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Wind Turbine Generator System

Safety and Function Test Report

for the

Atlantic Orient 15/50 Wind Turbine

by

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5.0 Test Objective

The objective of the safety and function test is given in the International Electrotechnical Commission's IEC WT01 [1]:

"The purpose of safety and function testing is to verify that the wind turbine under test displays the behavior predicted in the design and that provisions relating to personnel safety are properly implemented."

The IEC WT01 also states:

"The Certification Body shall verify satisfactory demonstration of the control and protection system functions. In addition, the dynamic behavior of the wind turbine at rated wind speed or above shall be verified by testing if this has not been verified within the scope of the load measurements."

6.0 Background

This test is being conducted as part of the U.S. DOE's Small Wind Turbine Field Verification Project. The primary purpose of this program is to provide consumers, manufacturers, and host site organizations with an independent assessment of the performance and reliability of small U.S. wind turbines. In addition, this test may be used to fulfill the safety and function test requirement identified in IEC WT01 Annex D for wind turbine certification.

Atlantic Orient Corporation developed the AOC 15/50 with assistance from the U.S. DOE and NREL. The test turbine, located at the National Wind Technology Center (NWTC), is owned by NREL and serves several functions, including:

- Developing NREL's certification testing capabilities
- Participating in an international round-robin testing program
- Testing wind/diesel hybrid test systems
- Developing improvements to the design of the AOC 15/50 model
- Demonstrating modern wind turbine technology.

7.0 Test Turbine

The configuration of the AOC 15/50 wind turbine is shown in Figure 1 and Figure 2. The turbine is a three-bladed, downwind, free-yaw, constant-speed, stall-regulated machine. Rotational energy is converted to electrical power in the nacelle, which contains the gearbox, generator, and parking brake (see Figure 2).

The blades were manufactured by Aerpac/Merrifield Roberts. They were designed by M. Zuteck and based on the NREL Thick-series-type (modified) airfoil. Composed of a wood/epoxy laminate, the blades are 7.2 m in length (from root to tip). The assembled rotor has a sweep area 15.0 meters in diameter.

AOC specifies a blade pitch of 3.24° at the tip for the 1850 m elevation of the NWTC. This setting causes the power curve to peak at 65 kW. However, the blades were set to 0.9° for portions of this test to correspond to the standard configuration for installations of 50-Hz turbines at sea level sites. This setting causes the turbine's power curve to peak slightly over 50 kW.

The rotor is connected directly to the gearbox low-speed shaft, and the generator is connected to the gearbox high-speed shaft. The rotational speed of the rotor at rated power is 65 rpm. The transmission's gear ratio of 1:28.25 turns the generator at a nominal 1800 rpm. The generator is a three-phase, 60-Hz, 480-volt, induction machine rated at 65 kW.

The tower is a 24.4-m high, freestanding, three-legged lattice steel structure.

The turbine uses three independent brake systems. Tip brakes mounted at the end of the blades provide aerodynamic braking. They use electromagnets to hold them in position. A capacitor/resistor network provides dynamic braking, and a mechanical brake is used for parking the rotor.

The controller is a Koyo DirectLogic 205 PLC, which is located in a small control shed at the base inside the turbine tower. The program used by the controller was originally developed in Canada for AOC. For this test, the program was modified by H. Link to increase safety and ease of operation. The program version used during the test is entitled Round Robin 86 (file name Rrobin86). Connection to the grid is via a 480VAC/13.2kVAC transformer located approximately 3 meters from the base of the tower. Table 1 lists configuration and operational data for the AOC 15/50 as tested.

Figure 1. Overall configuration of the AOC 15/50 test turbine.

Figure 2. Tower-top configuration of the AOC 15/50.

Table 1. Test Turbine Configuration and Operational Data

General Configuration:	
Make, Model, Serial Number	Atlantic Orient Corporation, AOC 15/50, S/N: none (this was the third AOC 15/50 turbine installed)
Rotation Axis	Horizontal
Orientation	Downwind
Number of Blades	3
Rotor Hub Type	Rigid
Rotor Diameter (m)	15
Hub Height (m)	25
Performance:	
Rated Electrical Power (kW)	50
Rated Wind Speed (m/s)	12.0
Cut-In Wind Speed (m/s)	4.9
Cut-In Wind Speed Dead Band (m/s)	3.6
Cut-Out Wind Speed (m/s)	22.3
Extreme Wind Speed (m/s)	59.5 (peak survival)
Rotor:	
Swept Area (m^2)	177
Online Rotational Speed (rpm)	65
Coning Angle (deg)	6
Tilt Angle (deg)	0
Blade Pitch Angle (deg)	0.9° toward feather during loads testing; 3.24° during overspeed testing
Direction of Rotation	CCW viewed from downwind
Power Regulation	stall regulation
Overspeed Control	centrifugal override of tip brake magnets
Drive Train:	
Gearbox Make, Type, Ratio	Fairfield/AOC, Planetary, 1:28.25
Generator: Make, Type, Speed, Voltage, Frequency	Magnatek, 3-phase induction, 1800 rpm, 480 VAC, 60 Hz
Braking System:	
Mechanical (Parking) Brake: Make, Type, Location	Sterns Series 81,000, on nacelle aft of generator
Aerodynamical Brake: Make, Type, Location	AOC, electromagnetic tip brakes, at the tips of all blades
Electrical Brake: Make, Type, Location	AOC, dynamic brake, connected to the tower droop cable at the base of turbine
Yaw System:	
Wind Direction Sensor	none
Yaw Control Method	free-yaw
Tower:	
Type	three-legged steel lattice
Height (m)	24.4

Control/Electrical System:	
Controller: Make, Type	Koyo, DirectLogic 205
Power Converter: Make, Type	none
Electrical Output: Voltage, Frequency, Number of Phases	480 VAC, 60 Hz, three phases

8.0 Test Site

The AOC 15/50 wind turbine under test is located at Site 1.1 of the NWTC (hereafter referred to as the test site), approximately 8 km south of Boulder, Colorado. The site is located in somewhat complex terrain at an approximate elevation of 1850 m above sea level. Figure 3 shows the location of the test site relative to Boulder and the front range of the Rocky Mountains, as well as a plot plan of the test site including all obstructions for 20 rotor diameters (with topography lines listed in feet above sea level). The meteorological tower is located 37.5 meters from the test turbine at a bearing of 292° true.

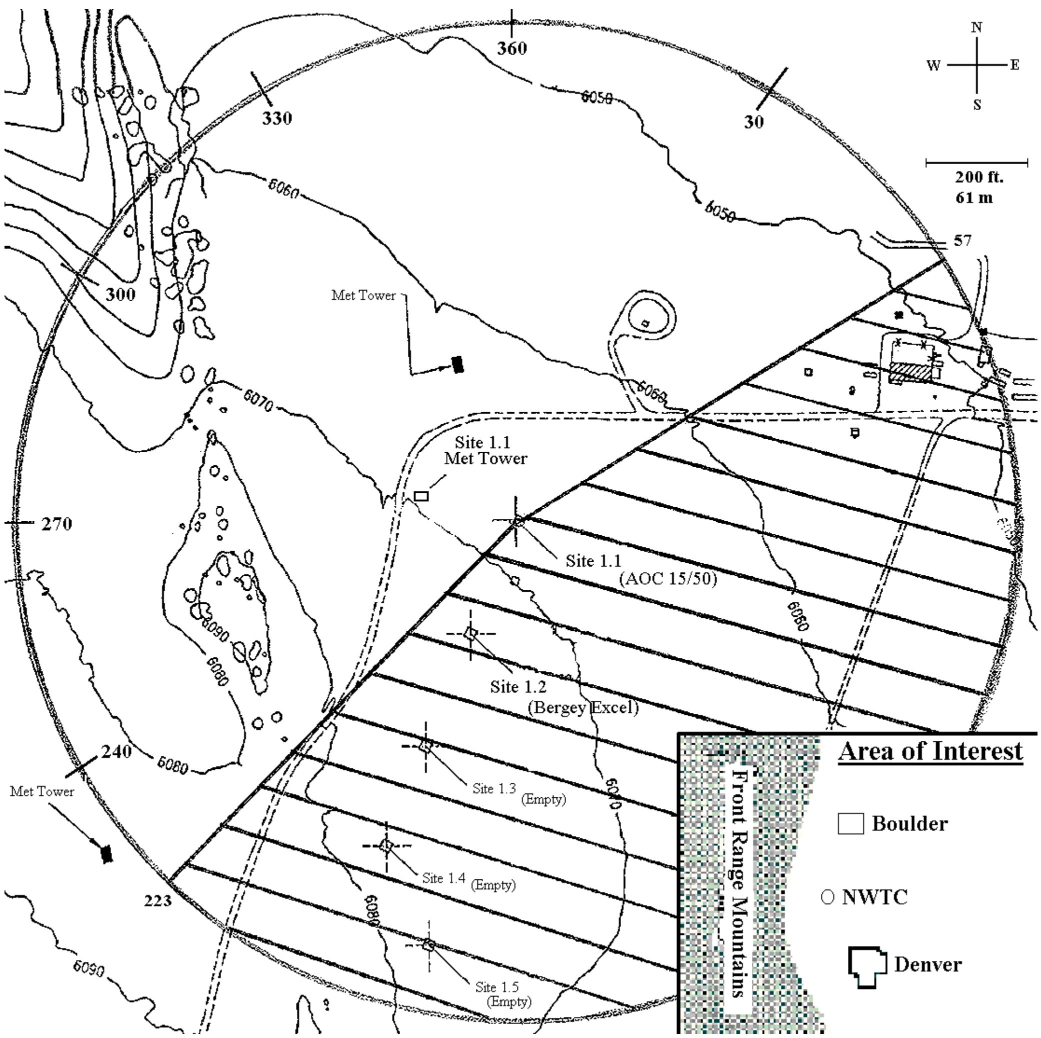

Figure 3. Location and plot plan of the AOC 15/50 test site.

9.0 Instrumentation and Testing Procedure

9.1. Instrumentation

Limited instrumentation was used for this test. Some data were used from the mechanical loads test. Detail on instrumentation used in that test is given in the mechanical loads test report [Ref 2].

9.2. Test Procedures

Yaw orientation

Observations will be made over time for a range of wind speeds. These observations will be written in the logbook.

Start-up

The start-up procedure consists of the following steps:

- PLC checks for no faults
- PLC checks for turbine enabled
- PLC checks for wind in band (4.9-22.3m/s)
- All brakes are energized (released)
- Turbine spins up
- At 1800 rpm (generator), the grid contactor closes.

Time series of start-up transients have been collected during the load test.

Shut-down

There are two shut-down sequences:

- Normal shut-down
- Emergency shut-down.

Observations of the shut-down sequence (closing and opening of relays) will be made, and time series of shut-downs will be reported.

Power production

Power production behavior is recorded as part of the power performance test. Any differences from the expected designed behavior will be reported.

Power limitation

Maximum power versus wind speed collected during the power performance test will be plotted.

Speed limitation

The turbine has an asynchronous generator and a gearbox. The rotor is thus defined by the grid frequency and the generator slip. If a fault should occur, the PLC monitors the generator speed and will trigger an emergency shut-down if a speed limit is passed. The second means of overspeed protection are the tip brakes. These are designed to open passively by a combination of aerodynamic and centrifugal forces. A test will be conducted to verify that the tip brakes deploy at a safe speed.

Rotor underspeed
The PLC monitors the generator speed. If the generator speed drops to 1760 rpm for more than 10 seconds or to 1500 rpm for more than 2 seconds, the turbine should shut down. Disconnecting the sensor output (wire 72) from Terminal Block 1 (TB 1) will simulate this condition.

Grid outage
To simulate a grid outage, the manual power switch for the turbine will be opened. The turbine should perform an emergency shut-down. This will be checked by observing relays and tip brakes.

Short loss of grid
The manual power switch will be opened and closed as quickly as possible. The turbine should go into an emergency shut-down. This will be checked by observing relays and the tip brakes.

Generator over temperature
Thermostats are embedded in the generator. At high temperatures, these thermostats open, initiating an emergency stop. Wire 17 will be disconnected from TB1 while the turbine is online.

Parking brake current
If the turbine measures no current on the parking brake circuit, which indicates that the parking brake is likely to be applied, the turbine shuts down. Wire 28 will be disconnected from Actionpak Terminal 4 while the turbine is online. The turbine should shut down.

Droop cable over-twist
No system is present to prevent droop cable over-twist. No test will be done to determine the damage from droop cable over-twist.

Excessive vibration
The turbine has no means to detect excessive vibration.

Grid monitor
The Time Mark grid monitor monitors the grid voltage, frequency, and imbalance. Normally the output of this sensor is high if the grid is within the set tolerances. If the grid monitor gives a low output, the turbine should shut down. The output of the grid monitor (wire 15) will be disconnected from the grid monitor, thus simulating a low output to the PLC.

Unauthorized changing of control settings
The turbine system will be checked to see whether settings can be changed.

Personnel safety:

Fall protection
A description of the fall arresting system and anchoring points on the turbine will be given.

Lock-out for maintenance
Locking devices for the rotor and the yaw motion will be applied. Findings will be noted.

Electrical safety
A visual inspection will be made to determine whether any hazardous situations exist. A qualified electrician will also be asked to look at the electrical system of the turbine.

Lightning protection
Description of the lightning protection for the NWTC installation will be recorded.

10.0 Results

Yaw Orientation

The turbine tracks wind direction well most of the time. The turbine frequently exhibits high yaw rates over a range of about 30° as it responds to varying wind speed and direction. The turbine occasionally operates upwind. The turbine is stable in that orientation and follows the wind for several hours at a time. At low wind speeds, the yaw bearing occasionally "sticks" and the turbine is unable to track the wind.

Start-Up

Figure 4 depicts a time series of a high wind start-up. In the start-up sequence, the brake is released, the turbine coasts up to 1800 rpm (generator rpm), and the turbine goes online.

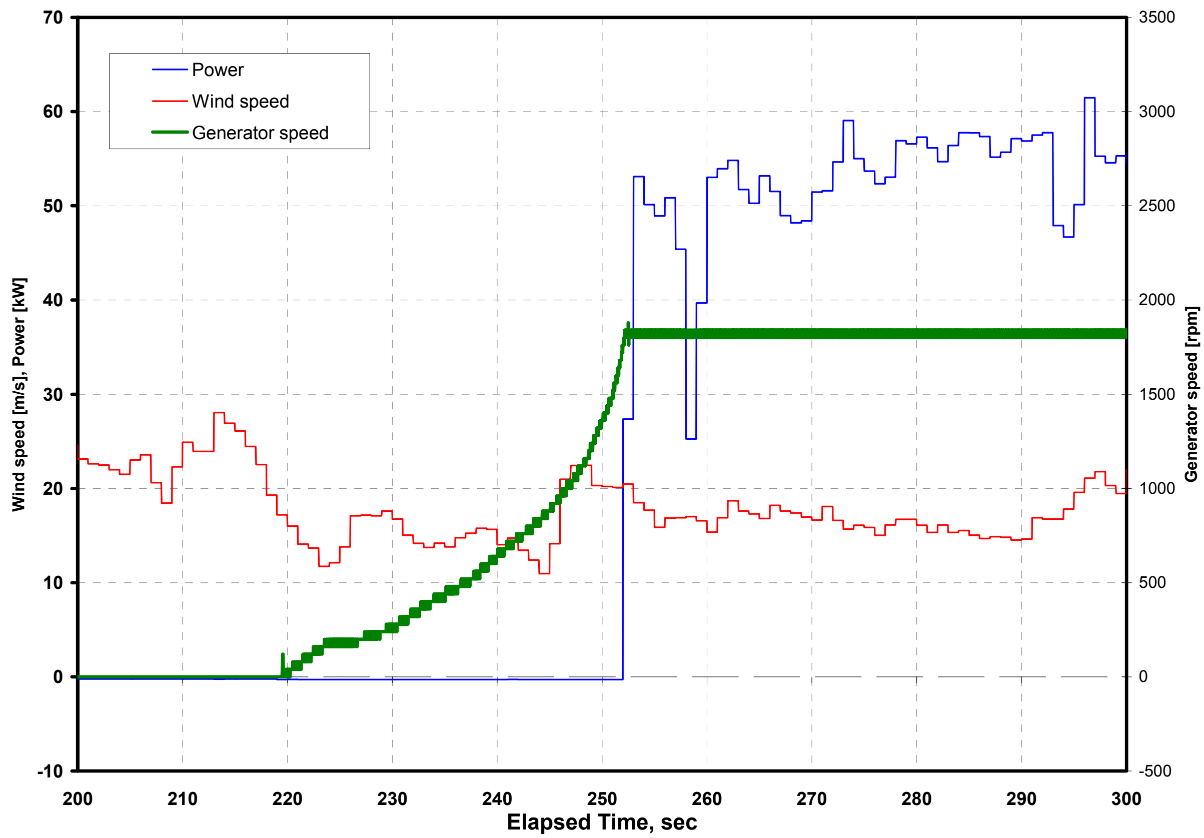

Figure 4: Time series of high-wind-speed start-up (19 m/s).

Shut-Down

The Emergency stop button on the control panel was pushed. The turbine shut down immediately. Both dynamic brake relays (M1 and M4) opened. Figure 5 gives a time series of an emergency shut-down in 13 m/s wind.

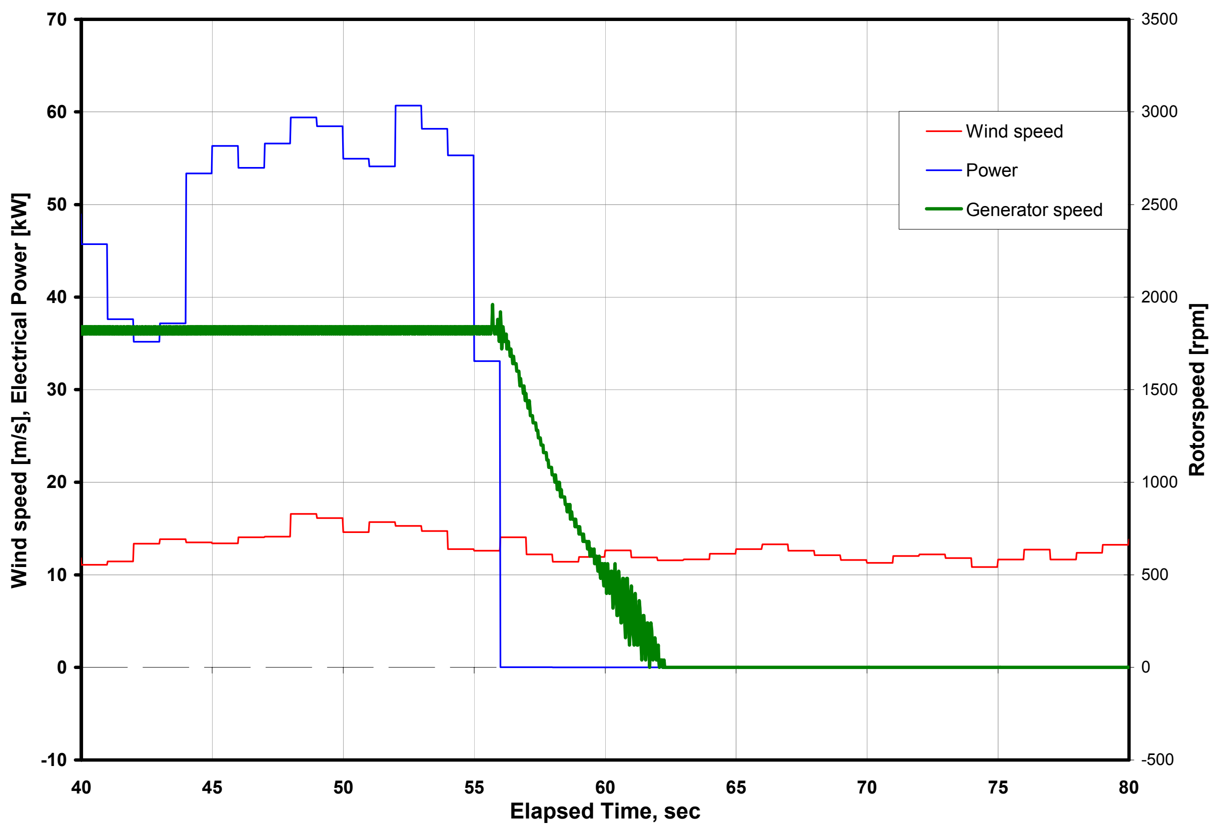

Figure 5: Time series of emergency shut-down.

Power Production

The power production does not show any abnormal behavior, other then the occasional upwind operation. Ten-minute average power is plotted against 10-minute average wind speed in Figure 6.

Power Limitation

Figure 6 shows the mean and maximum power of the AOC 15/50 as measured from January 2000 to July 2000. Each data point is based on a 10-minute period. The highest measured instantaneous power was 85 kW. The 10-minute average power peaked at about 56 kW. This indicates that the turbine's power limitation method (stall) works properly.

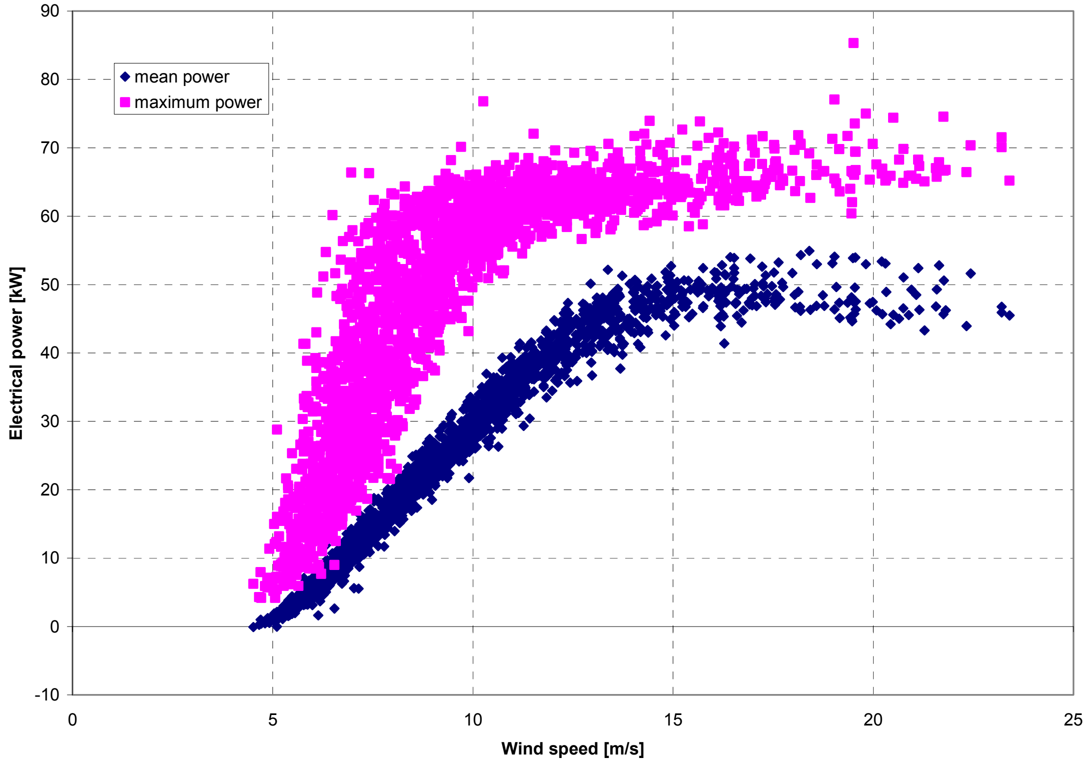

Figure 6: Mean and maximum power versus wind speed (10-minute data points).

Rotor Speed Limitation

A test was conducted to ensure that the tip brakes deploy from centrifugal and aerodynamic forces at a safe rotor speed. The test procedure and results are given in Appendix A. At least one tip brake always deployed at a safe rotor speed, and data indicated that a second tip brake would release at a slightly higher rotor speed.

Rotor Underspeed

After disconnecting wire 72 from TB1 to simulate a rotor underspeed, the turbine shut down immediately on a speed sensor fault—not an underspeed fault. A second test was performed with the turbine online. All three tip brakes were deployed to force an underspeed. The generator speed dropped from 1800 to about 1770 rpm. It was concluded that the set point of 1760 rpm is too low to detect a realistic situation in which the turbine is online and the rotor speed is too low. The set point was changed to 1780 rpm. The test was re-run, and this time the shaft negative power flag did go high. However, the timer that delays the shut-down for 10 seconds did not start, and thus the turbine did not shut down. After modifications were made to the PLC code, the test was re-run. This time the turbine did shut down.

Grid Outage

The grid connection switch was opened. The turbine shut down. Two of the three tip brakes came out.

Short Loss of Grid

The grid connection switch was opened and closed as quickly as possible (0.5 - 1 sec). The dynamic brake relay 4M opened, but then it closed again. The turbine did not shut down. The test was repeated by switching slower (1-2 sec). The turbine shut down after two tip brakes came out, and relays 4M and 1M opened.

Generator over Temperature

After disconnecting Wire 17 to simulate high generator temperatures, the PLC's Turbine Fault Flag (27) correctly went high, and the turbine shut down.

Parking Brake Current

Wire 28 was disconnected from Actionpak terminal 4. The turbine remained operating and did not shut down. Inside the PLC, the Parking Brake Fault (24) was not set high. It was found that the Actionpak settings were wrong. This was corrected and the test was re-run. During this test, the Parking Brake Fault flag did go high in the PLC. An additional test was performed with the turbine running, and this time the parking brake relay was pulled. The Parking Brake Fault flag did go high, and the turbine faulted and shut down.

Unauthorized Changing of Control Settings

There are no means to change the control settings on the control panel. A computer with the PLC software has to be connected to change settings. However, no password is required to do so.

Grid Monitor

Wire 15 was disconnected from the Time Mark grid monitor. Inside the PLC, Flag X2 (grid fault) went high. The turbine shut down.

Fall Protection

One of the tower legs is equipped with climbing pegs. Along this tower leg, a steel cable is available to attach a fall-arrest device. There are four lifting points on the drive train for positioning, but there are no dedicated anchor points for fall protection.

Lock-Out for Maintenance

Yaw movement can be prevented with a yaw lock that is engaged at the tower top. The parking brake normally prevents rotor movement; but the rotor can't be locked if the parking brake or generator is removed for servicing.

Electrical Safety

The electrical system on the NWTC turbine was upgraded to permit use of a 125-amp circuit breaker at the connection of the turbine to the utility grid. The original breaker was rated for 100 amps. This change required NREL personnel to increase the size of the 480-volt wiring in the control panel and the size of the power droop cable. The NWTC turbine now meets NEC requirements. NREL has not evaluated the latest version of the standard AOC 15/50 turbine wiring to verify that the design meets NEC requirements.

High-voltage wiring is routed through conduits whenever possible, and electrical boxes are properly labeled with warning signs. Several controls inside the control panel require access for normal inspection and maintenance activities. Originally this panel did not have any protection from accidental contact with 480-volt components. NREL installed acrylic shields to prevent accidental contact with these high-voltage components.

The droop cable has no protection for over-twist. If the turbine is not maintained properly, an excessive number of wraps on the droop cable will result in damage to the turbine and the possibility of exposure to energized circuits.

Lightning Protection

The electrical system and tower are grounded. No lightning rod is used on the drive train. The blades have no protection from lightning.

11.0 References

1. IEC WT01 (2001-04), International Electrotechnical Commission (IEC), IEC System for Conformity Testing and Certification of Wind Turbines - Rules and Procedures.
2. Wind turbine generator system mechanical loads test report for the AOC 15/50 wind turbine, R. Santos, E. Jacobson, May 15, 2000.

APPENDIX A: Overspeed Test

AOC 15/50 Overspeed Test

June 12, 2003

Jeroen van Dam
Eric Jacobson
Hal Link
Scott Wilde

Objective
An overspeed test of the AOC 15/50 was performed as part of the safety and function test. Under certain faulted conditions, the AOC relies on the tip brakes to keep the turbine within the design limits. The overspeed test was designed to show that the tip brakes will deploy at a safe rotor speed.

Background
Under normal operating conditions, an electromagnet keeps the tip brakes from deploying. If the turbine controller senses a fault or if wind speeds are outside of normal operating conditions, the controller cuts the power to the tip brake electromagnets. However, the rotor speed sensor has failed on occasion. If the sensor fails or if a gearbox failure decouples the generator from the rotor, the controller might not sense an overspeed condition. The combination of aerodynamic forces and centrifugal forces will overcome the magnetic force, and the tips will deploy. The tip brake magnets were originally designed for centrifugal release at 110% of normal operating speed, but there were many nuisance releases of tip brakes with these magnets. AOC increased the strength of the magnets, but the rotor speed at which the stronger magnets would release from centrifugal and aerodynamic forces was never determined.

Determination of Latching Force
The first step in the test method is to establish the range of release force likely to occur in AOC 15/50 turbines. Tip magnet strength has been found to vary due to magnet manufacturing differences, age, condition of the latching plate, and voltage supply to the tip brake circuit. The AOC User Manual specifies that latching force should be "about 60 lb" as measured by pulling on the trailing edge of the tip plate.

NREL measured the latching force on each of the tip brakes of the AOC 15/50 turbine. We also varied the voltage supply to the tip brake circuit. Figure A.1 shows these results. At normal NWTC grid voltage (120 VAC), the tip latching force is about 67 lbs.

Determination of Rotor Speed Needed for Tip Brake Release
Modifications to the turbine controller program were required to disable fault protection and normal grid contactor closure during this test. A generator speed sensor that had the necessary range of operation for this test was installed. It was set to de-energize the tip magnet circuit if the tip brakes did not deploy from centrifugal and aerodynamic forces. Based on strength calculations, NREL personnel determined that 120 rpm would be the maximum rotor speed allowed for this test.

Measurements were made of generator speed, wind speed, and tip brake circuit voltage. Wind speed was measured using an anemometer mounted on the turbine tower. This was a convenient measurement point, but it yields only an approximate indication of wind speed. This was sufficient for this part of the test, however, because tip brake release is not strongly affected by wind speed. Because of the 6° coning angle of the rotor, the highest stresses on the blades from overspeeding occur at low wind speeds.

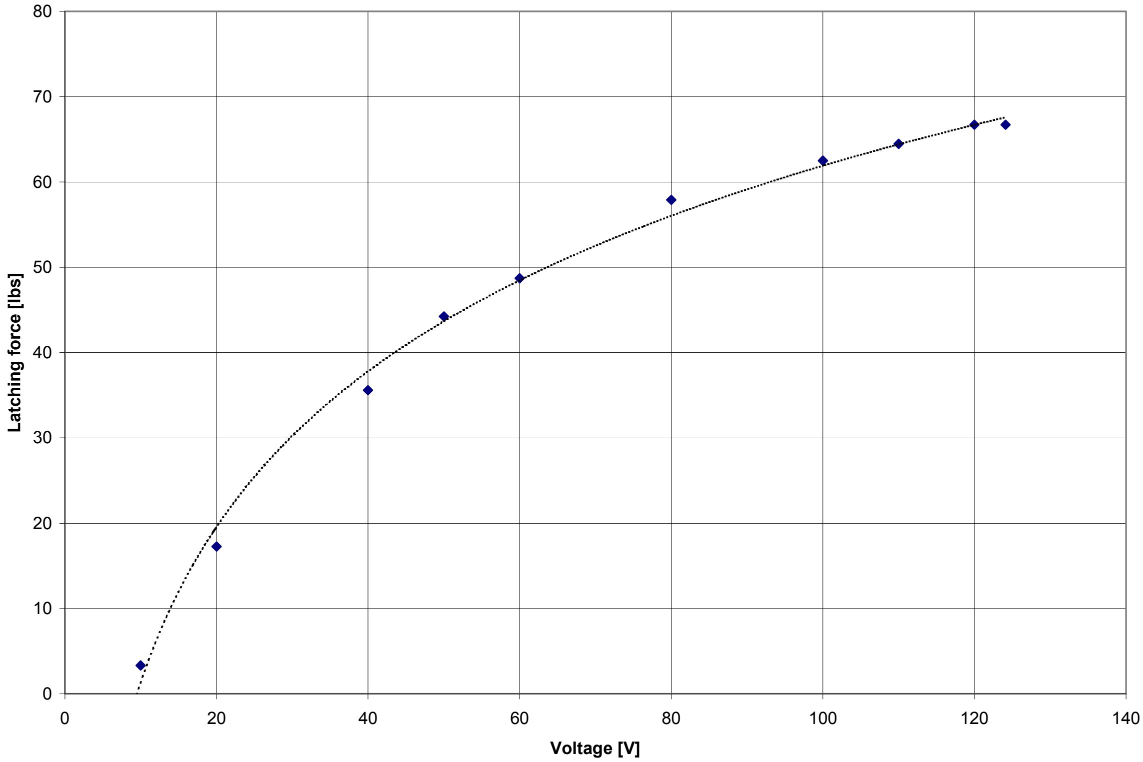

Figure A.1. Tip brake latching force as function of the tip voltage measured at the controller (Blade 3).

Table A.1 and Figure A.2 show the results of the tip release test. For every run, Table A.1 indicates the tip brake circuit voltage, the corresponding latching force, and observed maximum generator and rotor speed. The tip brake of blade three deployed first for all tests. During one test, the wind picked up enough to cause the rotor to spin up and deploy a second tip (Figure A.3). This test shows that the deploy speed of two of the tips are close to each other.

The maximum measured generator speed was 2583 rpm. The 60-Hz version of the AOC 15/50 has a gearbox ratio of 28.25. Thus the maximum rotor speed was 91.4 rpm.

Figure A.3 and Figure A.4 give some time traces of rotor speed and wind speed.

Conclusion

These tests indicate that the tip brakes deploy at safe rotor speeds.

Table A.1. Test Results of the Overspeed Test

	Tip magnet	Tip latching	Maximum	Maximum rotor

Test	voltage (V)	force (lbs)	generator speed (rpm)	speed (rpm)
1	20	17.3	2070	73.3
2	40	35.6	2282	80.8
3	60	48.7	2388	84.5
4	80	57.9	2467	87.3
5	100	62.5	2537	89.8
6	110	64.5	2573	91.1
7	120	66.7	2583	91.4
8	125	66.7	2583	91.4
9	124	66.7	2570	91.0
10	120	66.7	2540	89.9
11	110	64.5	2540	89.9
12	100	62.5	2523	89.3
13	80	57.9	2477	87.7
14	60	48.7	2441	86.4
15	40	35.6	2335	82.7
16	20	17.3	2113	74.8
17	10	3.3	1527	54.1
18	5	0	845	29.9
19	5	0	802	28.4

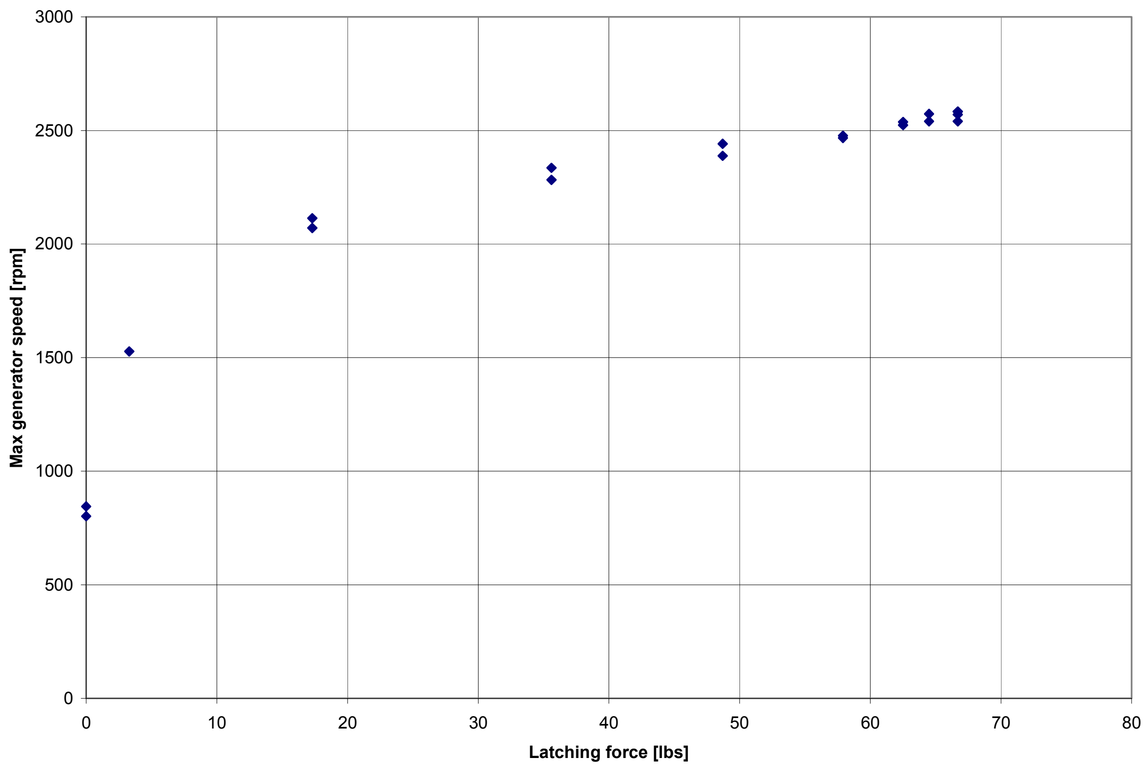

Figure A.2. Maximum rotor speed as a function of tip brake latching force.

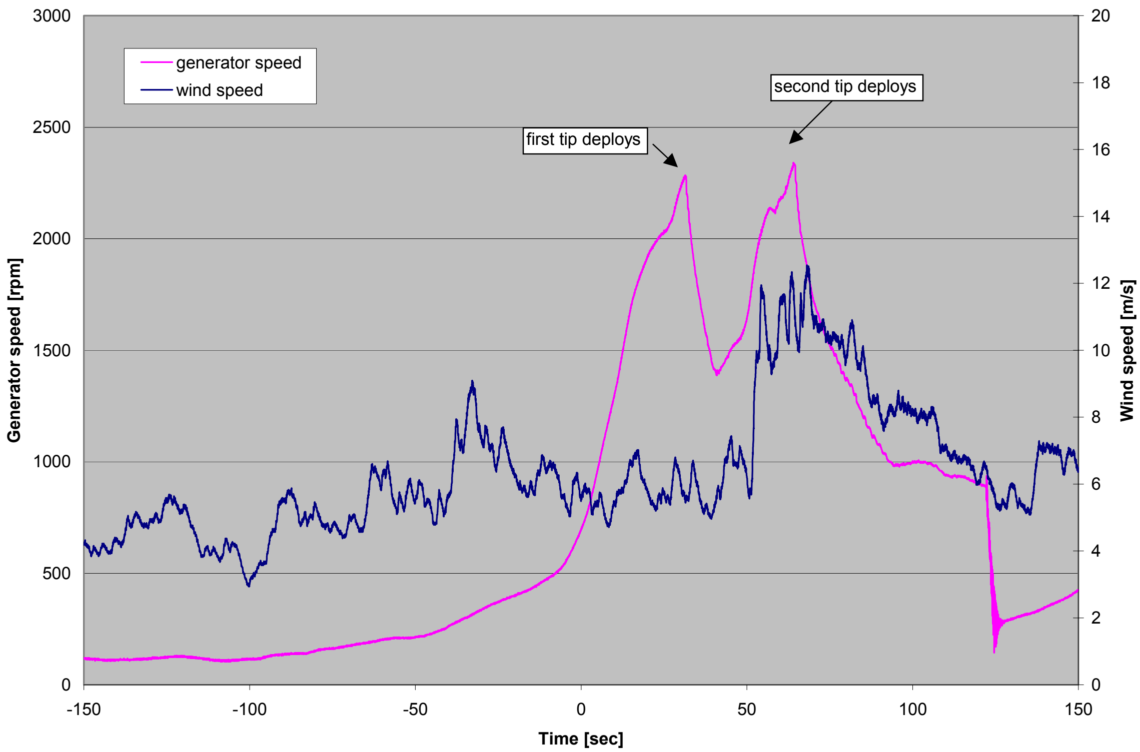

Figure A.3. Time trace of test 2, tip voltage 40V.

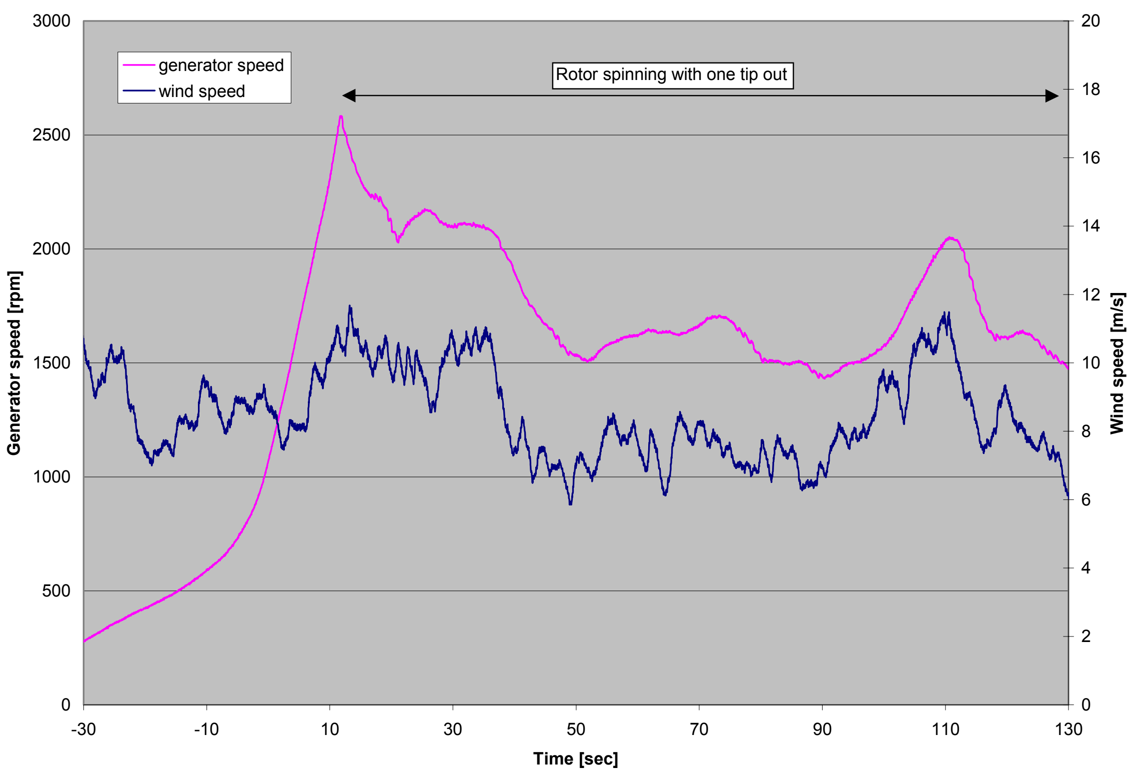

Figure A.4. Time trace of test 7, tip voltage 120 V.