First International Workshop on Grid Simulator Testing of Wind Turbine Drivetrains: Workshop Proceedings

V. Gevorgian, H. Link, and M. McDade
National Renewable Energy Laboratory

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NREL is a national laboratory of the U.S. Department of Energy
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Technical Report
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November 2013

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NATIONAL RENEWABLE ENERGY LABORATORY

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National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

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List of Acronyms

CGI	controllable grid interface
CU	Clemson University
HIL	hardware-in-the-loop
NREL	National Renewable Energy Laboratory
WTG	wind turbine generator

Executive Summary

This report summarizes the proceedings of the First International Workshop on Grid Simulator Testing of Wind Turbine Drivetrains, held from June 13 to 14, 2013, at the National Renewable Energy Laboratory's National Wind Technology Center, located south of Boulder, Colorado. The workshop was sponsored by the U.S. Department of Energy and cohosted by the National Renewable Energy Laboratory and Clemson University under ongoing collaboration via a cooperative research and development agreement.

Grid simulators are a new, emerging testing capability that is becoming a critical step in overall wind turbine generator testing portfolios in many countries throughout the world. Grid simulators allow wind turbine generator manufacturers to test both the mechanical and electrical characteristics of their machines in a controlled grid environment by replicating many electrical scenarios that were previously only partially available by field demonstrations. Such grid simulators give manufacturers a platform upon which to ensure that their systems meet stringent national and international electrical standards and grid codes and test grid compliance of new, innovative electrical topologies and controls. This will increase reliability and lower the cost of energy delivered by wind power. An important aspect of grid simulator testing is a capability to provide electrical testing beyond fault ride-through, including a complete suite of electrical testing solutions at the multi-megawatt level for the wind power industry.

Another benefit of grid simulator testing comes from the inclusion of hardware-in-the-loop testing capabilities that provide a platform above and beyond present standards for compliance testing (a static system) by simulating a detailed dynamic power system model in real time in which the device under test actually interacts with the simulated power system at full-scale power levels. Hardware-in-the-loop testing is particularly beneficial for performing parallel model verification, in which the differences between an actual device behavior and a detailed dynamic model of the device can be reconciled to provide a more robust and accurate model. This type of testing can identify and prevent costly and dangerous failures upon deployment. It also allows the customer to demonstrate their product in a safe and controlled environment, accelerate its introduction into the market, and reduce the risk of new-market introductions.

The purpose of the workshop was to provide a forum to discuss the research, testing needs, and state-of-the-art apparatuses involved in grid compliance testing of utility-scale wind turbine generators. This includes both dynamometer testing of wind turbine drivetrains ("ground testing") and field testing grid-connected wind turbines. Four sessions followed by discussions in which all attendees of the workshop were encouraged to participate comprised the workshop.

Discussions during the workshop identified several conclusions and priority action items for coordinating and improving the present set of testing equipment and methods:

1. Power electronic grid simulator test stands similar to those at the National Renewable Energy Laboratory and Clemson University are being pursued by all major test facilities in Europe and Asia involved in the testing and certification of wind power technologies;
2. Coordination and data sharing between labs is needed for improved safety, better understanding of testing methods and priorities, and more-realistic mimicking of failure modes and field events, etc.

3. The addition of hardware-in-the-loop testing capabilities to power electronic grid simulators enables a new area of research and testing to estimate the impacts of a wind turbine generator and its controls at various scales from a single wind power plant to an entire power system.
4. Standardization has been identified as a necessary future step to ensure valid and reliable grid simulator testing methods and conditions that can be replicated from lab to lab. (This is especially important for hardware-in-the-loop wind farm/power system level testing.)

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1 Introduction

The United States and its territories are integrating renewable energy resources at an increasing rate each year. At the same time, utilities and other electricity industry stakeholders are facing challenges that slow the progress of integration.

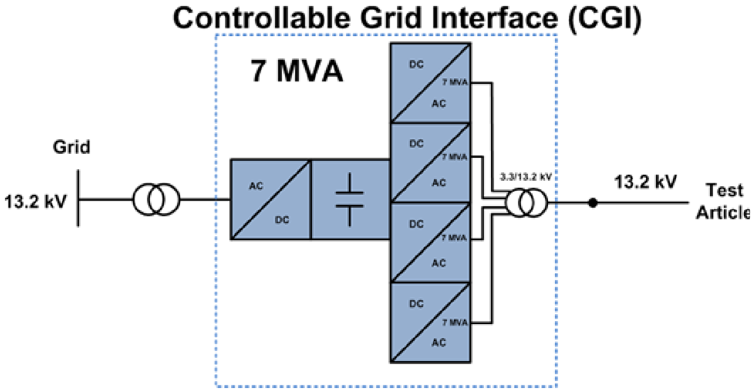


Figure 1. NREL 7-MVA CGI

The National Renewable Energy Laboratory (NREL) is positioned to help industry meet and solve these challenges. With the opening of NREL's 7-MVA controllable grid interface (CGI) grid simulator (Figure 2) facility in late 2013, NREL has the ability to test wind and solar energy technologies, and energy storage in a utility-scale grid environment. This capability allows industry to partner with NREL to test, optimize, and visualize the grid integration–related performance of the unit under test long before it is deployed in the field, saving time and resources while minimizing integration issues.

A 15-MW grid simulator is under construction at Clemson University's (CU's) Restoration Institute in North Charleston, South Carolina (Figure 2). The hardware-in-the-loop (HIL) simulator is designed to test multi-megawatt equipment at full scale for grid-code compliance, to validate electrical models, advance smart-grid technology, examine energy storage and converters, and integrate distributive resources more efficiently into the power system. Additionally, researchers will be able to investigate unique aspects of grid and cyber security, wireless sensors, high-current calibration, and energy storage.

NREL is in the final stages of commissioning, and CU is completing the construction of advanced, multi-megawatt, power electronic grid simulator systems capable of many types of grid compliance testing (including voltage fault ride-through, frequency response, and voltage support) for wind turbines. Both facilities are expected to be valuable testing assets for the wind industry to further improve wind turbine reliability and the development and testing of advanced grid-friendly controls.

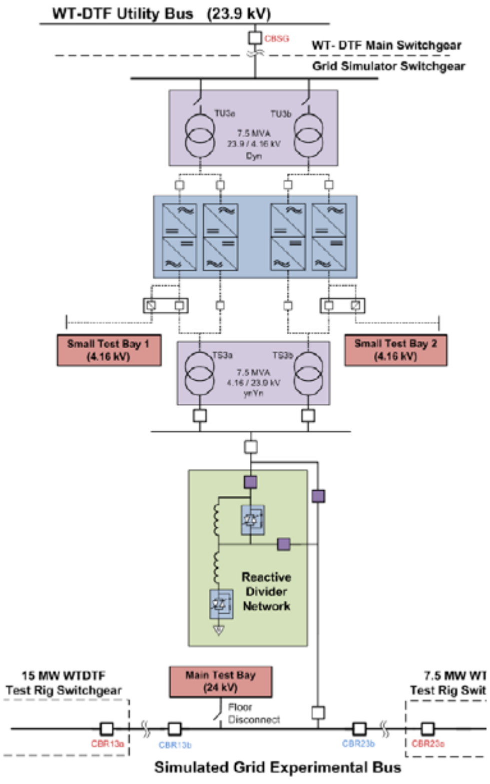


Figure 2. CU 15-MVA grid simulator

2 Workshop Motivation

In anticipation of the opening of the CGI and grid simulator facilities, NREL and CU held a 1.5-day workshop from June 13 to June 14, 2013, and invited participants from other testing laboratories and institutions throughout the world, wind turbine manufacturers, certification organizations, utilities, and academia to discuss testing challenges of wind turbine technologies related to grid integration and discover new ways to meet them by taking advantage of NREL's and CU's capabilities, as well as capabilities of other testing organizations. The workshop was divided into four different sessions, with a different topic of emphasis for session.

The participation of testing laboratories from the United States, Europe, and Asia in this workshop is a step toward establishing broader international collaboration (and possibly standardization) in grid simulation testing of renewable energy technologies.

Knowledge from the workshop is expected to help guide the research and testing conducted at NREL, CU, and other organizations. The workshop brought together experts in wind turbine testing, wind turbine manufacturers, wind power plant operators, and representatives from utilities to exchange knowledge, discuss experiences, and identify needs in wind power grid compliance testing that can be served by these test facilities. The workshop also provided valuable guidance in the development of advanced testing methods and procedures that will benefit the entire renewable energy industry.

3 Workshop Objectives

NREL and CU had three primary objectives for the Grid Simulator Testing workshop:

- Gain an understanding of the challenges faced by industry stakeholders in integrating wind power into the grid and identify crosscutting areas between testing needs and test apparatus capabilities
- Prioritize the list of critical challenges in grid simulator testing of wind turbine technologies
- Develop an action plan for addressing challenges, particularly by partnering with the wind industry and taking advantage of these advanced testing capabilities

To achieve these objectives, NREL developed the workshop agenda around five key topics:

1. Overview of the existing test facilities and methods
2. Overview of new test facilities under development (capabilities, hardware, testing portfolios, etc.)
3. Wind turbine manufacturer perspective on grid compliance testing needs and methods
4. Wind power plant operator/developer perspective on grid compliance testing needs and methods
5. Advanced testing concepts (HIL, real-time digital simulator, multi-lab testing schemes, etc.)

4 Agenda

Day 1: Thursday, June 13, 2013, 8:00 a.m. – 5:00 p.m.

Introduction: 8:30 a.m. – 10:00 a.m.

Welcome to NREL

Introduction and Purpose of Workshop, *NREL and CU, USA*

Overview of Grid Integration Aspects of Utility-Scale Wind Turbine Generators – *Vahan Gevorgian, NREL, USA*

Overview of Grid Integration Testing Requirements for Wind Power – *J. Curtiss Fox, CU, USA*

Introduction to Existing Capabilities and Testing Experience in Grid Simulator Area: 10:15 a.m. – 12:00 p.m.

Moderator – *J. Curtiss Fox, CU, USA*

Florida State University Center for Advanced Power Systems Experience – *Michael Steurer, Florida State University, USA*

CENER Dynamometer/Grid Simulator Experience – *Carlos Garcia de Cortazar, CENER, Spain*

Inductive Fault Simulator Field Testing Experience – *Carlos Alvarez, Barlovento/E2Q, Spain*

NREL Controllable Grid Interface – *Vahan Gevorgian, NREL, USA*

Discussion (summary of existing capabilities, field versus lab testing, existing limitations, etc.)

New/Upcoming Test Facilities: 1:00 p.m. – 3:00 p.m.

Moderator – *Andrei Mander, CU, USA*

CU Dynamometer and Grid Simulator Facilities – *Andrei Mander and J. Curtiss Fox, CU, USA*

National Renewable Energy Centre Drivetrain Test Grid Emulator – *Alex Neumann, National Renewable Energy Centre, United Kingdom*

Fraunhofer Institute for Wind Energy and Energy System Technology DyNaLab Grid Simulator – *Jersch Torben, Fraunhofer Institute for Wind Energy and Energy System Technology, Germany*

Wind Power Certification in China – *Zhang Yu, China General Certification Center, China*

Wind Turbine Certification – *Brian Gregory, Intertek, USA*

ABB Grid Simulator Product Line – *Pieder Joerg, Ester Guidi, ABB Medium-Voltage Drives, Switzerland*

Discussion

Wind Turbine Manufacturer Perspective: What Are the Values for Wind Industry? 3:20 p.m. – 5:00 p.m.

Moderator – *Hal Link, NREL*

Advanced Wind Power Plant Controls – *Nick Miller, General Electric*

Grid-Friendly Controls of Full-Converter Wind Turbines – *Robert Nelson, Siemens*

Discussion (any testing needs missed in the proposed facilities, any additional requirements to increase the value of proposed facilities for the wind industry, etc.)

Day 2: Friday, June 14, 2013, 8:30 a.m. – 12:00 p.m.

Wind Power Plant Operator/Developer Perspective: 8:45 a.m. – 10:15 a.m.

Moderator – *Vahan Gevorgian, NREL*

Grid Interconnection Aspects for Offshore Wind Power – *Bo Hesselbaek, DONG Energy*

An Overview of Grid Requirements in Denmark and the Technical University of Denmark's Advanced Grid Test Facility in Osterid – *Tom Cronin, Technical University of Denmark*

Fault Ride-Through and Other Compliance Tests – *Michael Frydensjberg, Siemens Wind Power A/S, Denmark*

Underwriters Laboratories Certification Requirements for Renewable Generation – *Tim Zgonena, Underwriters Laboratories*

Discussion

Advanced Testing Concepts (HIL Testing): 10:30 a.m. – 11:30 a.m.

HYPERSIM Real-Time Simulation Platform – *Richard Gagnon, IREQ, Canada*

Real-Time Digital Simulator for HIL Testing – *Tom Baldwin, Idaho National laboratory, USA*

Super Lab HIL Testing Concept – *NREL, CU, Idaho National Laboratory, USA*

Discussion

Closing Panel/Going Forward: 11:30 a.m. – 12:30 p.m.

Moderator – *Andrei Mander, CU*

Lunch and Tour: 12:30 p.m. – 3:00 p.m.

Lunch (served by NREL) and National Wind Technology Center Overview: 12:30 p.m.

National Wind Technology Center Tour: 1:30 p.m. – 3:00 p.m.

Adjourn: 3:00 p.m.

5 Participants

Last name	First name	Company	Country
Joerg	Pieder	ABB	Switzerland
Guidi	Ester	ABB	Switzerland
Ward	Alex	ABB	USA
Alvarez Ortega	Carlos	Barlovento/E2Q	Spain
Garcia de Cortazar	Carlos	CENER	Spain
Yu	Zhang	CGC	China
Fox	J. Curtiss	CU	USA
Benke	Michael	DNV KEMA	USA
Glasdam	Jakob	DONG Energy	Denmark
Hesselbaek	Bo	DONG Energy	Denmark
Steurer	Michael	FSU CAPS	USA
Nemila	Thomas	Goldwind USA, Inc.	USA
Gagnon	Richard	Hydro-Quebec's Research Institute	Canada
Giroux	Pierre	Hydro-Quebec's Research Institute	Canada
Arino	Javier	IDOM	Spain
Baldwin	Tom	INL	USA
Gregory	Brian	Intertek	USA
Torben	Jersch	IWES Fraunhofer	Germany
Park	Kyungwon	LSIS Co., Ltd	Korea
Neumann	Alex	NAREC	United Kingdom
Petter	Jeff	Northern Power	USA
Gonzales	Paul	RePower	USA
Kijas	Oliver	RePower	Germany
Lanning	Roark	RES Americas	USA
Parker	Chip	RES Americas	USA
Bech	John	Siemens Wind Power	Denmark
Frydensbjerg	Michael	Siemens Wind Power	Denmark
Nelson	Robert	Siemens Wind Power	USA
Cordaro	Joe	SRNL	USA
Cronin	Tom	Technical University of Denmark	Denmark
Gomez-Lazaro	Emilo	UCLM	Spain
Zgonena	Timothy	UL	USA
Mander	Andrei	CU	USA
Gevorgian	Vahan	NREL	USA
Link	Hal	NREL	USA
McDade	Mark	NREL	USA
Wallen	Robb	NREL	USA
Simms	Dave	NREL	USA

6 Summary of Presentations

This section provides a summary of all presentations at the workshop. The full set of presentation slides is shown in the appendix.

6.1 Day 1 – Opening Session

The workshop started with introductory presentations by Vahan Gevorgian of NREL and J. Curtiss Fox of CU. Gevorgian welcomed participants on behalf of NREL, gave an overview of NREL's vision of workshop goals and objectives, introduced attendees to testing activities and capabilities sponsored by the U.S. Department of Energy and developed at NREL, talked about U.S. perspective on grid integration for wind power, and outlined the framework and format of discussions. Fox presented a general overview of grid simulator testing rationale, implementation, and challenges. Both Gevorgian and Fox stressed the importance of grid simulator testing of wind turbine drivetrains from both fault response (voltage and frequency) and grid-friendly control standpoints. Both presenters also emphasized the advantages and issues related to the advanced testing concepts based on HIL/real-time digital simulator hardware and software platforms.

6.2 Day 1 – Session on Existing Grid Simulator Capabilities

This session was opened by Dr. Michael Steurer of FSU CAPS. Steurer presented FSU's experience and ongoing research using their 5-MW HIL grid simulator and dynamometer test facilities. For many years, FSU CAPS has been a flagship of grid simulator testing in the United States, mainly for naval applications. Steurer shared many important insights on megawatt-scale generator and inverter testing, real-time dynamic simulation, and other aspects of his facility operation that were relevant to the topic of the workshop.

The next presenter was Calros Garcia de Cortazar of CENER, Spain. CENER operates an 8-MW wind turbine dynamometer facility with power electronic grid simulator designed mainly for continuous 50-/60-Hz operation. Cortazar shared CENER's experience in testing megawatt-scale wind turbine drivetrains, operating the facility, and outlined future upgrade plans.

The third presenter in this session was Carlos Alvarez of Barlovento/E2Q, Spain. E2Q operates an inductive fault simulator for field testing of megawatt-scale wind turbines under low-voltage fault conditions. Alvarez provided an overview of Spanish grid codes and presented a summary of field testing activities involving technical details and safe operation of a mobile inductive fault emulator. His presentation provided important input, allowing participants to fully understand the challenges they might face in integrating similar testing capabilities in a laboratory environment.

The last presenter in this session was Dr. Vahan Gevorgian of NREL, who gave an overview of the ongoing dynamometer/CGI-related facility developments at NREL's National Wind Technology Center and shared technical specifications, design aspects, and testing capabilities of CGI. Gevorgian also talked about other gird simulation related activities at NREL, including the Energy Systems Integration Facility and future energy storage testing facility at the National Wind Technology Center.

Participants engaged in a group discussion at the end of this session.

6.3 Day 1 – Session on New/Upcoming Test Facilities

This session was opened with a presentation by Andrei Mander and J. Curtiss Fox of CU with a detailed summary of their new 15-MW test facility featuring a 15-MVA HIL grid simulator and two dynamometer test stands. CU's unique combination of power converter and reactive divider network provides a unique and flexible testing environment for grid compliance testing of wind turbine drivetrains and other generation technologies. Both presenters shared detailed information on the facility's mechanical and electrical design, control architecture, and data acquisition.

The next presenter was Alex Nuemann of the National Renewable Energy Centre, United Kingdom, who gave an overview of their activities in the area of research and development, testing, demonstration, and deployment of renewable energy technologies. The National Renewable Energy Centre's testing capabilities feature a 15-MW dynamometer for wind turbine testing and a 3-MW tidal turbine nacelle test facility. They are reviewing designs for a 10-MW power electronic grid emulator with inductive rig for fault simulation. This facility is undergoing commissioning and is expected to come online by the end of 2014.

Torben Jersch of IWES/Fraunhofer, Germany, presented information on their DyNaLab test facility featuring a 10-MW dynamometer stand and a 15-MVA power electronic grid simulator made by ABB. This grid simulator has the exact same electrical topology as NREL's CGI. The construction of DyNaLab started in July of 2013 and is expected to be completed by the end of 2014.

The next speaker, Zhang Yu, represented the China General Certification Center. His presentation focused on certification requirements and standards and grid interconnection requirements in China. Yu gave the audience a perspective on types of certification testing required by utilities in China and how the grid simulator testing facilities can help wind turbine manufacturers meet stringent grid code requirements.

Brian Gregory of Intertek, United States, gave the audience a perspective on relevant compliance and certification requirements for large utility-scale wind turbines in North America.

The last presenter in this session was Pieder Joerg of ABB, Switzerland. He provided a detailed overview of their power electronic grid simulator product line. ABB grid simulators are used by several testing labs throughout the world (NREL, CENER, IWES, etc.). He covered general aspects of using voltage-source power converters for mimicking realistic grid conditions for renewable technologies testing.

Participants engaged in a group discussion at the end of this session.

6.4 Day 1 – Session on Manufacturer's Perspective

Although representatives from several wind turbine manufacturers were present at the workshop (RePower, GoldWind, Northern Power, GE, Siemens), only two of them agreed to speak at the workshop. The first speaker, Nick Miller of GE, gave an overview of their grid-friendly plant and turbine-level controls and shared information about advanced drivetrain topologies, including built-in energy storage. Miller confirmed the importance of grid simulator testing for the industry and stressed the necessity in careful planning and implementation of such tests involving power electronic grid simulators to avoid unwanted/unrealistic interactions between power converters. He also pointed out that there is very little to be learned from a single turbine test and emphasized that a turbine should be part of a wind power park as a whole.

The same point was affirmed by the next presenter, Robert Nelson of Siemens, who talked about grid-friendly features of Siemens wind turbine generators (WTGs).

The presentations were followed by a group discussion. At the end of the last session, Gevorgian joined participants at dinner, and they discussed the outcomes of the first day of workshop.

6.5 Day 2 – Session on Wind Power Plant Operator/Developer Perspective

Bo Hesselbaek of DONG Energy, Denmark, started the second day of the workshop. DONG Energy is the largest developer of offshore wind power plants in the world. Hesselbaek gave a detailed overview of DONG Energy's activities and outlined technical challenges related to interconnection aspects of offshore wind power (alternating current versus direct current interconnection, harmonic issues, etc.). Hesselbaek stated that harmonics were the fundamental challenge for offshore wind power. He gave a perspective on how some such interconnection challenges can be mitigated and potentially resolved in testing stages using grid simulator test facilities. For this purpose, DONG ENERGY will send a postdoctoral (Jacob Gladsam) to spend several months at NREL's National Wind Technology Center to work with NREL on this topic.

The next presenter was Tom Cronin of the Technical University of Denmark. He gave an overview of Danish grid codes for wind power and presented the developments of the Danish National Test Centre for large wind turbines in Osterid, Denmark. This center will have a 16-MW-scale grid simulator with MV switchgear for testing wind turbine generators installed at the Osterid test site. The Technical University of Denmark's approach is similar to NREL's National Wind Technology Center concept of testing wind turbines using a power electronic grid simulator. The Technical University of Denmark's facility is expected to come online by mid-2015.

Next, Michael Frydensjberg of Siemens Wind Power form Denmark talked about experience in wind turbine fault ride-through testing and model validation. This presentation helped to improve understanding and opened a floor for discussion on potential challenges for reproducing the same testing scenarios in a laboratory environment using grid simulators.

The last speaker in the session was Tim Zgonena of Underwriters Laboratories. He talked about Underwriters Laboratories practices and standards in certification testing of inverters, converters, and other grid-interconnected renewable generation equipment with stress on testing the safety aspects of such equipment. He gave the audience insight on the latest developments of the UL1741 and IEE1547 standards and their applicability for testing inverter-coupled renewable generation.

6.6 Day 2 – Session on Advanced Testing Concepts

Richard Gagnon of Hydro-Quebec Research Institute, in Canada, opened this session with an overview of Hydro-Quebec's HyperSim real-time digital power system simulator, which is used for HIL testing of controllers for HVDC, FACTS, and protection relays. Hydro-Quebec's Research Institute is currently evaluating options to develop a real-time grid power simulator for testing distributed renewable generation in grid-connected and micro-grid applications. Gagnon shared many ideas on research-and-development opportunities for HIL grid simulators for testing and integrating wind power technologies.

Tom Baldwin of INL talked about the U.S. Department of Energy's "SuperLab" concept for multi-lab asset utilization and testing of grid integration aspects of renewable technologies and energy storage.

Next, Mander of CU and Gevorgian of NREL presented a summary of workshop conclusions and results, prioritized the issues, and outlined the next steps and future plans.

To conclude the workshop, the NREL team led a two-hour tour of the National Wind Technology Center site featuring CGI and dynamometer facilities.

7 Discussions

Many useful technical discussions took place during and after the presentations listed in the previous section. The workshop was structured to encourage maximum interaction among participants. Workshop discussions were guided by the following main framing questions:

1. What are the critical challenges faced by utilities in integrating large-scale wind power?
2. Which particular grid integration challenges can be addressed/mitigated by utilizing the unique testing capabilities offered by megawatt-scale grid simulator facilities?
3. How can participants learn from each other?
4. Is there a need for standardization of grid simulator testing methods and protocols?
5. What is the role of HIL testing?

The following secondary set of questions was also used to guide the discussions and receive feedback from workshop participants:

1. What are the advantages and disadvantages of various electrical topologies used in particular grid simulator facilities (capabilities, controllability, safety, cost, etc.)?
2. What are the optimum controller designs for grid simulators to create realistic testing conditions and avoid unwanted interactions between test apparatus and test article controllers?
3. What are the capabilities of grid simulator facilities for testing other types of inverter-coupled generation and energy storage?

8 Conclusions

Grid integration of wind power plants is complicated by wind resource variability and electrical characteristics of WTGs. The need for many types of ancillary services by wind power increases at higher levels of wind penetration, whereas the conventional generation that provide those services may become unavailable or less economic. Wind turbine manufacturers developed a suite of advanced wind power plant controllers designed to improve overall power system performance and reduce the need for additional ancillary services by conventional generation. Instead, wind power can provide the same set of ancillary services. The advantage of modern wind power plant controls is that they can coordinate the active and reactive power controls from multiple wind turbines and make an entire plant function as a single generation source with characteristics similar (or better) to the conventional synchronous generators and maintain (or, in some cases, improve) the reliability of the electric power grid.

According to information shared by the workshop participants, the grid simulator facilities in the United States and Europe were designed to accommodate testing of the whole suite of such "grid-friendly" controls by wind power and measure wind turbine response and impacts on individual components (both mechanical and electrical) under a controlled grid environment. Based on workshop discussions, the grid simulator testing portfolio can be segregated into two major areas in accordance with the nature of two basic types of ancillary services provided by wind power in the form of active and reactive power controls. The third major area of testing is testing the wind turbines under grid voltage fault conditions involving active and reactive power controls in a more transient manner.

8.1 Testing Associated With Various Types of Active Power Control

The active power output of wind power plants can be controlled in different timescales to provide several types of ancillary services related to system frequency response and frequency regulation. The ability of a power system to maintain its electrical frequency within a specified range is a crucial element to maintain a reliable and secure power system. An interconnected power system must have adequate resources to respond to a variety of contingency events to ensure rapid restoration of the balance between generation and load. Primary frequency response—also called primary control reserve and frequency responsive reserve—is the capacity available for automatic local response to frequency excursions through turbine speed governors and frequency responsive demand that adjusts to counter-frequency deviations to stabilize the frequency. System inertia is the cumulative synchronous generation and load inertia that slows the initial rate of change of frequency deviation. The combined response of primary frequency response and inertia is essential to arrest electrical frequency changes before triggering underfrequency load-shedding relays. In extreme cases, large deviations in frequency may result in generation protection relays or machine damage, or reaching unstable frequencies that could potentially lead to a blackout.

8.1.1 Testing of Wind Turbine Inertial Response

Modern variable-speed wind turbines utilize power converters to decouple a turbine's rotational speed from system frequency and allow both increased energy capture and smoother power production. In standard operational practices, wind turbines do not have a primary control reserve because they are controlled to operate at maximum power for the wind condition. Therefore, wind turbines do not contribute primary frequency control in the conventional way using primary control reserve. However, the kinetic energy stored in wind turbine inertia allows supporting primary frequency response for short periods of time. The inertia constants of megawatt-scale wind turbines of 2 sec to 6 sec are compatible with inertia constants of large power plants, so even high wind penetration does not reduce the amount of kinetic energy in the power system. The variable frequency converters of wind turbines allow instantaneous control over turbine electrical power. This fact in combination with large inertia allows the wind turbine to be controlled is such a manner that additional power from kinetic energy will be released to the grid during frequency drops. This can be achieved by implementing an additional control loop in the turbine power converter.

Power electronic grid simulators represent a unique opportunity to test the inertial control of variable-speed wind turbines by reproducing real frequency events on wind turbine terminals. Historically, inertial response tests have been conducted in the field by feeding a fake frequency signal into the WTG controller. The real frequency seen by wind turbine components remains unchanged during such tests. The advantage of grid simulator testing is that the wind turbine drivetrain (power converter, generator, or both, depending on turbine topology) and all ancillary equipment can be exposed to a real frequency excursion that happens in the power system after the loss of a generation (underfrequency) or load (overfrequency). The real measured frequency events from various power systems (both large interconnections and smaller island systems) can be reproduced by the grid simulators to test the inertial response of a wind turbine. The NREL CGI can play a unique role in such testing because it is the only grid simulator facility that allows both dynamometer testing of wind turbine drivetrains and field testing of real wind turbines. Other existing and planned future grid simulator facilities do not have such dual capability. It was noted by workshop participants that conducting inertial test on dynamometers requires accurate simulation of wind rotor inertia in dynamometer controls.

8.1.2 Testing Wind Turbine Primary Frequency Response

The primary frequency response by wind turbines can be integrated into the rotor-side active power control loop and demonstrate behavior similar to conventional synchronous generators. The wind turbine must operate in curtailed mode to provide reserve for primary response when frequency drops, similar to conventional synchronous generator with speed governors. Nonsymmetric droop characteristics can be implemented in wind turbines. The primary response parameters (deadbands, up and down droops, reserve margin) can be tuned up for optimum system performance.

The grid simulator facilities will allow testing wind turbine capability to provide primary frequency response and increase or decrease production in accordance to various droop characteristics. It was noted during the workshop that testing wind turbine primary frequency response controls on a dynamometer requires accurate mimicking of a turbine blade pitch controller. The NREL CGI will allow both dynamometer and field testing of wind turbines providing primary frequency response.

8.1.3 Testing Wind Participation in Automatic Generation Control and Ramp-Rate Limiting Testing

The ability of wind power plants to operate in a curtailed mode at a desired power set point creates opportunities for wind to participate in automatic generation control (AGC), and also provide a specified rate of change in power output between each successive step (ramp-rate limiting). AGC is also known as secondary frequency response. Such controls are usually tested in the field with wind turbines connected to the grid under real wind conditions. It was noted during the workshop that grid simulators add little value to such tests. However, implementing HIL/controls with power electronic grid simulators will allow testing the aggregate impacts of wind power providing such services on larger simulated power systems. Such an approach will allow evaluating and optimizing various turbine and plant-level controller designs.

8.2 Reactive Power/Voltage Control Tests

Modern variable-speed wind turbines allow precise voltage/VAR control to provide two major benefits: first, the impact of active power variability on grid voltages can be minimized; second, the accurate voltage control improves overall power system stability. The VAR/voltage control of a wind power plant can be implemented on a local collector bus level or at a point of interconnection some distance away from a wind power plant.

8.2.1 Testing Wind Turbines Providing Voltage Regulation

The specifics and benefits of voltage regulation tests were discussed at the workshop. The power electronic grid simulators allow emulating a voltage source behind specified line impedance and X/R ratio. This feature allows testing WTGs connected to stronger or weaker transmission lines. This type of testing will require the implementation of an HIL/RTDS hardware solution to model the dynamics of a transmission or distribution line with given parameters. More-complicated HIL schemes can be implemented to simulate the aggregate voltage regulation characteristics of an entire wind power plant connected to a transmission system or as part of a smaller isolated island grid. The grid simulator facilities provide unique environments for testing voltage regulation aspects of wind power under controlled grid conditions.

8.2.2 Testing Reactive Power Control Without Wind

Power converters of WTGs are capable of providing reactive power/voltage control during periods of no wind or when stopped during periods of extreme winds or system disturbances. From a systematic perspective, the reactive power capability is similar to STATCOM and other reactive devices. As in previous cases, grid simulators provide a unique testing platform for wind-free reactive power control demonstrations.

8.3 Grid Fault Testing

Grid fault testing of WTGs is a fundamental benefit of the grid simulator facilities. The grid faults and abnormalities can be in the form of balanced and imbalanced voltage amplitude variations, frequency variations, and harmonic distortions. The capabilities of various grid simulator topologies to emulate specific types of grid faults were one of the main topics of discussions throughout the entire workshop. The voltage fault ride-through by wind power is essential for reliable operation of a power system with large amounts of wind power and is an interconnection requirement by essentially every utility throughout the world.

8.3.1 Low-Voltage Fault Testing

Low-voltage fault testing is a basic service that all grid simulators are built around. Historically, low-voltage fault testing was conducted in the field using inductive voltage dividers. This method has proven to be efficient for unbalanced zero-voltage ride-through (ZVRT) and low-voltage ride-through (LVRT) testing of single grid-connected wind turbines. One disadvantage of inductive dividers is the dependence on a strong grid, and there are difficulties in conducting line-to-ground fault tests (risk of substation protection trip off because of a lack of isolation). The dynamometer laboratories are usually located in the urban areas in proximity to major load centers where using inductive voltage dividers for low voltage testing is not acceptable. From this perspective, the power electronic grid simulators become useful to conduct such tests in a lab environment because they provide complete isolation between a test bus where the fault is emulated and the rest of the grid. Power electronic grid simulators bring additional flexibility to low-voltage fault testing because such tests can be conducted by the grid simulator itself, or by a combination of grid simulator and inductive voltage dividers. Various types of one-, two-, and three-phase fault tests can be conducted this way. The CU grid simulator is a combination of power electronic converters and an inductive divider network. The NREL CGI is a power electronic solution only, but it has the capability and terminations available to incorporate an inductive voltage divider if such need arises in future.

Wind turbines with power electronic converters have a capability to control the magnitude of reactive current that turbines can feed into the fault from essentially zero to its current limit. Many utilities in Europe require wind power to control this reactive current in proportion to a magnitude of voltage drop (reactive current droop). The grid simulators are essential tools for testing such reactive droop capability for various types of wind turbine topologies.

All workshop participants seemed to be on the same page in regard to their approaches to voltage fault testing. It appears that other testing labs adopted the voltage fault testing approaches similar to those of NREL and CU.

8.3.2 High-Voltage Fault Testing

One fundamental disadvantage of inductive voltage dividers is the inability to conduct high-voltage fault tests. This is another area of testing in which grid simulators bring new capability to the wind industry. High-voltage ride-through (HVRT) is also an interconnection requirement in many utilities. In Europe, the rapid increase of offshore wind power brought the HVRT problem into a focus during recent years. The power electronic grid simulators provide unique platform for HVRT testing of various WTG topologies. The CU grid simulator is capable of 140% overvoltage tests, and the NREL CGI is capable of 130% overvoltage tests. Other test facilities have overvoltage capabilities similar to NREL and CU.

8.3.3 Voltage Imbalance Testing

Continuous voltage imbalances may exist in the power system. The power electronic grid simulators provide possibilities for reproducing such imbalances on wind turbine terminals for extended periods of time. This is a capability that was not possible with traditional testing methods. Another capability of power electronic grid simulators is to create low-frequency voltage modulations that mimic the sub-synchronous resonance conditions that might exist in the power grid.

8.4 Harmonic Analysis

Bo Hesselbaek of DONG Energy pointed out, and was reinforced by other industrial attendees, that among the primary limiting factors with developing offshore wind technologies are the challenges associated with the inherent harmonics created by the power converters of the WTGs. Because offshore applications require the use of submarine power cables that have significantly higher capacitances than overhead lines, the resonance frequencies seen in offshore applications tend to be much lower. The harmonic ranges shown in Hesselbaek's presentation indicate harmonic orders in the high teens to low twenties as being the most prominent in DONG

Energy's existing offshore wind power parks. To ensure confidence in the development and integration of offshore wind sites, detailed harmonic studies are needed for any WTG that might be deployed in these applications. Such harmonic studies would include both the susceptibility of a wind turbine to harmonic voltages and how the emission of harmonics from a WTG will impact the design of a complete offshore wind power park.

With respect to grid simulator testing facilities, the capabilities of reproducing harmonic content must be weighed against the natural harmonic content created by the power electronic converters that are inherent to each testing facility. With this, it is clear that each of the testing facilities will be capable of creating some low-order harmonics to test some of the harmonic interactions a WTG may have with the grid. The CU grid simulator's unique power electronic amplifier has the highest harmonic replication range (up to the 30th harmonic) and the least amount of background noise with respect to all of the technologies presented during the workshop. It should be noted that the frequency bandwidth of the power electronic converter utilized for the grid simulator will play a very important role in HIL testing scenarios.

8.5 HIL Testing

Participants agreed that HIL testing capability becomes an important part of grid simulator testing. The importance of HIL for dynamometer testing has been recognized by testing community for years to introduce impacts of "missing" turbine components (blade pitch system, wind rotor dynamics, etc.) into the testing process of wind turbine drivetrains. The same level of understanding is being developed for the grid simulator side of testing as well, in which HIL capability will allow introducing the impacts of "missing" components from the grid side. Creating a real-time HIL test system will also allow scalability when the dynamics of an entire wind power plant or entire power system can be emulated. All testing institutions present at the workshop are in the process of developing real-time HIL controls for their grid simulators and dynamometers. The input from Florida State University and Hydro-Quebec Research Institute was very important because it helped participants to understand the challenges of real-time HIL testing and gave guidance on possible hardware and software solutions for developing such capabilities.

Historically, all previous testing practices of grid compliance aspects of wind generation involved a single wind turbine connected to a strong power grid (IEC 61400-21 power quality testing standard for wind turbines). The increasing levels of wind penetration pose new requirements for such testing. A single wind turbine cannot be tested any longer in "isolation" from the other elements of the power system. The HIL-capable grid simulators will become new, unprecedented tools for testing the grid integration aspects of wind power.

8.6 Development of Test Methods and Protocols

One of the main important conclusions of the workshop was that the grid simulator testing community came to the realization that the interchange of nonproprietary information is important and mutually beneficial. Before the workshop, each testing organization was engaged with its relatively smaller group of stakeholders providing input and guidance in grid simulator capability development. Collaboration between labs will create an opportunity for interactions between many stakeholder groups from different countries and will lead to the development of better testing products. It was agreed among participants that some sort of "standardization" will be needed in the grid simulator testing area similar to IEC 61400-21, which provides unified power quality testing methods for wind turbines in the field. This is especially important for HIL/testing in which standard models of power systems (such as IEEE 14-bus or 39-bus test systems) can be used for evaluating the performance of various grid-friendly controls of WTGs.

8.7 Other Conclusions

We are not alone. The grid simulator testing of wind turbine drivetrains is a global trend; it is a hot topic in many countries.

We are not unique. Others are doing the same thing in a very similar way.

Perfect timing. It is remarkable that the timing for developing and commissioning such grid simulator capabilities is basically within one to two years for many countries.

Power electronics rule. All wind technology testing organizations adopted power electronic solutions for their grid simulators.

Safety is the name of the game. All testing labs put enormous effort into ensuring personnel and equipment safety during grid simulator testing.

Looking beyond wind. All testing organizations are looking into possibilities of expanding their grid simulator testing portfolios to other renewable technologies (PV, MHK, etc.) and energy storage.

9 Workshop Benefits to NREL/U.S. Department of Energy

The workshop provided the following benefits to NREL and the U.S. Department of Energy wind program:

1. The workshop promoted cooperation and information among the participating research organizations.
2. The workshop seeded new and hopefully lasting collaborations between NREL and CU as well as other testing organizations in Europe that are in the process of developing similar grid simulating capabilities.
3. The workshop has proven that the U.S. Department of Energy investment in NREL and CU grid simulation capabilities is relevant and timely. Other countries are on the same track with approximately the same construction and commissioning schedules.
4. The workshop established both NREL's and CU's role as leading institutions in grid simulator testing on a global scale.
5. The workshop confirmed the high value proposition by grid simulator capabilities. This was confirmed through presentations and discussions with turbine manufacturers that seem to fully understand the benefit of grid simulator testing and are already incorporating such testing into their future testing plans.

10 Future Steps

Participants agreed to meet annually and share information on progress. CU agreed to host the next workshop in May 2014 in Charleston, South Carolina. NREL and CU will work together to provide participation of a larger group of stakeholders from the U.S. electrical utilities and wind power plant operators.

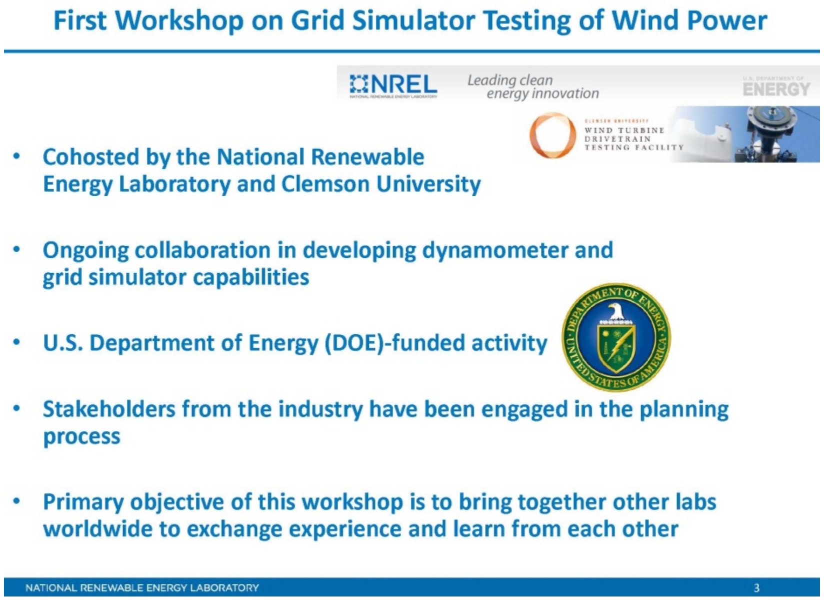
11 Appendix: Presentations

11.1 Introduction

11.1.1 Overview of Grid Integration Aspects of Utility-Scale Wind Turbine Generators – Vahan Gevorgian, NREL, USA

Workshop Agenda

- *Day 1*
  - *Badging and breakfast – 8:00 a.m.-8:45 a.m.*
  - *Morning sessions – 8:45 a.m.-12:00 p.m.*
  - *Lunch – 12:00 p.m.-1:00 p.m.*
  - *Afternoon session – 1:00 p.m.-5:00 p.m.*
  - *Group dinner in Boulder area (7 p.m.) – please let us know if you are coming*
- *Day 2*
  - *Arrival and breakfast – 8:00 a.m.-8:45 a.m.*
  - *Morning sessions – 8:45 a.m.-12:00 p.m.*
  - *Lunch – 12:00 p.m.-1:00 p.m.*
  - *National Wind Technology Center tour – 1:00 p.m.-3:00 p.m.*
  - *Adjourn – 3:00 p.m.*



First Workshop on Grid Simulator Testing of Wind Power

- **Cohosted by the National Renewable Energy Laboratory and Clemson University**
- **Ongoing collaboration in developing dynamometer and grid simulator capabilities**
- **U.S. Department of Energy (DOE)-funded activity**
- **Stakeholders from the industry have been engaged in the planning process**
- **Primary objective of this workshop is to bring together other labs worldwide to exchange experience and learn from each other**

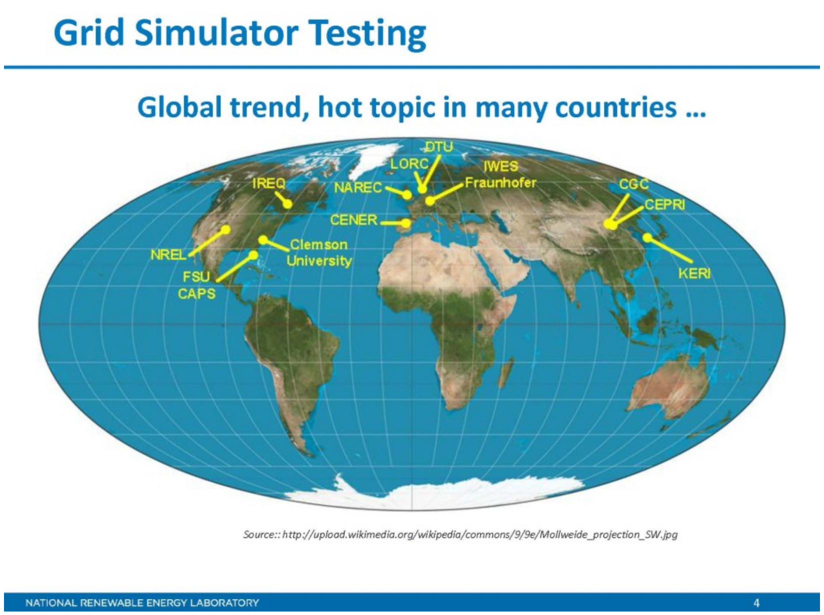
Overview of Workshop Goals

First International Workshop for Grid Simulator Testing of Wind Turbine Drivetrains

National Renewable Energy Laboratory, National Wind Technology Center

June 13, 2013

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.



Grid Simulator Testing

Global trend, hot topic in many countries ...

Source:: http://upload.wikimedia.org/wikipedia/commons/9/9e/Mollweide_projection_SW.jpg

U.S. Wind Generation

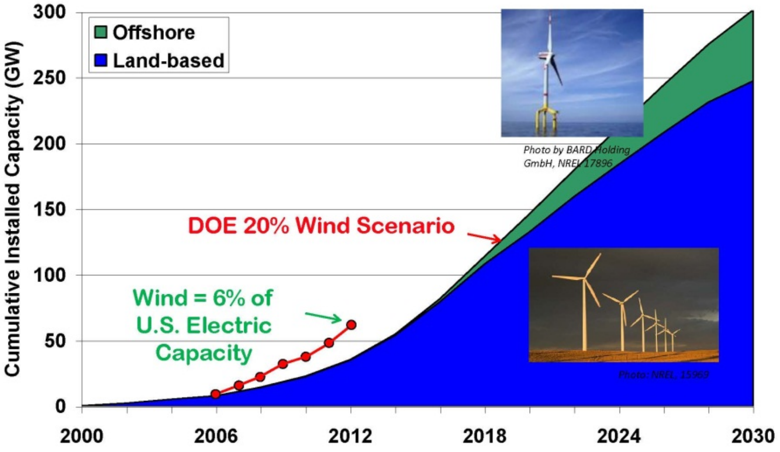
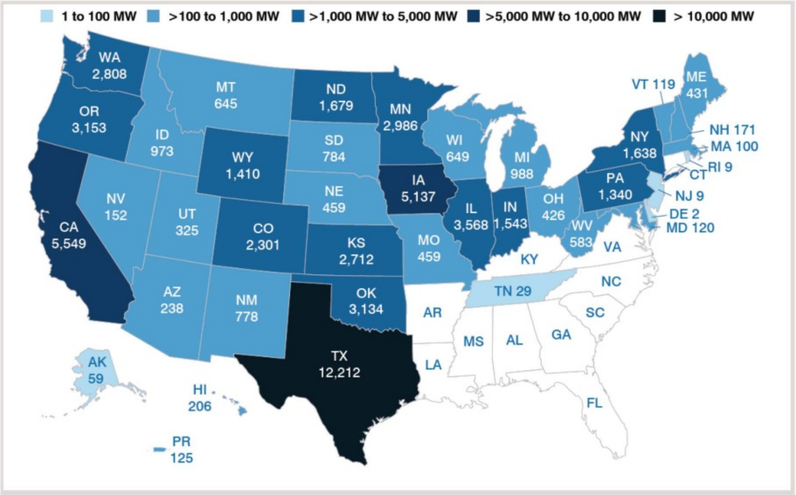


Photo by BARD Holding GmbH, NREL 17896

Photo: NREL, 15969

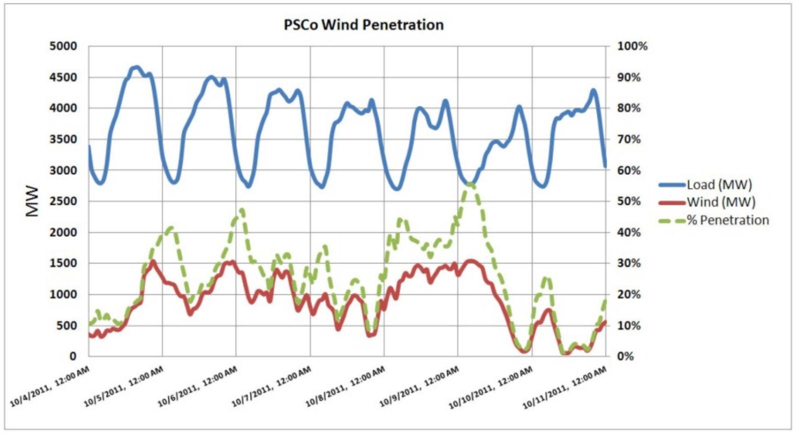
Source: AWEA 2012 Market Report

U.S. Wind Power by State



Source: AWEA 2012 Market Report

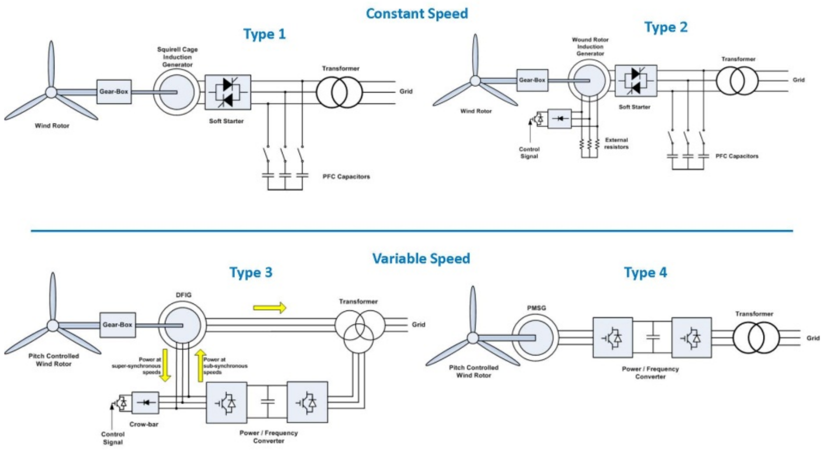
56% Penetration in Public Service Company of Colorado



Impacts on Testing

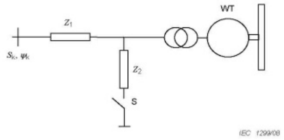
- **Large-scale integration of wind energy will present new challenges for testing community**
- **Evolving grid codes and interconnection requirements (often utility specific)**
- **Existing wind turbine testing practices "in isolation" from other parts of power system need improvements**
  - Interaction with other wind turbines in the plant
  - Interactions between grid and power plants
  - Impacts on power system reliability
- **Ancillary services by wind (various forms of active and reactive power control)**
- **New generation of testing methods and equipment**
- **Hardware-in-the-loop (HIL) testing**
- **Specifics of offshore operation (AC and DC)**
- **Grid simulator testing can become a useful tool for the industry**

Evolution of Wind Turbine Electrical Topologies



IEC 61400-21 Power Quality Testing Standard

- Field testing standard (not applied to dynamometer testing)
- Provides unified methodology to grid compliance testing
- Early years: Reactive power, Flicker, Harmonics
- Ed. 2: Low-voltage ride-through (LVRT), active/reactive power set point control
- Ed. 3: Some additions are expected:
  - High-voltage ride-through (HVRT)
  - Inertia
  - Voltage control

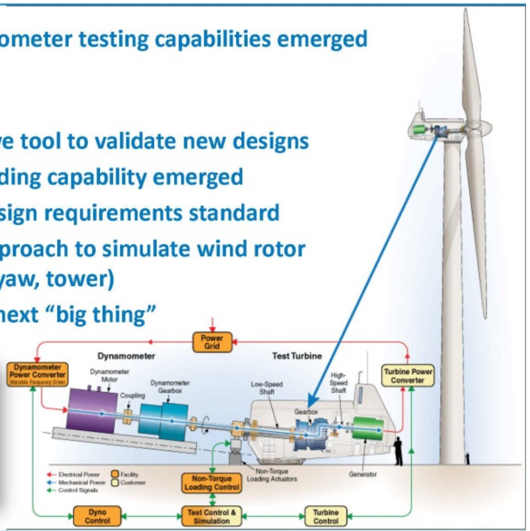


- Two separate pieces of equipment needed for LVRT and HVRT tests
- Frequency response testing can be conducted only by feeding a frequency signal into turbine controller

History of Wind Turbine Dynamometer Testing

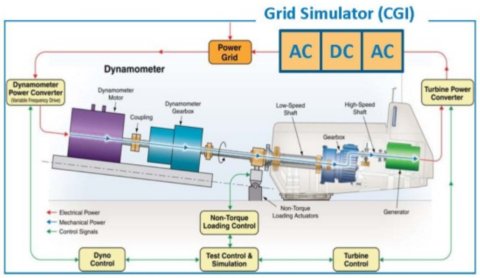
- Megawatt-scale dynamometer testing capabilities emerged around mid-1990s
- HALT/reliability testing
- Proven to be an effective tool to validate new designs
- Need in non-torque loading capability emerged
- IEC 61400-4 gearbox design requirements standard
- "Model-in-the loop" approach to simulate wind rotor dynamics (rotor, pitch, yaw, tower)
- Electrical testing is the next "big thing"

Photo by: Rob Wallen, NREL 17398

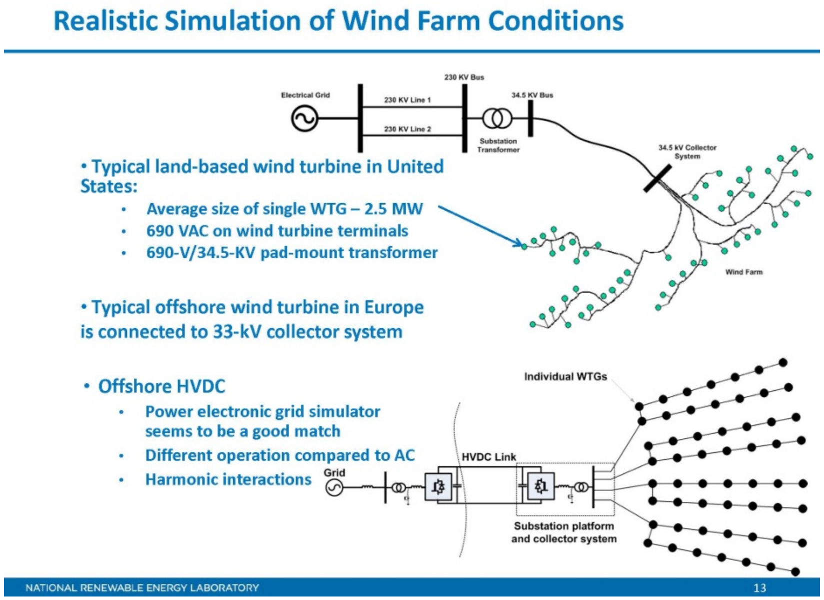


Grid Simulators for Dynamometer Testing

- Dyno. environment
  - Weaker grids
  - No disturbance to utilities is tolerated
  - Power electronics seem to be the best solution

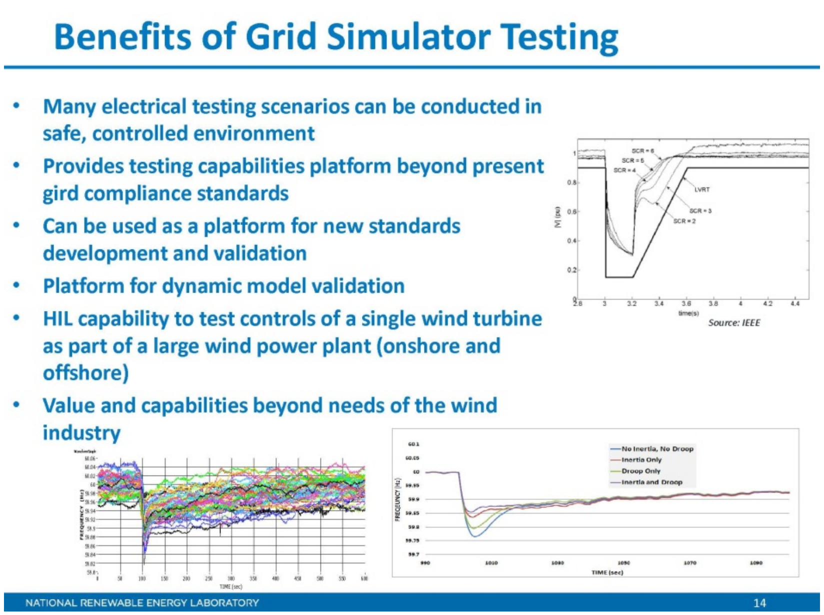


- Advantages of power electronics solution
  - Fast, flexible control (HIL)
  - Control of voltage (LVRT/HVRT, low-frequency modulations) and frequency
  - 50-Hz/60-Hz operation
  - Recreation of field events
- Disadvantages of power electronics solution
  - Possible harmonic interactions (topology dependent)
  - Sequence capabilities (topology dependent)



Realistic Simulation of Wind Farm Conditions

- Typical land-based wind turbine in United States:
  - Average size of single WTG – 2.5 MW
  - 690 VAC on wind turbine terminals
  - 690-V/34.5-KV pad-mount transformer
- Typical offshore wind turbine in Europe is connected to 33-kV collector system
- Offshore HVDC
  - Power electronic grid simulator seems to be a good match
  - Different operation compared to AC
  - Harmonic interactions



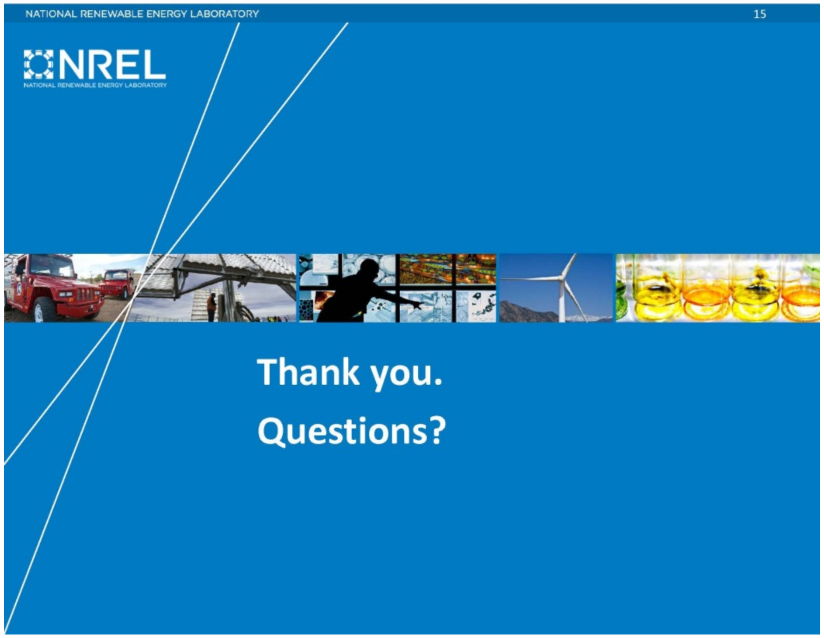
Benefits of Grid Simulator Testing

- Many electrical testing scenarios can be conducted in safe, controlled environment
- Provides testing capabilities platform beyond present gird compliance standards
- Can be used as a platform for new standards development and validation
- Platform for dynamic model validation
- HIL capability to test controls of a single wind turbine as part of a large wind power plant (onshore and offshore)
- Value and capabilities beyond needs of the wind industry

Source: IEEE

Goals for Workshop

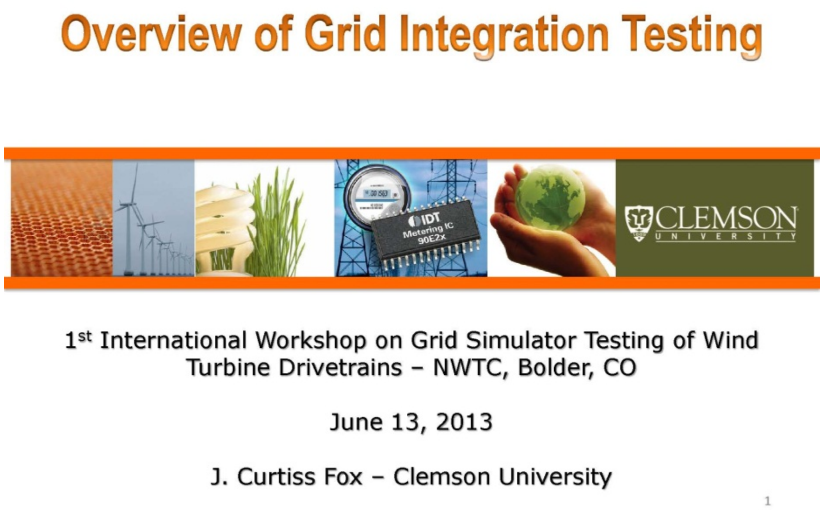
- Establish collaboration between testing labs worldwide to identify testing needs and capability gaps
- Establish a framework for sharing testing experience, test protocols and procedures, etc.
- Explore needs in having unified testing methods
- Further dialogue with wind O&Ms and plant operators to identify and meet their testing needs
- Next steps:
  - Future workshops
  - Engaging larger stakeholder groups (utilities and independent system operators)
  - Going beyond wind (photovoltaic inverters, energy storage testing, MHK, etc.)
- Success requires your active participation and discussion



Thank you.

Questions?

11.1.2 Overview of Grid Integration Testing Requirements for Wind Power – J. Curtiss Fox, CU, USA

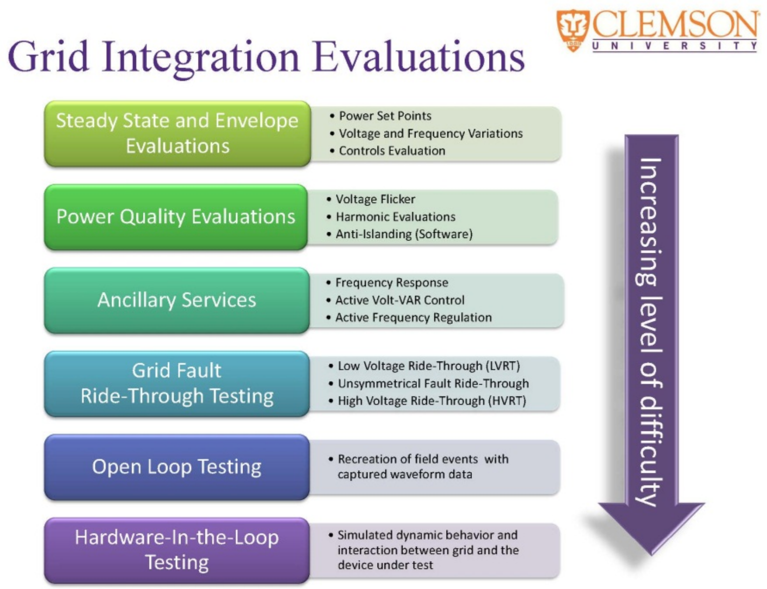


Overview of Grid Integration Testing

1st International Workshop on Grid Simulator Testing of Wind Turbine Drivetrains – NWTC, Bolder, CO

June 13, 2013

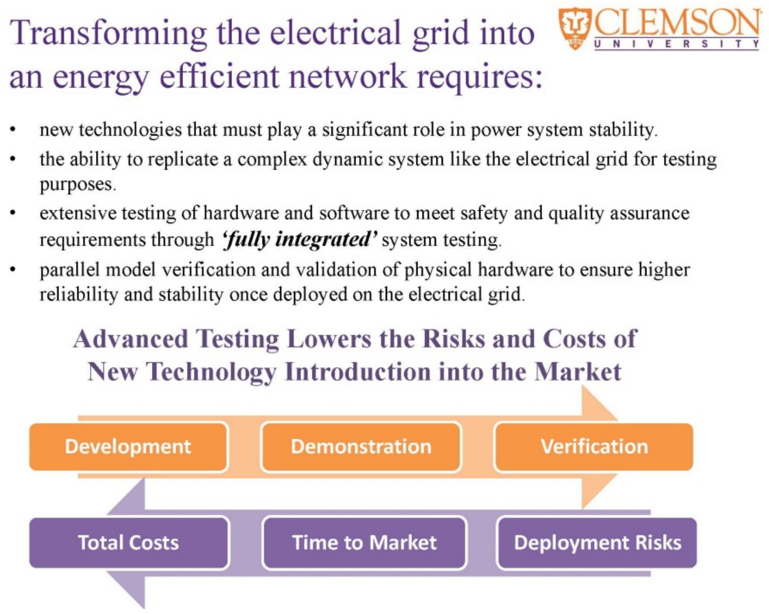
J. Curtiss Fox – Clemson University



Grid Integration Evaluations

- **Steady State and Envelope Evaluations**
  - Power Set Points
  - Voltage and Frequency Variations
  - Controls Evaluation
- **Power Quality Evaluations**
  - Voltage Flicker
  - Harmonic Evaluations
  - Anti-Islanding (Software)
- **Ancillary Services**
  - Frequency Response
  - Active Volt-VAR Control
  - Active Frequency Regulation
- **Grid Fault Ride-Through Testing**
  - Low Voltage Ride-Through (LVRT)
  - Unsymmetrical Fault Ride-Through
  - High Voltage Ride-Through (HVRT)
- **Open Loop Testing**
  - Recreation of field events with captured waveform data
- **Hardware-In-the-Loop Testing**
  - Simulated dynamic behavior and interaction between grid and the device under test

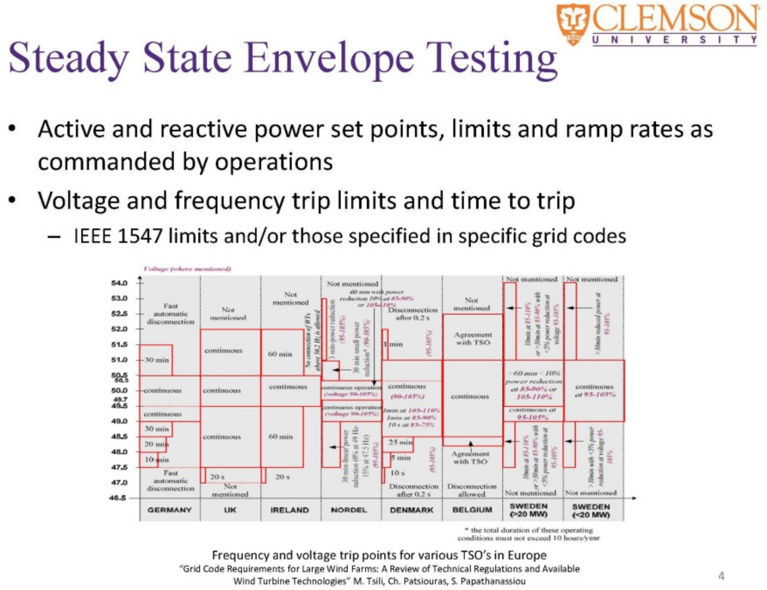
Increasing level of difficulty



Transforming the electrical grid into an energy efficient network requires:

- new technologies that must play a significant role in power system stability.
- the ability to replicate a complex dynamic system like the electrical grid for testing purposes.
- extensive testing of hardware and software to meet safety and quality assurance requirements through ***'fully integrated'*** system testing.
- parallel model verification and validation of physical hardware to ensure higher reliability and stability once deployed on the electrical grid.

Advanced Testing Lowers the Risks and Costs of New Technology Introduction into the Market



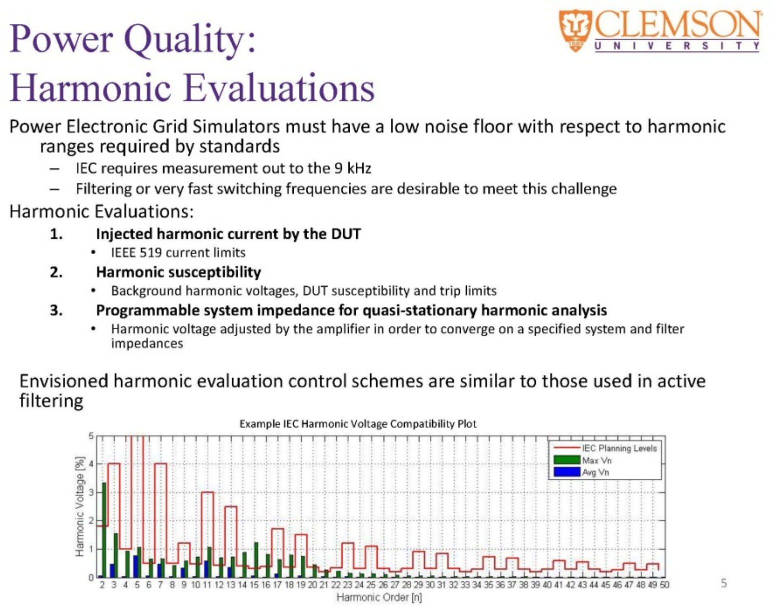
Steady State Envelope Testing

- Active and reactive power set points, limits and ramp rates as commanded by operations
- Voltage and frequency trip limits and time to trip
  - IEEE 1547 limits and/or those specified in specific grid codes

* the total duration of these operating conditions must not exceed 10 hours/year

Frequency and voltage trip points for various TSO's in Europe

"Grid Code Requirements for Large Wind Farms: A Review of Technical Regulations and Available Wind Turbine Technologies" M. Tsili, Ch. Patsiouras, S. Papathanassiou



Power Quality: Harmonic Evaluations

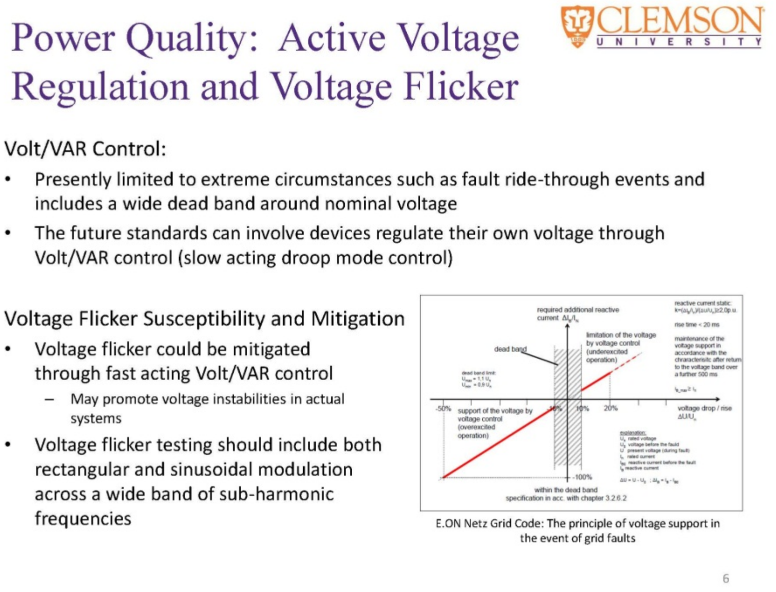
Power Electronic Grid Simulators must have a low noise floor with respect to harmonic ranges required by standards
  - IEC requires measurement out to the 9 kHz
  - Filtering or very fast switching frequencies are desirable to meet this challenge

Harmonic Evaluations:

1. **Injected harmonic current by the DUT**
   - IEEE 519 current limits
2. **Harmonic susceptibility**
   - Background harmonic voltages, DUT susceptibility and trip limits
3. **Programmable system impedance for quasi-stationary harmonic analysis**
   - Harmonic voltage adjusted by the amplifier in order to converge on a specified system and filter impedances

Envisioned harmonic evaluation control schemes are similar to those used in active filtering

Example IEC Harmonic Voltage Compatibility Plot



Power Quality: Active Voltage Regulation and Voltage Flicker

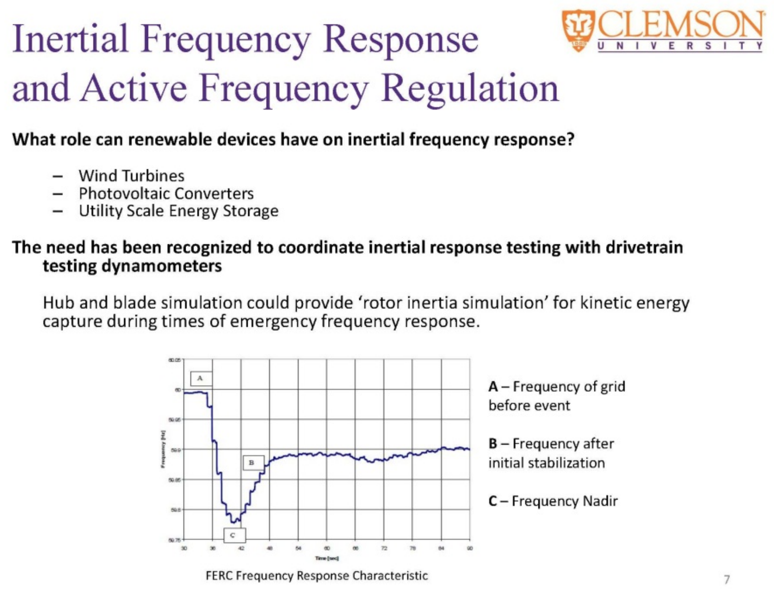
Volt/VAR Control:

- Presently limited to extreme circumstances such as fault ride-through events and includes a wide dead band around nominal voltage
- The future standards can involve devices regulate their own voltage through Volt/VAR control (slow acting droop mode control)

Voltage Flicker Susceptibility and Mitigation

- Voltage flicker could be mitigated through fast acting Volt/VAR control
  - May promote voltage instabilities in actual systems
- Voltage flicker testing should include both rectangular and sinusoidal modulation across a wide band of sub-harmonic frequencies

E.ON Netz Grid Code: The principle of voltage support in the event of grid faults



Inertial Frequency Response and Active Frequency Regulation

What role can renewable devices have on inertial frequency response?

- Wind Turbines
- Photovoltaic Converters
- Utility Scale Energy Storage

The need has been recognized to coordinate inertial response testing with drivetrain testing dynamometers

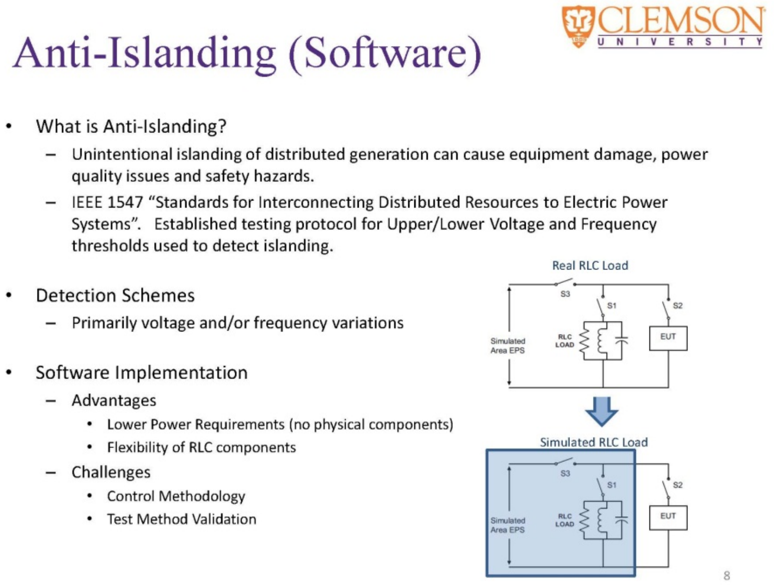
Hub and blade simulation could provide 'rotor inertia simulation' for kinetic energy capture during times of emergency frequency response.

A – Frequency of grid before event

B – Frequency after initial stabilization

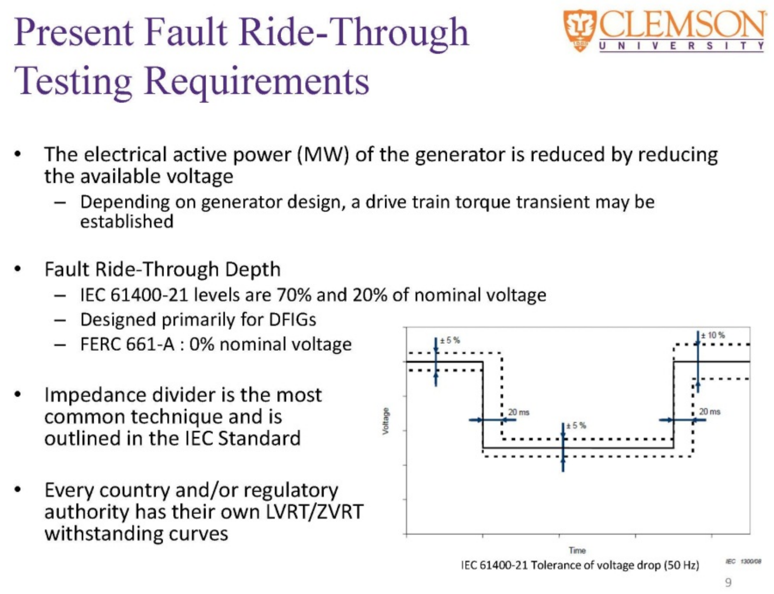
C – Frequency Nadir

FERC Frequency Response Characteristic



Anti-Islanding (Software)

- What is Anti-Islanding?
  - Unintentional islanding of distributed generation can cause equipment damage, power quality issues and safety hazards.
  - IEEE 1547 "Standards for Interconnecting Distributed Resources to Electric Power Systems". Established testing protocol for Upper/Lower Voltage and Frequency thresholds used to detect islanding.
- Detection Schemes
  - Primarily voltage and/or frequency variations
- Software Implementation
  - Advantages
    - Lower Power Requirements (no physical components)
    - Flexibility of RLC components
  - Challenges
    - Control Methodology
    - Test Method Validation



Present Fault Ride-Through Testing Requirements

- The electrical active power (MW) of the generator is reduced by reducing the available voltage
  - Depending on generator design, a drive train torque transient may be established
- Fault Ride-Through Depth
  - IEC 61400-21 levels are 70% and 20% of nominal voltage
  - Designed primarily for DFIGs
  - FERC 661-A : 0% nominal voltage
- Impedance divider is the most common technique and is outlined in the IEC Standard
- Every country and/or regulatory authority has their own LVRT/ZVRT withstanding curves

IEC 61400-21 Tolerance of voltage drop (50 Hz)

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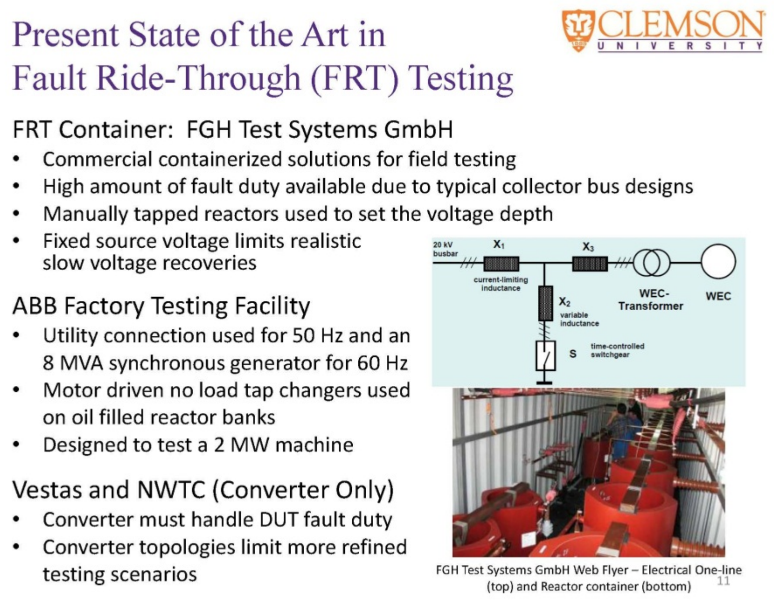

Present State of the Art in Fault Ride-Through (FRT) Testing

FRT Container: FGH Test Systems GmbH

- Commercial containerized solutions for field testing
- High amount of fault duty available due to typical collector bus designs
- Manually tapped reactors used to set the voltage depth
- Fixed source voltage limits realistic slow voltage recoveries

ABB Factory Testing Facility

- Utility connection used for 50 Hz and an 8 MVA synchronous generator for 60 Hz
- Motor driven no load tap changers used on oil filled reactor banks
- Designed to test a 2 MW machine

Vestas and NWTC (Converter Only)

- Converter must handle DUT fault duty
- Converter topologies limit more refined testing scenarios

FGH Test Systems GmbH Web Flyer – Electrical One-line (top) and Reactor container (bottom)

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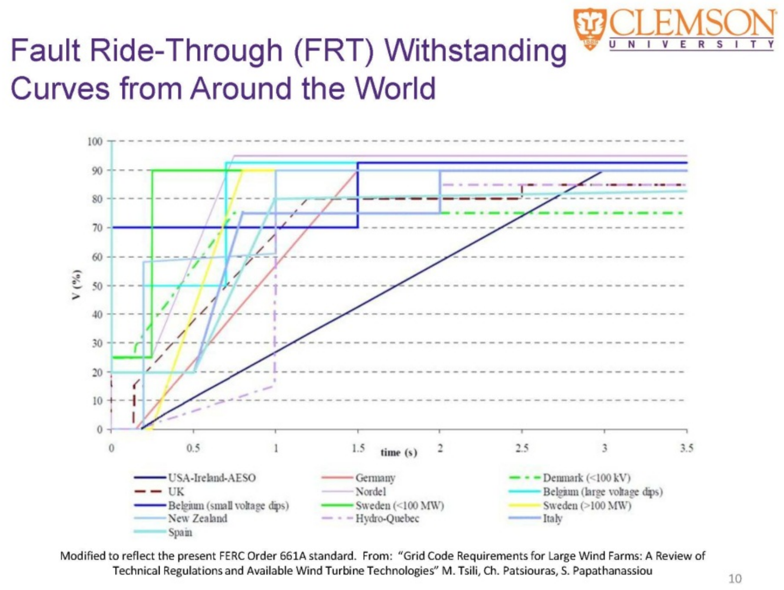

Fault Ride-Through (FRT) Withstanding Curves from Around the World

Modified to reflect the present FERC Order 661A standard. From: "Grid Code Requirements for Large Wind Farms: A Review of Technical Regulations and Available Wind Turbine Technologies" M. Tsili, Ch. Patsiouras, S. Papathanassiou

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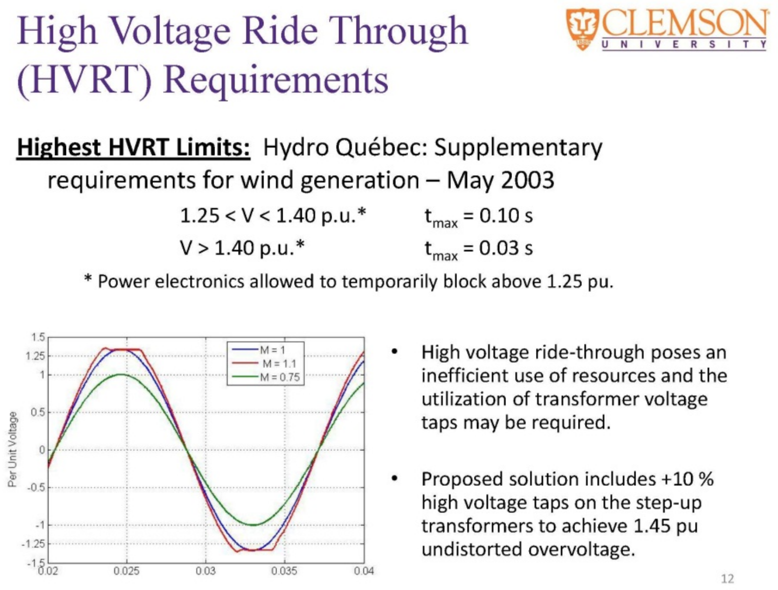

High Voltage Ride Through (HVRT) Requirements

Highest HVRT Limits: Hydro Québec: Supplementary requirements for wind generation – May 2003

$1.25 < V < 1.40$ p.u.* $t_{max} = 0.10$ s

$V > 1.40$ p.u.* $t_{max} = 0.03$ s

* Power electronics allowed to temporarily block above 1.25 pu.

- High voltage ride-through poses an inefficient use of resources and the utilization of transformer voltage taps may be required.
- Proposed solution includes +10 % high voltage taps on the step-up transformers to achieve 1.45 pu undistorted overvoltage.

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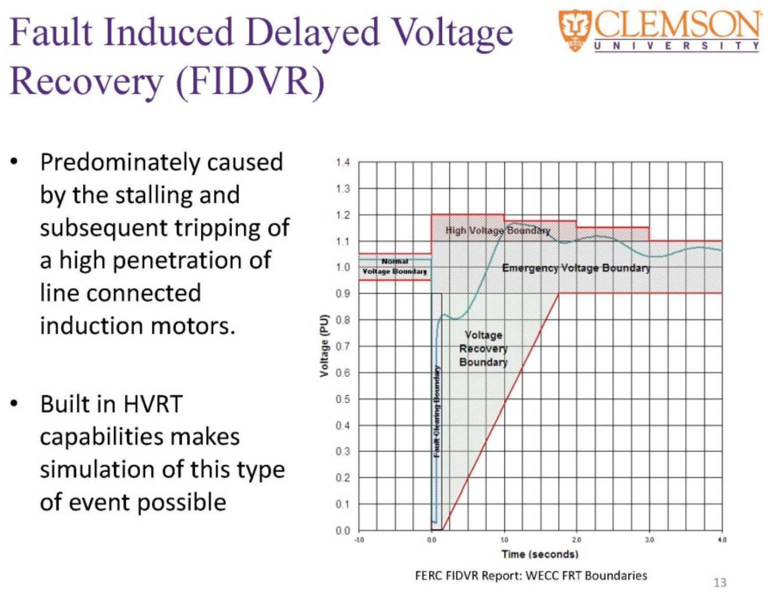
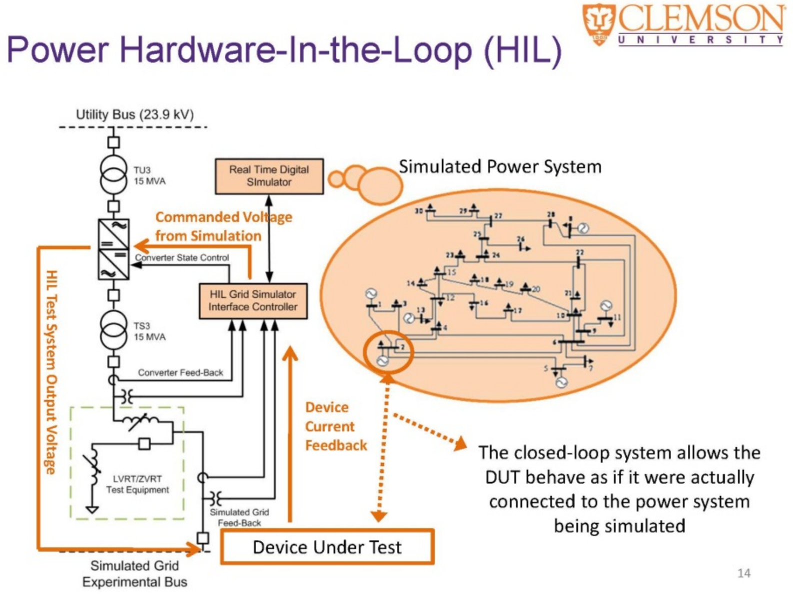


Fault Induced Delayed Voltage Recovery (FIDVR)

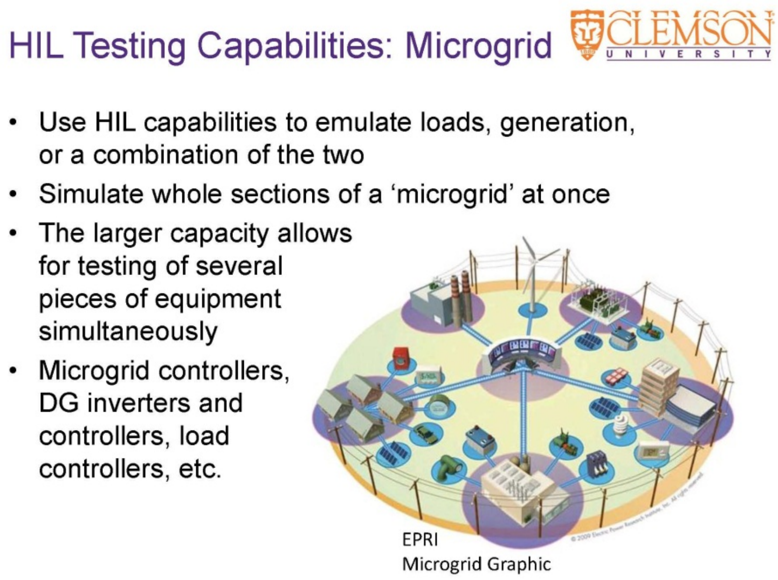
- Predominately caused by the stalling and subsequent tripping of a high penetration of line connected induction motors.
- Built in HVRT capabilities makes simulation of this type of event possible

FERC FIDVR Report: WECC FRT Boundaries



Power Hardware-In-the-Loop (HIL)

The closed-loop system allows the DUT behave as if it were actually connected to the power system being simulated



HIL Testing Capabilities: Microgrid

- Use HIL capabilities to emulate loads, generation, or a combination of the two
- Simulate whole sections of a ‘microgrid’ at once
- The larger capacity allows for testing of several pieces of equipment simultaneously
- Microgrid controllers, DG inverters and controllers, load controllers, etc.

EPRI
Microgrid Graphic

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

11.2 Introduction to Existing Capabilities and Testing Experience in Grid Simulator Area

11.2.1 Florida State University Center for Advanced Power Systems Experience – Michael Steurer, Florida State University, USA

FSU-CAPS Experiences with Large Scale Power Hardware-in-the-Loop (PHIL) Testing

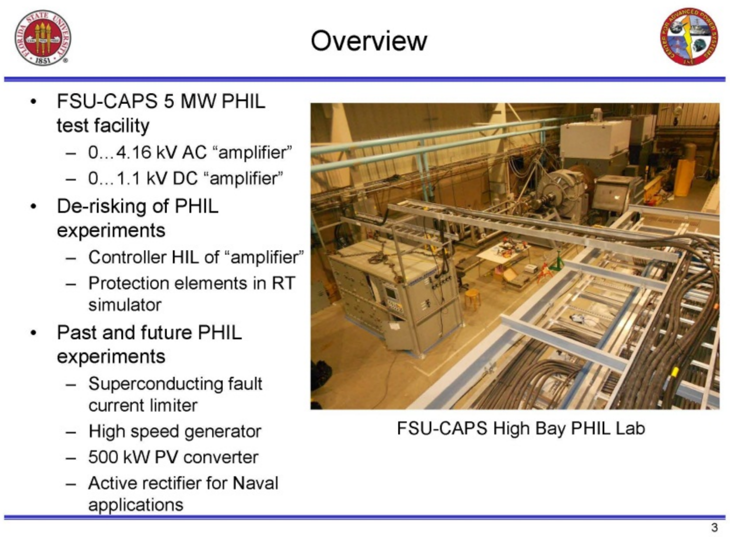
Michael “Mischa” Steurer

Leader Power Systems Research Group at FSU-CAPS

Email: steurer@caps.fsu.edu, phone: 850-644-1629

1st International Workshop on
Grid Simulator Testing of Wind Turbine Drivetrains

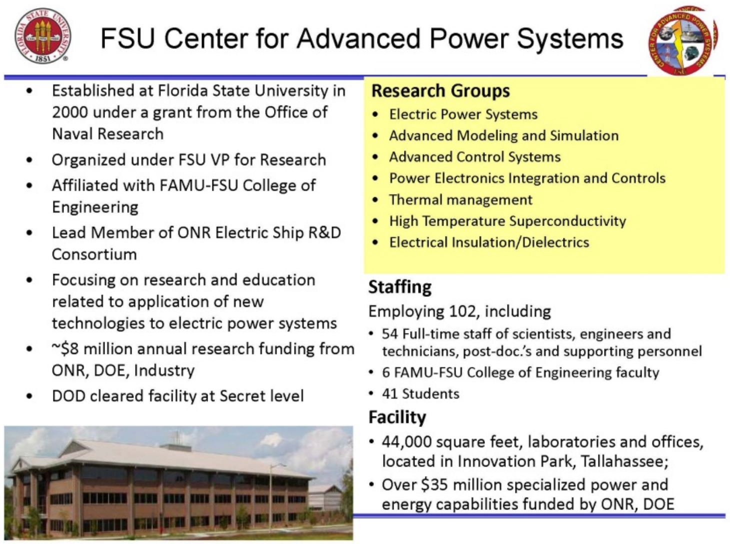
June 13, 2013, Boulder, CO



Overview

- FSU-CAPS 5 MW PHIL test facility
  - 0…4.16 kV AC “amplifier”
  - 0…1.1 kV DC “amplifier”
- De-risking of PHIL experiments
  - Controller HIL of “amplifier”
  - Protection elements in RT simulator
- Past and future PHIL experiments
  - Superconducting fault current limiter
  - High speed generator
  - 500 kW PV converter
  - Active rectifier for Naval applications

FSU-CAPS High Bay PHIL Lab



FSU Center for Advanced Power Systems

- Established at Florida State University in 2000 under a grant from the Office of Naval Research
- Organized under FSU VP for Research
- Affiliated with FAMU-FSU College of Engineering
- Lead Member of ONR Electric Ship R&D Consortium
- Focusing on research and education related to application of new technologies to electric power systems
- ~$8 million annual research funding from ONR, DOE, Industry
- DOD cleared facility at Secret level

Research Groups

- Electric Power Systems
- Advanced Modeling and Simulation
- Advanced Control Systems
- Power Electronics Integration and Controls
- Thermal management
- High Temperature Superconductivity
- Electrical Insulation/Dielectrics

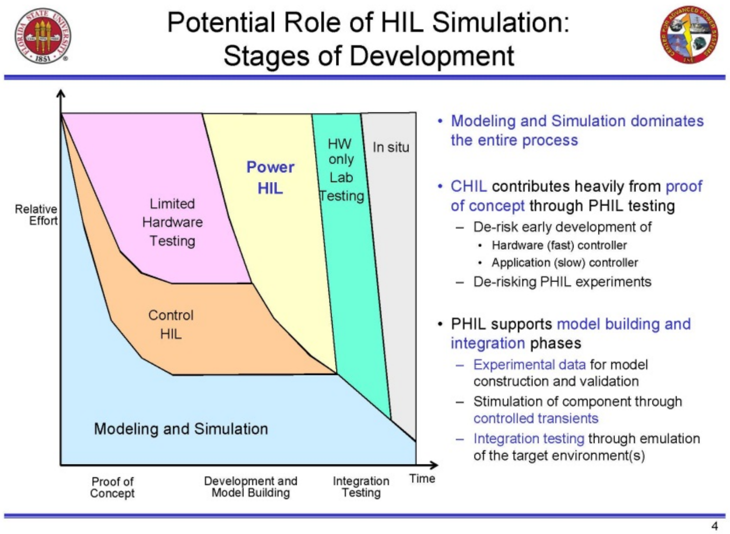
Staffing

Employing 102, including

- 54 Full-time staff of scientists, engineers and technicians, post-doc.’s and supporting personnel
- 6 FAMU-FSU College of Engineering faculty
- 41 Students

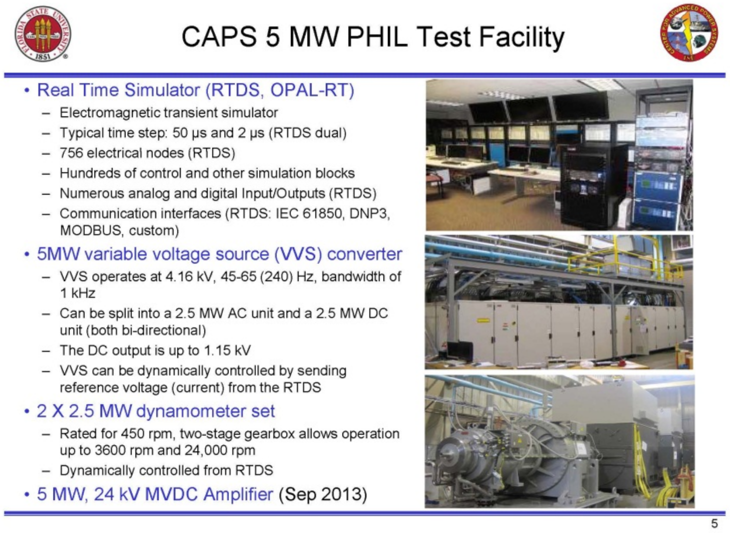
Facility

- 44,000 square feet, laboratories and offices, located in Innovation Park, Tallahassee;
- Over $35 million specialized power and energy capabilities funded by ONR, DOE



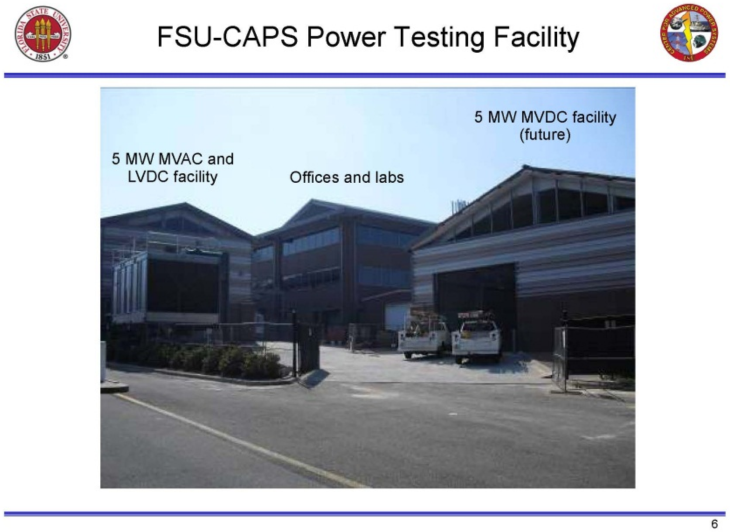
Potential Role of HIL Simulation: Stages of Development

- Modeling and Simulation dominates the entire process
- CHIL contributes heavily from proof of concept through PHIL testing
  - De-risk early development of
    - Hardware (fast) controller
    - Application (slow) controller
  - De-risking PHIL experiments
- PHIL supports model building and integration phases
  - Experimental data for model construction and validation
  - Stimulation of component through controlled transients
  - Integration testing through emulation of the target environment(s)

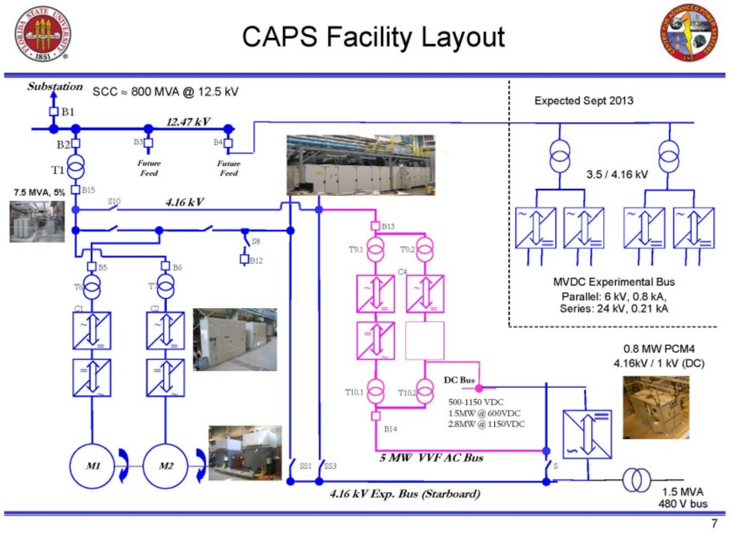


CAPS 5 MW PHIL Test Facility

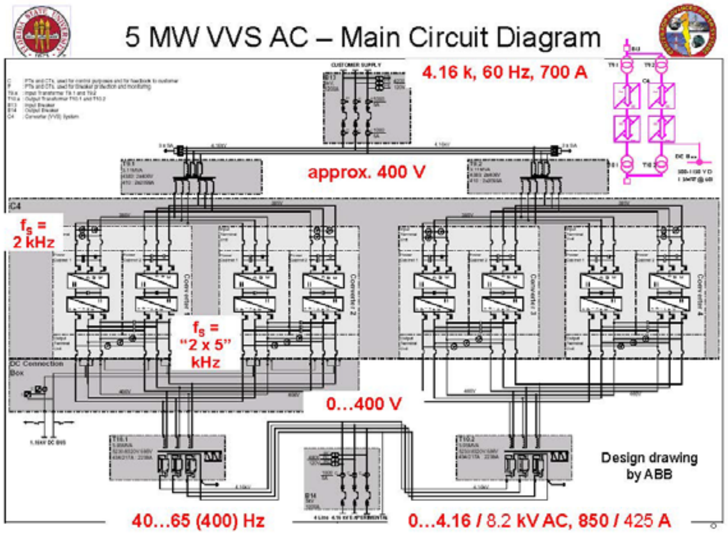
- Real Time Simulator (RTDS, OPAL-RT)
  - Electromagnetic transient simulator
  - Typical time step: 50 μs and 2 μs (RTDS dual)
  - 756 electrical nodes (RTDS)
  - Hundreds of control and other simulation blocks
  - Numerous analog and digital Input/Outputs (RTDS)
  - Communication interfaces (RTDS: IEC 61850, DNP3, MODBUS, custom)
- 5MW variable voltage source (VVS) converter
  - VVS operates at 4.16 kV, 45-65 (240) Hz, bandwidth of 1 kHz
  - Can be split into a 2.5 MW AC unit and a 2.5 MW DC unit (both bi-directional)
  - The DC output is up to 1.15 kV
  - VVS can be dynamically controlled by sending reference voltage (current) from the RTDS
- 2 X 2.5 MW dynamometer set
  - Rated for 450 rpm, two-stage gearbox allows operation up to 3600 rpm and 24,000 rpm
  - Dynamically controlled from RTDS
- 5 MW, 24 kV MVDC Amplifier (Sep 2013)



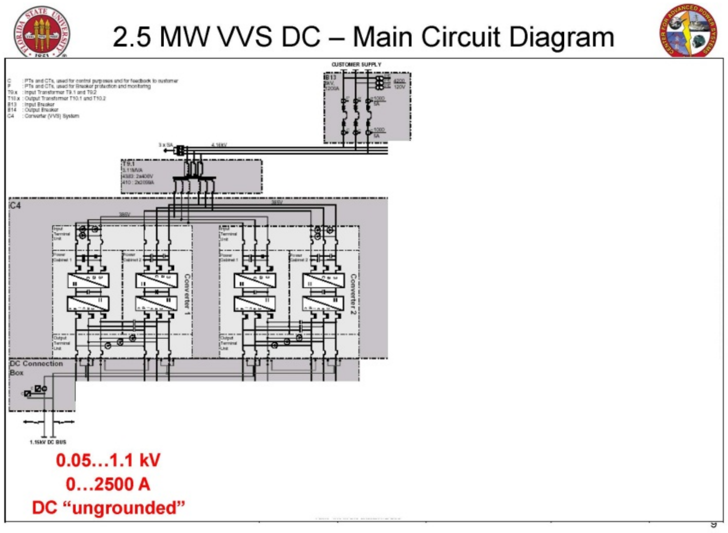
FSU-CAPS Power Testing Facility



CAPS Facility Layout

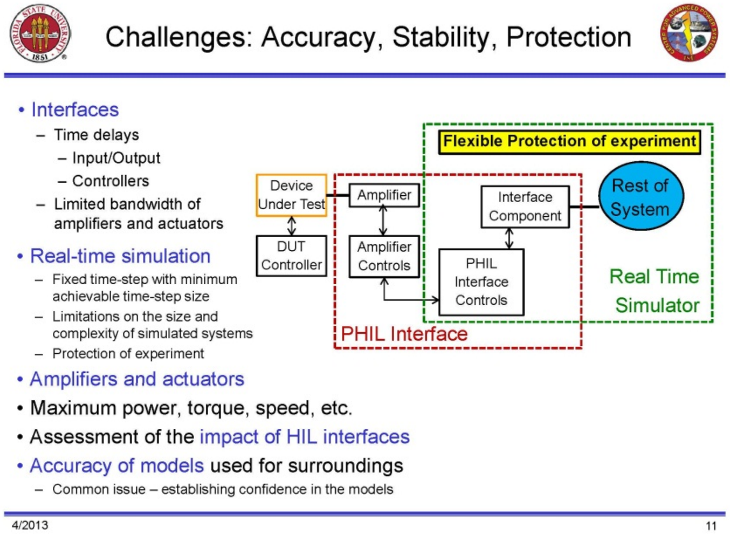


5 MW VVS AC – Main Circuit Diagram



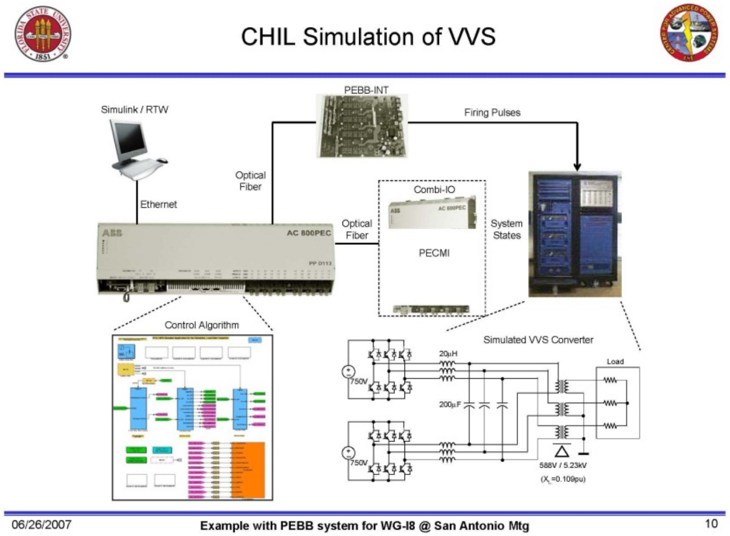
2.5 MW VVS DC – Main Circuit Diagram

0.05…1.1 kV
0…2500 A
DC "ungrounded"

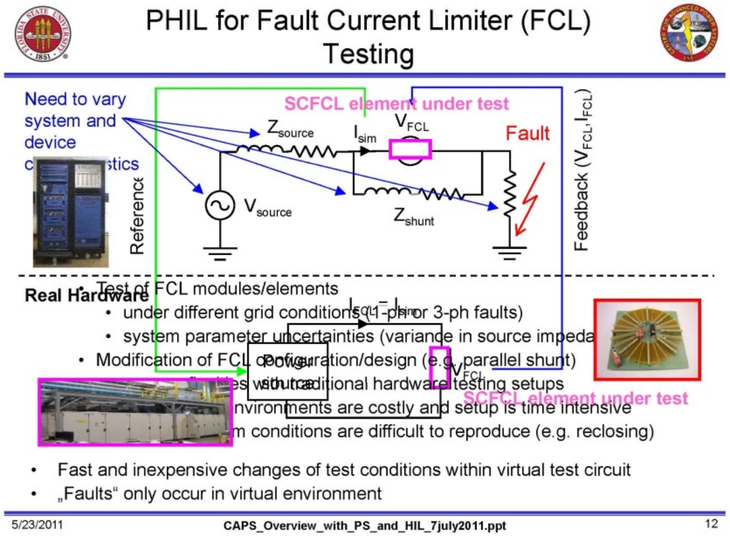


Challenges: Accuracy, Stability, Protection

- Interfaces
  - Time delays
    - Input/Output
    - Controllers
  - Limited bandwidth of amplifiers and actuators
- Real-time simulation
  - Fixed time-step with minimum achievable time-step size
  - Limitations on the size and complexity of simulated systems
  - Protection of experiment
- Amplifiers and actuators
- Maximum power, torque, speed, etc.
- Assessment of the impact of HIL interfaces
- Accuracy of models used for surroundings
  - Common issue – establishing confidence in the models



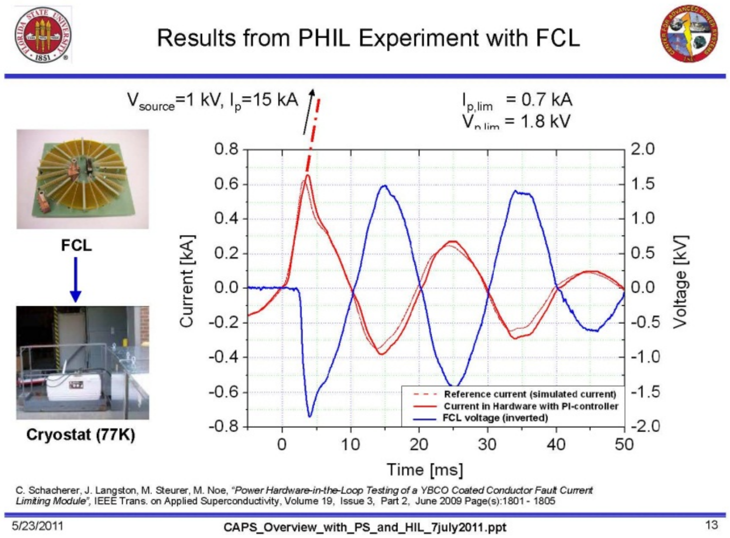
CHIL Simulation of VVS



PHIL for Fault Current Limiter (FCL) Testing

- Test of FCL modules/elements
  - under different grid conditions (1-ph or 3-ph faults)
  - system parameter uncertainties (variance in source impeda
- Modification of FCL configuration/design (e.g. parallel shunt)
  - es with traditional hardware testing setups
  - nvironments are costly and setup is time intensive
  - m conditions are difficult to reproduce (e.g. reclosing)

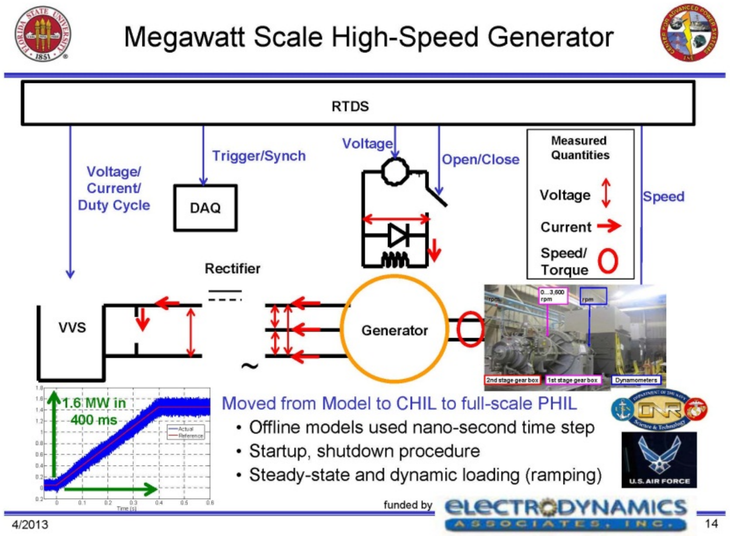
- Fast and inexpensive changes of test conditions within virtual test circuit
- „Faults" only occur in virtual environment



Results from PHIL Experiment with FCL

C. Schacherer, J. Langston, M. Steurer, M. Noe, *"Power Hardware-in-the-Loop Testing of a YBCO Coated Conductor Fault Current Limiting Module"*, IEEE Trans. on Applied Superconductivity, Volume 19, Issue 3, Part 2, June 2009 Page(s):1801 - 1805

5/23/2011 **CAPS_Overview_with_PS_and_HIL_7july2011.ppt** 13



Megawatt Scale High-Speed Generator

Moved from Model to CHIL to full-scale PHIL

- Offline models used nano-second time step
- Startup, shutdown procedure
- Steady-state and dynamic loading (ramping)

funded by ELECTRODYNAMICS ASSOCIATES, INC.

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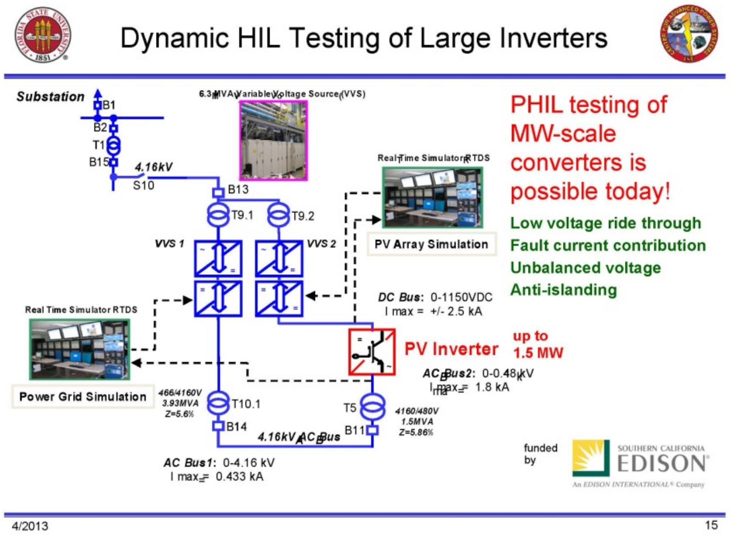

Dynamic HIL Testing of Large Inverters

PHIL testing of MW-scale converters is possible today!

Low voltage ride through
Fault current contribution
Unbalanced voltage
Anti-islanding

funded by SOUTHERN CALIFORNIA EDISON An EDISON INTERNATIONAL® Company

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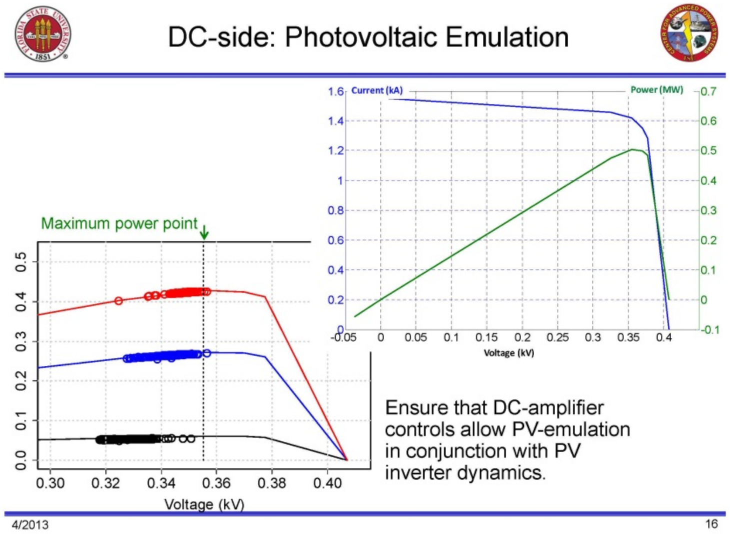

DC-side: Photovoltaic Emulation

Ensure that DC-amplifier controls allow PV-emulation in conjunction with PV inverter dynamics.

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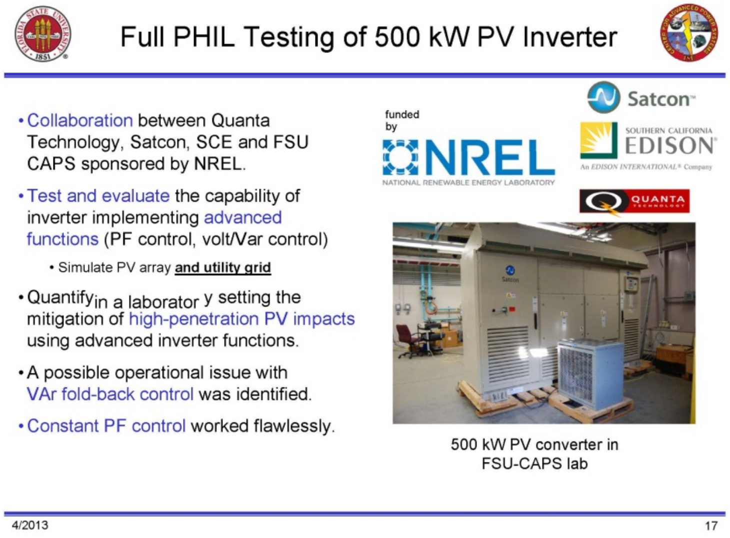


Full PHIL Testing of 500 kW PV Inverter

- Collaboration between Quanta Technology, Satcon, SCE and FSU CAPS sponsored by NREL.
- Test and evaluate the capability of inverter implementing advanced functions (PF control, volt/Var control)
  - Simulate PV array **and utility grid**
- Quantify in a laboratory setting the mitigation of high-penetration PV impacts using advanced inverter functions.
- A possible operational issue with VAr fold-back control was identified.
- Constant PF control worked flawlessly.

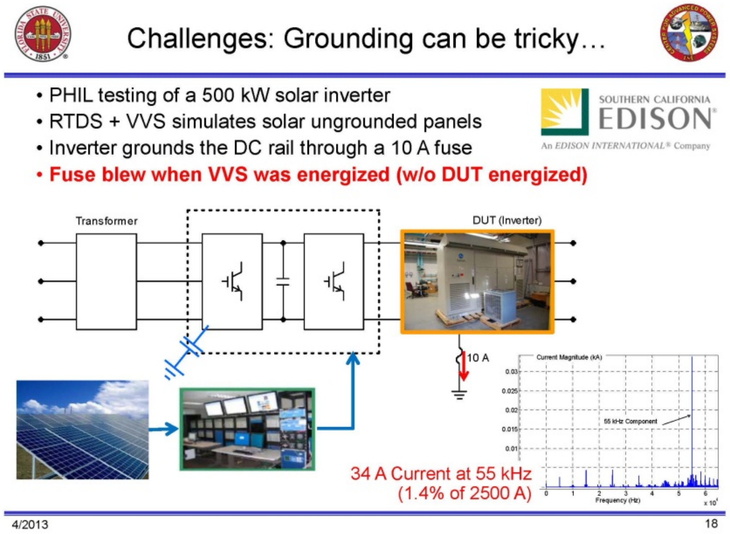
funded by NREL NATIONAL RENEWABLE ENERGY LABORATORY

Satcon

SOUTHERN CALIFORNIA EDISON An EDISON INTERNATIONAL® Company

QUANTA TECHNOLOGY

500 kW PV converter in FSU-CAPS lab

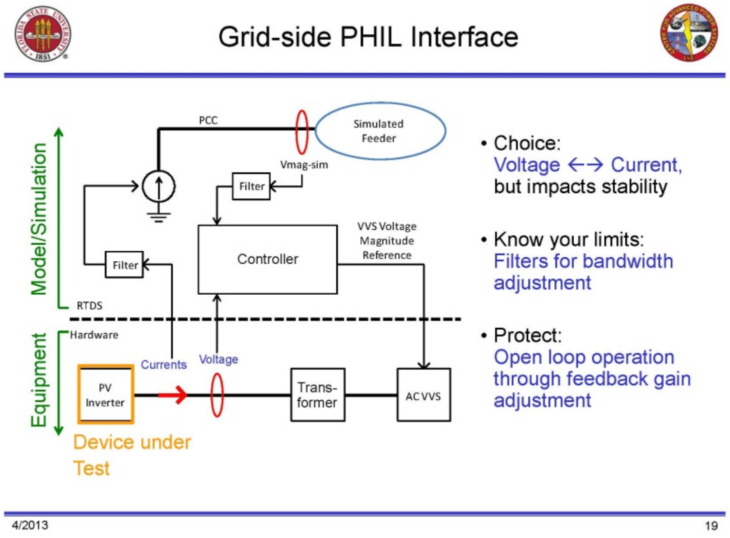


Challenges: Grounding can be tricky…

- PHIL testing of a 500 kW solar inverter
- RTDS + VVS simulates solar ungrounded panels
- Inverter grounds the DC rail through a 10 A fuse
- **Fuse blew when VVS was energized (w/o DUT energized)**

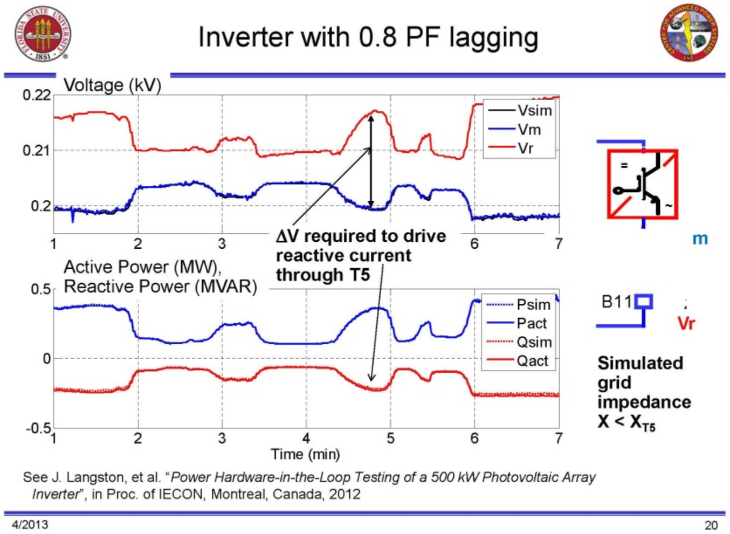
SOUTHERN CALIFORNIA EDISON An EDISON INTERNATIONAL® Company

34 A Current at 55 kHz (1.4% of 2500 A)



Grid-side PHIL Interface

- Choice: Voltage ←→ Current, but impacts stability
- Know your limits: Filters for bandwidth adjustment
- Protect: Open loop operation through feedback gain adjustment



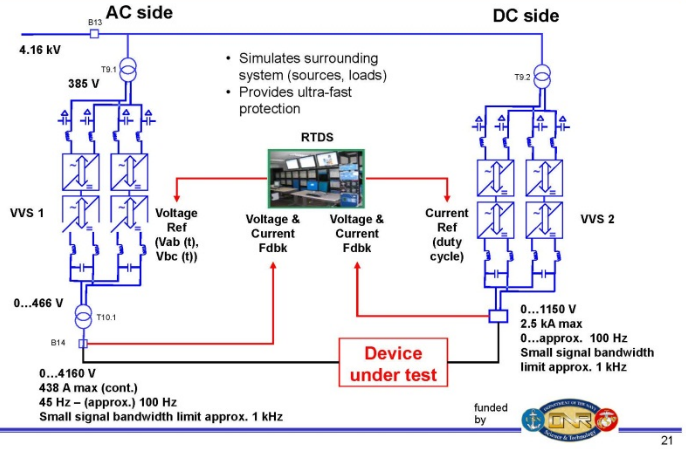
Inverter with 0.8 PF lagging

ΔV required to drive reactive current through T5

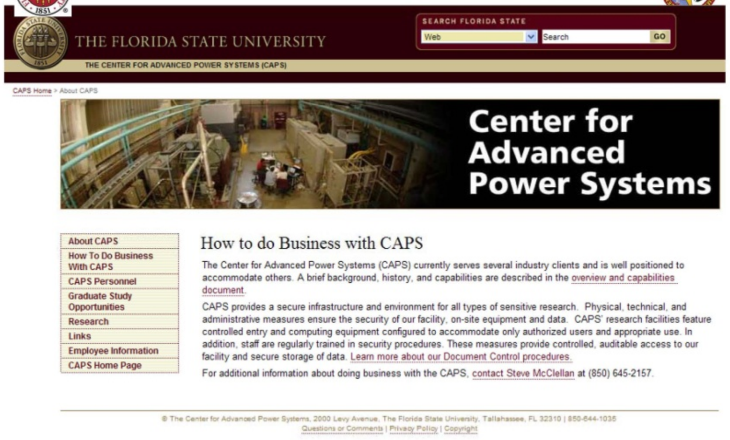
Simulated grid impedance $X < X_{T5}$

See J. Langston, et al. "*Power Hardware-in-the-Loop Testing of a 500 kW Photovoltaic Array Inverter*", in Proc. of IECON, Montreal, Canada, 2012

PHIL testing of SiC converter
4.16 kV_{AC}-1 kV_{DC}



- Simulates surrounding system (sources, loads)
- Provides ultra-fast protection



How to do Business with CAPS

The Center for Advanced Power Systems (CAPS) currently serves several industry clients and is well positioned to accommodate others. A brief background, history, and capabilities are described in the overview and capabilities document.

CAPS provides a secure infrastructure and environment for all types of sensitive research. Physical, technical, and administrative measures ensure the security of our facility, on-site equipment and data. CAPS' research facilities feature controlled entry and computing equipment configured to accommodate only authorized users and appropriate use. In addition, staff are regularly trained in security procedures. These measures provide controlled, auditable access to our facility and secure storage of data. Learn more about our Document Control procedures.

For additional information about doing business with the CAPS, contact Steve McClellan at (850) 645-2157.

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- http://www.caps.fsu.edu/documentcontrol.html

Concluding Remarks

- PHIL testing is advancing rapidly
  - A tool to address several challenges associated with transitioning technology (de-risking)
  - Emulate a wide range of surroundings and scenarios, simulate yet unrealized systems
- Impact of PHIL interface more pronounced at MW scale experiments
  - Aim for close coupling between reference and amplifier
  - Faster switching amplifiers
  - Real time simulation of models
- Simulation based preparation of MW scale experiments save time and money
  - Improve development cycle
    Discover hidden issues early
  - Model construction and validation

Team at work in FSU-CAPS control room

500 kW PV converter in FSU-CAPS lab

11.2.2 CENER Dynamometer/Grid Simulator Experience – Carlos Garcia de Cortazar, CENER, Spain

CENER | CENTRO NACIONAL DE ENERGÍAS RENOVABLES

GRID SIMULATOR TESTING OF WTG

Carlos Garcia de Cortazar

1st International Workshop on Grid Simulator Testing of Wind Turbine Drivetrains - Boulder, June 13, 2013

Gobierno de Navarra

1. CENER LEA
   WTG Test Laboratory

CENER | CENTRO NACIONAL DE ENERGÍAS RENOVABLES

índice

1. LEA – Wind Turbine Test Laboratory
2. BEG Electrical Generator Test Bench
3. 5 MW in a Grid Simulator Experience

Gobierno de Navarra

Wind Turbine Test Facility

CENER | CENTRO NACIONAL DE ENERGÍAS RENOVABLES

Gobierno de Navarra

Overview

LEA – WTG Test Laboratory

- Complements the research work of CENER in wind energy
  Dedicated to Tests of components, subsystems & full systems

- **Activities**
  - ❑ Blade tests
  - ❑ Experimental Windfarm
  - ❑ Power Train tests and Electrical Testing

BLADE TEST PLANT Capabilities

1. LEA – WTG Test Laboratory

- Perform structural tests on WTG blades
  - ❑ IEC TS-61400-23 standard / GL Guidelines
  - ❑ Static/Fatigue
  - ❑ Up to 75 m blade full length
  - ❑ Sections of up to 100m blades

- **Static Tests**
  - ❑ Mass, COG, moments of inertia
  - ❑ Stiffness bending/torsion
  - ❑ Ultimate strength

- **Fatigue Tests**
  - ❑ Modal analysis
  - ❑ Endurance/fatigue
  - ❑ Biaxial + Multipoint (UREX, GREX)

BLADE TEST PLANT

1. LEA – WTG Test Laboratory

EXPERIMENTAL WINDPARK

2. CENER LEA – WTG TEST LABORATORY

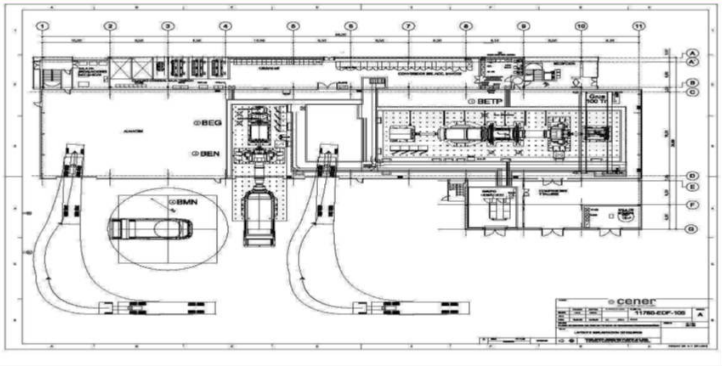
EXPERIMENTAL WINDPARK

2. CENER LEA – WTG TEST LABORATORY

- 6 calibrated positions
  - WTG prototypes for up to 30 MW evacuation capacity
  - Field tests on complex terrain (Wind Classes IA, IIA)
  - Fully CFD Characterised
- Wind Park features
  - 120 m high Met Masts instrumented at 5 different heights & Lidar
  - Field Offices & Redundant communications
  - Substation 20KV/66KV
- Technical Services
  - IEC Certification tests (Power Curve, Noise, PQ, Mechanical Loads)
  - Verification of response to voltage dips (LVRT)
  - Others (design, optimization, validation, etc.)
- Energy Production Income RD661/2007

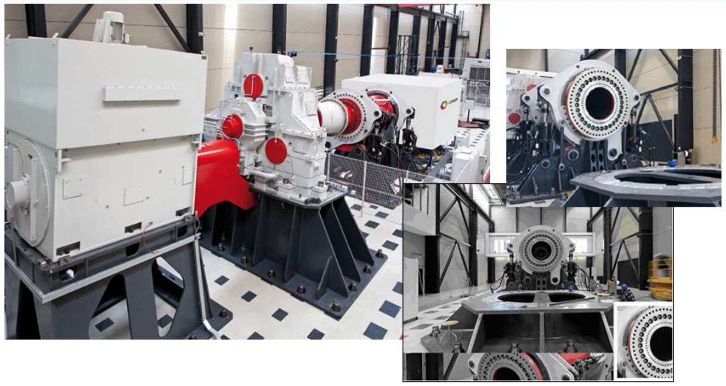
TEST BENCHES Configuration

3. CENER LEA – WTG TEST LABORATORY



POWER TRAIN Facilities

3. LEA – WTG Test Laboratory



TEST BENCHES Capabilities

3. LEA – WTG Test Laboratory

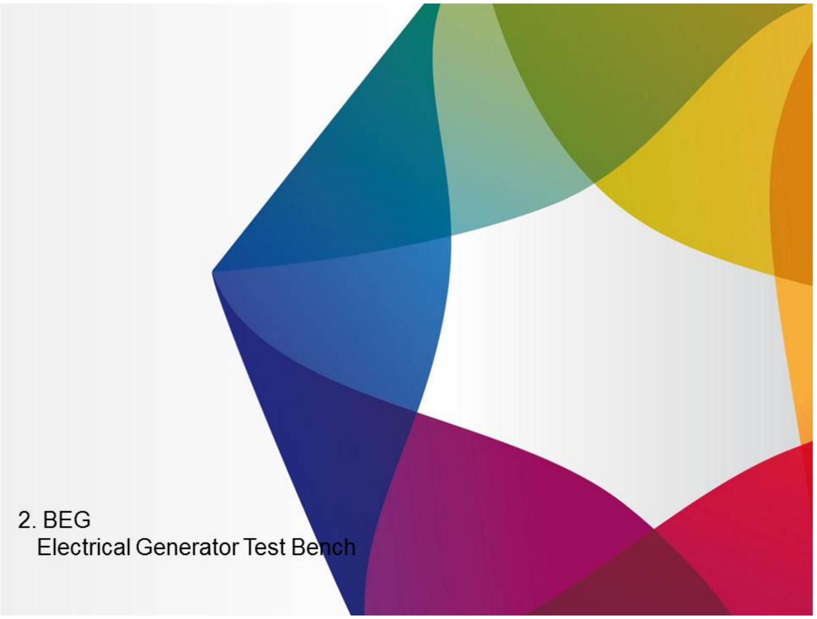
- **Power Train test bench**
  - ☐ Test of WTG power train up to 8MW
  - ☐ Functional tests on mechanical parts
  - ☐ Functional/load test of brake/coupling at high speed shaft HSS
  - ☐ Concentrated life test and HALT
    - ➢ bearings in the main shaft (LSS)
    - ➢ gears and bearings in the gearbox
- **Generator test bench**
  - ➢ Functional test of generator and power electronics
  - ➢ Electrical transient simulation (voltage dips)
  - ➢ Functional tests, vibration, acoustic noise, heating, etc.
  - ➢ Overspeed tests and transients surges

TEST BENCHES Capabilities

3. LEA – WTG Test Laboratory

- **Nacelle test bench**
  - ☐ functional, emergency stop, overspeed, climatic conditions, etc.
  - ☐ electrical transient simulation “Voltage dips”
  - ☐ EMC and acoustic test
  - ☐ Reactive power measurements

- **Nacelle assembly bench**
  - ➢ WTG erection and nacelle setup procedures
  - ➢ Use of auxiliary assembly cranes
  - ➢ Simulation of maintenance exercises, including major corrections
  - ➢ Staff training in the assembly and maintenance of WTG
  - ➢ Training in evacuation and security operations in WTG



2. BEG
Electrical Generator Test Bench

BEG

Electrical Generator Test Bench Overview

BEG

2. Electrical Generator Test Bench

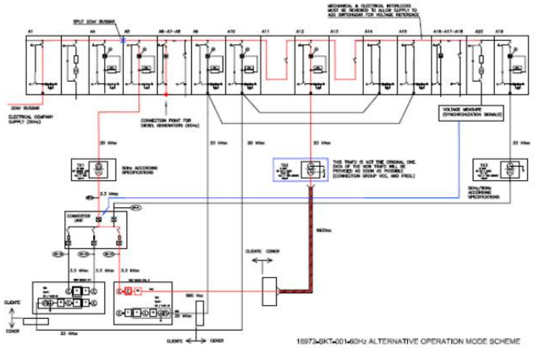
- **Adavantages**
  - ☐ Not depending on Wind conditions: maximum productivity
  - ☐ Development laboratory conditions: measurement devices, communication, working conditions, etc.
  - ☐ Easily different working points reproducibility

- **Disadvantages**
  - ➢ High frequency wind and mechanical forces not considered
  - ➢ On the field certification still required

3. Grid Simulator Test Experience
5 MW full converter generator Test

Grid Simulator Test Experience

3. Electrical Configuration



16973-SKT-001-60Hz ALTERNATIVE OPERATION MODE SCHEME

Grid Simulator Test Experience

3. Hardware involved equipments

Grid Simulator Test Experience

2. Conclussions

Proposal for Discussion

- ❑ Laboratory Tests accepted for certification
- ❑ Bidirectional influence in Grid Simulator Tests

www.cener.com

Carlos Garcia de Cortazar
PT Specialist
Tel: +34 699540893
cgarcia@cener.com

11.2.3 Inductive Fault Simulator Field Testing Experience – Carlos Alvarez, Barlovento/E2Q, Spain

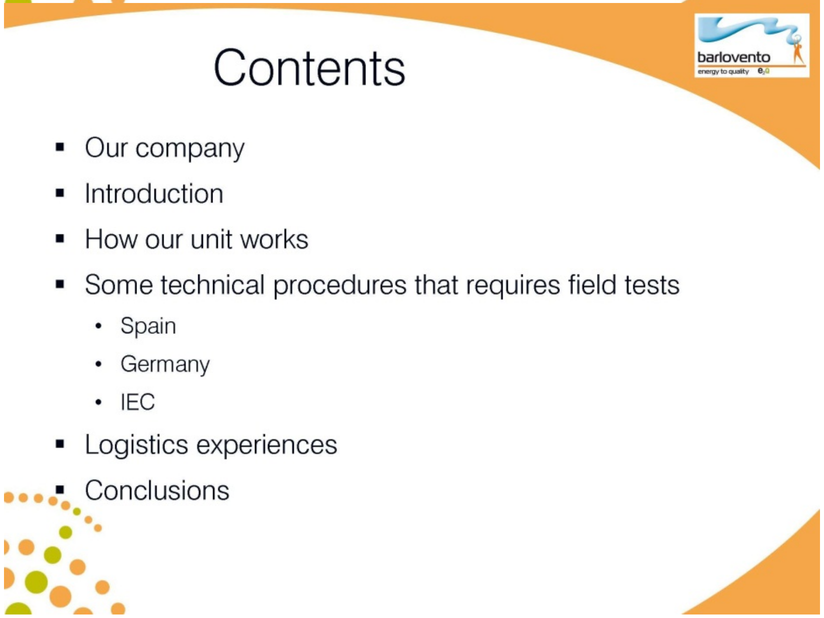
Testing Wind Turbines Generators with ULYSSES

Barlovento - Energy to Quality
Spain

Our company

ENERGY TO QUALITY: WHAT WE DO

- **FIELD MEASUREMENT**: ACCREDITED LVRT REPORTS OF WIND TURBINES ACCORDING TO SEVERAL GRID CODES (USA, Germany, Denmark, Ireland, UK, United States, etc…) AND POWER QUALITY ACCORDING TO IEC 61400-21 ed2, FGW TR3 rev 22 AND MEASNET
- **NUMERICAL SIMULATIONS**: RMS/EMT MODELING OF WIND TURBINES (POWERFACTORY, MATLAB, PSSE), ACCREDITATION OF EXISTING WIND FARMS AND NEW INSTALLATIONS.
- **MODEL VALIDATION**: WIND TURBINES, FACTS….



Contents

- Our company
- Introduction
- How our unit works
- Some technical procedures that requires field tests
  - Spain
  - Germany
  - IEC
- Logistics experiences
- Conclusions

Our company

BARLOVENTO: HISTORICAL OVERVIEW

Barlovento is an independent technical assessor and laboratory in wind and solar energies:

1998	- **Creation Barlovento Recursos Naturales S.L.**
2002	- **Start-up testing laboratory**
2004	- **MEASNET membership**
2005	- **Energy to Quality, S.L. (E2Q)**
2009	- **Barlovento Renovables Latinoamérica, S.A.C.**
2011	- **Barlovento Dacia (Romania), Barlovento Brasil**
2012	- **Bolivia, E2Q de México, Chile**

Our company

BARLOVENTO GROUP IN THE WORLD

Orange countries: Where we have projects

Blue countries: Where we have offices

Projects in more than 40 countries, along Europe, Asia, Africa and America

Our company

BARLOVENTO: AREAS OF WORK

- Barlovento Recursos Naturales has six main areas of work.

- **Resources and Environment** (measurement campaigns, site certification, site assessment, Wind Class studies, micrositing, production studies,…)
- **Test and Measurements** (Power Curve test, Power Quality test, Grid code certifications, LVRT test, noise measurements,...)
- **Due Diligence** ("purchase and sale" audits, technical audits, normative consultancy, arbitration,...)
- **Engineering** (engineering projects, wind farms basic/execution projects, tender preparation, technical specification for tenders, projects supervision and certification, remote operation of installations,…)
- **Electrical Laboratory** (test of equipment like inverters and solar panels, design and commercialization of measurement equipment like LVRT test equipment,…)
- **Special Projects** (meteorological studies, problem diagnosis, complex flow characterization, R&D experiments, preparation of technical in-house courses,…)

Our company

BARLOVENTO: ACTIVITIES

Our company

BARLOVENTO: EXPERIENCE OVERVIEW

- Barlovento Recursos Naturales is an Independent Technical Consultant on Renewable Energies:
  - Site Assessment: More than 1.500 Wind Farms worldwide
  - Wind resource consultancy : More than 15.000 MW already built
  - Solar resource consultancy: More than 500 MW already built
  - Lenders advising for project finance: More than 1600 MW
  - Wind measurement campaign: More than 1650 mast installed
  - Post-Construction Yield Analysis: More than 1000 MW

- Barlovento has more than 70 employees, 90% of then Renewable Energy specialists.
- Barlovento has been awarded on several international tenders as Morocco, Colombia, Peru, Egypt, Ecuador …
- Independent verification of performance guaranties, availability, power curve, power quality, … on wind and photovoltaic installations.

- **Energy to Quality S.L. – E2Q** (100% owned by Barlovento) is a **Laboratory dedicated to Electrical Consultancy and Tests for Renewable Energy:**
  - LVRT Test, Power Quality test, Grid code validations, …
  - Grid simulation,
  - Grid integration expertise.

- Active member of international organizations and Normalization bodies (IEC, Measnet, …)

Our company

BARLOVENTO: ACTIVITIES OVERVIEW

- WIND ENERGY
  - Measurement Campaigns
  - Resource and Production Reports
  - Regional Planning and Development
  - Wind Farm Design
  - Technical Advising and Assistance
  - Finance Due Diligence
  - Wind Turbine Testing
  - Post-Construction Analysis
  - Wind Farms in Exploitation: Guarantees
  - Engineering
  - Environmental Impact Assessment
- SOLAR ENERGY
  - Measurement Campaigns
  - Resource and Production Reports
  - Regional Planning and Development
  - Wind Farm Design
  - Technical Advising and Assistance
  - Finance Due Diligence
  - Inspection of operating plants
  - Testing and Monitoring
  - PV CONTROLERGY: WEB monitoring
  - Operation
- GRID INTEGRATION (E2Q)
  - Integration studies of renewable energies
  - Impact studies of wind farms in weak grids
  - Grid Integration of offshore wind farms
  - Monitoring of grid incidences
  - Electrical test
  - Power Quality
  - Voltage dip test
  - Simulation models of Grid Integration
- METEOROLOGY & ENVIRONMENT
  - Accredited Measurement Campaign
  - Wind & Solar Campaigns
  - Agrometeorology and environmental measurements
- DISTRIBUTED GENERATION
  - Energetic potential calculation
  - Feasibility studies
  - Measurements
  - Modeling of electric integration
  - Design and sizing of hybrid systems and generation micro-grids
  - Installation of hybrid systems and generation
  - Web applications

Our company

BARLOVENTO: **QUALITY ACCREDITATIONS**

Certificate of R&D&i Management AENOR[3] UNE 166002.

UNE 166002

IDI-0008/2007

Test Laboratory, accreditation ENAC following ISO 17025:

- Wind Turbines (Power curve[1,2]), member of MEASNET
- Wind Turbine noise measurements[1]
- Condition Monitoring
- Meteorological measurements[1,2]
- Photovoltaic systems monitoring[1]
- Power Quality[1,2] (E2Q)
- Electrical model validation[1] (E2Q)
- LVRT test[1] (E2Q)

Barlovento Recursos Naturales S.L

ENAC ENSAYOS 437 / LE1004

(1) Actividades Acreditadas Barlovento Recursos Naturales.

Energy to Quality S.L

ENAC ENSAYOS 613 / LE1315

(2) Actividades Acreditadas Energy to Quality.

Barlovento and E2Q are members of MEASNET

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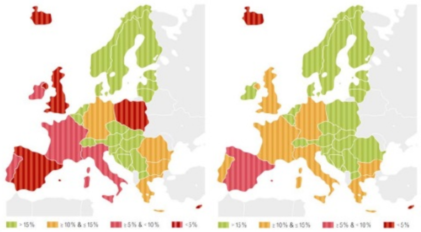
- Logistics experiences
- Conclusions

Introduction

SPANISH FIGURES

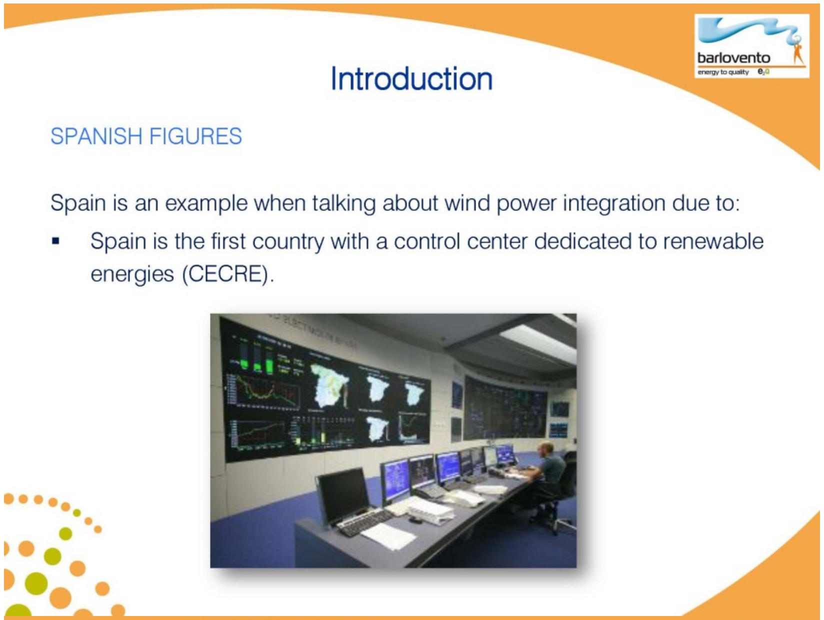
Spain is an example when talking about wind power integration due to:

- Huge experience in all technologies. First wind farm in 1986
- Wind power installed: **more than 20%** of the total power installed
- Spain is an island (in terms of electric energy production). That means that the Spanish power system is sensitive in terms of stability



Import capacity / net generation capacity

Source: ENTSOE

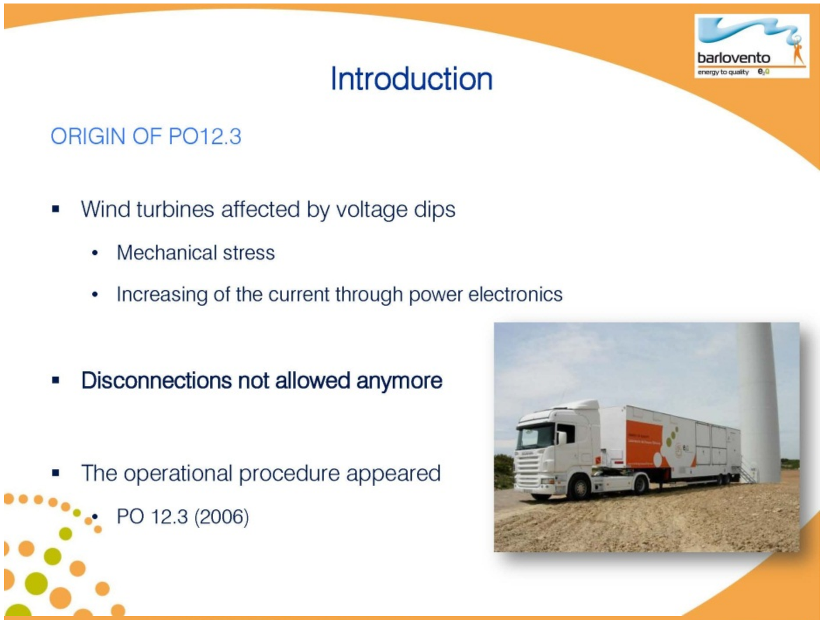


Introduction

SPANISH FIGURES

Spain is an example when talking about wind power integration due to:

- Spain is the first country with a control center dedicated to renewable energies (CECRE).



Introduction

ORIGIN OF PO12.3

- Wind turbines affected by voltage dips
  - Mechanical stress
  - Increasing of the current through power electronics
- **Disconnections not allowed anymore**
- The operational procedure appeared
  - PO 12.3 (2006)

Introduction

RECORDS IN SPAIN

Wind power hits:

- **Coverage of power demand**: **64.25%** (24/Sep/2012 - 3:03 am)
- Power production: 17056 MW (06/Feb/2013)
- Month generation 5632 GWh (april 2012)
- Instant production 16636 MW (18/04/2012)
- **2011: 22e6 tons of CO_2 saved**

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LVRT UNIT

ULYSSES DESIGN

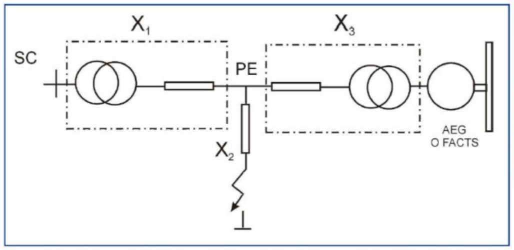
1.- INNOVATION:
- Prototype
- Mobile equipment → Not site-specific
- Restrictions on the size of components

2.- ELECTRICAL CONSIDERATIONS: VERSATILITY
- Voltage level??(12kV, 20kV, 30kV)
- Scc at the connection point??
- Rated power of the equipment under test??
- Contribution to the Icc from the WT??
- Selectivity of the protection scheme??
- Protection against Short-Circuits/allowing Short-Circuits??

3.- SAFETY OPERATION:
- Remote control
- Testing WT ride trough capabilities, not the NETWORK ride through capabilities → Important to limit Icc network
- Settings of the internal protection system: site-dependent and test-Dependent
- Measurement at MV level

LVRT UNIT

SCHEME OF THE LVRT UNIT DESIGNED BY E2Q



PVVC (2007)

LVRT UNIT

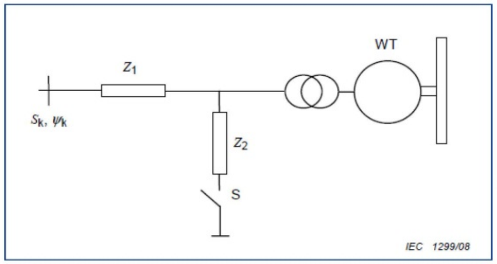
ULYSSES

The unit is able to perform short circuits of the desired residual voltage with precise duration.

Finished at the end of 2005 in Madrid, Spain

LVRT UNIT

SCHEME OF THE LVRT UNIT DESIGNED BY E2Q

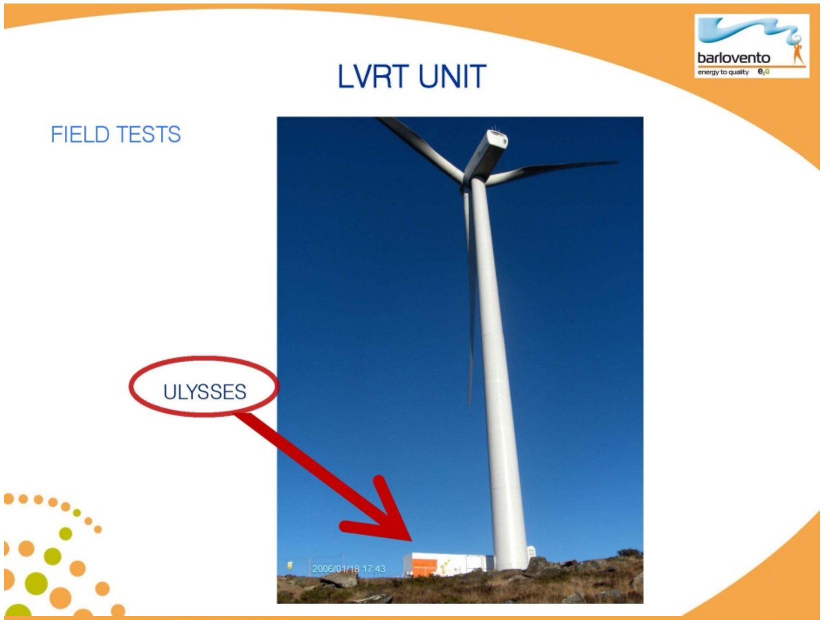


IEC 61400-21 (2008)

LVRT UNIT

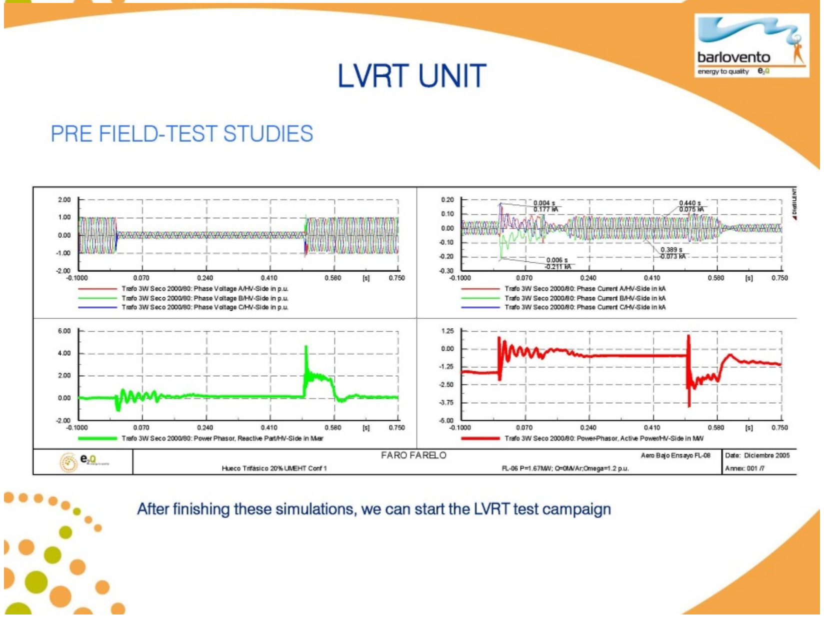
INSIDE THE TRUCK

Reactance room



LVRT UNIT

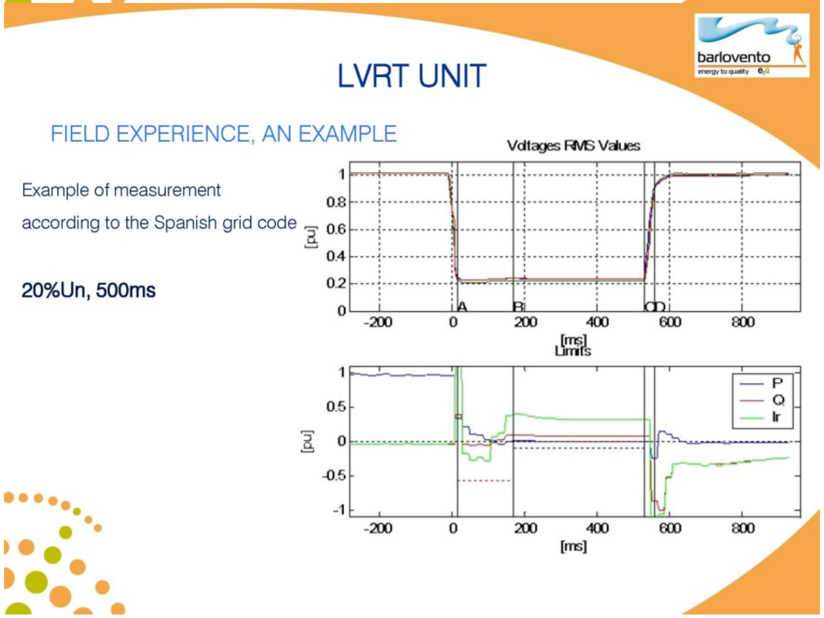
FIELD TESTS



LVRT UNIT

PRE FIELD-TEST STUDIES

After finishing these simulations, we can start the LVRT test campaign



LVRT UNIT

FIELD EXPERIENCE, AN EXAMPLE

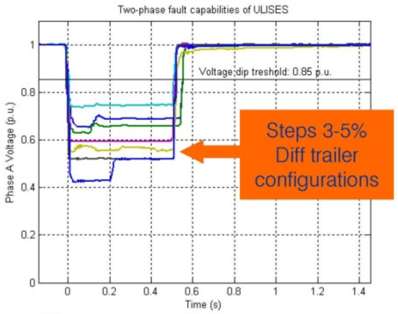
Example of measurement according to the Spanish grid code

20%Un, 500ms

LVRT UNIT

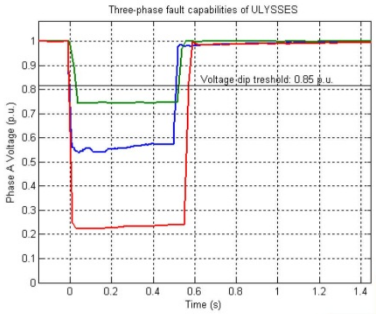
FIELD EXPERIENCE, DIFFERENT TYPES OF VOLTAGE DIP

2-Phase voltage dip
Phase A



Steps 3-5%
Diff trailer
configurations

3-Phase voltage dip
Phase A



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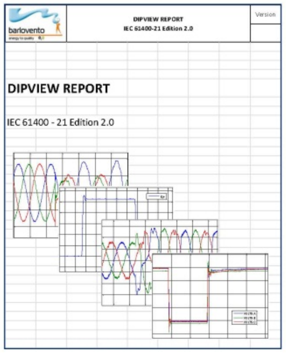
LVRT UNIT

ANALYSIS OF THE RESULTS

Energy to quality has developed his own software tool for analyzing the results of the voltage dip test campaign. It's called **Dipoffice 4.0** and it is possible to **analyze results according to any grid code** by introducing the requirements in an easy way.



DIPVIEW REPORT
IEC 61400-21 Edition 2.0

Version

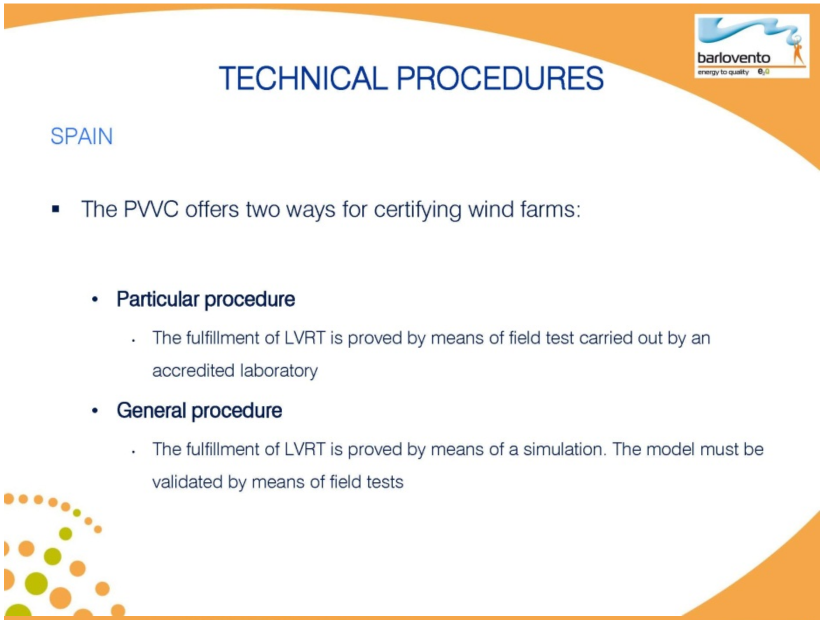
DIPVIEW REPORT

IEC 61400 - 21 Edition 2.0

TECHNICAL PROCEDURES

SPAIN

- In the P.O. 12.3, the requirements to be fulfilled are defined. However, **it is not defined the way of testing**.
- The Spanish Wind Energy Association (AEE) wrote the technical document where the way of testing according to PO 12.3 was defined. It is called "***Procedure for verification validation and Certification of the requirements of the PO 12.3 on the response of wind farms and photovoltaic plants in the event of voltage dips***" (PVVC)



TECHNICAL PROCEDURES

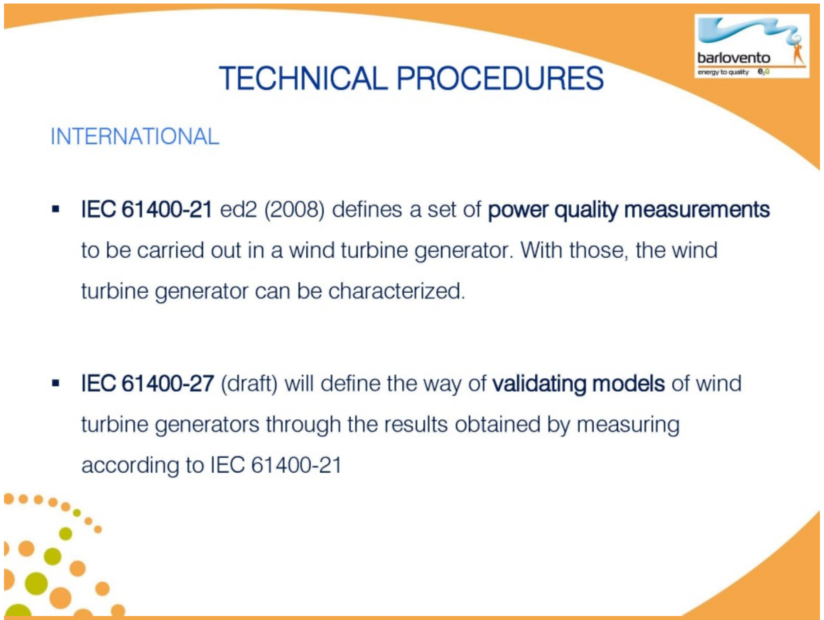
SPAIN

- The PVVC offers two ways for certifying wind farms:
  - **Particular procedure**
    - The fulfillment of LVRT is proved by means of field test carried out by an accredited laboratory
  - **General procedure**
    - The fulfillment of LVRT is proved by means of a simulation. The model must be validated by means of field tests

TECHNICAL PROCEDURES

GERMANY

- In Germany field test are required as well
- FGW is a set of technical rules for renewable energy measurements.
  - **TR3**: regarding **power quality measurement** (similar to IEC 61400-21)
  - **TR4**: regarding **validation of the model** by using field tests of TR3 (similar to IEC 61400-27)



TECHNICAL PROCEDURES

INTERNATIONAL

- **IEC 61400-21** ed2 (2008) defines a set of **power quality measurements** to be carried out in a wind turbine generator. With those, the wind turbine generator can be characterized.
- **IEC 61400-27** (draft) will define the way of **validating models** of wind turbine generators through the results obtained by measuring according to IEC 61400-21

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LOGISTICS EXPERIENCE

FIRST VISIT

LOGISTICS EXPERIENCE

PLACING THE UNIT

LOGISTICS EXPERIENCE

AND AFTER

sometimes the roads are not in the same conditions

LOGISTICS EXPERIENCE

WAREHOUSES

LOGISTICS EXPERIENCE

RECEPTION OF THE MATERIAL & FENCE AROUND

LOGISTICS EXPERIENCE

INSTALLING THE UNIT

LOGISTICS EXPERIENCE

BAD WEATHER

LOGISTICS EXPERIENCE

MULTIBRID AND ULYSSES

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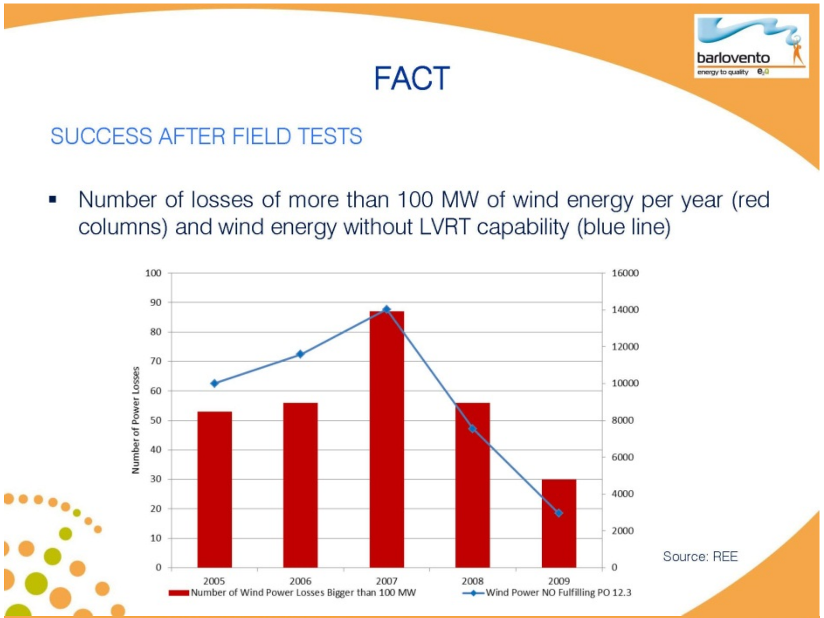


FACT

SUCCESS AFTER FIELD TESTS

- Number of losses of more than 100 MW of wind energy per year (red columns) and wind energy without LVRT capability (blue line)

Source: REE

SUMMARY

TO TAKE INTO ACCOUNT

- Field tests needed for a complete characterization of the WTG (IEC -21)
- Field tests guarantee accurate information to TSO
- Field tests avoid inappropriate results and derived problems
- Accredited entities guarantee quality results
- Field tests are a quality mark in the renewable energy market

Testing Wind Turbines Generators with ULYSSES

Thank you for your attention!
info@energytoquality.com

11.2.4 NREL Controllable Grid Interface – Vahan Gevorgian, NREL, USA

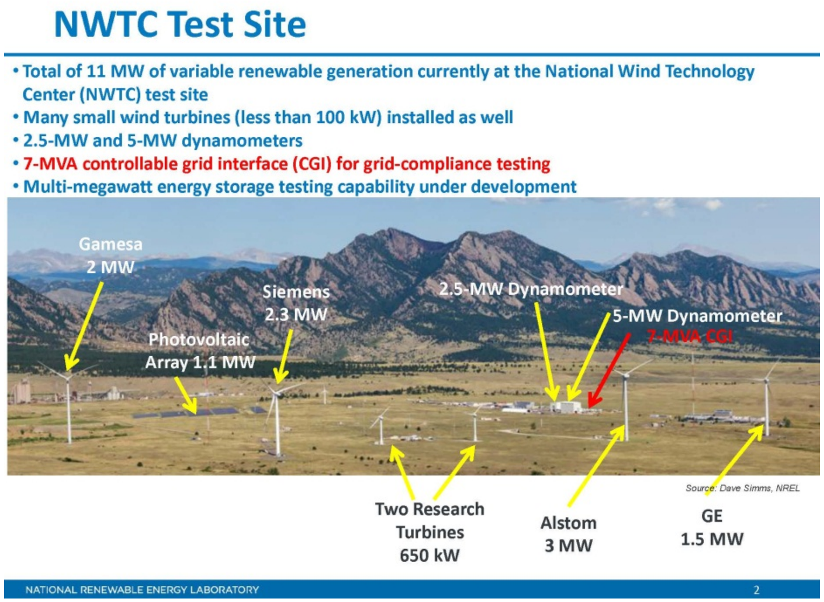
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

National Wind Technology Center Controllable Grid Interface

Vahan Gevorgian

June 13, 2013

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.



NWTC Test Site

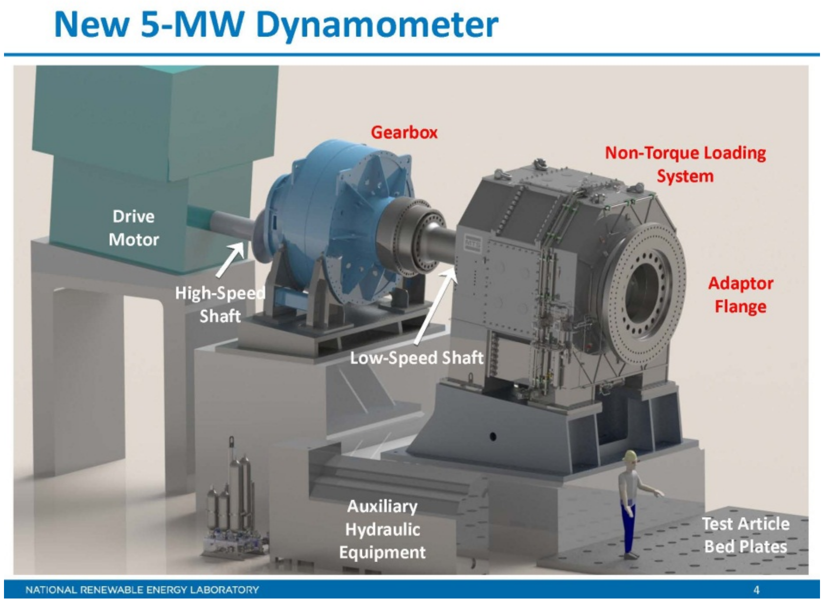
- Total of 11 MW of variable renewable generation currently at the National Wind Technology Center (NWTC) test site
- Many small wind turbines (less than 100 kW) installed as well
- 2.5-MW and 5-MW dynamometers
- 7-MVA controllable grid interface (CGI) for grid-compliance testing
- Multi-megawatt energy storage testing capability under development

Gamesa
2 MW
Siemens
2.3 MW
Photovoltaic
Array 1.1 MW
2.5-MW Dynamometer
5-MW Dynamometer
7-MVA CGI
Two Research
Turbines
650 kW
Alstom
3 MW
GE
1.5 MW

Source: Dave Simms, NREL

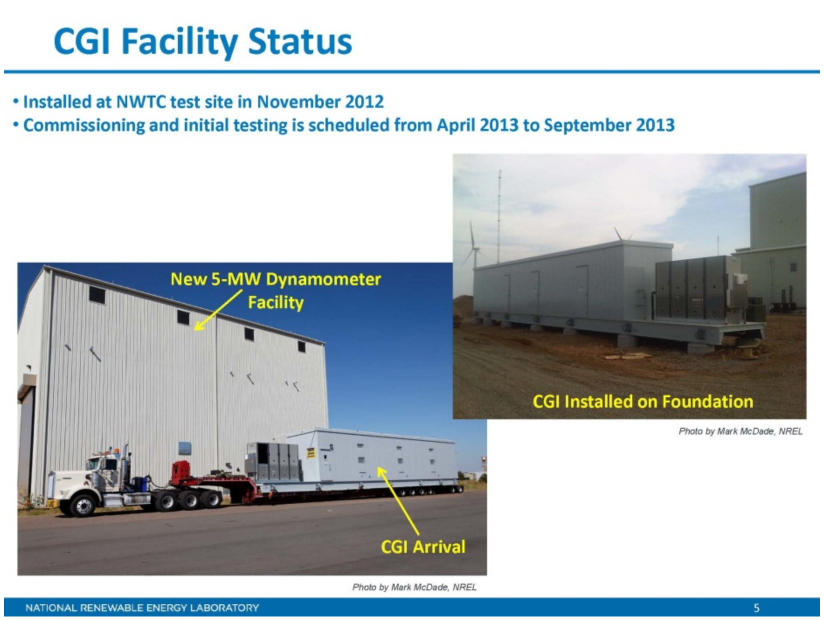
2.5-MW Dynamometer Facility

Photo by



New 5-MW Dynamometer

Gearbox
Non-Torque Loading
System
Drive
Motor
High-Speed
Shaft
Adaptor
Flange
Low-Speed Shaft
Auxiliary
Hydraulic
Equipment
Test Article
Bed Plates



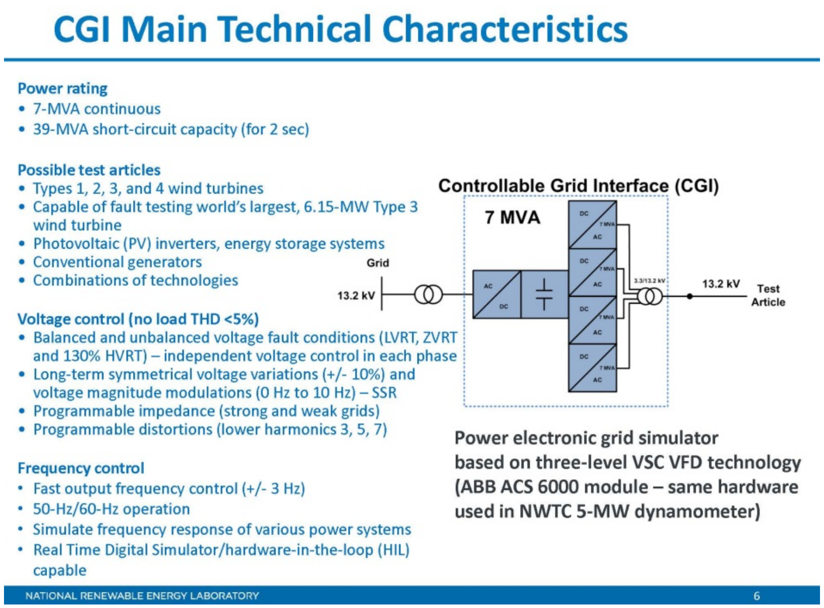
CGI Facility Status

- Installed at NWTC test site in November 2012
- Commissioning and initial testing is scheduled from April 2013 to September 2013

Photo by Mark McDade, NREL

Photo by Mark McDade, NREL

NATIONAL RENEWABLE ENERGY LABORATORY 5



CGI Main Technical Characteristics

Power rating
- 7-MVA continuous
- 39-MVA short-circuit capacity (for 2 sec)

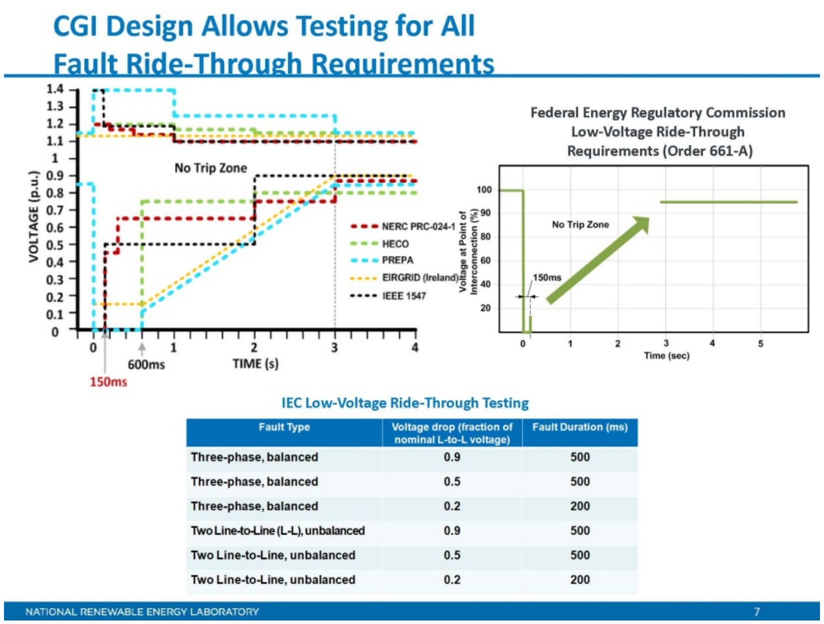
Possible test articles
- Types 1, 2, 3, and 4 wind turbines
- Capable of fault testing world's largest, 6.15-MW Type 3 wind turbine
- Photovoltaic (PV) inverters, energy storage systems
- Conventional generators
- Combinations of technologies

Voltage control (no load THD <5%)
- Balanced and unbalanced voltage fault conditions (LVRT, ZVRT and 130% HVRT) – independent voltage control in each phase
- Long-term symmetrical voltage variations (+/- 10%) and voltage magnitude modulations (0 Hz to 10 Hz) – SSR
- Programmable impedance (strong and weak grids)
- Programmable distortions (lower harmonics 3, 5, 7)

Frequency control
- Fast output frequency control (+/- 3 Hz)
- 50-Hz/60-Hz operation
- Simulate frequency response of various power systems
- Real Time Digital Simulator/hardware-in-the-loop (HIL) capable

Power electronic grid simulator based on three-level VSC VFD technology (ABB ACS 6000 module – same hardware used in NWTC 5-MW dynamometer)

NATIONAL RENEWABLE ENERGY LABORATORY 6



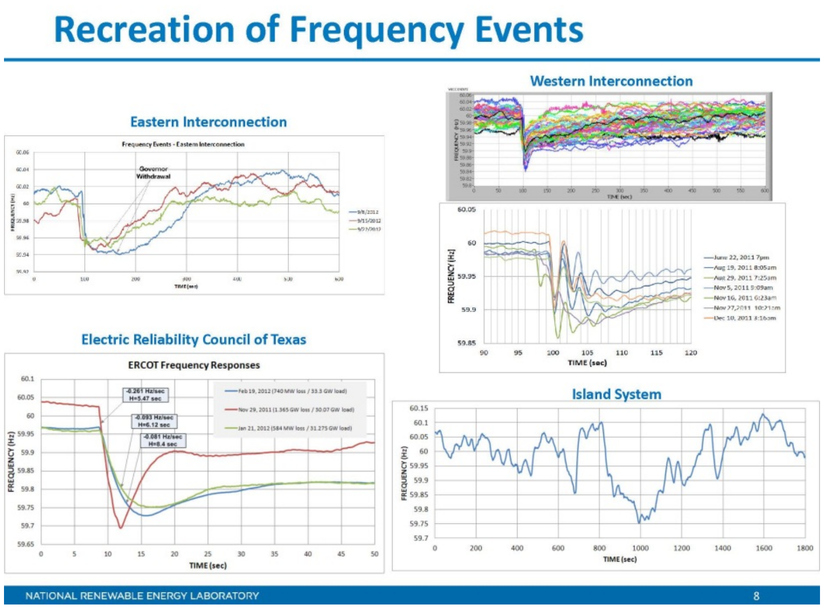
CGI Design Allows Testing for All Fault Ride-Through Requirements

Federal Energy Regulatory Commission
Low-Voltage Ride-Through
Requirements (Order 661-A)

IEC Low-Voltage Ride-Through Testing

Fault Type	Voltage drop (fraction of nominal L-to-L voltage)	Fault Duration (ms)
Three-phase, balanced	0.9	500
Three-phase, balanced	0.5	500
Three-phase, balanced	0.2	200
Two Line-to-Line (L-L), unbalanced	0.9	500
Two Line-to-Line, unbalanced	0.5	500
Two Line-to-Line, unbalanced	0.2	200

NATIONAL RENEWABLE ENERGY LABORATORY 7



Recreation of Frequency Events

Eastern Interconnection

Western Interconnection

Electric Reliability Council of Texas

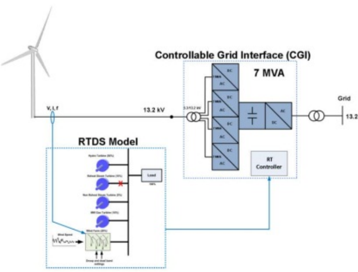
Island System

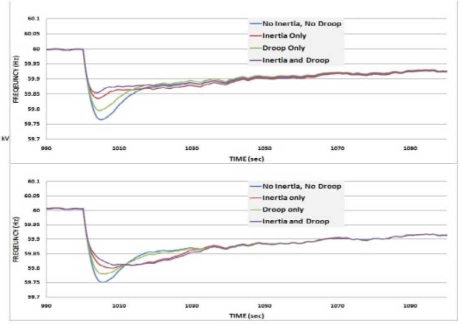
NATIONAL RENEWABLE ENERGY LABORATORY 8

Testing Wind Power to Provide Frequency Response

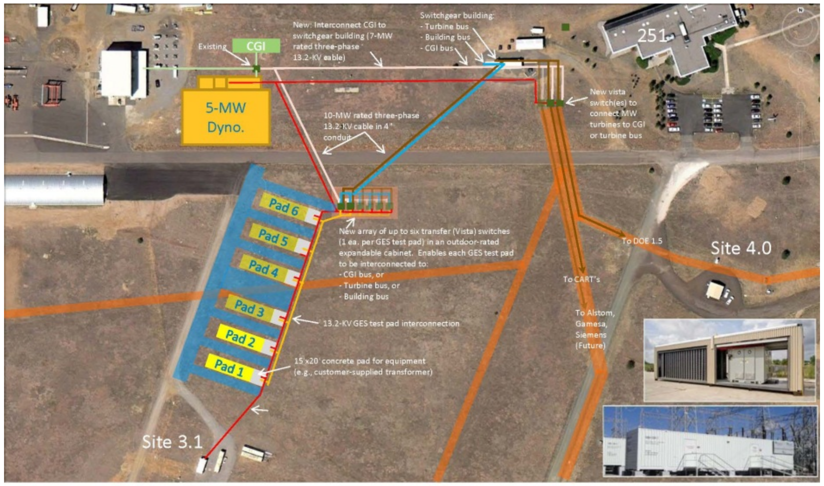
CGI is a useful tool for testing wind, PV, and storage to provide inertial and primary frequency response.

Example of Island Grid HIL Testing





Proposed Electrical and Facility Infrastructure for Grid Energy Storage (GES) Test Pads and Row 4 Turbine Interconnection to CGI



Source: Dave Simms, NREL, 6/6/13

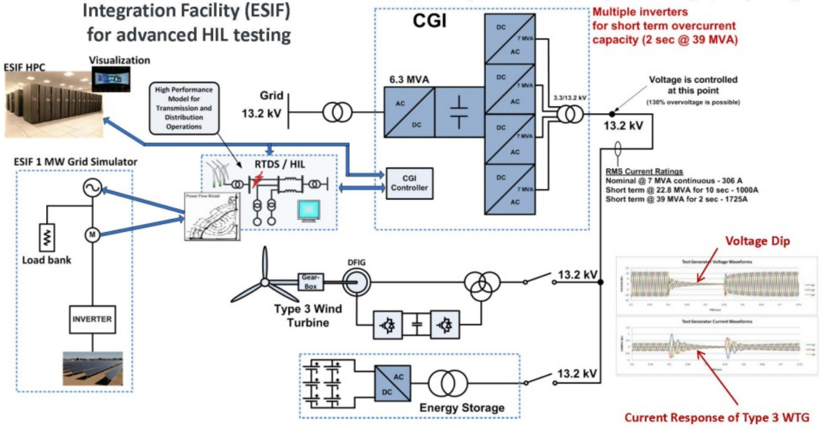
Proposed Electrical and Facility Infrastructure for Grid Energy Storage (GES) Test Pads and Row 4 Turbine Interconnection to CGI

Notes:
- Graphical infrastructure depiction only, not to scale – locations shown are approximate; final siting should be based on cost/ practical considerations
- GES test pads sized to house customer-supplied GES test articles (pictured) plus customer-supplied transformer and other equipment
- Translucent items depicted are optional depending on budget; plan and install as much as possible/practical anticipating future expansion
- The 5-MW Dyno. Control Room or the Site 3.1 Data Shed (partial N area) could serve as a client facility for GES test control/DAS/customer use

CGI for Wind Turbine, Energy Storage, and PV Inverter Testing

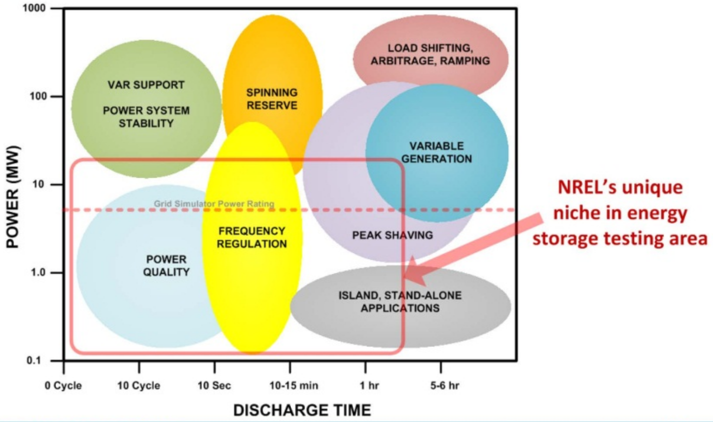
Link with Energy Systems Integration Facility (ESIF) for advanced HIL testing

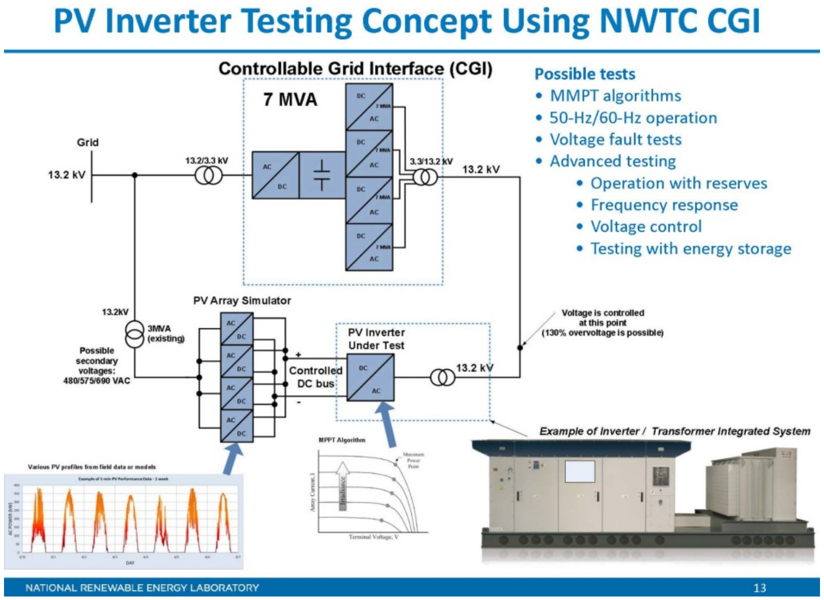
Large overcurrent capacity is needed for some wind turbine topologies and conventional generation low-voltage ride-through (LVRT) testing



NWTC's Unique Role in Energy Storage Testing

- CGI-connected tests for storage inverter LVRT testing, frequency response testing
- Utility connected tests in parallel with real megawatt-scale wind and PV resource variability
- Ideal conditions to test energy storage for frequency regulation and ramp limiting applications





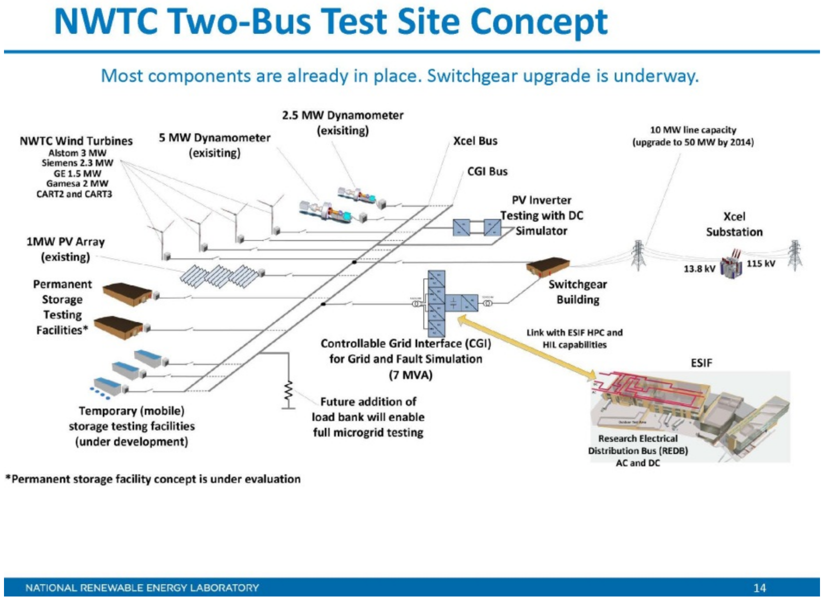
PV Inverter Testing Concept Using NWTC CGI

Possible tests

- MMPT algorithms
- 50-Hz/60-Hz operation
- Voltage fault tests
- Advanced testing
  - Operation with reserves
  - Frequency response
  - Voltage control
  - Testing with energy storage

Example of Inverter / Transformer Integrated System

NATIONAL RENEWABLE ENERGY LABORATORY 13

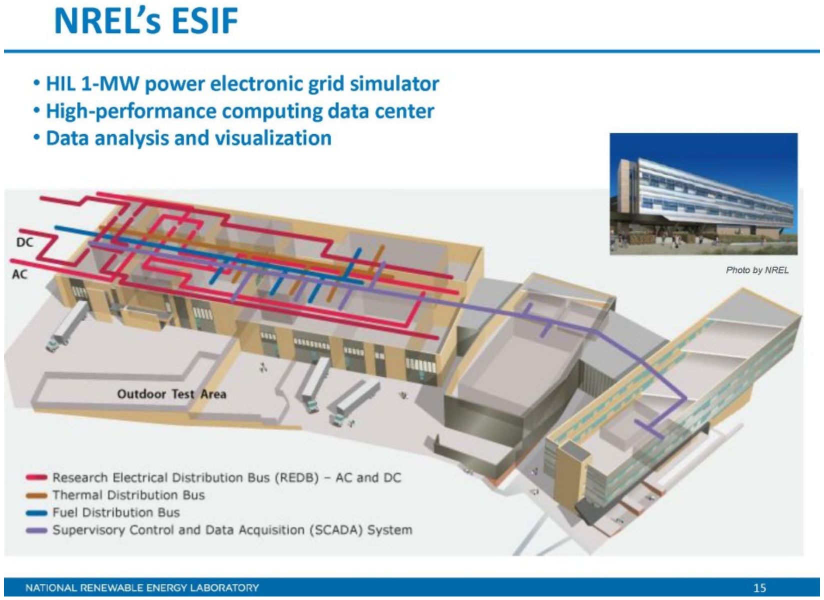


NWTC Two-Bus Test Site Concept

Most components are already in place. Switchgear upgrade is underway.

*Permanent storage facility concept is under evaluation

NATIONAL RENEWABLE ENERGY LABORATORY 14



NREL's ESIF

- HIL 1-MW power electronic grid simulator
- High-performance computing data center
- Data analysis and visualization

Photo by NREL

- Research Electrical Distribution Bus (REDB) – AC and DC
- Thermal Distribution Bus
- Fuel Distribution Bus
- Supervisory Control and Data Acquisition (SCADA) System

NATIONAL RENEWABLE ENERGY LABORATORY 15

11.3 New/Upcoming Test Facilities

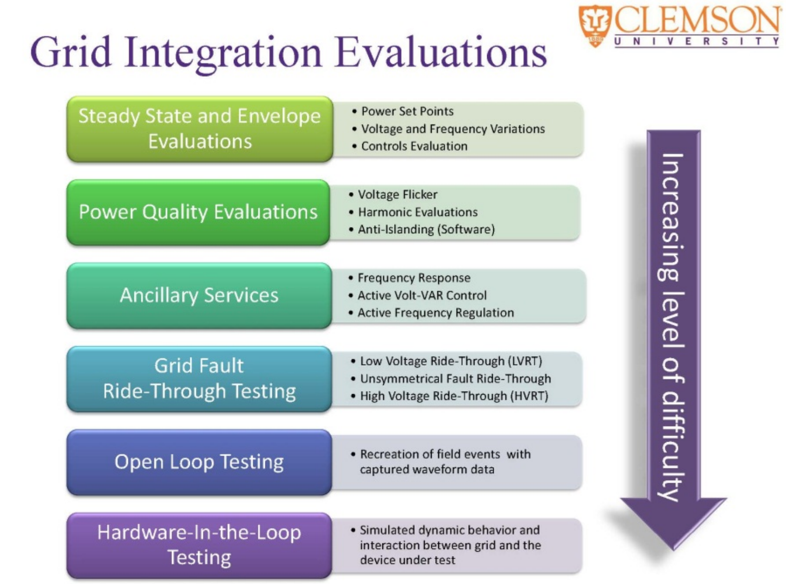
11.3.1 Clemson University Dynamometer and Grid Simulator Facilities – Andrei Mander and J. Curtiss Fox, Clemson University, USA

The Clemson University Grid Simulator

1st International Workshop on Grid Simulator Testing of Wind Turbine Drivetrains – NWTC, Bolder, CO

June 13, 2013

J. Curtiss Fox – Clemson University



Grid Integration Evaluations

CLEMSON UNIVERSITY

- **Steady State and Envelope Evaluations**
  - Power Set Points
  - Voltage and Frequency Variations
  - Controls Evaluation
- **Power Quality Evaluations**
  - Voltage Flicker
  - Harmonic Evaluations
  - Anti-Islanding (Software)
- **Ancillary Services**
  - Frequency Response
  - Active Volt-VAR Control
  - Active Frequency Regulation
- **Grid Fault Ride-Through Testing**
  - Low Voltage Ride-Through (LVRT)
  - Unsymmetrical Fault Ride-Through
  - High Voltage Ride-Through (HVRT)
- **Open Loop Testing**
  - Recreation of field events with captured waveform data
- **Hardware-In-the-Loop Testing**
  - Simulated dynamic behavior and interaction between grid and the device under test

Increasing level of difficulty

Grid Simulator Founding Partners

CLEMSON UNIVERSITY

DUKE ENERGY

SRNL

SCANA POWER FOR LIVING

Underwriters Laboratories

Santee Cooper

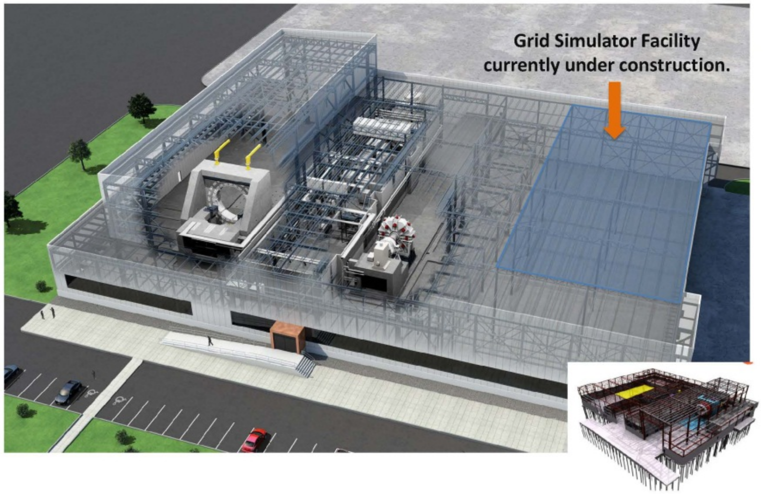
U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

TECO Westinghouse

Markets and Applications

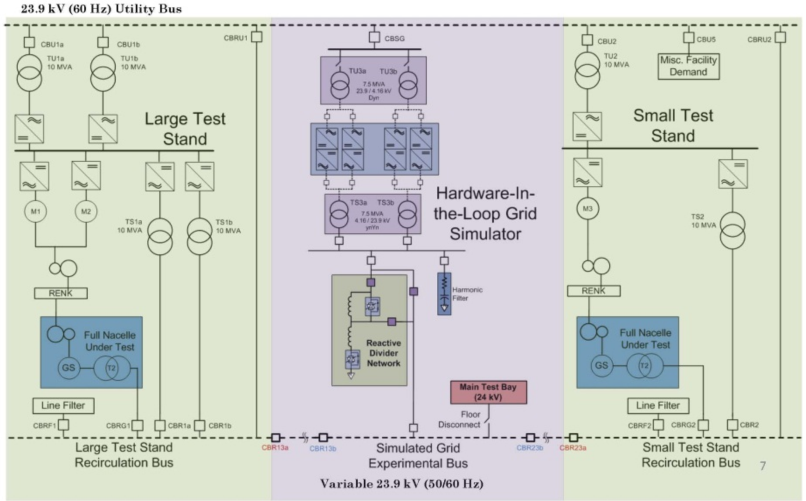
CLEMSON UNIVERSITY

Facility Layout

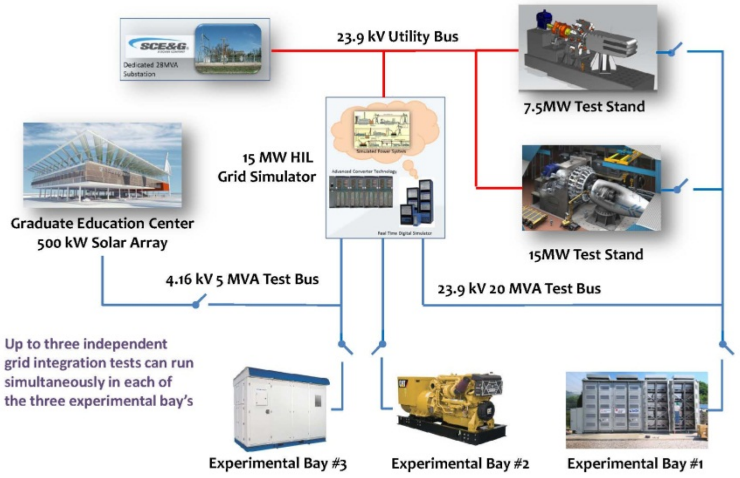


Grid Simulator Facility currently under construction.

Facility Single Line Diagram



Grid Integration Test Facility



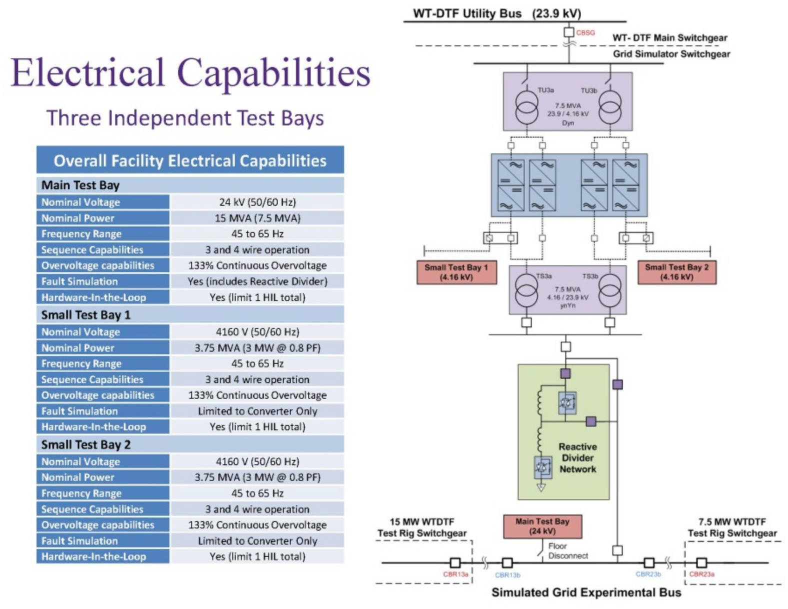
Up to three independent grid integration tests can run simultaneously in each of the three experimental bay's

Grid Integration Evaluations

Steady State and Envelope Evaluations	• Power Set Points • Voltage and Frequency Variations • Controls Evaluation
Power Quality Evaluations	• Voltage Flicker • Harmonic Evaluations • Anti-Islanding (Software)
Ancillary Services	• Frequency Response • Active Volt-VAR Control • Active Frequency Regulation
Grid Fault Ride-Through Testing	• Low Voltage Ride-Through (LVRT) • Unsymmetrical Fault Ride-Through • High Voltage Ride-Through (HVRT)
Open Loop Testing	• Recreation of field events with captured waveform data
Hardware-In-the-Loop Testing	• Simulated dynamic behavior and interaction between grid and the device under test

Increasing level of difficulty

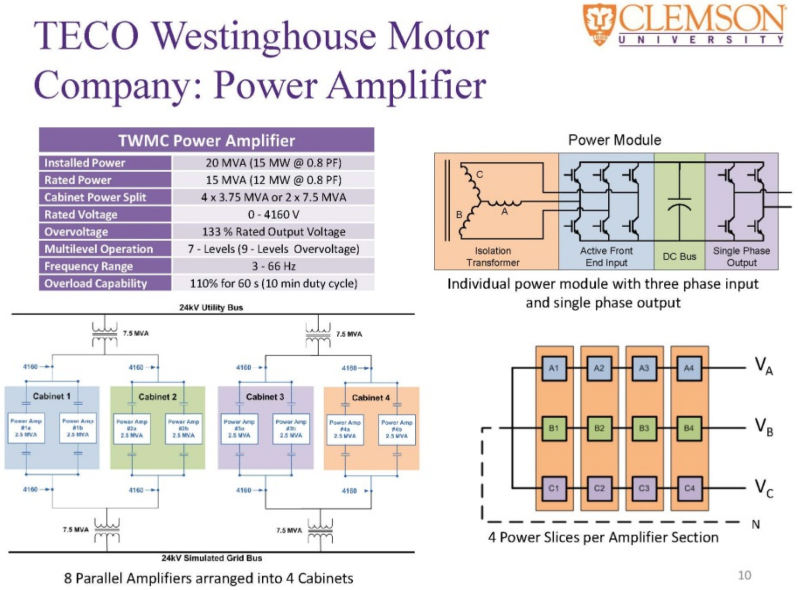
This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.



Electrical Capabilities

Three Independent Test Bays

Overall Facility Electrical Capabilities	
Main Test Bay	
Nominal Voltage	24 kV (50/60 Hz)
Nominal Power	15 MVA (7.5 MVA)
Frequency Range	45 to 65 Hz
Sequence Capabilities	3 and 4 wire operation
Overvoltage capabilities	133% Continuous Overvoltage
Fault Simulation	Yes (includes Reactive Divider)
Hardware-In-the-Loop	Yes (limit 1 HIL total)
Small Test Bay 1	
Nominal Voltage	4160 V (50/60 Hz)
Nominal Power	3.75 MVA (3 MW @ 0.8 PF)
Frequency Range	45 to 65 Hz
Sequence Capabilities	3 and 4 wire operation
Overvoltage capabilities	133% Continuous Overvoltage
Fault Simulation	Limited to Converter Only
Hardware-In-the-Loop	Yes (limit 1 HIL total)
Small Test Bay 2	
Nominal Voltage	4160 V (50/60 Hz)
Nominal Power	3.75 MVA (3 MW @ 0.8 PF)
Frequency Range	45 to 65 Hz
Sequence Capabilities	3 and 4 wire operation
Overvoltage capabilities	133% Continuous Overvoltage
Fault Simulation	Limited to Converter Only
Hardware-In-the-Loop	Yes (limit 1 HIL total)



TECO Westinghouse Motor Company: Power Amplifier

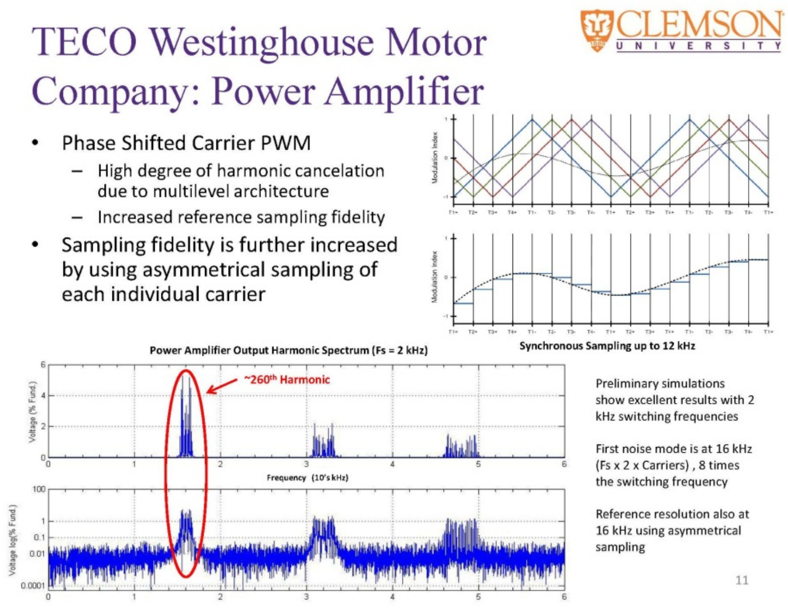
TWMC Power Amplifier	
Installed Power	20 MVA (15 MW @ 0.8 PF)
Rated Power	15 MVA (12 MW @ 0.8 PF)
Cabinet Power Split	4 x 3.75 MVA or 2 x 7.5 MVA
Rated Voltage	0 - 4160 V
Overvoltage	133 % Rated Output Voltage
Multilevel Operation	7 - Levels (9 - Levels Overvoltage)
Frequency Range	3 - 66 Hz
Overload Capability	110% for 60 s (10 min duty cycle)

8 Parallel Amplifiers arranged into 4 Cabinets

Power Module

Individual power module with three phase input and single phase output

4 Power Slices per Amplifier Section



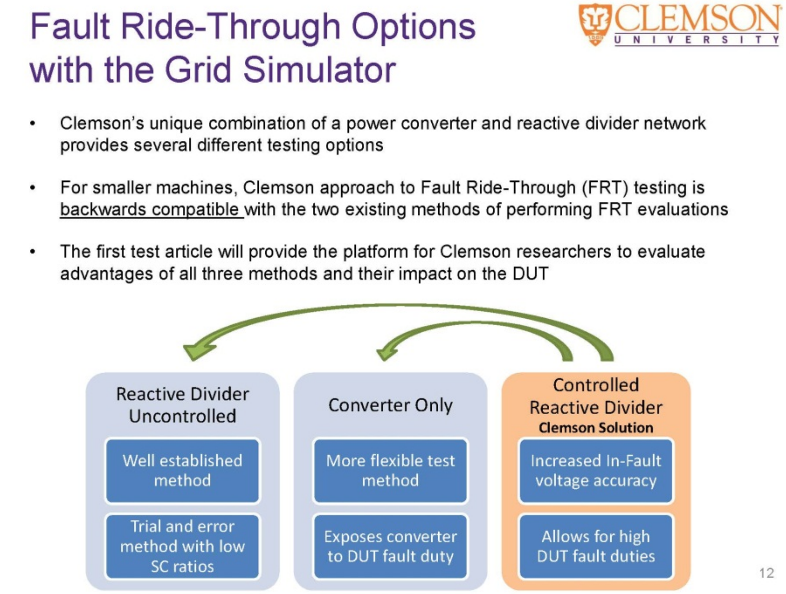
TECO Westinghouse Motor Company: Power Amplifier

- Phase Shifted Carrier PWM
  - High degree of harmonic cancelation due to multilevel architecture
  - Increased reference sampling fidelity
- Sampling fidelity is further increased by using asymmetrical sampling of each individual carrier

Preliminary simulations show excellent results with 2 kHz switching frequencies

First noise mode is at 16 kHz (Fs x 2 x Carriers) , 8 times the switching frequency

Reference resolution also at 16 kHz using asymmetrical sampling

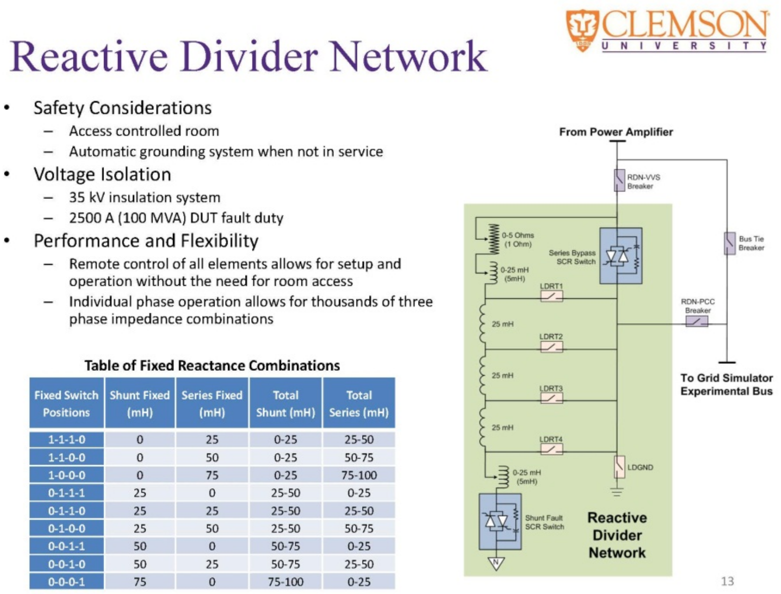


Fault Ride-Through Options with the Grid Simulator

- Clemson's unique combination of a power converter and reactive divider network provides several different testing options
- For smaller machines, Clemson approach to Fault Ride-Through (FRT) testing is backwards compatible with the two existing methods of performing FRT evaluations
- The first test article will provide the platform for Clemson researchers to evaluate advantages of all three methods and their impact on the DUT

Reactive Divider Uncontrolled	Converter Only	Controlled Reactive Divider **Clemson Solution**
Well established method	More flexible test method	Increased In-Fault voltage accuracy
Trial and error method with low SC ratios	Exposes converter to DUT fault duty	Allows for high DUT fault duties

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

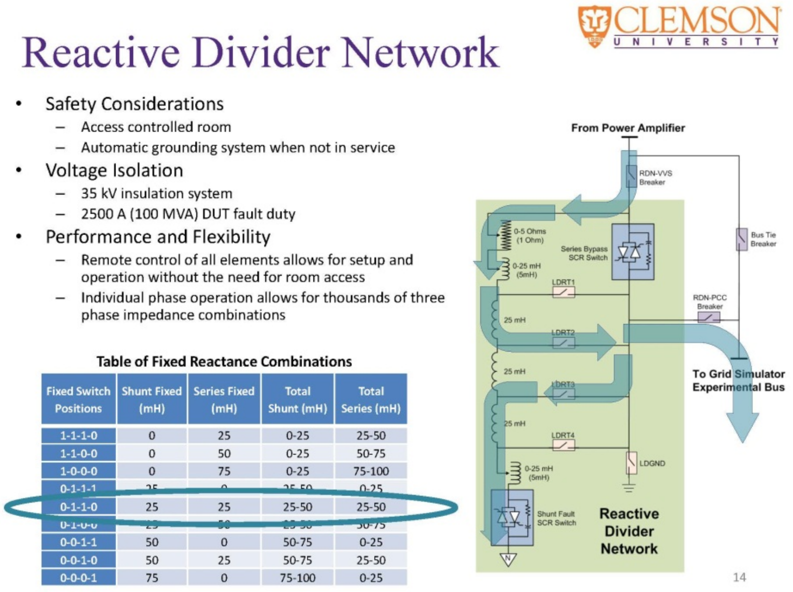


Reactive Divider Network

- Safety Considerations
  - Access controlled room
  - Automatic grounding system when not in service
- Voltage Isolation
  - 35 kV insulation system
  - 2500 A (100 MVA) DUT fault duty
- Performance and Flexibility
  - Remote control of all elements allows for setup and operation without the need for room access
  - Individual phase operation allows for thousands of three phase impedance combinations

Table of Fixed Reactance Combinations

Fixed Switch Positions	Shunt Fixed (mH)	Series Fixed (mH)	Total Shunt (mH)	Total Series (mH)
1-1-1-0	0	25	0-25	25-50
1-1-0-0	0	50	0-25	50-75
1-0-0-0	0	75	0-25	75-100
0-1-1-1	25	0	25-50	0-25
0-1-1-0	25	25	25-50	25-50
0-1-0-0	25	50	25-50	50-75
0-0-1-1	50	0	50-75	0-25
0-0-1-0	50	25	50-75	25-50
0-0-0-1	75	0	75-100	0-25



Reactive Divider Network

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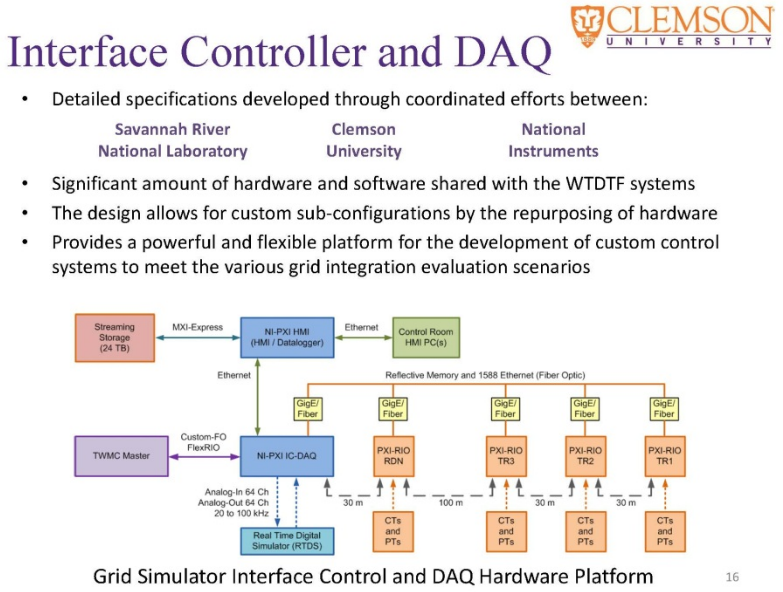
1-1-0-0	0	50	0-25	50-75
1-0-0-0	0	75	0-25	75-100
0-1-1-1	25	0	25-50	0-25
0-1-1-0	25	25	25-50	25-50
0-1-0-0	25	50	25-50	50-75
0-0-1-1	50	0	50-75	0-25
0-0-1-0	50	25	50-75	25-50
0-0-0-1	75	0	75-100	0-25

Reactive Divider Network



Interface Controller and DAQ

- Detailed specifications developed through coordinated efforts between:

Savannah River National Laboratory **Clemson University** **National Instruments**

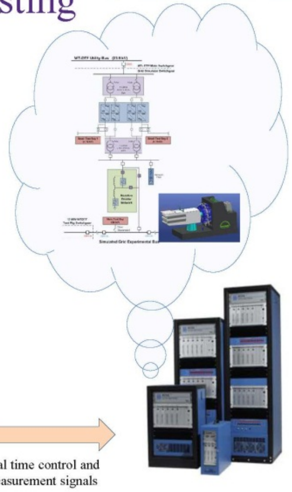
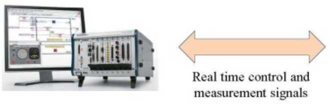
- Significant amount of hardware and software shared with the WTDTF systems
- The design allows for custom sub-configurations by the repurposing of hardware
- Provides a powerful and flexible platform for the development of custom control systems to meet the various grid integration evaluation scenarios

Grid Simulator Interface Control and DAQ Hardware Platform

Interface Controller HIL Testing

CLEMSON UNIVERSITY

- The RTDS simulates the physical Grid Simulator hardware and DUT hardware and control systems in real time
- A scaled version of the NI Interface Controller is used for real time control of the simulated hardware and DUT to aid in:
  - Control algorithm verification and tuning
  - Startup and operational procedures
  - Emergency stop conditions and shutdown methods
  - Human Machine Interface (HMI) design
  - Identifying commissioning activities and protocols
  - Segmenting and testing of communication interfaces and protocols

Real time control and measurement signals

National Instruments Interface Controller

Real Time Power System Simulator RTDS®

Interface Controller HIL Testing

CLEMSON UNIVERSITY

- The RTDS simulates the physical Grid Simulator hardware and DUT hardware and control systems in real time
- A scaled version of the NI Interface Controller is used for real time control of the simulated hardware and DUT to aid in:
  - Control algorithm verification and tuning
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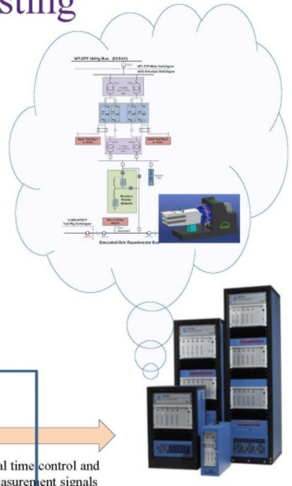
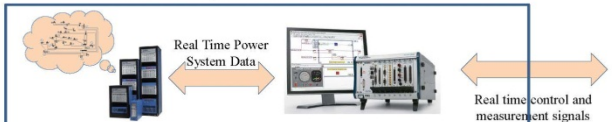
  - Emergency stop conditions and shutdown methods
  - Human Machine Interface (HMI) design
  - Identifying commissioning activities and protocols
  - Segmenting and testing of communication interfaces and protocols

Real Time Power System Data

Real time control and measurement signals

SRNL RTDS®
Simulating a Power System

National Instruments Interface Controller

Real Time Power System Simulator RTDS®

11.3.2 National Renewable Energy Centre Drivetrain Test Grid Emulator – Alex Neumann, National Renewable Energy Centre, United Kingdom

narec

National Renewable Energy Centre (Narec)

An Introduction to the Narec Grid Emulator

Alex Neumann, Director of Specialist Services

13th June 2013

narec

Advancing Offshore Renewable Energy

A Controlled and Independent Development Platform

Existing

- 50m blade test
- Still water tank
- Wave flume
- Simulated seabed
- Wind turbine training tower
- Electrical and materials laboratories

New

- **3MW tidal turbine drive train**
- Offshore anemometry hub
- 100m blade test
- **15MW wind turbine drive train**
- 99MW offshore wind demo site
- **Narec Grid Emulator and LVRT**

The National Renewable Energy Centre (Narec)

Overview

Open- access, independent, quality assured translational research, development and testing facilities for offshore wind, wave, tidal and electrical network technologies.

Clients and Collaborators

Manufacturers, project developers, utilities, universities, research organisations and supply chain companies.

Services

- Applied research and technology development services
- Specialist consultancy
- Certification and development testing
- Demonstration
- Systems integration
- Performance verification

R&D → TESTING → DEMONSTRATION → DEPLOYMENT

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15MW Nacelle Test Rig - Fujin

15MW Turbine Nacelle Testing Facility

Accelerated lifetime and design validation - grid compliance coming …

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15MW Fujin Facility Build Status

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15MW Fujin Build Status

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15MW Fujin Build Status

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15MW Turbine Drive Train Testing Facility

Objective

To perform independent testing of wind turbines to de-risk infield activities by allowing Narec to perform reliability and performance appraisal of new devices and system components through accelerated lifetime testing.

Key Characteristics

- 15MW capacity for testing entire systems
- Representative variable torque (max 14.3MNm) and speeds (max 30rpm)
- 6 degrees of freedom for applying load forces
- Bending moment (max 56MNm)
- Force Application System (FAS) frequency response 2.5Hz

Typical Testing Activities

- Entire nacelle prototype test capability (system or major component within system)
- New supplier validation testing (major component)
- Internal manufacturing conformance testing (system or major component within system)
- Endurance testing
- Improvements to models physical and numerical – condition monitoring validation
- Research and development

Timescale

- Construction of facility almost complete
- Commissioning July/August 2013
- First test to start August/September

energy technologies institute

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3MW Tidal Turbine Nacelle Test Facility - Nautilus

3MW Turbine Nacelle Testing Facility

Accelerated lifetime and design validation - grid compliance coming …

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Blyth 99MW Offshore Wind Demonstration Site

Deployment, demonstration and validation

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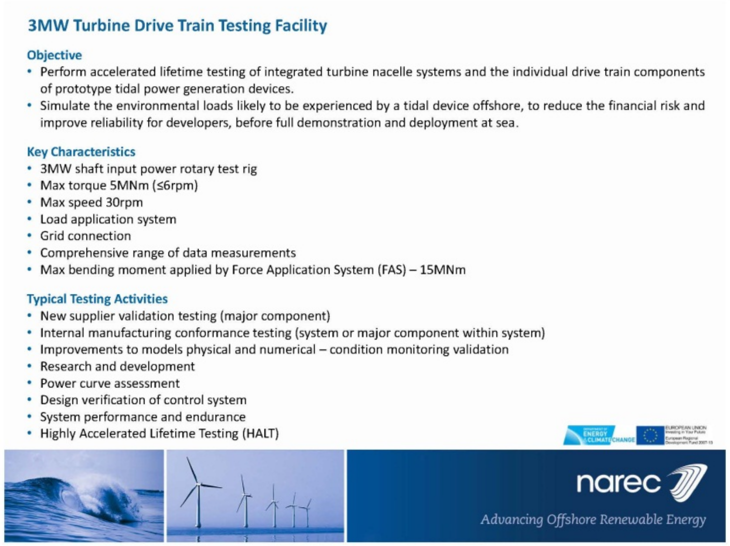

3MW Turbine Drive Train Testing Facility

Objective

- Perform accelerated lifetime testing of integrated turbine nacelle systems and the individual drive train components of prototype tidal power generation devices.
- Simulate the environmental loads likely to be experienced by a tidal device offshore, to reduce the financial risk and improve reliability for developers, before full demonstration and deployment at sea.

Key Characteristics

- 3MW shaft input power rotary test rig
- Max torque 5MNm (≤6rpm)
- Max speed 30rpm
- Load application system
- Grid connection
- Comprehensive range of data measurements
- Max bending moment applied by Force Application System (FAS) – 15MNm

Typical Testing Activities

- New supplier validation testing (major component)
- Internal manufacturing conformance testing (system or major component within system)
- Improvements to models physical and numerical – condition monitoring validation
- Research and development
- Power curve assessment
- Design verification of control system
- System performance and endurance
- Highly Accelerated Lifetime Testing (HALT)

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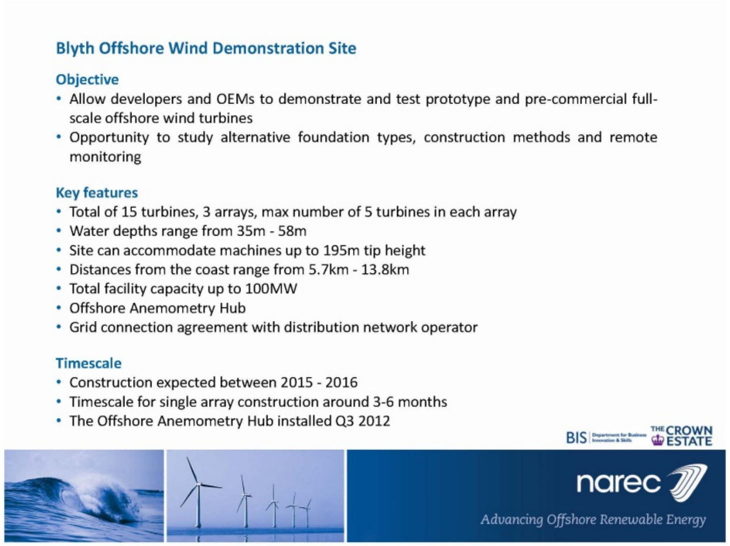

Blyth Offshore Wind Demonstration Site

Objective

- Allow developers and OEMs to demonstrate and test prototype and pre-commercial full-scale offshore wind turbines
- Opportunity to study alternative foundation types, construction methods and remote monitoring

Key features

- Total of 15 turbines, 3 arrays, max number of 5 turbines in each array
- Water depths range from 35m - 58m
- Site can accommodate machines up to 195m tip height
- Distances from the coast range from 5.7km - 13.8km
- Total facility capacity up to 100MW
- Offshore Anemometry Hub
- Grid connection agreement with distribution network operator

Timescale

- Construction expected between 2015 - 2016
- Timescale for single array construction around 3-6 months
- The Offshore Anemometry Hub installed Q3 2012

BIS THE CROWN ESTATE

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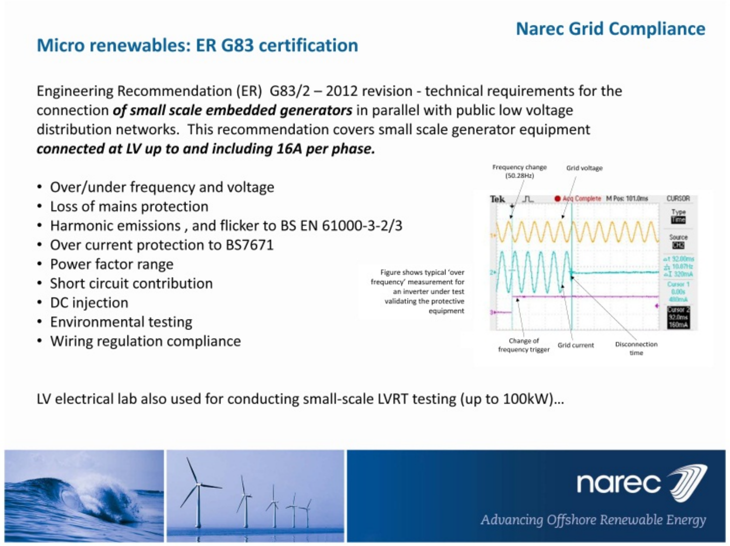
Wind Turbine Blade Testing Centre
Development and certification
Can test blades up to 100m, three test stands, static and fatigue capability



Narec Grid Compliance

Micro renewables: ER G83 certification

Engineering Recommendation (ER) G83/2 – 2012 revision - technical requirements for the connection ***of small scale embedded generators*** in parallel with public low voltage distribution networks. This recommendation covers small scale generator equipment ***connected at LV up to and including 16A per phase.***

- Over/under frequency and voltage
- Loss of mains protection
- Harmonic emissions , and flicker to BS EN 61000-3-2/3
- Over current protection to BS7671
- Power factor range
- Short circuit contribution
- DC injection
- Environmental testing
- Wiring regulation compliance

Figure shows typical 'over frequency' measurement for an inverter under test validating the protective equipment

LV electrical lab also used for conducting small-scale LVRT testing (up to 100kW)…

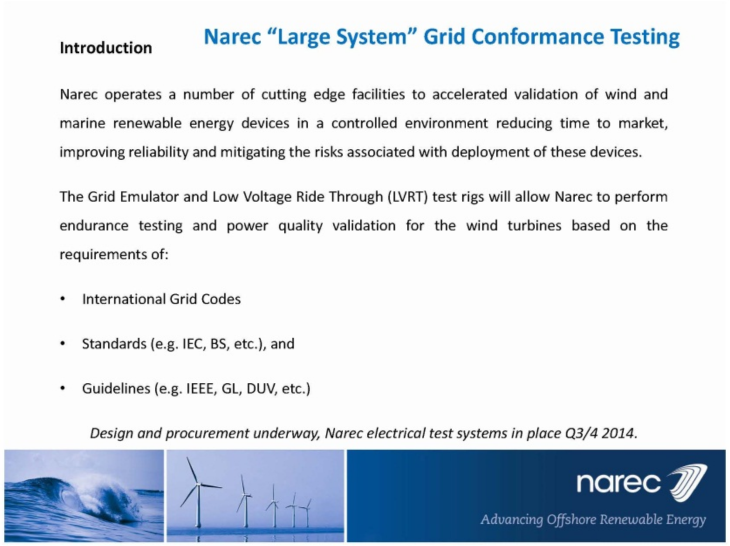
HV Electrical and Materials Laboratories

Certification, development, accelerated lifetime, endurance.

Independent and accredited

HV: Cables, insulating materials, generator windings, switchgear, transformers. etc…

LV: grid conformance, network simulation



Narec "Large System" Grid Conformance Testing

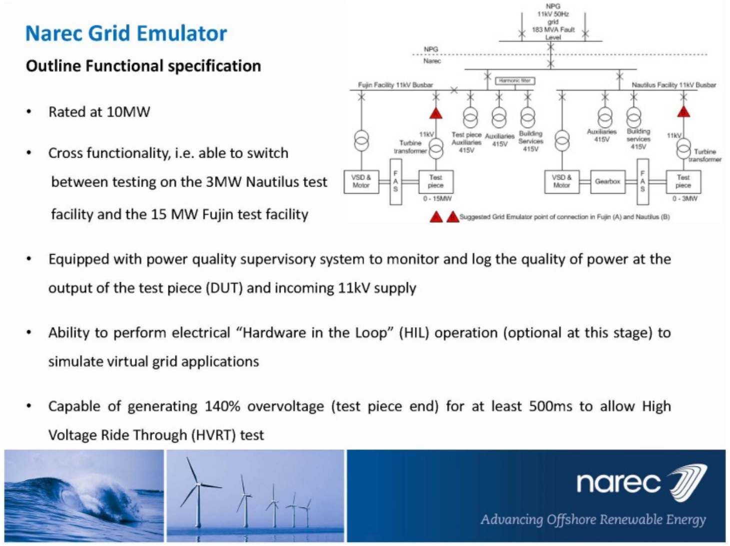
Introduction

Narec operates a number of cutting edge facilities to accelerated validation of wind and marine renewable energy devices in a controlled environment reducing time to market, improving reliability and mitigating the risks associated with deployment of these devices.

The Grid Emulator and Low Voltage Ride Through (LVRT) test rigs will allow Narec to perform endurance testing and power quality validation for the wind turbines based on the requirements of:

- International Grid Codes
- Standards (e.g. IEC, BS, etc.), and
- Guidelines (e.g. IEEE, GL, DUV, etc.)

Design and procurement underway, Narec electrical test systems in place Q3/4 2014.



Narec Grid Emulator

Outline Functional specification

- Rated at 10MW
- Cross functionality, i.e. able to switch between testing on the 3MW Nautilus test facility and the 15 MW Fujin test facility
- Equipped with power quality supervisory system to monitor and log the quality of power at the output of the test piece (DUT) and incoming 11kV supply
- Ability to perform electrical "Hardware in the Loop" (HIL) operation (optional at this stage) to simulate virtual grid applications
- Capable of generating 140% overvoltage (test piece end) for at least 500ms to allow High Voltage Ride Through (HVRT) test

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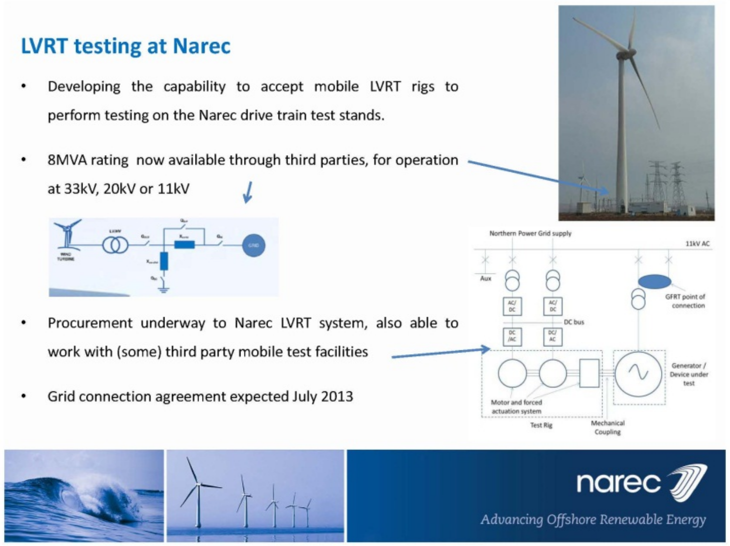

LVRT testing at Narec

- Developing the capability to accept mobile LVRT rigs to perform testing on the Narec drive train test stands.
- 8MVA rating now available through third parties, for operation at 33kV, 20kV or 11kV
- Procurement underway to Narec LVRT system, also able to work with (some) third party mobile test facilities
- Grid connection agreement expected July 2013

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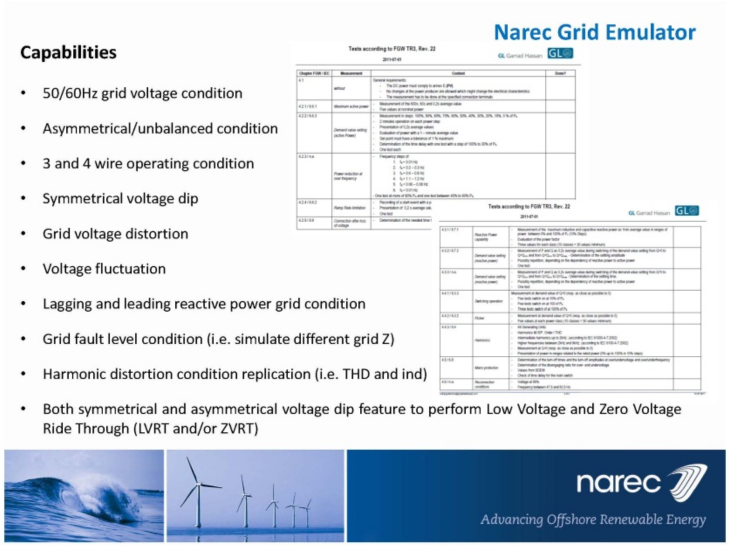

Narec Grid Emulator

Capabilities

- 50/60Hz grid voltage condition
- Asymmetrical/unbalanced condition
- 3 and 4 wire operating condition
- Symmetrical voltage dip
- Grid voltage distortion
- Voltage fluctuation
- Lagging and leading reactive power grid condition
- Grid fault level condition (i.e. simulate different grid Z)
- Harmonic distortion condition replication (i.e. THD and ind)
- Both symmetrical and asymmetrical voltage dip feature to perform Low Voltage and Zero Voltage Ride Through (LVRT and/or ZVRT)

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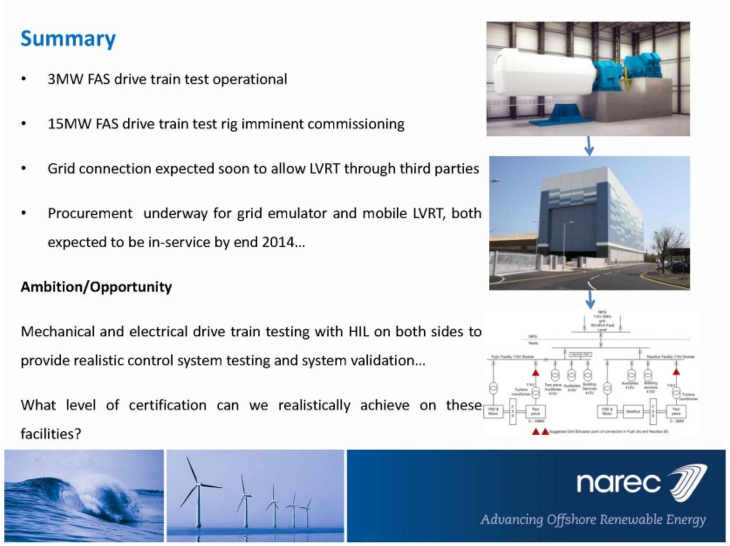

Summary

- 3MW FAS drive train test operational
- 15MW FAS drive train test rig imminent commissioning
- Grid connection expected soon to allow LVRT through third parties
- Procurement underway for grid emulator and mobile LVRT, both expected to be in-service by end 2014...

Ambition/Opportunity

Mechanical and electrical drive train testing with HIL on both sides to provide realistic control system testing and system validation...

What level of certification can we realistically achieve on these facilities?

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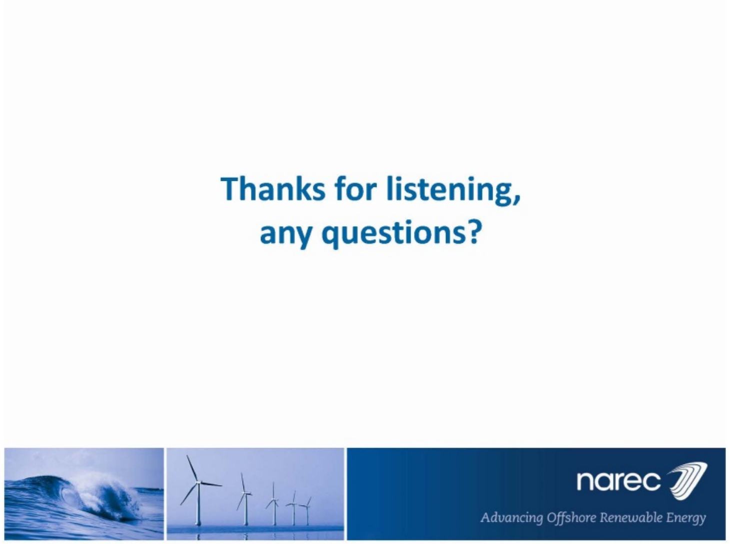

Thanks for listening,
any questions?

11.3.3 Fraunhofer Institute for Wind Energy and Energy System Technology DyNaLab Grid Simulator – Jersch Torben, Fraunhofer Institute for Wind Energy and Energy System Technology, Germany

Welcome

WIND. ASSURING CONFIDENCE
THROUGH COMPETENCE

LVRT Testing on DyNaLab

Electrical certification of Windturbines on Test Benches?

Torben Jersch

1st International Workshop on Grid Simulator Testing of Wind Turbine Drivetrains

13.06.2013 © Fraunhofer

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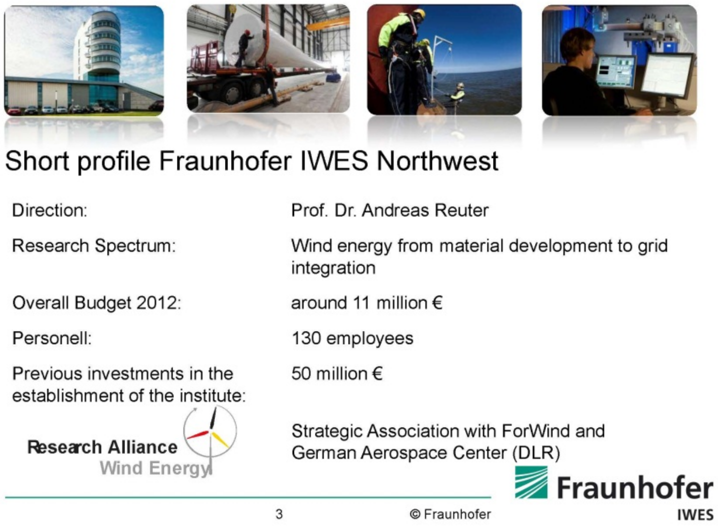

Short profile Fraunhofer IWES Northwest

Direction:	Prof. Dr. Andreas Reuter
Research Spectrum:	Wind energy from material development to grid integration
Overall Budget 2012:	around 11 million €
Personell:	130 employees
Previous investments in the establishment of the institute:	50 million €
Research Alliance Wind Energy	Strategic Association with ForWind and German Aerospace Center (DLR)

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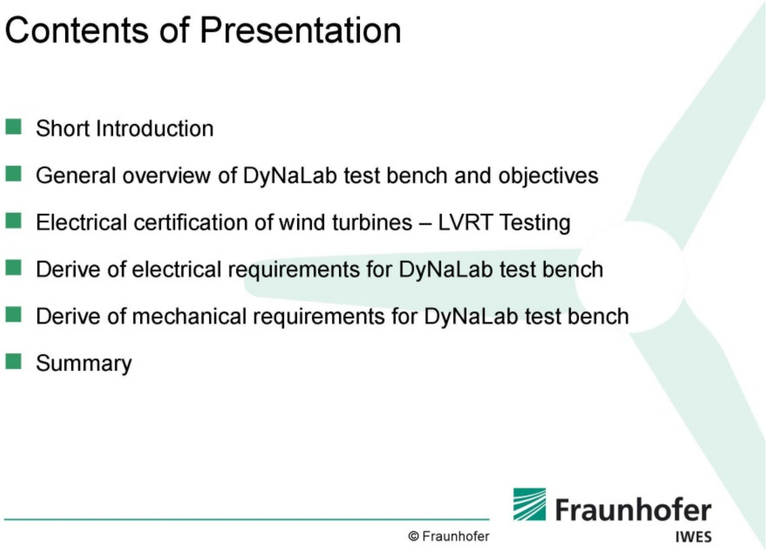
Fraunhofer IWES



Contents of Presentation

- Short Introduction
- General overview of DyNaLab test bench and objectives
- Electrical certification of wind turbines – LVRT Testing
- Derive of electrical requirements for DyNaLab test bench
- Derive of mechanical requirements for DyNaLab test bench
- Summary

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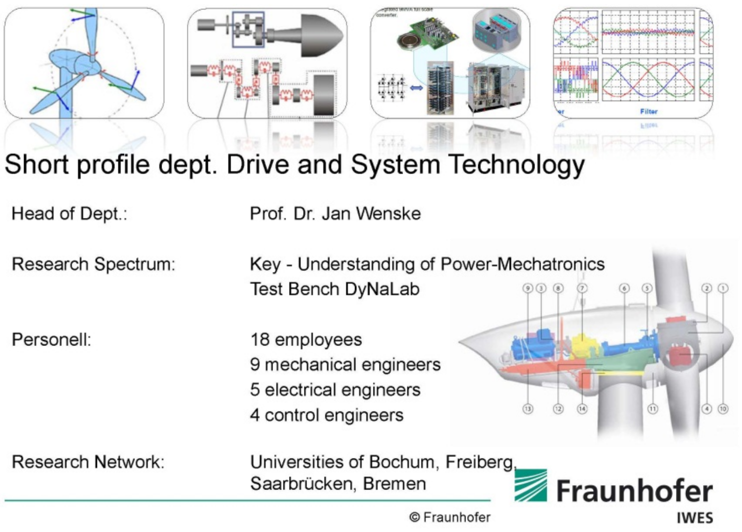

Short profile dept. Drive and System Technology

Head of Dept.:	Prof. Dr. Jan Wenske
Research Spectrum:	Key - Understanding of Power-Mechatronics Test Bench DyNaLab
Personell:	18 employees 9 mechanical engineers 5 electrical engineers 4 control engineers
Research Network:	Universities of Bochum, Freiberg, Saarbrücken, Bremen

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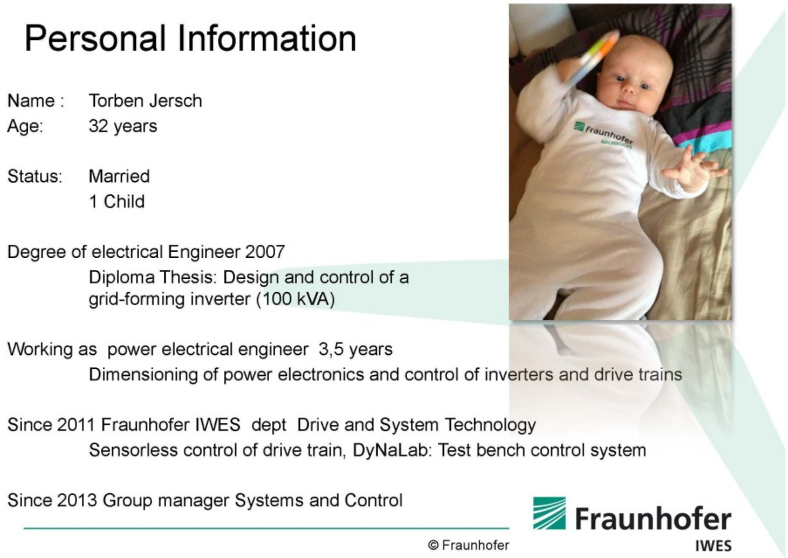

Personal Information

Name : Torben Jersch
Age: 32 years

Status: Married
1 Child

Degree of electrical Engineer 2007
Diploma Thesis: Design and control of a grid-forming inverter (100 kVA)

Working as power electrical engineer 3,5 years
Dimensioning of power electronics and control of inverters and drive trains

Since 2011 Fraunhofer IWES dept Drive and System Technology
Sensorless control of drive train, DyNaLab: Test bench control system

Since 2013 Group manager Systems and Control

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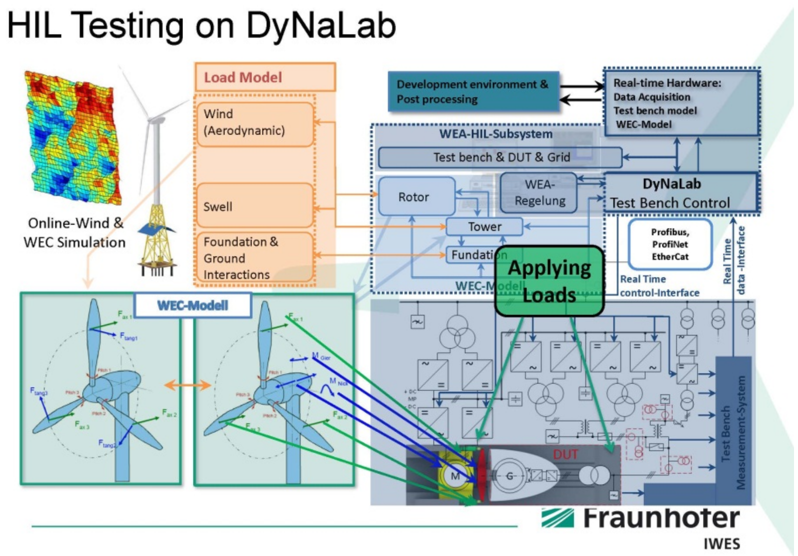

HIL Testing on DyNaLab

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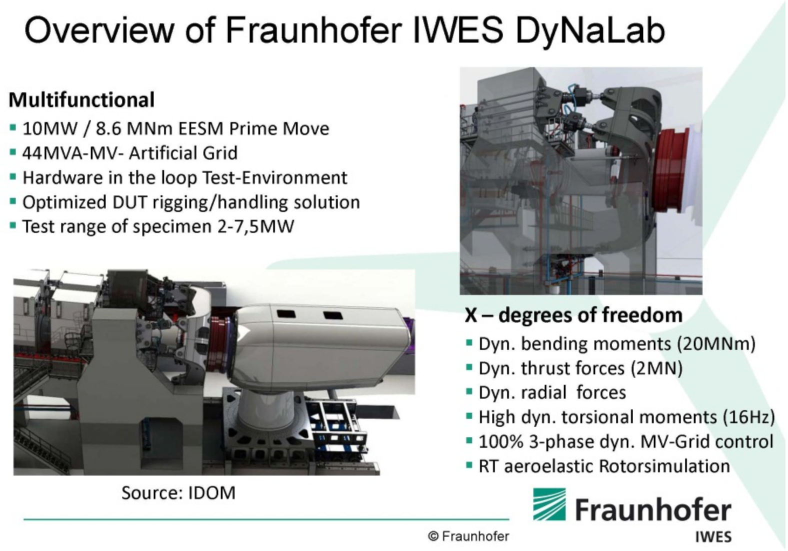

Overview of Fraunhofer IWES DyNaLab

Multifunctional

- 10MW / 8.6 MNm EESM Prime Move
- 44MVA-MV- Artificial Grid
- Hardware in the loop Test-Environment
- Optimized DUT rigging/handling solution
- Test range of specimen 2-7,5MW

Source: IDOM

X – degrees of freedom

- Dyn. bending moments (20MNm)
- Dyn. thrust forces (2MN)
- Dyn. radial forces
- High dyn. torsional moments (16Hz)
- 100% 3-phase dyn. MV-Grid control
- RT aeroelastic Rotorsimulation

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Scope of nacelle testing on test rigs

- ✓ Development testing / optimization
- ✓ Design verification / analysis / model validation
- ✓ „End of Line“ Tests / production conformity testing
- ? Accelerated lifetime tests / reliability testing
- ✗ Full lifetime and fatigue testing
- ? Partly wind turbine certification / support (savings at field tests)
  - ✓ Electrical certification of wind turbines — Big Benefit
- ✗ Complete Wind turbine certification testing

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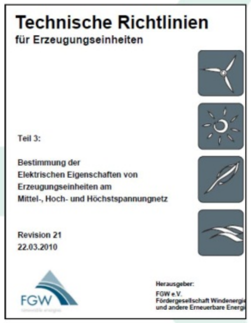
Testing of LVRT of Wind turbines on Test benches

- For electrical certification fulfill
  IEC 61400-21
- Key features for LVRT testing
- Technical guideline for power supply units
- Requirements of test benches for testing LVRT
  Voltage, Current, Inertia
- Short circuit current of WEC connected to grid
  Inverter $I_K = 2.2 \times I_{RATED}$
  Synchronous & DFIG $I_K = 7 \times I_{RATED}$



Technische Richtlinien
für Erzeugungseinheiten

Teil 3:

Bestimmung der
Elektrischen Eigenschaften von
Erzeugungseinheiten am
Mittel-, Hoch- und Höchstspannungnetz

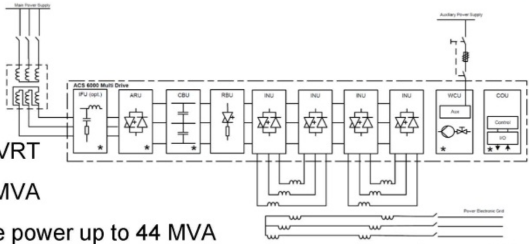
Revision 21
22.03.2010

Herausgeber:
FGW e.V.
Fördergesellschaft Windenergie
und andere Erneuerbare Energi

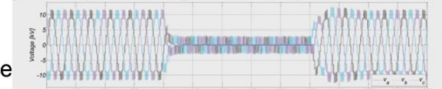
Fraunhofer IWES

Specification and concept of Grid Simulation

- Rated voltage
  0-36 kV
  up to 47 kV for HVRT
- Rated power 15 MVA
- Transient reactive power up to 44 MVA
- High dynamic for voltage control
- Independent control of voltage and phase angel of each phase
- Voltage THD < 2% overall
- Controllable grid impedance
- Frequency 45 – 65 Hz



Source: ABB



Source: ABB

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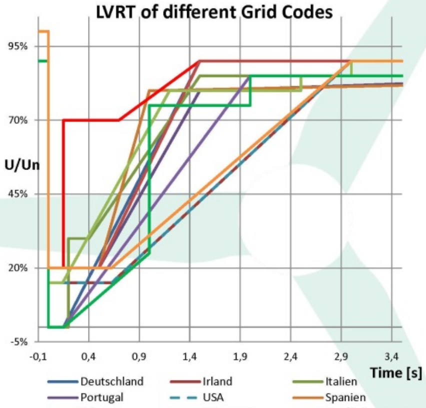
Testing of LVRT of Wind turbines on Test benches

- Inverter based grid simulation
- Voltage control down to 0V
- Dynamics of voltage change
  Rise and Fall
- Low leakage impendence of
  Transformers
- Future of grid codes:
  Multi dips
  Unbalanced voltages
  Changing phase angle



LVRT of different Grid Codes

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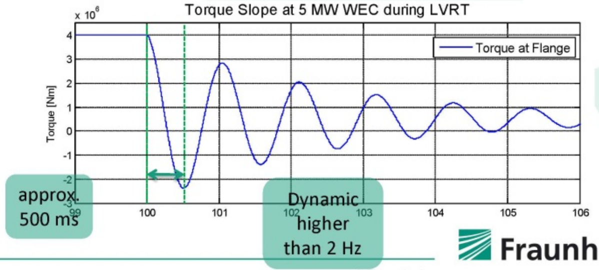
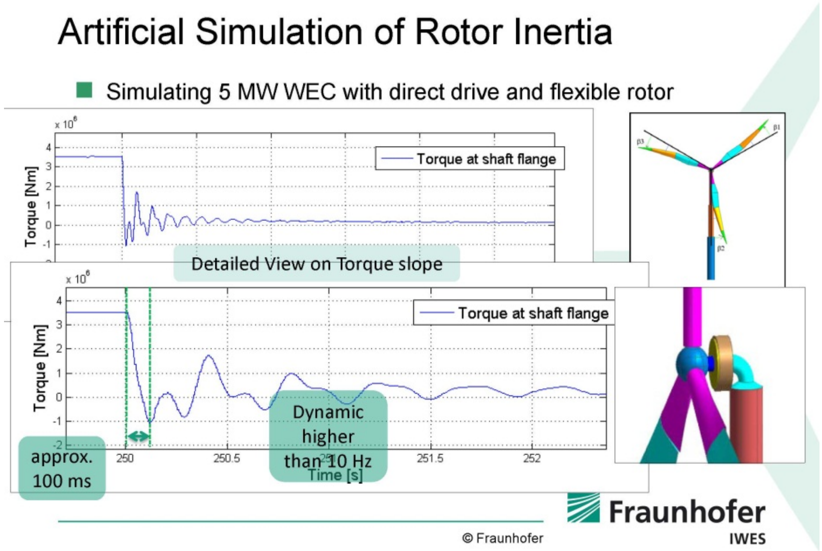
Artificial Simulation of Rotor Inertia

- Necessity of rotor inertia simulation
- Estimation of torque curve at flange between hub and shaft during LVRT event
- Simulating 5 MW WEC with gearbox



Torque Slope at 5 MW WEC during LVRT

Fraunhofer IWES



Artificial Simulation of Rotor Inertia

- Simulating 5 MW WEC with direct drive and flexible rotor

approx. 100 ms

Dynamic higher than 10 Hz

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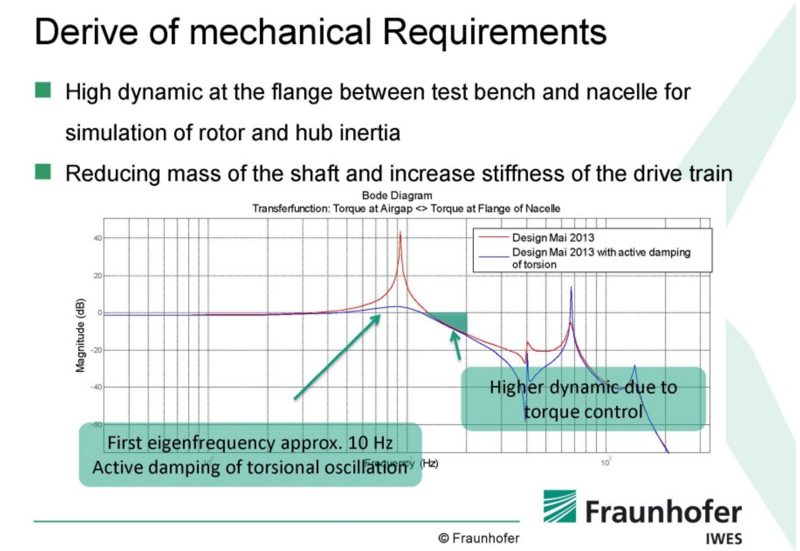

Derive of mechanical Requirements

- High dynamic at the flange between test bench and nacelle for simulation of rotor and hub inertia
- Reducing mass of the shaft and increase stiffness of the drive train

Bode Diagram
Transferfunction: Torque at Airgap <> Torque at Flange of Nacelle

Higher dynamic due to torque control

First eigenfrequency approx. 10 Hz
Active damping of torsional oscillation

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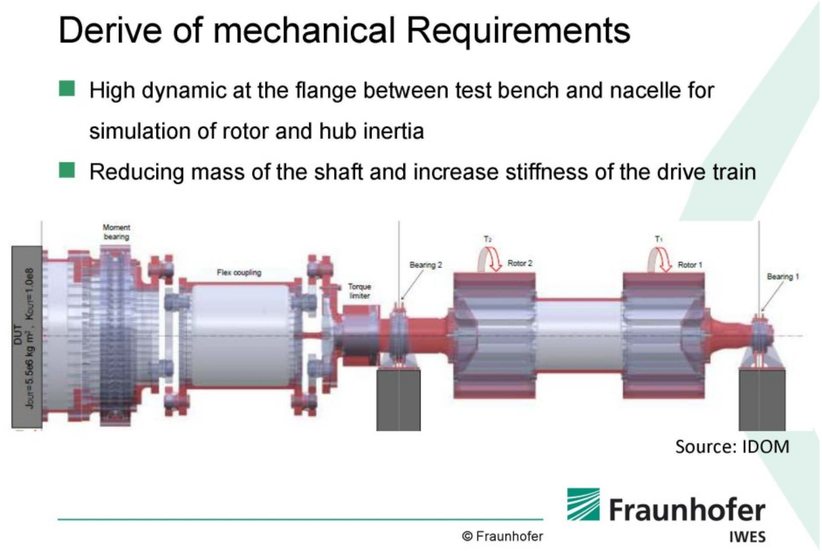

Derive of mechanical Requirements

- High dynamic at the flange between test bench and nacelle for simulation of rotor and hub inertia
- Reducing mass of the shaft and increase stiffness of the drive train

Source: IDOM

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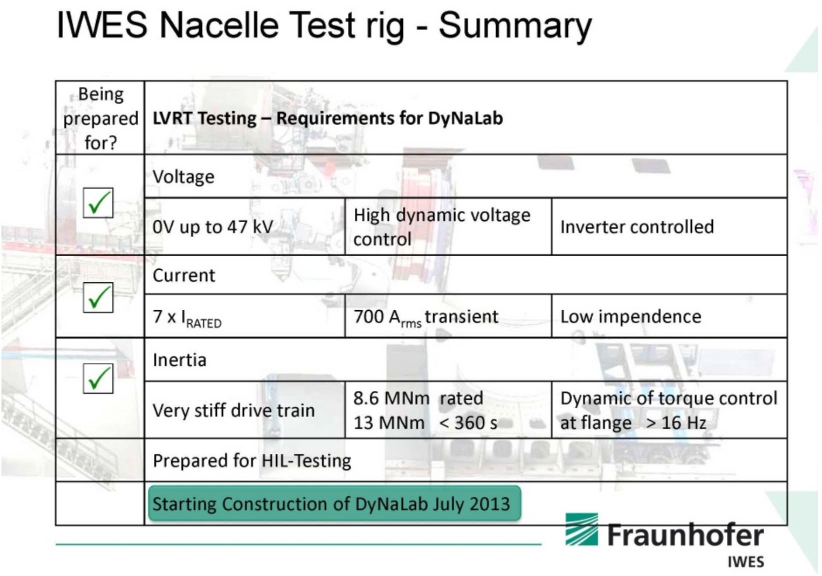

IWES Nacelle Test rig - Summary

Being prepared for?	**LVRT Testing – Requirements for DyNaLab**		
✓	Voltage		
	0V up to 47 kV	High dynamic voltage control	Inverter controlled
✓	Current		
	7 x I_{RATED}	700 A_{rms} transient	Low impendence
✓	Inertia		
	Very stiff drive train	8.6 MNm rated 13 MNm < 360 s	Dynamic of torque control at flange > 16 Hz
	Prepared for HIL-Testing		
	Starting Construction of DyNaLab July 2013		

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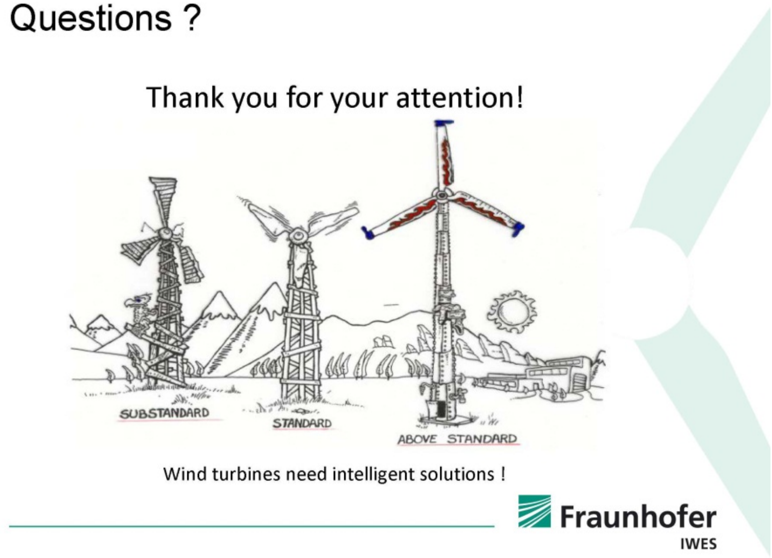

Questions ?

Thank you for your attention!

Wind turbines need intelligent solutions !

Fraunhofer
IWES

11.3.4 Wind Power Certification in China – Zhang Yu, China General Certification Center, China

鉴衡认证
More than A Certificate

Introduction on Certification and Testing of Wind Turbine in China

China General Certification Center（CGC）
June ,2013

Zhang Yu

鉴衡认证中心 China General Certification Center
使认证创造价值 Creating Values Through Certification

Who’s CGC

鉴衡认证
More than A Certificate

- ■Accredited since 2008 by China National Accreditation Service for Conformity Assessment（CNAS） - a IAF member
- ■For wind turbine certification and type testing.
- ■According to IEC standards.

鉴衡认证中心 China General Certification Center
使认证创造价值 Creating Values Through Certification

Content

鉴衡认证
More than A Certificate

- ■Who’s CGC
- ■Certification requirements and standards.
- ■Grid connection requirements
- ■Trends.

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Who’s CGC

鉴衡认证
More than A Certificate

We focus on

Wind
Solar
Energy
Bio-energy
RoHS
Low-carbon

For wind energy we provide:

- ➢Standards Development
- ➢Certification
- ➢Testing
- ➢Industry Study & Consulting
- ➢Wind farm services (due diligence etc.)
- ➢Training

- ■Founded in 2003 with the authorization of the government
- ■Earliest and biggest in wind
- ■Named as National Energy Lab for Wind & Solar Simulation, Testing & Certification
- ■Located in Beijing with 130+ employees.
- ■IEC TC 88 and CAC CBC member.

鉴衡认证中心 China General Certification Center
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Who's CGC

More than A Certificate

整机测试 Wind Turbines Testing：

- 功率特性 Power performance measurement
- 电能质量 Power quality measurement
- 载荷 Mechanical load measurement
- 噪声 Acoustic noise measurement

部件测试Component Testing：

Rotor blade test facility:

- *Static testing and Fatigue testing*
- *The blade length up to 100m*

- Blade Material testing
- Generator, bearing and drive chain testing facility（under construction）

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Certification requirements in China

More than A Certificate

- IEC series standards
- Not compulsory
- Required by all the developers
- Design evaluation will do currently
- International certificate recognition well implemented

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Content

More than A Certificate

- Who's CGC
- Certification requirements and standards.
- Grid connection requirements
- Trends.

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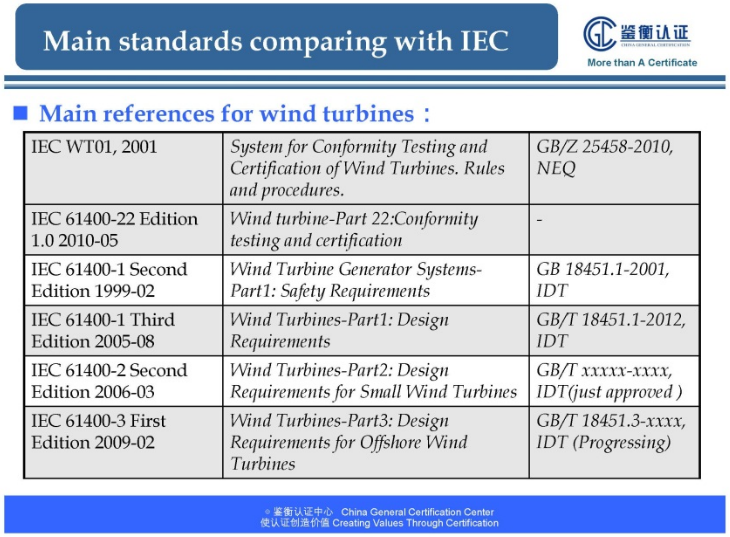

Main standards comparing with IEC

More than A Certificate

Main references for wind turbines：

IEC WT01, 2001	*System for Conformity Testing and Certification of Wind Turbines. Rules and procedures.*	*GB/Z 25458-2010, NEQ*
IEC 61400-22 Edition 1.0 2010-05	*Wind turbine-Part 22:Conformity testing and certification*	-
IEC 61400-1 Second Edition 1999-02	*Wind Turbine Generator Systems-Part1: Safety Requirements*	*GB 18451.1-2001, IDT*
IEC 61400-1 Third Edition 2005-08	*Wind Turbines-Part1: Design Requirements*	*GB/T 18451.1-2012, IDT*
IEC 61400-2 Second Edition 2006-03	*Wind Turbines-Part2: Design Requirements for Small Wind Turbines*	*GB/T xxxxx-xxxx, IDT(just approved)*
IEC 61400-3 First Edition 2009-02	*Wind Turbines-Part3: Design Requirements for Offshore Wind Turbines*	*GB/T 18451.3-xxxx, IDT (Progressing)*

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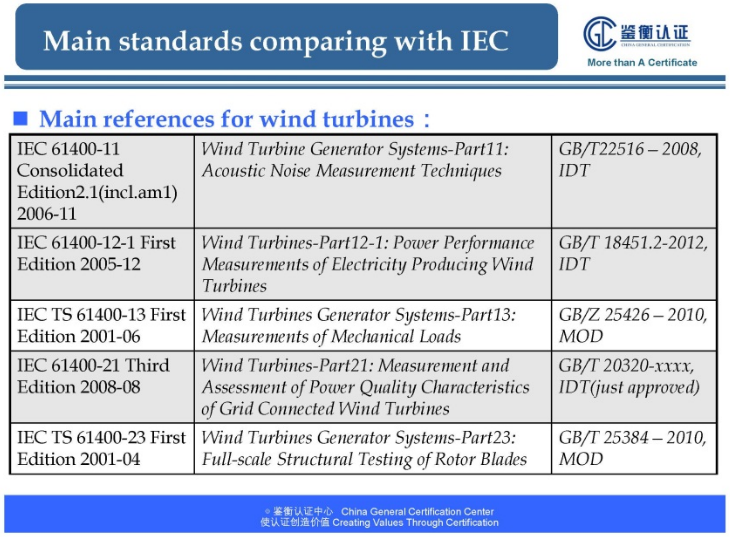

Main standards comparing with IEC

鉴衡认证 More than A Certificate

■ **Main references for wind turbines：**

IEC 61400-11 Consolidated Edition2.1(incl.am1) 2006-11	*Wind Turbine Generator Systems-Part11: Acoustic Noise Measurement Techniques*	*GB/T22516 – 2008, IDT*
IEC 61400-12-1 First Edition 2005-12	*Wind Turbines-Part12-1: Power Performance Measurements of Electricity Producing Wind Turbines*	*GB/T 18451.2-2012, IDT*
IEC TS 61400-13 First Edition 2001-06	*Wind Turbines Generator Systems-Part13: Measurements of Mechanical Loads*	*GB/Z 25426 – 2010, MOD*
IEC 61400-21 Third Edition 2008-08	*Wind Turbines-Part21: Measurement and Assessment of Power Quality Characteristics of Grid Connected Wind Turbines*	*GB/T 20320-xxxx, IDT(just approved)*
IEC TS 61400-23 First Edition 2001-04	*Wind Turbines Generator Systems-Part23: Full-scale Structural Testing of Rotor Blades*	*GB/T 25384 – 2010, MOD*

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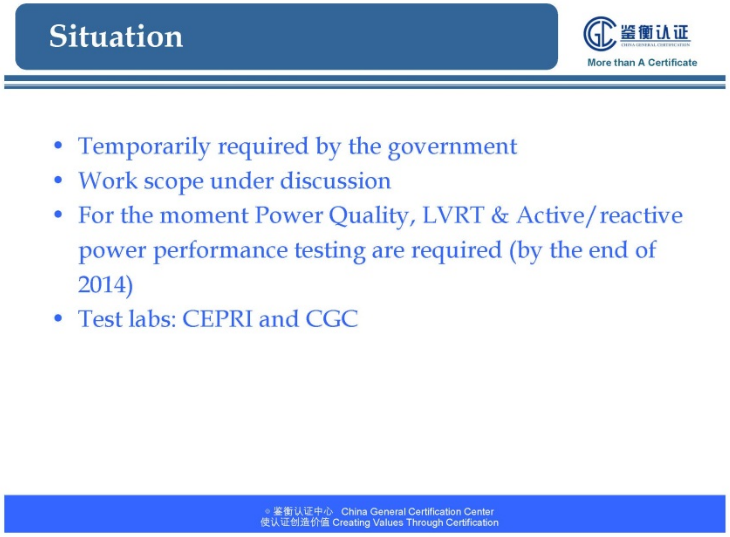

Situation

鉴衡认证 More than A Certificate

- Temporarily required by the government
- Work scope under discussion
- For the moment Power Quality, LVRT & Active/reactive power performance testing are required (by the end of 2014)
- Test labs: CEPRI and CGC

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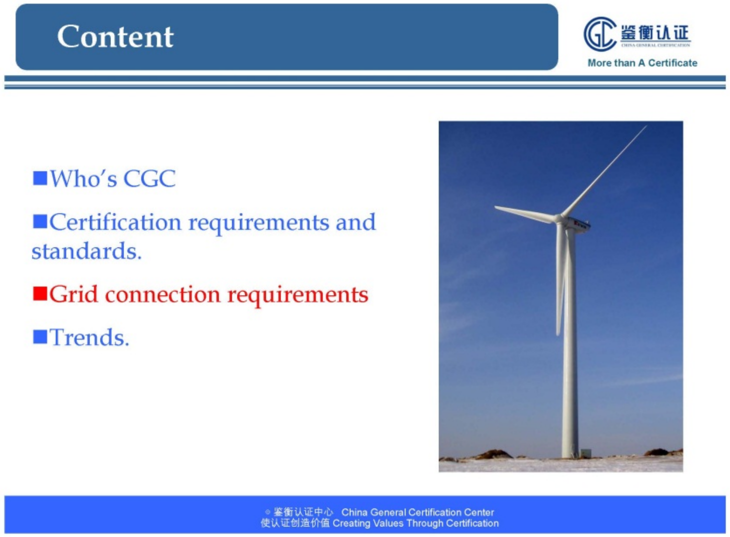

Content

鉴衡认证 More than A Certificate

■Who’s CGC

■Certification requirements and standards.

■Grid connection requirements

■Trends.

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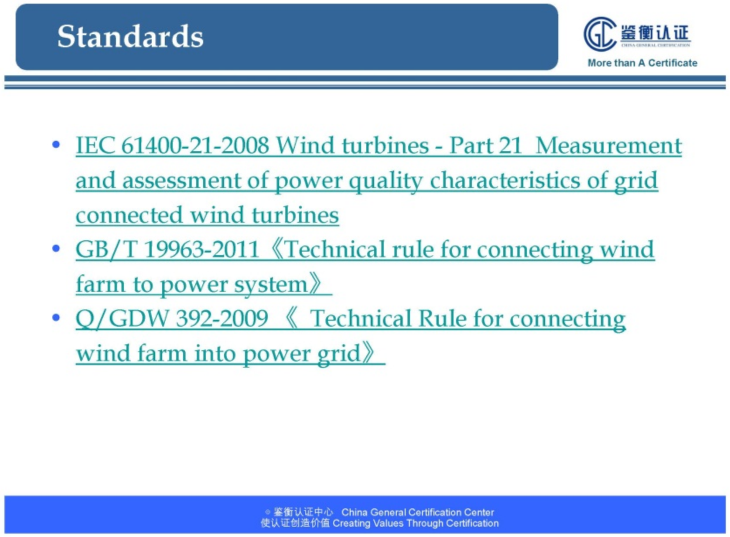

Standards

鉴衡认证 More than A Certificate

- IEC 61400-21-2008 Wind turbines - Part 21 Measurement and assessment of power quality characteristics of grid connected wind turbines
- GB/T 19963-2011《Technical rule for connecting wind farm to power system》
- Q/GDW 392-2009 《 Technical Rule for connecting wind farm into power grid》

鉴衡认证中心 China General Certification Center
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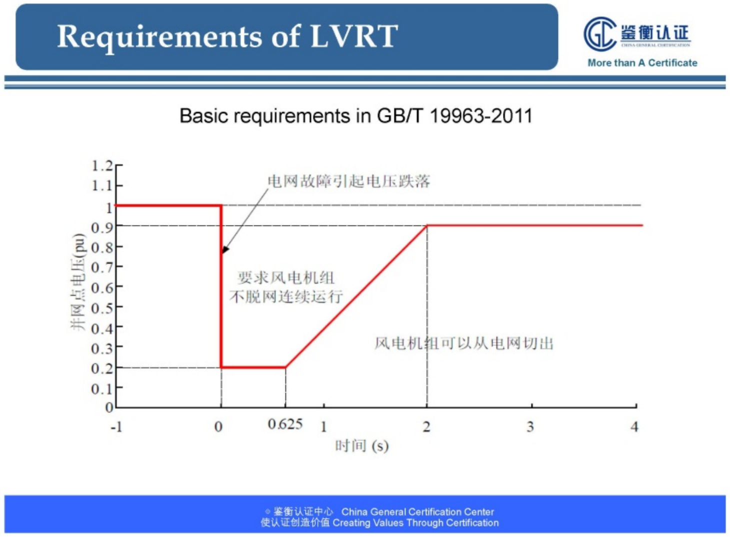
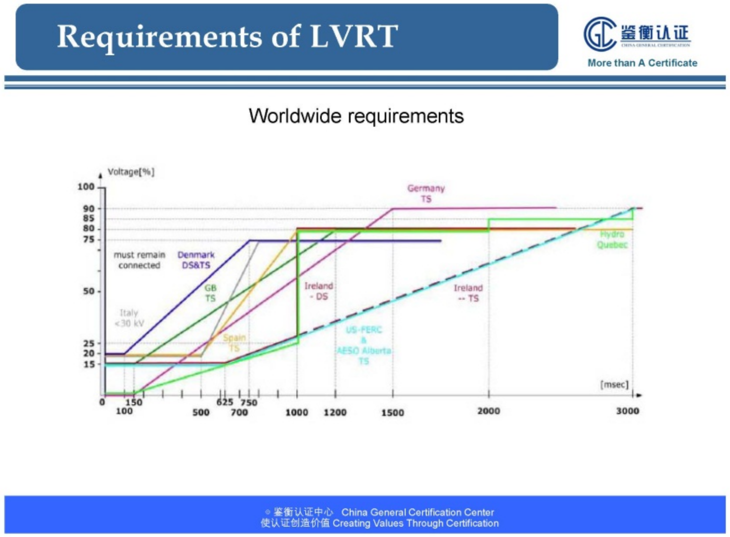


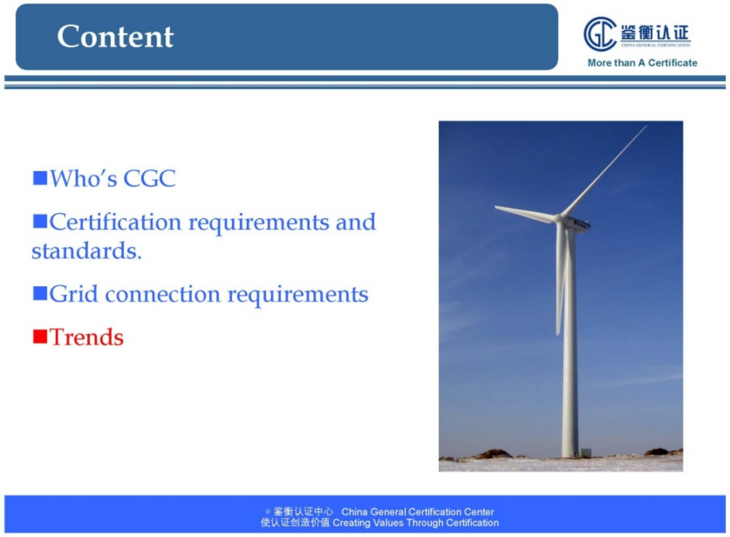
Requirements of LVRT

Basic requirements in GB/T 19963-2011



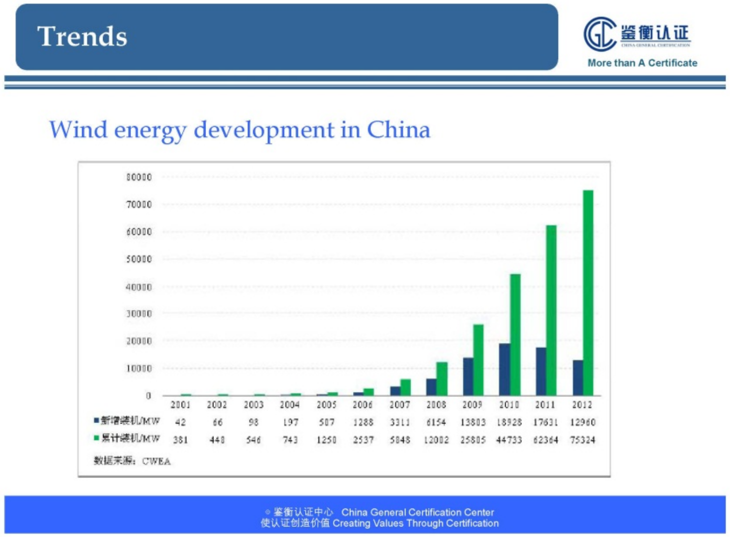
Requirements of LVRT

Worldwide requirements



Content

- Who's CGC
- Certification requirements and standards.
- Grid connection requirements
- Trends

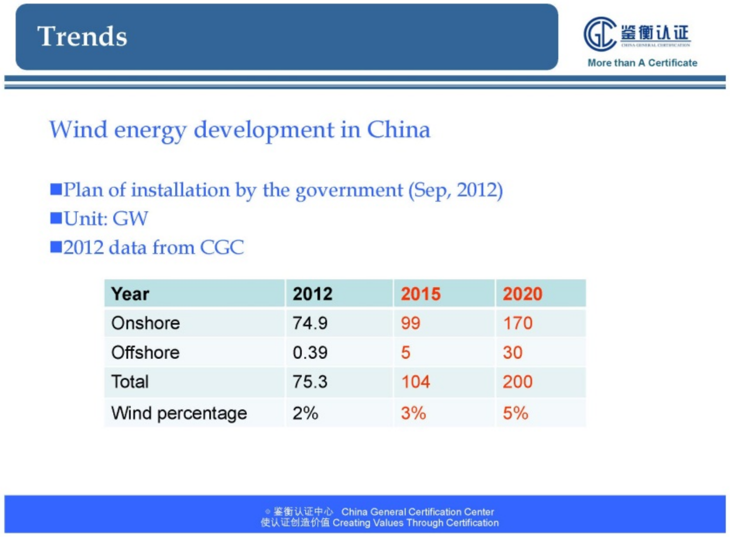


Trends

Wind energy development in China

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
■新增装机/MW	42	66	98	197	507	1288	3311	6154	13803	18928	17631	12960
■累计装机/MW	381	448	546	743	1250	2537	5848	12002	25805	44733	62364	75324

数据来源：CWEA



Trends

Wind energy development in China

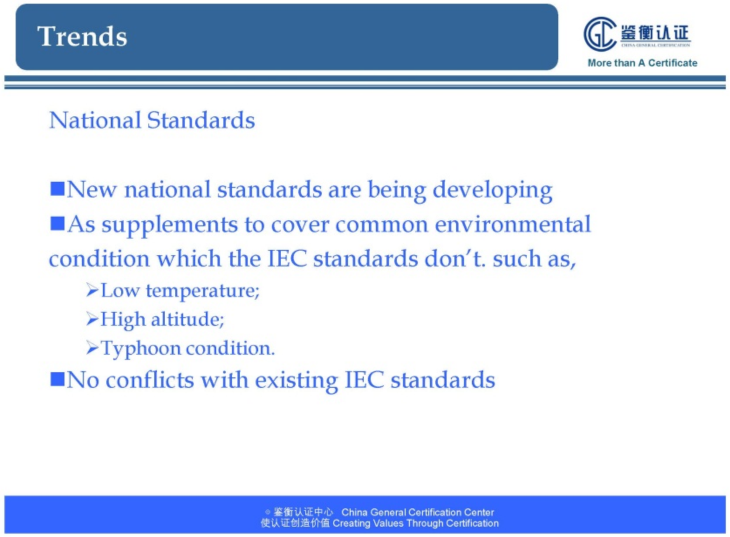
- ■Plan of installation by the government (Sep, 2012)
- ■Unit: GW
- ■2012 data from CGC

Year	2012	2015	2020
Onshore	74.9	99	170
Offshore	0.39	5	30
Total	75.3	104	200
Wind percentage	2%	3%	5%

Trends

Certification and other

- ■Type Certification will be required by the market
- ■Site-specific assessment may be demanded
- ■Requirements of grid connection will be finalized
- ■Wind power plants performance may be surveyed and data will be collected by a national supervisory center



Trends

National Standards

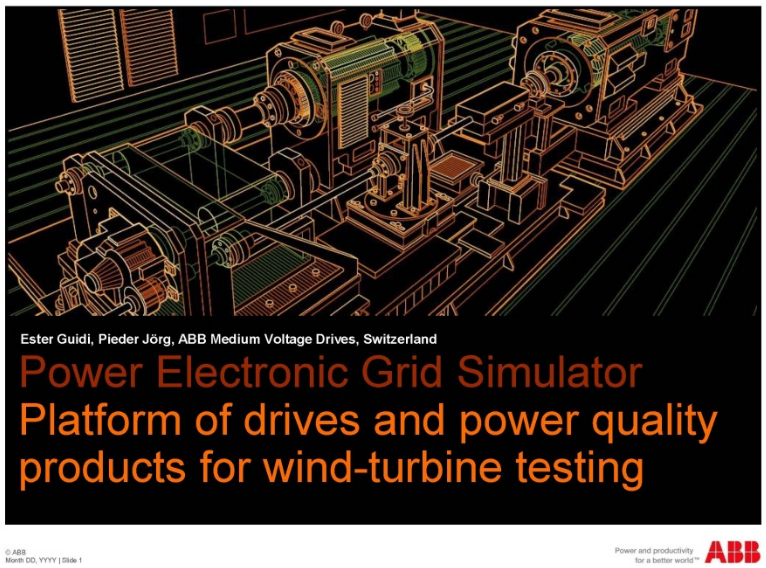
- ■New national standards are being developing
- ■As supplements to cover common environmental condition which the IEC standards don't. such as,
  - ➢Low temperature;
  - ➢High altitude;
  - ➢Typhoon condition.
- ■No conflicts with existing IEC standards

Thank you

China General Certification Centre（CGC）
Zhang Yu

Email:zhangyu@cgc.org.cn
Tel: +86 10 5979 6665ext.3111
Fax: +86 10 6422 8215
www.cgc.org.cn

11.3.5 ABB Grid Simulator Product Line – Pieder Joerg, Ester Guidi, ABB Medium-Voltage Drives, Switzerland



Ester Guidi, Pieder Jörg, ABB Medium Voltage Drives, Switzerland

Power Electronic Grid Simulator

Platform of drives and power quality products for wind-turbine testing

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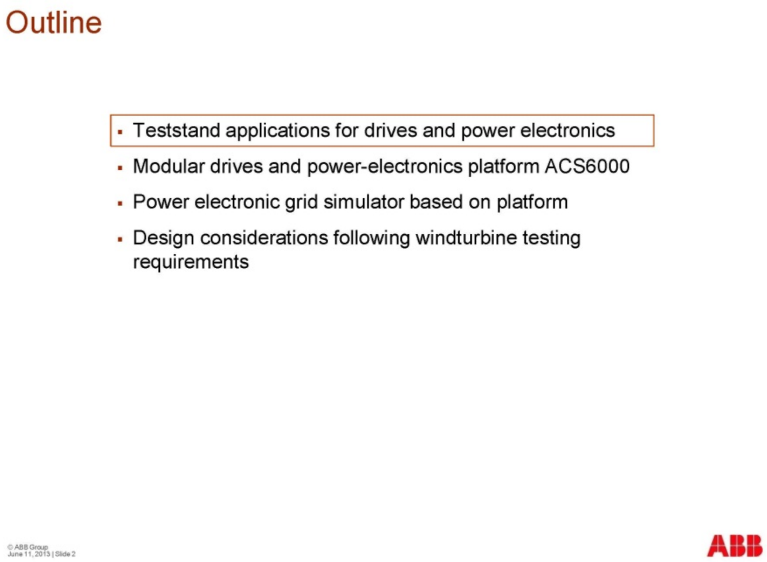
Month DD, YYYY | Slide 1

Power and productivity
for a better world™



Outline

- Teststand applications for drives and power electronics
- Modular drives and power-electronics platform ACS6000
- Power electronic grid simulator based on platform
- Design considerations following windturbine testing requirements

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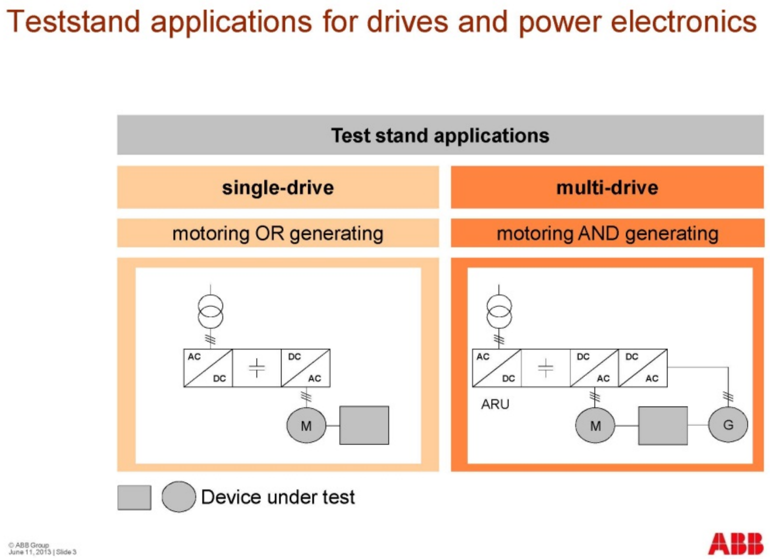

Teststand applications for drives and power electronics

Test stand applications	
single-drive	**multi-drive**
motoring OR generating	motoring AND generating

▨ ● Device under test

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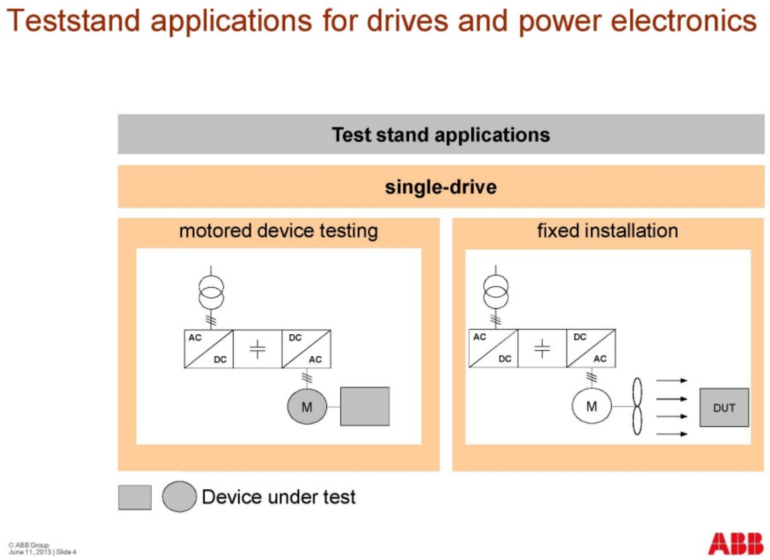

Teststand applications for drives and power electronics

Test stand applications	
single-drive	
motored device testing	fixed installation

▨ ● Device under test

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ABB's areas of activity

Test stand applications

Single drive	**Multi drive**
Device testing ▪ Compressor & turbo charger ▪ Pump ▪ Balancing plant ▪ Jet engine ▪ Gas Turbines ▪ Motor Generator set, …	▪ Gearbox ▪ Electrical generator ▪ Electrical motor ▪ Grid simulation ▪ Wind turbine ▪ …
Fix installations ▪ Wind tunnel ▪ Human centrifuge (pilot training) ▪ Soft starters for high energy labs	

Outline

- Teststand applications for drives and power electronics
- Modular drives and power-electronics platform ACS6000
- Power electronic grid simulator based on platform
- Design considerations following windturbine testing requirements

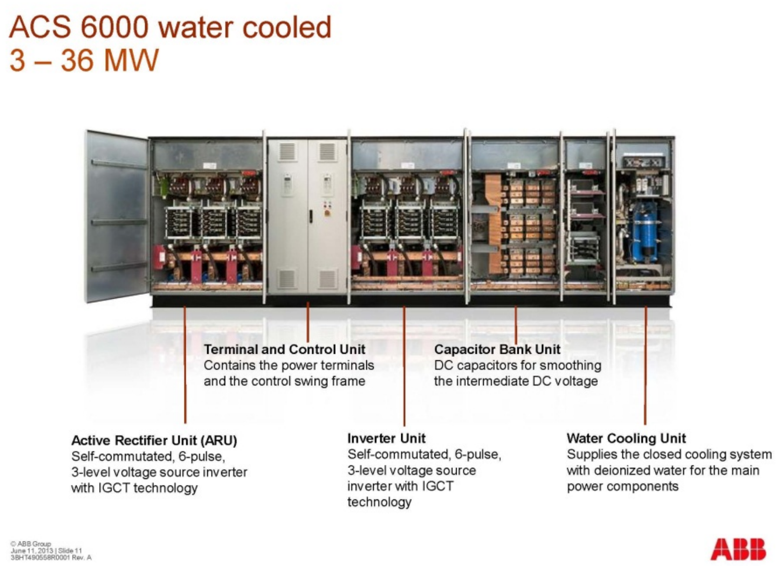
Teststand applications
Typical requirements towards electrics/automation

- High dynamic electric motor control over wide speed range
  - capability to control induction and synchronous motors
  - base speed of electrical motor:
    1Hz .. 75Hz / few rpm .. 3600rpm
  - wide field-weakening range (… 1:5)
  - high torque over-loadability (… 275%)
  - air-gap-torque control bandwidth (… 400Hz)
  - flexible automation integration (PLC, FB, fast I/O …)
- Versatile power electronic building blocks
  - load-cycling capable (reliability)
  - parallelable and multi-terminal capable (scalability)

ACS 6000
Modular drives and power-electronics platform

- Voltage range
  - 2.3…3.3 kV
- Power range
  - 3…27 MVA continuous and 36 MVA short term
- Output frequency range
  - 0…75 Hz (higher on request)
- Field weakening point
  - 3.125…75 Hz (lower / higher on request)
- Field weakening range
  - 1:5

ACS 6000 focus: Demanding applications



ACS 6000 water cooled 3 – 36 MW

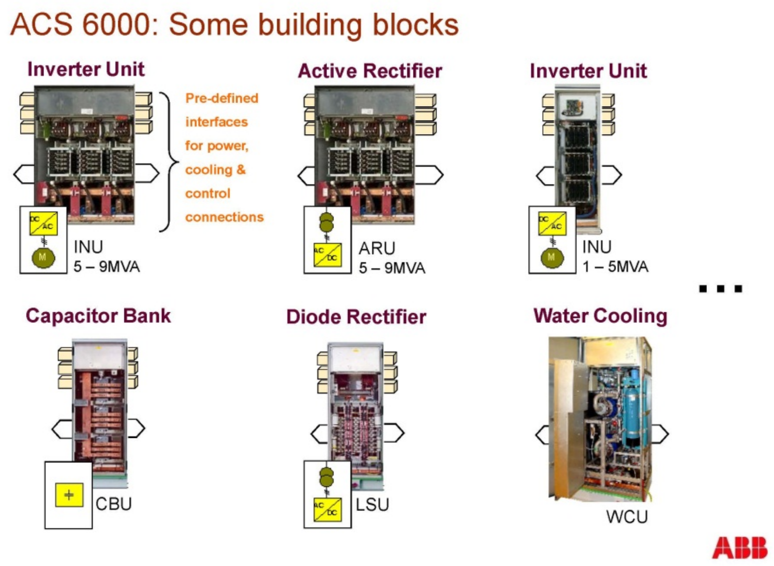
Terminal and Control Unit
Contains the power terminals and the control swing frame

Capacitor Bank Unit
DC capacitors for smoothing the intermediate DC voltage

Active Rectifier Unit (ARU)
Self-commutated, 6-pulse, 3-level voltage source inverter with IGCT technology

Inverter Unit
Self-commutated, 6-pulse, 3-level voltage source inverter with IGCT technology

Water Cooling Unit
Supplies the closed cooling system with deionized water for the main power components



ACS 6000: Some building blocks

Inverter Unit

Active Rectifier

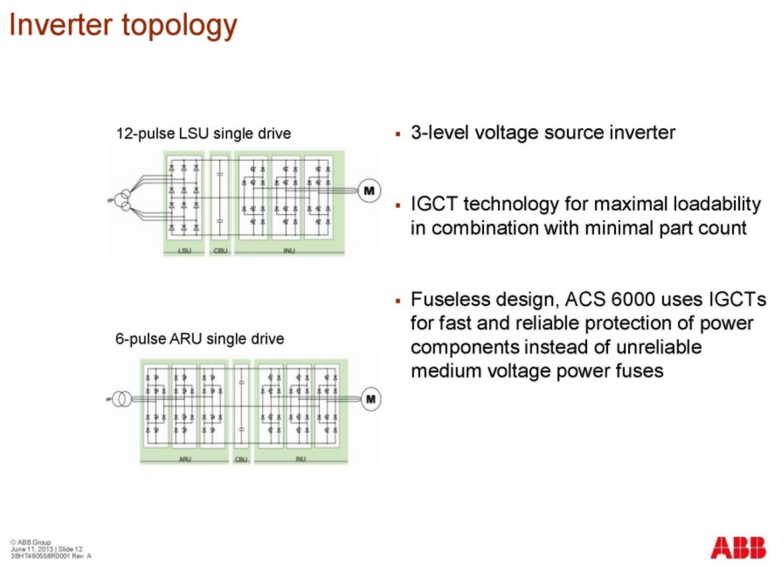
Inverter Unit

Pre-defined interfaces for power, cooling & control connections

Capacitor Bank

Diode Rectifier

Water Cooling



Inverter topology

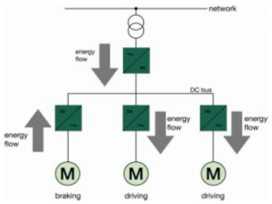
12-pulse LSU single drive

6-pulse ARU single drive

- 3-level voltage source inverter
- IGCT technology for maximal loadability in combination with minimal part count
- Fuseless design, ACS 6000 uses IGCTs for fast and reliable protection of power components instead of unreliable medium voltage power fuses

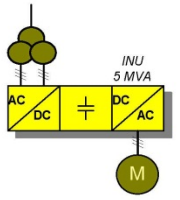
Common DC bus

Optimized energy flow with common DC bus, e.g. cold reversing steel mill

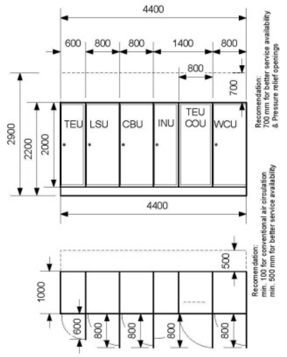


- Several motors (induction and synchronous) can be connected to the same DC bus → optimized energy flow
  - Braking energy generated in one motor can be transferred to other inverters via common DC bus without power consumption from supply network
- Optimum configuration can be reached by combining different inverter and rectifier modules within one drive

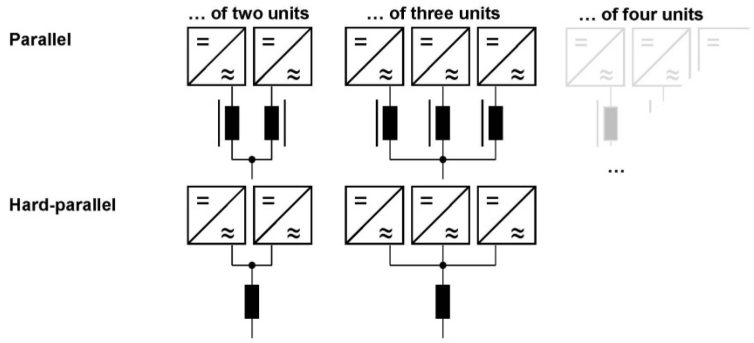
ACS 6000: Flexible solutions from 2Q single ...



ACS 6105_L12_1a5



ACS 6000: INU configurations

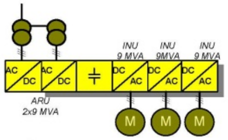


Parallel connection of inverter units:

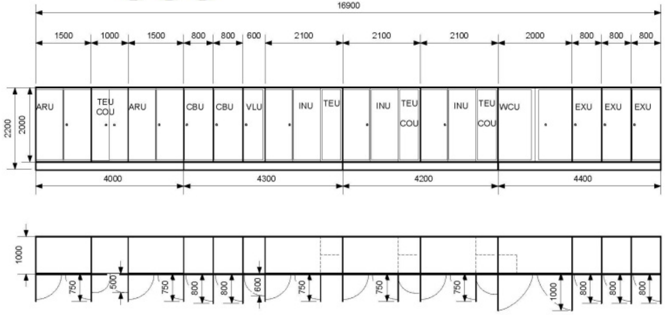
9, 18, 27, 36MVA as standard

e.g. 9MVA unit

ACS 6000: ... to 4Q multi drive



ACM 6209_A12_1s9_1s9_1s9



Outline

- Teststand applications for drives and power electronics
- Modular drives and power-electronics platform ACS6000
- Power electronic grid simulator based on platform
- Design considerations following windturbine testing requirements

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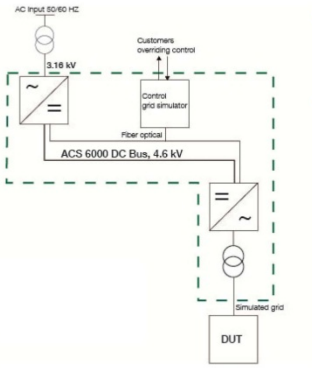
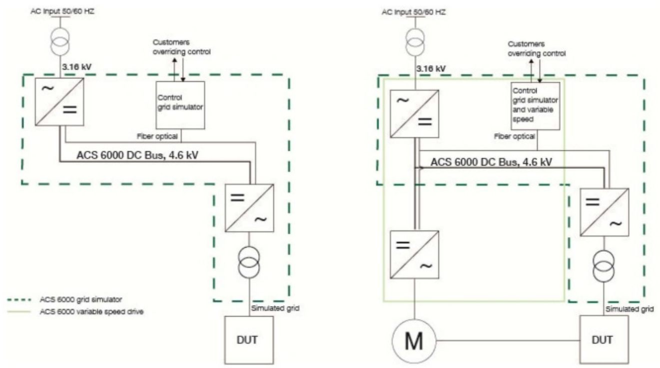
ACS 6000 grid simulator
Overview

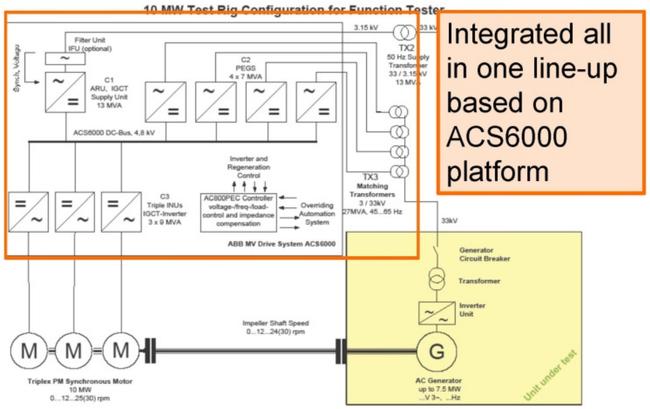


- Main benefit: Enables tests to be carried out off-line in a cost- and time-efficient manner
- Flexibility: suitable for any kind of electrical equipment that needs to be connected to the grid
  - Wind and Tidal Turbines
  - PV systems
  - Solar power
  - Fuel cells
  - Motor Gensets
  - Energy storage systems

ACS 6000 grid simulator
Combined functionality

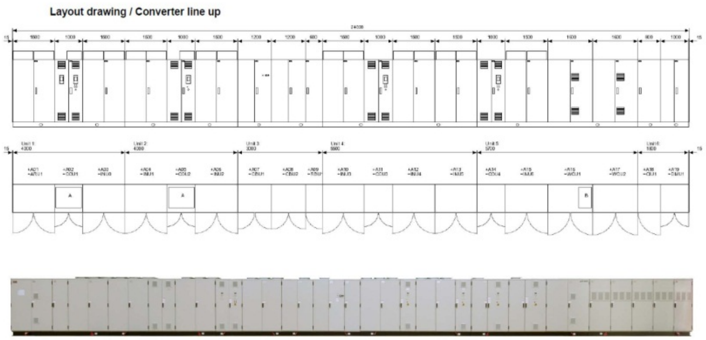


Project example – test stand for wind turbine
Combined functionality drive train and grid simulator



Integrated all in one line-up based on ACS6000 platform

ACS 6000 grid simulator
Example of a layout and dimensions



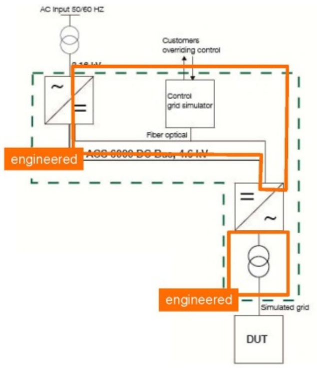
ACS 6000 grid simulator
Layout possibilies

- U-shape, L-shape, …

Outline

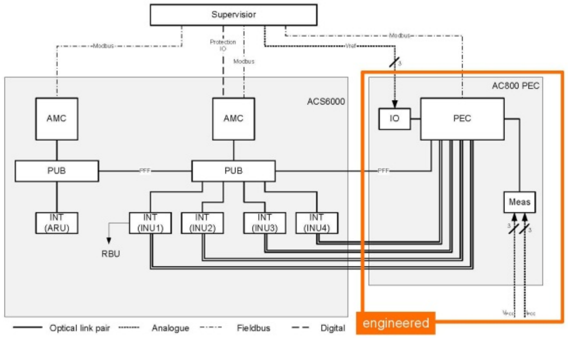
- Teststand applications for drives and power electronics
- Modular drives and power-electronics platform ACS6000
- Power electronic grid simulator based on platform
- Design considerations following windturbine testing requirements

ACS 6000 based grid simulator
Control and transformer engineered to application

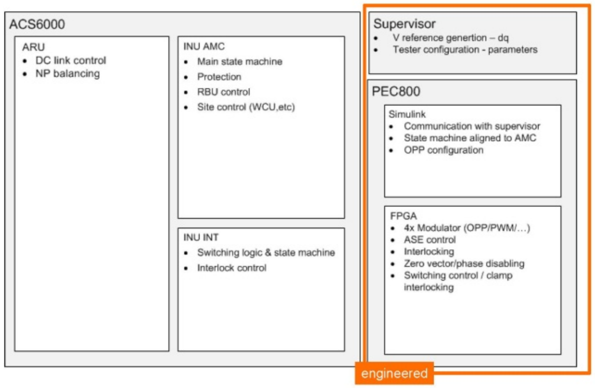


- Grid simulator inverter control and the output transformer are dedicated (“engineered”) for the grid simulator application
- Everything else is “off the shelf”
  - Power electronic hardware
  - Hardware protection
  - Mechanical design and cooling
  - Supervisory control and sequencing
  - Supply from public grid
  - …

ACS 6000 grid simulator
Control hardware overview



ACS 6000 grid simulator
Functional diagram



ACS6000

ARU
- DC link control
- NP balancing

INU AMC
- Main state machine
- Protection
- RBU control
- Site control (WCU,etc)

INU INT
- Switching logic & state machine
- Interlock control

Supervisor
- V reference genertion – dq
- Tester configuration - parameters

PEC800

Simulink
- Communication with supervisor
- State machine aligned to AMC
- OPP configuration

FPGA
- 4x Modulator (OPP/PWM/…)
- ASE control
- Interlocking
- Zero vector/phase disabling
- Switching control / clamp interlocking

engineered

ACS 6000 grid simulator
Control hardware features

- Main controller - PP D113
  - 36 Optical fiber modules (25us)
  - DDCS (DriveBus Comm)
  - Communication to the upper control via Anybus-Modules or CEX
  - Profibus-DPV1 Master
  - CANopen Slave
  - ControlNet Slave
  - DeviceNet Slave
  - Modbus-RTU S, -TCP S
  - Profibus-DP S, -DPV1 S, EtherCAT S
  - Profinet RTI - IO
- Fast IO – UA D149
  - PowerLink (native protocol – 25 us)
  - 32 DI (24V)
  - 16 DO (24V)
  - 12 AI (±10V, ±20mA)
    - Isolated in groups of 3
  - 4 isolated AO (±10V, ±20mA)

Overview: Configurations of matching transformer
What is the function of the transformer

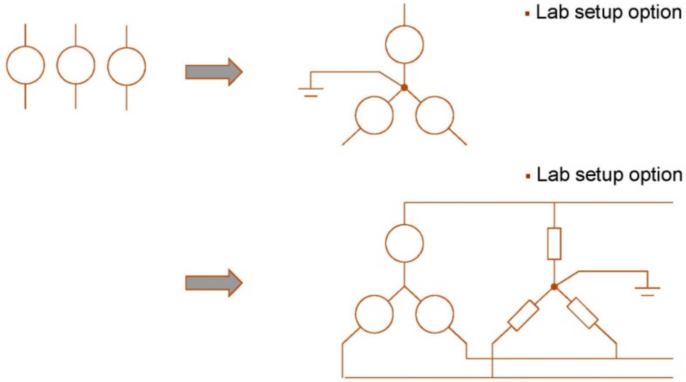
- Match the converter voltage to the desired testbus-voltage
- Sum-up the power (resp. currents) of the different inverters, e.g. of 4 inverters
- Cancel inverter harmonics to improve THDv
- Provide galvanic insulation between DUT and simulator for simpler test-design and protection

Overview: Configurations of matching transformer
What works and what not

- What doesn‘t work
  - 3 winding transformer („12-pulse“) → circulating currents
  - Parallel transformers → circulating currents
- What basically works
  - Series connection of HV winding for summing up
  - Y configuration of LV winding with starpoint to NP
  - Delta configuration of LV winding
  - 3 single phase trafos with H-bridge driven LV winding

© ABB Group

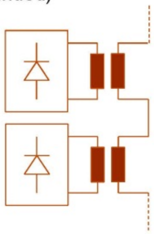
What you get as result
3 independent floating voltage sources



- Lab setup option 1
- Lab setup option 2
- or any other configuration of 1, 2 or 3 sources

Overview: Configurations of matching transformer
HV side configuration: Series connection

- Series connection allows summation of voltages with cancellation of harmonic voltages
- This turns the separate inverter units into a multi-level/multi-cell converter
- Tapings are relatively easy to implement
- The star-point is accessible and can be freely treated (hard grounded, soft-grounded)



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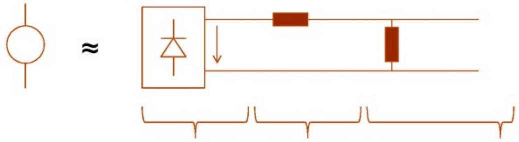
How does the voltage source look like
Potential and achievable short-circuit power



inverter is ideal voltage source with no internal impedance	transformer leakage inductance is visible grid impedance during normal operation	transformer thermal rating defines the short-circuit currents, that the grid simulator can really sink or source
it can run up to a maximum current	minimum is ~5% of rated transformer power	maximum is installed power electronic power
e.g. 3.15kV$_{AC\_LL}$ / 2000A 11MVA per unit 44MVA for 4 units	e.g. 16MW cont. rating 5% → 320MVA short-circuit power	e.g. converter will limit short-circuit at 44MVA

Conclusion

- ABB builds the grid simulators on a platform, which is widely used in demanding industrial applications
- The grid simulator is enabled by an application specific control hardware and software, and a dedicated matching transformer
- Compatibility with drives allows setups which include the dynamometer on the same DC-bus, thus isolating it from the local lab supply grid
- The used hardware and its configurations have been (partly widely) used since the launch of ACS 6000 in 1998
    - Dynamometer: High-power rolling-mill drive, direct drive mine-hoist
    - Grid simulator: Static VAR compensator, grid-interties (16 2/3 Hz <-> 50Hz) and for large energy storage

Power and productivity
for a better world™

11.4 Wind Turbine Manufacturer Perspective: What Are the Values for Wind Industry?

11.4.1 Advanced Wind Power Plant Controls – Nick Miller, General Electric

GE Energy

1st International Workshop on
Grid Simulator Testing of Wind Turbine
Drivetrains

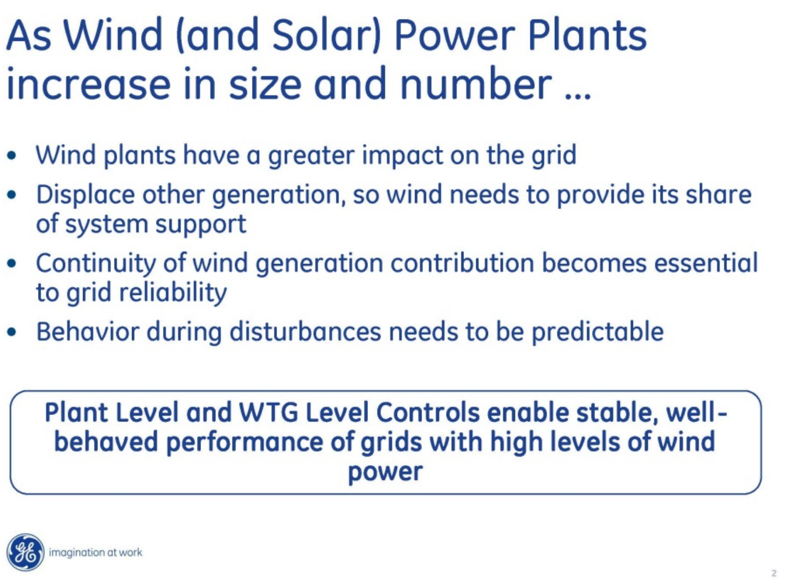
GE Wind Plant Advanced Controls

Nicholas W. Miller

GE Energy Consulting

June 13, 2013

imagination at work



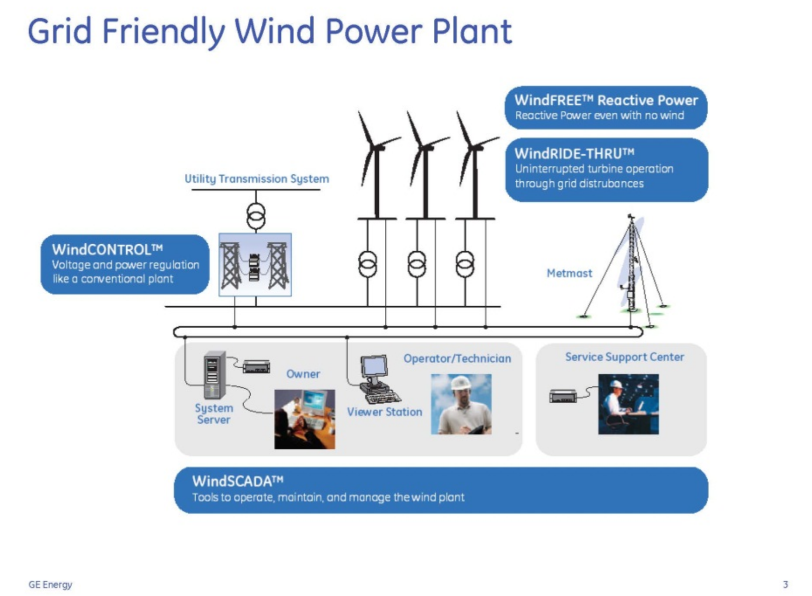
As Wind (and Solar) Power Plants increase in size and number ...

- Wind plants have a greater impact on the grid
- Displace other generation, so wind needs to provide its share of system support
- Continuity of wind generation contribution becomes essential to grid reliability
- Behavior during disturbances needs to be predictable

Plant Level and WTG Level Controls enable stable, well-behaved performance of grids with high levels of wind power

imagination at work

2



Grid Friendly Wind Power Plant

WindFREE™ Reactive Power
Reactive Power even with no wind

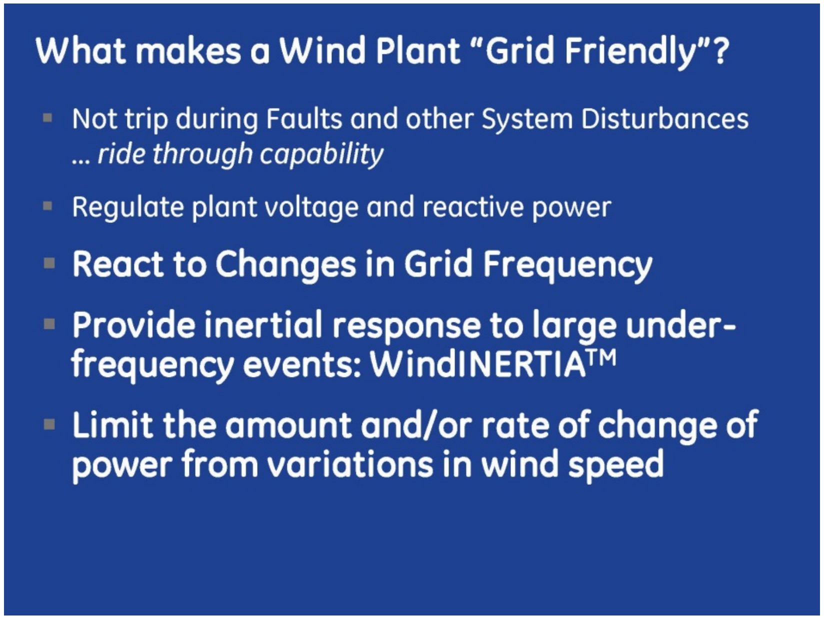
WindRIDE-THRU™
Uninterrupted turbine operation through grid distrubances

WindCONTROL™
Voltage and power regulation like a conventional plant

WindSCADA™
Tools to operate, maintain, and manage the wind plant

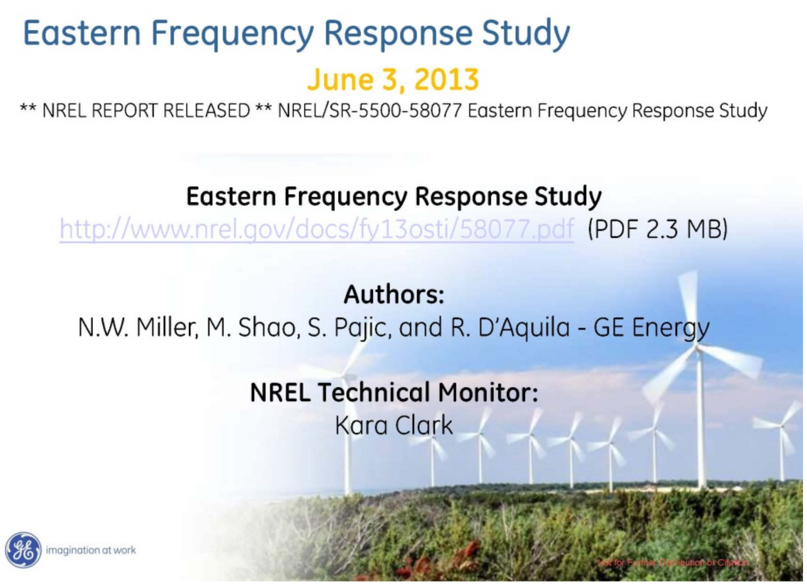
GE Energy

3



What makes a Wind Plant “Grid Friendly”?

- Not trip during Faults and other System Disturbances ... *ride through capability*
- Regulate plant voltage and reactive power
- **React to Changes in Grid Frequency**
- **Provide inertial response to large under-frequency events: WindINERTIA™**
- **Limit the amount and/or rate of change of power from variations in wind speed**



Eastern Frequency Response Study

June 3, 2013

** NREL REPORT RELEASED ** NREL/SR-5500-58077 Eastern Frequency Response Study

Eastern Frequency Response Study

http://www.nrel.gov/docs/fy13osti/58077.pdf (PDF 2.3 MB)

Authors:

N.W. Miller, M. Shao, S. Pajic, and R. D'Aquila - GE Energy

NREL Technical Monitor:

Kara Clark

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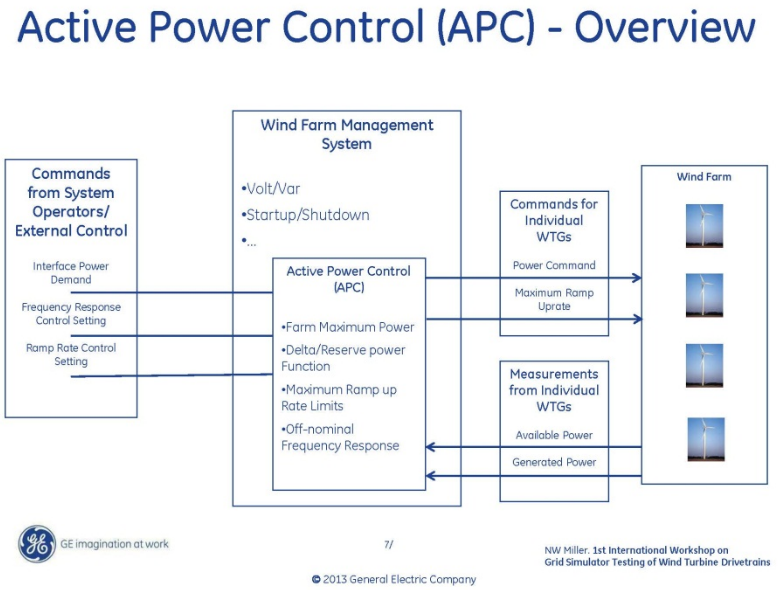
Not for Further Distribution or Citation



Active Power Control (APC) - Overview

Commands from System Operators/ External Control

- Interface Power Demand
- Frequency Response Control Setting
- Ramp Rate Control Setting

Wind Farm Management System

- •Volt/Var
- •Startup/Shutdown
- •…

Active Power Control (APC)

- •Farm Maximum Power
- •Delta/Reserve power Function
- •Maximum Ramp up Rate Limits
- •Off-nominal Frequency Response

Commands for Individual WTGs

- Power Command
- Maximum Ramp Uprate

Measurements from Individual WTGs

- Available Power
- Generated Power

Wind Farm

GE imagination at work

7/

NW Miller. **1st International Workshop on Grid Simulator Testing of Wind Turbine Drivetrains**

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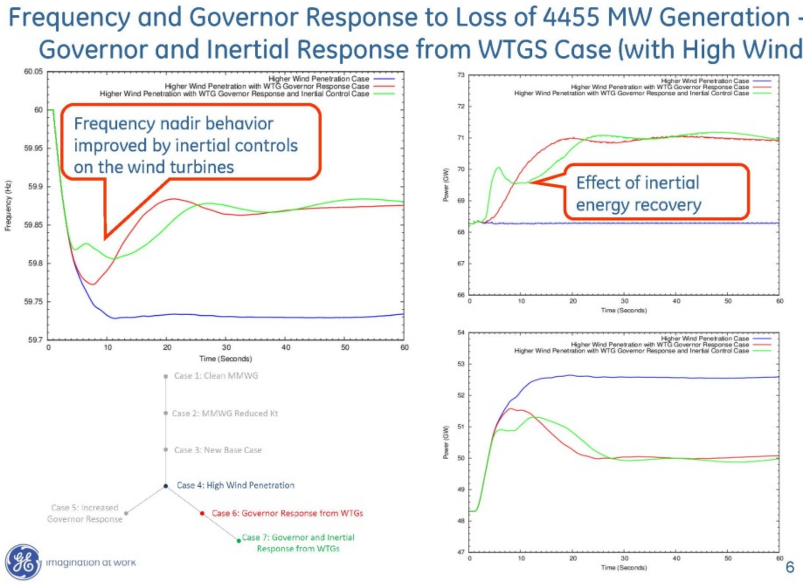


Frequency and Governor Response to Loss of 4455 MW Generation - Governor and Inertial Response from WTGS Case (with High Wind

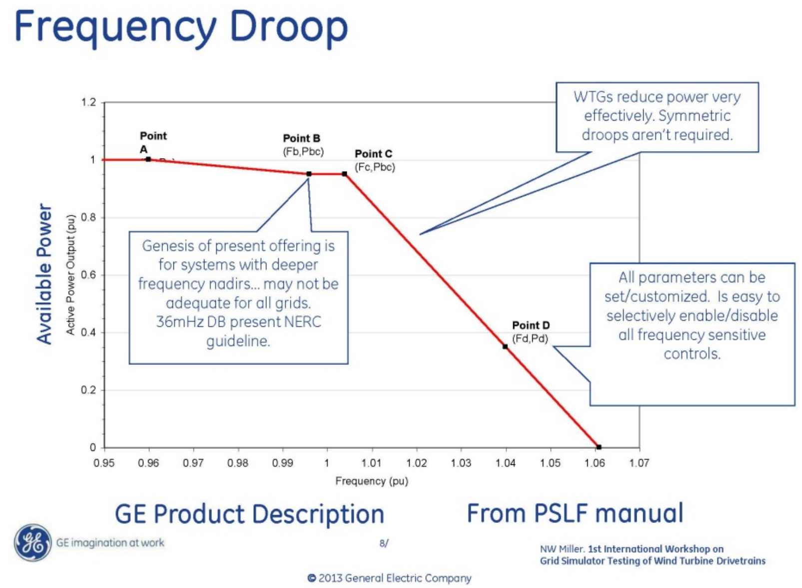
Frequency nadir behavior improved by inertial controls on the wind turbines

Effect of inertial energy recovery

- Case 1: Clean MMWG
- Case 2: MMWG Reduced Kt
- Case 3: New Base Case
- Case 4: High Wind Penetration
- Case 5: Increased Governor Response
- Case 6: Governor Response from WTGs
- Case 7: Governor and Inertial Response from WTGs

imagination at work

6



Frequency Droop

Genesis of present offering is for systems with deeper frequency nadirs… may not be adequate for all grids. 36mHz DB present NERC guideline.

WTGs reduce power very effectively. Symmetric droops aren't required.

All parameters can be set/customized. Is easy to selectively enable/disable all frequency sensitive controls.

GE Product Description

From PSLF manual

GE imagination at work

8/

NW Miller. **1st International Workshop on Grid Simulator Testing of Wind Turbine Drivetrains**

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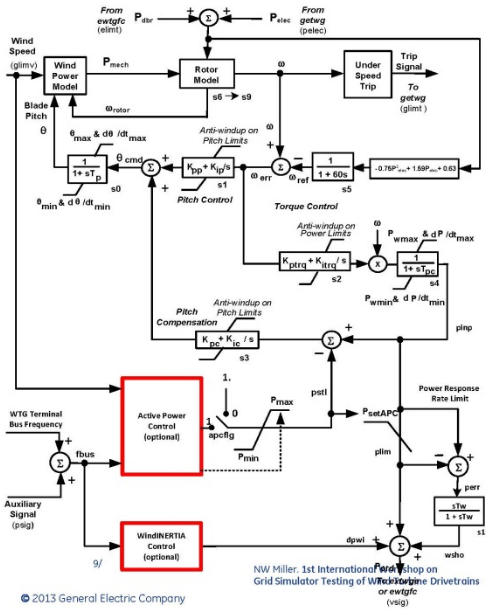
WindINERTIA and APC in Turbine and Turbine Control – PSLF Model

Details



GE Energy

WindINERTIA™: Inertial Response Option for GE Wind Turbine Generators

Nicholas Miller
Kara Clark
Robert Delmerico
Mark Cardinal

WINDPOWER 2009
Chicago, IL, May 4-7

Frequency Droop– What's New

- Retrofit on plants in ERCOT
- Now required in AESO
- Some refinement associated with
  - Reference (Available vs Rated Power)
  - Reduced deadbands

Sleepy issue (in North America at least) is rapidly waking up…
"does it really work"
and
"what does it do to our machines?"
Will be asked more often and louder….

Control Concept

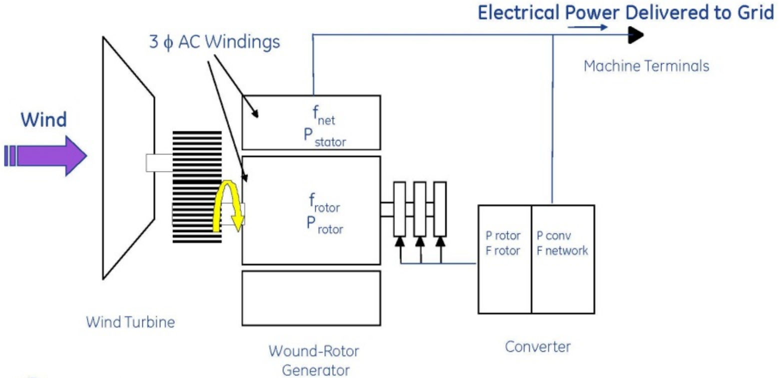
- Use controls to extract stored inertial energy
- Provide incremental energy contribution during the 1st 10 seconds of grid events;
  - Allow time for governors and other controls to act
- Target incremental energy similar to that provided by a synchronous turbine-generator with inertia *(H constant)* of 3.5 pu-sec.
- Focus on functional behavior and grid response: do not try to exactly replicate synchronous machine behavior

Constraints

- Not possible to increase wind speed
- Slowing wind turbine reduces aerodynamic lift:
  - Must avoid stall
- Must respect WTG component ratings:
  - Mechanical loading
  - Converter and generator electrical ratings
- Must respect other controls:
  - Turbulence management
  - Drive-train and tower loads management

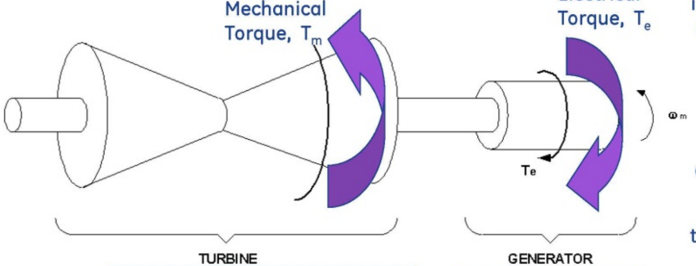
How does it work?

Basic components of a GE Double-fed Asynchronous Wind Turbine Generator:



How does it work? Part 2

Basic machine equations for all rotating machines



$$J\frac{d\omega}{dt} = T_a = T_m - T_e$$

$$H \equiv \frac{1}{2}\frac{J\omega_{mo}^2}{VA_{base}}$$

$$H = \frac{\text{Kinetic Energy Stored in the Rotor (Watt - sec)}}{VA_{base}}$$

Basic Notation:

J is the inertia of the entire drive-train in physical units

H is the inertia constant – it is scaled to the size of the machine.

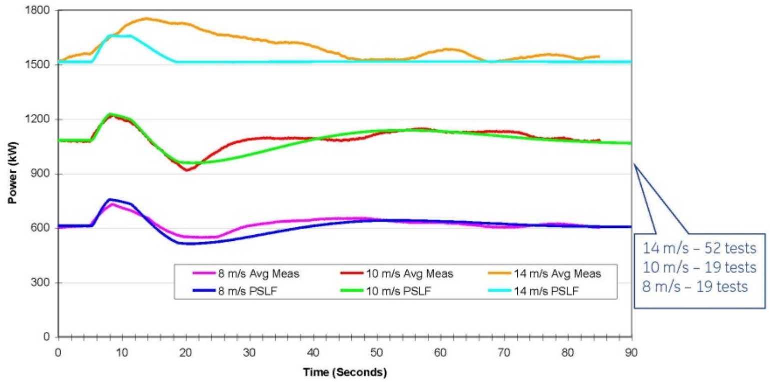
A typical synchronous turbine-generator has an H of about 3.5 MW-sec/MW.

Field Tests Approach and Constraints:

- Not possible to drive grid frequency
- Controls driven with an external frequency signal
  - (very similar to frequency of previous example)
- Performance a function of wind speed
  - (also, not possible to hold wind speed constant during tests)
- Since WTG must respect other controls
  - Turbulence & drivetrain and tower loads management affect performance of individual WTGs at any particular instant
  - Exact performance of single WTG for a single test is not too meaningful
  - Aggregate behavior of interest to grid

WindINERTIA validation tests:
Multiple tests over varying wind conditions

Simulations vs Field Test



WindINERTIA simulations capture key aspects of observed field performance

GE Hybrid Wind Turbine program

What Incorporate battery storage into turbine electrical and controls system

Why To enable new active power control features and enhance existing ones

Whoa! What's different ???

Wind Turbines, Battery Included, Can Keep Power Supplies Stable

Advances like GE's new hybrid wind turbines could make renewable energy more practical.

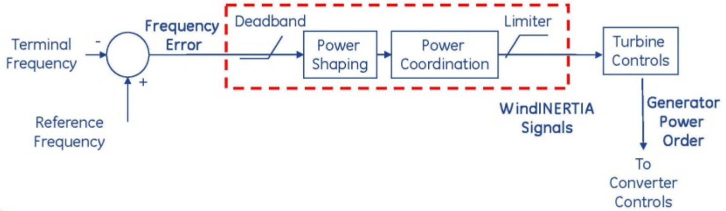
By Kevin Bullis on May 7, 2013

GE recently sold the first of a new line of "hybrid" wind turbines that comes with a battery attached. The turbine's battery can store the equivalent of less than one minute of the turbine operating at full power. But, by pairing the battery with advanced wind-forecasting algorithms, wind farm operators could guarantee a certain amount of power output for up to an hour.

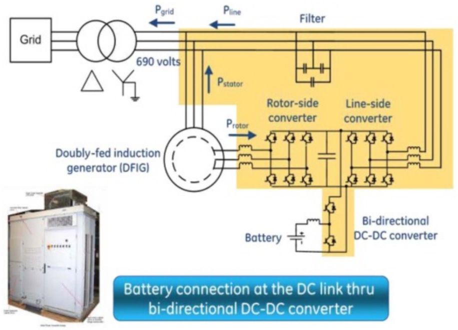
This could make integrating intermittent renewable energy far easier, and lower the cost of wind power. Indeed, even relatively small batteries could double the amount of renewable energy the power grid can handle.

WindINERTIA – What's New

- Present design based on hydro system
- Explorations underway to "tune" these parameters for other systems, e.g., faster but shallower events
- Maintain due diligence on mechanical and electrical stress



What have we done?



Battery connection at the DC link thru bi-directional DC-DC converter

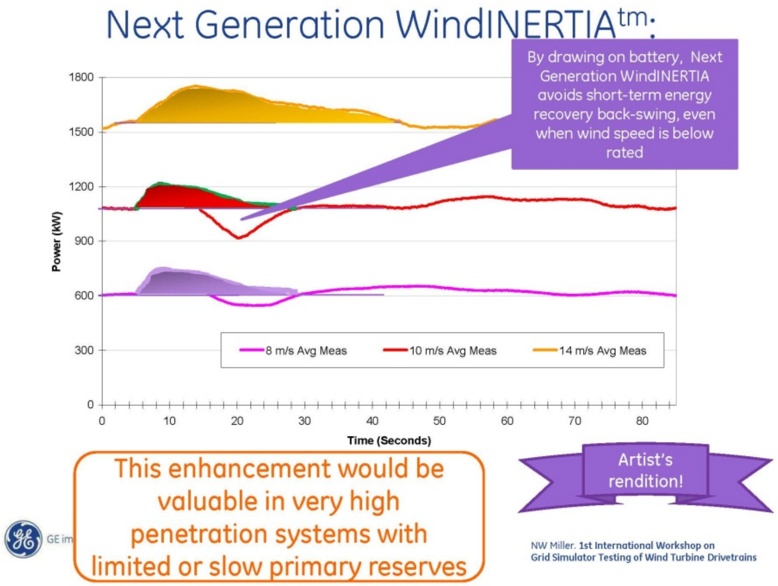
World's 1st GE 1.6-100 Hybrid powered by GE Durathon. Located at Tehachapi, CA

A different beast….

Why Incorporate battery storage into turbine electrical and controls system?

Enhanced functionality:

- Loads control
  - further protection from mechanical stresses of grid events
  - drive-train damping
- Enhanced inertial control
- Enhanced frequency response



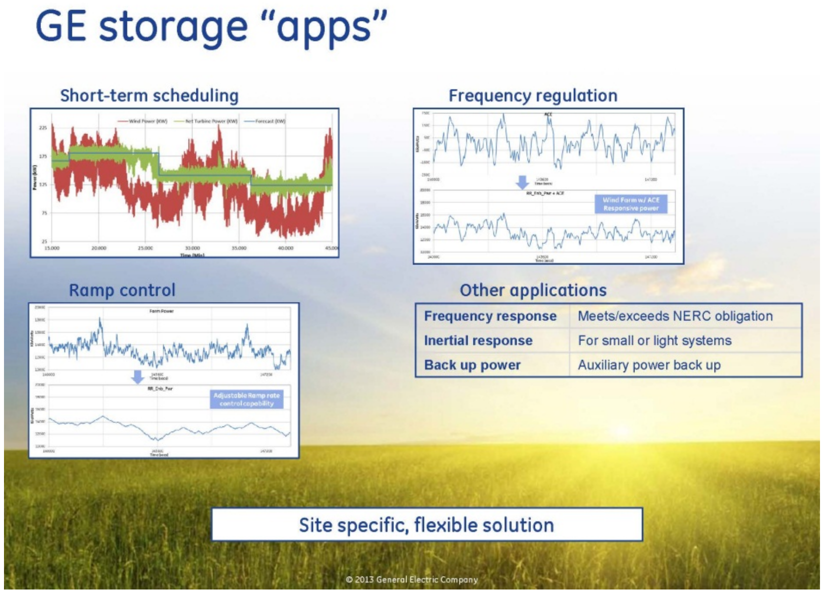
Next Generation WindINERTIA^{tm}:

By drawing on battery, Next Generation WindINERTIA avoids short-term energy recovery back-swing, even when wind speed is below rated

This enhancement would be valuable in very high penetration systems with limited or slow primary reserves

Artist's rendition!

NW Miller. 1st International Workshop on Grid Simulator Testing of Wind Turbine Drivetrains



GE storage "apps"

Other applications

Frequency response	Meets/exceeds NERC obligation
Inertial response	For small or light systems
Back up power	Auxiliary power back up

Site specific, flexible solution

Closing thoughts on CGI/DT testing

- In real systems, voltage AND frequency both change
- Positive sequence fundamental frequency response is critical: 60/50Hz power pays the rent
- More realism in testing is very welcome
- WTGs don't run in a vacuum: testing on complex integrated systems is welcome
- Behavior of **wind plants**, not individual turbines is ultimately what is important to the grid
- Unbalance and non-fundamental frequency behavior can be very important, and even limiting:
  - Unbalance; grounding,
  - Natural frequencies (both subsynchronous and supersynchronous)
  - High-frequency control interaction

Great care is needed to create meaningful tests

GE imagination at work

24/

NW Miller. 1st International Workshop on Grid Simulator Testing of Wind Turbine Drivetrains

GE Energy

Thanks

imagination at work

GE Energy

For more information or to contact us please visit
www.ge-energy.com/ease

Nicholas W. Miller
nicholas.miller@ge.com

imagination at work

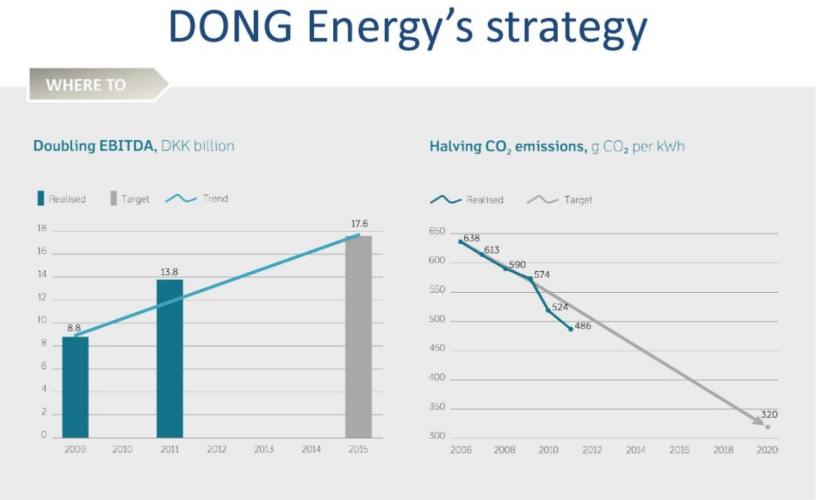
11.5 Wind Power Plant Operator/Developer Perspective

11.5.1 Grid Interconnection Aspects for Offshore Wind Power – Bo Hesselbaek, DONG Energy

DONG Energy Wind Power

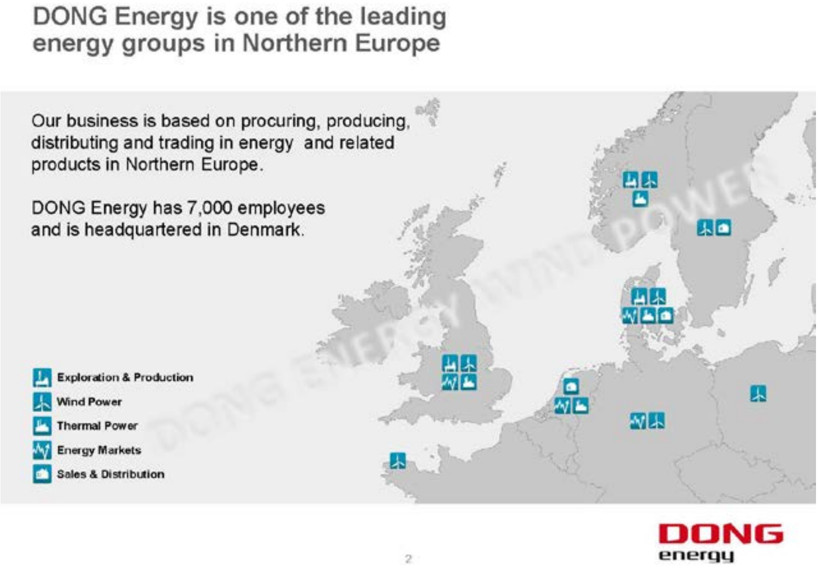
The challenges of connecting offshore wind

Bo Hesselbæk, MSc.EE, MBA
Manager of Grid Analysis
DONG Energy Wind Power
bohes@dongenergy.dk



DONG Energy's strategy

WHERE TO

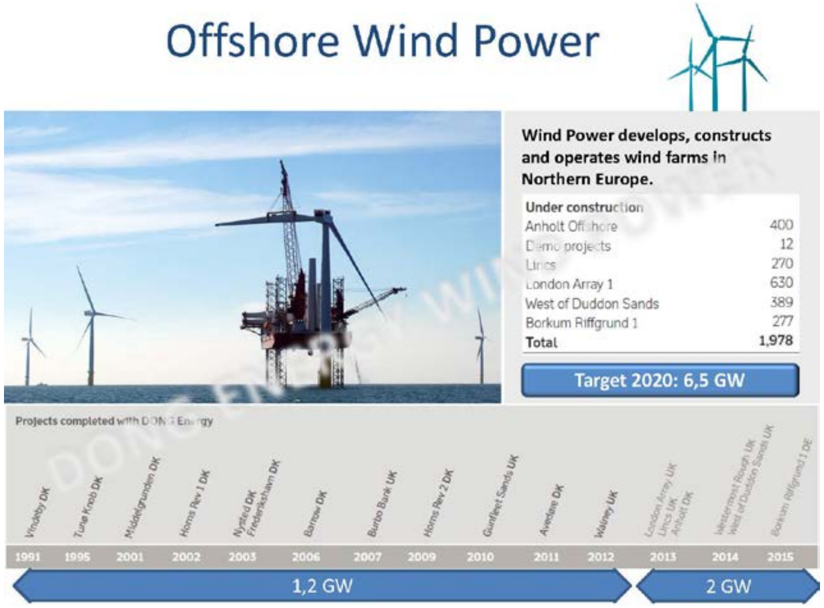


DONG Energy is one of the leading energy groups in Northern Europe

Our business is based on procuring, producing, distributing and trading in energy and related products in Northern Europe.

DONG Energy has 7,000 employees and is headquartered in Denmark.

DONG energy



Offshore Wind Power

Wind Power develops, constructs and operates wind farms in Northern Europe.

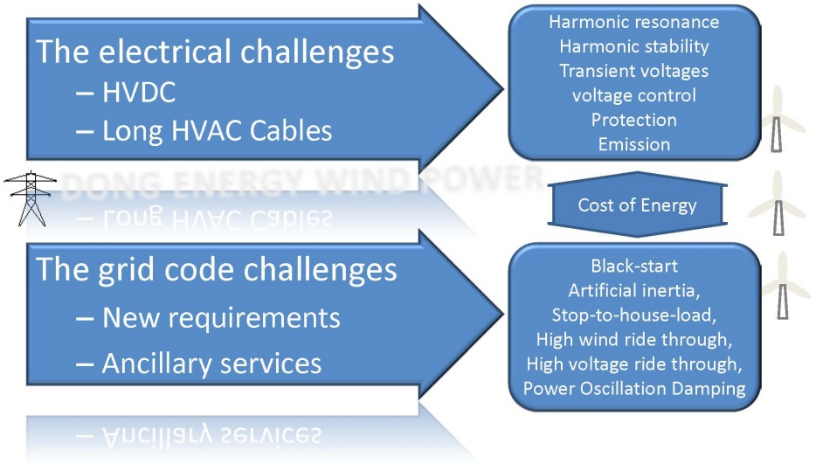
Under construction	
Anholt Offshore	400
Demo projects	12
Lincs	270
London Array 1	630
West of Duddon Sands	389
Borkum Riffgrund 1	277
Total	**1,978**

Target 2020: 6,5 GW

The challenges of connecting offshore wind

- Larger turbines
- Bigger wind farms
- Further from the power system

The challenges of connecting offshore wind



The electrical challenges
- HVDC
- Long HVAC Cables

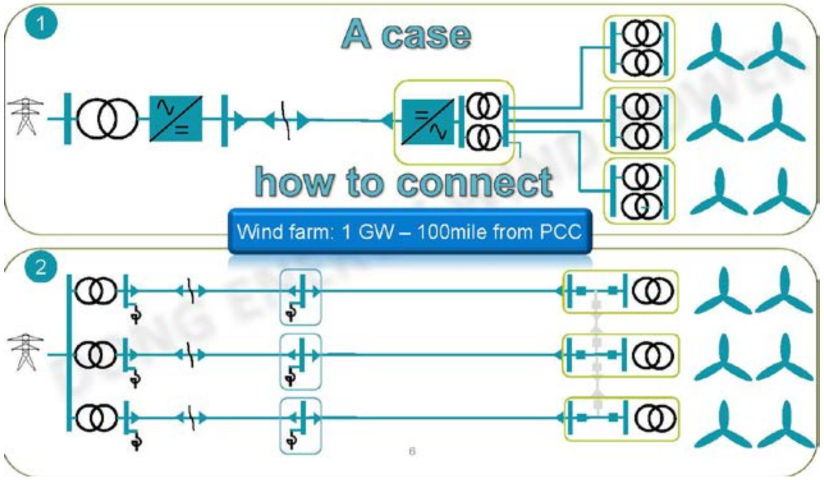
Harmonic resonance
Harmonic stability
Transient voltages
voltage control
Protection
Emission

Cost of Energy

The grid code challenges
- New requirements
- Ancillary services

Black-start
Artificial inertia,
Stop-to-house-load,
High wind ride through,
High voltage ride through,
Power Oscillation Damping

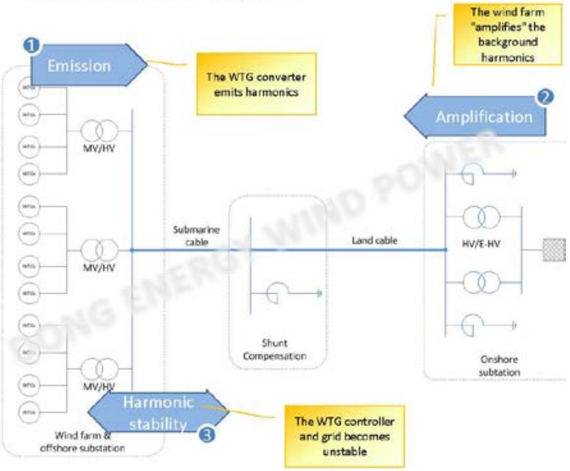
The challenges of connecting offshore wind

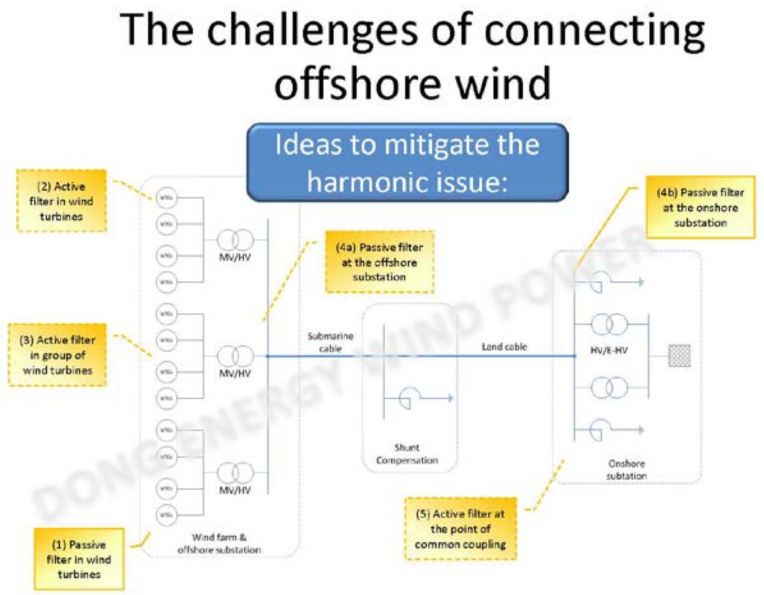


The challenges of connecting offshore wind

Harmonic issues

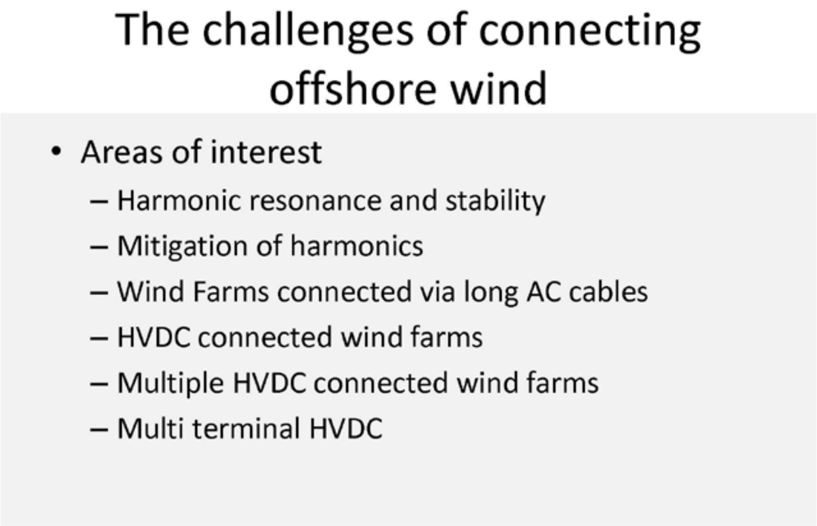
We need to understand:
WTG
converter
controller
array design
export cable
power system





The challenges of connecting offshore wind

Ideas to mitigate the harmonic issue:



The challenges of connecting offshore wind

- Areas of interest
  - Harmonic resonance and stability
  - Mitigation of harmonics
  - Wind Farms connected via long AC cables
  - HVDC connected wind farms
  - Multiple HVDC connected wind farms
  - Multi terminal HVDC

DONG Energy Wind Power

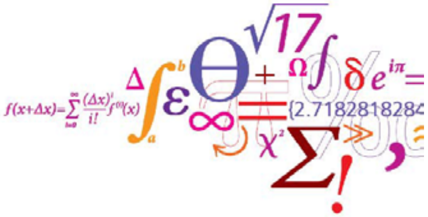
The challenges of connecting offshore wind

Bo Hesselbæk, MSc.EE, MBA
Manager of Grid Analysis
DONG Energy Wind Power
bohes@dongenergy.dk

11.5.2 An Overview of Grid Requirements in Denmark and the Technical University of Denmark's Advanced Grid Test Facility in Osterid – Tom Cronin, Technical University of Denmark

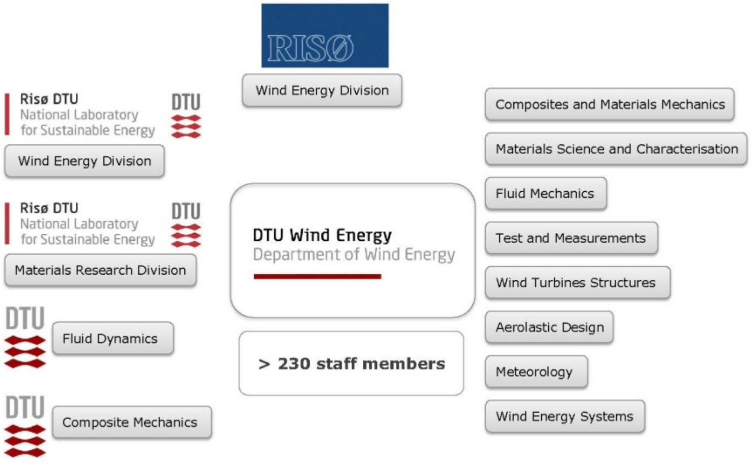
An Overview of Grid Requirements in Denmark and the DTU Advanced Grid Test Facility at Østerild

Tom Cronin
DTU Wind Energy
Technical University of Denmark



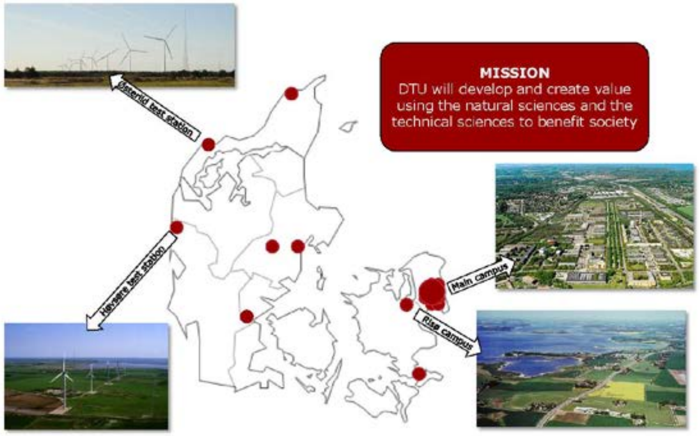
DTU Wind Energy
Department of Wind Energy

DTU Wind Energy



DTU Wind Energy

DTU – Excellence since 1829



MISSION
DTU will develop and create value using the natural sciences and the technical sciences to benefit society

Overview of this presentation

- DTU Wind Energy
- What's the reason for me being at this workshop?
- The Danish grid requirements
  - Who, what and how?
- The DTU Advanced Grid Test Facility
  - Why, what, where and when?

Danish grid codes

ENERGINET.DK

- "Technical regulation 3.2.5 for wind power plants with power output greater than 11kW"
- Issued by the Transmission System Operator: Energinet.dk
- Website: www.energinet.dk
- Due to history of Danish wind power, the Danish grid codes have been at the forefront
- Comprehensive grid codes are needed if have high penetration
- Occasions in Western Denmark when wind power exceeds consumption
- National annual average around 25%
- Average wind production to increase to meet the goal of 50% by 2025.
- Grid codes need to keep in front of this development.

The Danish Grid Codes - structure

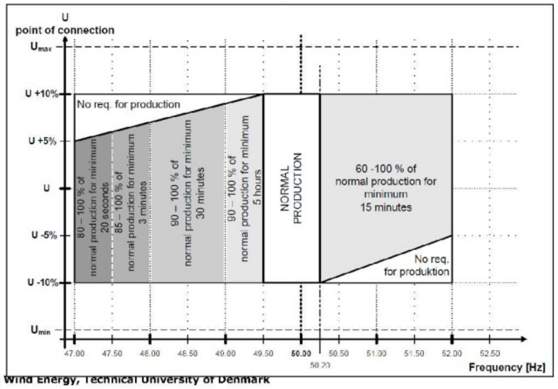
- Tolerance of voltage and frequency deviations
  - Normal operation
  - Abnormal operation
- Electricity quality
- Control and monitoring
- Protection
- Data communication and exchange of signals

All diagrams courtesy of Energinet.dk

Tolerance of frequency & voltage deviations

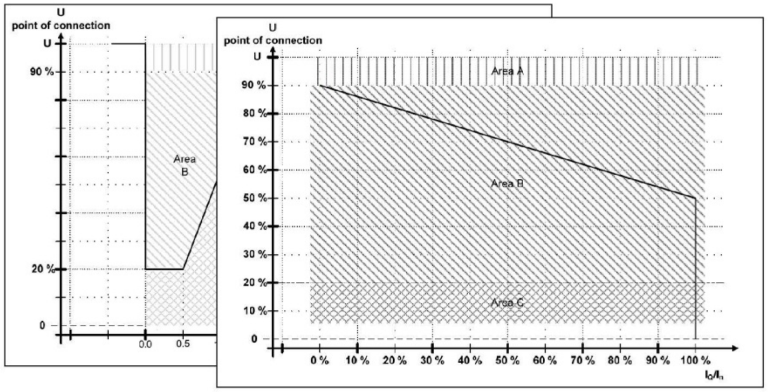
"A *wind power plant* must be able to withstand frequency and voltage deviations in the *point of connection* under normal and abnormal operating conditions while reducing the active power as little as possible."

Normal Operation



Tolerance of frequency & voltage deviations

Abnormal Operation



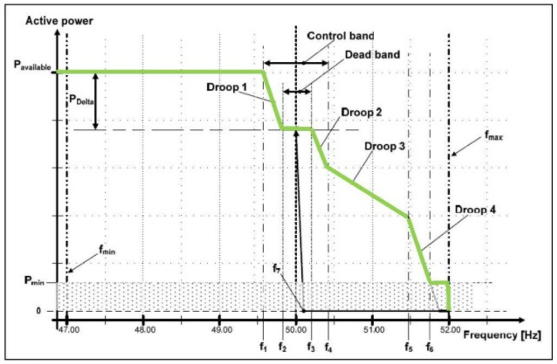
Electricity quality

The grid codes consider:

- Voltage fluctuations
  - Rapid voltage changes
  - Flicker (continuous and switching)
- High frequency currents and voltages
  - Harmonics
  - Inter-harmonics
  - Disturbances greater than 2 kHz

Control & Monitoring: Active power control

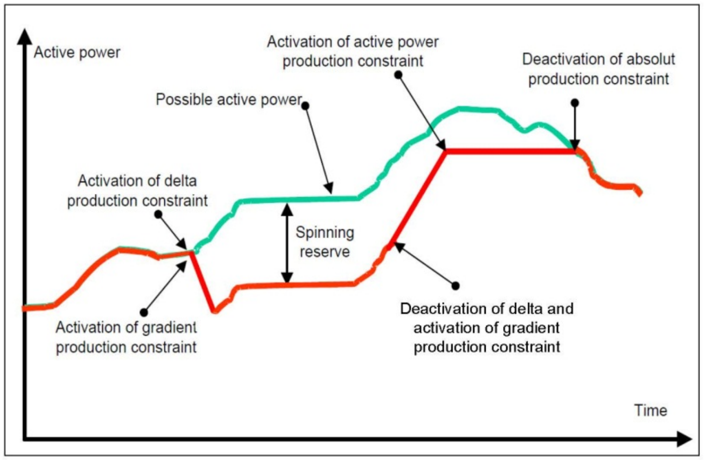
- Frequency control
  - Remotely set droop curves dictate active power vs. frequency



Control & Monitoring: Active power control

- Absolute production constraint
  - Used to prevent overload of system/power lines
- Delta production constraint (spinning reserve)
  - To create a reserve in preparation of frequency control
- Power gradient constraint
  - To prevent system instability dues to fast and large changes in wind speed

Active power control: example

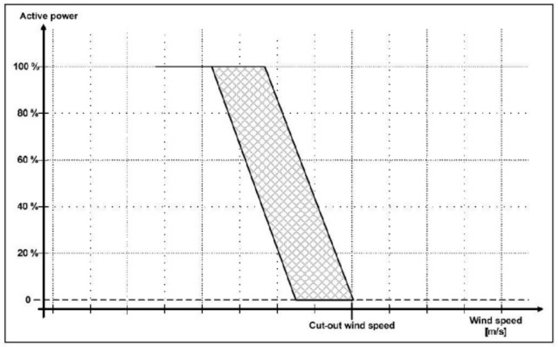


Control & Monitoring: Reactive power control

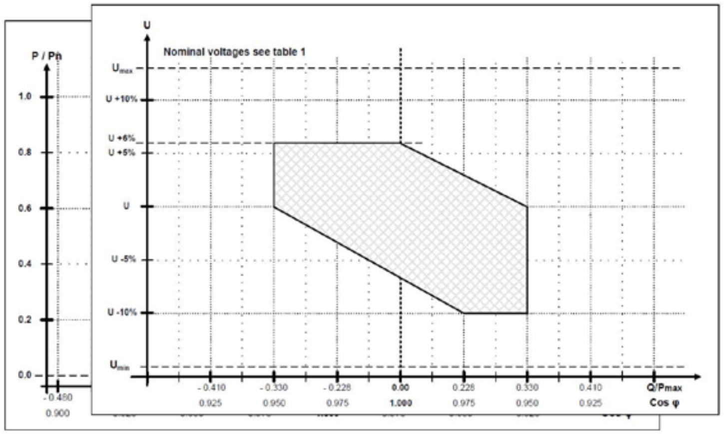
- Q control
  - Reactive power is independent of active power
- Power factor control
  - Reactive power is proportional to active power
- Voltage control
  - Controls the voltage at the voltage reference point , wrt reactive power output

Active power control limits

- Must be able to down-regulate from 100% to 20% of power plant capacity
- Near cut-out wind speed: additional control



Reactive power control limits



Grid codes and the DTU Grid Test Facility

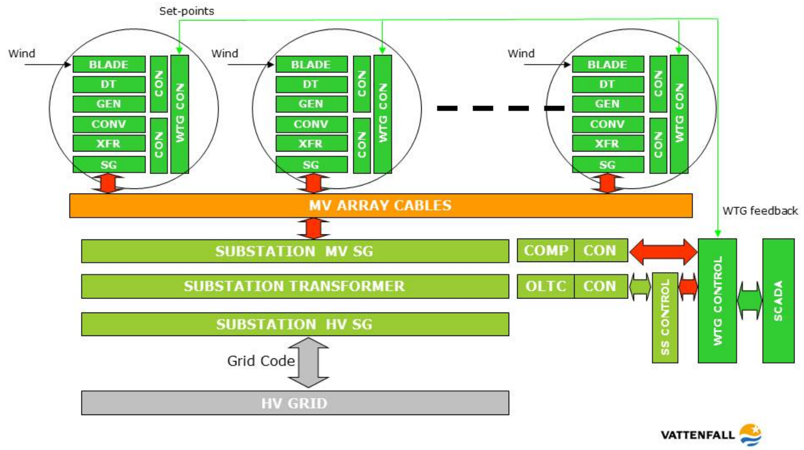
- **In 2011, our feasibility study looked at**
  - Global grid codes
  - Manufacturers' requirements
  - Developers' needs
  - Research areas
  - Equipment alternatives
- **Conclusion**

  Optimum facility combines a converter-based unit and an impedance-based unit

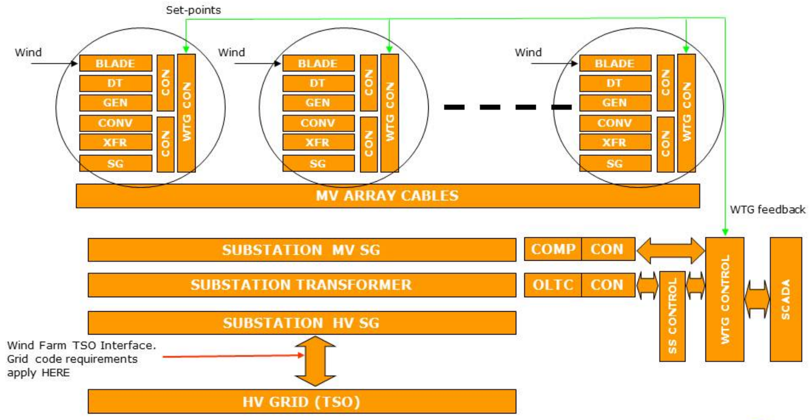
Vestas
Siemens Wind Power
DONG Energy
Vattenfall
ABB
Siemens
DTU
Aalborg University

- **The DTU Advanced Grid Test Facility**
  - 10MW, upgradable to 16MW
  - Grid codes – verification of compliance esp. frequency control
  - Wind turbine testing/development/proving
  - Development of future standards and grid codes
  - Simulation models – validation
  - Wind farm testing

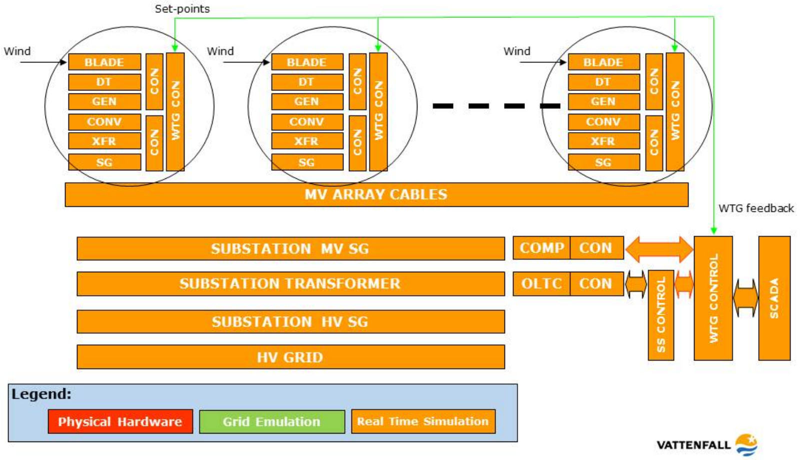
Contract structures...



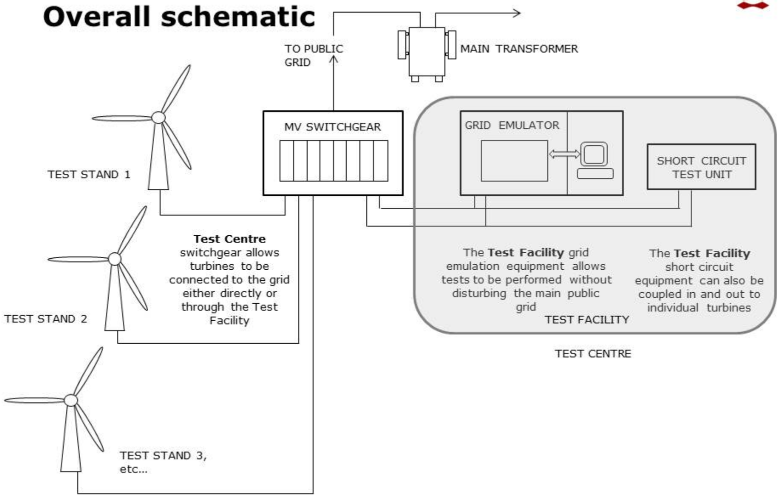
Wind Farm Performance Requirements



Wind Farm Test - scope



Overall schematic



TO PUBLIC GRID

MAIN TRANSFORMER

MV SWITCHGEAR

GRID EMULATOR

SHORT CIRCUIT TEST UNIT

TEST STAND 1

TEST STAND 2

TEST STAND 3, etc...

Test Centre switchgear allows turbines to be connected to the grid either directly or through the Test Facility

The **Test Facility** grid emulation equipment allows tests to be performed without disturbing the main public grid

The **Test Facility** short circuit equipment can also be coupled in and out to individual turbines

TEST FACILITY

TEST CENTRE

To be located at the Danish National Test Centre for Large Wind Turbines, Østerild

Test Centre:
- Opened Oct 2012
- For turbines up to 250m height
- Up to 16MW

Grid Facility:
- €4M secured
- Further funding negotiations
- Transportable
- Ready 'mid 2015'

GREEN LABS DK

Courtesy of Siemens Wind Power

11.6 Advanced Testing Concepts (Hardware-in-the-Loop Testing)

11.6.1 HYPERSIM Real-Time Simulation Platform – Richard Gagnon, IREQ, Canada

Hydro-Québec Research Institute (IREQ) Simulation and Distribution Testing Facilities

Richard Gagnon, Pierre Giroux
IREQ

First International Workshop on Grid Simulator Testing of Wind Turbine Drivetrains
June 14th, 2013 Boulder, CO, USA

Hydro Québec

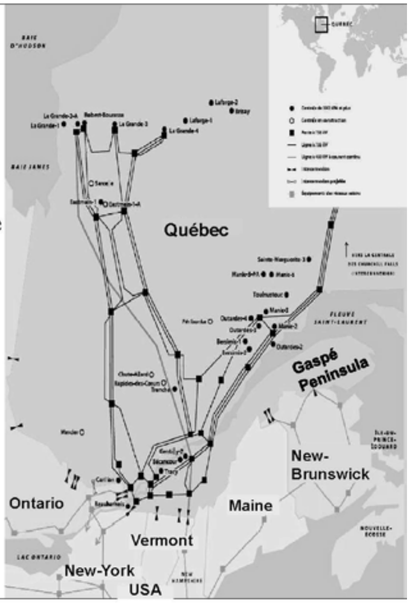
Contents

- > **Video: Hydro-Québec is …**
- > **Hydro-Québec Power System Simulation Activities**
- > **IREQ's Distribution Test Line**
- > **Ideas of some R&D Avenues in an Open Innovation Perspective**

Hydro-Québec's Power System:

Major Generating and Transmission Facilities

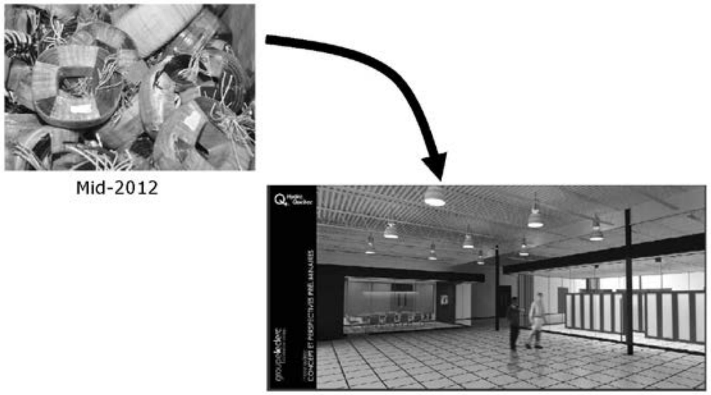
- > Hydro-Québec generates, transmits and distributes electricity, mainly using renewable energy sources, in particular hydroelectricity.
- > Installed capacity: 36 000 MW
- > 15 interconnections with systems in neighboring provinces and states.
- > By 2015, HQ will be carrying about 4 000 MW of wind power over the transmission system.



Hydro-Québec Power System Simulation Activities

- > Hardware-in-the-Loop (HIL) testing of controllers for HVDC, FACTS (SVC, UPFC, …) and protection relays
- > Developing power equipment models (FACTS, Wind Generators, …)
  - Detailed 3-phase Electromagnetic Transient (EMT) models
  - Phasor models for Stability Studies
- > Developing simulation tools: *HyperSim* Real-Time Simulator, Matlab/SimPowerSystems and EMTP-RV

IREQ's Power System Simulator



Mid-2012

Today

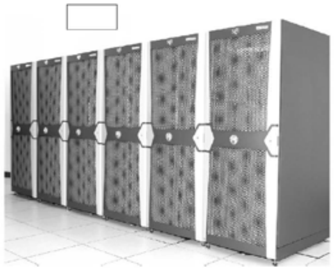
IREQ's Power System Simulator
2 * 500 MW Back-to-Back HVDC
Québec – USA Interconnection

HyperSim Digital Simulator

> **Software**
  - Based on nodal method (EMTP)
  - Graphical user interface
  - Automatic testing environment
  - Interface to MATLAB Real-Time Workshop

> **Hardware**
  - SGI multiprocessor computer
  - Fast input/output modules for HIL testing of real controllers

> **Applications:**
  - HIL testing of real controllers
  - Studies of very large power grid in Off-line mode (like a very fast EMTP simulation)

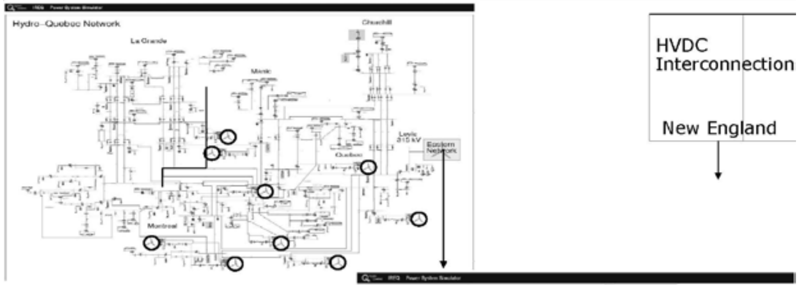


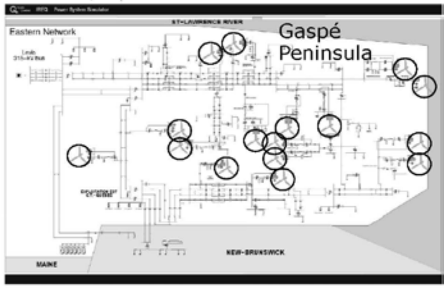
Applications: Examples

> **Protection system testing:**
  - HQ-TransÉnergie et HQ-Production have their own HyperSim facilities.
  - Also in HQ substations for maintenance and training.

> **HVDC Testing**
  - Outaouais HVDC Interconnection, (Quebec-Ontario)
  - Châteauguay HVDC Interconnection (Quebec-USA)
  - LG2-Nicolet-Boston Multi-terminal HVDC
  - Champlain-Hudson Power Express Interconnection (?)

> **Wind turbines and Wind Power Plants (WPP)**
  - Model Validation
  - Ability to Simulate "Black Box" Manufacturer's Models
  - Large-Scale Integration Studies (Real-time or Off-line)





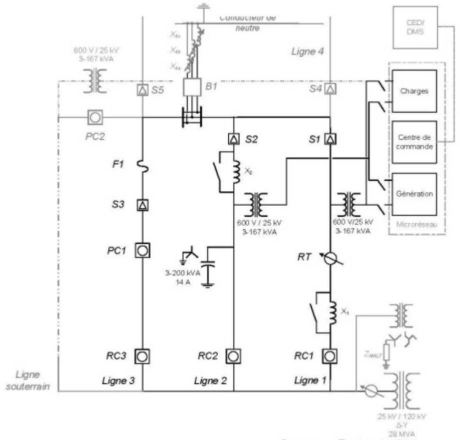
780 bus
189 lines
25 WPPs (DFIG single-machine eq.)
35 synch. generators
7 SVC
6 synch. Condensers
Series compensation
1 Multi-Terminal HVDC interconnection

IREQ's Distribution Test Line

CASIR : IREQ's High Performance Computing Data Center

- 84 TFlops of x86 processing
- 21 TFlops of GPU processing
- 4124 CPU cores (x86)
- 16 TB of distributed RAM
- 120 TB GPFS parallel file system
- QDR/FDR (40/50 Gbps) Infiniband network
- A team of 3 scientists specialized in HPC

Distribution Test Line



Five technology areas:

- Advanced Protection & Microgrid Controller
- Distributed Energy Ressources (DER)
- Underground Infrastucture
- Metering & Telecommunications
- Distribution Management System (DMS)

Distribution Test Line - Details of DER

> **Synchronous generators**
  - 400 kVA diesel, Caterpillar engine

> **Induction generator**
  - 200 kVA dc motor driven Baldor IM

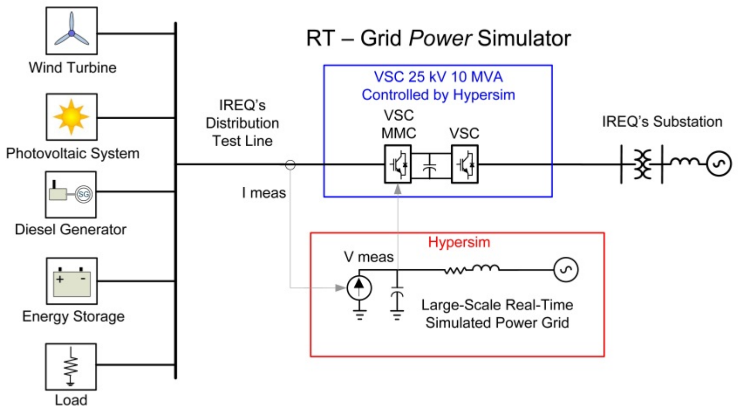
> **Inverters**
  - 250 kVA SMA PV inverter, dc supply fed
  - 135 kVA Satcon inverter, solar concentrator fed
  - 250 kVA BESS converter with 100 kWh Li-ion FePO4 batteries

> **Controllable RLC load - this could incorporate some interruptible component**

Ideas of some R&D Avenues in an Open Innovation Perspective

- **More Real-Time Performance**
  (very demanding power electronics applications, very large grid simulation…)
- **More interoperability between simulation tools**
  (Common Models, Human Interface, …)
- **Multi-Domain Simulation**
  (Phasor – EMT, Telecommunications, Thermal, Magnetic …)
- **Manufacturer Virtual Controller**
  ("black box concept", …)
- **RT - Grid *Power* Simulator**
  (Characterization of wind turbine, storage systems, electric car, …)

Up to now it's just a concept, but …



RT – Grid Power Simulator *for* Testing and Integrating of Wind Turbines

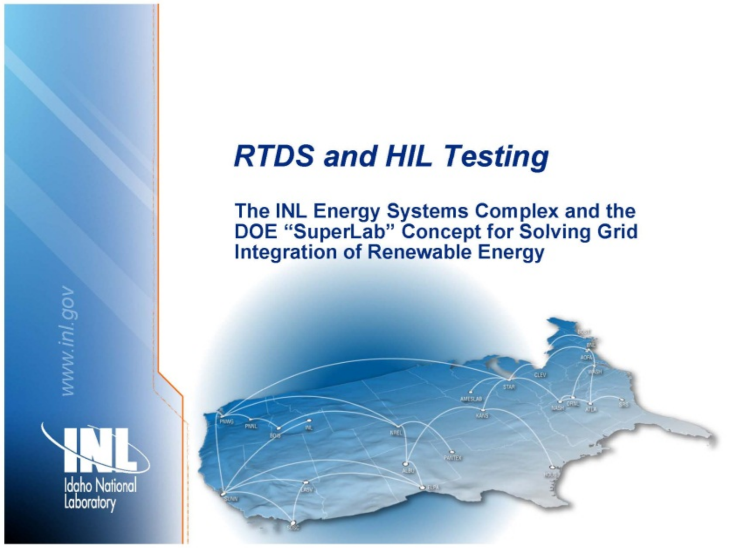
> **Model validation and performance validation for:**
  - Low Voltage Ride Through
  - High Voltage Ride Through
  - Inertia Emulation
  - Subsynchronous Resonances
  - Subsynchronous Control Interactions (series compensation and HVDC)
  - Connection to Weak AC system

> **Development and Validation of Advanced Protection Systems in Distribution Network**

> **Development and Validation of Advanced Controllers for Wind-Diesel-Storage Systems in Isolated Network**

Hydro Québec

11.6.2 Real-Time Digital Simulator for HIL Testing – Tom Baldwin, Idaho National laboratory, USA

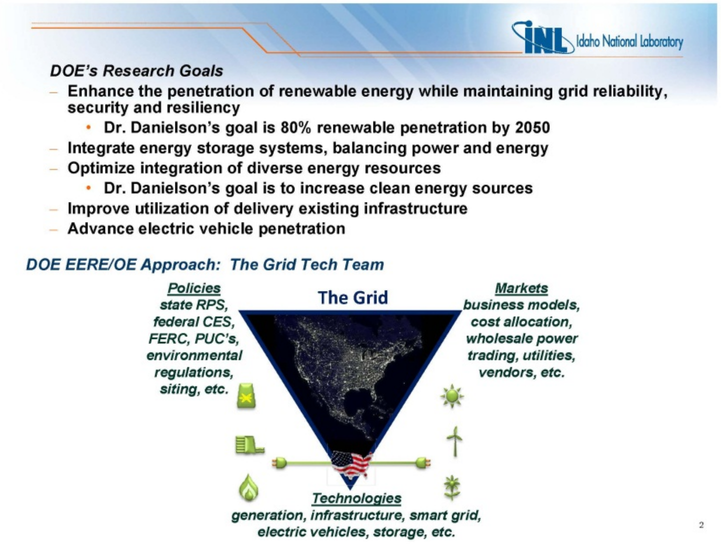


RTDS and HIL Testing

The INL Energy Systems Complex and the DOE "SuperLab" Concept for Solving Grid Integration of Renewable Energy

www.inl.gov

Idaho National Laboratory



Idaho National Laboratory

DOE's Research Goals

- Enhance the penetration of renewable energy while maintaining grid reliability, security and resiliency
  - Dr. Danielson's goal is 80% renewable penetration by 2050
- Integrate energy storage systems, balancing power and energy
- Optimize integration of diverse energy resources
  - Dr. Danielson's goal is to increase clean energy sources
- Improve utilization of delivery existing infrastructure
- Advance electric vehicle penetration

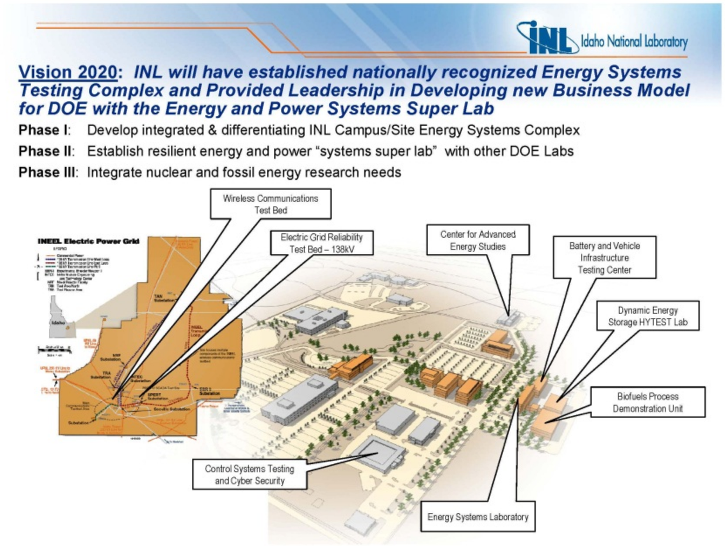
DOE EERE/OE Approach: The Grid Tech Team

The Grid

Policies
state RPS, federal CES, FERC, PUC's, environmental regulations, siting, etc.

Markets
business models, cost allocation, wholesale power trading, utilities, vendors, etc.

Technologies
generation, infrastructure, smart grid, electric vehicles, storage, etc.



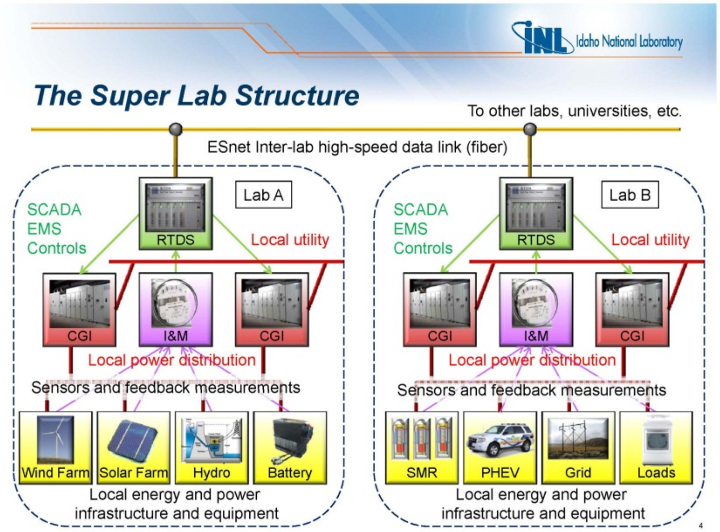
Idaho National Laboratory

***Vision 2020**: INL will have established nationally recognized Energy Systems Testing Complex and Provided Leadership in Developing new Business Model for DOE with the Energy and Power Systems Super Lab*

Phase I: Develop integrated & differentiating INL Campus/Site Energy Systems Complex

Phase II: Establish resilient energy and power "systems super lab" with other DOE Labs

Phase III: Integrate nuclear and fossil energy research needs



Idaho National Laboratory

The Super Lab Structure

To other labs, universities, etc.

ESnet Inter-lab high-speed data link (fiber)

Analysis, Testing & Optimization of Dynamic Energy Systems

- Innovation
- Collaboration
- HiL demonstration

"Runtime integration and cooperation of simulation tools & hardware assets"

- Acausal dynamic simulations
- Causal dynamic simulations
- Multi-domain hybrid models

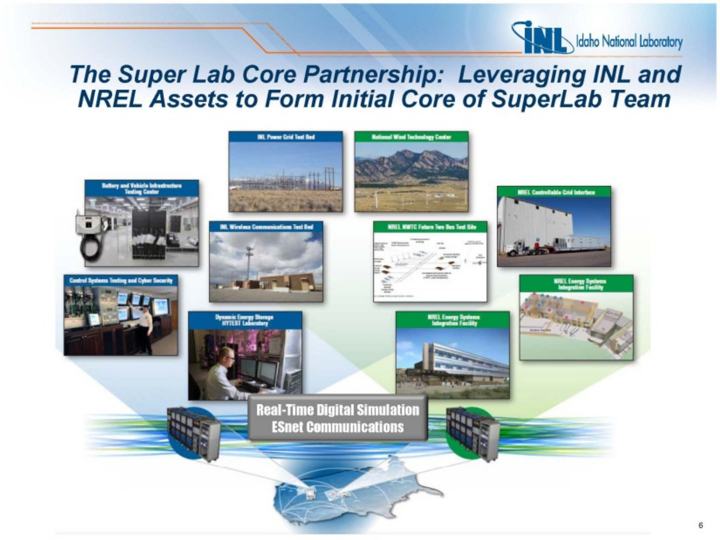
- Dynamic Performance Analysis
- Dynamic Cost/Economic Analysis
- Multidimentional Optimization

- Energy Sciences Network (ESnet)
- INL RTDS & communication links
- Collaborators' assets

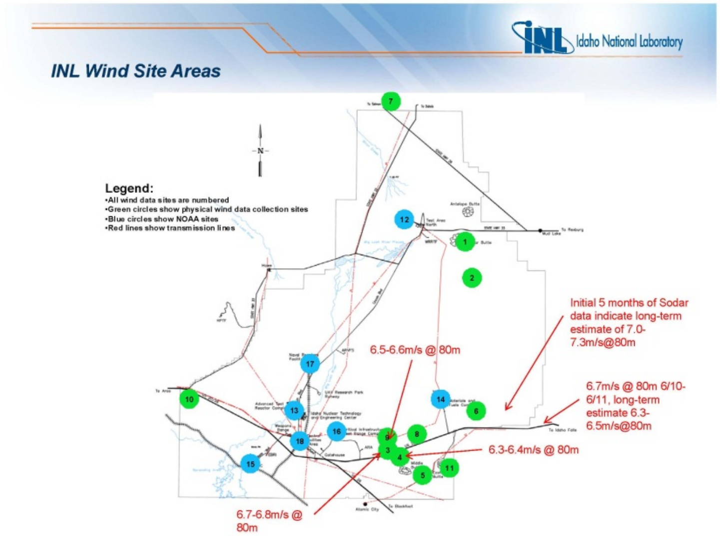
- Fortran, C/C++, Java, Python programs
- MATLAB/Simulink, LabView, Scilab
- RELAP, ASPEN, HYSYS, FAST/AeroDyn

- Resilient Control Systems
- Diagnostics & Prognostics
- Predictive Monitoring & Controls

- INL Powergrid Test bed
- INL Telecommunication Test Bed
- Power / Thermal Converters
- Realistic Electrical / Thermal Components (e.g., SCADA, transformers, heat exchangers)



The Super Lab Core Partnership: Leveraging INL and NREL Assets to Form Initial Core of SuperLab Team



INL Wind Site Areas

Legend:

- All wind data sites are numbered
- Green circles show physical wind data collection sites
- Blue circles show NOAA sites
- Red lines show transmission lines

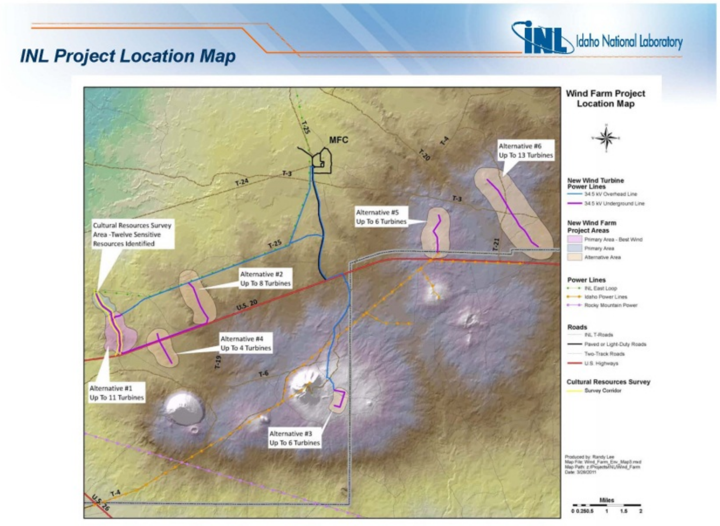
Initial 5 months of Sodar data indicate long-term estimate of 7.0-7.3m/s@80m

6.5-6.6m/s @ 80m

6.7m/s @ 80m 6/10-6/11, long-term estimate 6.3-6.5m/s@80m

6.3-6.4m/s @ 80m

6.7-6.8m/s @ 80m



INL Project Location Map

Wind Farm Project Location Map

New Wind Turbine Power Lines
- 34.5 kV Overhead Line
- 34.5 kV Underground Line

New Wind Farm Project Areas
- Primary Area - Best Wind
- Primary Area
- Alternative Area

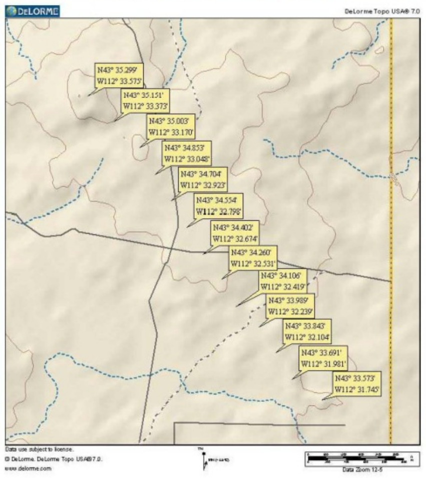
Power Lines
- INL East Loop
- Idaho Power Lines
- Rocky Mountain Power

Roads
- INL T-Roads
- Paved or Light-Duty Roads
- Two-Track Roads
- U.S. Highways

Cultural Resources Survey
- Survey Corridor

Produced by: Randy Lee
Map File: Wind_Farm_Env_Map3.mxd
Map Path: z:\Projects\INL\Wind_Farm
Date: 3/28/2011

Area #6 Potential Turb Layout



Overview/Status

- Class 3 wind site identified: commercially viable
- At area #6, with low wind turbine model, gross capacity factor estimated between 38-40%.
- Many locations around INL have been assessed to characterize the wind resources, and best wind sites identified.
- Possible alternatives identified for electrical interconnection
- No anticipated fatal flaws
  - Biological survey—mitigation looks promising
  - Cultural survey—mitigation looks promising
- Power line connection design will not impact safety system

Project Description

- Total wind farm nameplate capacity is planned at 20MW
  - Potential for larger project size
  - This will be driven by project economics and turbine availability at time of contract award
- Total number of turbines combined from all areas will range between 8-13 turbines
  - Depending on the nameplate size of the wind turbine chosen for the project
  - Wind turbine nameplate size will range between 1.5-3.0MW.
  - Wind turbine hub height will be between 80-100 meters depending on turbine chosen
  - Wind turbine rotor diameters will likely be between 82-117 meters depending on turbine chosen

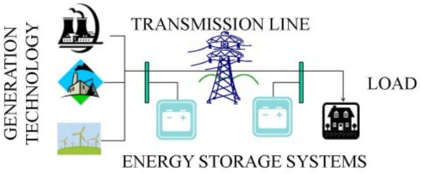
Super Lab Capabilities

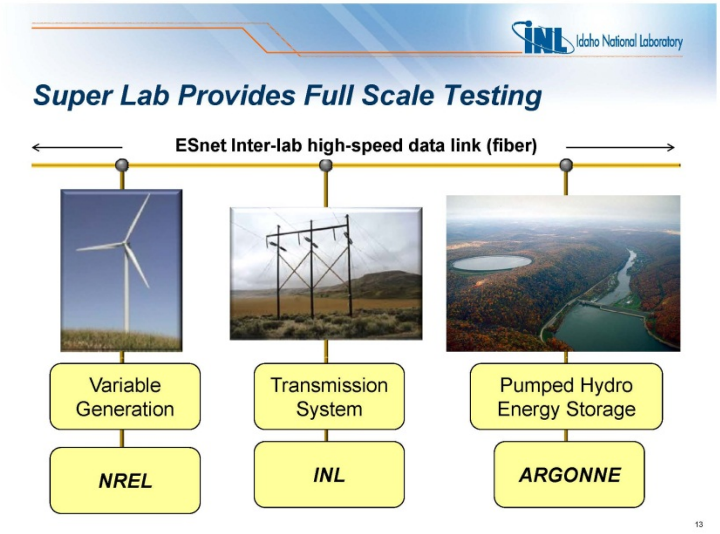
- Super Lab concept will pave the way for research testing of models such as the Renewable Energy and SuperGrid Integration project

Issue	Goal
Unable to meet demand if largely dependent upon variable generation	Use ESS to control variable generation Maximize transmission system capacities at all times

Pdemand = Pbase + Pdispatchable + Pvariable

Transmission system capacity built to handle peak demand, but is rarely met





Super Lab Provides Full Scale Testing

ESnet Inter-lab high-speed data link (fiber)

Variable Generation

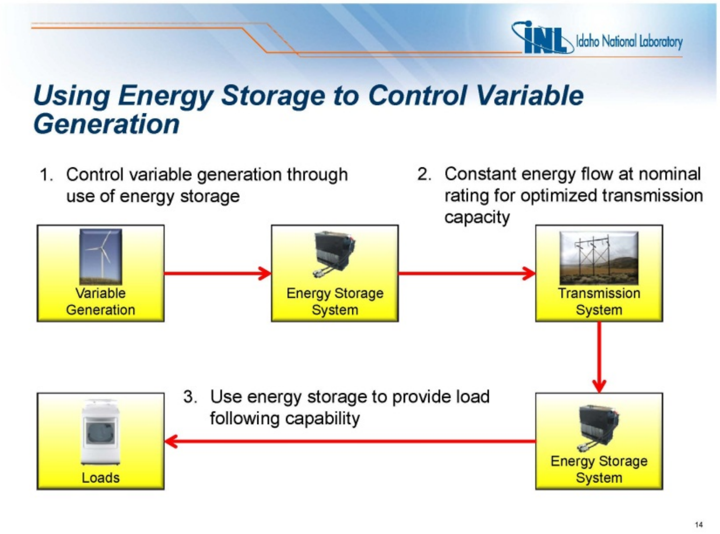
Transmission System

Pumped Hydro Energy Storage

NREL

INL

ARGONNE



Using Energy Storage to Control Variable Generation

1. Control variable generation through use of energy storage
2. Constant energy flow at nominal rating for optimized transmission capacity
3. Use energy storage to provide load following capability

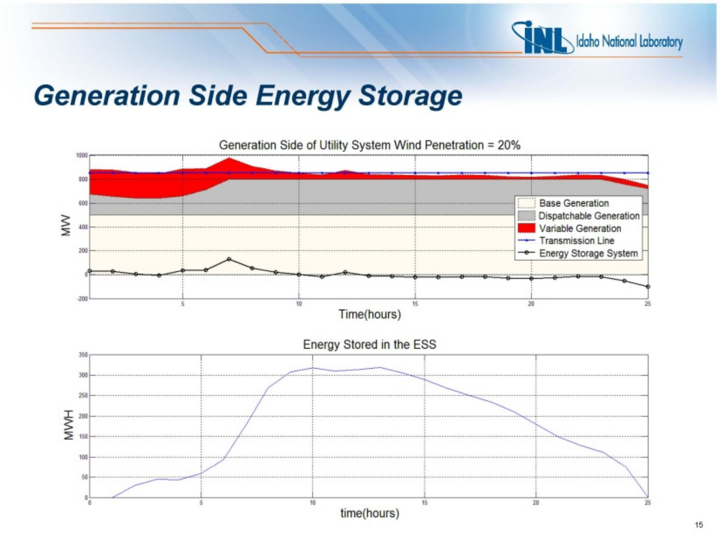
Variable Generation

Energy Storage System

Transmission System

Energy Storage System

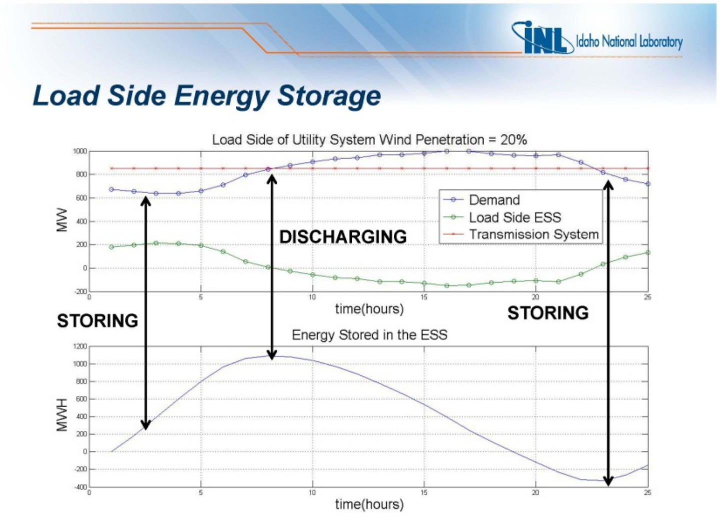
Loads



Generation Side Energy Storage

Generation Side of Utility System Wind Penetration = 20%

Energy Stored in the ESS



Load Side Energy Storage

Load Side of Utility System Wind Penetration = 20%

DISCHARGING

STORING

STORING

Energy Stored in the ESS

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Capability Summary

- Energy storage is required on both generation and load side of a system
  - Controls variable generation
  - Optimizes transmission system capacities
  - Satisfies demands during both peak and off-peak time periods
- Energy storage size/stability depends upon location:

	Generation Side	Load Side
Size	% variable generation dependence	Demand profile
Stability	Transmission line capacity	Transmission line capacity

- Super grid enables full scale testing of energy storage and grid integration

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General Benefits

For DOE

- Provides a new and needed business model to help achieve greater national impact.
- Leverage investments across the DOE
- DOE-EERE: Addresses enhancing penetration of renewable energy and EVs
- For DOE-OE: Helps address grid integration and cyber security challenges
- Provides new business model between two of the three DOE "energy labs"

For INL

- Strengthens INL differentiator/offering
- Opens up new DOE and DoD market opportunities
- Becomes focal point for next level of integration and research
- Creates INL national branding opportunity
- Leverages INL / DOE complex assets - strengthening position with DOE
- Strengthens INL's regional impact and HES position

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Backup Slides

INL ENERGY SYSTEMS TESTING COMPLEX

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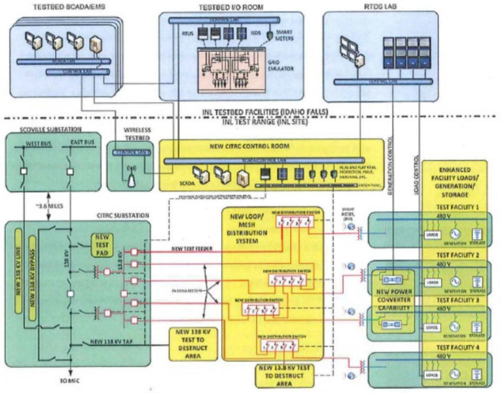
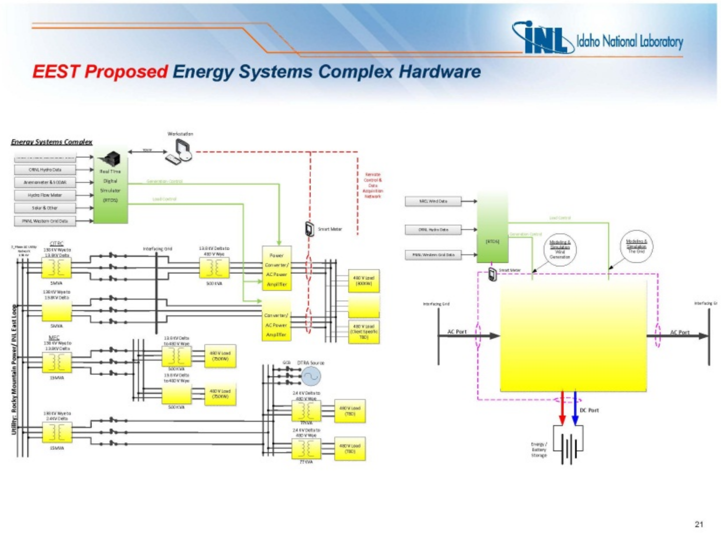
NHS Proposed Electric Grid Reliability Test bed (EGRTB) Hardware





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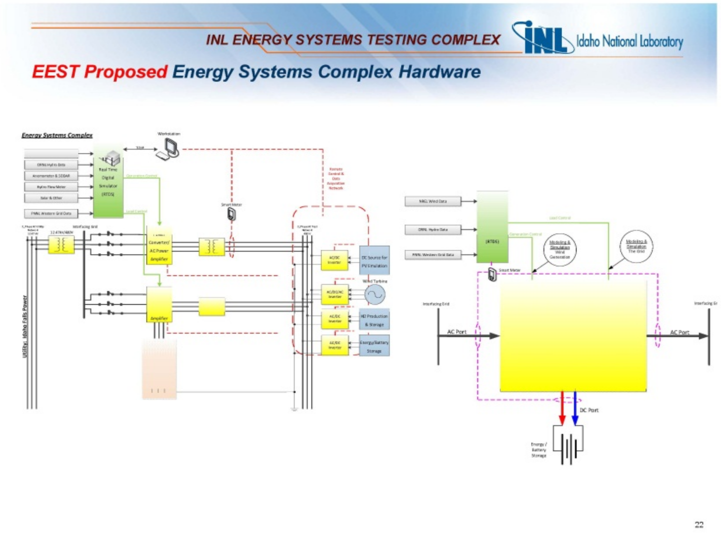
EEST Proposed Energy Systems Complex Hardware



INL ENERGY SYSTEMS TESTING COMPLEX

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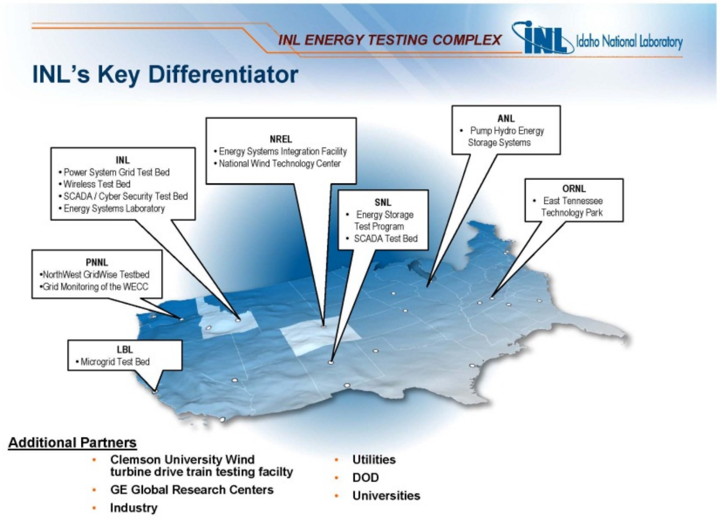
EEST Proposed Energy Systems Complex Hardware



INL ENERGY TESTING COMPLEX

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INL's Key Differentiator

INL
- Power System Grid Test Bed
- Wireless Test Bed
- SCADA / Cyber Security Test Bed
- Energy Systems Laboratory

NREL
- Energy Systems Integration Facility
- National Wind Technology Center

ANL
- Pump Hydro Energy Storage Systems

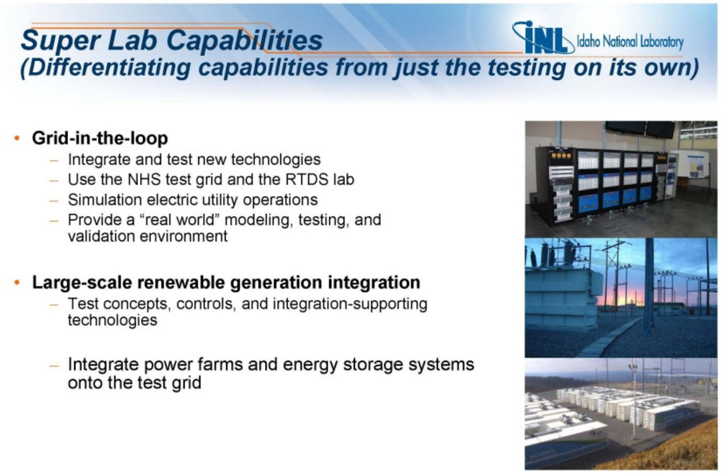
ORNL
- East Tennessee Technology Park

SNL
- Energy Storage Test Program
- SCADA Test Bed

PNNL
- NorthWest GridWise Testbed
- Grid Monitoring of the WECC

LBL
- Microgrid Test Bed

Additional Partners
- Clemson University Wind turbine drive train testing facilty
- GE Global Research Centers
- Industry
- Utilities
- DOD
- Universities



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Super Lab Capabilities
(Differentiating capabilities from just the testing on its own)

- **Grid-in-the-loop**
  - Integrate and test new technologies
  - Use the NHS test grid and the RTDS lab
  - Simulation electric utility operations
  - Provide a "real world" modeling, testing, and validation environment
- **Large-scale renewable generation integration**
  - Test concepts, controls, and integration-supporting technologies
  - Integrate power farms and energy storage systems onto the test grid