Final Technical Report

on

Recovery Act:
Clemson University Wind Turbine Drivetrain Test Facility

Award Number: DE-EE0003023

For Project Period

January 1, 2010 to December 31, 2015

Submitted by

Mr. James Tuten, Project Manager, 843-554-7226 x122, jtuten@clemson.edu
Dr. Imtiaz Haque, Principal Investigator, 864-283-7217 SIH@clemson.edu
Dr. Nikolaos Rigas, Co-Principal Investigator, 843-730-5072 NRIGAS@clemson.edu

Date of Report: March 30, 2016

Acknowledgment:

"This report is based upon work supported by the U. S. Department of Energy under Award No. DE-EE0003023 ".

Disclaimer:

"Any findings, opinions, and conclusions or recommendations expressed in this report are those of the author(s) and do not necessarily reflect the views of the Department of Energy"

Proprietary Data Notice:

If there is any patentable material or protected data in the report, the recipient, consistent with the data protection provisions of the award, must mark the appropriate block in Section K of the DOE F 241.3, clearly specify it here, and identify them on appropriate pages of the report. Other than patentable material or protected data, reports must not contain any proprietary data (limited rights data), classified information, information subject to export control classification, or other information not subject to release. Protected data is specific technical data, first produced in the performance of the award, which is protected from public release for a period of time by the terms of the award agreement. Reports delivered without such notice may be deemed to have been furnished with unlimited rights, and the Government assumes no liability for the disclosure, reproduction or use of such reports.

Executive Summary

In November of 2009, Clemson University was awarded a competitive grant from the U.S. Department of Energy to design, build and operate a facility for full-scale, highly accelerated mechanical testing of next-generation wind turbine drivetrain technologies. The primary goal of the project was to design, construct, commission, and operate a state-of-the-art sustainable facility that permits full-scale highly accelerated testing of advanced drivetrain systems for large wind turbines. The secondary goal was to meet the objectives of the American Recovery and Reinvestment Act of 2009, especially in job creation, and provide a positive impact on economically distressed areas in the United States, and preservation and economic recovery in an expeditious manner.

The project was executed according to a managed cooperative agreement with the Department of Energy and was an extraordinary success. The resultant new facility is located in North Charleston, SC, providing easy transportation access by rail, road or ship and operates on an open access model such that it is available to the U.S. Wind Industry for research, analysis, and evaluation activities. The 72 m by 97 m facility features two mechanical dynamometer test bays for evaluating the torque and blade dynamic forces experienced by the rotors of wind turbine drivetrains. The dynamometers are rated at 7.5 MW and 15 MW of low speed shaft power and are configured as independent test areas capable of simultaneous operation. All six degrees of freedom, three linear and three rotational, for blade and rotor dynamics are replicated through the combination of a drive motor, speed reduction gearbox and a controllable hydraulic load application unit (LAU). This new LAU setup readily supports accelerated lifetime mechanical testing and load analysis for the entire drivetrain system of the nacelle and easily simulates a wide variety of realistic operating scenarios in a controlled laboratory environment. The development of these two dynamometer test rigs is the first significant achievement for the project. These test rigs embody a new manner of test due to the system configuration and completely new design with a free floating loading hub in the LAU. This project provided the catalyst for the advancement to this new test rig configuration that has been adopted by every significant wind turbine test rig constructed since the inception of this project. There are currently two different vendors supplying these new systems. Catalyzing this new design is the second major success of the project.

With the increased market penetration of wind energy over the past decade, many regions and countries have developed specific electrical grid specifications and performance codes for large wind farms to ensure operational reliability and stability. These grid codes provide requirements for interconnection with the grid during low or high voltage phenomena, typically encountered during and after system fault events. Given the installed infrastructure of the Wind Turbine Drivetrain Testing Facility (WTDTF), a natural expansion of facility capability was to include the necessary equipment for performing fault ride-through evaluations of wind turbines to the Low Voltage Ride Through (LVRT) codes. Once the decision was made to expand the scope of the original grant into fault ride-through testing, it was clear that there are several markets, not just wind, which could benefit from this type of test and that simple fault ride-through testing could be extended into a broader scope of electrical testing capabilities. It was at this point that Clemson University pursued and was awarded a second grant to build a 15 MW Hardware-In-the-Loop (HIL) Grid Simulator in order to establish world class electrical testing capabilities to compliment the mechanical testing at the WTDTF. This third significant achievement resulted

in the 15 MW HIL Grid Simulator as the corner stone of the Duke Energy eGRID Center and is collocated with the WTDTF in the SCE&G Energy Innovation Center at Clemson University's Restoration Institute in North Charleston, SC, USA.

Before the eGRID was completed, it was recognized that the ability to test solar farm equipment was but a small step away thru the addition of enhanced equipment to provide for DC testing. In yet another expansion/success, a 2.5 MW rectifier system was designed and implemented by Clemson staff to enhance the Center's capabilities.

The construction of the Facility started as a $98M project under the American Recovery and Reinvestment Act of 2009. This program required over 250,000 man-hours of on-site construction labor reworking the brownfield facility on the former Navy Base, clearly satisfying one of the major goals of the Reinvestment Act. This was done while winning numerous awards for design and construction of the facility, including the Top US Project for 2014 from the Trade Journal Engineering News Record.

A completely new engineering group was formed by Clemson to operate the facility creating over a dozen additional research related jobs. One offshoot of this group was a new sub-group of staff focused on the simulation and analysis necessary to model and understand the operation of the test stand and wind turbines in general. This group has proven invaluable in the development of new control strategies for test as well as analysis to understand the results that are being achieved by ongoing tests. This group is working closely with the WTDTF staff and their customers during day-to-day operations.

Construction of the facility and its ongoing operations has created a number of educational opportunities for staff and University interns. Frequent professional tours and meetings have been attracted to the facility as it has become a local landmark. The facility has hosted between ten and twenty University interns each summer during the course of the project. These positions have been covered by various collaborative programs developed due to the excitement generated by the facility.

Finally, the momentum initiated by the facility successes facilitated the development of a new educational campus for the University. A generous $5M gift by a prominent local family initiated the construction of a new engineering building adjacent to the test facility. This new $23M facility to teach Masters and PhD engineering programs in the Charleston region will be the first such advanced class offerings in the region. The Zucker Family Graduate Education Center will open in the fall of 2016 with a focus on energy-related engineering fields. Educational staff are in the process of relocating to the area as the number of grants, contracts, and spinoff research activities develop.

The project was a major collaborative developmental activity managed by Clemson University staff that involved the DOE and many partners and organizations. The involved personnel and organizations are listed in Appendix A. The resultant facility and significant work items executed during the project are presented in the Report.

Table of Contents

PROJECT OVERVIEW **8**

PROJECT OBJECTIVE 8
BACKGROUND: 8
PROJECT TIMETABLE: 10
FACILITY LOCATION: 10
INDUSTRIAL ADVISORY BOARD: 12
SPECIFICATIONS AND CONTRACTS: 14

OVERALL FACILITY LAYOUT AND DELIVERED SYSTEMS **18**

DEVELOPMENT OF THE 7.5 MW TEST RIG: 22
DEVELOPMENT OF THE 15MW TEST RIG: 27
FOUNDATION SYSTEMS: 32
MEDIUM VOLTAGE SYSTEMS: 36
DATA AND COMMUNICATION SYSTEMS 40
NON-CONVENTIONAL COOLING: 42
HYDRAULIC SYSTEMS: 43
LOGISTICS/CRANES: 45
MECHANICAL MODELING, SIMULATION, AND ANALYSIS LABORATORY: 47
7.5 MW Tech Rig Controller Modification Support *49*
Load Application Unit Accuracy Evaluation and Uncertainty Analysis *49*
Main Shaft Alignment *50*
Driveline Torsional Property Determination *50*

FACILITY OPERATIONS **51**

FACILITY CERTIFICATION: 51
STAFF DEVELOPMENT, SAFETY AND TRAINING: 52
INTERNS: 54
PATENTS: 55
PRESENTATIONS/TOURS: 55
INDUSTRIAL PARTNERS: 55
AWARDS: 56

APPENDIX A PROJECT TEAM **57**

APPENDIX B GRID SIMULATOR OVERVIEW **59**

List of Figures

FIGURE 1 OVERALL PROJECT TIMETABLE 10
FIGURE 2 BUILDING 69 EXTERIOR PRIOR TO RENOVATION 11
FIGURE 3 BUILDING 69 INTERIOR PRIOR TO RENOVATION 12
FIGURE 4 INDUSTRIAL ADVISORY BOARD 14
FIGURE 5 PROJECT TEAM MEMBERS 15
FIGURE 6 OVERALL SITE LAYOUT. 19
FIGURE 7 OVERALL FACILITY INTERIOR LAYOUT 20
FIGURE 8 EIC FRONT LOBBY WITH "POWER WALL" 21
FIGURE 9 FRONT FAÇADE OF RENOVATED EIC FACILITY 21
FIGURE 10 7.5 MW TEST RIG 22
FIGURE 11 SPEED/ TORQUE/ POWER CURVES 7.5 MW RIG 26
FIGURE 12 7.5 MW TEST RIG 26
FIGURE 13 15 MW OVERALL CONFIGURATION, FRONT VIEW, DESIGN PHASE 28
FIGURE 14 15 MW MOTOR AND GEARBOX CONFIGURATION, REAR VIEW, DESIGN PHASE. 28
FIGURE 15 MULTI-FLOW GEARBOX INTERNAL ARRANGEMENT 29
FIGURE 16 SPEED /TORQUE/POWER CURVES 15 MW TEST RIG 30
FIGURE 17 FRONT SIDE OF 15 MW TEST RIG 31
FIGURE 18 REAR SIDE OF 15 MW TEST RIG 31
FIGURE 19 NEW PILES FOR STRUCTURAL PILECAP 32
FIGURE 20 FOUNDATION SYSTEMS FOR THE 7.5 MW RIG VERSUS THE FOUNDATION FOR THE 15MW RIG 33
FIGURE 21 7.5 MW FOUNDATION ANCHOR EMBEDMENT'S 34
FIGURE 22 PILINGS AND BASE LAYER OF 15 MW FOUNDATION WITH ISOLATING WALL 34
FIGURE 23 15 MW FOUNDATION REINFORCING STEEL 35
FIGURE 24 FACILITY ONE-LINE DIAGRAM 38
FIGURE 25 MAIN FACILITY 23.9 KV SWITCHGEAR 39
FIGURE 26 DATA SYSTEM DEVELOPED BY SRNL 39
FIGURE 27 DATA SYSTEM CONFIGURATION FOR THE WTDTF., 15 MW RIG 41
FIGURE 28 CONTROL ROOM CONSOLE 42
FIGURE 29 INSTALLED 1500 TON COOLING TOWER 43
FIGURE 30 HYDRAULIC POWER SUPPLY 44
FIGURE 31 GRAPHICAL REPRESENTATION OF HYDRAULIC POWER SUPPLY. 45
FIGURE 32 CRANE CONFIGURATION FOR THE TEST FACILITY 46
FIGURE 33 PORTABLE GANTRY CRANE LIFT OF 7.5MW LAU 47
FIGURE 34 SIMLAB 48
FIGURE 35 DIAGRAM OF THE DYNAMIC TEST RIG MODEL BEING DEVELOPED IN THE SIMLAB 49
FIGURE 36 SPECIALIZED SIMLAB EQUIPMENT 51
FIGURE 37 CLEMSON RESEARCH OPERATIONAL SAFETY SYSTEM 53

Table of TABLES

Table 1 Facility Requirements 13
Table 2 PROJECT SCHEDULE & MILESTONES 17
Table 3 Clemson Wind Turbine Drivetrain Testing Facility Milestones 18
Table 4 7.5 MW Test Rig Physical Characteristics 24
Table 5 7.5 MW LAU Static Loading Characteristics 24
Table 6 7.5 MW LAU Dynamic Loading Characteristics 25
Table 7 7.5 MW LAU Displacements 25
Table 8 15 MW Test Rig Physical Characteristics 29
Table 9 15 MW LAU Loading Characteristics 30

Acronyms

CU	Clemson University
eGRID	Electrical Grid Research Innovation and Development
CFM	Cubic Feet per Minute
CM@R	Construction Manager at Risk
DUT	Device Under Test
EIC	Energy Innovation Center
HIL	Hardware-In-the-Loop
HMI	Human–Machine Interface
HVRT	High Voltage Ride-Through
IAB	Industrial Advisory Board
ISO	International Standards Organization
KBS	Knowledge Based Safety
LAU	Load Application Unit
LVRT	Low Voltage Ride-Through
OEM	Original Equipment Manufacturer
PMP	Project Management Plan
SCADA	Supervisory Control and Data Acquisition
SCE&G	South Carolina Electric and Gas
SOPO	Statement of Project Objectives
STEM	Science Technology Engineering & Math
UUT	Unit Under Test
VPN	Virtual Private Network
WTDTF	Wind Turbine Drivetrain Testing Facility

Project Overview

Project Objective: Design, construct, commission and operate a state-of-the-art sustainable facility that permits full-scale highly accelerated testing of advanced drivetrain systems for large wind turbines. Meet the objectives of the American Recovery and Reinvestment Act of 2009, especially in job creation, and positive impact on economically distressed areas in the United States, and preservation and economic recovery in an expeditious manner.

Background: In November of 2009, Clemson University was named the awardee of a competitive grant from the U.S. Department of Energy to build and operate a facility for full-scale, highly accelerated mechanical testing of next-generation wind turbine drivetrain technology. The project started January 1, 2010 to engineer, construct, and operate a Wind Turbine Drivetrain Test Facility (CU WTDTF) for highly accelerated testing of drivetrains for wind turbines up to 15MW. The design and capabilities for this new facility were very loosely defined in the proposal due to the uncertainty of the task. The team from Clemson set out to define and refine the project directives given that the facility was starting from a “clean sheet of paper” perspective as no wind turbine facility of the scale of the desired test rigs had ever been built.

The project started as, and continued to be, a constantly changing effort to define, design, and build the envisioned testing facility called the Wind Turbine Drivetrain Testing Facility. (WTDTF). During the course of the project two additional capabilities/projects were added. Given the installed infrastructure of the WTDTF, a natural expansion of facility capability was to include the necessary equipment for performing fault ride-through evaluations of wind turbines to the Low Voltage Ride Through codes. Once the decision was made to expand the capabilities (scope) of the original grant into fault ride-through testing, it was clear that there were several markets, not just wind, which could benefit from this type of test and that simple fault ride-through testing could be extended into a broader scope of electrical testing capabilities. It was at this point that Clemson University pursued and was awarded a second grant to build a 15 MW Hardware-In-the-Loop (HIL) Grid Simulator in order to establish world class electrical testing capabilities to compliment the mechanical testing at the WTDTF. The 15 MW HIL Grid Simulator became the corner stone of the Duke Energy eGRID Center and is co-located with the WTDTF in the SCE&G Energy Innovation Center at Clemson University’s Restoration Institute in North Charleston, SC, USA. Finally, a capability to test solar farm type equipment that requires utility levels of DC power was added into the electrical capabilities in the facility. The details of the steps and changes along the way to migrate the facility from the initially envisioned WTDTF into the SCE&G Energy Innovation Center are well documented in the project reports for the two Grants. In this Final Report, the focus will be the key capabilities of the mechanical test facility and its supporting systems. Highlights on key changes and lessons learned will be presented.

As previously stated, the objective of the Wind Turbine Drivetrain Testing Facility (WTDTF) was to provide a shared resource to accelerate the development and deployment of next-generation wind turbine technology with the ultimate goal of reducing the cost of energy delivered. The facility is not located at the main Clemson University Campus, but rather is located in North Charleston, SC, on the Clemson University Restoration Institute (CURI) campus. This location on the old Navy Base was made available to the University as part of the State matching requirement. It was selected primarily because it provides easy transportation access by ship, rail or road due to its location on the deepwater Cooper River, near an active rail line and several rail yards, and near the Interstate. The existing surrounding infrastructure will provide for loading and unloading of drivetrains, general logistical movement of supplies and equipment, machine shop facilities and access to additional office space. The facility operates on an open access model such that it is available to the U.S. Wind Industry for research, analysis, and evaluation activities. It is housed in the completely renovated Building 69 on the Charleston Naval Complex. This brownfield complex was the result of the closure of the Charleston Naval Shipyard in 1995. While the central navy shipyard was never deactivated and continues to flourish as an active private ship repair facility, large parts of the surrounding areas were turned over to the State and continued to deteriorate with buildings dating as far back as the early 1900's. The renovation of Building 69, and the subsequent other improvements fully satisfied the stimulus objectives for the American Recovery and Reinvestment Act. The main building was renovated to include two drivetrain test bays, a large utility bay to support the hydraulic, electrical, and cooling needs of the facility, overhead cranes for moving equipment, and office and laboratory spaces for personnel, tooling, and instrumentation. The remainder of the building was used to house the Duke Energy eGrid. The footprint of the building remained the same although the structure and interior changed significantly. Several older, smaller structures around Building 69 were removed to allow for the facility.

The project resulted in construction of two independent dynamometers, one 7.5 MW capable unit and a second unit capable of 15 MW, both continuous ratings with appropriate blade forces and moments. The two dynamometers are configured as independent test areas capable of simultaneous operation. All six degrees of freedom, three linear and three rotational, for blade and rotor dynamics are replicated through the combination of a drive motor, speed reduction gearbox and a controllable hydraulic load application unit (LAU). The concept implemented for these two dynamometers was a new concept at the time of the project inception. The concept replaces the blade and hub assembly of a standard turbine with a large direct coupled rotating ring housed inside a large hydraulic loading structure. A series of hydraulic cylinders support and surround the rotating ring making up the LAU. This structure approximates the inertial mass of the typical installed hub and also provides freedom of movement. Further dynamometer details will follow in later sections. This setup readily supports accelerated lifetime mechanical testing and load analysis for the entire drivetrain system of the nacelle and easily replicates a wide variety of realistic operating scenarios in a controlled laboratory environment.

The large test rig was designed for full dynamic operation up to at least 1 HZ force oscillations, while dynamic forcing capability is planned for the smaller test rig at a later date as conditions warrant.

There were several programmatic constraints that defined the overall approach to the execution of the project.

- The final facility had to be self-sufficient. There were no sustained outside budgets to operate the facility should it prove marginal in its operation. It was to be an open shared facility to attract the widest possible set of customers.
- The facility was to be "World Class" in its capabilities.
- The execution schedule was set up aggressively to assure time for operations and potential project slippage if needed to assure completion within the project timeline.

These principles were those that guided the management team throughout the project. During the course of the project continual adjustments to the project plan and technical content were necessary to keep the project in adherence of these principals.

Project Timetable: The project started in January of 2010. An overall perspective of the project timeline is given in Figure 1 along with the high level project Milestones.

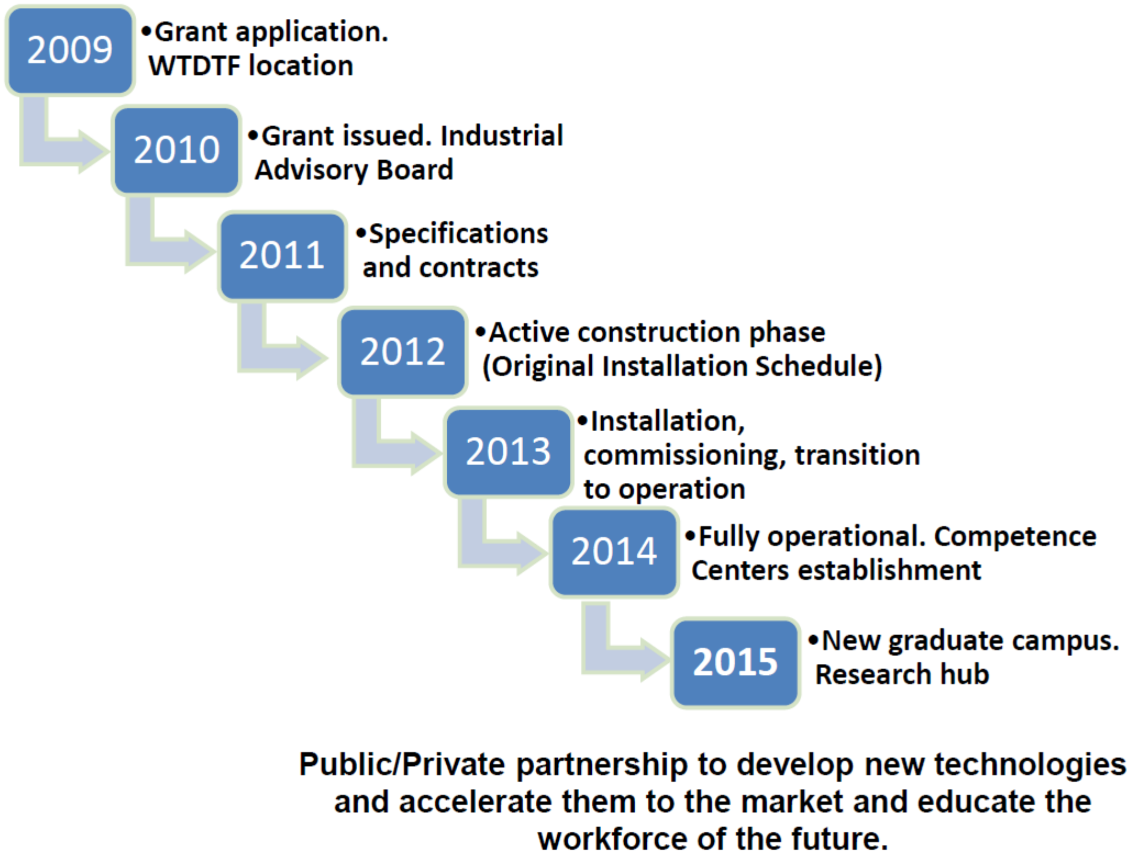


Figure 1 Overall Project Timetable

Facility Location: The location for the facility was defined during the proposal submission since a significant portion of the project cost match was represented by Building 69 on the old brownfield Naval Complex. Building 69 was a large open space warehouse for the Naval base. This 82,000 sq-ft building was selected as ideal due to its location on the waterfront, its high bay open construction, very sturdy floor and deep foundations. The first efforts for the project were to clean up the facility and surrounding area. During this effort the first of many challenges were encountered as it was discovered that:

- The site presented a number of challenges due to its location in a flood zone, a hurricane zone, a contaminated land use control area, and a seismic D zone with poor soil conditions.
- The building needed to be brought up to current structural codes, especially the seismic standards that have changed significantly since construction in 1988. The changes were envisioned as doable, but more extensive than anticipated.

- More extensive building modifications than anticipated were required for the large test rigs due to the proposed size of future wind turbine designs. As a minimum, the roof of a portion of the building would have to be removed in order to accommodate the necessary crane geometries.

- Of specific interest were the foundations and support components for the building. While the building was extensively piled, these earlier piles were not considered sufficient to support the new test rigs. Detailed work in this area continued and outside consultants were brought in to explore and validate the options in this area. This particular effort pushed the state of the art in foundation design more than envisioned.

All these issues were subsequently worked thru, but resulted in a much different allocation of resources than normal. Specifically the building retrofit costs were higher than typical due to the scale of the required utilities. The cost of the foundations made up about a third of the building costs, which is about triple the industry norm. An exterior view of the original building at project start is shown in Figure 2, and interior view in Figure 3.

Figure 2 Building 69 Exterior Prior To Renovation

Figure 3 Building 69 Interior Prior To Renovation

Industrial Advisory Board: Once the contract was underway and work initiated on the cleanup of the facility, one of the most important activities of the program was undertaken. It was viewed imperative that the facility be closely tied to its customers, the Original Equipment Manafacturer's (OEM'S) in the Wind Industry. This view was driven by the belief that only by building what the industry needed would the facility be successful. In order to achieve this goal, a panel of industry representatives was convened and presented with the plans for the facility. This Industrial Advisory Board (IAB) was made up of the DOE and representatives from almost all the major wind turbine OEM's and represented almost 90% of market capacity as shown in Figure 4 by the Red Stars. This group was difficult to engage in open dialog due to the very competitive nature of the industry, but due to Clemson's independent, non-profit nature, we were able to get perspectives and viewpoints thru one-on-one interactions. This guidance proved invaluable and resulted in a more focused set of design guidelines for the facility. By incorporating the industries desired facility attributes through a number of modifications, a new set of requirements for the facility was developed. These changes were made over a period of months as tradeoffs were made within the originally envisioned capabilities for the facility as defined by DOE and the original proposal. The key requirements from the combined directives of the DOE and industry thru the Industrial Advisory Board are listed in Table 1.

Table 1 Facility Requirements

Industrial Advisory Board Summary of Requirements
Operate as a Shared Facility Model with Open Access o Contain a 7.5 MW Test Stand with Static Off-axis load applicator (Upgradeable to dynamic) and be Capable of handling turbines up to 24 feet in diameter o Contain a 15 MW Test Stand with Dynamic Off-axis load applicator (Upgradeable to higher forces) and be Capable of handling turbines up to 30 feet in diameter
Operate two independent test stands simultaneously with parallel activities, while maintaining full work confidentiality for both sets of test activities with secure data collection activities.
Be applicable to both Direct Drive and Geared Turbine Testing
Capable of both 50 and 60 Hz System Testing (US and World Standards)
Provide Low Voltage and Zero Voltage Ride Through Testing with access to 15 MW HIL Grid Simulator Laboratory
Provide test article accessibility by ship, rail or road
Provide a 750 Channel High-speed Secured Data Acquisition System with Real-time Monitoring Capability for each test area
Be an Accredited facility

These requirements significantly modified the technical requirements of the project from those initially envisioned by the proposal team. The modifications were all made through tradeoffs and adjustments to the design requirements being researched for the overall facility design. As an example, the industry found the inclusion of a second smaller test rig much more valuable than the ability to perform environmental testing, a capability originally envisioned. So resources were reallocated from environmental testing equipment toward a second Load Applicator Unit. Many other similar adjustments were made as documented in the project files.

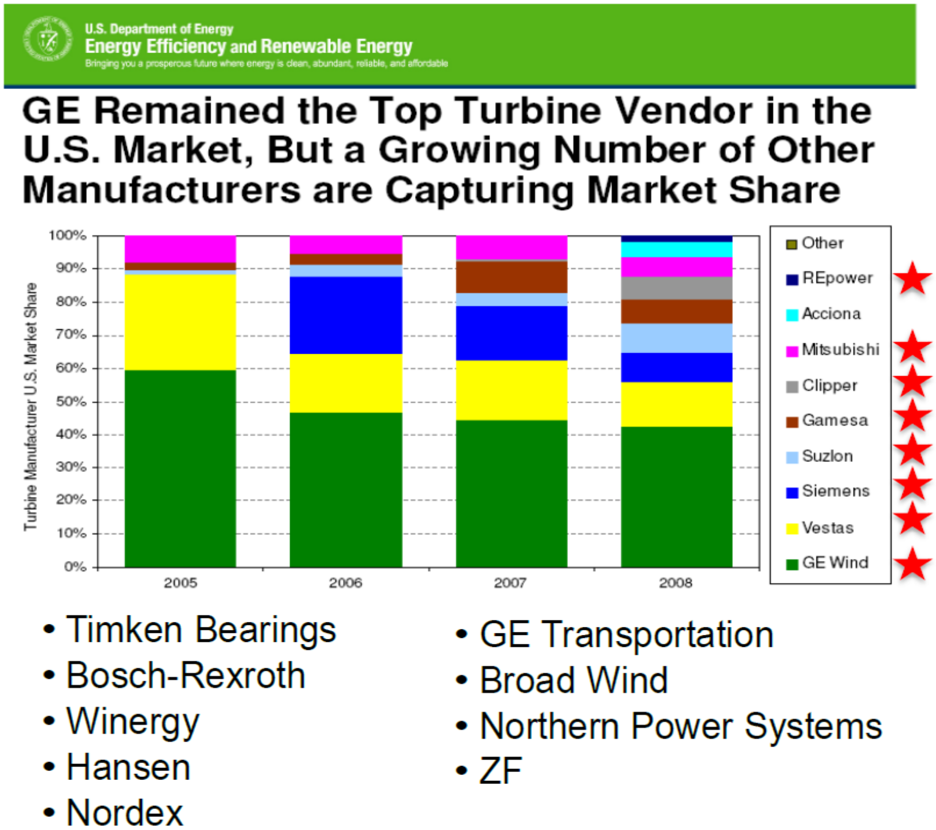


Figure 4 Industrial Advisory Board

Specifications and Contracts: After definition of the required configurations for the test rigs was achieved, the development of detailed specifications and contracts for the test rigs and the facilities could be completed. A number of partners in the project were already on-board, but a number of other components and partners were needed. The final set of significant partners is illustrated in Figure 5. A summary of personnel and organizations involved with the project is included in Appendix A. Many of the specifications were pushing the state-or-the-art and/or required the design and implementation of new and unique technology systems. A number of technical challenges were identified in the definition phase and cataloged so they could be managed. These issues included:

- ✓ Managing the huge torques (15 M Nm)
- ✓ Pushing existing proven gear box designs to achieve Highly Accelerated Lifetime Testing (HALT) without test equipment failures
- ✓ Systems engineering and interactions
- ✓ Integration of dynamic load applicator units (new technology)
- ✓ Dynamic isolation of the test rigs (foundation issues)
- ✓ Grid simulation at a multi-megawatt level
- ✓ Noise isolation for operational efficacies
- ✓ Repeatability of testing parameters
- ✓ Calibrating applied loads to field conditions (field similitude)
- ✓ Use of advanced sensors across multiple measurement systems
- ✓ Ensuring long term viability in a changing market

These concerns were managed with a number of different approaches, but mostly by careful analysis of the technical designs and configurations. The strong team on the project was augmented when necessary, but in general the team proved to be capable and competent.

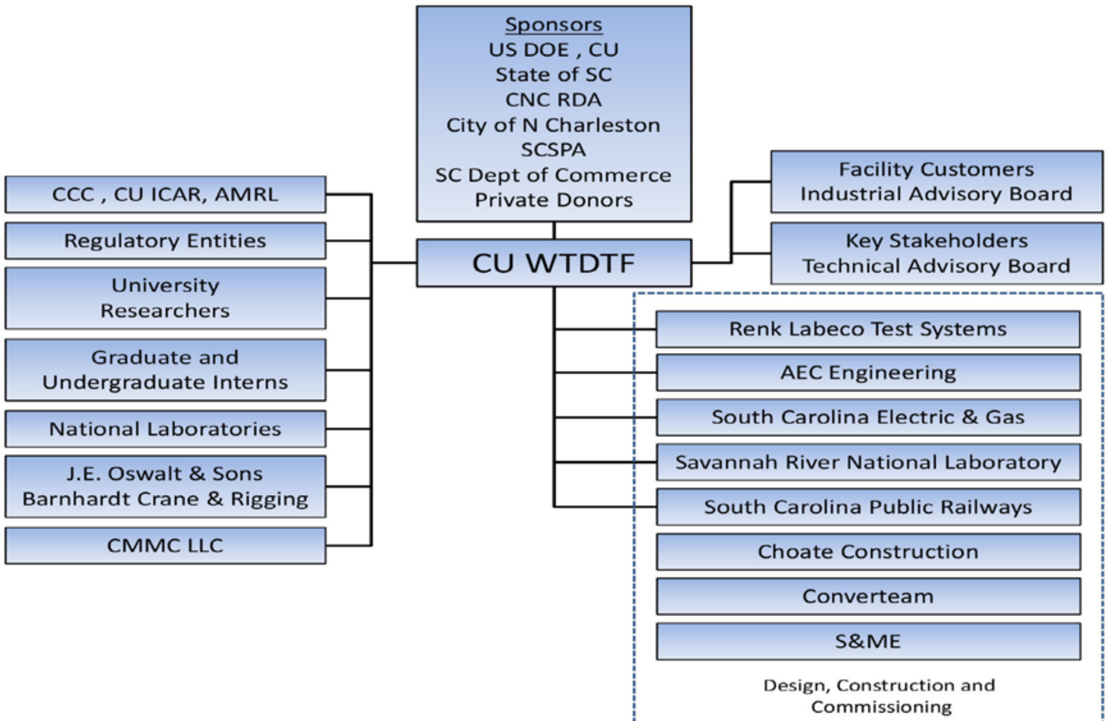


Figure 5 Project Team Members

One important aspect leading to the success of the project was the decision to outsource the system integration work of the large test rigs to RENK. Team members realized that the massive scale of the project equipment and associated risk required a team with experience in the design, assembly, and integration of such testing systems. RENK has this experience as a company, which was recognized during their early proposal participation. RENK has previously provided dynamometers to Clemson at the Clemson University Center for Automotive Research (CUICAR) and therefore had an established relationship with the University. Their experience in large shipboard gearboxes as well as various transportation test rigs to include military helicopter, armored vehicles, tanks, and rail equipment was well researched.

While the design, assembly, and installation of the actual test rigs was assigned to RENK as a contractor, the opposite shift in responsibility happened with the facility systems design. In the original proposal, FLUOR Corporation was envisioned as managing the entire project and integration effort. After completion of the initial engineering evaluations and the development of a Basis of Design document, it was decided that Clemson should be responsible for the facility systems and management of the delivery of the facility systems in close cooperation with all team members. This shift created several changes. The installation of the foundation systems was shifted from RENK to Clemson University due to the high level of integration into the building required by the foundations. Long component design and procurement lead times were in conflict with the short time period for project execution so the facility systems proved to be a significant challenge. This was mostly because the support systems needed to be ordered and frequently put in place before the testing hardware was fully designed. We managed this effort through space allocations and resource assignments and in a few cases, calculated estimates. Clemson also converted the building portion of the project from the Design-Build type contract envisioned to separate Engineering and Construction Management contracts with overlap. This change allowed the project to be expedited and allowed for closer management of all ongoing tasks. The close cooperation between the engineering team and the construction team as required by the Construction Manager at Risk (CM@Risk) process greatly helped keep the project on track. This applied to the following systems:

- Building foundations and structural components
- Test rig foundations
- Logistical Support including cranes
- Facility cooling systems
- Equipment cooling systems
- Facility electrical systems, medium voltage
- Facility electrical systems, conventional
- Facility IT and Information systems
- Facility Safety and Security Systems

After developing a revised vision for the facility, a revised Project Management Plan (PMP) was submitted on September 23, 2011 along with the revised SOPO shown in Table 2 that incorporated all the changes incurred during the initial phases of the project. A new overall set of detailed project milestones was developed and tracked thru to project completion as shown in Table 3 as part of this new PMP. During the project execution phase, there was a concerted effort put forth by all team members. In the following sections, details of the delivered project results will be presented.

Table 2 PROJECT SCHEDULE & MILESTONES

DE-EE0003023						
SOPO Task Number	Title / Task Description	Task Completion Date				Progress Notes
		Original Planned	Revised Planned	Actual	Percent Complete	
1	Develop Test Rig Specifications and Building Modifications	Jul-10		Jul-10	100%	Complete
2	Basis of Design	Aug-10		Oct-10	100%	Complete
3	Preliminary Equipment and Building Designs	Aug-10		Jun-11	100%	Complete
4	Final Equipment and Building Design	Aug-11	Aug 12	Sept 12	100%	Complete,
5	Construction, Fabrication and Installation	Apr-12	Dec 13- 7.5 Feb 14 –15	Dec 13- 7.5 Feb 14 –15	100%	7.5 MW Complete 15 MW Complete
6	Commissioning	Jul-12	Feb 14 7.5MW Nov 14 15MW	Nov 14 7.5MW Nov 15 15MW	100%	7.5 MW Commissioning Complete. 15 MW Commissioning complete W/O article
7	Certification	Oct-12		Sept 15	100%	Task Complete
8	Facility Operation	Sep-12		Nov 14	100%	Commercial Testing Underway
9	Project Management and Reporting	Dec-14		Dec 15	100%	Complete

Table 3 Clemson Wind Turbine Drivetrain Testing Facility Milestones

	Milestone	Completion Date
1	Renk preliminary design review	12-10-10
2	A&E selection completed	12-21-10
3	A&E design work initiated	3-4-11
4	Start of hardware procurement	1-19-11
5	SCDHEC Dig Permits issued	4-1-11
6	Minor demolition started Major Building demolition started, old sections Major Building Demolition, new sections	9-20-10 4-1-11 9-19-11
7	Data acquisition system prototypes ordered	3-15-11
8	Construction Management Company selected	4-21-11
9	Motors and Drives ordered/ Electrical transformers ordered	4-1-11 5-1-12
10	Cranes specified/ ordered/installed	8-15-11/10-1-11/7-5-13
11	7.5 MW Foundation work initiated/completed	8-16-11/6-29-12
12	Rail Spur started/completed	5-14-12/8-31-13
13	7.5MW testing equipment delivery started	2-15-13
14	Temporary electrical infrastructure functional	6-15-13
15	15 MW Foundation work initiated/completed	10-1-11/9-1-13
16	Cooling Equipment Installed	8-15-13
17	Final electrical infrastructure installed	9-1-13
18	Automation and Data System Ready for install	12-15-13
19	7.5 MW Unit commissioning start	3-5-14
20	15MW testing equipment delivery	10-3-13
21	7.5MW test stand operational	8-10-14
22	Facility dedication	11-21-13
23	15 MW Unit commissioning	11-18-15

Overall Facility Layout and Delivered Systems: The final site configuration shown in Figure 6 was reached after significant research into various tradeoffs and configuration evaluations. This effort took several iterations to bring the desired product within budget constraints, including the removal of a second level of offices and support spaces. The layout and configuration inside the building changed frequently as the size of various electrical and hydraulic components changed due to design maturation. The final configuration shown in figure 7 incorporates an attractive entrance and front personnel parking area with entry into a central front lobby shown in Figure 8. Test article delivery is into the building thru two long ramps on the back side of the building with access via large folding doors (9 m by 12 m and 12 m by 18 m). A new rail spur was constructed on the west side of the building to facilitate the delivery and loading/unloading of items by rail in an unimpeded manner. The transformer area for the Grid Sim facility is located to the west of the facility. The drydock area and piers are to the east of the building to facilitate water delivery of large items. The gearbox and the LAU ring for the 15 MW test rig were delivered by barge over the pier-head and moved into the facility by multi-axle movers. A central corridor between the two test rigs houses the electrical utility gear for the facility and transformers as well as the hydraulic room. The control rooms are on the opposite side of the test rigs with offices and the Grid Simulator facility to the west side of the building. This configuration facilitates optimum physical separation of the power systems from the data and control systems to assist with minimizing power induced noise on the data and control systems.

The overall building shown in Figure 9 maintained the same footprint but became fully automated with the latest control and energy management systems. All the building systems are controlled by a local facility network (SCADA system) that is tied to the main Clemson Facilities Management database where trends, faults, and warnings are logged and communicated. Many energy conserving features such as automatic occupancy based light switching and rainwater collection for grey water use allowed the building to achieve a LEEDS "Gold" rating. In addition, the building is equipped with security systems including electronically controlled door locks and badge readers and camera monitoring for exit and project critical areas.

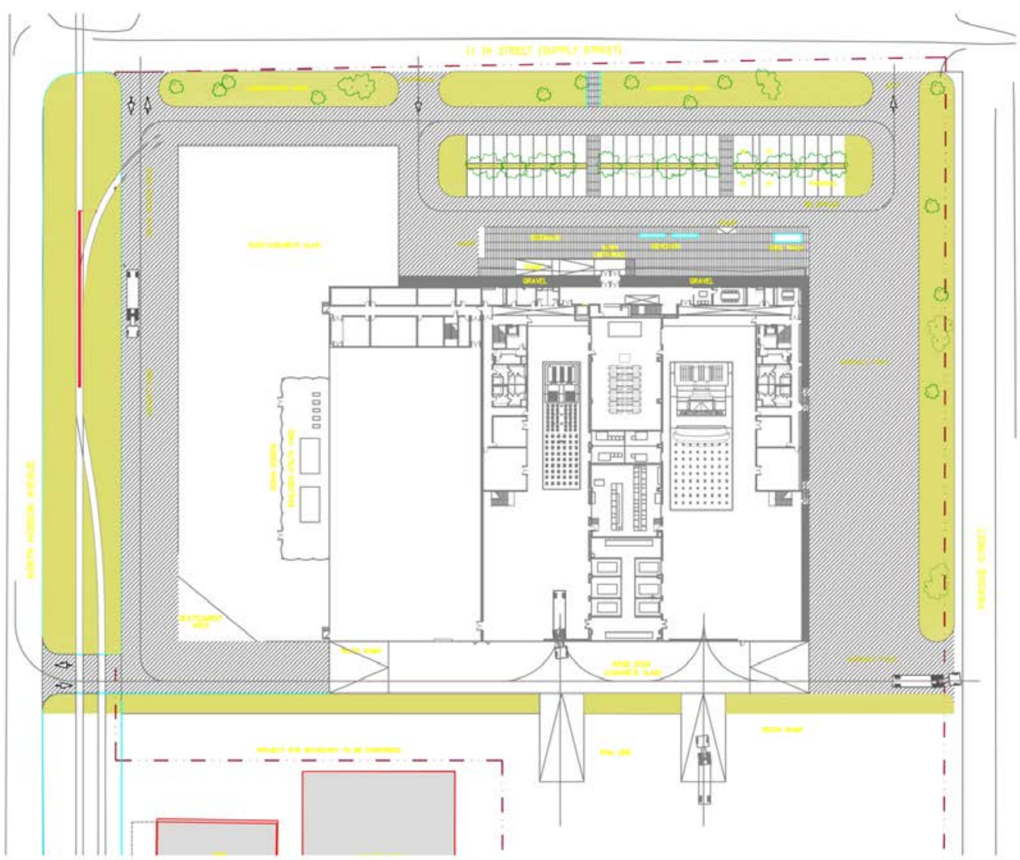


Figure 6 Overall Site Layout.

1.- 15 MW Test Rig
2.- 15 MW Control Rooms
3.- Facility Transformers
4.- Facility Hydraulics
5.- Conference Room
6.- Partner Offices
7.- 7.5 MW Test Rig
8.- 7.5 MW Control Rooms
9.- Common Services
10.- Staff Offices
11.- Partner Work Space
12.- Grid Simulator Area
13.- Grid Simulator Switchgear
14.- Grid Simulator Transformer
2.- Middle Level - Mezzanine
3.- Upper Level - Motor Drives and Facility Switchgear
8.- Middle Level - Mezzanine

Figure 7 Overall Facility Interior Layout

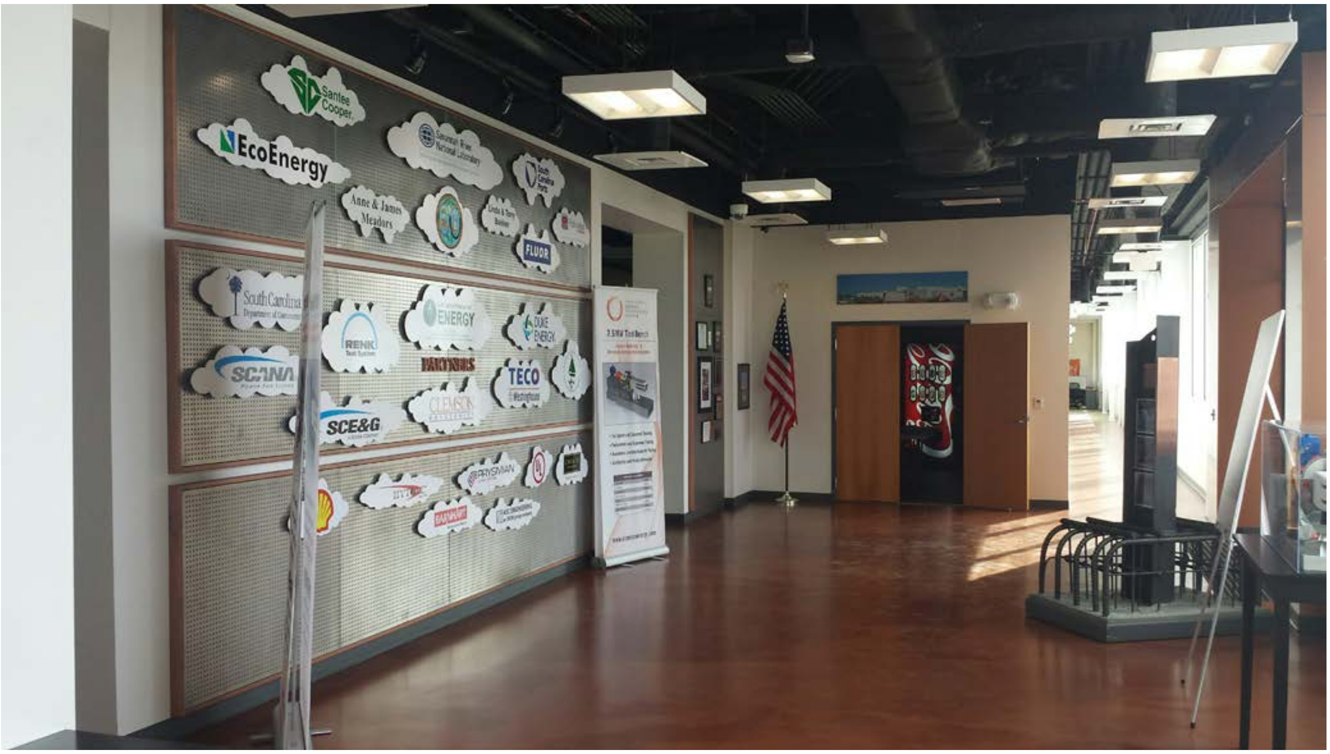


Figure 8 EIC Front Lobby with "Power Wall"

Figure 9 Front Façade of Renovated EIC Facility

Test Dynamometer Development and Overview: The primary purpose of the facility is to test the next generation of wind turbine drivetrain prototypes, especially the anticipated large off shore systems. At its inception, the goal for the Request for Proposal was to be able to test full nacelles in a more realistic way than previous test systems. Early dynamometer test facilities were typically rotate only (torque) dynamometers. This was a standard arrangement used to test rotating equipment and is perfectly sufficient for equipment subject to balanced rotating loads. In the case of wind turbines, these stands consisted of a variable speed motor connected to large gearbox. The test rigs frequently were constructed by using two of the same gearbox, a "back-to-back" arrangement. This test configuration is fully functional, but frequently the "driving" gearbox becomes the test specimen. The other issue with this arrangement is that the test specimen was not subjected to realistic loads in terms of thrusts and moments such as those that might be produced by functioning turbine blades. The rotating blades for a wind turbine produce substantial thrust and off-axis moments. These additional unbalanced loads are not addressed when using a standard rotating dynamometer. Second generation turbine test dynamometers add a long shaft between the two gearboxes, a shaft mounted thrust bearing, and hydraulic cylinders to exert both thrust loads and moments through the use of four point bending geometry. At the time the project started, the largest dynamometer being used for wind turbine testing was in operation at the National Renewable Energy Centre of Spain (CENER) with a maximum power capability of 5 MW. This dynamometer used the above mentioned long shaft and hydraulic cylinders to simulate blade and hub loading.

Development of the 7.5 MW Test Rig: The conventional dynamometer arrangement was only briefly considered during the proposal stages of the program. Preliminary design investigations indicated that there were no manufacturers of bearings with the force capability necessary to provide the desired loads. Driven by this consideration, RENK postulated an arrangement for the proposal where the hub and blades of the wind turbine are simulated by a large rigidly-connected loading disk contained in a large housing and supported by slide bearings. This disk is loaded thru the use of hydraulic cylinders and slide bearings and driven by a large low speed shaft through a flexible gear tooth coupling. This configuration is illustrated in Figure 10 where the four main functional components to the test rigs are illustrated. These are the Drive Motor, the High Speed Coupling, the Adaptation or Reduction Gearbox, and the Non-Torque Loading Device, referred to as the Load Application Unit (LAU). The general operating characteristics for the 7.5 MW test rig are presented in Tables 4 and 5. The power/speed curve for the current rig is presented in Figure 11.

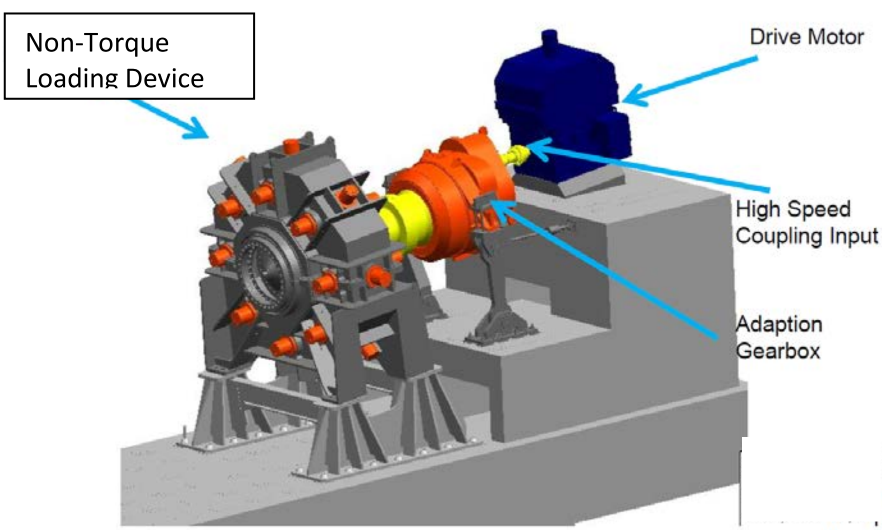


Figure 10 7.5 MW Test Rig

The 7.5 MW LAU was designed primarily as a quasi-static loading test rig for the off-axis loads. It is capable of low frequency dynamic loading, but the servo valves and hydraulic components would need to be upgraded to provide for full dynamic loading of test specimens. Instrumentation and control upgrades would also need to be implemented. The forces available through these optional upgrades are presented in Table 6 with the corresponding displacements presented in Table 7. Extensive specifications for the design were developed based upon design goals of the program. The program turned into a developmental project once the complexity of the requirements was recognized and a number of changes to requirements and specifications were made during the program to adjust to the changing of the needs and limitations of the test rig as engineering and physical limitations were discovered.

Many requirements for supporting and operating the test rig were developed and were used to define and then refine the facility support needs for the installed test equipment. The completely new piece of equipment that became the Load Application Unit (LAU) was developed from scratch based upon these design requirements in a true technology development effort. The gearbox was developed as a modification of an existing gearbox design. The motor and variable speed drive was selected based upon a detailed bidding process to select the most beneficial product. Even after selection of specific vendors or components, modifications and substitutions continued to be made to address technical, budgetary, and political issues such as Buy America. The remainder of the support systems were designed and pre-assembled by various team sub-contractors prior to delivery to the facility. It was Clemson's responsibility, thru the facility design engineers, to modify the existing building design as appropriate and add all the necessary facility interfaces for power, cooling, logistics, and structural support. The team worked closely to implement all these systems that will be covered in subsequent sections.

The 7.5 MW test rig was completed in early 2014 and immediately entered a commissioning Phase using a GE 1.6 MW turbine as a test specimen. The commissioning continued until October of 2014. At this time, Clemson formally accepted delivery of the test rig. Clemson immediately entered into a test campaign for GE using the 1.6 MW turbine. The test campaign lasted until March of 2016. During this time a large number of tests were performed for GE. The capabilities of the test rig have been well documented and shared with appropriate DOE staff to the extent possible due to client confidentially. Since the test rig is based upon a completely new methodology, there is extensive learning still in progress by all parties. The OEM's are just beginning to identify the new types of questions and loading scenarios that may be implemented. Both Clemson and the customer engineers are learning new procedures, methods, and results on a regular basis. A photo of the assembled test rig with a turbine attached is shown in Figure 12.

Table 4 7.5 MW Test Rig Physical Characteristics

Features	
Power (Electrical Closed Loop)	8,500 kW
Number of Motors	1
Number of Converters	2
Test Rig Dimensions (L x W x H)	26 x 18 x 9 m
Test Specimen	
Maximum Diameter	8 m
Maximum Length	15 m
Test Rig Drivetrain	
Test Power, continuous	7,500 kW
Nominal Test Torque	6,000 kNm
Nominal Test Speed	12 rpm
Max Test Speed	20 rpm
Inclination (Adjustable)	4 ° to 6 °
Shaft Height to Specimen	≈ 5,000 mm

Table 5 7.5 MW LAU Static Loading Characteristics

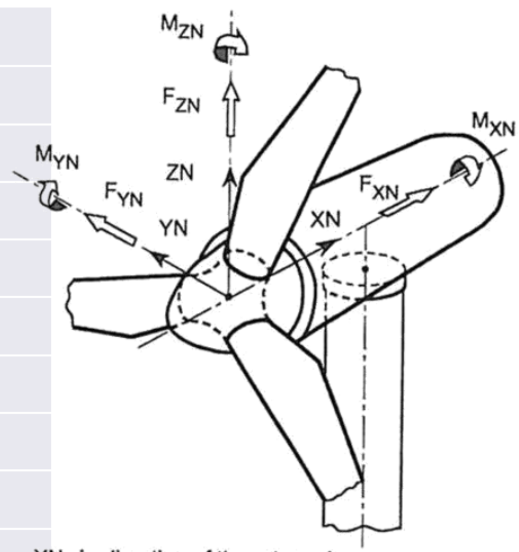
Coupling Between Gearbox and LAU		
Maximum Torque		6,500 kNm
Maximum Speed		20 rpm
LAU		
Axial Coupling Displacement		± 20 mm
Radial Coupling Displacement		± 20 mm
Max Coupling Angular Misalignment		0.8 °
LAU Static Loads		
Axial Force	± 2,000 kN	C_A > 200 kN/mm
Radial Force	± 2,000 kN	C_R > 200 kN/mm
Bending Moment	± 10,000 kNm	C_B > 716 MNm/rad

Table 6 7.5 MW LAU Dynamic Loading Characteristics

dynamic loads				
		at stiffness		
bending moment	$M_B = 0.7{*}M_{Bmax}+0.3{*}M_{Bmax}{*}\sin 2PI\ 1Hz$	C_B	> 6 000	MNm/rad
radial force	$F_R = 0.7{*}F_{Rmax}+0.3{*}F_{Rmax}{*}\sin 2PI\ 1Hz$	C_R	> 700	kN/mm
axial force	$F_A = 0.7{*}F_{Amax}+0.3{*}F_{Amax}{*}\sin 2PI\ 1Hz$	C_A	> 700	kN/mm

Table 7 7.5 MW LAU Displacements

dynamic displacement (option)		
axial		
Fa	600	[kN]
Ca	700	[kN/mm]
Dsa	0,86	[mm]
radial		
Fr	600	[kN]
Cr	700	[kN/mm]
Dsr	0,86	[mm]
bending		
Mb	3.000	[kNm]
Cb	6.000	[MNm/rad]
Da	0,03	[°]



XN in direction of the rotor axis
ZN upwards perpendicular to XN
YN horizontally sideways, so that XN, YN, ZN rotate clockwise

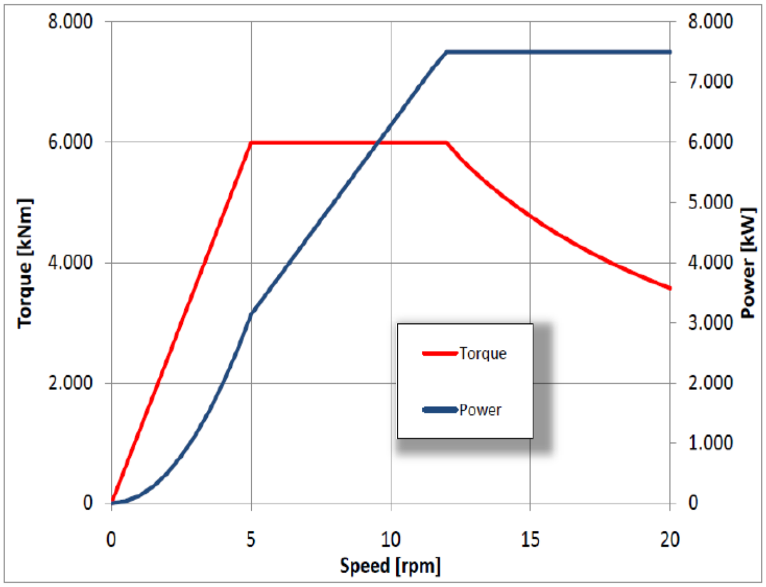


Figure 11 Speed/ Torque/ Power Curves 7.5 MW Rig

Figure 12 7.5 MW Test Rig

Development of the 15MW Test Rig: The design of the larger 15 MW test rig proceeded in parallel with the design of the 7.5 MW test rig. In addition to being much larger, the rig was fundamentally different in its geometry. The larger dynamometer contains the same major components arranged a slight bit differently. In fact, many of the components used on the two test rigs are the same. The LAU for the 7.5 rig was built in a large bottom-mounted support housing. The thrust load specifications for the 15 MW test rig forced the support structure to assume a heavily integrated gusset configuration to tie the loads into the foundation better as shown in Figure 13. The configuration of the dual motor drive and reduction gearbox is shown in Figure 14. The motors and motor drive components are interchangeable as are the loading cylinders and bearings. Many sensors and control components are also interchangeable. The gearbox for the 15 MW dynamometer was a completely new custom design developed by RENK specifically for this application. This gearbox is referred to as a "multi-flow" gearbox because the tremendous torque developed by the gearbox requires multiple shafts and gear teeth to drive the final output flange. A generic overview of the gearbox internal arrangement is shown in Figure 15. The gearbox starts with dual input shafts, one from each motor. These two shafts drive a series of four stationary planet shafts, which in turn drive a total of eight stationary planets. These eight output gears then drive the final output flange. By starting with dual input shafts, several advantages are gained. First it allows the motors for the facility to all be identical. It also provides for a balanced load input into the gearbox by providing two input torques on opposite sides of the main gearbox casing. This arrangement was also dictated because there is a limitation in the designs of motor power drives at about 10 MW due to the sizes of available power electronic devices. This is an example of the types of design tradeoffs and balance that were necessary to continually evaluate during the development of the test rigs.

The general operating characteristics for the 15 MW test rig are presented in Tables 8 and 9 while the power/speed curve is presented in Figure 16. One additional major difference between the 7.5 test rig and the 15 MW test is the dynamic capability of the larger rig. The 15 MW LAU was designed as a dynamic loading platform from its inception, as reflected in the operating characteristics and the design specifications. The 15 MW LAU is also capable of a major force upgrade through the addition of an additional set of loading cylinders. The initial acceptance tests for the 15 MW test rig were completed in October of 2015 and the rig was accepted by Clemson. The rig has undergone extensive commissioning tests. Details of the support subsystems and facility modifications will be presented in following sections. Photo's of the front and back of the finished 15 MW test rig are shown in Figures 17 and Figure 18.

Both the 7.5 MW test rig and the 15 MW test rig use a number of common parts including identical hydraulic cylinders and cylinder components. This compatibility will increase ease of maintenance, reduce parts inventories, and therefore increase rig availability. Most electronic and control systems also share common components.

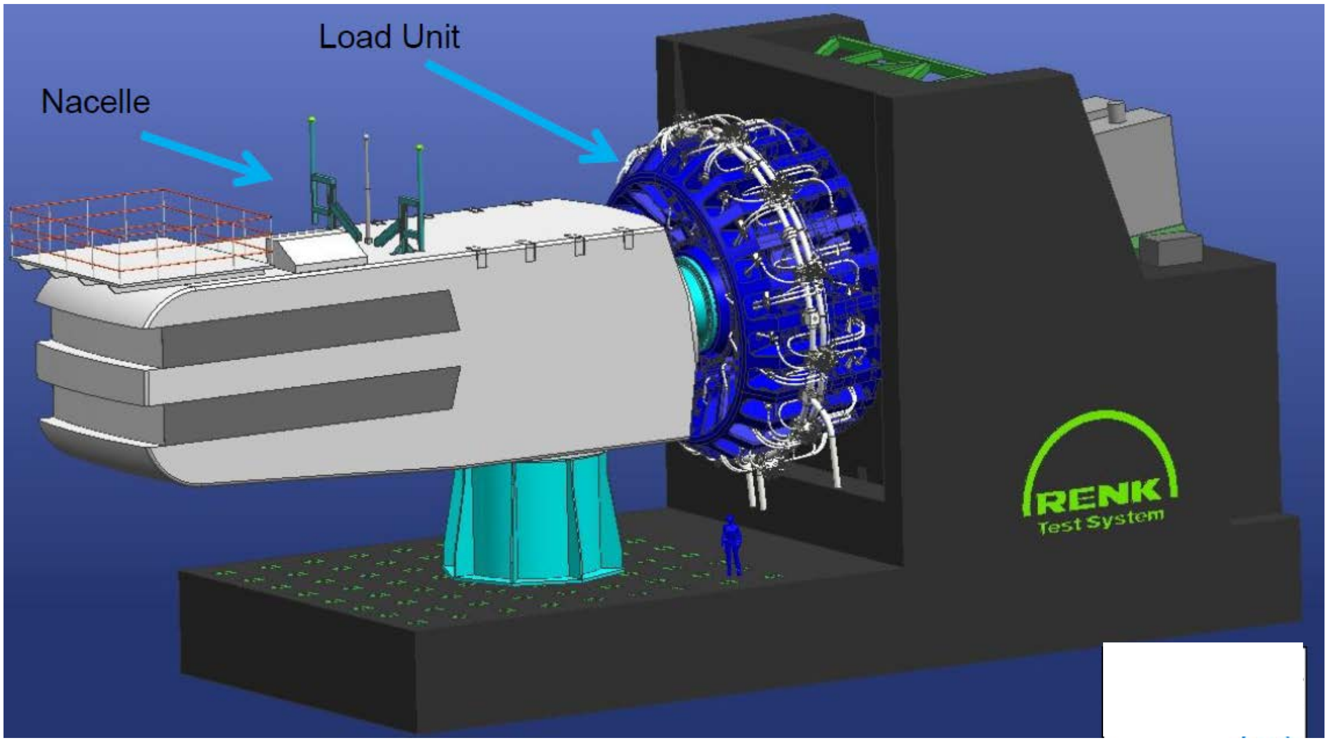


Figure 13 15 MW Overall Configuration, Front View, Design Phase

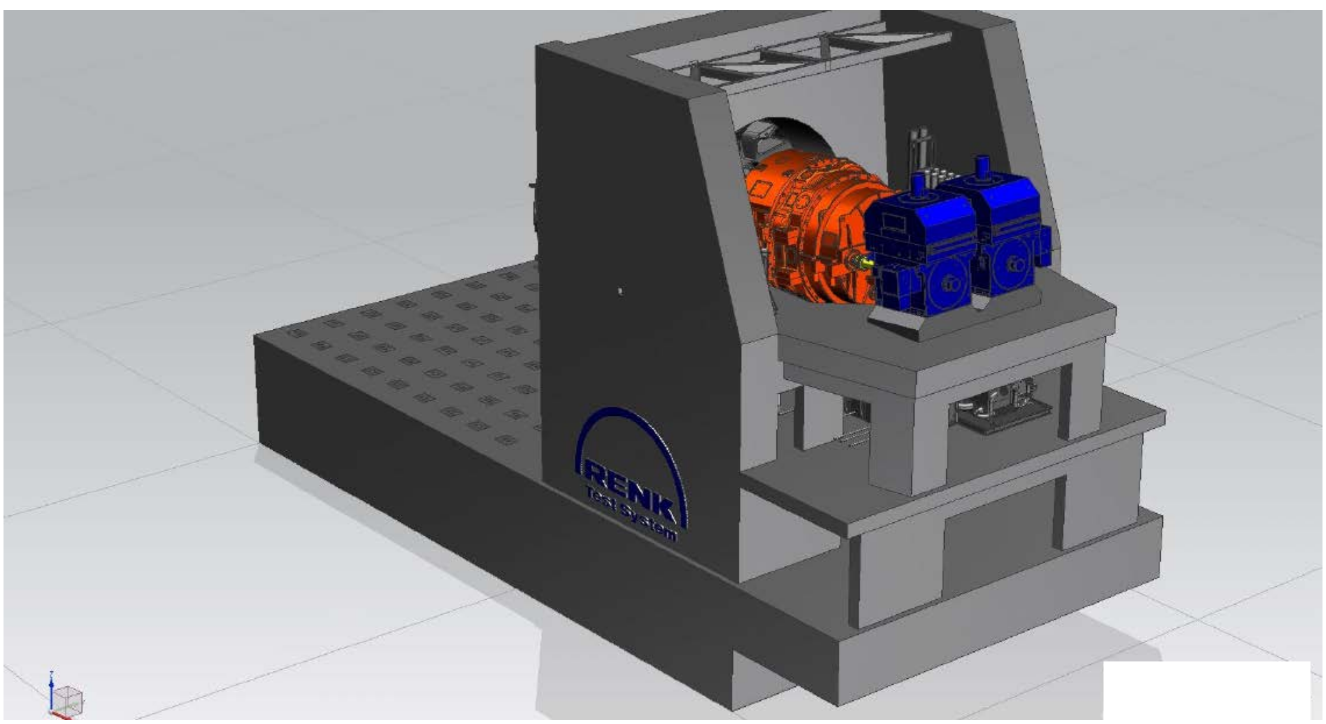


Figure 14 15 MW Motor and Gearbox Configuration, Rear View, Design Phase.

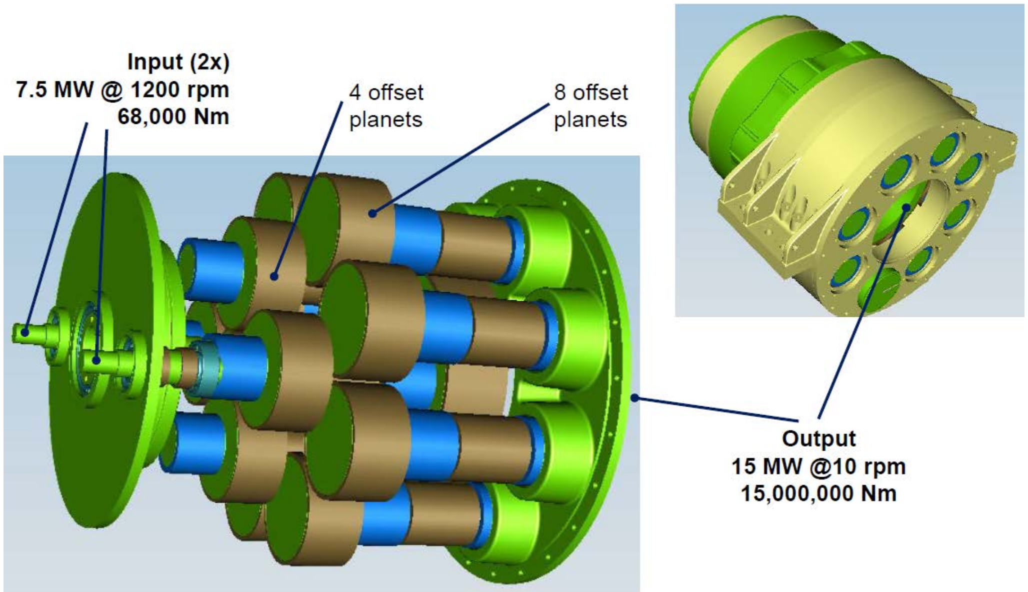


Figure 15 Multi-Flow Gearbox Internal Arrangement

Table 8 15 MW Test Rig Physical Characteristics

Features	
Power (Electrical Closed Loop)	15,700 kW
Number of Motors	2
Number of Converters	4
Test Rig Dimensions (L x W x H)	35 x 12 x 11 m
Test Specimen	
Maximum Diameter	13 m
Maximum Length	20 m
Test Rig Drivetrain	
Test Power	15,700 kW
Nominal Test Torque	15,000 kNm
Nominal Test Speed	10 rpm
Max Test Speed	17 rpm
Inclination	6 °
Shaft Height to Specimen	≈ 7,000 mm

Table 9 15 MW LAU Loading Characteristics

Coupling Between Gearbox and LAU		
Maximum Torque	16,000 kNm	
Maximum Speed	17 rpm	
LAU		
Axial Coupling Displacement	± 20 mm	
Radial Coupling Displacement	± 20 mm	
Max Coupling Angular Misalignment	0.8 °	
LAU Static Loads		
Axial Force	± 4,000 kN	C_A > 400 kN/mm
Radial Force	± 8,000 kN	C_R > 800 kN/mm
Bending Moment	± 50,000	C_B > 3,580 MNm/rad
LAU Dynamic Loads		
MB = 0.7* MBmax+		C_B > 6,000 MNm/rad
FR= 0.7* FRmax+ 0.3*FRmax *sin2π		C_R > 700 kN/mm
FA= 0.7* FAmax+ 0.3*FRmax*sin2π		C_A > 700 kN/mm

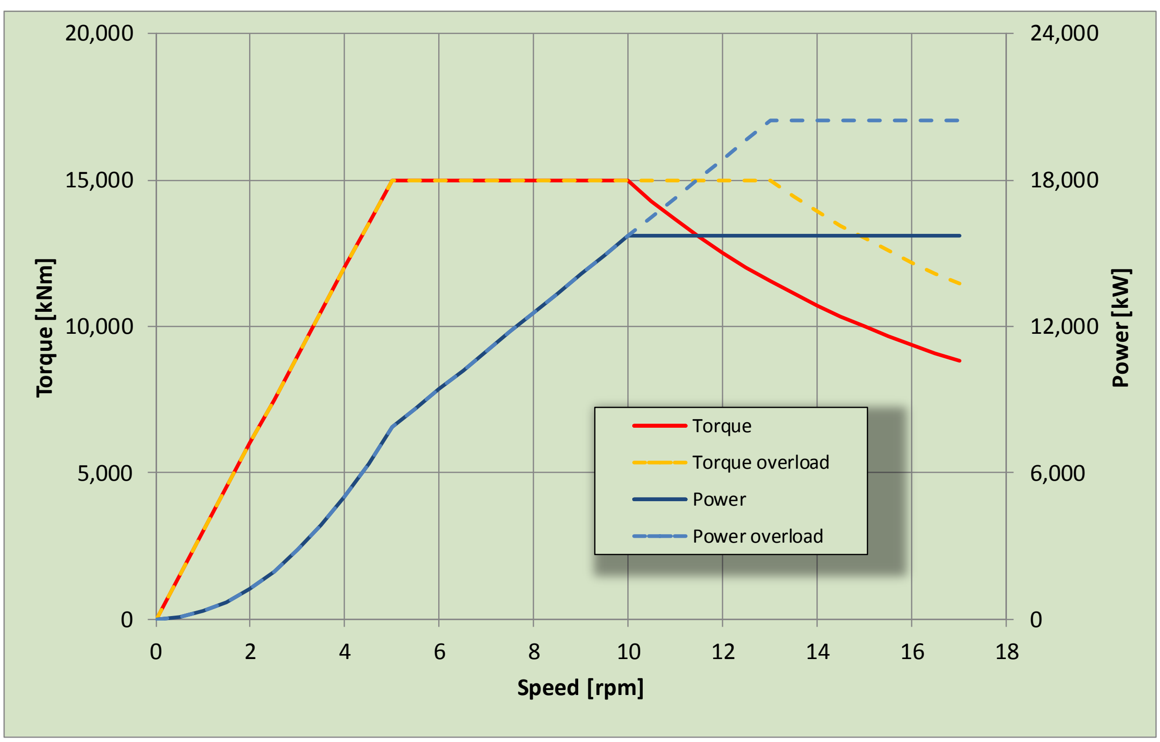


Figure 16 Speed /Torque/Power Curves 15 MW Test Rig

Figure 17 Front Side of 15 MW Test Rig

Figure 18 Rear Side of 15 MW test Rig

Foundation Systems: The foundation systems necessary to support the building and crane systems and the test rigs were the most challenging civil component of the project. Approximately 30% of the construction costs were tied up in the foundation structures. All large structures in the Charleston region are built with deep friction piles. The existing building was fully pile supported, just not at the level necessary to support the enlarged structure of the test facility. Five hundred new piles up to 18m long were driven under new steel building support columns. Many of these steel H piles were driven under the existing roof in segments as shown in Figure 19.

Figure 19 New Piles for Structural Pilecap

As far as research uncovered, there has never been a dynamic loading system of the magnitude of the facility test rigs built upon friction piles. Extensive engineering evaluation and analysis was necessary to bring closure to the design. This effort enlisted team members as well as outside consultants. In the end the foundations were built according to the developed designs and have performed well. Over 800 new piles were driven under the existing building and the test rig foundations to provide the stability needed for the test rig equipment. Due to the large forces generated by the test rigs, the test rig foundations are massive with huge amounts of reinforcing steel and concrete within the structures. The base slab thickness for the 7.5 MW rig is 3 m thick and the base slab for the 15 MW rig is 4 m thick. The foundation for the 15 MW rig is 15.2 m wide by 30.5 m long and contains over 650 tons of rebar encased in 1900 cubic yards of concrete weighing approximately 7,200,000 lbs. Both slabs are isolated from the surrounding building structure by isolating foam and a wooden retaining wall and lag piles. These slabs and the structural mounting pads were constructed to very tight tolerances. Typical deviations for the mounting pads are less than 0.8 mm. A graphic showing the relative sizes of the two foundations is shown in Figure 20.

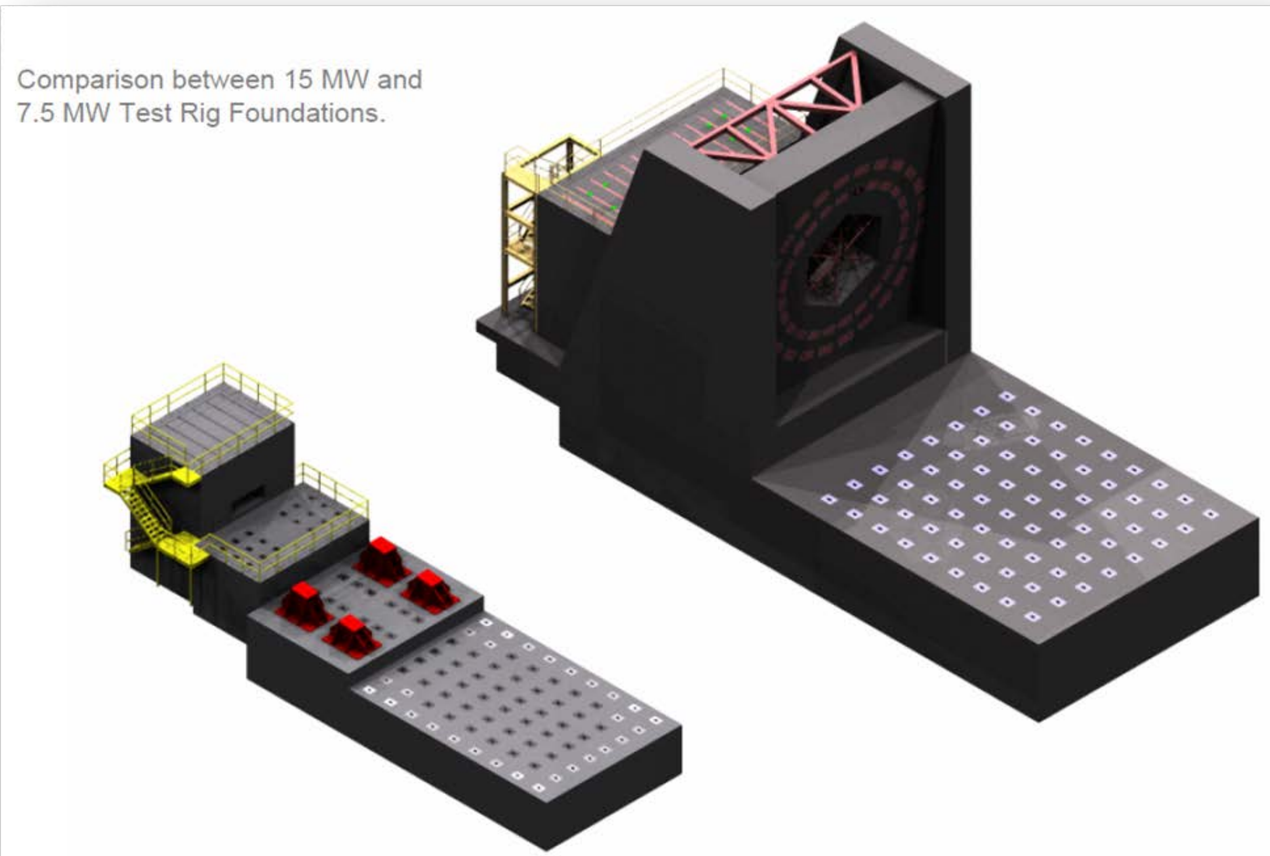


Figure 20 Foundation Systems for the 7.5 MW Rig versus the Foundation for the 15MW Rig

The foundations were build up within the footprint of the building after the friction piles were driven to provide support. The anchoring embedment's in the foundation for the 7.5 MW are shown in Figure 21. Similar anchor systems were incorporated into the 15 MW foundation. The bottom layer of the 15 MW is shown in Figure 22.

Figure 21 7.5 MW Foundation Anchor Embedment's

Figure 22 Pilings and Base Layer of 15 MW Foundation with Isolating Wall

The anchoring and reinforcement necessary to resist the bending moments created by the LAU units required extensive modeling and analysis to assure the designers that the structure would withstand the anticipated forces, while limiting the resultant deflections. The resultant reinforcing steel cage for the 15 MW mounting foundation is shown in Figure 23. Specially formulated self-consolidating concrete mixes were required in order to assure that there were no voids or gaps within the structures. The completed structure was previously illustrated in Figures 17 and 18. This assembly required very tight tolerances to assure proper mounting of the final components. The mounting surfaces of the shown embedment ring were accurately positioned within 0.8 mm in the final structure.

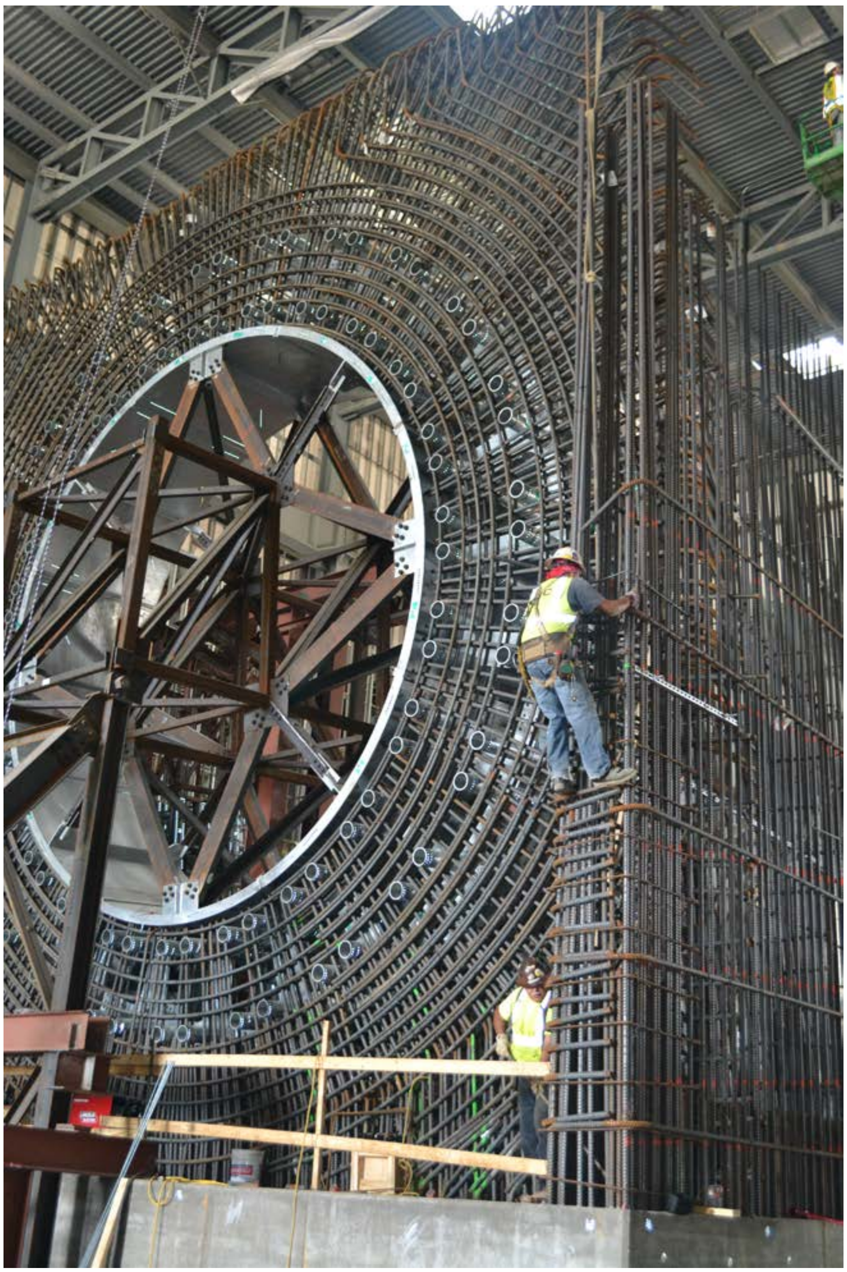


Figure 23 15 MW Foundation Reinforcing Steel

Medium Voltage Systems: As the facility design progressed it was quickly realized that the facility was going to need extensive amounts of power. Most of this power would be used to drive the large dynamometer variable speed drives and the hydraulic pumps for the LAU systems. Conversations with the local utility indicated that the facility should upgrade from the originally intended 13.8 KV supply to a 23.9KV supply voltage for the facility. Just this relatively simple change would decrease the required wire sizes enough to significantly reduce the cost of running the feeds and lines to and within the facility. The overall EIC facility one-line diagram is presented in Figure 24. The configuration is very flexible and allows for a large number of interconnections between the test equipment, including the Grid Simulator. A 28 MW dedicated transformer was procured by the local utility to be able to drive the needs of the facility. The location of this transformer and associated substation became the subject of many technical and legal discussions. As the project was drawing to a close, the location for the dedicated transformer was finally agreed to and final land-related legal issues for a new sub-station to be installed on Clemson property were finalized. This new substation will be connected directly to new 125KV transmission lines that have been installed along the adjoining roadway. These lines were installed to bring power a distance of about two miles from a nearby major distribution substation located in the redeveloping Naval Base area. In the interim period, the facility operates off an existing service line. While the line was somewhat limited in power capacity, it proved more than adequate due to the limited size of turbines currently available for test. Power draw is limited due to the recirculation of all generated power back into the facility.

Figure 24, depicts a simplified single-line electrical diagram of the Energy Innovation Center and illustrates how the three test bays can operate independently or be easily coupled together for complete electrical testing of a wind turbine on either of the dynamometers. In Figure 24, the 15 MW dynamometer is shown on the left, the eGRID's 15 MW Grid Simulator in the middle and the 7.5 MW dynamometer to the right. To connect either of the wind turbine dynamometers to eGRID, switchgear is built into the system to allow for easy coupling of each recirculation bus to the experimental bus. When not being utilized for electrical testing with either of the dynamometers, the 15 MW Grid Simulator can be partitioned off and utilized for the testing of other devices in the electrical test bay area.

The main switchgear for the facility was located on the third floor of the utility corridor in order to minimize cable runs between the switch gear and the motor drives, and subsequently the motors. This switchgear is shown in Figure 25. Clemson was able to engage Prysmian Cable as a project partner and have them supply the medium voltage cable. There are literally miles of 500 MCM and larger cable in the facility, much of it operating at 5000 VAC or higher. Due to the complicated power switching envisioned for the operation of the facility, it was decided that the management of all medium voltage switching and its configuration would be done via remote switching from a centralized location in the Grid Simulator area. This decision was reinforced as the realization that a comprehensive power and voltage monitoring system would need to be implemented throughout the facility by the Grid Simulator project. In addition to monitoring equipment installed in each breaker cabinet, each cabinet can be remotely switched, providing an added degree of safety for operations. Because of the very high power levels available, it is a constant effort to evaluate and limit the allowable current in the various power feeds. Breakers in the facility are set for very fast trip times and minimal voltage and current excursions. These steps are necessary for safety of both the personnel and the equipment located throughout the facility.

The eGRID facility, developed through a second DOE grant, is a significant addition to the original project scope. This facility filled out the remainder of the building floorplan and was accomplished with a cooperative effort between Clemson, Power Industry Partners, and DOE. This effort became a completely separate project with its own project description and reporting. A summary overview is contained in Appendix B.

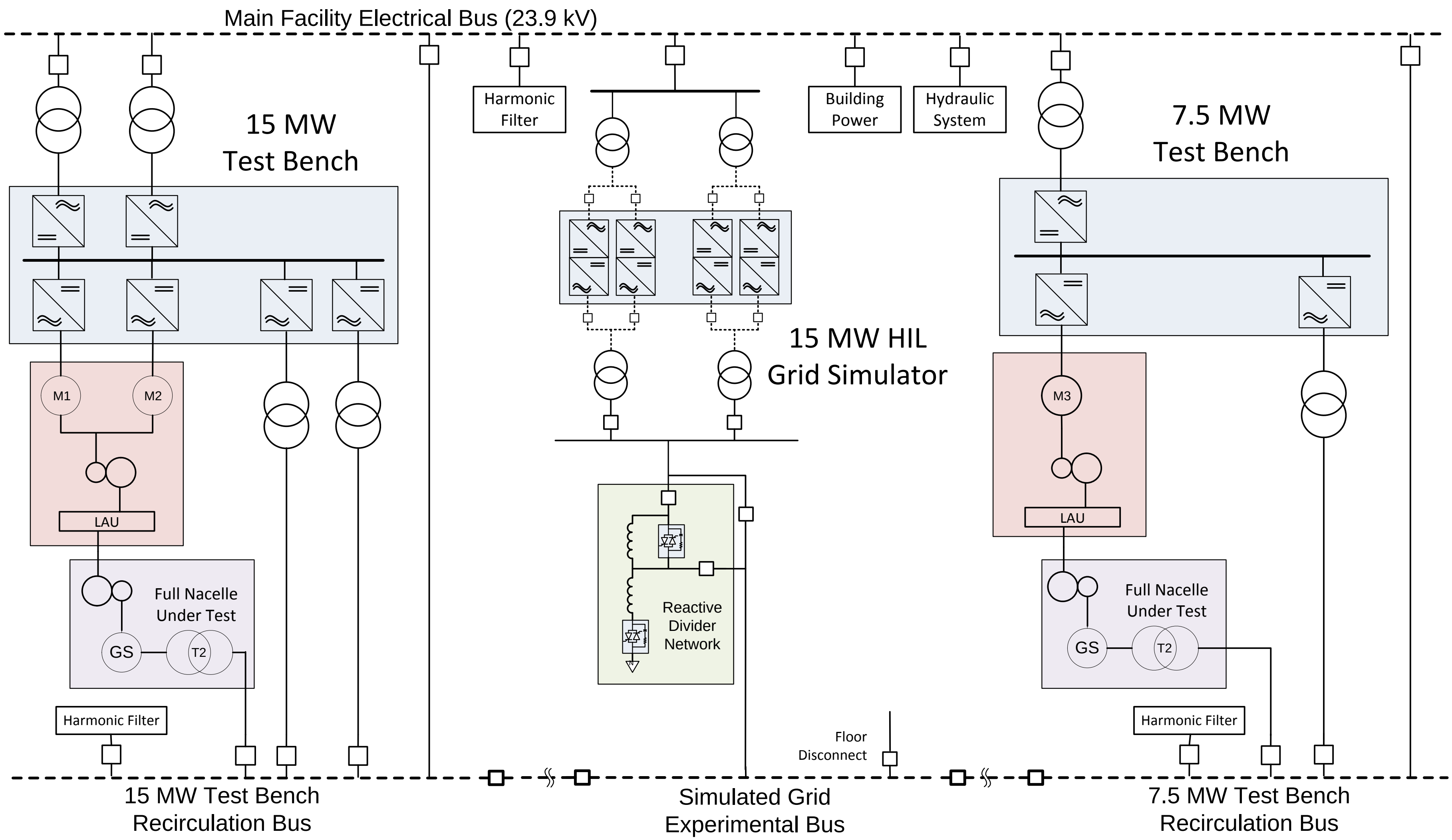


Figure 24 Facility One-Line Diagram

Figure 25 Main Facility 23.9 KV Switchgear

Figure 26 Data System Developed by SRNL

Data and Communication Systems

Savannah River National Laboratory (SRNL) designed, configured, tested, and assisted with installation for the data acquisition systems for each area of the facility. Clemson procured the required components and turned them over to SRNL for implementation. This effort included the data acquisition systems for each of the test bays, (7.5 MW Rig and 15 MW Rig). Each data system has up to a 750 channel capacity which does not include the separate vibration and grid monitoring systems. The cabinates making up one system are shown in Figure 26.

SRNL was also responsible for defining the Integrated System that monitors the state-of-the-art Drive Train Test Facility from the following subsystems:

- Electrical Grid Monitoring System
- Vibration Monitoring System
- Facility Instruments and Sensors
- Facility Communication System
- Wind Turbine Vendor Sensors
- Sensors from Renk Control System

Specialists from the Clemson IT staff worked closely with staff from SRNL to define and implement the facility communication archictecture. The system diagram for the 15 MW test rig (#1) is illustrated in Figure 27. The system for the 7.5 MW test rig is virtually identical. The communications networks for the facility serve a number of different purposes. This multiple layer system provides the following capabilities:

- Secure test rig vendor remote real time access to critical information via an encypted 10Gbps Internet Connection.
- Secure firewalling of each test area from all other areas.
- Implementation of a separate facility control network.
- Implementation of a separate test rig control network.
- Independent data network for each test area.
- Protected vendor/supplier maintanence communications and remote access via VPN.
- Firewalled/protected access to outside internet activities and resources.
- Time stamped data logging for all data in the building via a syncronized GPS based data clock.
- Defined storage and protection for test rig data and configuration information.

These capabilities were also expanded into the eGRID facility as that facility was integrated into the overall Energy Innovation Facility. SRNL was also responsible for the design of the electrical grid monitoring system implemented throughout the facility. A very capable set of integrated Schweitzer Engineering Laboratories (SEL) relays were implemented to control and monitor all power within the facility. SRNL supervised the installation of the SEL power monitoring system by contractors reporting to Clemson and assisted with the setting of the initial safety settings.

SRNL was also responsible for the design, configuration, and installation of the control room consoles and wiring. The consoles for each test rig are the same and include a console area for Clemson for running the test rig as well as a separate console for data access for the test article supplier. The console and control room for the 15 MW test rig is shown in Figure 28. A separate data system room is adjacient to the control rooms. This room contains the system control computers, the main data storage systems, the data system front-ends when not in use, and the networking racks. The test areas, data areas, and the control rooms are interconnected by conduits and cable trays to facilitate rapid modification of the configuration as needed for differents tests and equipment.

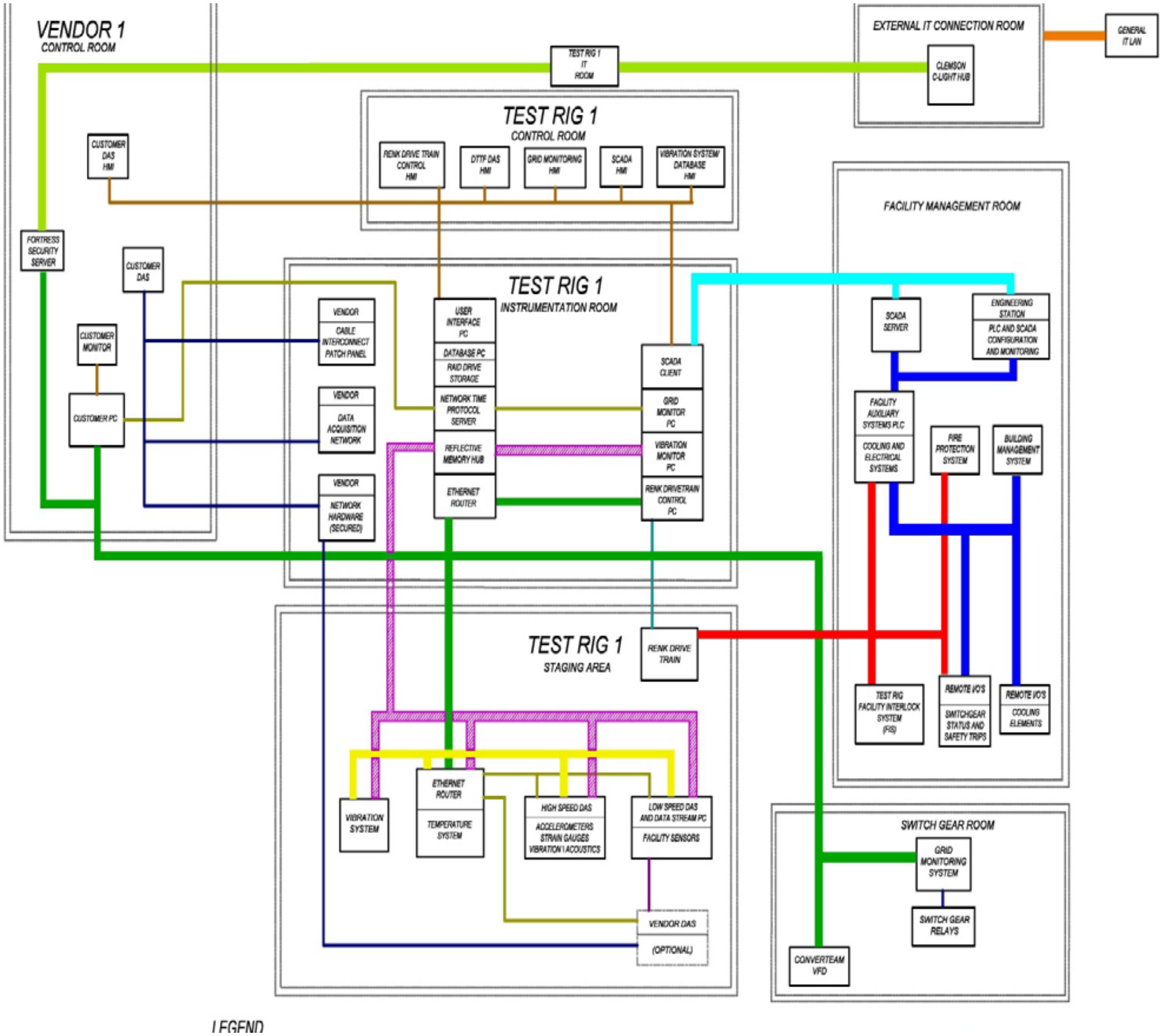


Figure 27 Data System Configuration for the WTDTF., 15 MW Rig

Figure 28 Control Room Console

Non-Conventional Cooling: An integrated cooling system for the entire facility was developed by the engineering team to keep the large drive motors, motor power electronics, gearboxes, and hydraulic systems in the facility cool. An open loop shared evaporative cooling system was selected as the most appropriate design for the equipment. Therefore piping linking all the systems together was installed allowing a component to draw cooling water as needed from the common supply loop. The system was designed to support operations at maximum power consumption by all components. The piping, pumps, and heat exchangers are all adequate for the envisioned life of the facility and will support full power operations of both test systems. Because of budget constraints, an analysis was done as to the cooling needs for testing up to a 9MW turbine, since at the current time, the largest turbine prototypes are under 9MW. It was determined that it was possible to defer the installation of a second specified cooling tower until such time as it is needed. The current single 1500 ton cooling tower has proven more than adequate during the first years of operation. In fact, the tower fan has seldom operated. Should the need arise in the future, either a portable rental cooling unit or a second tower can be installed during the test planning phases of any testing effort. The existing tower and adjacent space for an additional tower is shown in Figure 29.

Figure 29   Installed 1500 Ton Cooling Tower

Hydraulic Systems: The LAU units for both of the test rigs need extensive hydraulic power to operate. This power is supplied via a multi-pump hydraulic supply located in the utility corridor. Seven 600 HP main motors, each driving two hydraulic pumps can be staged as necessary to provide whatever level of hydraulic oil may be necessary for testing. The hydraulic pumps provide high pressure oil for two specific purposes. The first is to drive the hydraulic cylinders that support the LAU drive disks and provide the defined force and moment loading onto the main shaft of the Unit Under Test (UUT). The second is to provide lubrication to the slide bearings between the cylinders and the LAU disk. The same oil is used for both purposes from a common 300 bar supply line. Oil flows from the cylinders via bypass orifice ports that are used to feed the slide bearings and lubricate the LAU. In addition to the main pumps, the room is equipped with several booster pumps, pilot pumps, accumulators, heat exchangers, filters, and other maintenance equipment. This includes its own 15 ton overhead crane for the assembly and maintenance of the pumps and hydraulic equipment. The room is supplied 480V power from three dedicated 2.5 MW transformers in the adjoining electrical utility space. These transformers are connected to the 23,900 VAC main. The hydraulic system is largely self-contained and was developed as a separate system. The system was designed, manufactured, assembled, and tested prior to shipping to Clemson. It was then disassembled and delivered to the site where it was quickly reassembled into the hydraulic room. As a largely independent system, the power and control modules run the hydraulic facility and provide remote control of the system and soft start capability for the equipment and well as pressure regulation. The facility is integrated with the master controllers for each test rig so that the hydraulic system is operated remotely from the control rooms via the control modules.

Approximately 70,000 liters of hydraulic oil is contained in the main hydraulic reservoir. A photo of the hydraulics' room is shown in Figure 30 A graphic representation is shown in Figure 31.

In addition, each test rig has its own smaller positioning supply that is used to set up the rig and perform various checkout operations, especially positioning and connection of the LAU. The same oil is used with a smaller pump and reservoir located at each test rig. The smaller pump and lower pressures used by this system makes for slower more controllable movement under safer conditions. The positioning systems are controlled with an operator-held portable controller that allows the operator to be visually near the test rig and to closely monitor the position of the LAU.

Finally, each rig has a separate skid for supplying gear oil to each gearbox. Each gearbox has a system of pumps, filtration and heat exchangers to properly lubricate the reduction gearboxes via an internal spray system for the gearing and pressurization for the hydrostatic shaft bearings.

Clemson is also working with an emerging technology under development by a company called Next Generation Filtration to provide enhanced filtration and water separation for both the hydraulic and gear oil systems. Up to six filtration systems will be donated to the project to extend the life of the oil through the use of these new systems.

Figure 30 Hydraulic Power Supply

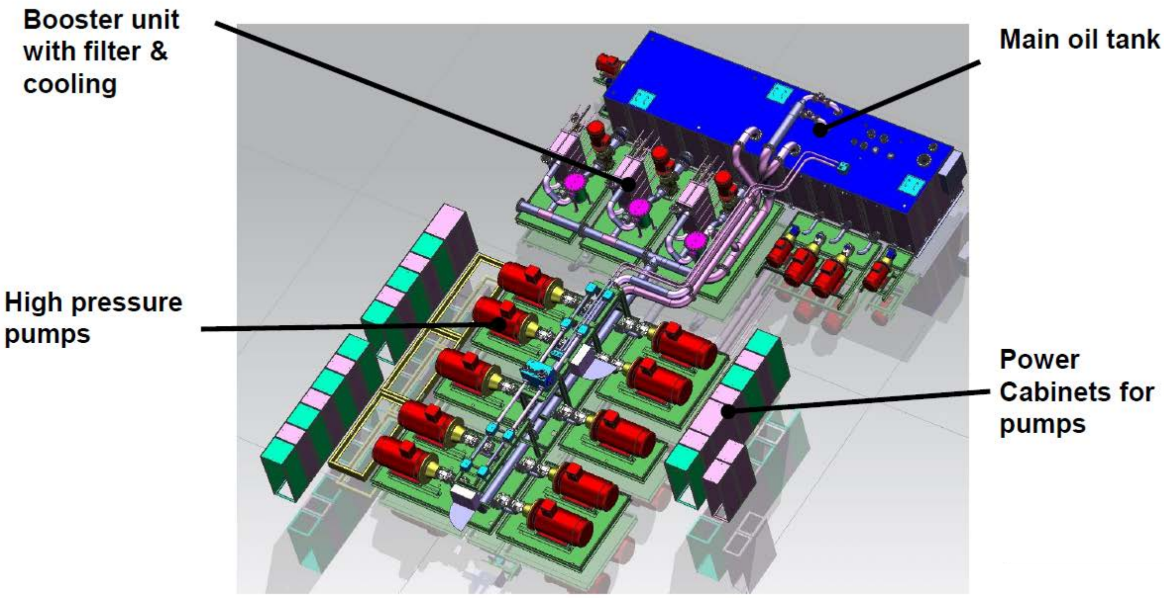


Figure 31 Graphical Representation of Hydraulic Power Supply.

Logistics/Cranes: The issue of logistics affected the overall design and operation of the facility more than any other due to the size and weights of potential items for test. A number of different configurations for providing logistical support were evaluated and considered. The site has rail access so the initial configuration of the rail on the site included providing rail access to both the test bays and to the waterfront. Conversations with customers and movers quickly indicated that this rail configuration might be more constraining than useful. Most movement of heavy equipment is now handled via steerable, configurable multi-wheel, multi-axle trailers or trackers. These trackers are very flexible and maneuverable and well suited for tight confines. Therefore the site logistical design was based upon the use of these trackers. The rail spur was straightened and space provided to be able to transfer any load from a specialized rail car to one of these trackers.

Similarly, movement of materials from the harbor went thru a transformation. Initial configurations used the drydock for ship access. It was quickly determined that the drydock was too shallow for any large ocean going vessels. But Pier J, which is adjacent and just north of the site has the largest heavy loading of any pier in the region. If need be, this pier can be used for loading and unloading of specialized heavy cargo. Further research and economic study uncovered an even better way of receiving heavy cargo to the site. The gearbox for the 15 MW rig shipped at over 340 tons. The best way to get this piece to the facility turned out to involve unloading it at the North Charleston Terminal less than a mile up the river and bringing it to the site via barge crane, It was then placed on a multi-wheel tracker on the side of the drydock and (relatively) easily moved to the building. All of these resources are available from multiple vendors locally so the competition keeps the logistics costs in check.

The initial request from the IAB was to put a 200 ton crane system in the 7.5 MW test bay and a 400 ton crane in the 15 MW test bay. However, due to site and economic considerations a different approach was used. The final crane configuration based upon balancing need and cost is shown in Figure 32. Experience to date has proven the crane capacities to be workable for two reasons.

First it is frequently possible to assemble a test article in place. As long as the weight of the individual components is lower than the overhead crane capacity, assembly can be completed. Secondly, if larger capacities are needed, the necessary equipment is readily available locally due to the facilities port location. Because of these resources it is possible to bring in alternative portable equipment to make any necessary moves at a much more realistic cost than the multi-millions of up-front capital that would have been necessary to equip the facility with the large cranes and the structural infrastructure to support the large cranes. This set of assumptions has been put into practice several times during the building of the facility. The first instance was to place the gearbox for the 15 MW test rig into its final installation position. This gearbox with cradle weighed over 340 tons. It was off loaded from a ship to barge at the nearby ship terminal, floated down the river a short way and transferred from the barge to a multi-wheeled tracker at the quay wall adjacent to our facility. The gearbox was then moved into the facility on the tracker. One of the local firms was then hired to move the gearbox into position using portable gantry cranes without incident. We have used these cranes on other occasions with good success to move the assembled LAU for the 7.5 test rig and also to assemble the 15 MW LAU. The movement of the 7.5 MW LAU took less than a day to accomplish and is illustrated in Figure 33. To expedite such moves, Clemson implemented an Indefinite Delivery Contract (IDC) for a number of logistical services to include rigging, cranes, transport, and engineering. These services can be activated in a matter of a day or two without having to wait for the typically extended state procurement processes. Clemson also had a custom spreader bar fabricated to optimize the lifting configuration presented by the dual hoist configuration. The dual hoist configuration was optimized to enable the lifting of large nacelles and components with the ceiling constraints of the facility.

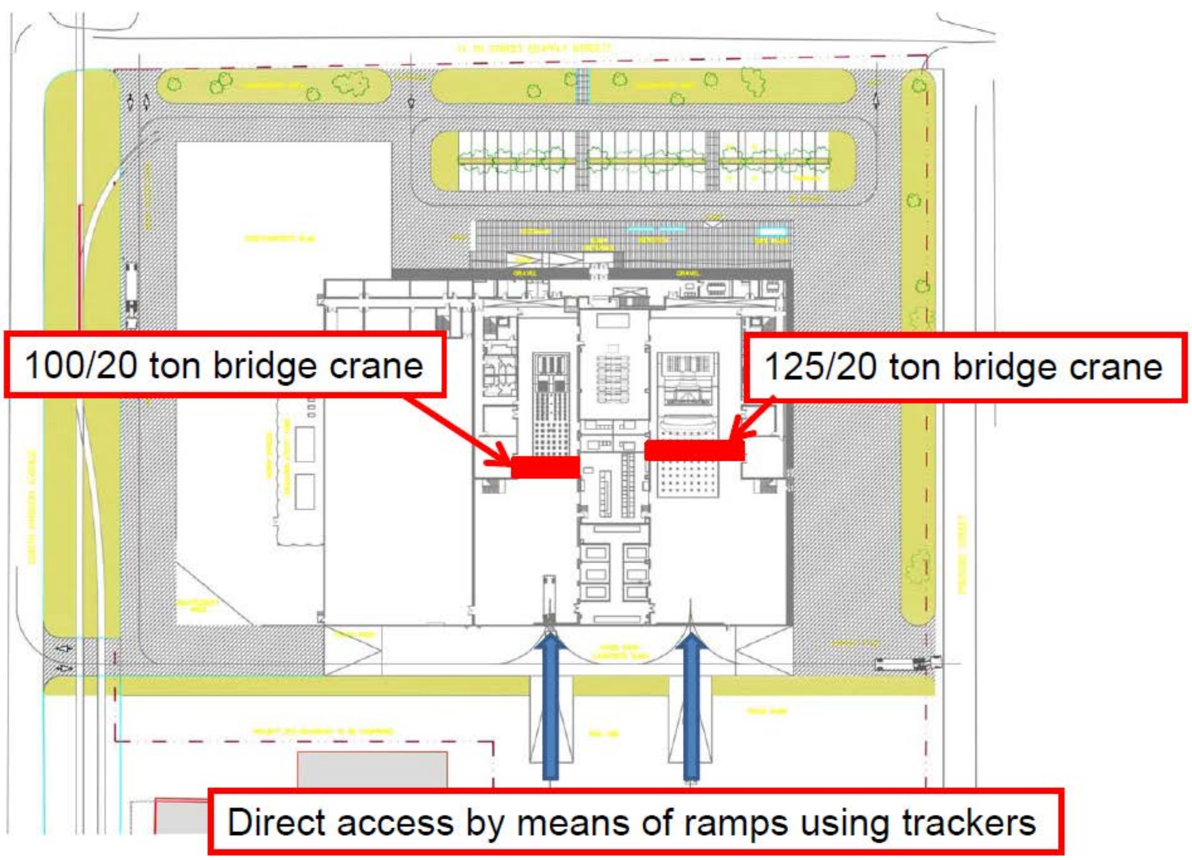


Figure 32 Crane configuration for the Test Facility

Figure 33   Portable Gantry Crane Lift of 7.5MW LAU

Mechanical Modeling, Simulation, and Analysis Laboratory: In order to better understand the operation of the test rig and to aid with test and safety planning, a modeling, simulation, and analysis group emerged out of the Energy Innovation Center's (EIC's) natural growth and development. A team of research scientists and engineers make up the modeling, simulation, and analysis group and have a dedicated laboratory with specialized hardware and software used for studying the test equipment and the devices being tested. The laboratory is referred to as the SimLab and shown in Figure 34.

The SimLab's mission statement is to, "Impact the wind industry by advancing the state-of-the-art of nacelle testing and satisfy our customers by pursuing safe, efficient, fruitful test campaigns." Researchers and scientists affiliated with the simulation lab fulfill this mission through a number of different activities.

Figure 34 SimLab

The modeling of the hardware that has been developed under the project has proven invaluable in beginning to understand the new technology that these test rigs represent. Researchers and scientists in the SimLab develop in-depth understanding of the test equipment (both hardware and software) through dynamic modeling, simulation, and analysis. The SimLab's activities help to develop the in-depth equipment knowledge that allow our test engineers to use the equipment safely, effectively, and efficiently.

The SimLab is continuously engaged in research and testing projects aimed at supporting its mission. At the highest level, SimLab personnel develop dynamic models of the test equipment and devices under test to aid in operating the test rig and delivering successful test campaigns. Figure 35 is a diagram of the type of models being developed in the SimLab. The dynamic model includes a multi-body model of the physical test hardware as well as dynamic models of the sub-systems and control loops that contribute to the test rig's overall behavior.

Members of the SimLab directly support physical testing by operating the test rig as needed. SimLab engineers may be needed to assist with the day-to-day test rig operations such as generating test profiles, operating the test rig, analyzing test data, etc. The uncertain nature of the testing environment can create a sudden demand for personnel to assist with troubleshooting, interpreting data, re-running tests, and redesigning tests.

All members of the Clemson team assist with research related to the facility's testing capabilities and apply for competitive grants. As part of Clemson University, the EIC is committed to scholarly pursuits in addition to providing customers with high-quality, cost-competitive testing, simulation, and analysis services. To date, both the SimLab and the eGRID team have been leading the way in the dissemination of generated knowledge by publishing in peer-reviewed journals and presenting at industry meetings and conferences. To date, the SimLab has published one journal paper, six conference papers, one technical report, presented one poster. Additionally, SimLab personnel have presented at many technical meetings including the Drivetrain Reliability Collaborative hosted by NREL and the Grid Simulator Workshop hosted jointly by Clemson University and NREL.

The SimLab team has been leading the effort to engage in collaborative research efforts with external organizations. The EIC maintains a collaborative research and development agreement (CRADA) with the National Renewable Energy Laboratory, which is the only other location in the united states where it is possible to do mechanical and electrical testing on full scale wind turbine nacelles.

SimLab personnel also make an effort to engage with customers and promote a collaborative and inquisitive environment during testing. Such interaction has resulted in smaller simulation-based projects being done in parallel with physical testing and has spawned several projects that were eventually worked on by the EIC's summer interns.

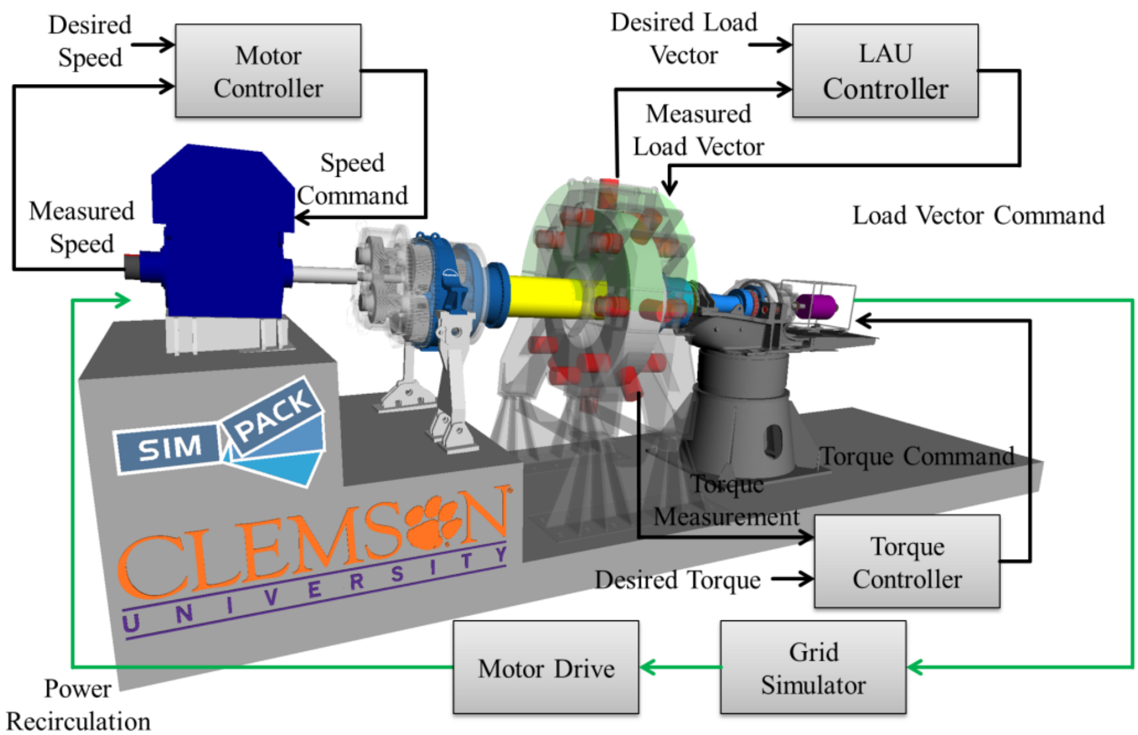


Figure 35 Diagram of the dynamic test rig model being developed in the SimLab

The following subsections outline some of the highest impact projects competed to date.

7.5 MW Tech Rig Controller Modification Support

The 7.5 MW test rig was originally designed to be a static or quasi-static test rig, meaning that the applied loads were only meant to change slowly. Customers, however, consistently inquired about the dynamic performance of the test rig prompting the EIC to upgrade the dynamic capability of the test rig. SimLab personnel worked closely with the original equipment supplier to modify, install, and test a control system with expanded dynamic performance and improved control capabilities.

Load Application Unit Accuracy Evaluation and Uncertainty Analysis

The 7.5 MW test rig's Load Application Unit (LAU) is a unique and powerful piece of equipment used to apply linear forces and bending moments in five degrees of freedom to the main shaft of the device under test. SimLab researchers used a combination of statistical analysis and test data along with knowledge of the construction of the LAU to quantify the uncertainty of the loads applied by the LAU. These properties are important to customers because the level of uncertainty influences the types of conclusions that may be drawn from test data.

Main Shaft Alignment

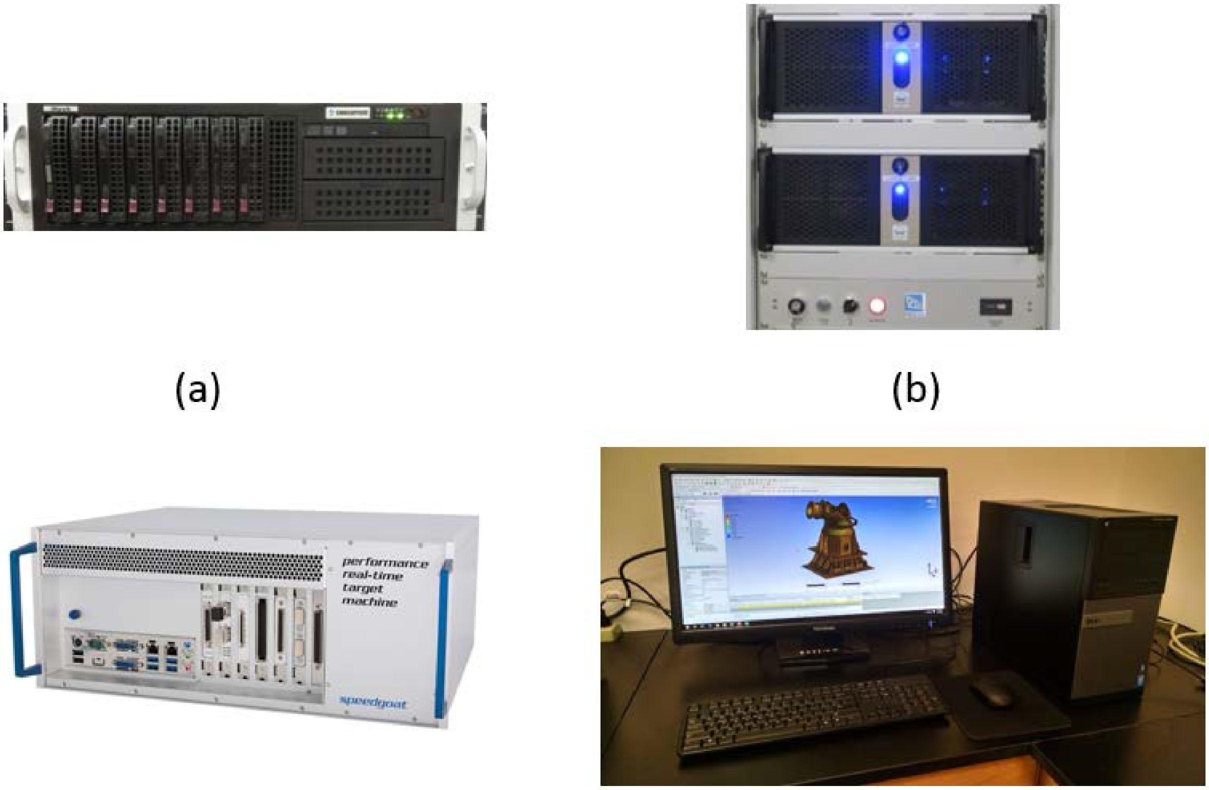
The main shaft of the test rig is approximately 1.5 meters in diameter yet it needs to be aligned with the main shaft of the device under test to within approximately 0.1 millimeters linearly and 0.005 degrees angularly. SimLab personnel worked with test engineers to analyze data and develop a method to determine the magnitude and direction of the main shaft misalignment so that it may be corrected.
SimLab personnel also developed a software based strategy for mitigating the effects of misalignment for the situation when misalignment cannot be corrected mechanically.

Driveline Torsional Property Determination

One of the objectives of both the 7.5 MW and the 15 MW test rigs is to replicate field conditions in the laboratory environment. Admittedly, the nacelle is in a very different environment when on the test stand as compared to its natural environment on the top of a tower with blades attached. SimLab personnel have developed dynamic models of the test equipment including the device under test in order to study the behavior of the complete system. Understanding the system characteristics aids in interpreting and analyzing test data.

The SimLab has acquired several pieces of specialized equipment shown in Figure 36 to assist with achieving its mission. These additions to the original program are the direct result of the successes of the original program and a recognized need to continue technology development.

a) *Concurrent Real-Time Simulation Computer:* This computer is used to run MATLAB, Simulink, and SIMPACK models in real-time. This computer can also communicate to other real time systems via reflective memory
b) *RENK Dynamic Data System (RDDS) or test control computer:* This is the same computer system used to control both the 7.5 MW and 15 MW test rigs. This allows for SimLab personnel to have access to the exact same human machine interface in the SimLab as the test engineers have in the control room. In the test bays, RDDS communicates and controls actual test equipment. In the SimLab, RDDS communicates and controls real-time models of the test hardware running on the Concurrent real-time system.
c) *Speedgoat Performance Real-Time Target:* This computer is designed to run MATLAB and Simulink models in real-time and communicate with other real-time systems over a variety of communication protocols. This is a versatile real-time system and can act as a surrogate nacelle controller for a variety of SimLab activities.
d) *Numerical Analysis Workstation:* SimLab personnel built a workstation for performing finite element analysis to evaluate and design mounting and interface fixtures for nacelle testing. The prediction of stresses and displacements is a major concern in the design of test fixtures, especially when the prolonged accelerated life tests are to conducted.



(a) (b)

(c) (d)

Figure 36   Specialized SimLab Equipment

Facility Operations

Facility Certification: The Wind Turbine Drivetrain Testing Facility (WTDTF) is committed to one day becoming a certified testing facility for the full scale testing of wind turbine nacelles.
Seeking certification typically involves an audit by a certifying body. In the context of a testing facility, the certifying body will verify two things:

1. That the facility's test and measurement equipment has been properly calibrated and that the calibrations are current
2. That the testing services the facility provides are in accordance with an agreed-upon standard

Unfortunately for the WTDTF, calibration procedures do not currently exist for the main dynamometers or the Load Application Units, nor does calibration equipment exist that can be used to characterize the facility's custom test and measurement equipment, especially the LAU's. Furthermore, it is not possible to determine whether or not the WTDTF's testing services conform to accepted standards because those standards don't yet exist. Since the loading mechanisms used in the two test rigs have never been implemented before, the team is breaking new ground in the loading environment and the defining of input and resultant loads.

Staff at the WTDTF are engaging in activities to address both of these shortcomings. At this early time in the maturity of the facility, it is not believed beneficial to implement a full laboratory instrumentation and measurement certification such as ISO 17025. The team evaluated this standard with the help of SRNL. SRNL follows this standard for many facets of their work, especially in the nuclear areas. The clients from the industry on the Industrial Advisory Board were consulted as to the value of implementing ISO 17025 as it also puts requirements on the customer and their equipment. The overall resources for implementing a ISO 17025 program were not deemed a good use of resources by either the team or the customer. Rather, for all standard instruments, normal protocols of calibration and certification are followed based upon pragmatic needs. Instrument and sensor calibrations are checked as needed to verify proper operation. Second, the engineers at the WTDTF have designed and built custom fixtures that allow for the loads produced by the 7.5 MW test rig to be measured by commercially available load cells. These load cells can be calibrated and offer a way to quantify the test rig's accuracy and repeatability. Additionally, the uncertainty of the test rig is being studied from a theoretical perspective as part of internal research activities. We envision this work continuing for a protracted period of time.

To address the lack of testing standards Clemson University is taking part in the International Energy Agency's (IEA) Task 35 working group, Ground Based Testing for Wind Turbines and Their Components. The goal of this working group is develop a set of recommended practices for the ground testing of full scale wind turbine nacelles that will, "address the lack of uniform procedures for ground testing" (AdHoc Group Report to the Executive Committee of the International Energy Agency July 2013, ISBN 0-9786383-9-5). Ultimately, these recommended practices should lead to technical requirements that, "will be recognized internationally by standards and certification organizations" (AdHoc Group Report to the Executive Committee of the International Energy Agency July 2013, ISBN 0-9786383-9-5).

During the commissioning of the test rigs, it was determined that the performance of the test rig is strongly influenced by the test article due to the complex system interactions between the test rig and the article under test, especially when evaluating dynamic characteristics. Given the very competitive nature of the industry, this interaction makes it difficult to release data on specific equipment without violating the IP rights of the equipment manufacturer.

During the commissioning activities, a number of performance measurements were documented into a commissioning report which can be shared within the limitations of the manufacturer's release of data pertinent to their turbine. These reports have been shared with appropriate DOE personnel as part of project reporting.

Clemson's staff continue to interact with both US and International labs and officials as the collective group works on protocols for testing and accreditation within the industry. A significant perspective was obtained by touring and benchmarking the equivalent test facilities in Europe. Currently, no true accepted protocols are in place in the technical community.

Staff Development, Safety and Training: Management at Clemson has placed emphasis on safety for the facility since its inception. The facility construction project logged over 250,000 man-hours of on-site labor without a lost time accident. The management goal is to keep this record intact.

It must be realized that the collective facility of the Wind Turbine Testing Facility and the e-GRID are completely new facilities. There are no accepted operating procedures or pool of staff that can be transferred from another operating facility as one would typically encounter when building a new industrial facility. All staff are new and the operating team is being developed as the facility is developing. The current full time staff count is approaching 19, with a number of visitors and customer staff frequently on site along with contractors for specific work and maintenance activities. Facility construction was completed in late 2013 and equipment commissioning started immediately. Employees were hired with expertise in the mechanical and electrical engineering fields to develop the necessary understanding of the test equipment and its operation. At the same time, Clemson is an educational institution with an emphasis on research. Hiring for the facility focused on both the operation of the facility and also on the skill sets necessary for the development of test methods, materials and methods for energy research. These processes involve cutting edge technology as well as methods that fall outside the realm of normal industrial operations. Performing this type of research work poses numerous challenges to employee safety. This is especially true for this facility because of the size of the equipment and the large amount of energy either available or stored within the facility systems. The facility is far from the normal University Laboratory. The overall “newness” and unknown behavior of the large systems adds to the level of caution necessary until operating experience can be developed.

A safety professional was hired to assist in identifying, evaluating and controlling the exposures that are created by the operation of the facility and from the research processes. A plan was developed which was to establish a baseline safety understanding and culture, then building on the culture by providing safety training and perspective. This Knowledge Based Safety (KBS) approach plans to grow and enhance the research safety process throughout the Clemson facility. This program is called CROSS (Clemson Research Operational Safety System). A graphic was developed to illustrate the system and is shown in Figure 37.

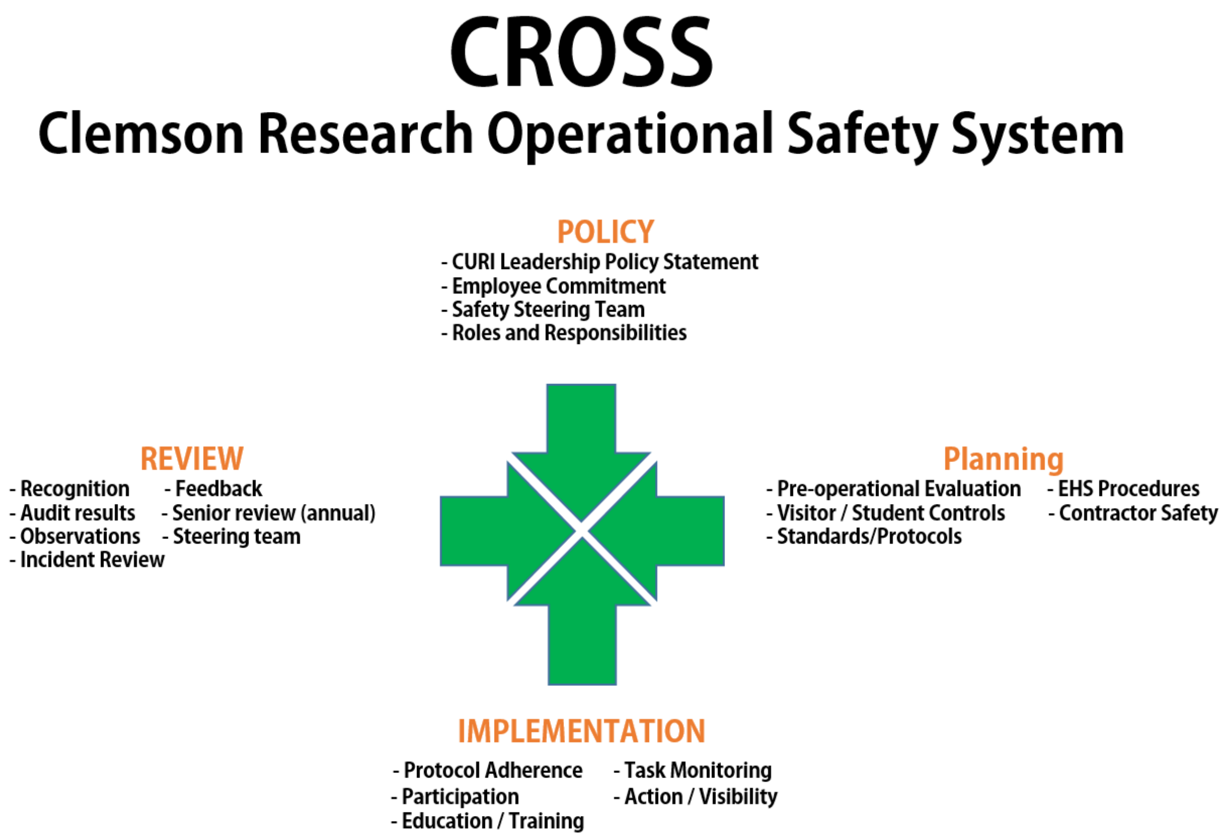


Figure 37 Clemson Research Operational Safety System

This dynamic system regularly changes to fit the operations efforts to assure a loss free environment. The safety process involves all employees and contractors to assure that the exposures which have a potential to produce injury are discovered and mitigated through various means before any exposure situation is encountered or work actually started. The safety training efforts that have taken place to date are detailed and will show how this process enhanced the overall operation by preventing loss. At the close of the DOE contract, 36,340 work hours have been completed without injury using this approach.

The key requirement to ensure safe operation is the ability to recognize risk. If the risk of a process or action is recognized, then steps can be taken to minimize or mitigate it. Therefore, the first step to working safely is to understand safety parameters of the environment at hand. With the hiring of a Safety professional, Clemson made a strong commitment to provide safety education and therefore develop a safety culture for the facility. The OSHA 10 hour training curriculum was provided and completed by **(all)** employees working within the EIC (Energy Innovation Center). This baseline instructional series was provided over a 10 week period covering many aspects of OSHA and OSHA regulations. Although this was an opportunity to explain what was required by law, Clemson made it clear that the regulations were minimum guidelines to reference but best practices were to be instituted to bring about a higher level of effort and understanding.

Many safety training programs were developed specifically for the EIC. Safety training was provided on many topics and each employee is now championed in providing the effort to control exposures. A Safety Steering Team (SST) identifies and directs efforts to assure they are in-line with regularly changing exposures. With the effort and hours required to attend classes in the extensive list of topics it is clear this training is a major part of the developing Clemson facility. Below is a list of topics that have been debuted and communicated thru classes, lectures, and hands on training.

- Safety CROSS Program
- Electrical Safety
- Safety Task Analysis
- Lockout and Energy Control
- Aerial Lift Safety
- Interns Safety Orientation
- Respirator Safety
- 1st Aid, CPR and AED Training
- Waste Controls
- Research Safety Policy
- Confined Space
- Crane Safety
- Critical Lifting Planning
- Global Harmonization
- OSHA 10 hour Industrial
- Safety Task Analysis
- Arc Flash Safety
- Contractor Safety
- Design Team Safety
- Forklift Safety
- Fall Protection
- Emergency Action Program
- Incident Investigation
- SPCC (Spill Prevention Counters and Control)
- Machine Specific Protocol for Control
- Personal Protective Equipment
- Rigging Safety
- Hot Work Permitting / Welding
- Ergonomics

The safety culture has grown exponentially in the last two years. Everyone participates and has the authority to stop any task due to safety concerns.

Interns: The Energy Innovation Center has an internship program that allows high school and college student (Clemson University and other universities) to work with practicing engineers and make an impact on the wind industry. Throughout the project starting with the construction effort, students have applied for and accepted summer internships at the facility. The first interns were from the Construction Management program at Clemson. Since then, up to 15 interns each year have assisted with efforts in the facility by assisting with operation and maintenance/configuration of the test rigs and performing various studies related to energy. The students are typically junior or senior Mechanical or Electrical engineering or Computer Science students. Multiple regional schools including Clemson, The Citadel, Georgia Tech, and others have been represented. Past summer interns have worked on various projects including:

- Hydraulic servo valve modeling
- Test rig dynamic modeling
- Reflective memory communication configuration
- Test rig control system research
- Test data analysis and post processing
- Electrical Energy Consumption and Rate Calculation
- STEM equipment Development
- Solar farm and weather data development
- Development of a 3-D printed scale representation of the 7.5 MW test Rig

Patents: There were no Patents filed during the construction of the Wind Turbine Drivetrain Testing Facility. There were several patents associated with the eGRID and reported in that project.

Presentations/Tours: Throughout the course of the project, presentations have been made on the project to local technical and business groups. Staff continue to host tours of the facility for professional groups on a weekly basis. Again these groups may be interested in technical, business, or partnering activities. A website is maintained for the project at www.clemsonenergy.com. Various articles and video of the project are presented at this site. Much of the testing is now considered client property and restricted. This in turn creates limited access to the test cells during active testing.

The facility continues to serve as a base for many educational activities. In addition to the professional tours, targeted tours for local science and engineering STEM programs are frequently hosted. Various workshops and competitions for STEM initiatives are frequently held using either the open office area or the mezzanine of the 15 MW test rig. Professional Groups such as IEEE use the facility frequently for meetings and workshops.

Industrial Partners: As an educational institution, Clemson frequently partners with industry on many fronts. These partnerships take many forms from cost sharing as denoted in Appendix A, Project Team, to continuing commercial supplier discounts. A list of the industrial partners and their contribution to the project is in this Appendix. The lobby of the facility has a “Power Wall” where the names of the project partners and donors are displayed. We continue to add to this display as the facility continues to evolve and add more partners. Significant partnerships have been created with Duke Energy through cooperation on the eGRID facility and the overall building is now known as the SC&G Energy Innovation Center, or EIC due to the partnership with the local utility, SCE&G.

Awards:

ENR (Engineering News-Record) Southeast 2014 National Best of the Best Projects Competition: Clemson University's SCE&G Energy Innovation Center was selected in the Energy/Industrial Category. (March 2015)

Engineering Excellence Award from the American Council of Engineering Companies of SC (ACEC-SC): SCE&G Energy Innovation Center was selected in the Building and Technology Systems Category (Feb 2015)

ENR's (Engineering News-Record) The Top 25 Newsmakers: Nick Rigas selected (January 2015)

The Trailblazer Award from the Chas Metro Chamber of Commerce: Awarded to CURI (Oct 2014)

ENR Southeast 2014 Best Project: SCE&G Energy Innovation Center was selected in Energy/Industrial Category (August 2014)

LEED Gold Certification by the U.S. Green Building Council for the SCE&G Energy Innovation Center (July 2014)

Appendix A Project Team

Recipient: Clemson University
Award Number: DE-EE0003023
Project Title: Recovery Act: Clemson University Wind Turbine Drivetrain Test Facility
Project Period: January 1, 2010 to December 31, 2015

Working Partners:

Clemson University, North Charleston, SC, 29405

Savannah River National Laboratories, Aiken, SC 29808

Fluor Corporation, Greenville, SC 29607

S&ME, Mt Pleasant, SC, 29464

SCANA (South Carolina Electric & Gas Company), Cayce, SC, 29033

South Carolina Public Railways, Now Palmetto Rail, Charleston, SC 29403

LeMessurier Consultants, Boston, MA, 02135

AEC ENGINEERING, Now IDOM, Minneapolis, MN 55401

Choate Construction Company, Mt Pleasant, SC, 29464

RMF Engineering, Inc., Charleston, SC, 29492

B&B Demolition Specialists LLC, North Charleston, SC 29405

Aiken Cost Consultants, Inc, Greenville, SC 29601

GS2 ENGINEERING & ENVIROMENTAL CONSULTANTS, INC, Columbia, SC 29209

Ryan Structural Engineers, LLC, Mt Pleasant, SC, 29466

DOE Project Team:

DOE HQ Program Manager – Jose Zayas
DOE Field Contract Officer – Pam Brodie
DOE Field Contract Specialist – Laura Merrick
DOE Field Project Officer – Gary Nowakowski
DOE/CNJV Project Monitor – Melissa Callaway

Cost-Sharing Partners:

Clemson University

Charleston Naval Complex Redevelopment Authority

State of South Carolina, SC Ports Authority –

Renk Labeco Test Systems Corporation –

South Carolina Public Railways

South Carolina Department of Commerce

State of South Carolina

James Meadors – Philanthropist

Tony Bakker – Philanthropist,

Industrial Partners and their Contribution:

Shell Oil – Hydraulic and gear oils
Prysmian- Discounted medium voltage cable
Barnhart- Logistical Services
Choate- Construction Management
AEC- Consulting Engineering
Teco Westinghouse- Power Amplifiers
HyTorq- Hydraulic tools
UL- Testing Consulting
RE^3 Optimization Systems- Oil filtration

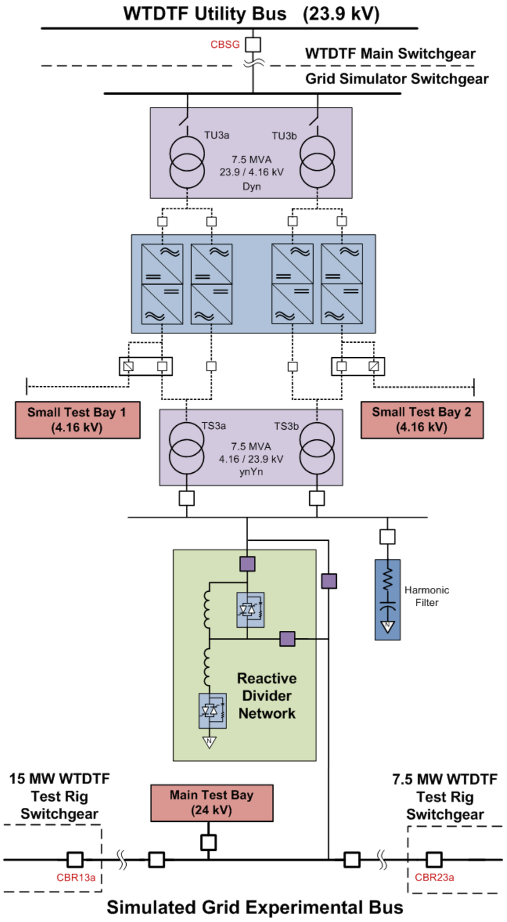
APPENDIX B GRID SIMULATOR Overview

15 MW Hardware-In-the-Loop Grid Simulator Facility

www.ClemsonEnergy.com

Main Test Bay	
Nominal Voltage	24 kV (50/60 Hz)
Nominal Power	15 MVA (20 MVA Installed)
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)

Facility Single Line Diagram



Electrical and 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)

Grid Fault Ride-Through Testing
- Low Voltage Ride-Through (LVRT)
- Unsymmetrical Faults
- 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

Project Partners

Duke Energy

Santee Cooper

SCANA

TECO-Westinghouse Motor Company

Savannah River National Laboratory

Underwriters Laboratory

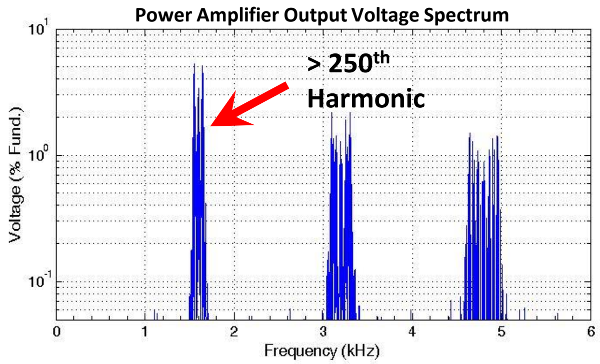
US DOE EERE

AEC/Idom Engineering

Hi Line Engineering (a GDS Company)

Choate Construction

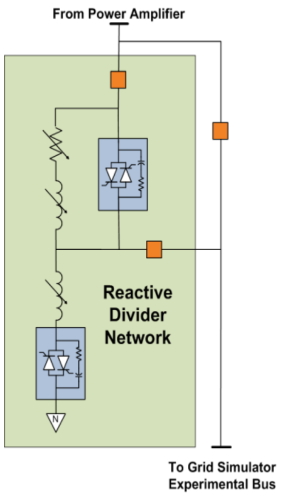
TECO-Westinghouse Motor Company 20 MVA Power Amplifier



- Modular design that is easily reconfigurable for various voltage and power levels
- Installed amplifier power of 20 MVA in four sections of 5 MVA each with a nominal voltage of 4160 V
- Output voltage range from 480 V to 13,800 V (manual reconfiguration required)
- The multi-level architecture and PWM strategy greatly reduces the harmonic noise in the output voltage created by the amplifier
- Custom communication allows for reference voltage sampling at rates up to 12 kHz

The Reactive Divider Network

- Electrically isolated for 100 MVA
- Thermally designed for over 35 MVA for a 3 second duration with a 10 minute duty cycle between faults
- Combines fixed and tapped air core reactors to provide thousands of possible fault combinations
- Precise timing through the use of semiconductor based switches
- More robust representation of fault events than using the power amplifier alone

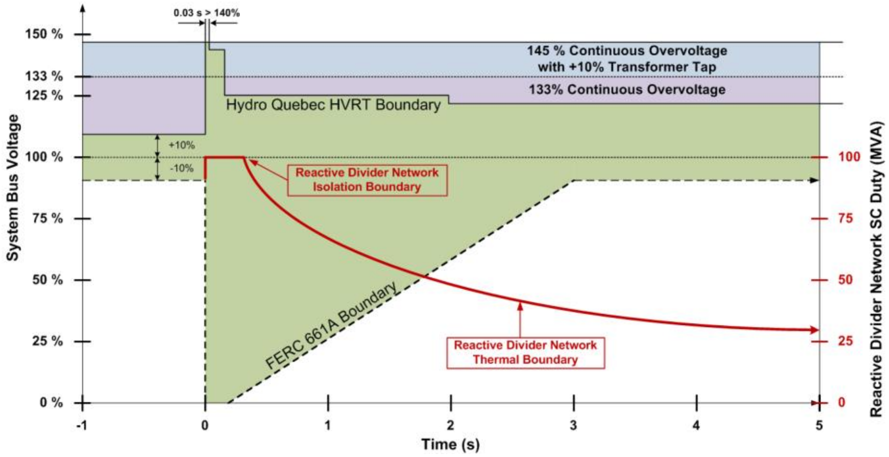


Real Time Digital Simulator (RTDS®)

An expandable parallel computer that solves electromagnetic transients associated with power system models in real-time and an extensive software library of components and controls.

Targeting 3 racks for a total of 144 three phase system buses.

Low and High Voltage Ride-Through Capabilities



- Power amplifier has 133% built-in continuous over-voltage without modulation index saturation
- 145 % over-voltage possible with +/- 10 % output transformer taps
- Coupling of LVRT and HVRT allows for the emulation of more realistic events (i.e. Fault Induced Delayed Voltage Recovery)

Interface Control and Data Acquisition System

- National Instruments PXIe based real-time systems with onboard FPGAs computational capabilities
- Uses high speed, low latency GE Reflective Memory for remote I/O
- Custom high speed serial fiber optic communication between the interface control and the power amplifier
- Locally wired connections to the RTDS® system for Hardware-In-the-Loop applications