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Power Performance Testing Activities in the DOE-EPRI Turbine Verification Program

J. VandenBosche, T. McCoy, and Heather Rhoads
Global Energy Concepts, LLC

B. McNiff
McNiff Light Industry

B. Smith
National Renewable Energy Laboratory

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National Renewable Energy Laboratory

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POWER PERFORMANCE TESTING ACTIVITIES IN THE DOE-EPRI TURBINE VERIFICATION PROGRAM

John VandenBosche, Tim McCoy, and Heather Rhoads
Global Energy Concepts, LLC
5729 Lakeview Dr. NE, Suite 100
Kirkland, WA 98033 USA
425-822-9008
tmccoy@globalenergyconcepts.com
jvandenbosche@globalenergyconcepts.com
hrhoads@globalenergyconcepts.com

Brian McNiff
McNiff Light Industry
43 Dog Island Road
Harborside, ME 04642 USA
207-326-7148
bmcniff@hypernet.com

Brian Smith
National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, CO 80401-3393 USA
303-384-6911
Brian_Smith@nrel.gov

Abstract

As part of the U.S. Department of Energy/Electric Power Research Institute (DOE-EPRI) Wind Turbine Verification Program, Global Energy Concepts (GEC) is engaged in planning and conducting power performance tests for wind turbines in Searsburg, Vermont; Glenmore, Wisconsin; Algona, Iowa; Springview, Nebraska; Kotzebue, Alaska; and Big Spring, Texas. The turbines under investigation include a 550-kW Zond Z-40 FS, a 600-kW Tacke 600e, two 750-kW Zond Z-50s, a 66-kW AOC 15/50, a 660-kW Vestas V-47, and a 1.65-MW Vestas V-66. The testing is performed in a variety of terrain types, including mountains, plains, deserts, and coastal tundra; and under a wide range of atmospheric conditions from arid to arctic. Because one goal of this testing program is to gain experience with the new International Electrotechnical Commission (IEC) 61400-12 standard, all of the measurements are being performed in accordance with this new standard.

This paper presents the status of the power performance testing at each site, the methodologies employed, test results available, and lessons learned from the application of the IEC standard. Any sources of uncertainty are discussed, and attention is given to the relative importance of each aspect of the IEC standard in terms of its contribution to the overall measurement uncertainty.

Introduction and Background

The Turbine Verification Program (TVP) is a joint effort between DOE, EPRI, and several utilities to evaluate early production models of advanced wind turbines and to verify the performance, reliability, maintainability, and cost of new wind turbine designs and system components in a commercial utility environment. GEC serves as the support contractor to provide project management guidance, monitoring, and reporting. As part of TVP's technical support, GEC has been conducting third-party power performance tests at most of the TVP project sites in accordance with the IEC's recently adopted 61400-12 standard[1].

TVP's power curve tests will achieve one of the primary objectives of the program, which is to verify the performance of new commercial wind turbines. The tests will also help the project owners determine whether the turbines are meeting their warranties, and will serve as an operations and maintenance (O&M) tool for the host utilities to evaluate whether the turbines' power output is changing over time. The analysis will provide baseline measured power curves that can be used to calculate expected versus actual energy and will help the wind industry gain experience with exercising the IEC standard. Another goal of the testing is to verify the usefulness of the second wind Advanced Distributed Monitoring System (ADMS) for collecting accurate power-curve data.

This paper discusses the TVP's evaluation approach, the equipment selected, the use of the IEC standard, the lessons learned, and preliminary results of the tests conducted to date; and makes recommendations regarding the approach to power performance testing and potential improvements to the IEC standard.

Status

TVP plans to conduct seven power performance tests as listed in Table 1. Two of the tests are completed, and test reports were issued. For three other tests, the data collection is complete, and the final reports are awaiting post-calibration of test sensors. Tests on the two turbine types in Big Spring, Texas, are currently in the planning stage.

In 1999, assisted by McNiff Light Industries (MLI), TVP completed the first power performance test on a Zond Z-40FS at the 6.05-MW Green Mountain Power (GMP) wind facility near Searsburg, Vermont.[2] This was followed by a test of a Tacke 600E at the 1.2-MW Low-Wind-Speed Turbine Project test site near Glenmore, Wisconsin,[3] and a test of a Zond Z-50 at the 2.25-MW Iowa Distributed Wind Generation Project (IDWGP) in Algona, Iowa.[4] We recently completed the test data collection for the ten 66-kW Atlantic Orient Corporation (AOC) 15/50 turbines in Kotzebue, Alaska, and the two Zond Z-50 turbines at the 1.5-MW Nebraska Distributed Wind Generation Project (NDWGP) near Springview, Nebraska. Data analysis and reporting for the Kotzebue and Springview tests is underway and awaiting post-calibration of the reference anemometers. We have reached an agreement in principle to test one V47 and one V66 at York Research Corporation's 34.3-MW wind power plant in Big Spring, Texas, although details of the test are still being planned.

Table 1. Current Status of TVP Power Performance Testing Activities

Project	Turbine (Hub Height)	Test Report Status	Test Dates Start	Test Dates Finish
Searsburg, VT	550 kW Z-40FS (40 m)	Complete	Dec. 13, 1998	April 11, 1999
Glenmore, WI	600 kW Tacke 600e (60 m)	Complete	Dec. 7, 1998	April 20, 1999
Algona, IA	750 kW Z-50 (50 m)	Pending sensor post-calibration	Nov. 11, 1999	Jan. 10, 2000
Kotzebue, AK	66 kW AOC 15/50 (26 m)	Pending sensor post-calibration	Nov. 1, 1999	May 31, 2000
Springview, NE	750 kW Z-50 (65 m)	Pending sensor post-calibration	April 19, 2000	May 26, 2000
Big Spring, TX	660 kW V-47 (65 m) 1.65 MW V-66 (80 m)	Test plan under development		

Approach

TVP's general approach is to follow the IEC standard as closely as possible, regarding selecting the instrumentation, siting the meteorology (met) tower, mounting anemometers, collecting test data and processing procedures, preparing the uncertainty analysis, and reporting the results. The equipment used for the completed and ongoing tests is summarized in Table 2 and described below.

Table 2. Power Performance Test Equipment

Project	Wind Speed	Wind Dir.	Power Transducer	Temperature	Pressure	Data Logger
Searsburg, VT	Max 40c	NRG 200P	OSI GW5	NRG 110S	Vaisala PTB101B	Campbell Scientific CR10X
Glenmore, WI	Max 40c	NRG 200P	Second Wind Phaser	NRG 110S	Vaisala PTB101A	Second Wind ADMS
Algona, IA	Max 40c	NRG 200P	Second Wind Phaser	NRG 100S	Vaisala PTB101A	Second Wind ADMS
Kotzebue, AK	Max 40c	NRG 200P	Second Wind Phaser	RM Young 41342 F	Vaisala PTB101A	Second Wind ADMS
Springview, NE	Max 40c	NRG 200P	Second Wind Phaser	RM Young 41342 VC	Vaisala PTB101A	Second Wind ADMS

The data acquisition system for all tests, except Searsburg, was the ADMS made by Second Wind, Inc. The ADMS was installed at these projects for use by the site operators as a Supervisory Control and Data Acquisition System (SCADA). We made no modifications to the SCADA software or hardware for the power performance testing, although the systems were designed with that in mind when they were installed. The ADMS is a highly versatile and functional system that is used by many commercial wind farms for O&M. One of the goals of power performance testing in the TVP program was to verify whether or not the ADMS could be used for accurate power-curve testing without the need for an additional data acquisition system.

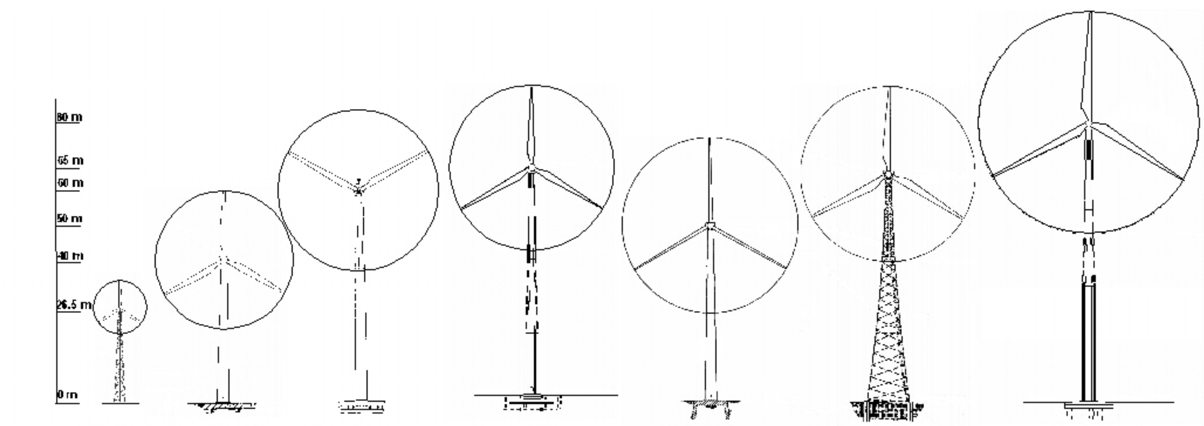
The TVP decided to use Max 40c cup anemometers because they are inexpensive and rugged. While there are more accurate anemometers on the market, the Max 40c meets the requirements of the IEC standard and is used extensively within the wind energy industry. A recent report increased the confidence in the calibration of the Max 40c.[5]

An OSI power transducer was used for the first test in Searsburg, but Second Wind Phasers were used for all other tests since then. While the Phaser has not been certified by an approved laboratory as meeting the requirements of the IEC standard, we believe it is accurate enough for power performance testing in accordance with the IEC standard. Second Wind specifies the accuracy of the Phaser to be within 0.2% of full scale.

The IEC standard requires that data be utilized only for periods when the test turbine is available, although it does not specify a precise definition of availability. In the absence of another definition, GEC used the TVP definition of availability, which considers all downtime regardless of cause. This is narrower than other availability definitions used in the wind industry because it considers the turbine to be unavailable when power lines are out and when the turbine is intentionally shut down due to site tours, testing, or other site activities. The TVP definition of availability does consider the turbine to be available if it is stopped due to a normal function of the controller. For instance, the TVP availability definition considers the turbine to be available during cable untwist events and during high-wind shutdowns. Data from these events were included in the valid database.

Challenges Faced

The power performance tests at the TVP sites involve significant challenges because of the variety of turbines being tested, the topography of the sites, climatic conditions at the sites, and ownership of the projects. The turbine sizes range from the AOC 15/50, which has a 15-m rotor diameter and a 26.5-m hub height, to the Vestas V-66 with a 66-m rotor diameter and an 80-m hub height. These variations are shown in Figure 1. The variation in turbine size presented a challenge in obtaining met towers tall enough to reach hub height, and also in sizing the power transducers appropriately.



	AOC 15/50	Zond Z-40 FS	Tacke 600e	Vestas V-47	Zond Z-50 (Algona)	Zond Z-50 (Springview)	Vestas V-66
Hub Height (m)	26.5	40	60	65	50	65	80
Rotor Dia. (m)	15	40	46	47	50	50	66
Rated Power (kW)	66	550	600	660	750	750	1,650

Figure 1. Size comparison of test turbines

The test sites had significantly different topographies. The IEC standard has strict criteria that the site topography must meet or a site calibration is required. Test sites in the TVP program range from Algona, Iowa, which is completely flat, to Searsburg, Vermont, which includes steep mountainous terrain and trees in all directions. At Searsburg, Vermont, GMP, Vermont Environmental Research Associates, and (NRG) worked together to perform a site calibration at Searsburg. Because the turbine was already installed at the time of the site calibration, they used an anemometer on the end of a stinger attached to the aft end of the nacelle (as shown in Figure 2) to obtain wind speed measurements at the turbine's location. Wind speed data were collected simultaneously from the met tower. The turbine was kept offline, and the nacelle was yawed 90 degrees out of the wind during the site calibration test. Site-calibration data were divided into sectors that were 22.5 degrees in width, and a ratio of met tower wind speed to turbine wind speed was calculated for each sector. The calculated wind speed ratios are shown in Table 3.

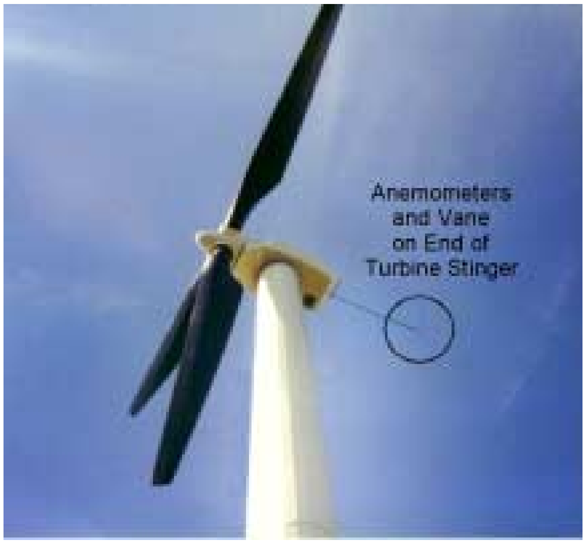


Figure 2. Site calibration setup at Searsburg, VT

Direction Range	Hours of Data	Turbine/Met Tower Wind Speed Ratio (Scalar)
270.0° to 292.5°	27.2	0.961
292.5° to 315.0°	48.8	1.024
315.0° to 337.5°	23.7	1.033
337.5° to 360.0°	14.5	1.074

Table 3. Site calibration results at Searsburg, VT

The Springview, Nebraska, site was particularly interesting because it was relatively flat, although it had a gully that exceeded the topographic requirements of the IEC standard by a small amount. To assess the suitability of the site, GEC located the test turbine (Turbine 1) and the met tower on a topographic map as shown in Figure 3. It was not clear from an examination of the topographic map whether the terrain would pass the test outlined in the IEC standard. To determine precisely whether or not the site passed the topographic requirements, GEC digitized the topographic map as shown in Figure 4. The digitized topographic map was numerically evaluated to determine the best-fit slope of the terrain. The curve-fitted slope met the requirements of the IEC standard, although the actual terrain was found to deviate from the curve-fitted slope by a larger amount than allowed. The IEC standard allows a deviation from the curve-fitted slope of 4 m (13 ft), and the Springview site had a deviation of 6.5 m (21 ft).

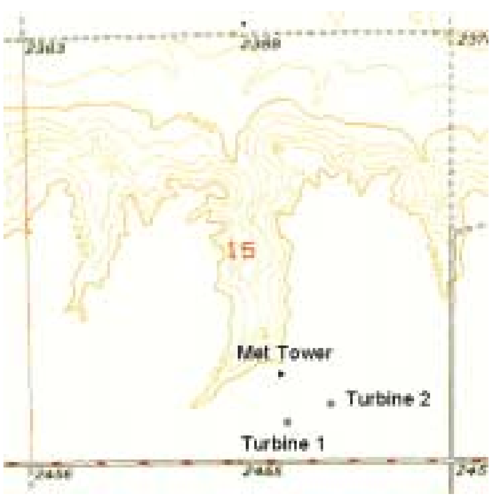


Figure 3. Topographic map of the test site in Springview, NE

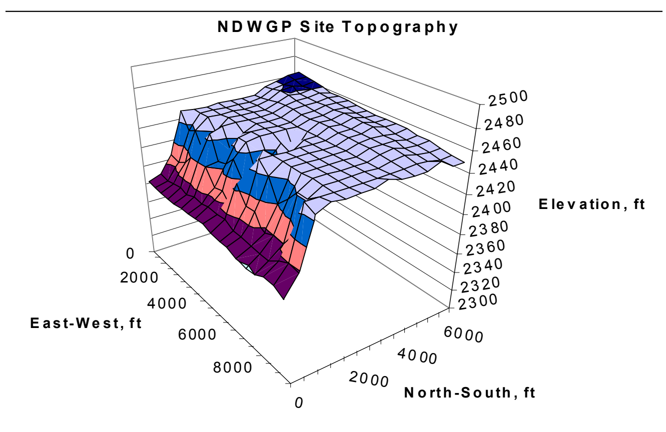


Figure 4. Digitized terrain map of the test site in Springview, NE

Test Results

The first test completed was the Zond Z-40 FS in Searsburg, Vermont. The measured power curve, adjusted to sea level density, is shown in Figure 5. The curve shown in Figure 5 includes error bars determined by applying the uncertainty analysis procedure outlined in the IEC standard.

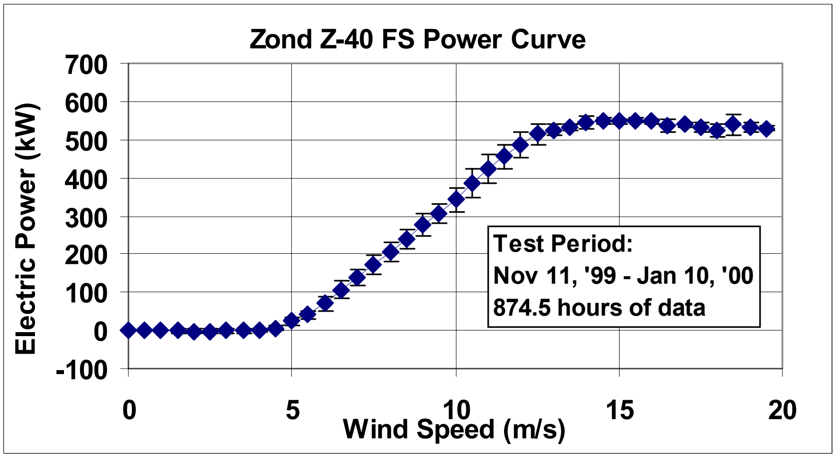


Figure 5. Results of power performance test in Searsburg, VT

The second test completed was the Tacke 600e in Glenmore, Wisconsin. Figure 6 shows the measured power curve, again adjusted to sea-level density and error bars. The error in each wind speed bin for the Glenmore test were different than the errors for the Searsburg test because of uncertainties associated with the different sensors and data acquisition systems used in the two tests. In addition, the raw data for Glenmore has less scatter than for the Searsburg data.

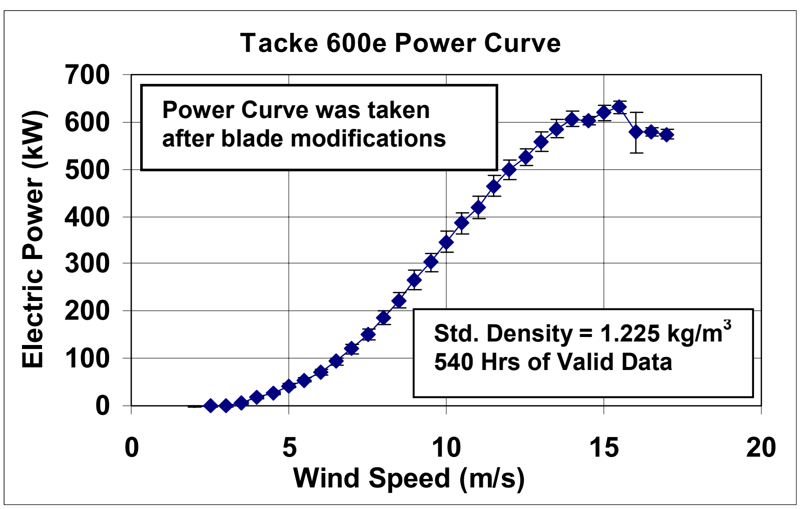


Figure 6. Results of power performance test in Glenmore, WI

The third test completed was the Zond Z-50 in Algona, Iowa. The measured power curve, adjusted to sea-level density, is shown in Figure 7. The error bars for the Algona test are quite small due to very little scatter in the raw data, which is a great improvement compared to Zond's earlier model Z-40 FS, tested in

Searsburg. The Zond Z-50 regulates power very tightly at 750 kW, resulting in almost no scatter in the data above rated wind speed.

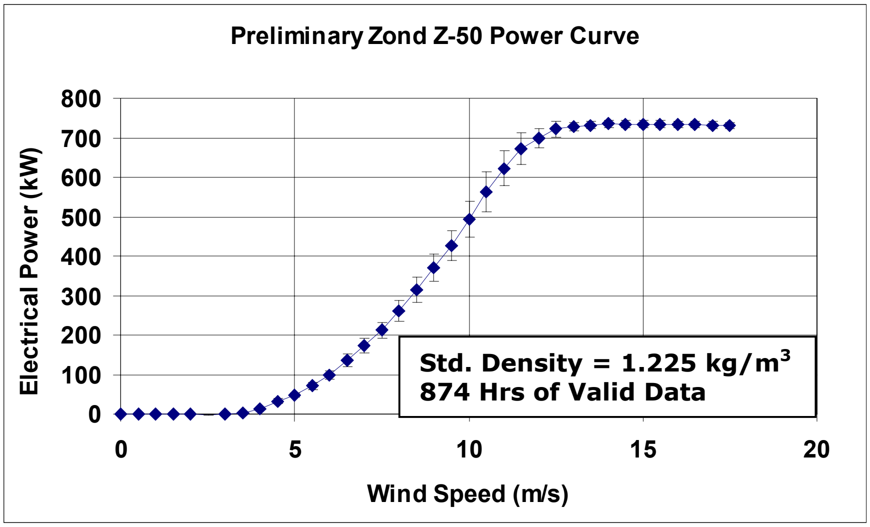


Figure 7. Preliminary results of power performance test in Algona, IA

The fourth test completed was the AOC 15/50 in Kotzebue, Alaska. The measured power curve, adjusted to sea-level density is shown in Figure 8. No error bars are shown for this power curve because we haven't yet completed the uncertainty analysis. It should be noted that both the Algona and the Kotzebue power curves are preliminary and subject to post-calibration of the test sensors. However, TVP does not anticipate that the results of either test will change significantly as a result of sensor post-calibration.

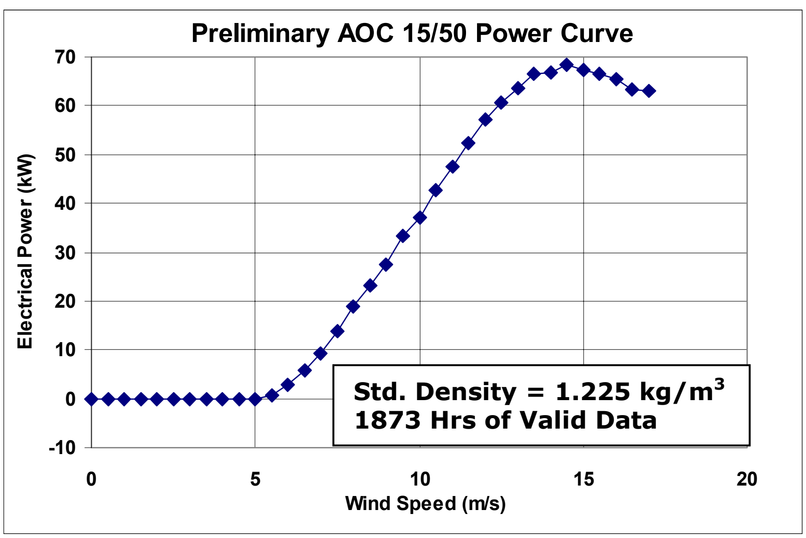


Figure 8. Preliminary results of power performance test in Kotzebue, AK

Lessons Learned

Following the IEC standard for measuring power performance was not particularly difficult for the TVP tests with a few exceptions. Through this exercise, we gained familiarity with the applicability of using the IEC standard with regard to various site conditions and turbine types. We also gained experience in using a variety of sensors and data acquisition systems for power performance testing in accordance with the IEC standard.

The first TVP power curve test was the most challenging because of complex terrain, icing conditions, lightning activity, and the remote location of the Searsburg site. GEC and MLI applied the IEC standard as closely as possible given the site aspects and logistics of third party testing. However, when the results were converted to a curve of C_p versus wind speed, they turned out to be too high to be believable. As shown in Figure 9, the C_p reaches a value of nearly 0.6 for electrical power. The Betz limit states that the aerodynamic efficiency of a wind turbine can not exceed 0.593, even for a hypothetical ideal rotor. The realistic limit for rotor efficiency is closer to 0.52, and additional losses in the drive train, generator, and controller are inevitable. Therefore, the highest realistic value that might be expected for an electrical C_p is approximately 0.47. Clearly, the results from the Searsburg test exceed that value for a reasonable C_p. Even the lower limits of the error bars of a few of the data points on the C_p graph exceed 0.47. GEC and MLI exhaustively examined the data from the Searsburg test and do not believe that there is any problem with the sensors, data acquisition system, or data processing techniques. We believe that the erroneous values result from problems in the site calibration procedure. Further study is required to determine the appropriateness of the site calibration procedure for use in extremely complex terrain.

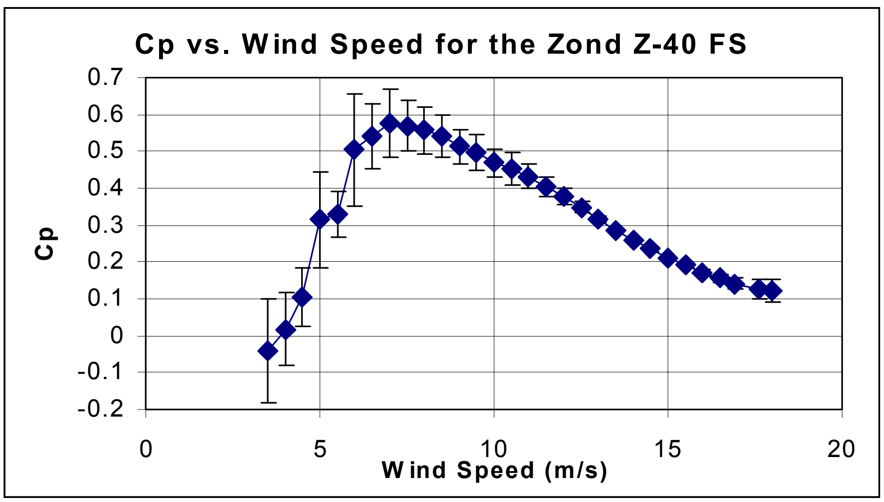


Figure 9. Cp vs. wind speed curve for Searsburg, VT

Another lesson we learned is that control of the turbine configuration during the test period is vital. Data collection in Glenmore had to be restarted twice because of changes to the turbine. After several months of data were collected and the test was nearly complete, Tacke added vortex generators to the blades in order to reduce edgewise oscillations. This clearly constituted a change in turbine configuration, and data collection had to be restarted. Shortly after the first change, Tacke re-pitched the blades on the test turbine and data collection had to begin yet again. While these changes to the turbine configuration extended the test period and increased the cost of the test, they also provided the opportunity to examine the effects of the vortex generators and blade pitch. Figure 10 shows a comparison of the Tacke power curves before and after the blade modifications, together with the warranted power curve for the turbine. While the curve measured before the blade modifications did not meet the full requirements of the IEC standard, the data clearly showed that the blade modifications resulted in a lower power output as a tradeoff for reduced blade oscillations.

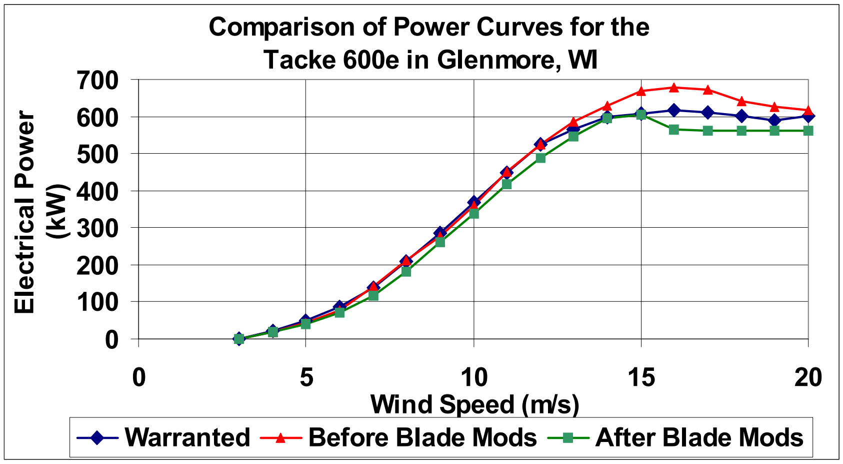


Figure 10. Comparison of two measured power curves to the warranted power curve for the Tacke 600e in Glenmore, WI

As part of the data analysis procedure, the IEC standard requires a calculation of annual energy production in which the measured power curve is applied to Rayleigh wind speed distributions for a variety of average wind speeds. The result of that calculation is shown in Figure 11 for the Glenmore, WI, test. The actual energy production is also shown for 1999, which had an average wind speed of 6.9 m/s. The actual 1999 production agrees well with the prediction for a Rayleigh site with an average wind speed of 7.0 m/s based on the measured power curve. The actual energy production is slightly lower than the predicted production, which is a gross energy value before considering losses for availability, turbulence, controls, etc.

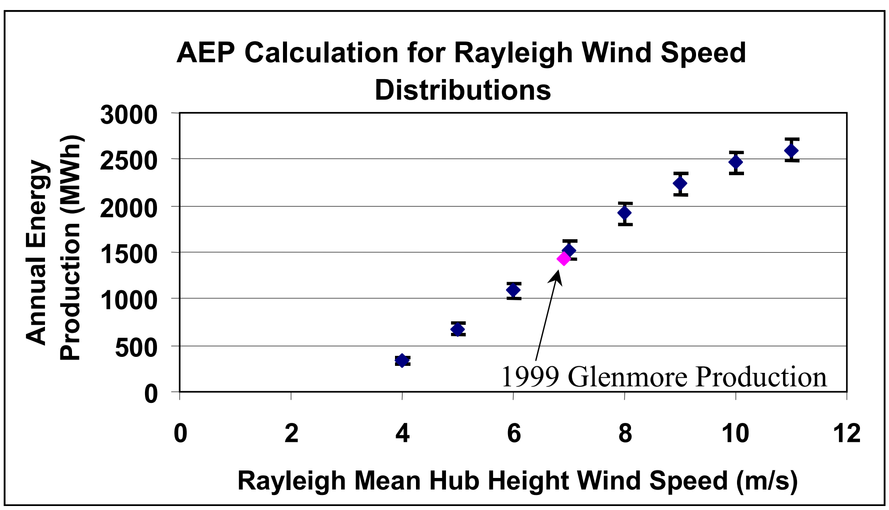


Figure 11. Annual energy production calculation for Glenmore, WI

An important step in processing data for the TVP power performance tests was examining a scatter plot of raw test data, shown in Figure 12 for the Z-50 in Algona, Iowa. The scatter plots were useful for identifying extreme outlying data points that could represent icing conditions or other anomalies that need to be discarded from the valid database. The raw data for the Z-50 was very tightly grouped compared to other turbines tested in the TVP. The data is particularly well-grouped above rated power where the Z-50's variable speed controller and PID pitch controller were able to control power output within precise tolerances. Even the standard deviation of the data points is very small above rated power for the Z-50, a stark contrast to the Z-40, which was found to have a great deal of data scatter above rated power.

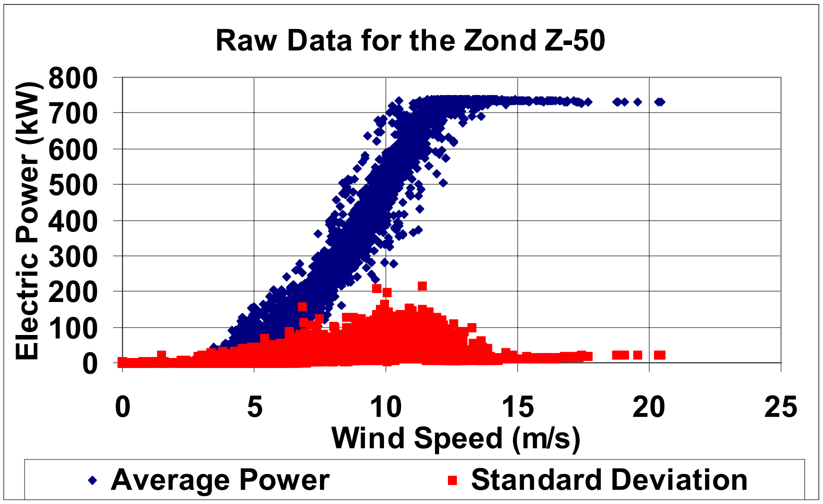


Figure 12. Scatter plot of raw data for the Z-50 in Algona, IA

While performing the uncertainty analysis, GEC calculated the contribution that each component of uncertainty adds to the total value in each wind speed bin. The results of this analysis for Algona are shown in Figure 13. Below rated power, the uncertainty in the wind speed measurement is by far the largest contributor to the total value of uncertainty. This could be improved by using an anemometer with higher accuracy and by having a better understanding of flow distortion between the met tower and the test turbine. The Algona site is very flat and easily met the requirements of the IEC standard without the need for a site calibration. However, site effects still led to a 4% uncertainty in the wind speed measurement. By comparison, sensor accuracy and calibration contributed 0.5% and 1.5% to the wind speed, respectively. Above rated power, the wind speed has relatively little effect on the total uncertainty because the power curve is very flat, thus reducing the sensitivity to uncertainty in wind speed measurement. The uncertainty above rated power is dominated by Category B (sensor accuracy) effects on the electrical power measurement.

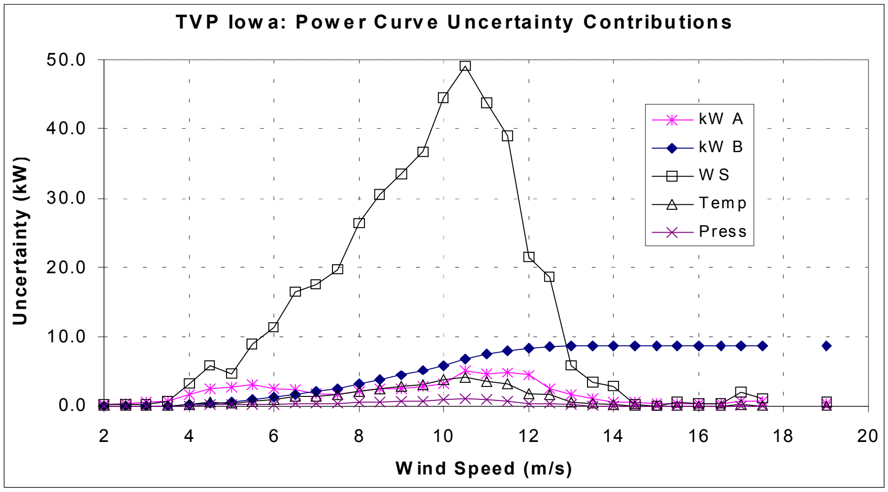


Figure 13. Contributions to uncertainty for the power performance test on a Z-50 in Algona, IA

One element of the IEC standard that is particularly vague and could be problematic is the requirement to remove data from the valid database when the test turbine is unavailable. In the absence of a strict definition of availability in the IEC standard, many test engineers opt to use an online indication for selection of valid data. However, there are many cases when a turbine is available but not online. As an example, the power curve for the AOC 15/50 in Kotzebue was calculated both with available data and with online data. There were many times when the wind was above the cut-in wind speed, in the range of 5-10 m/s, but the turbine was not online dbecause of cold-weather slow-starting considerations. Figure 14 shows a comparison of the available and online power curves, together with the warranted power curve for Kotzebue. The online power curve meets or exceeds the warranted power levels at most wind speeds. However, the available power curve falls below the warranted curve at wind speeds up to approximately 10 m/s due to the slow-start periods. If the definition of availability had not been agreed upon by all parties in advance of testing, this issue might have led to a dispute between the turbine manufacturer and owner.

Another aspect of the IEC standard that is unclear is the definition of turbine rated power. The manufacturer rates the AOC 15/50 as a 50-kW turbine. The TVP has chosen to consider it to be 66 kW based on its maximum sustained power level. This definition affects the range of wind speed bins that must be filled with valid test data. Both the manufacturer's rated power and the TVP rating are indicated for the AOC 15/50 in Figure 14.

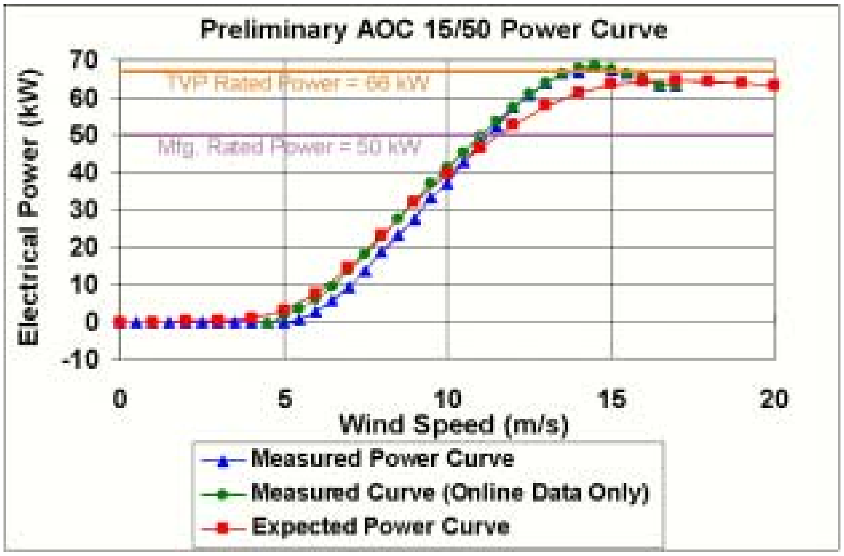


Figure 14. Comparison of online and available power curves for the AOC 15/50 in Kotzebue, AK

Conclusions and Recommendations

TVP has conducted power performance tests in accordance with the IEC 61400-12 standard on five different turbines to date and two more tests are anticipated within the next year. The following conclusions and recommendations can be made based on TVP's experience with power performance testing:

- Conducting power performance tests in accordance with the IEC standard is not an extremely difficult proposition and should not cost an inordinate amount of time and money as long as the planning process and testing is conducted thoroughly and diligently.
- Existing project SCADA systems can be utilized to obtain reasonably accurate power performance measurements with minimal effort and expense. SCADA systems may not strictly meet the IEC standard because they are not usually traceable, and because end-to-end calibrations can be difficult to perform in the field. However, with attention to detail, a good SCADA system can be suitable for power performance testing.
- Site wind speed calibration can be critical to obtaining an accurate power performance measurement. Details of the procedure used are important in obtaining useful results.
- The site calibration section of the IEC standard is difficult to apply in highly complex terrain and further study is needed to define useful methods in such sites.
- Wind speed is usually the biggest contributor to uncertainty in power performance testing. Considerable effort is justified to achieve the highest possible accuracy in wind speed measurement. Other factors that contribute to uncertainty, such as temperature and pressure measurements, are negligible compared to wind speed.
- Control of the turbine configuration during power performance testing is critical to achieving accurate results and keeping the test period and budget within reasonable limits.
- It is important to determine a detailed definition of turbine availability before power performance testing begins. This is particularly critical if the power performance measurement will be used for contractual purposes.

- For future revisions of the IEC standard, TVP recommends that the IEC remove the requirement for hub-height mounting of temperature and pressure sensors; clarify the intent and application of turbine availability measurements; clarify the requirement for end-to-end calibration of the data acquisition system; and clarify the site calibration procedure.

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