Subcontractor Report

August 2004 • NREL/SR-500-36289

Turbine Research Program Cold Weather Turbine Project

Period of Performance: May 27, 1999—March 31, 2004

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Operated for the U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
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Executive Summary

Northern Power Systems completed the Cold Weather Turbine (CWT) project, which was funded by the National Renewable Energy Laboratory (NREL), under subcontract #XAT-9-29200-01. The project's primary goal is to develop a 100-kW wind turbine suited for deployment in remote villages in cold regions. The contract required testing and certification of the turbine to the International Electrotechnical Commission (IEC) 61400-1 international standard through Underwriters Laboratories (UL). The contract also required Northern Power Systems to study design considerations for operation in extreme cold (–80°F at the South Pole, for example). The design was based on the successful proof of concept (POC) turbine (developed under NREL and NASA contracts), considered the prototype turbine that would be refined and manufactured to serve villages in cold regions around the world.

The project began with a design evaluation and testing of the POC turbine. Next, tradeoff studies were completed for the blade, brake system, yaw system, and turbine erection system. Once selections were made for these subsystems, the detailed design phase began in earnest. NREL staff members helped develop tools for turbine simulation and data analysis for certification. Subsystem tests were conducted before the manufacturing drawings were completed to prove critical subsystems before the turbine was erected. Manufacturing drawings were then developed, and the turbine was fabricated and tested. The certification process spanned the project; initial design documents were created at the end of the final design process.

The prototype turbine was based on the proven POC turbine design, a 100-kW, three-bladed, stall-controlled, variable speed, direct drive wind turbine. This configuration was chosen for this market because of its high reliability requirements in harsh conditions. The turbine was designed as a "little big turbine," which means it provides many features of a large modern turbine: protected climbing, routine maintenance accomplished within the confines of the nacelle, active yaw, and remote supervisory control and data acquisition (SCADA) capabilities. The turbine was also designed so that all components except the tower could be shipped in a 40-ft International Standards Organization (ISO) container. Special steels, lubrication, and heaters were added to meet the low-temperature requirements.

The first turbine was installed at the National Wind Technology Center (NWTC) in February 2001. A complete battery of certification testing, including power performance, power quality, noise, loads, and safety and function tests, was performed on this turbine. These tests were conducted by NWTC staff to IEC standards. A second turbine was installed in Kotzebue, Alaska, in May 2002. Power performance tests were also conducted on this turbine.

In keeping with the project goals, Northern Power Systems successfully designed, built, and tested a prototype of the NorthWind 100™ (NW100) wind turbine. In February 2004, the NW100 was the first wind turbine to receive a design conformity statement from UL to IEC 61400-1. The two prototype turbines have operated for two and three years, respectively.

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1 Introduction

1.1 Background

The CWT project is part of the U.S. Department of Energy's (DOE's) Turbine Research Program, which was initiated in 1990 to help U.S. industry incorporate advanced technologies into new wind turbine designs. The Turbine Research Program has three phases:

- Conceptual Design Studies, which seeks to identify and evaluate improvements in wind turbine technology that will significantly reduce costs
- Near Term Product Development, which involves fabricating and testing prototype turbines
- Next Generation Product Development, which is intended to stimulate new concepts and bring new, advanced technologies to wind turbine designs to significantly reduce the cost of energy.

The CWT program is funded under the third phase of the Turbine Research Program. This phase has two parts: Innovative Subsystems Projects (NGIS) and Turbine Development Projects. Early work involved the development of a 100-kW direct drive generator (referred to as DDGen) under NGIS. This work was coupled with Northern's Polar Turbine Development Program, funded by Phase I and II NASA Small Business Grants for Innovative Resarch (SBIR) in support of the NASA Polar Analog Program. These programs resulted in the design and deployment of the "Polar Turbine" POC prototype turbine. The CWT program is a natural extension of this activity.

1.2 Goals

The overall goal of the program is to develop a pre-production prototype with the necessary features and certification documentation to launch a production sequence. The program goals are:

- Develop a complete turbine design for cold regions (for grid-connected or remote-grid applications)
- Manufacture the pre-production prototype turbine
- Perform a complete battery of certification tests
- Develop documentation required for certification
- Identify further refinements to move to production
- Identify changes required for arctic applications
- Obtain a design conformity statement.

1.3 History

The main milestones of the program are shown in Table 1.

Table 1. NREL-Defined Milestones

Milestone	Program	Year
Developed Polar Turbine Concept Design	NASA Polar SBIR	1994-1996
Developed 100-kW Direct Drive Generator Design	DDGen Program	1996-1998
POC Turbine Installed	DDGen Program	March 1999
CWT Kickoff Meeting	CWT	August 1999
Final Design Review	CWT	June 2000
Test Readiness Review	CWT	December 2000
Turbine Installed at the NWTC	CWT	February 2001
Turbine Installed at Kotzebue, AK	---	May 2002
UL Certification	CWT	February 2004

1.4 Goals Achieved and Other Successes

The main goals of the program were achieved. An innovative turbine design was created and tested, and Northern obtained a design conformity statement for the turbine, as well as conformity statements for a number of turbine tests. Two prototypes were built; one has undergone rigorous testing at the NWTC, and the second has been operating above the Arctic Circle in Kotzebue, Alaska, for the past two years. A path to take the turbine to production has been identified.

In addition, the NW100 design received the R&D 100 Award for 2000 ("38th Annual R&D 100 Awards," September 2000), which recognizes the top new technologies in a given year, and it was the first wind turbine to receive a design conformity statement through Underwriters Laboratories (UL) to IEC 61400-1.

2 Market

The NW100 is designed to be a highly reliable power system for the remote, cold weather village power market. It is also intended to be a robust energy source for isolated research bases, such as those found on the Antarctic Continent. The turbine incorporates design features that make it especially suited to these applications.

All aspects of the NW100 design are suited to the needs of the cold weather environments found in such markets as Northern Canada and Alaska. The regions where this turbine finds its greatest appeal typically involve standalone electric grids in isolated villages. These grids suffer from power quality and system stability issues—problems that can be exacerbated by fixed-speed turbines that are not designed to handle the unique requirements. The variable-speed drive on the NW100 design eliminates current in-rush during control transitions and operation and is designed to comply with the Institute of Electrical and Electronics Engineers (IEEE) 519 power quality specifications.

Under the Distributed Wind Technology initiative, funded by DOE, Northern Power Systems is now developing a "farm version" of the NW100. This new design will build on the NW100 platform but will be detuned of some cold weather features and optimized for more temperate climates, a greater range of wind classes, and wider market opportunities.

3 Turbine Description

3.1 Design Philosophy

The NW100 turbine was designed according to the following principles:

- The three-bladed, rigid rotor is designed for safe, stall-regulated operation without an aerodynamic braking system such as tip brakes or tip flaps. This fixed-pitch design minimizes moving parts and increases reliability.
- The direct drive generator has inherent advantages for an extreme environment turbine. The elimination of the gearbox from the turbine design removes a component known for unreliable operation in wind turbines, especially at extreme temperatures.
- The NW100 uses a fail-safe main shaft disk brake and an electrical dynamic brake to meet code requirements for two separate, independent braking systems.

3.2 Turbine System

The NW100 is a 19.1-m-diameter, 100-kW direct drive, three-bladed, variable-speed, stall-controlled wind turbine with a rigid hub and fixed-pitch blades. The variable frequency generator output is rectified and then inverted by a power converter system for connection to conventional utility or isolated village-scale grid systems, with a 480-Volts AC, three-phase output. The NW100 has an upwind orientation with active yaw control. The turbine controller is Programmable Logic Controller (PLC)-based, with a master controller located at the tower base and a slave module located in the nacelle. The standard hub height is 25 m. The turbine is designed to operate in temperatures as low as –46°C (–50°F). The tower top structure is shown in Figure 1, and the electrical power circuit is shown in Figure 2. Table 2 provides a summary of the turbine specifications. See Section 4.8 for a description of the design modifications required for deployment in extremely cold regions.

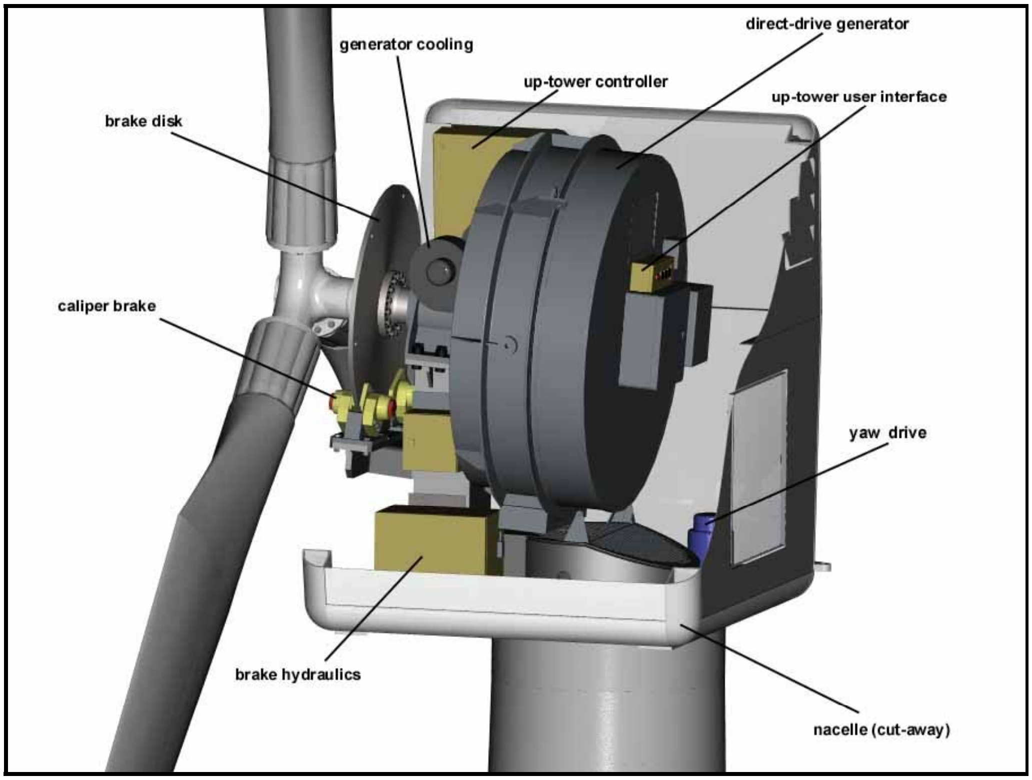

Figure 1. The NW100 direct drive design provides reliability and simplicity.

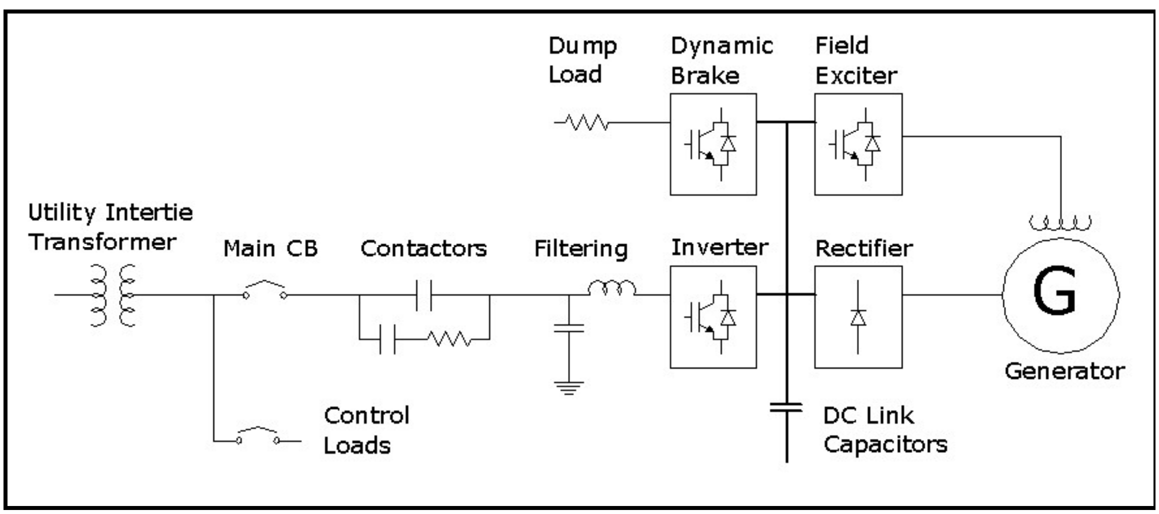

Figure 2. The power electronics system provides full power conversion and supplies superior quality power to weak village grids.

Table 2. The NW100 Turbine Specifications

Power rating, kW	100
Rotor diameter, m	19.1
Swept area, m^2	287
Hub height, m	25
Rated rotor speed, RPM	63.5
Power regulation	Variable-speed stall
Rated wind speed, m/s	14
Cut-in wind speed, m/s	4
Cut-out wind speed, m/s	25
Operating temperature range, °C	–46 to 50
WTGS design class	IA
Remote monitoring	Standard

3.3 Safety System

The NW100 has two braking systems: a caliper brake and an electrical dynamic brake. The spring-applied caliper brake acts on a disk mounted between the rotor and generator. The electrical dynamic brake applies torque through the generator and consists of a power converter with integral controls that shunts power from the rectified output of the generator to a resistive load bank. The electrical dynamic brake is self-exciting in the case of grid failure. During an emergency stop, both the mechanical and the electrical dynamic brakes are commanded on. A limit switch on the mechanical brake turns off the electrical dynamic brake so that both brakes are not used on every emergency stop.

3.4 Power Control

Power is controlled by modulating the generator field in response to rotor speed. A field-speed lookup table is used to select the field setting. The rated speed is set by steeply increasing the demanded field near the desired rated speed. This allows the turbine to operate at variable speed at low wind speed and to achieve virtually constant speed at high wind speed. This strategy allows increased energy capture at low wind speeds and reliable control of power at high wind speeds.

3.5 Power Curve

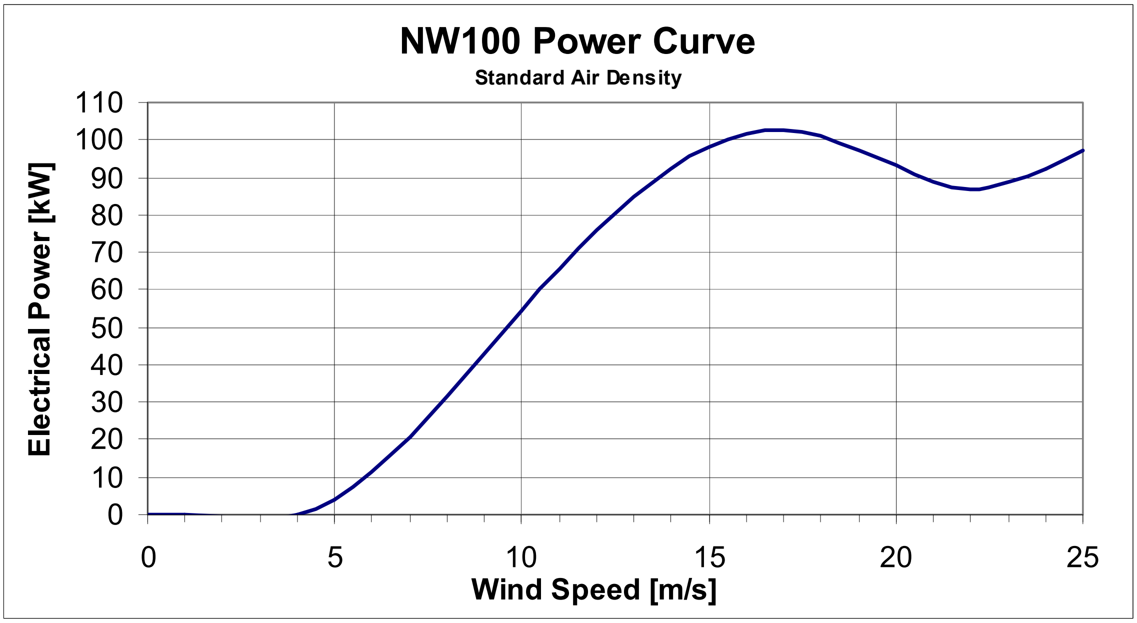

Figure 3. The NW100 power curve provides excellent energy capture at low wind speeds.

3.6 Masses

The masses of the major NW100 turbine subassemblies are shown in Table 3. The subsystems were designed within the weight limits of cranes and other lifting devices available to remote village power locations.

Table 3. Mass of Key NW100 Components

Subsystem	Mass (kg)
Rotor assembly	818
Nacelle	6,376
Tower	8,018
Total System	**15,212**

4 Design Effort

4.1 Introduction

The starting point for the NW100 design effort was the POC turbine. The turbine system design was largely retained; the most significant change was the use of a dynamic brake as the secondary braking system in place of blade rotating tips on the POC machine. The POC machine successfully performed its primary function, which was to prove-out the basic direct drive, variable-speed, stall-controlled system design concept for the NW100 turbine.

For a number of reasons, most of the NW100's components and subsystems were redesigned. Several major components used on the POC machine were acquired from decommissioned turbines to speed turbine fabrication and testing and to save on development costs. The POC machine also was not designed for the low-temperature market, so changes in material were required to meet the contract and target market requirements. The blades, hub, several major generator components, mainframe, yaw system, tower, and controller were redesigned under the CWT program.

The design stage was a multiphase effort that consisted of an evaluation of the POC turbine, identification of the major areas of focus, definition of tradeoffs to be performed, tradeoff studies, final design, and subsystem tests. The details of the design effort and the results are provided in the following sections.

4.2 Project Team

- Northern Power Systems (Waitsfield, Vermont): primary contractor
- Tillotson Pearson, Inc. (TPI) (Warren, Rhode Island): blade development
- Dynamic Design Engineering, Inc. (Dynamic Design) (Davis, California): blade development
- MDZ Consulting (Mike Zuteck, Clear Lake Shores, Texas): blade development
- National Renewable Energy Laboratory (NREL) (Golden, Colorado): design review, certification testing, software support

4.3 System Design

4.3.1 Control and Safety System Definition

The control and safety systems were developed using failure modes and effects analysis, or FMEA, in which all possible component failures are examined in terms of the potential effects on the system as a whole. A major requirement for wind turbine design certification is the employment of multiple independent braking systems. The NW100 satisfies this requirement by using a fail-safe mechanical brake on the main shaft and an electrical dynamic brake that can slow the rotor and maintain it at a safe speed. The complete description of the control and safety systems is covered in full detail in the control and protection document; an overview of the major components and functionality is provided here.

The control system of the NW100 is composed of a PLC Central Processing Unit (CPU) and input/output (I/O) rack (base PLC) located in the base controller, a PLC slave rack (nacelle PLC) in the nacelle, an analog control board (DB/Exc) for regulating generator field current and dynamic brake current, and a digital signal processor (DSP)-based control board for the inverter. The base PLC in the base controller coordinates the operation of the other three peripheral controllers. The base PLC also handles a host of digital and analog I/O functions, including control and monitoring of switchgear, thermal management, and turbine rotor speed control. The base PLC controls the yaw drive and mechanical brake by commands via a communications link to the nacelle PLC.

Embodied in the PLC program is the turbine state machine, which ensures that the operation of the turbine is deterministic and therefore not prone to unexpected behavior. The turbine transitions from state to state based on well-defined transition criteria.

NW100 Turbine States	
State Number	State Description
0	PLC Off
1	Offline
2	Startup
3	Online
4	Normal shutdown
5	Part torque brake
6	Full torque brake
7	Service

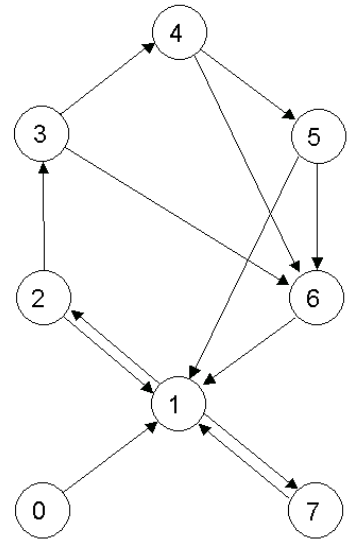

Figure 4. The NW100 state machine ensures that the turbine operates in a deterministic manner.

When the base turbine controller is powered up, the turbine comes up in the Offline State (State 1). A local operator can manually put the turbine into the Service State (State 7) to provide a safe condition for maintenance activities. All remote commands are disabled in the Service State, and only a local operator can change the turbine state from service back to offline.

All faults must be cleared to start the turbine (State 2). There are two main categories of faults: normal faults, which cause normal shutdowns, and emergency faults, which cause emergency shutdowns. Most faults are normal faults; only the most critical faults, such as inverter faults, dynamic brake faults, rotor over speed, and E-Stop control loop activation, are defined as emergency faults.

During normal operation (State 3), the base PLC sends field current commands to the field exciter control board in response to turbine rotor speed to regulate turbine speed and therefore power. The dynamic brake is controlled by the DB/Exc controller to prevent overvoltage on the DC link during State 3 operation.

During a normal shutdown sequence (States 4 and 5), the PLC increases the torque on the generator by elevating the field current command (State 4). After the turbine slows to approximately 30% of rated speed, the base PLC commands the mechanical brake on at partial torque (State 5), which brings the rotor to rest.

During an emergency shutdown sequence (State 6), the PLC commands the mechanical brake on at full torque, and commands the DB/Exc to perform a preset dynamic braking sequence. If the mechanical brake turns on, the dynamic brake is shut off automatically, and the turbine rotor is brought to rest. If the mechanical brake does not turn on, the dynamic brake continues to load the generator down to very low speed and then connects the generator field winding across the DC link to provide self-excitation to the generator. This self-excitation provides sufficient loading at all wind speeds to keep the rotor speed at a safe level (less than 20% of rated in all wind conditions).

During grid loss or failure of the base PLC, the net effect is an emergency shutdown.

The protection system of the NW100 includes all components of the control system, plus additional components that ensure the turbine and its components are protected if any part of the control system fails. A key protection subsystem is the E-Stop control loop. This is a hard-wired circuit of normally closed switch contacts that, when opened, disconnects power to the mechanical brake and therefore initiates a full torque (emergency) shutdown of the turbine. The switch contacts that can activate the E-Stop loop include the PLC watchdog timer contact, an over-speed safety relay contact, and several mushroom-style pushbuttons located in both the base and nacelle (all major service areas of the turbine).

The personnel safety features of the turbine include provisions for mains disconnect and lock-out tag-out, a safety climb system on the access ladder inside the tower, lanyard tie points for safe access to the outside of the nacelle, and a deterministic service state that prevents remote or unauthorized commands from affecting the state of the turbine while local operators are performing service activities.

4.3.2 Turbine System Dynamics

Figure 5 depicts the Campbell diagram for the turbine. The system dynamics are characterized by a soft (natural frequency between 1P and 3P) tower and stiff (natural frequency above 3P) blades.

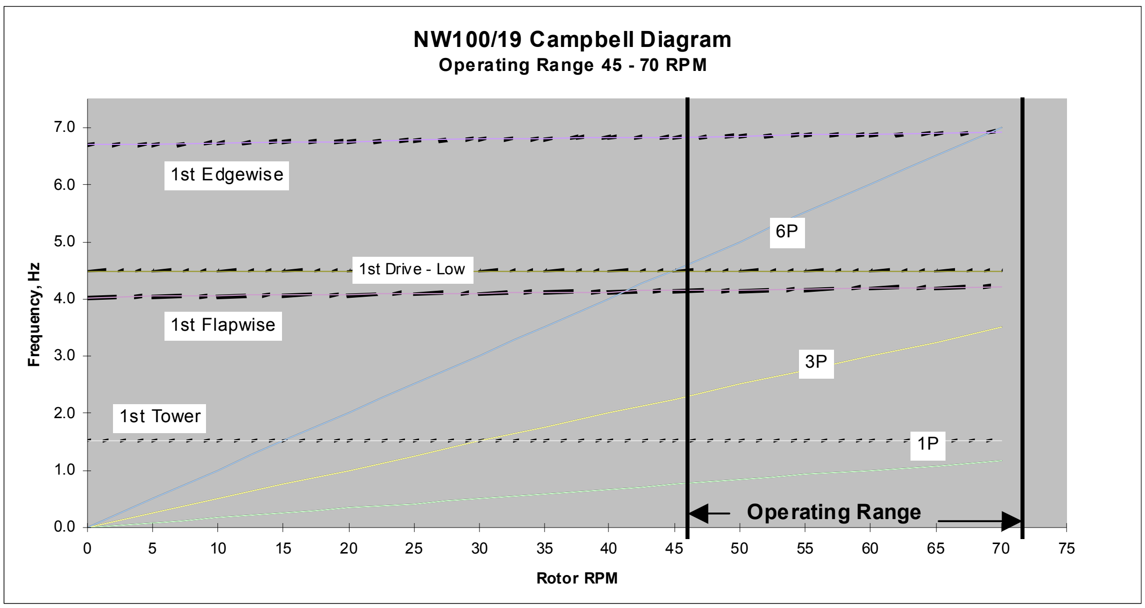

Figure 5. The Campbell diagram shows that the first tower frequency is above the 1P rotor frequency in the operating range, providing safe dynamic operation.

4.3.3 Loads

4.3.3.1 Introduction. Generating the loads document was an iterative process. The loads were calculated several times, initially with the YawDyn (Laino 2001) code, then with increasing levels of sophistication in the structural dynamic model as the blade and tower structural designs were refined, drive train dimensions were finalized, and post-processing requirements were defined. Data from the final loads document and comparisons to certification test data are presented in this report.

4.3.3.2 Design Class and Design Load Cases. The loads were calculated in accordance with IEC 61400-1 2nd edition (IEC 1999) for an IEC WTGS Class IA site with a design air density of 1.336 kg/m^3. Specifications for this wind regime are given in Table 4.

Table 4. Wind Regime Specifications

Parameter	Value	Reference
$V_{ref\ (mps)}$	50	Class I
$V_{avg\ (mps)}$	10	Class I
I_{15}	0.18	Type A turbulence

A complete set of design loads cases was used early in the program to generate the design loads. This set of load cases was based on IEC requirements and a detailed failure modes and effects analysis of the turbine and controls.

4.3.3.3 Analysis Approach. The analysis approach Northern chose was to use the FAST_AD code (Jonkman et al. 2002) as the primary dynamic simulation tool. FAST_AD is a time domain multiple-degree-of-freedom wind turbine simulation model. Using this model, loads were calculated at various critical sections under a variety of wind and machine state conditions. The output data were first processed to produce extreme and fatigue loads for structural components, main bearings, and yaw gearing. Some signals required for design are not output by the FAST_AD program. Tower and nacelle aerodynamic drag forces and tower loading at several sections were computed with quasi-steady assumptions.

Various other models, including SNWind (Kelley and Buhl 2000) and IECWind (Laino 2001), were used for wind simulation; AeroDyn (Laino 2003) for aero calculations; Crunch (Buhl 2002) for data processing; and WT_Perf (Buhl 2001) for preliminary power curve estimates.

4.3.3.4 Development of the Input Files. Mass and dimensions were based on as-built properties. Mass and stiffness distributions for the blades and tower were based on as-built properties analysis of the blade sections and on tower design information (shell diameter and thickness distributions). The power controller was modeled with a torque speed lookup table and a first order lag.

Significant effort was expended on understanding and modeling three-dimensional (3-D) effects during stalled operation of the turbine and their effects on the performance and loads on the machine.

The procedure for generating the airfoil tables started with the development of two-dimensional (2-D) airfoil tables. The S821, S820, and S821 NREL airfoils are used on the NPS100 blade. No wind tunnel data exist for these sections, so Eppler code predictions were combined with empirical data from other airfoils to obtain the tables used in this loads analysis. The airfoil tables were developed by Marshall Buhl and Jim Tangler of NREL.

A spreadsheet was constructed to develop the 3-D corrections based on the equations in Du and Selig (1997). The 2-D data were used as input. Corrections were made to sections 4-10 only, since outboard of station 10 the chord length divided by rotor radius (c/r) value is below the point at which 3-D effects are expected. Several iterations were required to correlate the power predictions to measured test data.

Comparisons of the power curve, run statistics, and damage equivalent loads (DELs) were then made to NWTC test data. Results are shown below.

4.3.3.5 Power Predictions and Comparisons. Power performance tests were conducted on the NW100 by NWTC staff. Ten-minute average data to about 17 mps were acquired. One-minute average data were acquired to approximately 20 mps and are shown for reference purposes. The results are shown in Figure 6, along with the FAST_AD code prediction. The low power region is well predicted; the power level in the region just before the onset of stall is overpredicted. Peak power predictions look quite good, but higher wind speed data are required to draw broad conclusions. The FAST_AD prediction is unacceptable for energy calculations but appears to be adequate for starting the loads calculations.

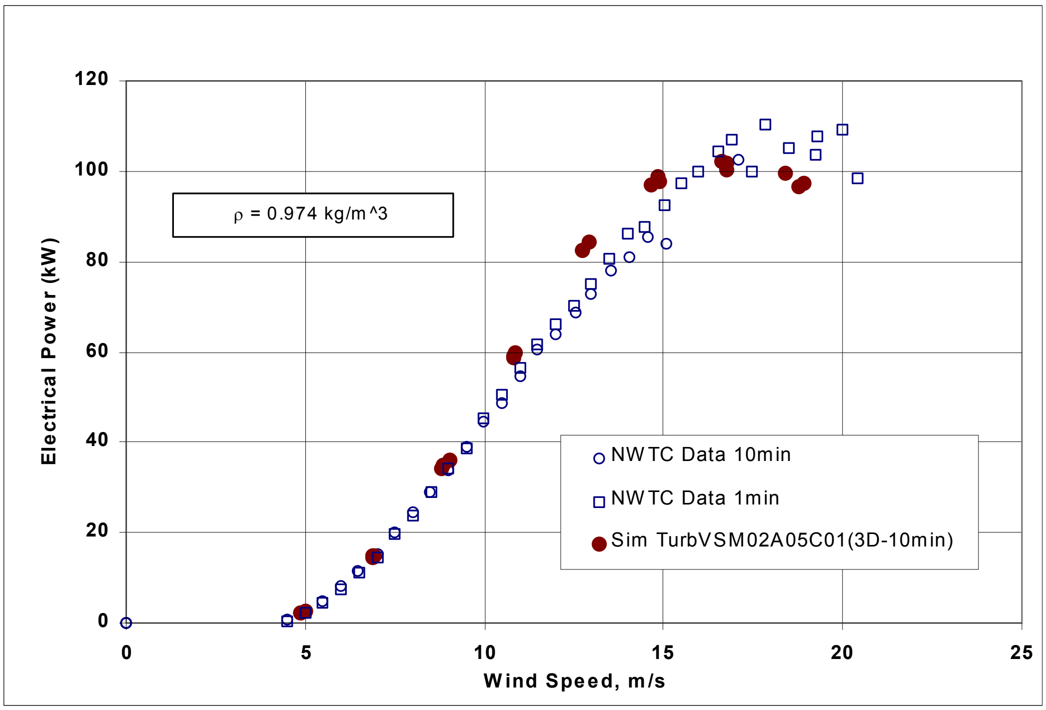

Figure 6. The predicted power was compared to measurements performed at the NWTC, and a high correlation level was obtained.

4.3.3.6 Loads Predictions and Comparisons. Calculated loads were compared to loads acquired during the NW100 certification test program carried out at the NWTC as a way of validating the design loads. A FAST_AD model of the NWTC prototype turbine was developed (the blade stiffness is slightly different from the production design) and used to generate loads for wind speeds of 5 mps to 25 mps in 2-mps increments. SNWind was used to generate wind files at 22% turbulence intensity at each wind speed in accordance with IEC 61400-1 for Class A turbulence (IEC 1999). Statistics and DELs for the blade flap, shaft, and tower moments were computed using the Crunch program. The DELs were computed for each bin (NOT scaled by the wind speed distribution). Comparisons of the measured data to turbine simulations are shown in Figure 7 and Figure 8.

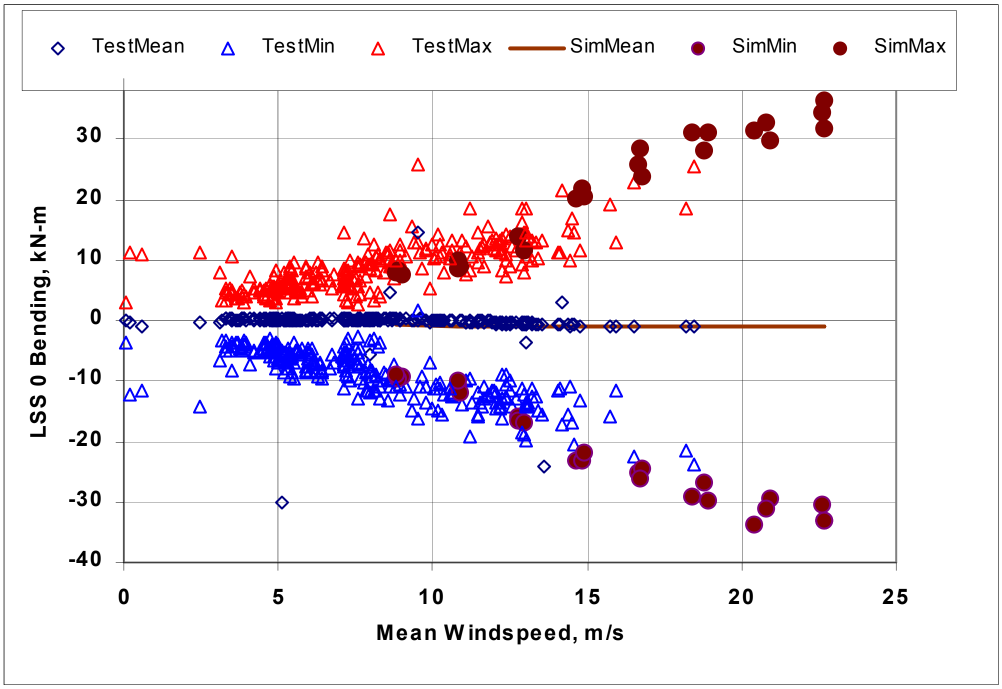

Figure 7. Scatterplots of per-file statistics from simulations and test data were compared to ensure the accuracy of the design loads used in the structural analysis.

In summary, the complete simulation and processing path have been tested, and the results generally agree with the field data. The calculated fatigue loads should give conservative estimates of lifetime; the differences in calculated versus field maximum loads are covered by the partial load factor used to produce the design loads.

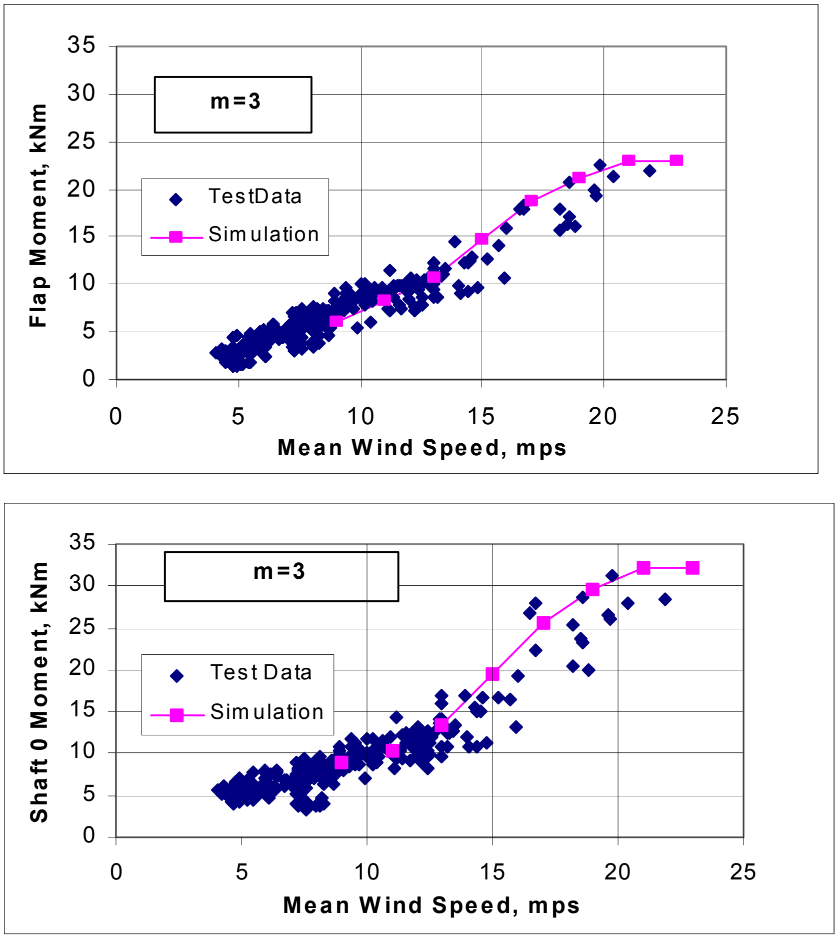

Figure 8. The simulated damage equivalent fatigue loads for blade flap moment match those of the NWTC test data.

4.4 Trade Studies

Early in the design process, trade studies of key subsystems were completed in an effort to maximize performance and minimize turbine cost. Blades, mechanical brake, yaw system, and the turbine erection system were evaluated. Results of the respective studies follow.

4.4.1 Blade Tradeoff

The blades shown in Table 5 were evaluated for use on the NW100. Based on cost, energy production, cold weather strength of similar blade roots, and lower turbine loads in comparison to the other candidate blades, the TPI ERS-0100 blades were chosen for the NW100. The original rotor diameter target was 20 m; that goal could not be achieved, but the results of the study applied to the 19-m version as well.

Table 5. Blades Evaluated for NW100

Blade Manufacturer	Diameter (m)	Energy Capture (kWh/yr)	Temp Spec (°C)	Cost/set ($US)
LM 8.0P	16.7	187	-20	14,183
LM 9.7P	19.8	281	-30	24,247
Ventis 10m	20.0	-----	-----	29,604
TPI ERS-0100	**20.0**	**275**	**-----**	**17,000**

4.4.2 Brake System Tradeoff

The main objective of the tradeoff study was to find the most economical fail-safe main shaft braking system that best met performance criteria. The braking system was judged on several criteria:

- Compliance with the brake system specification
- Overall brake system cost
- Minimization of caliper depth (dimension perpendicular to brake disk plane).

The caliper actuation method was the first design feature studied. Three viable methods of actuation—spring, hydraulic, and electromechanical—were considered. There were no electromechanically actuated caliper brakes large enough to meet our torque requirements with two or three calipers. Hydraulically actuated calipers were ruled out because they are not as explicitly fail-safe as spring-applied calipers and their performance would be more affected by low temperatures than spring-applied calipers. The remaining option was spring-applied calipers. All the spring-applied calipers considered were designed to be released hydraulically.

Caliper clamping force and disk size were optimized to obtain the required brake torque. It became apparent that changing the radial dimension of the brake disk affected other components of the machine. The bearings and the shaft are so designed because shaft bending causes the brake to deflect. A larger brake disk requires a larger shaft to reduce deflection, which in turn requires bearings of a larger bore. In other words, reducing caliper cost by using smaller calipers with a larger disk could easily be offset by the requirement of a larger shaft and bearings.

Based on the selection criteria, the Dellner SKP95-27 brake system with a 1.25-m-diameter brake disk was selected for the NW100 design.

4.4.3 Yaw System Tradeoff

The objective of this study was to establish a yaw drive system configuration that would minimize cost. Each system employed electric motor-driven gear components as commonly applied in industrial applications. The two candidate systems for the tradeoff study were:

- Dual drive unit system (as used on the POC turbine)
- Single drive system.

The POC dual drive system employed torque-limiting devices on the electric motor shafts to alleviate gear component overload. The single drive system has gearing components sized for increased capacity that negates the need for the torque-limiting components. Advantages of the dual drive system include a reduced gear face width requirement and less concentrated loading on the bull gear because of the load sharing of the dual drive pinions. Despite these advantages, the single drive system was less expensive than the double drive system and was therefore selected for use in the design.

4.4.4 Turbine Erection System Tradeoff

Turbine sites not accessible by mobile crane service require a turbine erection system that encompasses all handling and hoisting equipment, tower modifications, and ground level attachment points. The equipment will be shipped with the turbine components in standard high cube shipping containers. All turbine components and erection equipment will be removed by standard earth-moving machines and ancillary equipment. Provision for skidding equipment from the containers will be included in component design and packing. Equipment will be suitable for operation from a temporary portable generator. Turbine erection equipment will be removed from the turbine and stored indoors when not in use. The four candidate systems were:

1. Turbine and combined tower tilt-up
2. Tower and derrick tilt-up, hoist turbine
3. Tower tilt-up, hoist derrick, hoist turbine
4. Turbine and tower hydraulic tilt-up.

Initial results showed that System #4 was the least expensive option. More recently, we found that our System #4 cost estimates were low and that System #2 showed more promise as the least expensive craneless erection scheme. A concept has been vetted for System #2, but final design and engineering are not yet complete.

4.5 Structural and Mechanical Component Designs

4.5.1 Rotor

The NW100 blade design was based on the ERS0100 blade, developed by a team that included Dynamic Design, MDZ Consulting, and TPI Composites under a DOE program funded through Sandia National Laboratories. The aerodynamic design of the NW100 version of the blade remained unchanged, but the blade was extended, the bolt circle size was increased, and the structural design was improved (based on component testing results and field experience with the ERS0100 blade deployed on the 56-100 turbines in Salano County, California). A lightning-protection system was developed and included in the new design. Embedded root studs, which perform extremely well at low temperatures, were key to the design.

The hub is a Northern Power Systems design. Based on our tradeoff studies, we chose a cast four-flanged hub made of A352 LCC, a low-temperature steel. Casting of this component was problematic for the prototype machines. Many iterations of gating and minor design changes were required to reduce the potential for casting defects. These changes led to a passable design for the cold weather market.

4.5.2 Drive Train

The generator housing design from the POC turbine was retained, but material changes were made in the bearing block substructure to satisfy the low-temperature specification. The bearing set was identical to the POC machine, but the shaft was changed to incorporate a flange-type connection to the hub.

The bedplate design was revisited in light of the low-temperature requirements. The POC design was largely based on the use of common structural sections. The new design, which was fabricated from plate steel, increased the complexity of the design but was necessary to incorporate available low-temperature steel shapes to address the low-temperature specification.

A new cold-weather-compatible brake system was implemented. This system included heaters, insulated enclosures, and temperature measurement to ensure the hydraulic system operated properly regardless of outside temperature. A single drive yaw system was used for the prototype design, and a new yaw friction system was developed and implemented.

To avoid the tooling cost of a fiberglass mold, the nacelle was fabricated of aluminum sheet and structural sections. The service features of the POC design were retained, allowing easy access to critical service points. The aluminum nacelle added the benefit of lightning protection by providing a Faraday cage that conducts a lightning strike away from critical electronic components.

4.5.3 Tower

A Nordtank 23.4-m tower was used on the original NW100 POC machine. This tower allowed economical testing of the drive train but had several design deficiencies. A new tower was designed to correct these deficiencies. The new NW100 prototype tower design was based on a constant taper. The flange thicknesses were increased and the gusset stiffeners removed. The tower top was redesigned to accept the yaw friction system, and the square door detail was changed to a more structurally efficient bulkhead-type design. A material was chosen that satisfied the low-temperature requirements. These improvements led to a more efficient and aesthetically pleasing design with suitability for low-temperature applications.

4.5.4 Component Reserve Summary

Each critical structural component was analyzed to determine its safety and function when subjected to the applied loading. The analysis was performed using a variety of tools. Finite element models, as shown in Figure 9, were used for most major structural components. The stresses from the models were input to spreadsheets to determine static and fatigue reserves. In addition, Northern developed a technique for conducting multiaxial fatigue analysis of the hub. Stresses at a number of locations in the finite element model were calculated as a function of the individual blade loads. These unit stress functions were combined with the raw fatigue load data, using the NWTC’s Crunch program, and fatigue stress ranges were determined. A damage accumulation procedure based on these ranges and material strengths was used to calculate reserves. Northern also developed a spreadsheet to analyze bolted joints, based on the VDI 2230 standard (VDI 1988). The advanced analysis tool set provided the analytical backbone necessary to support an IEC 61400-1-certified turbine.

The reserves for the most critical components are shown in Figure 10. The bedplate is the most tightly designed component with a static reserve of 0.95 and a fatigue reserve of 0.99. This was acceptable because of conservative assumptions used in the analysis. All other critical components have a reserve greater than 1.0. The values for some components are larger than shown but were truncated to 2.0 for clarity. In addition to the critical structural components, every major bolted joint was analyzed according to the VDI 2230 standard. All static and fatigue reserves of the joints are greater than 1.0. Also, the static and fatigue reserves of the main bearings, yaw bearing, yaw drive, yaw brake, and caliper brake were calculated. The reserves for all of these components are greater than 1.0.

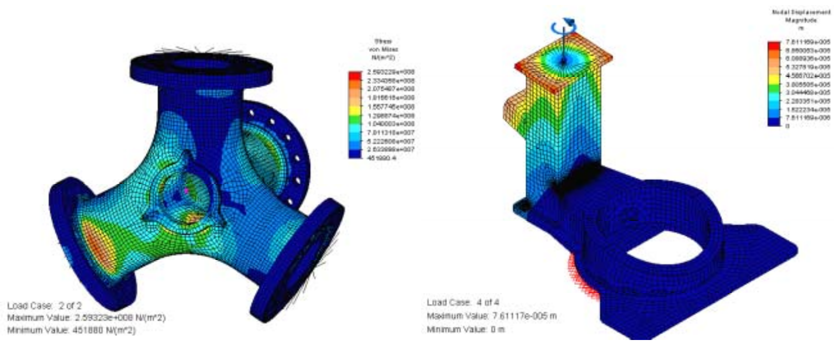

Figure 9. Finite element models were combined with state-of-the-art NREL software and Northern spreadsheets for structural analysis.

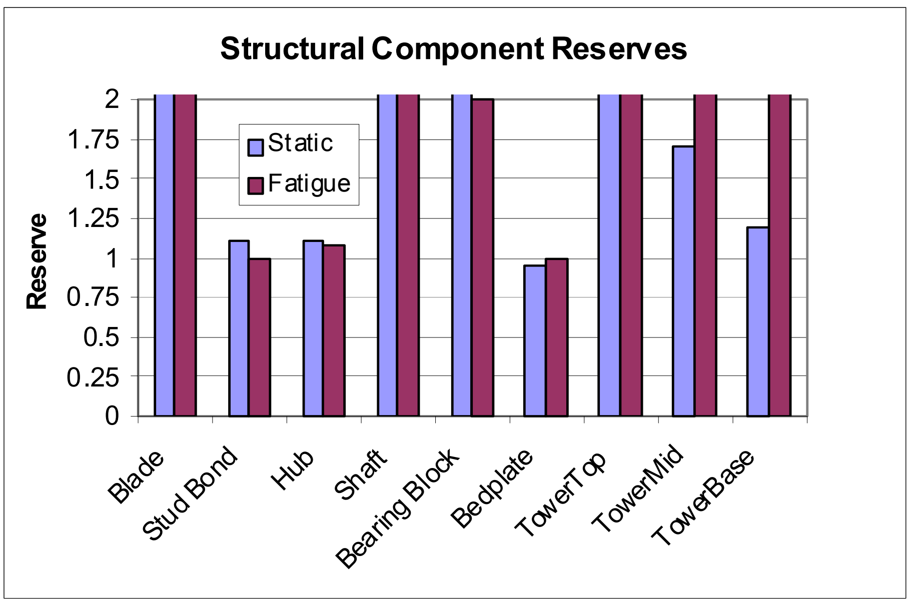

Figure 10. The reserves for all structural components were calculated to ensure the safety of the turbine as required for the IEC 61400-1 standard.

The values for some components are larger than shown but were truncated to 2.0 for clarity.

4.6 Electrical Component Designs

4.6.1 Generator

The generator is a wound-rotor salient-pole synchronous machine designed to operate at low speed. The electromagnetic design of the generator was largely retained from the design used in the POC turbine. The most significant change was the design of a new trapezoidal winding for the field poles that added additional copper and reduced field losses. The generator is forced-air cooled with ambient air, which enters the turbine at the bottom of the tower.

4.6.2 Power Converter

The power converter design was updated from the original POC turbine configuration to incorporate latest-generation Integrated Gate Bipolar Transistor (IGBT) power-switching technology. The passive rectifier on the generator side of the DC link was retained. In the POC design, the field exciter was fed from the AC line, which limited its transient response. The field exciter on the prototype NW100 is an IGBT-based DC/DC converter powered from the DC link, which provides a dramatic improvement in transient performance and control bandwidth over the POC turbine. The addition of an IGBT-based dynamic brake to the prototype design improves the braking load control capability during shutdowns and provides a fast-acting safety device to protect the DC link from over-voltage.

4.6.3 Controller

The up tower electrical assemblies underwent minor revisions between the POC and the prototype design. The control philosophy of the yaw system and the mechanical brake was not changed. The POC turbine had separate enclosures for the base controller and the power converter. In the prototype design configuration, the power converter is integrated into the controller enclosure, which reduces space requirements dramatically and saves money. The PLC-based controller design was largely retained from the POC version, but the control program (and overall approach) was updated extensively during integration and testing of the newer power converter technology.

4.7 Subsystem Tests

4.7.1 Brake System

The caliper brake system was qualification tested to ensure the system could operate as required in very low temperatures and to verify general operation. The primary reasons for testing the brake system were: 1) the system was a new product for Northern, 2) the system was interfacing with control hardware and logic designed by Northern, and 3) the system would be used outside its normal temperature specification.

The system was bench tested at room temperature and then in a cold chamber at incrementally lower temperatures as low as –58°F (–46°C). Testing included system pressure measurements, cycling, and the determination of the low-temperature operating limit for the overall system.

When the testing was complete, the Dellner brake system qualified for use on the turbine. The calipers performance was excellent. The only low-temperature issues concerned the hydraulic system and the sensors. During testing, crucial modifications were made to the insulation configuration and limit switches that made the qualification possible. We concluded that the manifold temperature is key to brake system functionality. The T-manifold resistive temperature device (RTD) must reach about –0.4°F (–18°C) for the valves to work reliably, and this RTD was added to the turbine design as a PLC input signal. Logic for a warm-up sequence was added to the PLC code. The warm-up sequence adds heat to the manifold by energizing the solenoid valves and keeps the brake applied and the turbine shut down until the manifold temperature is –0.4°F (–18°C) or higher. An insulated enclosure around the hydraulic pack is required, and an alternative to the standard rubber-encapsulated limit switches is needed.

4.7.2 Blade Root Stud Testing

Because no data were available for root insert adhesive strength at cold temperatures, we determined that the blade root studs should be tested. The objective was to validate the root interface strength at room and arctic temperatures for certification. Special double-ended test specimens were fabricated to achieve the mechanical properties of the blade root properties and account for the purely axial loading of test specimens.

Blade Root **Stud Test**

Figure 11. Blade root stud performance is difficult to predict, so testing at low temperatures was performed at the NWTC.

Three fatigue tests and one static test were performed at room temperature. Four fatigue tests were carried out at temperatures at or below –58°F (–46°C). Figure 11 shows the blade root and test setup for cold-temperature testing of the studs.

Figure 12 summarizes the results of the low-temperature testing. Low-temperature environmental conditions appear to have a *positive* effect on the strength of the root stud joint. We concluded that knockdown factors do not need to be applied to the root-hub interface design to account for cold-temperature turbine operation.

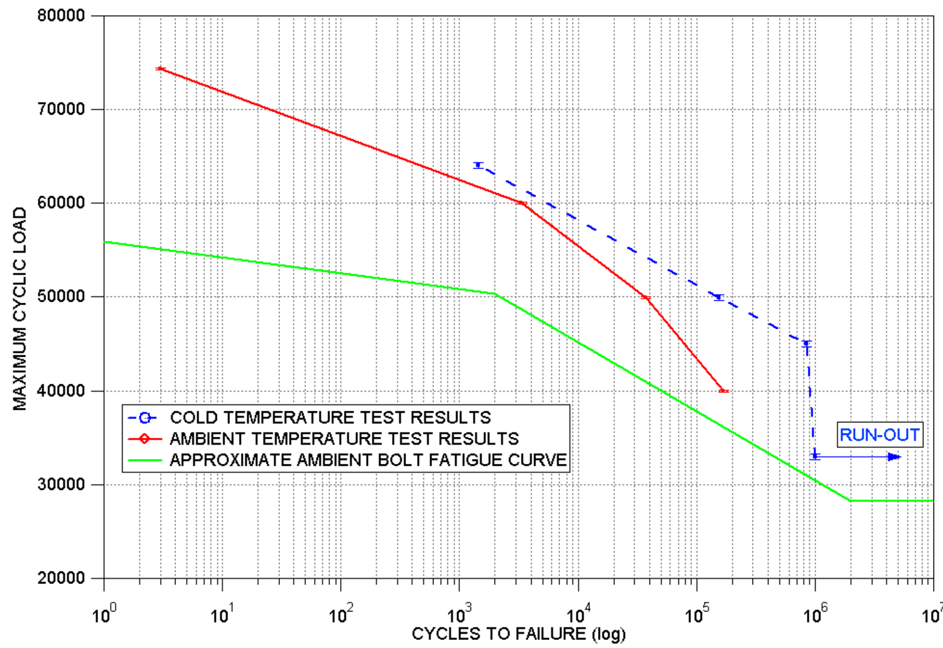

Figure 12. Fatigue testing of the blade roots at low temperatures showed that the design exceeded requirements.

4.7.3 Blade Testing

The following report excerpt (Hunsberger et al. 2001) summarizes the test results:

> Static load envelope tests were conducted at the National Renewable Energy Laboratory (NREL) on a newly manufactured Northern Power Systems (Northern) NW-100 blade, which was built by TPI Composites (TPI). A four-point static load distribution was applied using a whiffle tree connected to a 35-ton overhead bridge crane. The blade was cantilevered for loading in three different directions to simulate the most extreme load case for edge bending, negative flap bending, and positive flap bending, respectively. The static blade pulls were conducted at the National Wind Technology Center (NWTC) in the Industrial User Facility (IUF).
>
> The blade successfully reached the target test loads for the edge and negative-flap cases. The blade failed during positive-flap load direction, at a root moment of 117.8 kNm, which was 93% of the target load. The failure was caused by a catastrophic buckling of the shear web at the 29% span location, which led to an immediate full collapse of the section.
>
> Subsequent analysis showed that, although the failure loads were lower than the target test loads, the applied test loads at the point of failure (29% span) just exceeded the design requirements. This was possible because the applied loads were higher in the failure region due to conservative geometry of the test apparatus that was designed to slightly over-test the blade in this region. However, the test load distribution at failure did not reach the required design loads at other critical span-wise locations, such as the root, and therefore the tests were inconclusive for qualifying the blade load capacity to withstand the given loads. Further concerns were raised when analysis showed that this blade failed at a lower load than the baseline ERS-100 blade, previously tested at NREL in 1999. Expectations were that design changes made to the ERS-100 blade should have incrementally increased the strength of the NW100 blade.
>
> A postmortem inspection of the failed NW100 blade, conducted on May 9, 2001, revealed that several details of the as-built blade did not meet the intended manufacturing tolerances. These discrepancies may have contributed to a general weakness in the compressive strength of the shear web, which was noted on the ERS-100 test blade as well.

The manufacturing and design problems identified were relatively small and have since been addressed with minimal modifications to the laminates, adhesive, tooling, and process. It is recommended that a follow-on set of NW100 blades be tested to verify the final configuration.

4.7.4 Generator and Converter Testing

Detailed performance evaluations of the drive train were conducted at Northern's dynamometer facility.

Figure 13. The Northern dynamometer was used to verify the generator and power electronics design before it was installed on the tower.

The Northern Power Systems dynamometer consists of a Baldor 250-HP motor and drive system connected to the generator under test through a 25:1 gearbox. The low-speed output shaft of the gearbox is connected to the NW100 main shaft flange.

Each of the NW100 generators underwent open-circuit voltage and short-circuit current characterizations. The NW100 converter's integral field exciter was used as a field current source. The data were used to develop an electrical model of the generator, and in turn, a full electrical system model including the converter power flow and control algorithms. Each NW100 converter underwent basic QC and power throughput testing on the Northern dynamometer before being shipped to the field for installation. The set of required tests included field current step responses and heat rise tests for both the converter and the generator. One generator and one converter were retained after deployment of the prototypes to establish a platform for further testing and debugging.

Numerous tests were conducted (and discoveries made) with the dynamometer platform since the prototypes were deployed, including:

- UL representatives were on hand for the official heat rise testing of the generator, according to UL 2200 (UL 1998). Based on the results, the generator design was certified.
- Several flaws in the turbine controls design, including software and control issues in both the turbine controller and the power converter DSP controller, were isolated and eliminated.

- We characterized the generator's electrical parameters in an effort to better understand the phase-to-phase short circuit failure mode and its potential effects by performing a standstill frequency response test, according to IEEE 115-1995. From these data, we developed a more sophisticated electrical model of the generator, which accurately predicts both steady state and transient performance. We also developed an algorithm for detecting a generator short circuit.
- We conducted an extensive end-to-end system efficiency measurement test to better understand the power performance of the machines in the field. The full data set included mechanical shaft speed and torque, stator phase temperatures, ambient (inlet) temperatures, and all electrical currents, voltages, and resistances of interest. Initially the data were used to tune the electrical system model to more closely match the prototype performance. Later, the data were used to develop a thermal model of the generator that predicts the steady state stator and rotor temperatures at any (torque, speed) operating point. This thermal model has since been used to determine the operating envelope of the prototype generator design.

The NW100 controller also served as a test bed for developing and refining Northern's SmartView ™ SCADA system, now in full operation on the NW100 in Kotzebue, Alaska.

4.8 Deployment at the South Pole

The turbine design could be readily adapted and optimized for operation at the South Pole. Indeed, this application was considered in the design stage, but market demands oriented the design for the higher-temperature specification.

Potential design modifications will flow from considerations of the basic environmental, logistical, and electrical interconnection requirements. These include site average wind speed, extreme wind speed, site average wind shear, altitude, air density, survival temperature, minimum operating temperature, maximum lift height, and grid support requirements.

The current implementation of the technology was intended for temperatures as low as –50°F (–45°C) and wind speeds of 10 mps average. The South Pole turbine would require operation in temperatures of –80°F (–62°C) and wind speeds on the order of 5 mps. The South Pole version of the turbine would therefore require design modifications that address the lower temperatures and energy-capturing capacity of the machine.

The low average and extreme wind speeds and the flexibility of selecting the rated speed and power level of the machine enable an increase of rotor size by using blade extenders. This change is recommended.

A review of safety system needs would be conducted. The low average and extreme wind speeds may enable reduced torque requirements, which would open up the possibility of using electromechanically actuated brakes.

Mechanical implementation changes would include substitution of structural materials and lubricants, localized heating design, and possible substitution of select mechanical subsystems. Select component testing would be required prior to deployment to qualify these subsystems. Finally, some simple variations in the operating logic of the machine may be required to optimize performance at the South Pole.

5 Manufacturing and Installation

5.1 Turbine Fabrication

Each step of the NW100 design and fabrication included processes required by Northern's Quality Assurance program. During design, all engineering documents and drawings were tracked with our document control system. During fabrication, a QA notebook was created for each turbine that included the quality assurance documentation for every critical turbine part. These documents included (where relevant) material specifications, material properties test results, quality class inspection results, radiographs, and conformity statements.

Each subsystem was tested during turbine assembly for accuracy of assembly and functionality. These quality control tests were documented, signed off by two engineers, and placed in the QA notebook, which is kept on record.

5.2 Installation and Commissioning

Once in the field, each step in the turbine installation was checked and signed off by the responsible engineers. Once the turbine was installed, a full battery of commissioning tests was completed and documented. Once each commissioning checklist was completed and recorded in the respective QA notebook, the turbine was considered “commissioned” and ready for normal operation. Figure 14 shows the rotor being installed on the NWTC turbine.

Figure 14. The first NW100 prototype was installed at the NWTC for functional testing and loads evaluation.

6 Field Testing

6.1 NWTC Turbine Testing

Extensive field testing was carried out at the NWTC Test Site. The goal was to characterize a number of important turbine attributes and to document the results for submission to UL for type testing certificates. The specific tests were safety and function, loads, power performance, power quality, and noise testing.

The goal of the safety and function test is to ensure all turbine subsystems operate properly, and in particular, to verify that the safety systems function under a variety of machine fault and grid conditions. The most rigorous tests were loss of power to the PLC, loss of grid, and mechanical brake fault. The turbine passed these tests with minimal changes in operational logic. Figure 15 shows a trace of the dynamic brake limiting rotor speed under mechanical brake fault conditions.

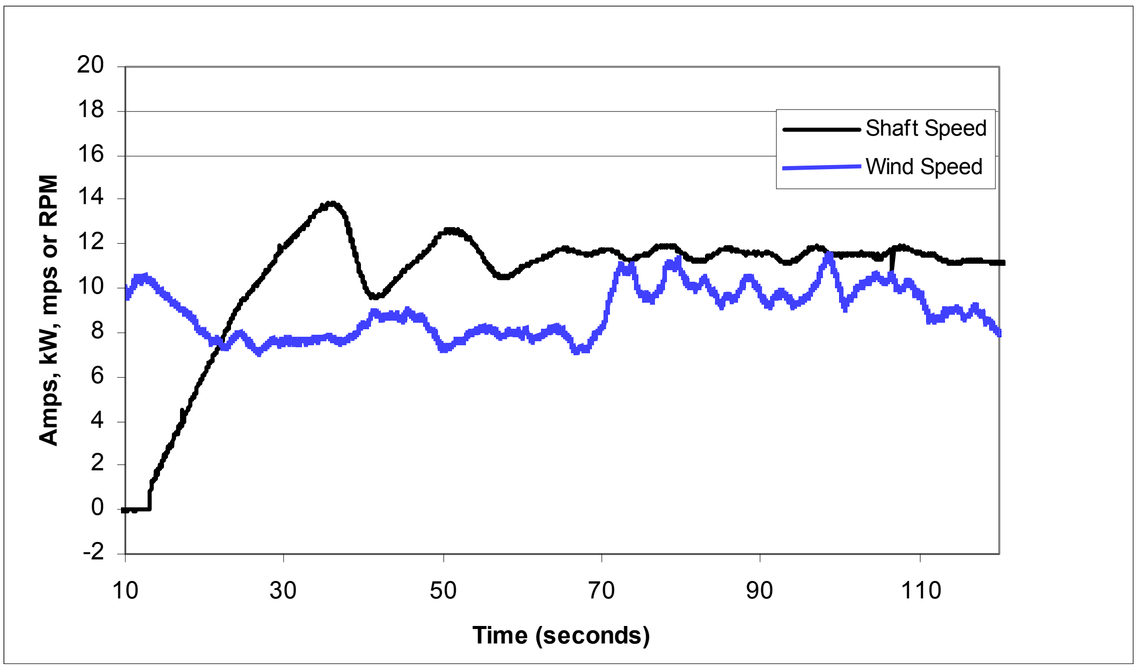

Figure 15. The dynamic brake system limits rotor to a safe speed in the event of a combined mechanical brake failure and grid outage.

The goal of the loads testing was to acquire and document turbine loading under a variety of machine state and grid conditions according to IEC 61400-13 (IEC 2001b). Strain gauge bridges were installed at several blade locations: on the hub shaft, on the bedplate, and at several tower locations. These sensors were complemented by machine state, power, wind speed and direction, shaft speed, and yaw position sensors. High-quality data were collected from wind speeds of 5 to 23 mps during turbine operation and 44 mps while the turbine was parked. The turbine loads were adequately characterized by the testing and were used to validate the dynamic simulation tools.

The goal of the power performance testing was to acquire data to construct a power curve to IEC 61400-12 requirements (IEC 2001a). Several iterations were required as the machine was tuned to operate at optimum tip speed ratio in below-rated conditions. Results showed that the turbine does operate at near-optimum tip speed ratio over a range of wind speeds.

The power quality testing was conducted according to IEC 61400-21 (IEC 2001c). The goal was to characterize the harmonic content of the inverter output current and ensure the power quality met the IEEE-519 (ANSI 1993) requirement of 5% Total Demand Distortion (TDD) for any power generation equipment. The compliance of the inverter to IEEE-519 has come into question because power quality testing performed at the NWTC during design certification showed a slightly higher TDD of 6% at some power levels. This issue has not been resolved, but a number of NWTC site-specific interconnection anomalies may play a role. The interconnection transformer has a higher kilovolt-amp (kVA) rating (500 kVA) than the converter was optimized for (125 kVA), and there are a number of other loads in parallel on the same transformer, including two data sheds and an AOC 15/50 wind turbine. The inverter control algorithms were programmed out-of-house, and as such, no tuning of the control loops has been possible to account for actual grid impedances at the site.

The noise testing, which was carried out in accordance with IEC 61400-11 (IEC 1999), showed that the NW100 is a quiet turbine with source sound levels of 93.4 decibels–A (dBA), comparable with the quietest turbines on the market today.

6.2 Kotzebue Turbine Testing

Power performance testing was carried out on the Kotzebue turbine under the U.S. DOE Turbine Verification Program. This testing allowed the turbine performance to be characterized at its target design site, with attendant high densities. This was an important test and showed the flexibility of the turbine control routine, which adjusts the rated speed of the turbine to hold rated power in high wind conditions over a range of densities. Test results showed good correlation with the NWTC power curve when corrected to standard atmosphere.

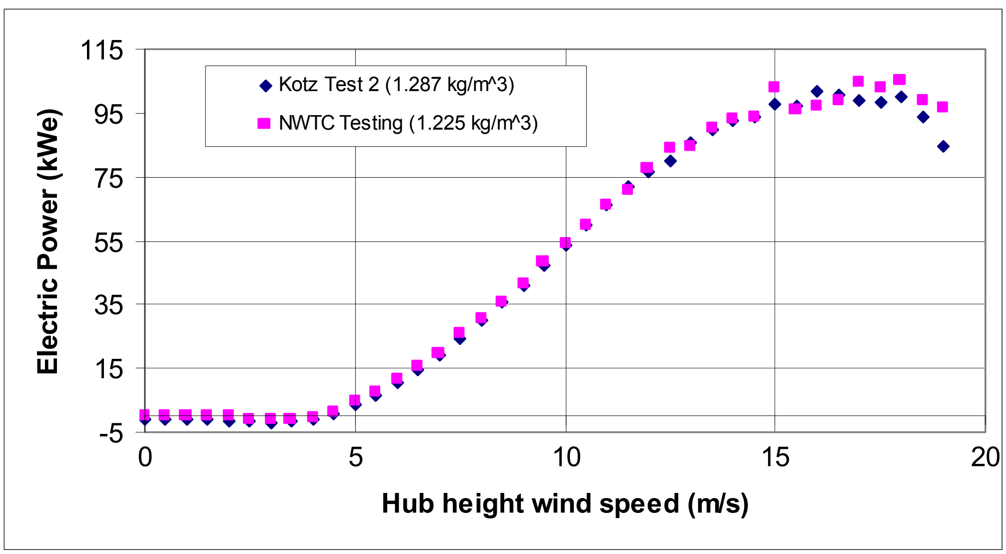

Figure 16. Experimental measurements of the power curve showed consistent operation at both installations.

Northern also collected operational data from the turbine through a remote interface. These data are discussed here.

7 Prototype Operations

7.1 Operational Summary

Two prototypes were built: "NWTC," installed at the National Wind Technology Center in Boulder, Colorado, and "Kotzebue," installed at the Kotzebue Electric Association's wind farm in Kotzebue, Alaska. Table 6 contains key operations data from each prototype.

Table 6. Key Operations Data for the NWTC and Kotzebue Prototypes

	NWTC	Kotzebue
Time online (h) as of 3/9/04 (kWh)	3,213	7,398
Availability	n/a	86.4%
Energy produced as of 3/9/04 (kWh)	80,446	218,507
Days in operation	1,033	671
Average annual energy production (AEP)	28,425	118,860
Average annual specific energy (kWh/m^2)	99	415

7.2 Field Experience

The two NW100 turbines in the field provided invaluable data. Operations and maintenance experience on the prototypes have been processed into useful, practical design input and have effectively closed the loop between design engineers and service technicians. Some of the most useful field data have been in the form of component failures and problems. Table 7 is a comprehensive list of the component failures we have seen on the two prototypes.

Table 7. Component Failures on the NWTC and Kotzebue Prototypes

Turbine	Failed Component	Cause of Failure
NWTC	Slip rings	Arc-over caused by brush dust
NWTC	DC link capacitor	Miswired bootstrap circuit
NWTC	Yaw pinion	Mis-specified heat treatment
NWTC	Yaw brake	Pad wear through
NWTC	DC link capacitor and brake IGBT	Dynamic brake conductor thermal damage
NWTC	DC link capacitor bleeder resistor	Shipping damage + PLC logic error
NWTC	Solenoid valve - hydraulic pack	Undiagnosed
Kotzebue	Yaw gearbox	Stripped drain plug
Kotzebue	Encoder cable connection	Cold-related solder failure
Kotzebue	Touch control panel	Extreme-cold related
Kotzebue	CPU: Base PLC	Extreme-cold related

7.3 Design Modifications Made

Table 8 lists the major design changes made since prototype installation. Each change was implemented via a design change order and then retrofitted on both prototype turbines.

Table 8. Minor Design Changes on Prototypes

Date	Component	Change
10/7/2002	Brake pads	Changed to lower coefficient of friction pads
10/7/2002	Brush holder bars	Changed to (non-conducting) G-10 fiberglass
6/20/2003	Brake limit switches	Changed from mechanical limit switches to proximity switches
6/20/2003	Over-speed relay	Changed to UL-listed part
1/13/2003	Yaw brake pads	Pad material changed to RF-34 and increased thickness to 3/8"
2/18/2004	Circuit breaker CB33	Changed from 6A to 10A

In addition, the PLC code was updated numerous times based on prototype operation. Improvements were made in fault detection, operating logic, and data capture.

Many set points were tuned after commissioning, including the field/speed lookup tables and various high and low thermal limits.

7.4 Outstanding Issues

The field exciter circuit continues to experience intermittent faults. Although some of these faults in the past appear to have been caused by brush dust accumulation on the slip rings, there seems to be another cause for some of the errors. This cause may be temperature related, and we are still working to fully diagnose it.

Some control components are not available with extreme cold-temperature ratings and are therefore enclosed in heated enclosures. However, these components are susceptible to damage during extended grid outages when heat is not available. In particular, the PLC is only rated to 32°F (0°C), but it has been exposed to much lower temperatures during grid failures.

8 Certification Effort

8.1 Design Conformity

We put significant effort into developing the design conformity certification documentation. Over the course of the effort, Northern developed rigorous document control procedures, tools for analysis of loads data, structural and mechanical components, and knowledge of several structural standards, including Eurocode3 (European Committee for Standardization, 1992) and BS7608 (British Standards Institute, 1993) for weldments and VDI 2230 (VDI 1998) for bolted connections. We also developed techniques for performing FMEA.

Master documents were created for each major component (loads, blade, manuals, etc.) of the certification documentation. Analysis results, description of methods employed, and input data were collected in these documents. Table 9 displays the list of master documents created for the certification effort. During the certification process, supporting calculations were performed to fill out deficiencies in the documentation and were supplied to NWTC personnel. In total, 428 technical documents (including revisions) and engineering memos were transmitted to NWTC staff over the course of the project.

Table 9. Master Documents Created for Certification

Category	Title	P/N	Revision
Design control	Design control	04-00075	A
Turbine description	Turbine description	04-00061	D
Drawing package	Drawings	04-00089	N/A
Control and protection	C&P	04-00062	C
Loads document	Loads	04-00059	C
Structural comps	Blade	04-00076	A
	Hub	04-00078	C
	Main shaft	04-00079	B
	Stator housing	04-00081	B
	Bedplate	04-00083	C
	Tower	04-00085	C
	Nacelle	04-00257	A
	Bolted connections	04-00086	D
Mechanical components	Main bearings	04-00254	A
	Main shaft brake	04-00080	A
	Yaw bearing	04-00084	B
	Yaw drive	04-00233	A
	Yaw brake	04-00258	A
Manuals	O&M	04-00069	E
	Installation	04-00087	D
	Safety	04-00088	A

8.2 Type Testing

The turbine testing performed by NWTC staff led to the issuance of multiple test certificates by UL: safety and function, loads, power performance, power quality, and noise.

9 Conclusions and Recommendations

9.1 Conclusions

Northern Power Systems successfully designed, built, and tested a prototype of the NW100 wind turbine. In February 2004, it became the first wind turbine to receive a design conformity statement from UL to the IEC 61400-1 standard. As a result of the certification effort, Northern matured its design control procedures, technical capabilities, and engineering efficiency through many discussions with the NWTC staff. These interactions were invaluable to the development of rigorous engineering documents. Tests showed that with few exceptions, the design goals of the program were met. In addition, two prototype turbines in Alaska and Colorado have operated well for 2 and 3 years, respectively.

9.2 Recommended Design Improvements

The core technologies of the NW100 result in a robust, well-performing turbine. The following areas of the current design will be addressed to further improve the turbine design as it moves toward production:

- Blade root and hub: The current hub design required the use of cast steel because dimensions were overly constrained by the blade root diameter. This led to high material costs and problematic manufacturing, which resulted in a high-cost hub. A larger diameter blade root would allow the use of cast irons, which are easier to use and would lead to a lower cost component. The small diameter blade root also leads to higher strength requirements for the blade stud bond. The strength of the root in extreme winds came into question, and the extreme wind specification had to be reduced because the studs were not strong enough. Only one static stud test was performed; more testing may show that the root strength is sufficient for the IEC WTGC Class I environment.
- Blade planform: The blade planform design could probably be improved, which would increase aerodynamic efficiency. The large root chord seems to exacerbate 3-D effects, which require either non-optimal pitching or slower rated rotational speed. The former leads to lower energy production, the latter to higher generator costs.
- Softer braking: The current braking systems impart an unnecessarily high torque spike on the drive train during emergency shutdown. This is primarily due to a very fast dynamic brake torque ramp time. The loads are within the design envelope, but reducing the dynamic brake ramp time will make for a smoother operating machine.
- Stator housing: The stator housing could be lightened if the nacelle were lifted from attachments on the bedplate.
- Bedplate: An internal web, orientated in the fore-aft direction and located at the center line of the pedestal, would greatly improve the load-carrying capacity by reducing unwanted deflections of the (larger dimensioned) pedestal sides. This would complicate construction if standard sections could not be used.
- Material choices: The materials were likely chosen conservatively, and lower grade materials with guaranteed impact properties would allow the use of more standard structural sections.
- Refinement of slip ring/field exciter circuit: Brush wear on the current design creates an unacceptable amount of dust that can cause short circuits.
- Power electronics located up-tower: “Power plant” concept will reduce losses, capital cost, production time, and field assembly time.
- Tower: The frequency of the tower could be reduced based on the operational speed at the design density. The current tower had margin built in because of planned installation at the NWTC, which led to a higher rotor speed at low density, higher tower frequency caused by the soft design, and thus higher cost.

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14. ABSTRACT *(Maximum 200 Words)*
Northern Power Systems completed the Cold Weather Turbine (CWT) project, which was funded by the National Renewable Energy Laboratory (NREL), under subcontract #XAT-9-29200-01. The project’s primary goal is to develop a 100-kW wind turbine suited for deployment in remote villages in cold regions. The contract required testing and certification of the turbine to the International Electrotechnical Commission (IEC) 61400-1 international standard through Underwriters Laboratories (UL). The contract also required Northern Power Systems to study design considerations for operation in extreme cold (–80°F at the South Pole, for example). The design was based on the successful proof of concept (POC) turbine (developed under NREL and NASA contracts), considered the prototype turbine that would be refined and manufactured to serve villages in cold regions around the world.

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