



From Plant to System: Developing Real-time Test Benches for Converter-based Power Systems

From model validation and controller testing to integrated system-level verification

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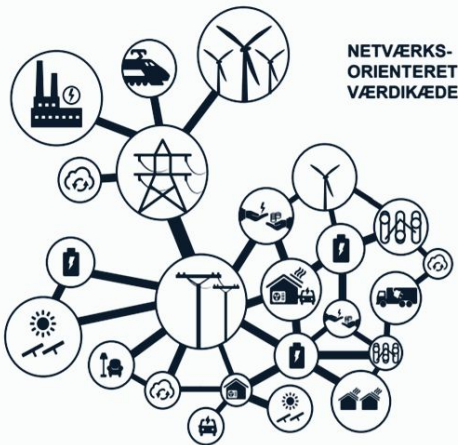
2026 MADRID USER'S GROUP MEETING
MADRID, SPAIN



Fundamental Changes in *System Complexity*

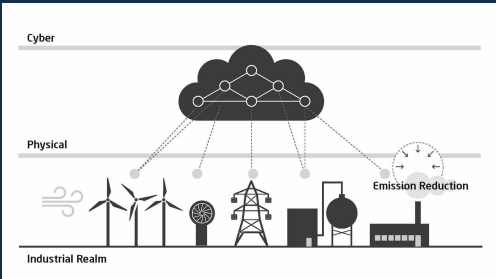
01

Highly distributed system with billions of active units



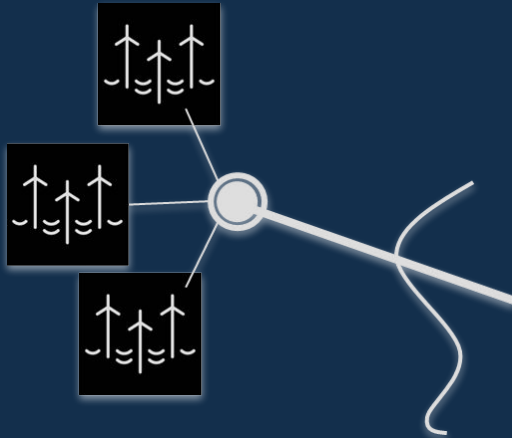
02

Adding a new cyber-layer of data and digital control



03

New large-scale offshore energy grids



Spain Blackout: *What can we DO to help them?*

APRIL 28, 2025

60 Million

People left without electricity

- Severe disruption to national transport & rail networks
- Complete shutdown of digital payment systems & telecommunications
- Widespread impact on critical infrastructure and daily life



Atocha Train Station, Madrid

People take shelter and spend the night inside the station following the massive power failure across the Iberian peninsula.

Photo Credit: Anadolu

DTU RT-Center Research Infrastructure Vision

Approved by Danish National Research Infrastructure Roadmap 2025

CORE GOAL



"The vision is to establish a second-to-none, real-time, high-fidelity research infrastructure for complex, converter-based, and digitalised power systems, providing the foundation for a secure and rapid green transition."

PILLAR 01

Simulation

Real-time digital simulation providing high-fidelity modeling for complex, converter-based power systems.

PILLAR 02

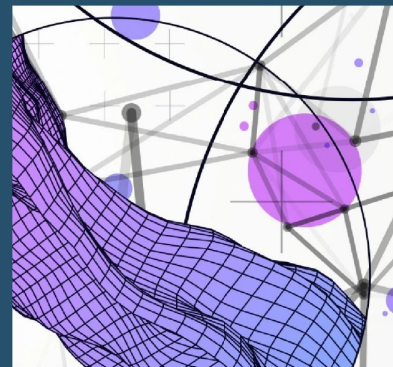
Testing

Empirical validation and hardware-in-the-loop verification

ROADMAP 2025

Dansk Roadmap for Forskningsinfrastruktur 2025

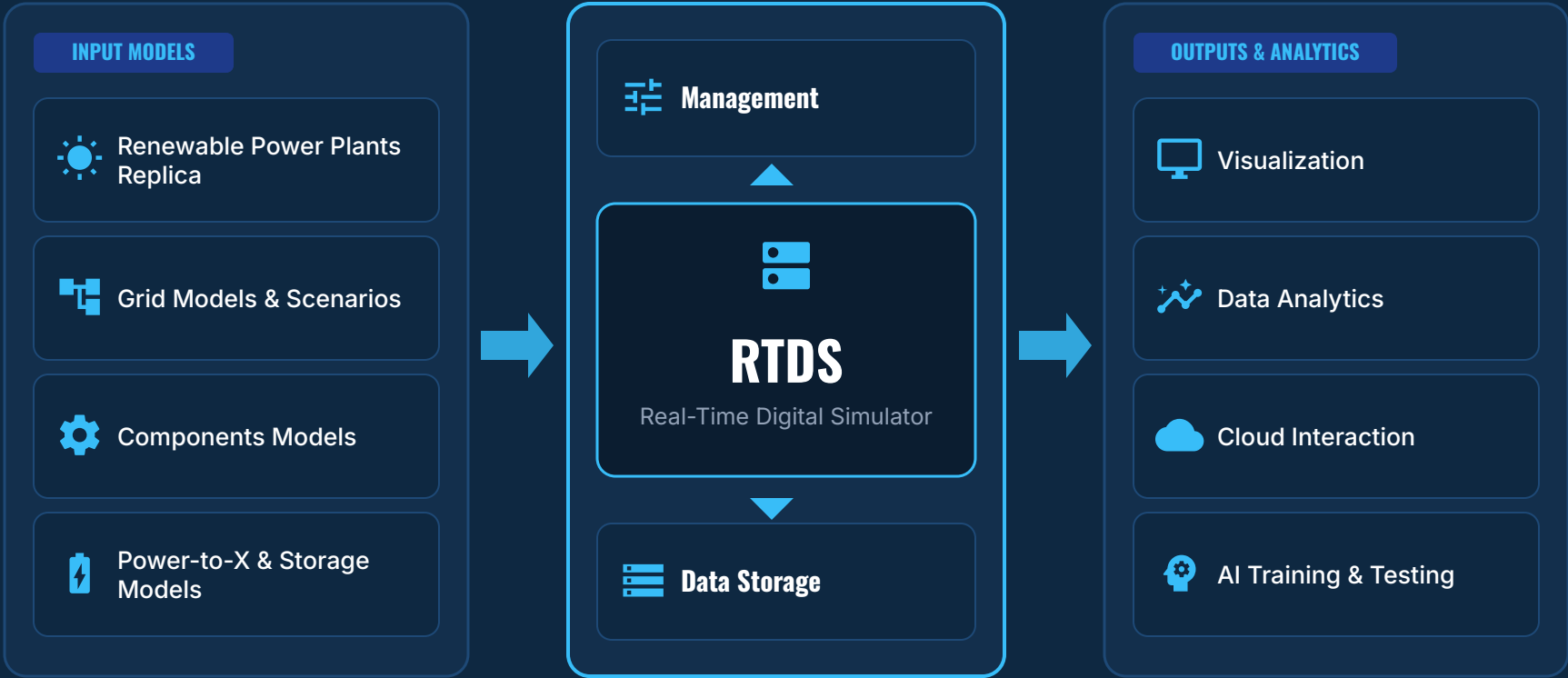
December 2025



Uddannelses- og
Forskningsministeriet

RT-Center infrastructure overview

High-Fidelity Hardware-in-the-Loop Architecture Overview



DTU Supported Major Use Cases

UC1



Designing a **100% renewable power system** using validated real-time models of the Danish grid.

UC2



Infrastructure for **protection testing, cybersecurity testing, and extreme weather events** studies.

UC3



Real-time models and HiL-setup necessary for **designing energy islands**.

UC4



HiL/SiL **grid compliance testing** infrastructure for Wind Turbines (WTs) and Wind Power Plants (WPPs).

UC5



Datasets and cloud service interfaces (incl. Energy Data DK and GPU-based HPC) for **AI applications** testing.

DTU Testing System Evolution Towards Integrated Setups

Technical specifications are needed for subsystems to ensure system-level tests are trustworthy

01

offline EMT

Electromagnetic
Transient offline
simulation models for
fundamental dynamic
analysis.

02

cHiL

Controller
Hardware-in-the-Loop
real-time testing with
physical replica
controllers.

03

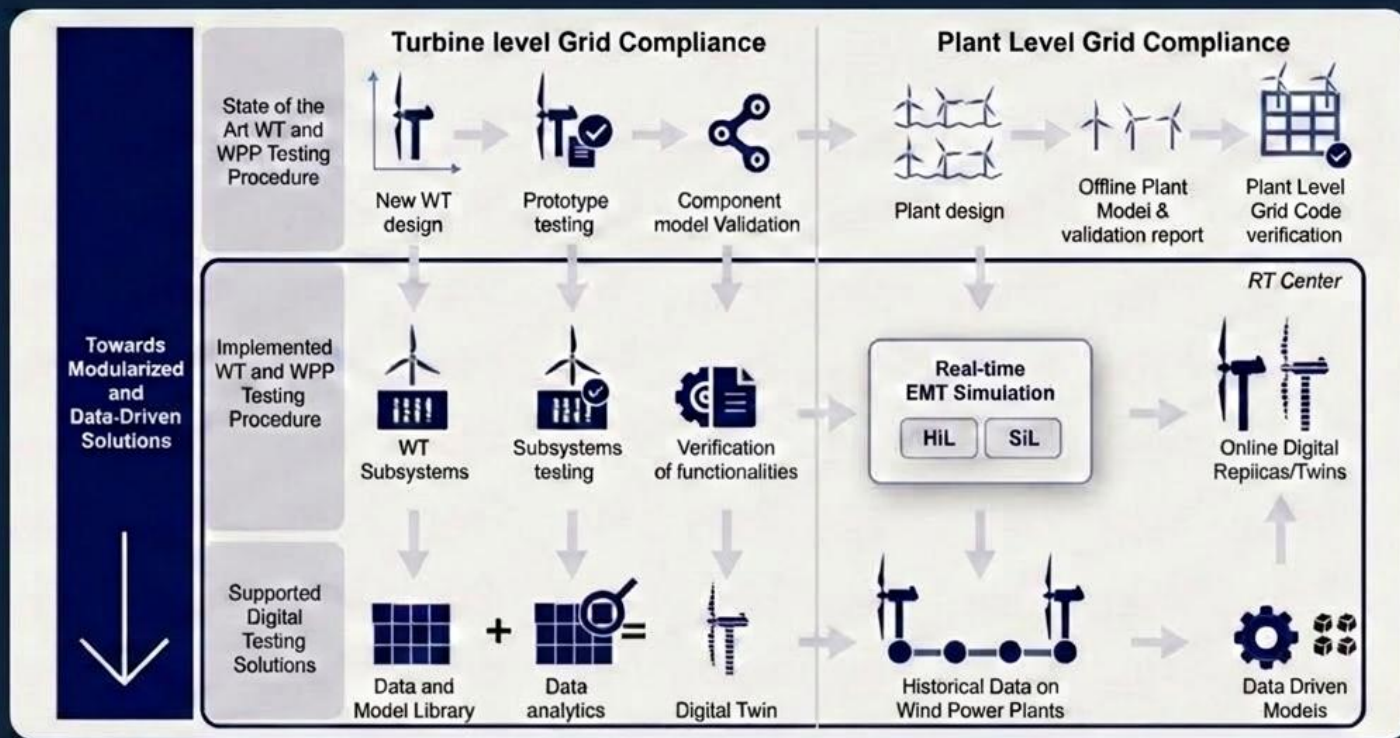
SiL

Software-in-the-Loop
validation for scalable
testbench setup.

04

System test bench

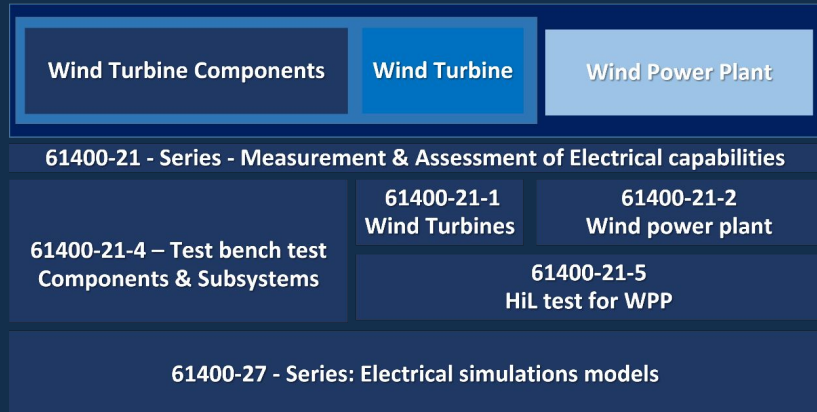
Integrated
system-level
verification for full
operational security.



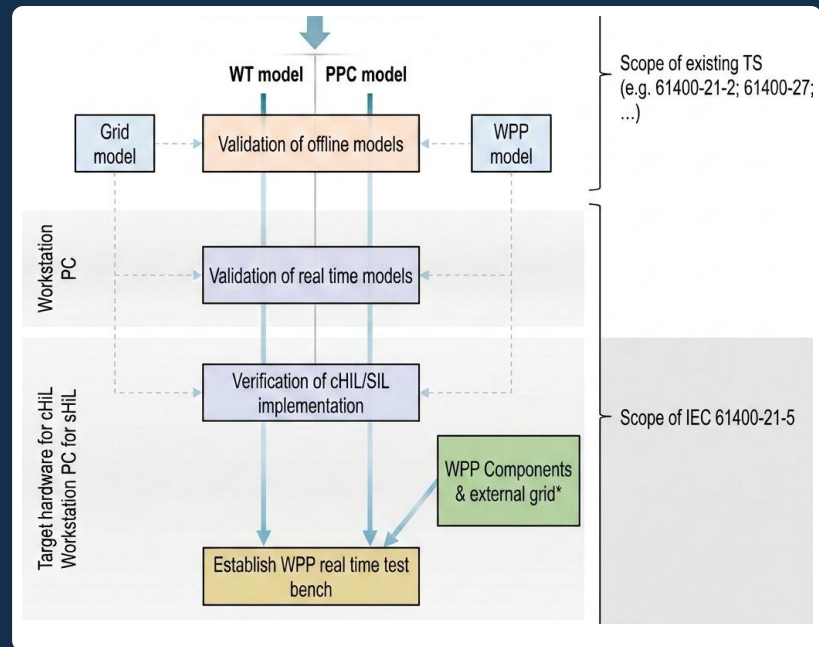
IEC61400-21-5 HiL Testbench Specification for WPP

Wind energy generation systems – Part 21-5: Configuration, functional specification, and validation of hardware-in-the-loop test bench for wind power plants

IEC61400-21 SERIES STANDARD ARCHITECTURE



VALIDATION & IMPLEMENTATION



WPP Testing System Setup

Key concepts definitions and test bench architecture

OVERVIEW & CONCEPT DEFINITIONS

- Defines key concepts such as WT and WPP control replica and replica
- Accepts **SiL** (Software-in-the-Loop) alongside **HiL** for creating a complete WPP test bench.

CONTROL REPLICA STRUCTURE

WT: Converter control + turbine control + WT protection

WPP: PPC + WT control replica + protection functions + other

WT & WPP CONTROL REPLICA IMPLEMENTATION

cHiL

SiL

REPLICA ARCHITECTURE

WT replica

WT control replica

- Turbine controller
- Converter controller
- WT Protection

WT physical model

- Aerodynamic model
- Drivetrain
- Generator
- Converter electric
- Other subsystems

WPP test bench

WPP control replica

- PPC
- WT control replica
- WPP Protection

WPP physical model

- WT physical model
- Line
- Transformer
- Other components

DTU WPP Representation in Use Cases

 Overview of key use cases and their primary verification objectives

USE CASE 01

Grid interaction studies of the wind power plant

MAIN OBJECTIVE

To validate/verify the electric design and dynamic control performance

USE CASE 02

Reliability and selectivity of protection system

MAIN OBJECTIVE

To validate/verify the WPP protection design philosophy and settings

USE CASE 03

Interoperability between wind power plant & HVDC

MAIN OBJECTIVE

To validate/verify control coordination between the WPP and the HVDC

USE CASE 04

Control functionality & performance testing

MAIN OBJECTIVE

To validate/verify the control functions at the plant level

USE CASE 05

Control coordination & external system integration

MAIN OBJECTIVE

To validate/verify critical internal plant control functions and interplant controls

USE CASE 06

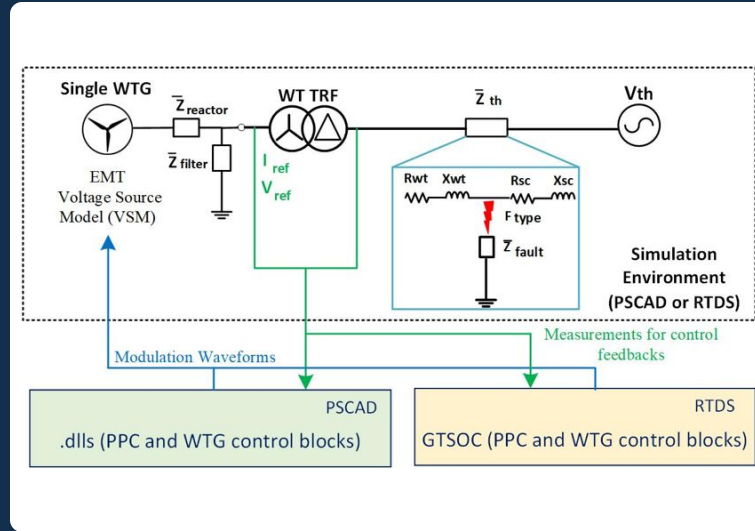
Lifetime monitoring of real-time models

MAIN OBJECTIVE

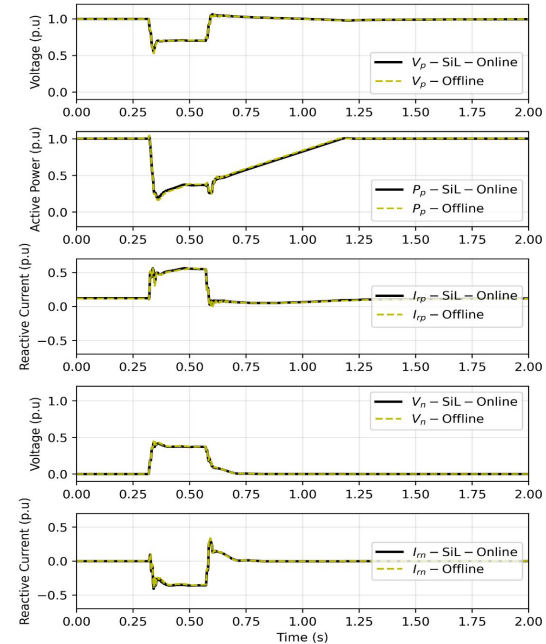
To verify the WT and WPP models using the control replica after WPP is operational

ARCHITECTURE & CONTROL INTEGRATION

Software-in-the-Loop (SiL) technology integrates actual control and protection source code directly into real-time simulators (PSCAD / RTDS) for dynamic EMT analysis.



REAL-TIME VS OFFLINE VALIDATION RESULTS



DTU From plant test bench to system test bench



Key architectural layers for multi-domain real-time simulation

LAYER 05

Management System Software

Manager for grid codes, scenarios & events, SCADA, AI training model integration

LAYER 04

Data Interface

SCADA interface

Data Management API

Grid code setting interface

LAYER 03

RT Hardware

WT & WPP control replica

Power Plant Controller

HVDC control replica

FACTS device control replica

Protective relays

Other grid controls

LAYER 02

RT Simulation Platform

RTDS Simulator

HiL Interfaces

SiL setups

LAYER 01

Models

Renewable generation

Wind, solar, biogas, etc.

Grid Models

Transmission system, HVDC,
FACTS devices

Large load

Data center and electrolyzer

Storage

Battery, heat, hydrogen, etc.



01

Common Architecture

Establishes a unified 5-layer hierarchy integrating hardware, models, interfaces, and control systems into one standardized framework.



02

Verified Models & Interfaces

High-fidelity HiL/SiL setups validated against real Danish grid data and industrial control replicas for compliance.



03

Scalable Evidence

Delivers continuous validation capabilities transitioning smoothly from single plant components to full power system levels.