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Wind Turbine Testing in the NREL Dynamometer Test Bed

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WIND TURBINE TESTING IN THE NREL DYNAMOMETER TEST BED

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ABSTRACT

A new facility has recently been completed at the National Renewable Energy Laboratory that allows full-scale dynamometer testing of wind turbine components, from generators to complete wind turbines. This facility is equipped with a 2.5 MW motor, gearbox, and variable speed drive system to deliver shaft torque. To simulate other aspects of wind turbine loading an MTS fatigue-rated loading system is fully integrated into the facility. This will allow actuators to cyclically load the structure in a variety of ways.

Enron [formally Zond] Wind Corporation has installed the first test article in the facility to help mature the Z-750 series wind turbine design. Tests include brake and control system tuning, endurance testing of gear elements and bearings, and structural testing. Some aspects of the power converter will also be tested. This paper describes the Dynamometer Test Bed and its capabilities. Also, an overview of the Zond testing program is presented.

INTRODUCTION

Wind turbine systems have grown larger during the past decade. Although the cost of wind energy continues to decrease, the per-turbine costs have increased making the empirical approach of prototype field-testing increasingly risky. For new turbine designs, megawatt scale prototypes are expensive to build and long, single-unit production lead times consume the margins of production schedules. With the typical rush from prototype to production, manufacturers often identify field problems too late to be corrected before large volume manufacturing runs are started. This can lead to premature field failures and costly retrofits.

Wind turbine drive problems are well-documented and may include gearbox failures and wear, bearing life issues, generator failures, and controller induced system failures.[1-3] Problems might arise during initial start-up, under extreme wind conditions, or may be related to long-term operation. In any case, the time to find and solve these problems is when the first units are tested.

For years, turbine manufacturers have relied on laboratory testing critical components, such as the rotor blades, to reduce their potential exposure to catastrophic field events.[4] Until now they have not had access to facilities capable of testing the whole turbine drive system, which is at the core of every turbine design.

At the National Renewable Energy Laboratory (NREL) a new Dynamometer Test Bed(DTB) was built to test wind turbine drive train systems and components. Born from industry requests, this new facility could dramatically alter the approach to evaluating new wind turbine systems. It is now being used to verify the drive train design of the Enron [formally Zond] Wind Corporation's Z-750 turbine system.

FACILITY DESCRIPTION

General Description

The DTB is located at NREL's National Wind Technology Center (NWTC) and is dedicated to testing wind turbine drive systems. These are normally comprised of some combination of gears, couplings, bearings, shafts, lubricant systems, gearboxes, generators, controllers, and power conversion systems. The size of the systems that can be tested range from 100 kW to 2.5 MW.

The dynamometer's prime mover is a variable-torque, variable-speed motor that is controlled by a variable frequency drive system. This 4160 VAC motor is coupled to a 2.5 MW, three-stage epicyclic gearbox. Test articles can be connected to the motor high-speed shaft, the low speed shaft of the gearbox, or an intermediate shaft depending on the speed and torque requirements.

TABLE 1 - DYNAMOMETER SHAFT OUTPUT RANGES

Location	Ratio to Motor	Max Speed (rpm)	Max Power (kW)	Speed at Max Power (rpm)
Low Speed Shaft	51.38:1	43.5	2500	23
Intermediate	15.4:1	146	2500	78
High Speed	1:1	2250	2500	1200

Table 1 shows the operational capabilities at each shaft. System control logic allows the torque and speed to be continuously varied via manual operator command signals or in an automated manner by Supervisory Control and Data Acquisition (SCADA) command.

Figure 1 shows the two operating envelopes, one for each drive shaft option, and a practical wind turbine design limit curve that was used to guide the dynamometer design. A representative group of actual wind turbine designs (existing or planned) are represented as data points on this figure. These data are plotted based on their rated output multiplied by a factor of between 1.3 and 1.7. This represents the approximate scaling factors that would be required to accelerate a full lifetime of operation into a few months of continuous operation during an endurance test.

The drive motor and gearbox assembly is mounted to a 169-kN (38-ton) elevating drive table that has a vertical adjustment span of 3.05-m (10-ft), with tilting capabilities from 0 to 6 degrees. A 1.52-m (5-ft) deep pocket under the drive table allows the top of the table to be lowered 0.61-m (2-ft) in below grade level. This range will accommodate shaft elevations of up to 3.05-m (10 ft). Vertical table motion is

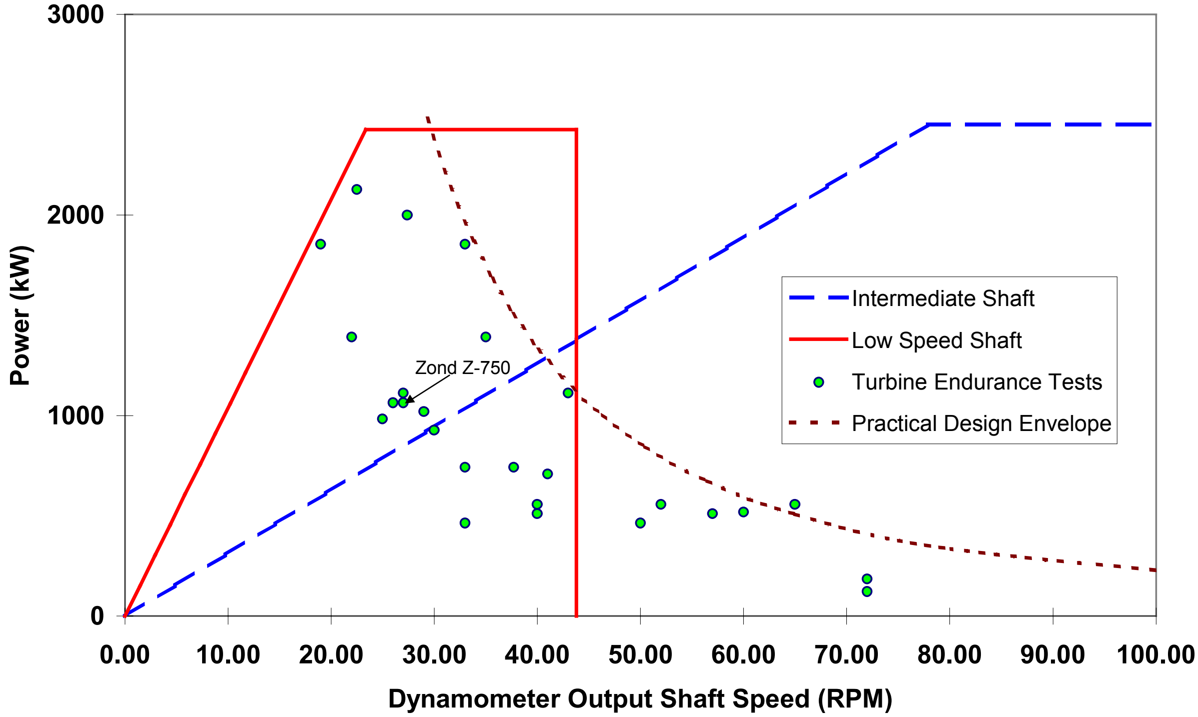

FIGURE 1 – NREL'S 2.5 MW DYNAMOMETER OPERATING ENVELOPE

actuated using four 222-kN (50-ton) motorized screw jacks that are located at each corner of the table. The screw jacks are operated in front and back pairs with an absolute position accuracy of .25-mm (0.010-in). This fine adjustment capability was built into the system to allow precise alignment between the drive system shafts and the test article shaft. When the proper table position is reached, the table is fastened to the vertical faces of two reaction walls on either side of the drive table. This connection is made using 10 steel angle brackets that bolt through the drive table and attach to vertical T-slots that are machined into steel plates mounted to the wall.

The table motion is controlled by a programmable logic controller (PLC) that receives exact position information from absolute position encoders located at each jackscrew. This information is translated into shaft position and angles by the PLC.

The facility is equipped with a 222-kN (50-ton) electric overhead bridge crane that runs the length of the 27.4-m (90-ft) test bay. The crane is pendant controlled with multiple speed capabilities.

All test articles are mechanically coupled to one of the three shafts in the drive system. Test articles can be mounted to slotted base plates imbedded in the floor of the south end of the facility or to a grid of imbedded fasteners north and south of the reaction walls.

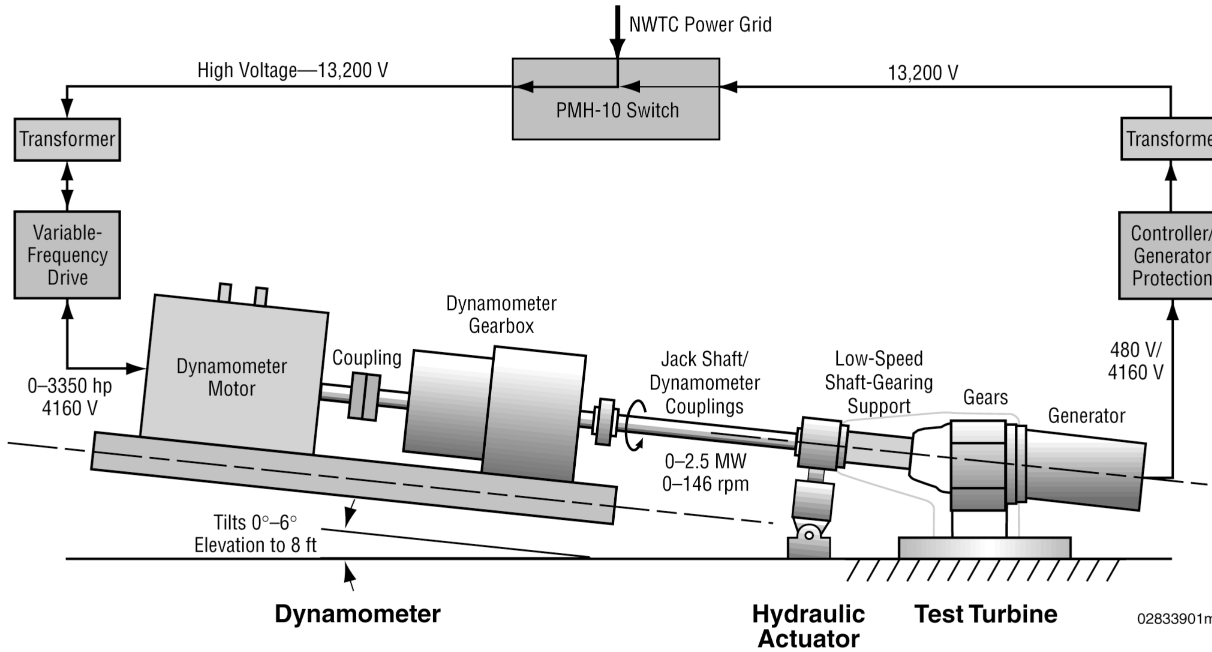

FIGURE 2 – NREL'S 2.5 MW DYNAMOMETER POWER LOOP

Figure 2 shows a schematic layout of the power loop for the DTB. Shaft power is typically converted back to electrical energy by the test article and regenerated back into the NWTC power grid at either 480 volts or 4160 volts, where it is reused by the dynamometer. Only the power losses of the drive system need to be added locally at the PMH-10 junction outside the facility to keep the system running at steady state. Figure 3 shows a photo of the DTB.

Shaft Bending Loads

Most of the loading experienced by a wind turbine is introduced by wind forces at the mainshaft in the form of shaft torsion and bending. Although numerous dynamic, aerodynamic, and inertial effects combine to create the various load cases, each of the cases can usually be reduced to the torsional and bending reactions at the mainshaft/hub interface. Shaft torsion alone is often sufficient when testing the gear teeth of a given design. However, if a test of the gear case, bearings, shafts, bedplate, yaw support, or couplings is desired, additional shaft bending loads must be applied. The dynamometer drive produces the torsional input, but the bending loads must be applied by side-loading the jack-shaft system.

In the NREL dynamometer, shaft bending is applied using a servo-hydraulic system, with an actuator capable of delivering up to 110 kips. Using the hydraulic actuator system, shaft-bending loads can be synchronized with the rotation of the turbine shaft to give periodic, per-rev shaft loading, representative of true field conditions.

FIGURE 3 – PHOTO OF 2.5 MW DYNAMOMETER

Regenerative Power

During in-field transient conditions the components of a wind turbine drive system are either accelerating or decelerating. For a true simulation of the operating wind turbine the inertia and stiffness of the dynamometer's rotating components should match the rotor system of the test article. This is not easy to do since these properties are fixed in the dynamometer's design. However, inertia matching can be achieved by increasing or decreasing the dynamometer drive power under closed-loop torque control to mimic expected acceleration rates for representative rotor mass properties during rotational speed changes. Stiffness matching may be done by clever jack-shaft design.

Torque Versus Speed Control

The dynamometer drive can be operated under either torque control or speed control. In speed control mode, the dynamometer can be operated using a manual throttle control dial, or it can be driven through the SCADA system according to a prescribed speed time-history. This mode has been useful for testing the Z-750 variable speed system. However, speed control may not be as useful when testing a fixed speed induction or synchronous turbine system, or when inertial effects are critical.

Torque control mode has not been fully implemented yet, but it may prove to be more useful for generating a fixed power output or for generating a variable torque load on constant speed generators. Transient load testing will require torque control to balance the rotating inertia. The ultimate goal is to make the dynamometer behave like the wind, and force the test article's control system to respond in real time to random turbulent fluctuations. Under closed-loop control, a random wind time history such as SNLWIND3D [5] will be used to compute real-time torque values through a simple C_p versus □ (power coefficient versus tip-speed-ratio) transfer function, or through a more complex aerodynamics code such as AeroDyn [6]. Turbine responses would be monitored to assess proper controller function.

TYPES OF TESTS

The primary advantage of dynamometer testing is that loads to the test turbine can be controlled. The types of testing are divided into wind turbine system tests and component tests. In most cases, one must install a representative drivetrain of the wind turbine to be tested to transmit the loads from the dynamometer. Some of the different types of testing that may be conducted are described below, but the authors do not presume that this is an exhaustive list.

Wind Turbine System Tests

Drivetrain Endurance Testing - Endurance testing is done to demonstrate the fatigue life of a particular drive system to ensure that it can survive its full operating life. Endurance testing will involve 3 to 6 months of continuous operation at elevated loads, combined with the application of the significant transient load cases that are part of long-term operating spectrum. Transverse shaft loads are applied to simulate actual operating rotor bending loads that can influence the tooth contact stresses, and the fatigue life of bearings, shafts, and housings. Such testing requires high, steady-state power levels that vary from 1.3 to 1.7 times the rated capacity of the test article.

Turbulent Wind Simulation Testing - This type of testing can demonstrate the proper operation of the turbine's systems under design conditions. Operating the dynamometer under closed-loop torque control, random wind turbulence data are converted into shaft torque by a computer algorithm using feedback from the turbine's own control system. Severe stochastic torque conditions can be simulated demanding that the turbine control system perform at its operational limits under all conditions.

Load Event Testing - This type of testing allows measuring the turbine system response under extreme operating events. Transient torsion and bending loads are applied to the drive train system to simulate the true field environment. System inertia can be matched by using the regenerative power system of the electric variable speed drive. Transverse bending loads can be applied to drive shafts, bearing housings, or yaw systems to recreate specific design load cases. This type of testing also includes self-induced loads that arise from the test turbine's own components and do not enter through the rotor system. Examples of self-induced loads are brake system tests, generator failures and grid faults, and normal generator transients.

Component Testing

Testing of individual turbine components is commonly the focus of testing versus the evaluation of a whole system. The dynamometer can be used for qualifying and optimizing various other components prior to field installation or retrofit. Tests can be conducted on gears, shafts, housings, bearings, generators, isolated control systems, brakes, or power electronics components, with or without a representative drive train assembly.

Gearbox Testing - Gearboxes have been the source of widespread field failure throughout the wind industry. It is often necessary to test, evaluate, and optimize the individual effects of operation on the gearbox sub-components to increase life or decrease turbine cost. [7] Some gear tests include:

- evaluating and mitigating gear tooth loads,
- evaluating and mitigating tooth wear mechanisms,
- optimizing gear lubricant properties,
- optimizing oil system levels, temperatures, and filtration,
- gear case stress measurements,
- bearing life testing, and
- evaluating proper tooth meshing under specific loads to establish optimum lead and profile modifications.

Generators – The generator is a critical part of the drivetrain system. It contributes significantly to the mechanical loads generated in the entire driveline both in normal operation and when faulted. The generator performance under a range of conditions can be isolated and tested on the dynamometer. Some generator tests include:

- evaluating electrical characteristics and fault settings,
- evaluating bearing and winding temperatures,
- measuring torque-speed characteristics,
- determining breakaway torque and extreme operating performance,
- determining system efficiencies, and
- measuring transient response characteristics.

Control systems can also be tuned and evaluated during this process. This can be done on high or low-speed (direct-drive) generators. To accommodate direct-drive generators that may have oversized radial dimensions, the dynamometer test bay has a pit built into the test section floor. In these instances, part of the generator may be mounted in the pit below the surface of the test bay floor to allow proper height matching with the dynamometer output shafts.

Z-750 TEST PROGRAM

Z-750 Background

Under the cost-shared U.S. Department of Energy (DOE)/NREL sponsored Near-term Research and Testing subcontract, Zond has endeavored to reduce fabrication and installation costs of the Z-750 series wind turbine through value-engineering methods. To support that activity, NREL has installed a fully configured Z-750 wind turbine in the DTB to evaluate measures for reducing costs while maintaining high quality and the ability to tolerate the various operational and design loads. The components we focused on in this test program include the gear-case, all gear elements, shafts and couplings, the brake, and, to some extent, the bearings.

The testing was broken down into four phases: contact tests, brake event tests, micro-pitting tests, and endurance tests. Each of these is discussed below to describe the goals and the process involved.

Tooth Contact Tests

Contact tests are performed to verify that proper meshing is occurring during elastic loading of the gears. This is done at various torque load levels using a simple gear tooth painting technique that displays the wear pattern. A dynamometer is required to do this properly because it is very difficult to select accurate and repeatable load levels in the field. The results are used in the design, manufacturing, and quality process to optimize the gear geometry and materials. This phase has been successfully completed for the Z-750s current gearset. Figure 4 shows and example of the wear pattern observed by running the dynamometer at a constant load for 1 hour.

FIGURE 4 – EXAMPLE OF CONTROLLED WEAR GEAR TOOTH CONTACT PATTERN

Brake Event Tests

The Z-750 is equipped with a high-speed, shaft mounted, spring applied, hydraulically released brake to allow for stopping the rotor in the event of pitch system malfunction. Such a redundant system is called for in the International Electrotechnical Commission (IEC) standards [8] and the Germanischer-Lloyd approval documents. The second phase of testing reduced the brake application reaction loads through the drive train though various mitigation techniques. These techniques were focused on decreasing the brake application response time while providing for gentler torque rise and drive train reaction. As described by McNiff et al [3], a reduction in these drive train loads in a demonstrable and repeatable manner can allow for concomitant reduction in system elements required to properly transfer these loads. This, of course, leads to a lower cost structure. This phase has also been successfully completed after the evaluation of four such methods.

Micro-pitting Tests

The micro-pitting studies in Phase 3 is currently in process, and it is, by far, one of the most exciting, because it could have a wide-reaching affect on future wind turbine gearbox design practices for all large turbine models. Micro-pitting is a failure precursor that is currently at epidemic levels throughout the wind industry (and other industries as well), and is the result of conformal lapping of mating gear surfaces that results in fine (100 μ–in) pits in the surfaces. These fine pits progress over a short period of time to deeper depressions that penetrate the case hardening. Ultimately, reduced surface is available to properly transfer and react to the contact stresses and bending loads, thereby exacerbating the problem. This can lead to macroscopic pitting and premature tooth failure.

Enron would like to reduce their exposure to any possible premature damage by being proactive in evaluating various micro-pitting mitigation methods. In light of this, Phase 3 is focused on first establishing baseline micro-pitting signatures through accelerated high power operation. Then various mitigation methods will be tested to quantify the differences. These methods will include alternative surface finishes, surface plating, and special lubricants and lubricant additives.

Endurance Tests

The final and best product configuration resulting from the first three phases of testing will be evaluated in a final endurance test in Phase 4. This endurance test will require almost continuous operation (with stops for system checks and periodic maintenance) at an elevated power level of about 1000 kW. Additionally, asymmetrical rotor loads, yaw action, and other moments will be simulated using a shaft-mounted actuator. It is expected that 1600 to 2000 hours will be required to simulate 30 years of life on this test article.

SUMMARY

A 2.5-MW dynamometer facility has been completed at the National Wind Technology Center, and the first test article has been used to mature both the wind turbine and the facility itself. It is expected that this new testing tool will accelerate the maturation of wind turbine designs and lead to more reliable wind turbines and drive train components in the range of 100 kW to 2.5 MW. Design load case simulations can be applied directly to the complete wind turbines in a laboratory environment. Such simulations include transient loading, endurance tests, and unusual load cases.

Gear tooth contact testing and brake load mitigation tests have been completed on the first test article, an Enron Wind Z-750. Testing of gear tooth micro-pitting mechanisms and mitigation techniques are now under way, and the turbine will soon be subjected to a complete system endurance test.

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