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The Scaled Wind Farm Technology Facility: a Turbine-Turbine Interaction Purpose-Built Facility

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ABSTRACT

In the past decade wind energy installations have increased exponentially driven by reducing cost from technology innovation and favorable governmental policy. Modern wind turbines are highly efficient, capturing close to the theoretical limit of energy available in the rotor diameter. Therefore, to continue to reduce the cost of wind energy through technology innovation a broadening of scope from individual wind turbines to the complex interaction within a wind farm is needed. Some estimates show that 10 - 40% of wind energy is lost within a wind farm due to underperformance and turbine-turbine interaction. The US Department of Energy (DOE) has recently announced an initiative to reshape the national research focus around this priority. DOE, in recognizing a testing facility gap, has commissioned Sandia National Laboratories (SNL) with the design, construction and operation of a facility to perform national research in turbine-turbine interaction and wind plant underperformance. Completed in 2013, the DOE/SNL Scaled Wind Farm Technology Facility (SWiFT) has been constructed to perform early-stage high-risk cost-efficient testing and development in the areas of turbine-turbine interaction, wind plant underperformance, wind plant control, advanced rotors, and fundamental studies in aero-elasticity, aero-acoustics and aerodynamics. This paper will cover unique aspects of the construction of the facility to support these objectives, testing performed to create a validated model, an overview of research projects that will use the facility, and finally some preliminary results from turbine-turbine interaction experiments.

KEYWORDS

Scaled Wind Turbine Testing, Turbine-Turbine Interaction, Wind Plant Underperformance, Model Validation, Wind Plant Control

1. INTRODUCTION

1.1 Motivation

In the past decade wind energy installation has increased exponentially driven by reducing cost from technology innovation and favorable government policy. In recent years wind energy has either led or been second to natural gas in terms of total annual power installation in the US. Modern wind turbines are highly efficient, capturing close to the theoretical limit of energy available in the rotor diameter. Therefore, to continue to reduce the cost of wind energy through technology innovation, a broadening of scope from individual wind turbines to the complex interaction within a wind farm is needed. Some estimates show that 10 - 40% of wind energy is lost within a wind farm due to underperformance and turbine-turbine interaction.

1.2 Scope and Objectives

SWiFT was constructed as a cost-effective innovation platform for the study of both wakes and rotors as shown in Figure 1. The cost effectiveness is achieved by using smaller, but still relevant turbines allowing for much more rapid and even radical experimentation. The platform is supported by a state-of-the-art facility control center where all data collection is streamed; and a large assembly area for rotor and equipment preparation.

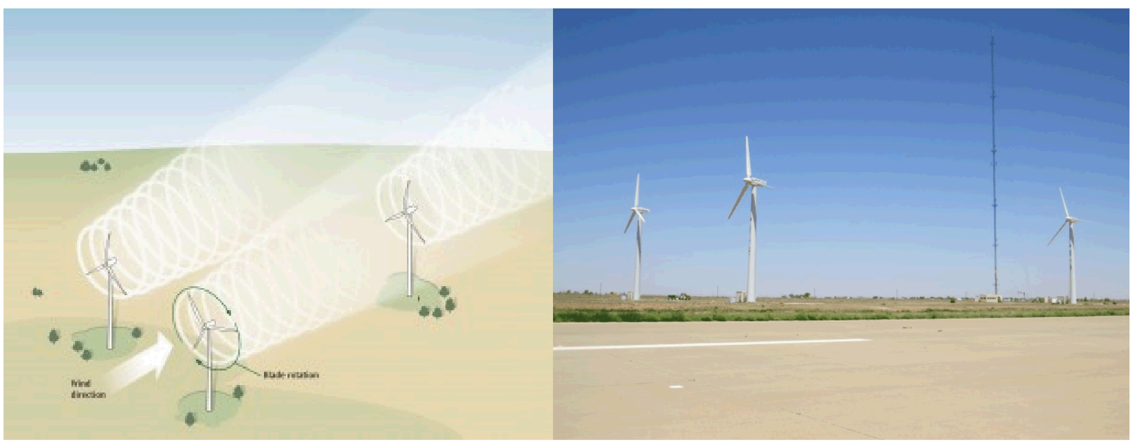

Figure 1. Turbine–turbine interaction schematic with wakes denoted by white helices and white fog (left). SWiFT Facility (right).

The primary objectives of SWiFT are:

- Reduce power losses and damage caused by turbine–turbine interaction through study of complex flow;
- Enhance wind farm energy capture by developing next generation rotor technology;
- Improve the validity of aerodynamic, aero-elastic, and aero-acoustic simulations used to develop innovative technologies; and
- Improve wind plant reliability with new technology.

2. SCALED WIND FARM TECHNOLOGY FACILITY

2.1. Site Layout

The SWiFT Facility was designed to study turbine-turbine interaction, test advanced rotor concepts and meet international testing standards. Furthermore, the facility was intended to represent conditions of a majority of US wind installations and to enable rapid testing.

To accomplish these goals, the facility was located in Lubbock, TX at the southern end of the US wind corridor. This location provided a high wind resource with an average wind speed of 7.5 m/s, a predominant Southern wind direction, and a flat minimally rough terrain. The climate in this area was also favorable for all-year testing and maintenance. Both the high wind resource and availability of the site are key contributors to meeting goals for rapid experimental testing.

To address turbine-turbine interaction and advanced rotor testing, a triangular 3-, 5-, 6-diameter layout of three turbines was designed with the predominant wind direction aligned with the 5- diameter spacing as shown in Figure **4**. This layout allows for turbine-turbine interaction studies to be performed at a spacing of 5 and 6 diameters when data is filtered by wind direction. Furthermore, the arrangement provides for advanced rotor testing by comparison of the leading row turbines spaced 3- diameters to maximize coherence of the inflow. Furthermore, simultaneous testing of an advanced rotor and a baseline rotor provides improved statistical accuracy of the data assuming that turbine variation is controlled or measured. Lastly, two inflow anemometer towers were located precisely 2.5 diameters upwind of the leading row turbines to match international testing standards.

SWiFT currently consists of three research-scale wind turbines (modified Vestas V27s) with two owned by DOE/SNL, one owned by Vestas, and all managed by SNL. Vestas joined the facility to leverage research performed by SNL and to enable a technology accelerator for rapid product improvement. The long-term plan is to add seven additional identical research-scale wind turbines with the next four already pre-approved.

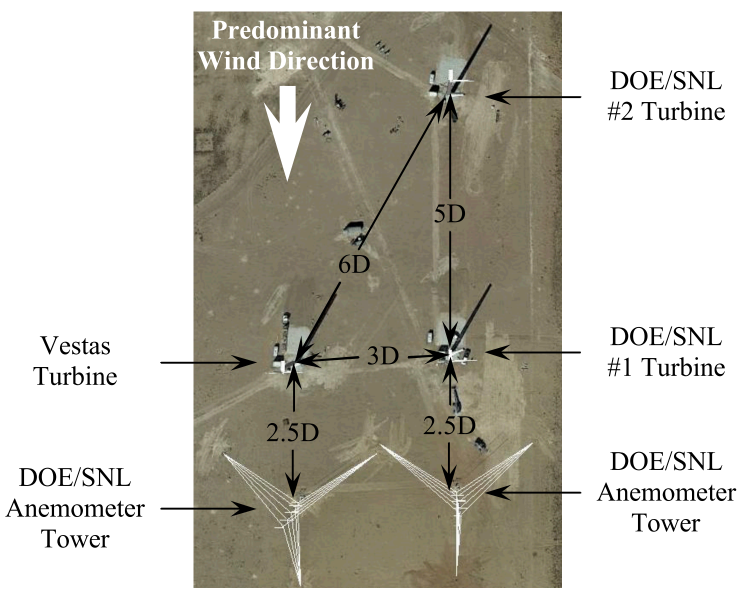

Figure 2. Layout of SWiFT Facility.

2.2. Turbine Selection and Modifications

To enable rapid and cost-efficient research, the SWiFT Facility utilizes functionally scaled testing. Functional scaling is the scaling of specific aerodynamic and structural features so that performance of the SWiFT turbines is easily relatable to larger utility-scale turbines. Functional scaling is not purely geometric scaling. The advantages of scaled testing relative to full-scale are:

- blades and molds are approximately five percent of the cost,
- cranes are two percent of the cost,
- crane scheduling is reduced from months-ahead to days-ahead, and
- failure risk is substantially less.

The legacy Vestas V27 (no longer in production) was selected to meet these objectives of scaled testing with a reliable and robust turbine. The original V27 was a collective pitch, two speed, active yaw machine with a 31.5 meter hub-height, 27 meter rotor, and 225 kW 43 rpm generator. Significant modifications were made to all three turbines including the conversion to full variable speed (0 - 55 rpm) with Type 4 power-conversion (Figure 3), increase in the blade length to 15 meters, increase in tip-speeds to 80 m/s, increase in Reynolds Number to $2x10^6$, and increase in generation to 300 kW.

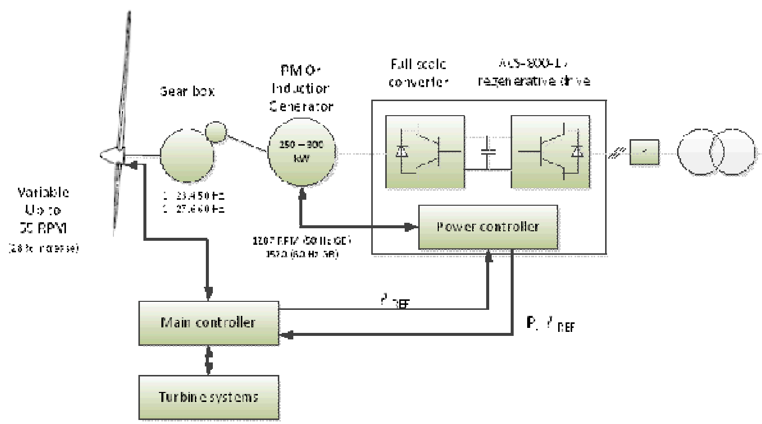

Figure 3. Modified V27 variable speed controller with full power conversion.

2.3. Turbine Instrumentation

The turbines have been thoroughly instrumented beyond the standard wind turbine sensors so that the complete state of the turbine can be measured at all times. Additional, instrumentation includes high-accuracy yaw and azimuth sensors, temperature sensors within the gearbox and generator, an inertial measurement unit in the nacelle, tower deflection, bending, torsion and thrust via strain gages, and a complete rotor monitoring system. The rotor monitoring system shown in Figure **4** has the ability to measure and control a multitude of analog and digital sensors and actuators, as well as a fiber optic interrogator to measure strain, temperature and pressure via fiber optic cables. The system was built with battery backup and is easily reconfigurable. The legacy rotor blades were also instrumented for root bending via fiber optic and future rotors will be more heavily instrumented.

Figure 4. Rotor instrumentation data acquisition system (left) and rotor blade fiber optic instrumentation (right).

2.4. Inflow Instrumentation

As shown in Figure **5** two heavily instrumented anemometer towers are installed upwind of the front row of wind turbines. These towers provide thorough characterization of the distributed inflow to the wind turbine. The primary feature is a distribution of three-dimensional sonic anemometers that are distributed from below the rotor through a measurement above the rotor. Each one of these sonics are capable of resolving the complete wind speed vector which includes the magnitude and direction. The anemometer tower was shifted slightly southeast to guarantee that the vertical distribution of sonic anemometers were precisely 2.5 diameters south of the wind turbine (within inches). To accomplish this, the physical dimensions of the anemometer, the boom are length and the overhang of the turbine, were all taken into account.

Additionally, there is an array of cup anemometers and a wind vane to meet existing and future international standards. Lastly, there is a distribution of atmospheric temperature, pressure and humidity sensors.

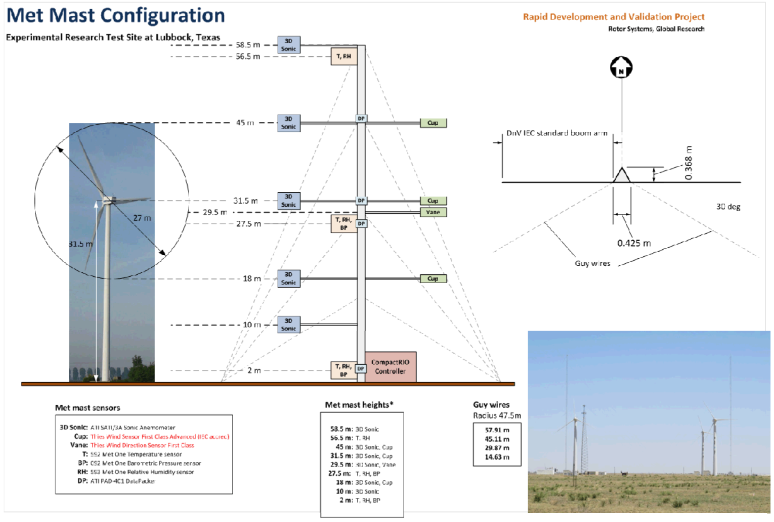

Figure 5. Inflow Anemometer Tower Schematic.

2.5. Site-wide Time-Synchronized Control and Data Acquisition Network

A key feature of the SWiFT Facility is a time-synchronized control and data acquisition network. The synchronization is provided by a GPS located in each wind turbine and anemometer tower (5 total) that controls the local data acquisition and controller computational clock. The devices are then synchronized due to the common GPS reference. Additionally, high-quality hardware was used such that the GPS signal can be lost for months before there would be a discernible difference between the individual computational clocks. In addition, the control and data acquisition network is the same which means every point of data and every controls decision are precisely synchronized. Furthermore, to enable wind plant research and control every data measurement and controls decision is shared site-wide. This leads to the ability to precisely synchronize all data on the site and also use any sensor to make a controls decision on any degree of freedom.

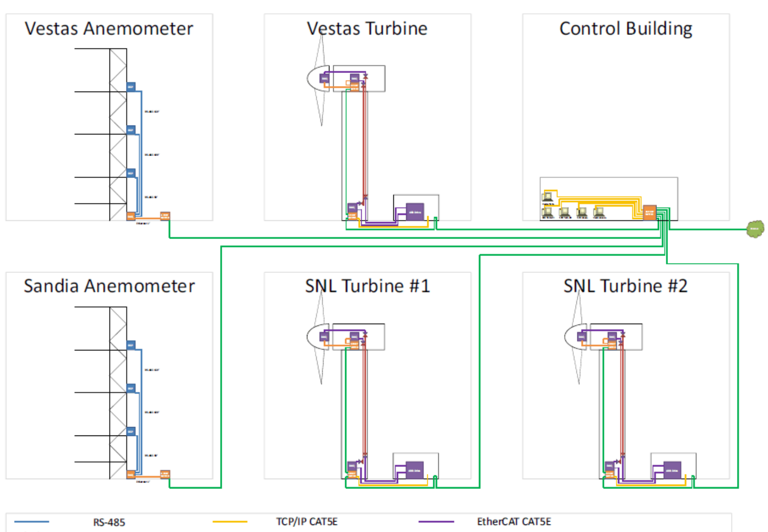

Figure 6. Schematic of SWiFT Time-Synchronized Control and Data Acquisition Network

2.6. Model Validation Efforts

Modal and mass properties tests were performed on all components (rotors, hub, tower, nacelle), subcomponents (tower on foundation) and the full system (on both DOE/SNL turbines) to produce an accurate and validated model of the facility as shown in Figure 7. Further details of this work will be detailed and presented in the final paper.

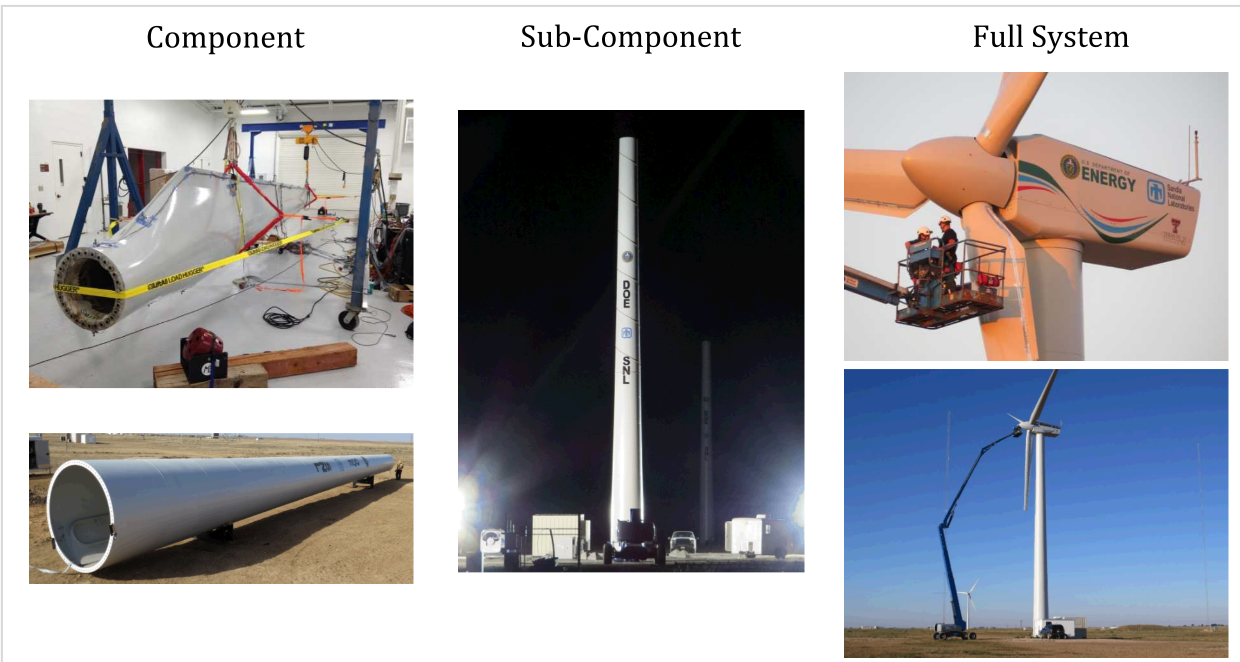

Figure 7. Modal and mass-properties testing for model validation.

3. TURBINE-TURBINE INTERACTION RESULTS

Currently underway, this paper will present the first detailed results on the interaction of multiple turbines and specifically the impacts on performance and fatigue. Greater detail on these subjects will be presented in the paper.

4. SUMMARY

The world's first purpose-built turbine-turbine interaction and wind plant performance facility has been designed and constructed. This paper will present the first results from this unique world-class facility.