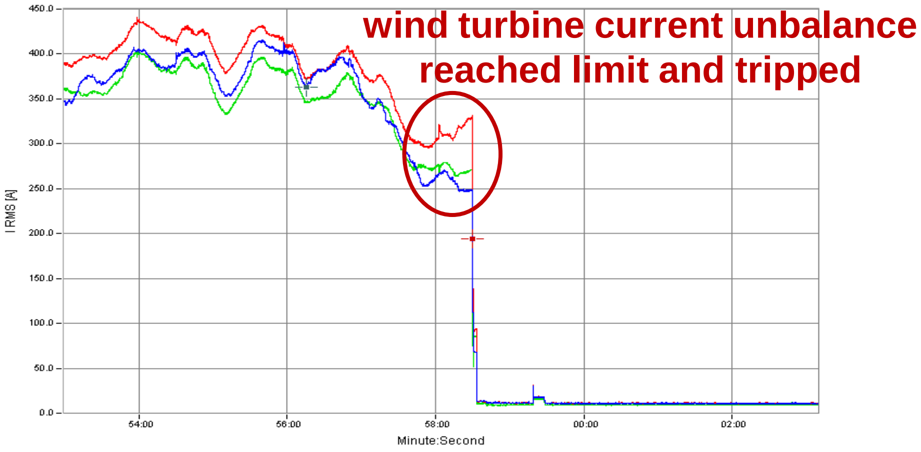
Grid Adaptability Test

- Inspired by the frequent tripping of wind turbines caused by railroad traction substations.
- Documents formed as NB/T 31054-2014, GB/T 36994-2018, IEC TS 61400-21-4 annex (CDTS stage).





ICS 27.180
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中华人民共和国国家标准

GB/T 36994—2018

风力发电机组　电网适应性测试规程

Wind turbines—Test procedure of grid adaptability

China National Standard

GB/T 36994-2018

Wind turbines – Test procedures of

grid adaptability

2018-12-28 发布　　2019-07-01 实施

国家市场监督管理总局
中国国家标准化管理委员会　发布

IEC DTS 61400-21-4 © IEC 2024　　211　　88/1048/DTS

Annex J
(informative)

Grid adaptability test using grid emulator

J.1 Overview

Grid adaptability refers to the endurance capability and response characteristic of WTs under grid variation conditions, such as voltage deviation, frequency deviation, three-phase voltage unbalance, voltage fluctuation and flicker, harmonic voltage, etc. The grid adaptability test is carried out using a grid emulator, which should be able to generate the necessary grid variations. The test levels of grid adaptability should follow the corresponding requirements in Clause 5.

J.2 Grid adaptability test setup

The test device is the grid emulator, which is used to generate the required grid operation conditions, including voltage deviation, frequency deviation, three-phase voltage unbalance, voltage fluctuation and flicker, and harmonic voltage. The test point is the POC of the WT under test. The test setup shown in Figure J.1 is recommended.

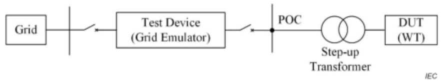

Figure J.1 – Recommended grid adaptability test setup

The operation conditions and specifications of the test device should satisfy the following requirements:

a) The nominal capacity of the test device should be equal to or larger than the nominal capacity of the WT under test.
b) The influence of the test device on the grid should meet the IEC and national requirements.
c) The voltage deviation setting range should cover the required range. The minimum step size of voltage output should be equal to or less than 1 % U_n.
d) The frequency deviation setting range and the RoCoF setting range should cover the required ranges. The minimum step size of frequency output should be equal or less than 0.1 Hz, and the minimum step size of RoCoF output should be equal or less than 0,1 Hz/s.
e) The three-phase voltage unbalance setting range should cover the required range. The voltage amplitude and phase should be adjustable. The minimum step size of three-phase voltage unbalance output should be equal to or less than 0,1 %.
f) The voltage fluctuation and flicker output ability should cover the required range.
g) The harmonic voltage output ability should cover the required range.

Before the grid adaptability test of a WT, the no-load test should be conducted. If the performance requirements of the test device are satisfied, the on-load test can be conducted. The example of maximally allowed errors between the test device outputs under no-load test and on-load test are listed in Table J.1 corresponding to each test condition.

Grid Simulator Tests in China

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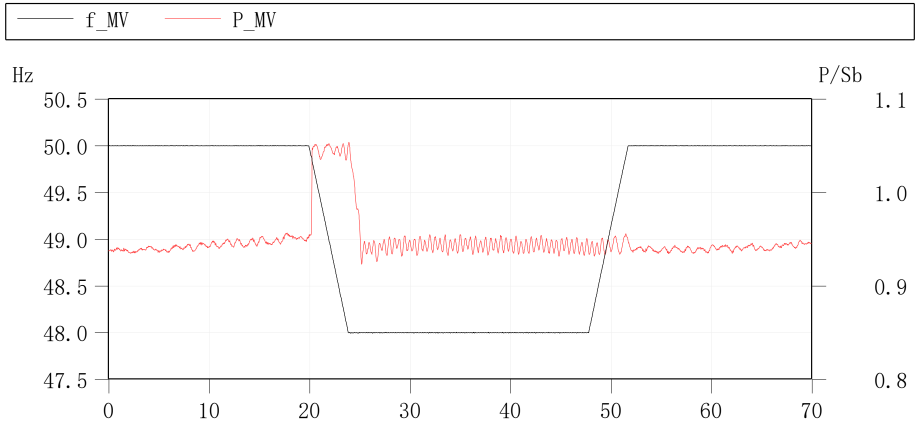
Grid Adaptability Test

- Voltage deviation, frequency deviation, three-phase unbalance, voltage flicker and harmonic voltage.

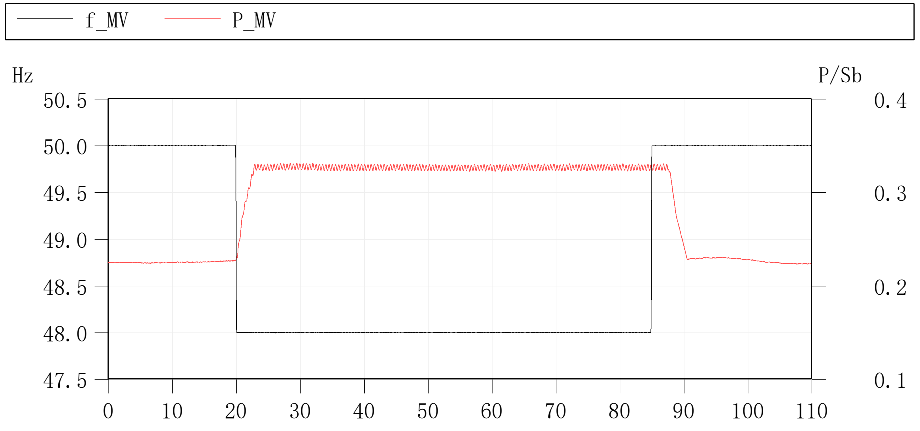
Stable operation requirements in GB/T 36994-2018

Test items	Set points	Duration time
Voltage deviation	0.90p.u.	30min
	1.10p.u.	30min
Frequency deviation	48.0Hz	30min
	51.5Hz	30min
Three-phase voltage unbalance	2.0%	30min
	4.0%	1min
Voltage fluctuation and flicker	1.0 (P_{st})	10min
Harmonic voltage	2.4% (3rd~25th odd)	2min each
	1.2% (2nd~24th even)	2min each
Interharmonic voltage	0.16% (5th~95th)	2min each

* Requirements may change in recent revisions.



Inertial response test example



Primary frequency regulation test example

Grid Simulator Tests in China

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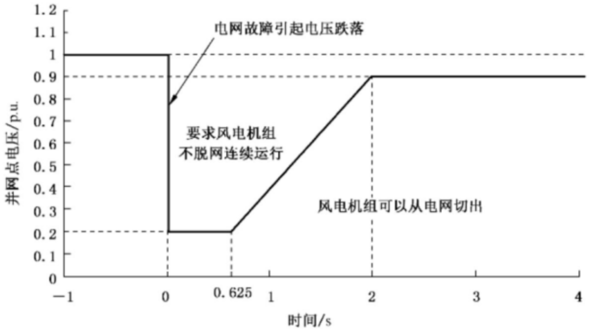
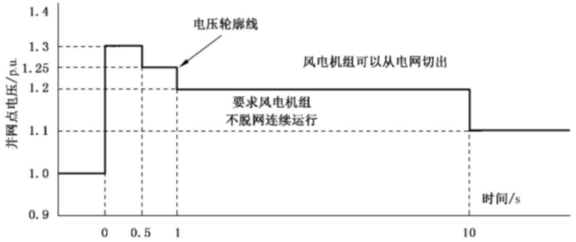
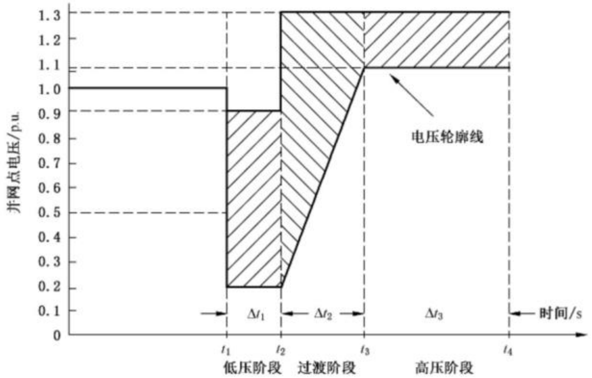
Undervoltage and Overvoltage Ride-through

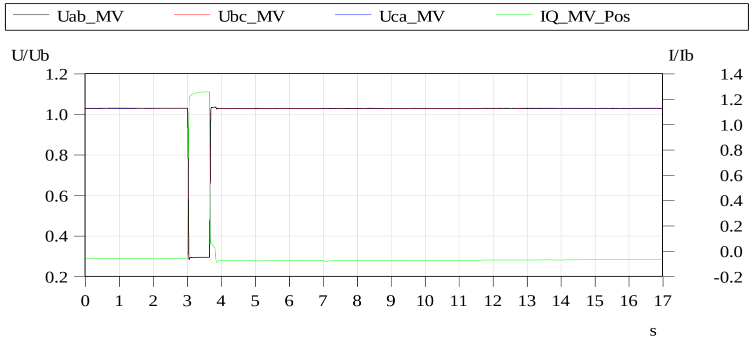
- Undervoltage, overvoltage and cascaded voltage ride-through tests with grid simulators.

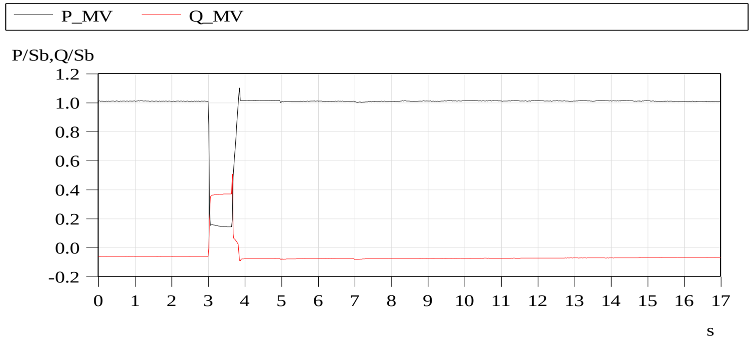


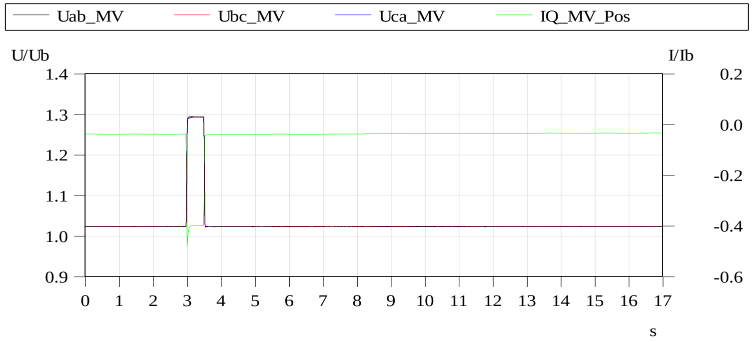


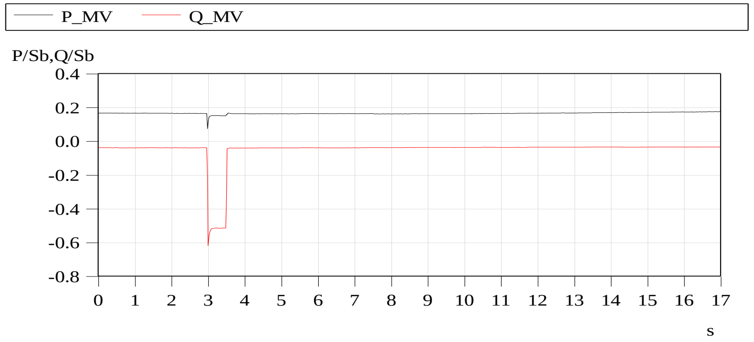


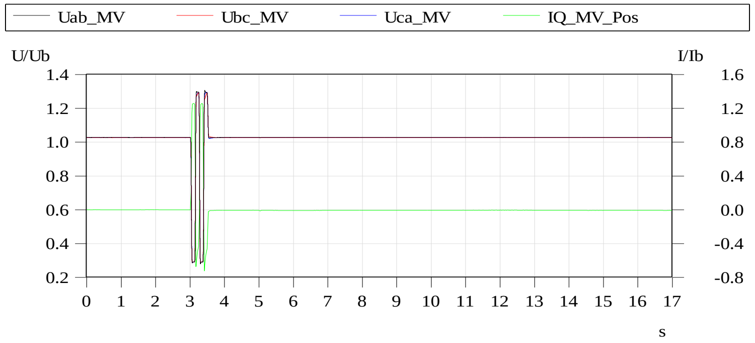
GB/T 19963.1-2021

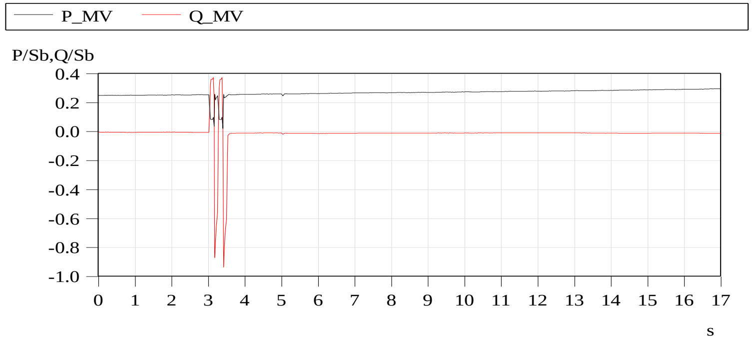






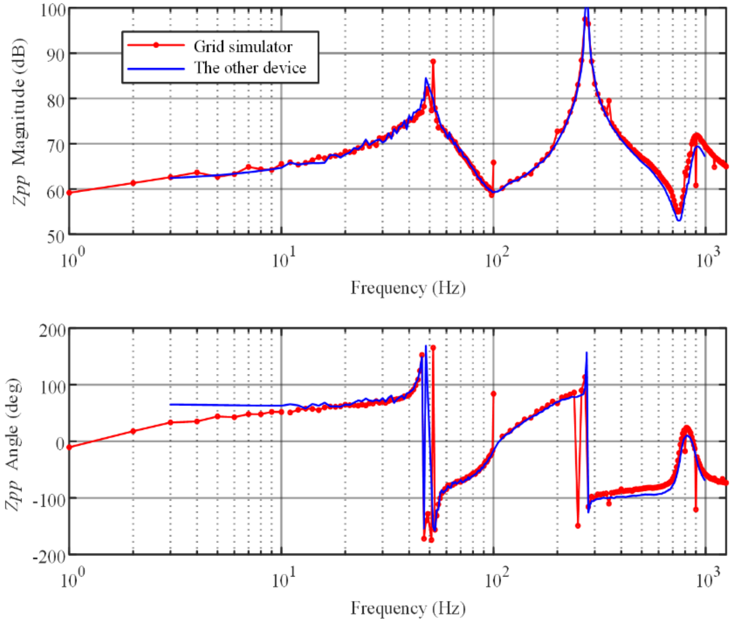


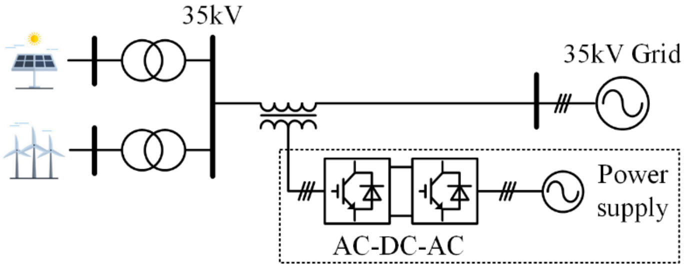




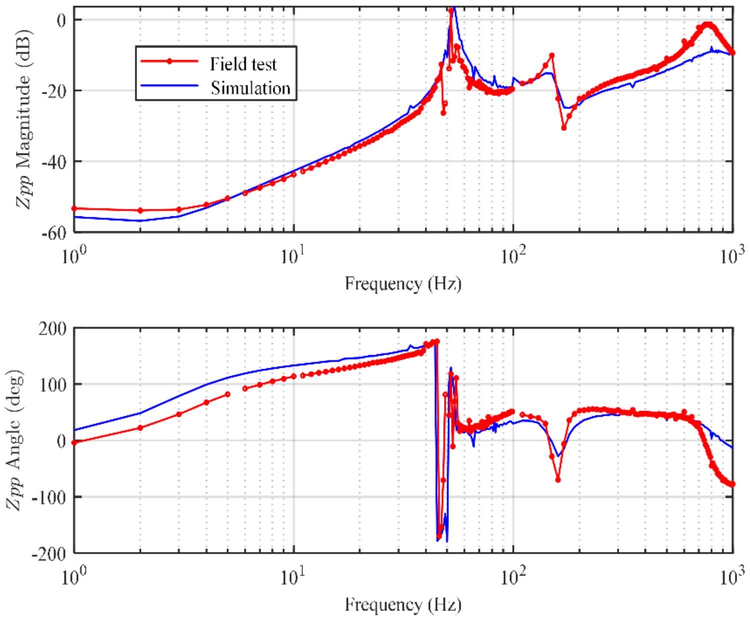
Impedance Measurement

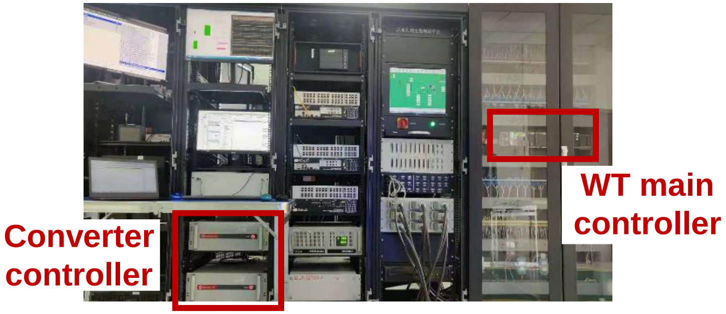
- Positive and negative sequence impedance measurements within 1Hz~1250Hz.



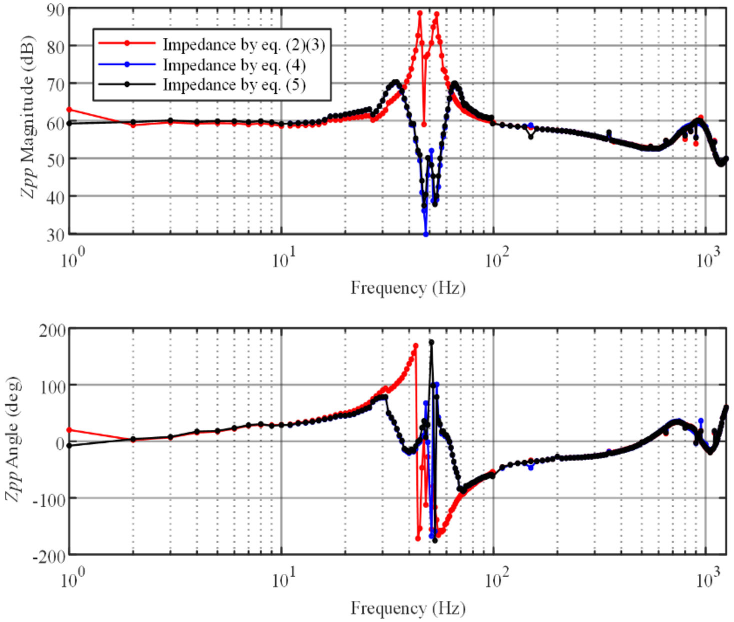


Comparison between test devices





Comparison with cHiL simulation



$$Z_{pp}(f_p)=\frac{V_p(f_p)}{I_p(f_p)} \qquad Z_{nn}(f_p)=\frac{V_n(f_p-2f_1)}{I_n(f_p-2f_1)}$$

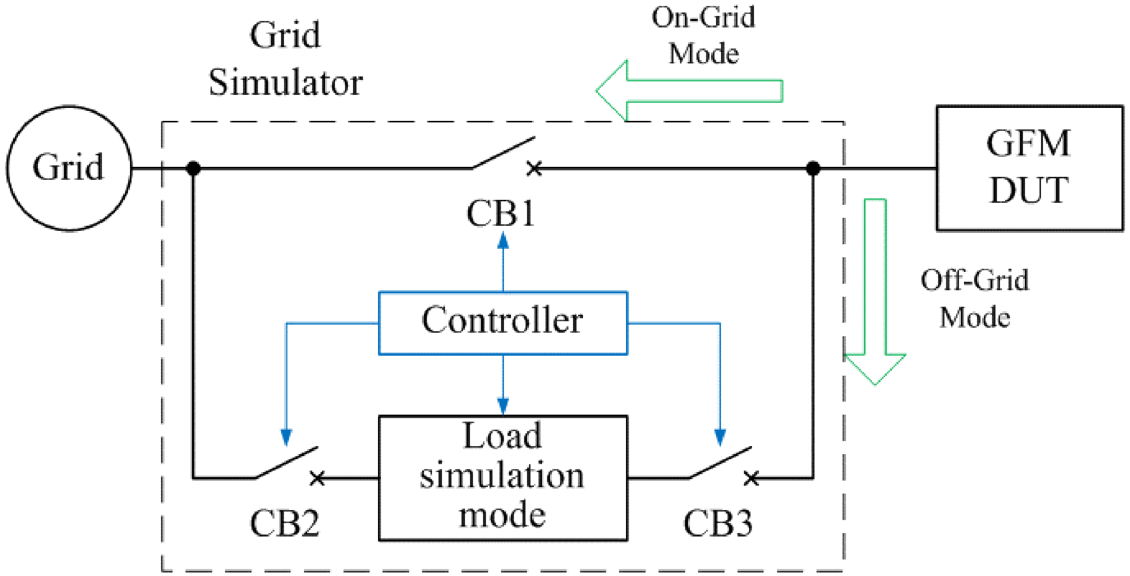
$$\begin{bmatrix} Z_{pp} & Z_{pn} \\ Z_{np} & Z_{nn} \end{bmatrix}=\begin{bmatrix} V_p^1 & V_p^2 \\ V_n^1 & V_n^2 \end{bmatrix}\begin{bmatrix} I_p^1 & I_p^2 \\ I_n^1 & I_n^2 \end{bmatrix}^{-1}$$

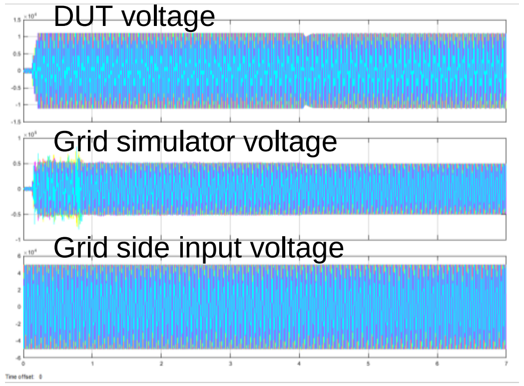
Comparison between calculations

Grid Forming

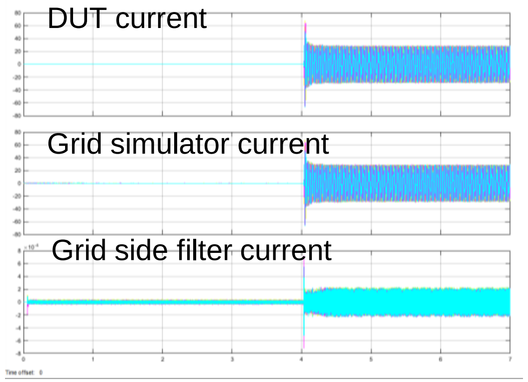
- Operate as a controllable load to validate the grid forming capability (as a voltage source) of the DUT.

GFM Test Items	Instruction
On-Grid Mode	CB1 closed,CB2 and CB3 opened, Load simulator is bypassed, GFM DUT work on On-Grid mode
Off-Grid Mode	CB1 opened,CB2 and CB3 closed, Load simulator working on current control mode, GFM DUT work on Off-Grid mode
On-Grid to Off-Grid	CB1,CB2 and CB3 closed, Load simulator working on current control mode, and control the current of CB1 branch to zero, then open the CB1
Off-Grid to On-Grid	CB1 opened,CB2 and CB3 closed, Load simulator working on current control mode, then open the CB3 and close the CB1





Voltage waveform of off-grid mode test



Current waveform of off-grid mode test

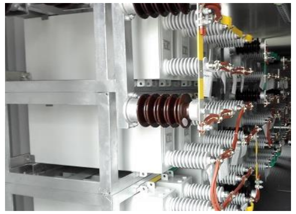
Grid Forming

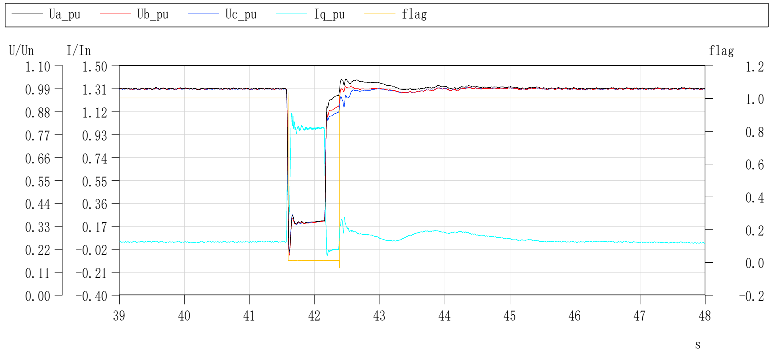
- Grid forming tests in China currently also consider instantaneous inertia response, weak grid operation capability, mode switch between grid following and grid forming, and active damping capability, etc.

Grid forming test items

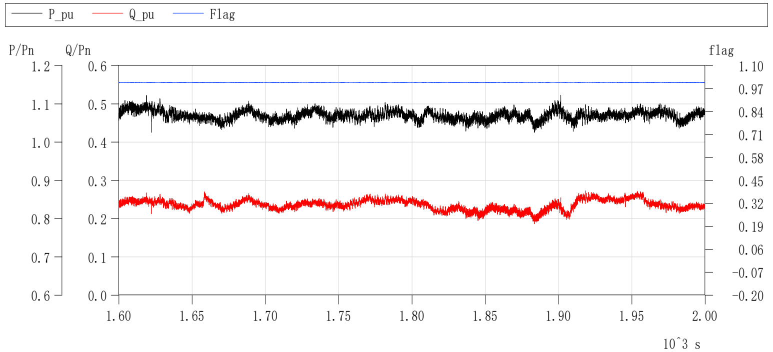
No.	Test items
1	Inertial response
2	Primary frequency regulation
3	Voltage phase angle response
4	Transient voltage support
5	Voltage and frequency adaptability
6	Low SCR operation capability
7	Active damping
8	Mode switch
9	Black start and supply the load

* Test items are not fully standardized yet.

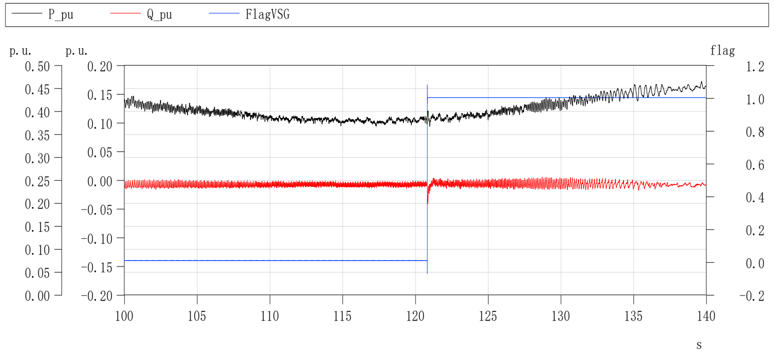




GFM switching to GFL during LVRT



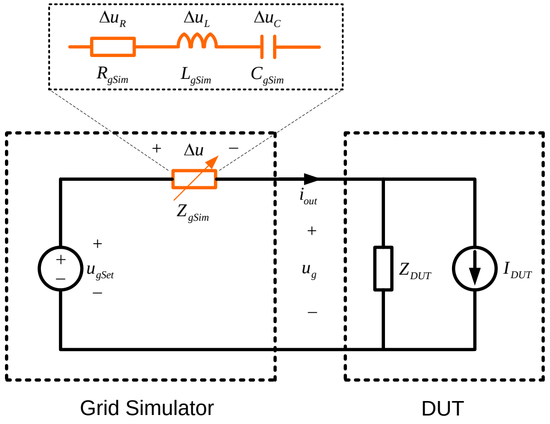
Weak grid test using real reactors

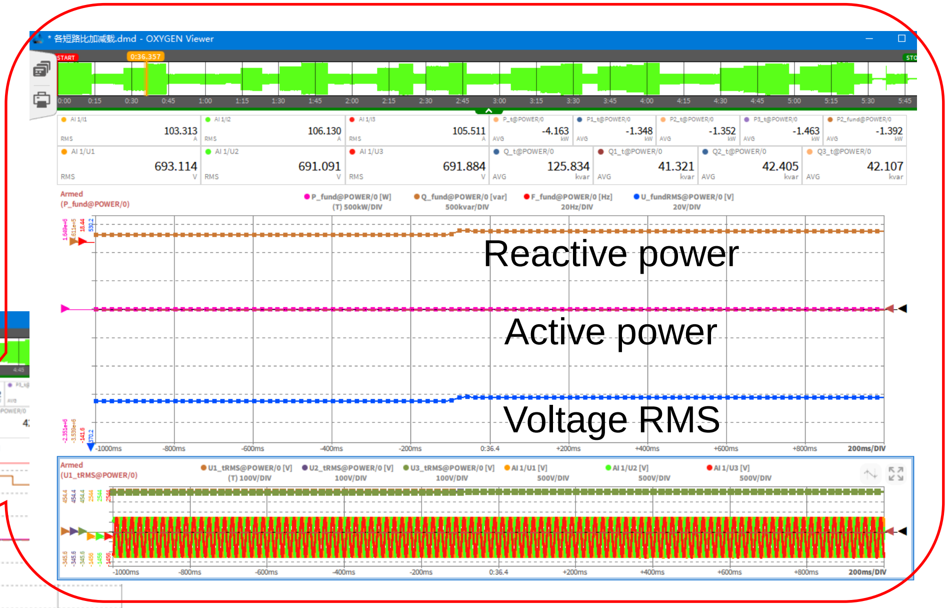


Switching from GFL to GFM

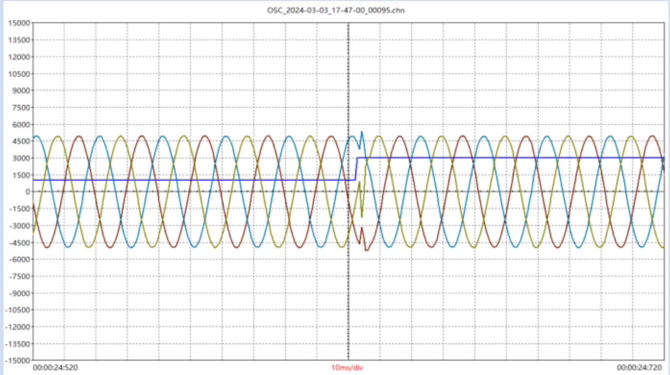
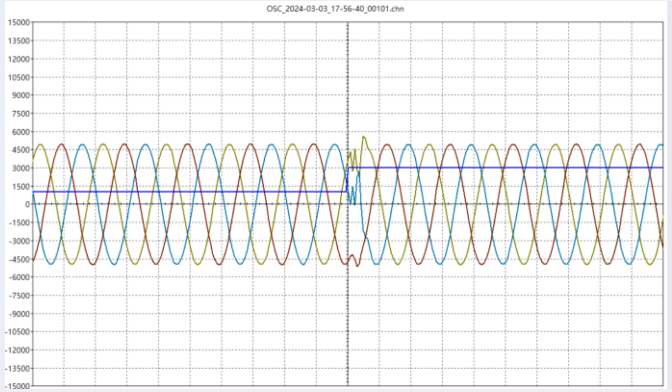
Impedance Simulation and Voltage Phase Angle Jump

- Variation of the virtual grid impedance to simulate a weak grid environment with low SCR.
- Step change of the three-phase voltage phase angle.





Voltage(RMS) of Low SCR test for WT

Angle step	Voltage waveform
30° jump	
60° jump	

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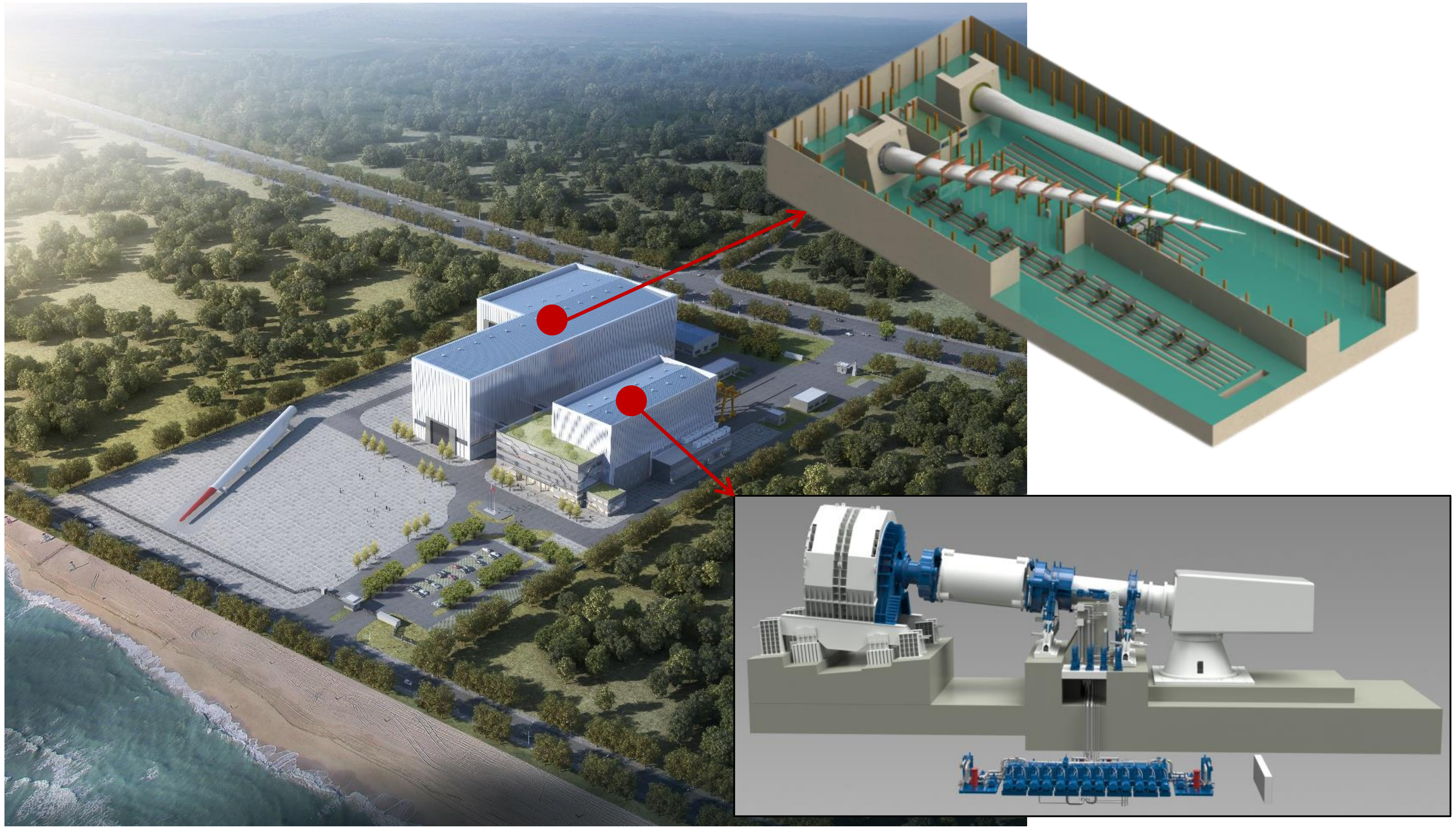
Contents

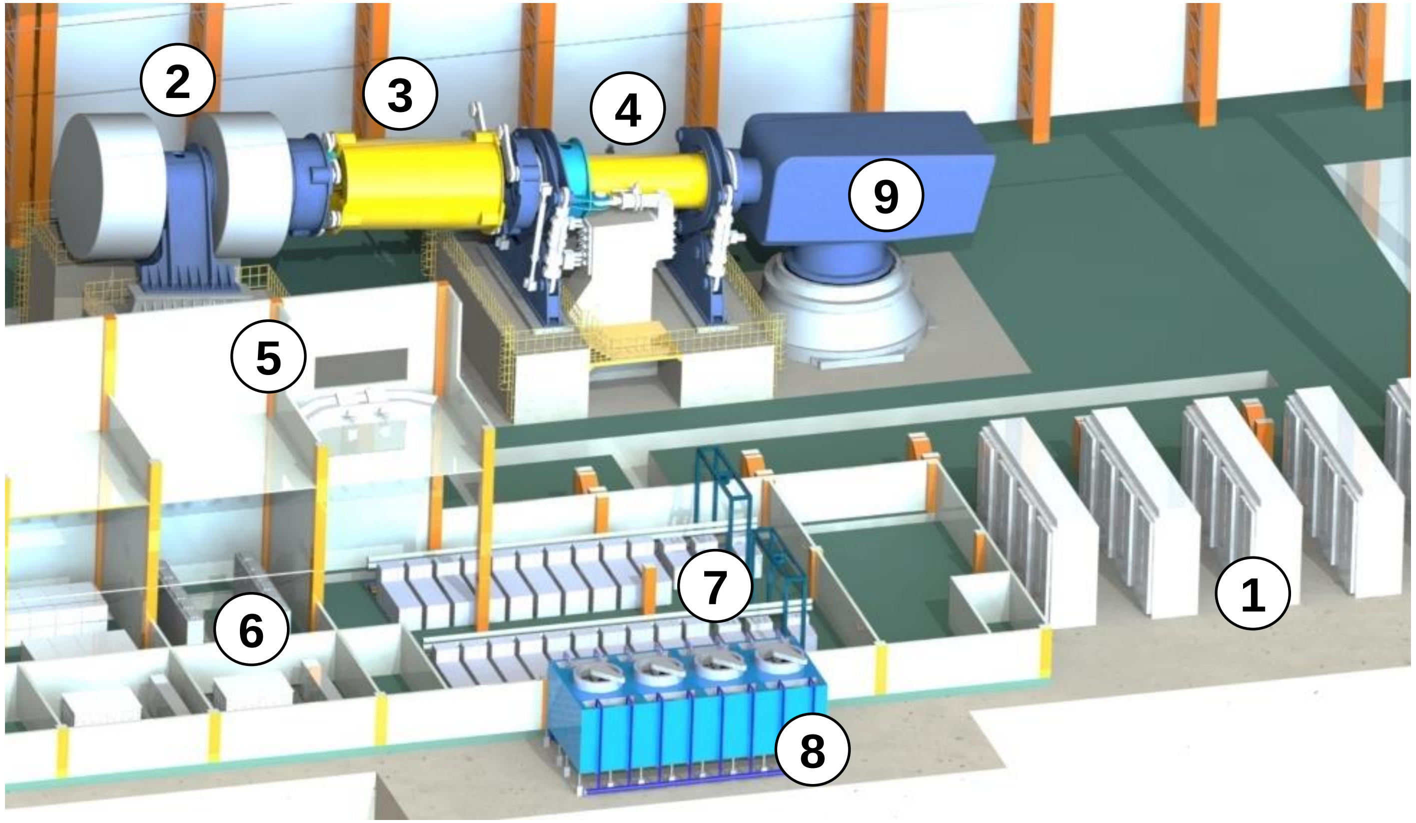
General Overview and Objectives

- National offshore wind power test and research base located in Fujian Province, southeast China.
- Include a 25MW drivetrain test bench, two 150m blade test benches (static and fatigue), and a test wind farm with 30+ onshore/offshore test locations.



Subsystems and Specifications

- 6 DOF load application system: drive motors and 5 DOF non-torque loading device.
- Grid simulation system: grid simulator with real-time digital simulation for pHiL.



1. Grid simulator
2. Drive motors
3. Torque limiter & coupling
4. 5 DOF non-torque loading device
5. Control room
6. Motor driving converter
7. Hydraulic station
8. Cooling subsystem
9. Turbine drivetrain under test (DUT)

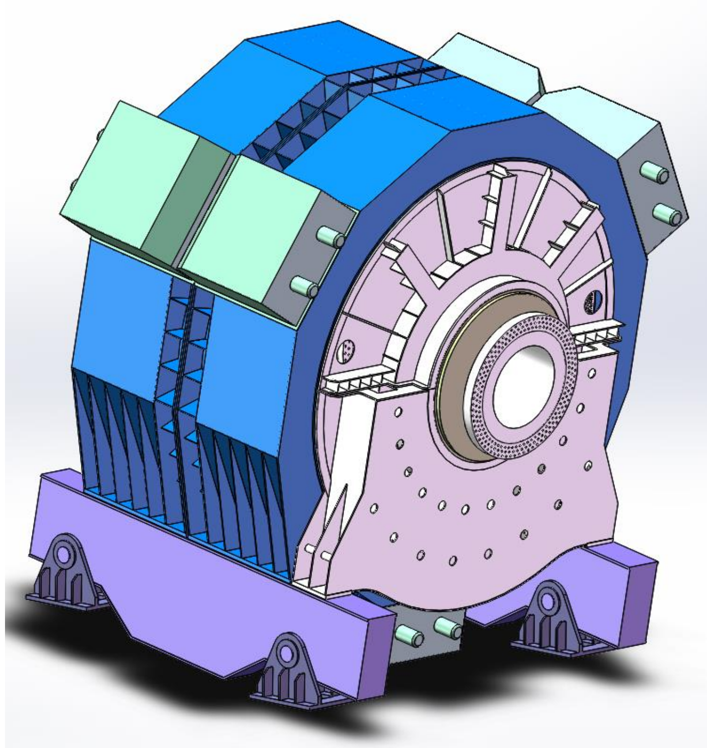
Subsystems and Specifications

Drive Motors

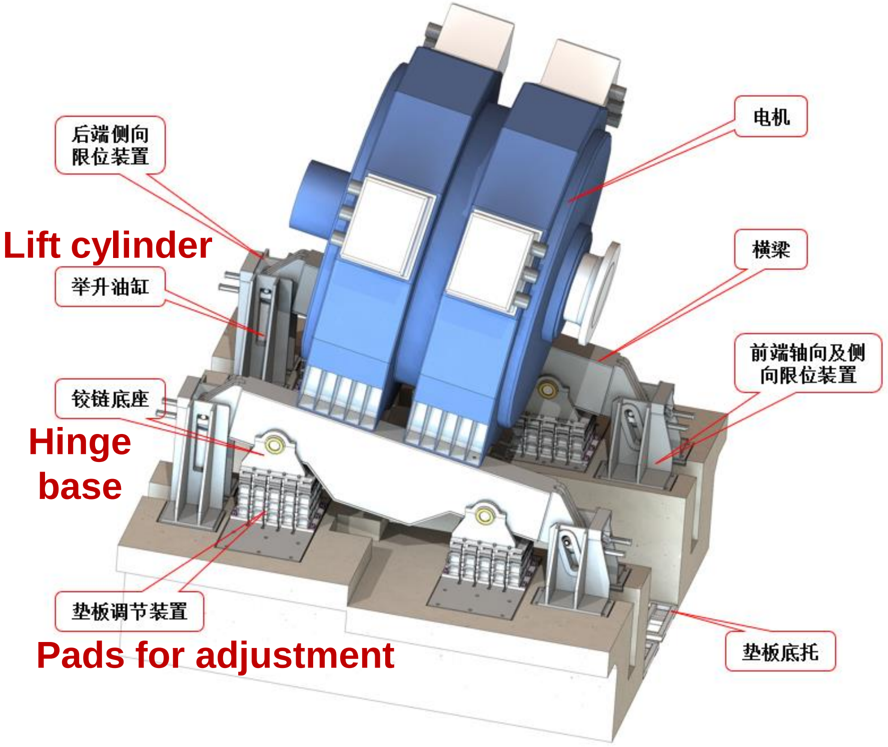
- Series connection of two synchronous motors with electrical excitation, nominal torque 35MNm.
- Adjustable tilt angle 6 ~ 10 degrees for adaptation to DUTs from different manufacturers.

Specifications of drive motor

Specifications	Values
Nominal power	12.5MW×2
Nominal voltage	3.3kV
Nominal speed	7rpm
Max. speed	13rpm
Nominal torque	35MNm
Overload capability	130%
Number of poles	120



3D diagram of drive motors



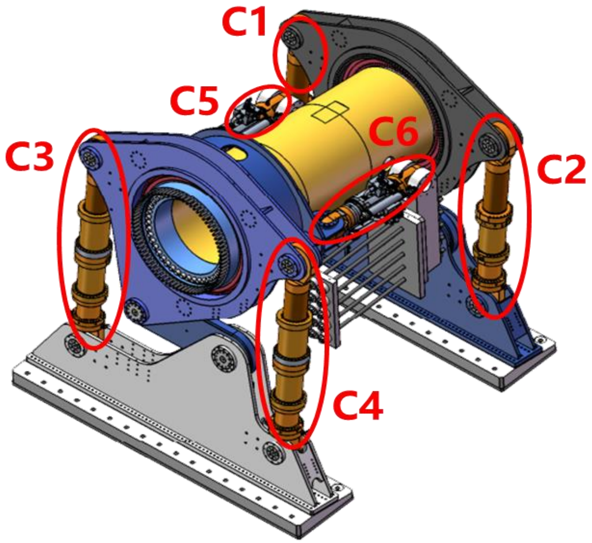
Hydraulic tilt angle adjustment

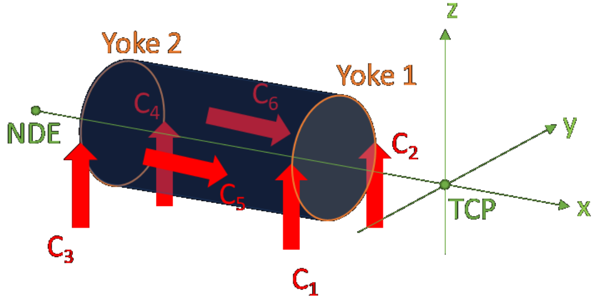
5 DOF Non-torque Loading Device

- Loading with 6 hydraulic cylinders, max. static moment 90MNm, max. static force 11MN.

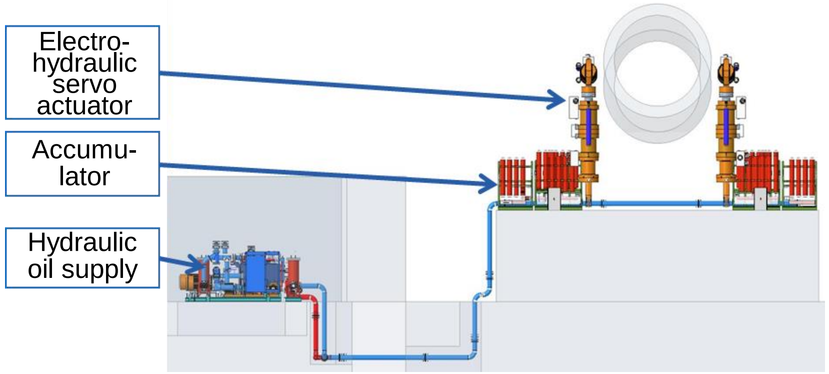
Specifications of 5 DOF load application

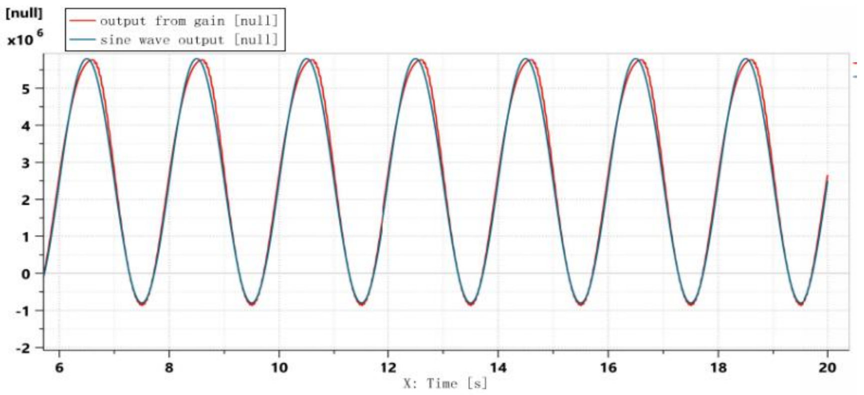
Specifications	Values
Max. static moment loading	90MNm
Max. dynamic moment loading	65MNm
Max. static radial force	11MN
Max. dynamic radial force	6.6MN
Max. static axial force	11MN
Max. dynamic axial force	6.6MN
Max. dynamic loading frequency	1Hz





5 DOF load decoupling under different tilt angles





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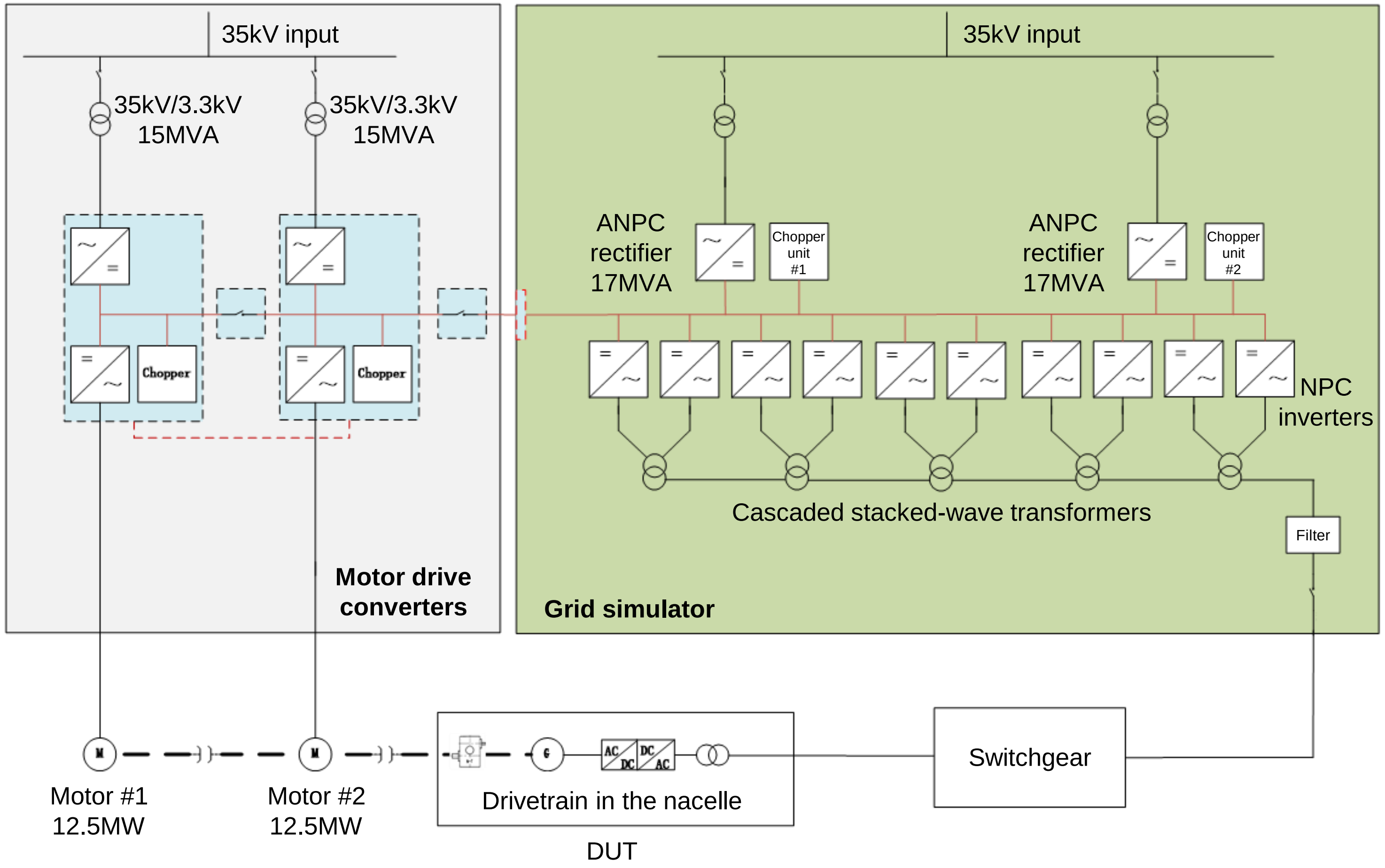
Grid Simulator

- IGCT-based grid simulator with 2 ANPC rectifier input (34MVA) and 10 NPC inverter output (90MVA).
- Cascaded output with 35kV voltage. Common AC or DC bus connection with motor converters.

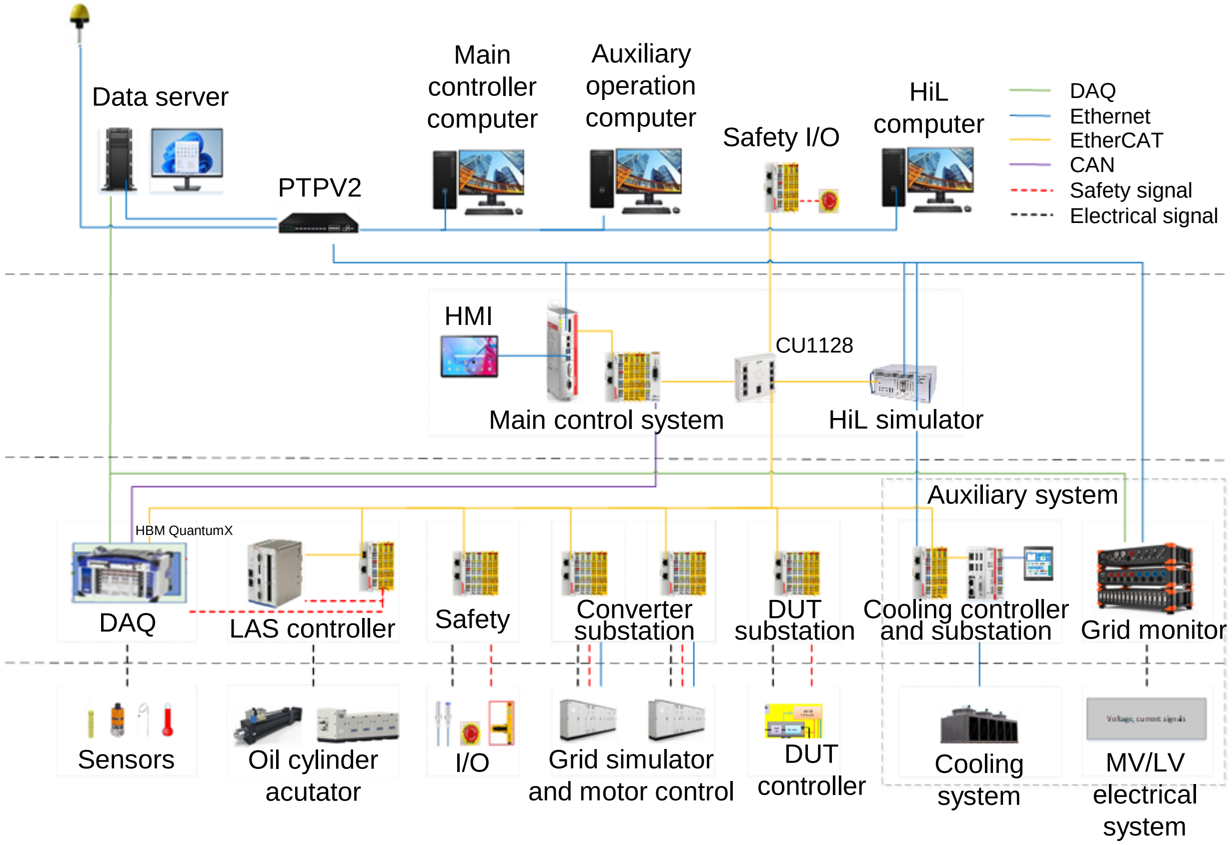


Specifications of grid simulator

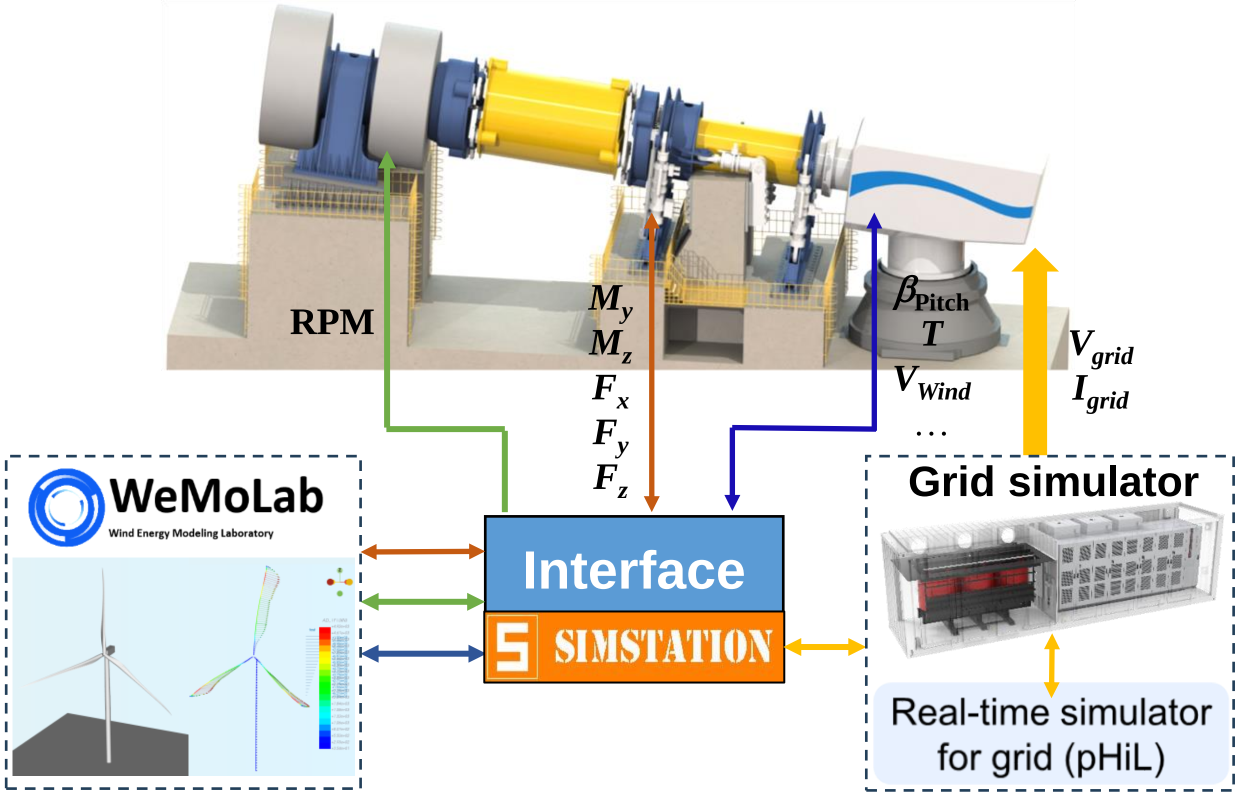
Specifications	Values
Output power	90MVA
Nominal voltage	35kV
Frequency range	45Hz ~ 66Hz
Voltage range	0 ~ 150%
Voltage flicker Pst	1 ~ 10
Voltage unbalance	0 ~ 10%
Harmonic voltage generation	1Hz ~ 1250Hz
Combined harmonics injection	THD≤10% Accuracy ±0.5%

Test Bench Control and Operation

- Multi-level control architecture for the operation of the test bench.
- Enable mHiL and pHiL operation to accurately replicate the operation of DUT in the field.



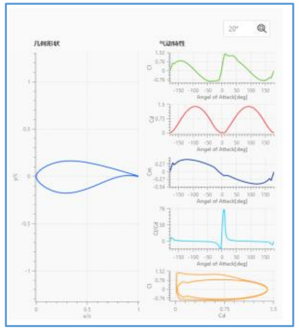
Topology of test bench control

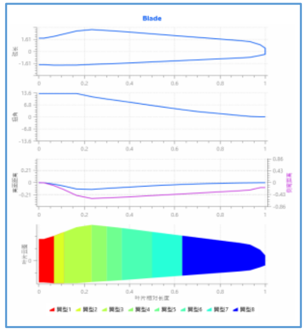


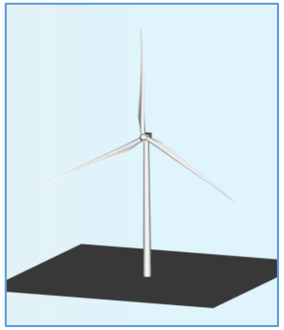
HiL system and data exchange

WeMoLab

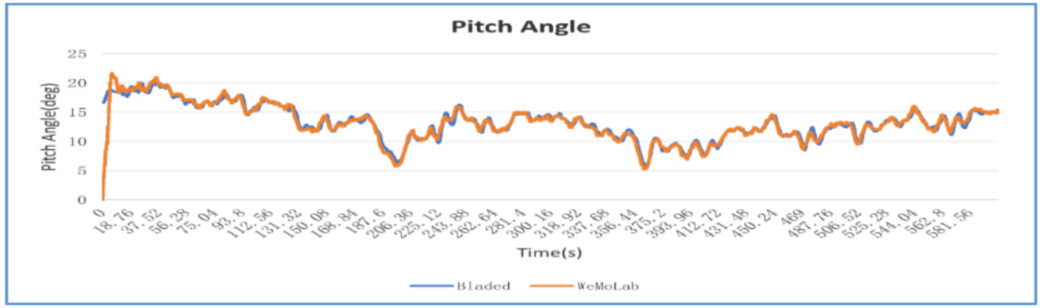
- Wind turbine simulation software developed by CEPRI, with support to mHiL operation.
- Co-simulation of aerodynamic-hydrodynamic-structural-electrical-control characteristics.

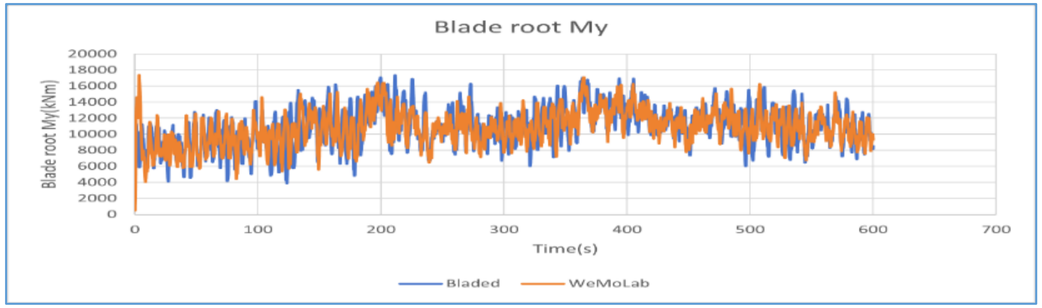


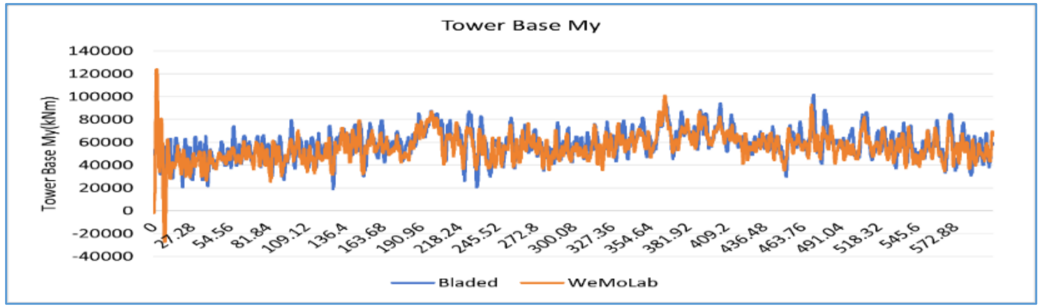




WeMoLab
国产风电机组仿真软件







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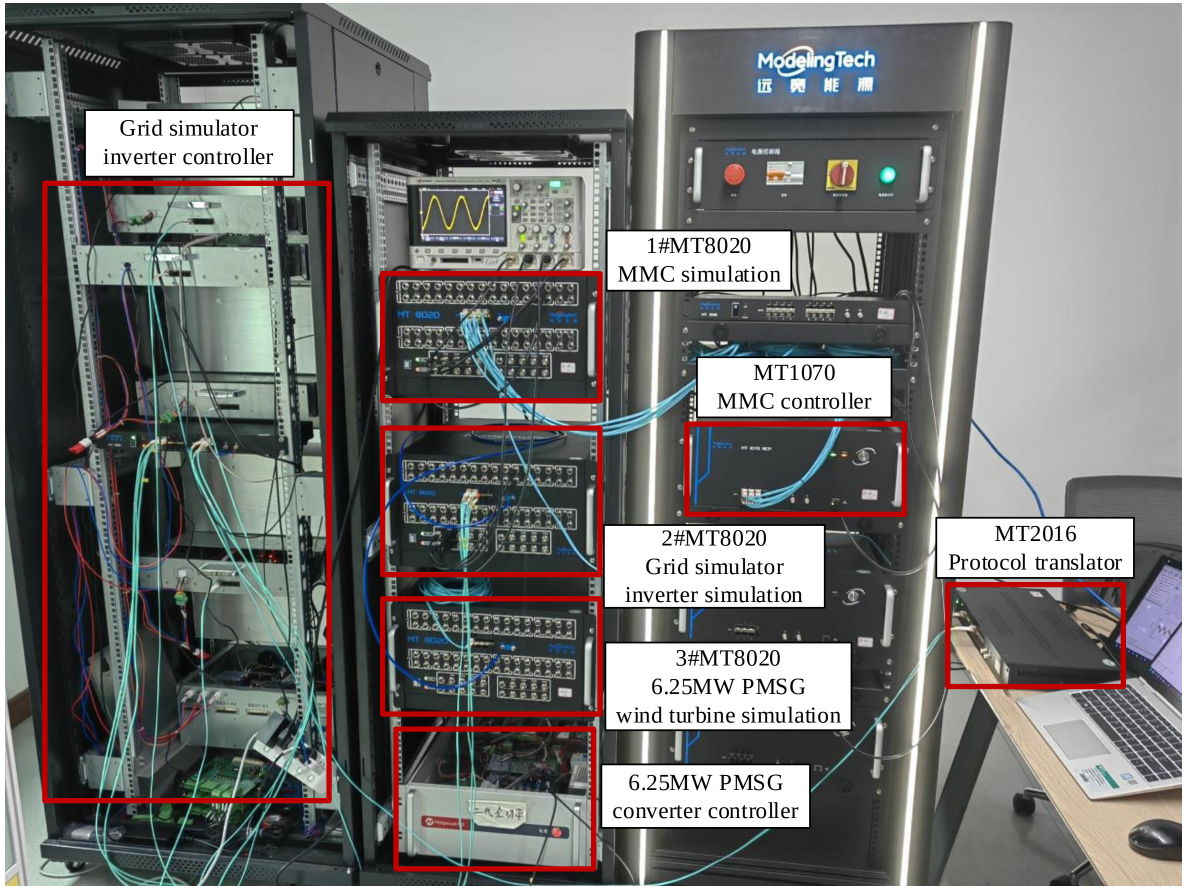
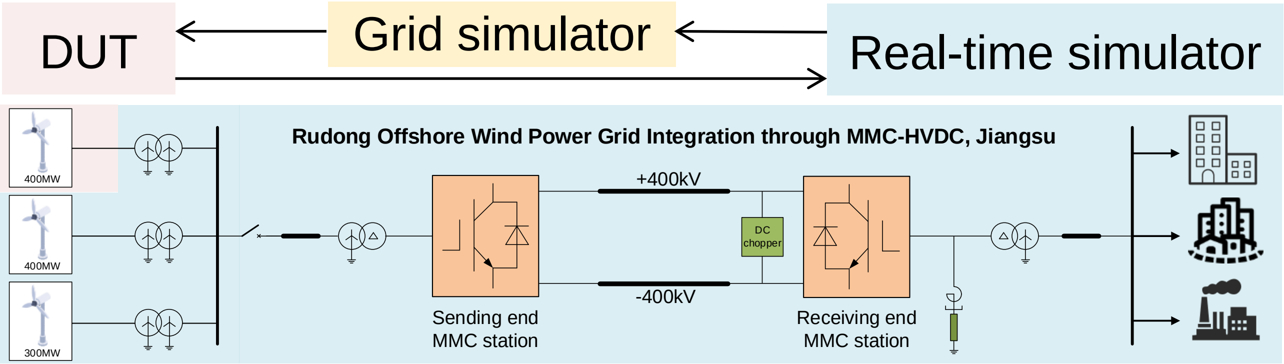
Grid Integration Real-time Simulation

- Multi-core CPU simulators with FPGA for small-step power electronic simulation.
- Fiber-optic communication with the grid simulator controller to transmit references and measurements.



Developing of wind turbine connected by MMC-HVDC

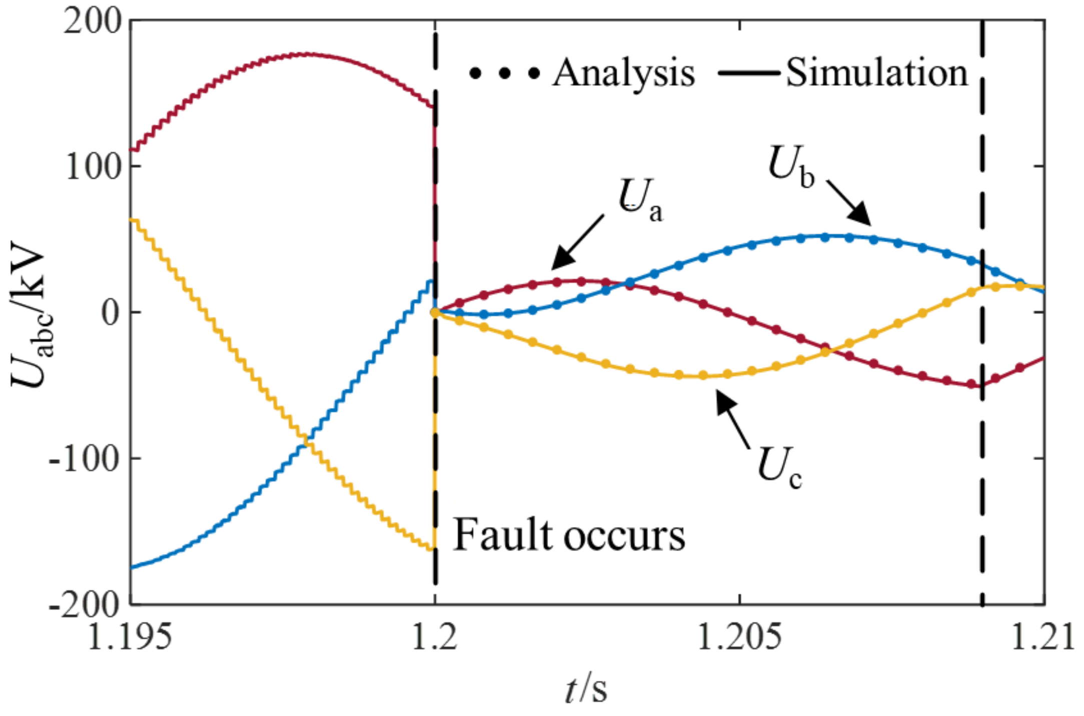


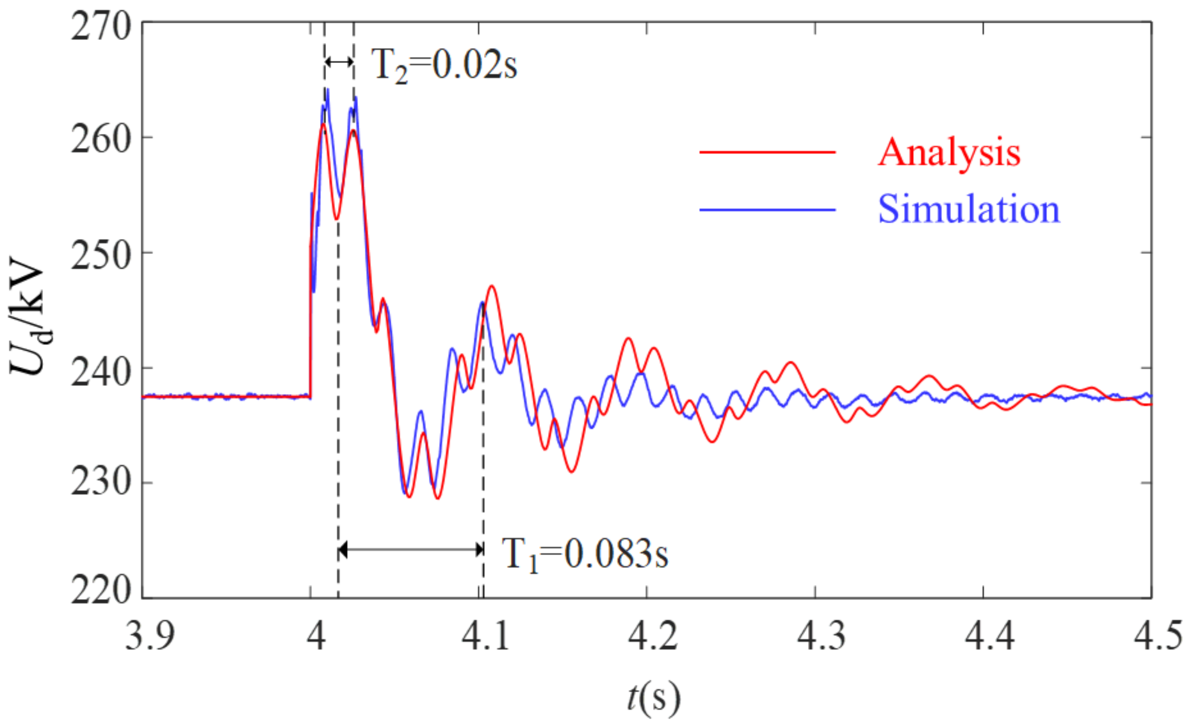
Specifications of grid integration real-time simulator

Specifications	Values
Min. CPU simulation step size	20μs
Max. MMC modules in each bridge arm	512
Min. MMC simulation step size in FPGA	1μs
Latency from simulator to voltage amplification	Currently: ~800μs Aim: <500μs

Equivalent Emulation of Operating Conditions

- Simplify the grid-integration system but equivalently keep some key characteristics.
- Mathematically express the system dynamics and integrated in the grid simulator controller.





Equivalently model the MMC-HVDC as a simplified system and mathematically analyze the dynamics for testing

Current Status

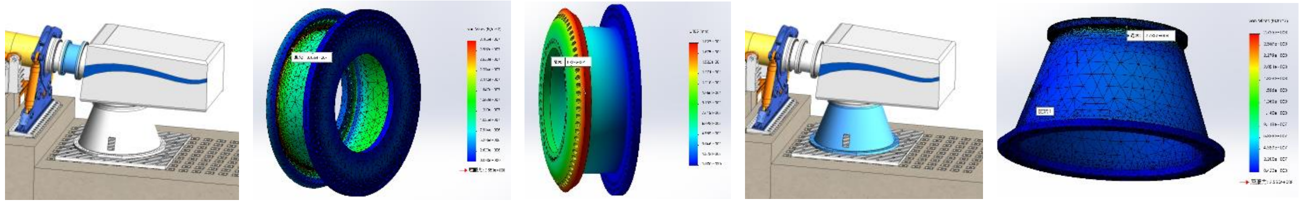
- Key subsystems manufacturing almost finished. System commissioning will start from Q4 2024.
- Plan to start the test of the first DUT (CSSC 18MW) from the first half of 2025.


Test Bench Hall

CSSC 18MW

Specifications of DUT

Specifications	Values
Nominal power	18MW
Nominal speed	7rpm
Max. speed	7.84rpm
Blade length	126m




Grid Simulator


Motor Stator


Hydraulic Oil Supply


Mechanical System

Future Plans

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Testing of Multi-megawatt Wind Turbine for Grid Compliance and Certification

- Electrical characteristic test according to IEC 61400-21 and related documents.
- model validation and compliance assessment, referring to IEC 61400-27 and IEC TS 63102.

IEC DTS 61400-21-4 © IEC 2024 19 88/1048/DTS

WIND ENERGY GENERATION SYSTEMS –

Part 21-4: Measurement and assessment of electrical characteristics – Wind turbine components and subsystems

1 Scope

This part of IEC 61400, which is a Technical Specification, specifies a uniform methodology, defining measurement, testing and assessment procedures of electrical characteristics of Wind Turbine components and subsystems, as basis for the verification of the electrical capabilities of Wind Turbines and Wind Turbine families.

This document includes the following aspects:

– definitions of test bench, subsystems and interface;
– dDefinitions of system requirements for the test bench to perform relevant measurements (grid strengths, Short circuit power , THD, ...);
– measurement procedures for quantifying the electrical characteristics;
– test & measurement procedures for verifying and validating the electrical characteristics of components & subsystems in relation to grid compliance requirements;
– procedures for the transferability of the component and subsystem test results, measured at the test bench, to WT product families;
– documentation requirements and validation procedures of components, subsystems and wind turbines.

The results of the measurements and assessments of the Wind Turbine components & subsystems will be used as input for the verification of electrical capabilities as described in IEC 61400-21-1 and for the validation & verification of the electrical simulation models for Wind Power Plants (WPP) as described in IEC 61400-27.

Out of scope of this technical specification are:

– design requirements of test bench systems;
– model development of WT subsystems and WT as e.g. described in the IEC 61400-27 series;
– Power Plant control function test (e.g. FSM, Voltage Control) as described in IEC 61400-21-2;
– specific component design test and validation of the wind turbine equipment (switchgears, cables, transformer, generator etc.), which are covered by other IEC standards;
– mechanical, structural loads and lifetime test;
– noise and acoustical measurements;
– ;certification procedures and grid compliance at wind power plant level;
– communication system functional and performance tests as defined in e.g. the IEC 61400-25 series.

NOTE

For the purposes of this document, the following terms for system voltage apply, based on IEC 60038:

Low voltage (LV) refers to 100 V < U_n ≤ 1 kV;

Medium voltage (MV) refers to 1 kV < U_n ≤ 35 kV;

IEC DTS 61400-21-4

ICS 27.180
CCS F 11

GB

中华人民共和国国家标准

GB/T 19963.1—2021
代替 GB/T 19963—2011

风电场接入电力系统技术规定
第1部分：陆上风电

Technical specification for connecting wind farm to power system—Part 1:On shore wind power

Technical specification for connecting wind farm in power system —

Part 1: On shore wind power

Part 2: Off shore wind power

2021-08-20 发布 2022-03-01 实施

国家市场监督管理总局
国家标准化管理委员会 发布

GB/T 19963

IEC

IEC TS 63102

Edition 1.0 2021-09

TECHNICAL SPECIFICATION

colour inside

Grid code compliance assessment methods for grid connection of wind and PV power plants

INTERNATIONAL ELECTROTECHNICAL COMMISSION

ICS 27.160; 27.180 ISBN 978-2-8322-1022-1

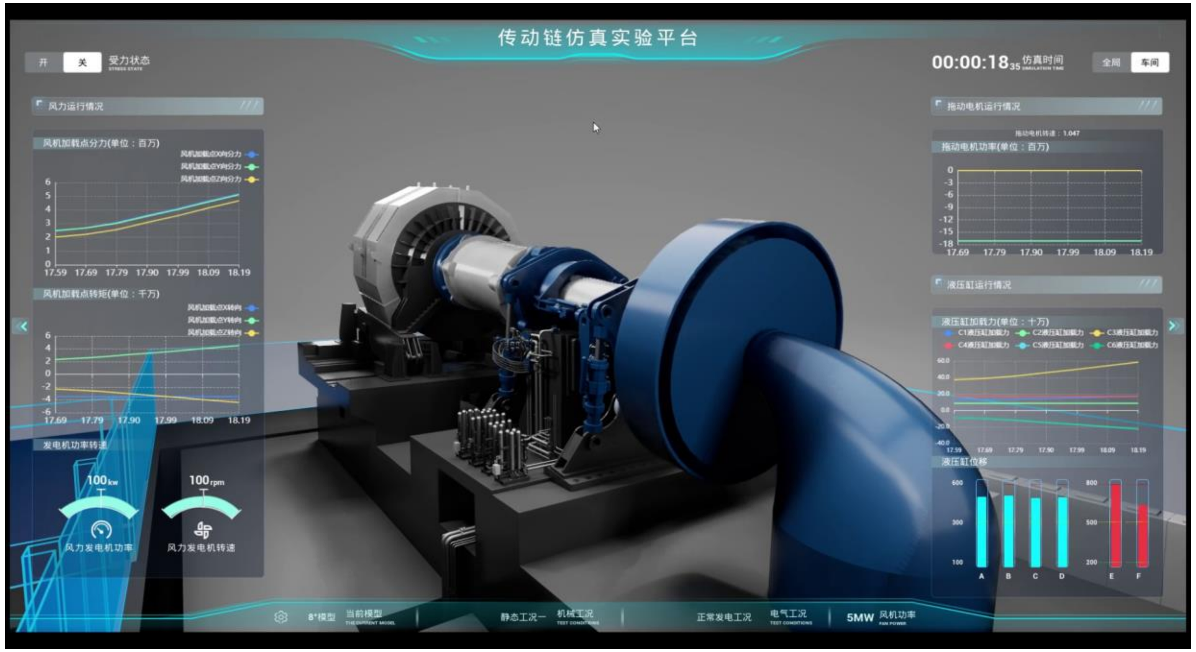
IEC TS 63102

Operating area
Frequency range
Voltage range
Reactive power capability
Short circuit ratio
Power quality
Harmonics
Control performance
Active power control (setpoint and ramp)
Frequency response
Reactive power control
Voltage control Q(U) - characteristic

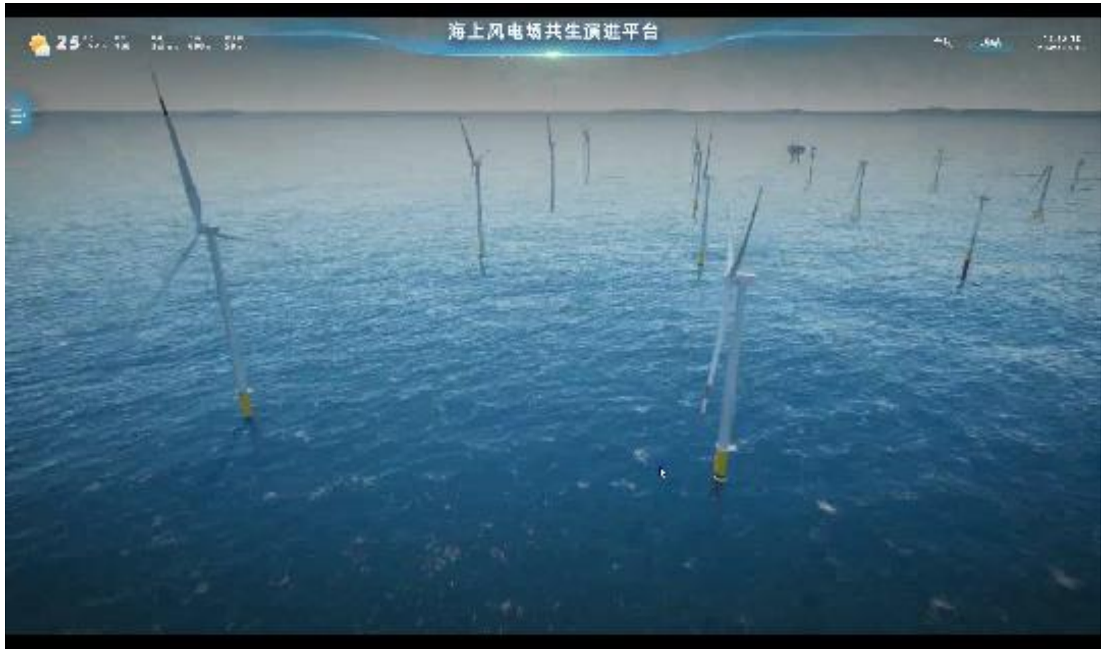
Future Plans

Data Collection and Digital Twin Development

- Digital twin systems of both the drivetrain test bench and the future offshore wind farms.



Data-driven modeling and simulation of the test bench



Digital twin of the offshore wind farm

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Thank you!

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