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Power Performance Testing Progress in the DOE/EPRI Turbine Verification Program

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

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Abstract

As part of the U.S. Department of Energy/Electric Power Research Institute (DOE-EPRI) Wind Turbine Verification Program (TVP), tests are conducted to characterize the power performance of individual wind turbines at each wind project. 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. Initial results and experiences of the testing were reported the WindPower 2000 conference [1].

This paper presents the status of the power performance testing and new results from the past year. New tests were performed on a 660 kW Vestas V47 and a 1.65 MW Vestas V66 at the Big Spring, Texas, TVP project. Some of the test turbines reported on in the previous paper were modified in the past year to improve their power performance. Updated information that compares and contrasts the turbine performance before and after the modifications are presented for the 750 kW Zond Z-50 turbine in Springview, Nebraska, and the 66 kW AOC 15/50 turbine in Kotzebue, Alaska.

Introduction and Background

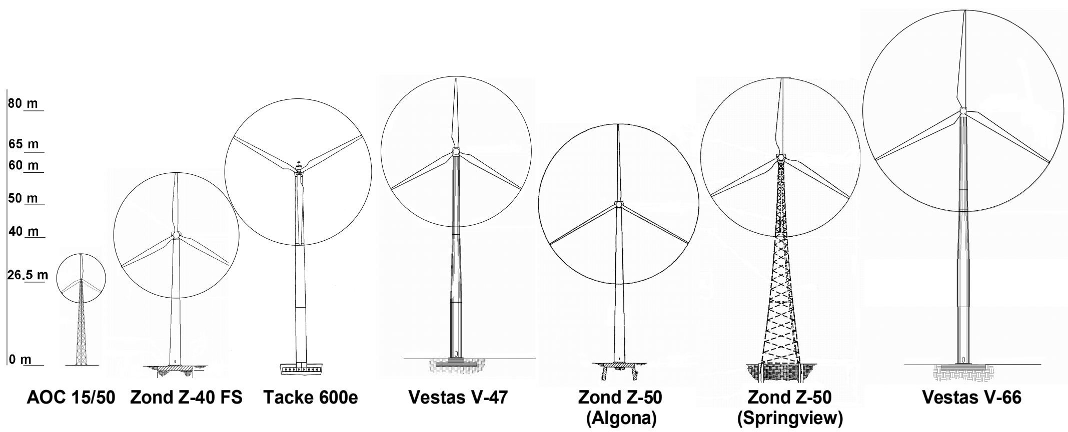
The TVP is a joint effort between DOE, EPRI, and several utilities to evaluate early production models of advanced wind turbines and to verify the performance, reliability, maintainability, and cost of new wind turbine designs and system components in a commercial utility environment. Global Energy Concepts (GEC) serves as the TVP support contractor to provide project management guidance, monitoring, and reporting. As part of this technical support, GEC has been collaborating with the National Renewable Energy Laboratory (NREL) to conduct third-party power performance tests at most of the TVP project sites in accordance with the International Electrotechnical Commission's (IEC) 61400-12 standard [2]. The IEC standard was chosen for these tests because certification agencies, operators, manufacturers, and trade associations are adopting it worldwide as the industry standard.

TVP conducts power performance tests on at least one turbine at each project for several reasons: to establish a baseline power curve for each turbine model under the unique operating conditions at the site;

to help the project operator verify that the measured turbine performance meets the manufacturer's specifications; to help the project operator develop operations and maintenance (O&M) tools for regularly monitoring and tracking changes in turbine power output over time; and to develop a better understanding of overall wind farm project performance. The tests also help the wind industry gain experience with exercising the IEC standard in commercial wind projects and evaluate the feasibility of using a commercial supervisory control and data acquisition system (SCADA), such as the Second Wind Advanced Distributed Monitoring System (ADMS), as a data acquisition system that satisfies the IEC power performance test requirements.

Status

Since the start of the TVP, power performance testing has been conducted on seven turbine types at six facilities. As shown in Figure 1, 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 V66 with a 66-m rotor diameter and an 80-m hub height.



	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

Results from five of these tests were presented at last year's conference; details of these tests are not repeated in this paper. A summary of the facilities and turbines tested during the past year is presented in Table 1.

TABLE 1. CURRENT STATUS OF TVP POWER PERFORMANCE TESTING ACTIVITIES

Project	Turbine (Hub Height)	Test Status	Test Dates	
			Start	Finish
Kotzebue, AK	66 kW AOC 15/50 (26-m)	Complete; retest conducted	Nov. 1, 1999	May 31, 2000
Springview, NE	750 kW Z-50 (65-m)	Complete; retest conducted	April 19, 2000	May 26, 2000
Big Spring, TX	660 kW V47 (65-m)	Complete; pending post-calibration	Feb. 10, 2001	Mar. 31, 2001
Big Spring, TX	1.65 MW V66 (80-m)	Complete; pending post-calibration	April 13, 2001	May 4, 2001

As noted in the table, testing at the 660 kW V47 and 1650 kW V66 turbines at Big Spring, Texas, began during the past year. Testing of both turbines has been completed and plans are being made to remove sensors for post-calibration. Additional data have been collected for the Zond Z-50 turbine at the Springview, Nebraska, facility and the Atlantic Orient Corporation (AOC) 15/50 turbine at the Kotezbue, Alaska, facility following modifications that were made to improve turbine power performance.

Approach

GEC and NREL have played an active role in planning the TVP power performance tests. They have worked with the project participants to reach agreement on the methodology and conduct of the tests, coordinated the equipment selection and installation process, and collected, analyzed, and reported on the test data. The equipment used for the recent tests is summarized in Table 2.

TABLE 2. POWER PERFORMANCE TEST EQUIPMENT

Equipment Type	Model
Anemometer	Max 40c
Vane	NRG 200P
Power Transducer	Second Wind Phaser
Temperature Sensor	RM Young 41342 VC
Pressure Sensor	Vaisala PTB101A
Data Acquisition System	Second Wind ADMS

In general, the test team attempted to follow the IEC standard as closely as possible in selecting the instrumentation, locating the meteorology tower, mounting the meteorology sensors, collecting test data and processing procedures, preparing the uncertainty analysis, and reporting the results. Exceptions to the standard were taken and noted when it was impossible or impractical to meet the standard due to business concerns, economic considerations, or other constraints.

The Second Wind ADMS was used as the data acquisition system for all tests. The ADMS was installed at each project to help site operators monitor and track turbine operation and to provide TVP with a common system for collecting and transmitting turbine performance data to a central location. No modifications were made to the SCADA software or hardware for the power performance testing, although power curve monitoring is a standard feature of the ADMS. Using the ADMS considerably reduced the time and expense of installing extra equipment at each site and gave TVP an opportunity to evaluate whether or not a commercial SCADA system could be used for accurate power curve testing that complied with the IEC standard.

Calibrated Max 40c cup anemometers were used for all tests because they are relatively inexpensive and rugged. While there are more accurate anemometers on the market, the Max 40c meets the requirements of the IEC standard, is relatively inexpensive, and is used extensively within the wind energy industry.

Second Wind Phaser® power transducers were used for all tests. The Phaser is a versatile transducer that has also been used by TVP to make power quality measurements at distributed wind projects, as reported by Green [3] and Randall [4]. Second Wind specifies the accuracy of the Phaser to be within 0.2% of full scale. Calibration testing is in process at NREL to verify that the Phaser meets the accuracy requirements of the IEC Standard.

A limitation of the existing IEC standard is that it states that all data collected while the test turbine is unavailable shall be discarded, but it does not provide clear guidance on how to determine when the turbine is available. In the absence of another definition, GEC used the TVP definition of availability, which considers all downtime regardless of cause. This definition is narrower than others used in the wind industry because it considers the turbine to be unavailable during periods of line outage and when the turbine is intentionally shut down due to site tours, testing, or other site activities. TVP availability does consider the turbine to be available if it is stopped due to a normal function of the controller; for instance, the turbine is available during cable untwist events and during high-wind shutdowns. Data from these events were included in the valid database.

Challenges Faced

As with several other TVP sites where power performance tests have been conducted, the Big Spring site did not meet the topographic requirements specified in the IEC standard at either test turbine, and site calibrations were not performed prior to the installation of the wind turbines. Digitized terrain and topographic maps of the area surrounding the V47 Turbine 26 are shown in Figure 2, indicating the complexity of the terrain. Because site calibrations were not performed, an exception was taken to the IEC standard for both Big Spring tests.

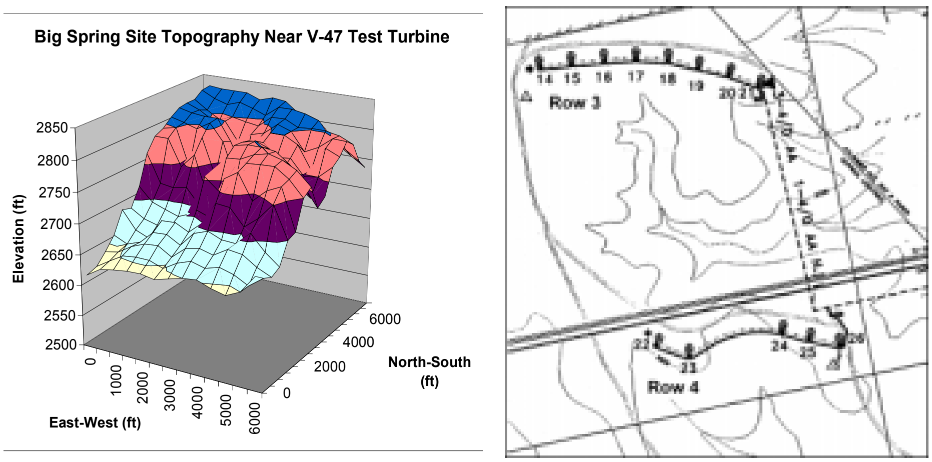


FIGURE 2. DIGITIZED TERRAIN MAP AND TOPOGRAPHIC MAP OF V47 TURBINE TEST SITE AT BIG SPRING, TEXAS

An additional problem identified at the Big Spring site was with the configuration of the meteorological tower. Federal Aviation Administration (FAA)-required warning beacons atop each meteorological tower prevented mounting the test anemometers as recommended by the IEC standard. These beacons are relatively large compared to their distance from the primary anemometers and may therefore disturb airflow to some extent. Although the beacons were considered as obstacles for determination of valid measurement sectors using the equations provided in the standard, these equations were apparently not specifically intended for small, close obstructions, but rather for larger, more distant obstructions, such as neighboring wind turbines, buildings, etc. It is unclear whether or not it is reasonable to treat the beacons in the same manner as these other types of obstacles. In addition, because of the FAA beacons and the lengthy rows of turbines, the measurement sectors considered valid were relatively small. For the V66 test turbine, the valid measurement sector was only 96 degrees wide. Fortunately, the tests were conducted during periods of good winds, so the small measurement sectors did not substantially hinder the collection of sufficient quantities of data.

There were also problems with the reliability of the wind vanes at the Big Spring site during both the V47 and V66 test periods. During the V47 test, the hub height vane at the nearby meteorological tower was malfunctioning and did not provide usable data. An exception to the standard was taken by using a secondary vane 15 m below hub height. To help minimize the impact associated with use of a lower vane, the range of valid wind directions was reduced by 5 degrees on each end to help ensure that the wind direction at hub height was within the valid direction sector. During the V66 test, both the primary and secondary vanes on the nearby meteorological tower were malfunctioning. Wind direction data from one of the other meteorological towers at the site were used instead. Because the valid direction sector was so small for the V66, it was not reduced further as was done for the V47. Data from the nearby tower were compared to the other towers once the sensors were repaired, and additional data will be collected in the coming months using the correct vanes to verify the uniformity of wind directions across the site.

Test Results

Big Spring, Texas V47 Test

Power performance testing of the Vestas V47 Turbine 26 at the Big Spring site was conducted between February 10 and March 31, 2001. The measured power curve is presented in Figure 3. It was determined by applying the method of bins for normalized site air density data, using the IEC data normalization procedure for a turbine with active power control. The turbine appears to perform according to the manufacturer’s specifications, starting power production near 4 m/s and controlling power at the rated power level of 660 kW at about 15 m/s.

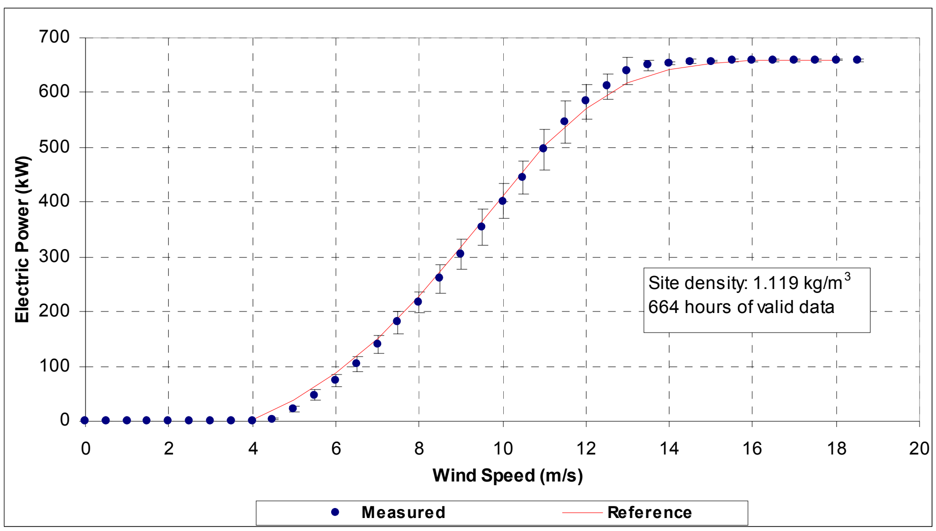


FIGURE 3. RESULTS OF POWER PERFORMANCE TEST OF VESTAS V47 AT BIG SPRING, TEXAS

As part of the data analysis procedure, the IEC standard requires an estimation of annual energy production (AEP) by applying the measured power curve to Rayleigh wind speed distributions for annual average wind speeds ranging from 4 to 11 m/s. Figure 4 shows AEP estimates for the V47 tests, including error bars that represent the measurement uncertainty. Actual AEP for the V47 turbine (adjusted to 100% availability) is also plotted for a 12-month period that had an average wind speed of 8.2 m/s. The actual AEP agrees well with the estimated AEP based on the measured power curve.

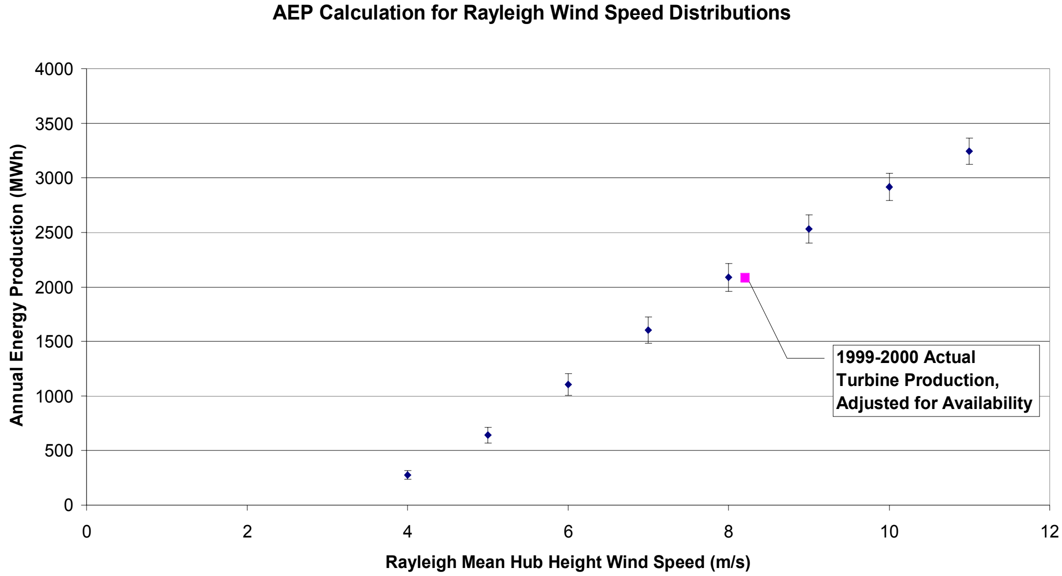


FIGURE 4. ESTIMATED ANNUAL ENERGY PRODUCTION FOR VESTAS V47 TEST TURBINE AT BIG SPRING, TEXAS

Big Spring, Texas, V66 Test

Power performance testing of the Vestas V66 Turbine B at the Big Spring site was conducted between April 13 and May 4, 2001. Electrical storms at the site on May 4 damaged data collection and communication equipment, but sufficient data had been collected to satisfy the IEC standard. The measured power curve, normalized to the site air density, is presented in Figure 5. The turbine appears to perform according to the manufacturer's specifications, meeting the cut-in wind speed of 4 m/s and regulating power at the rated power level of 1650 kW at about 15 m/s.

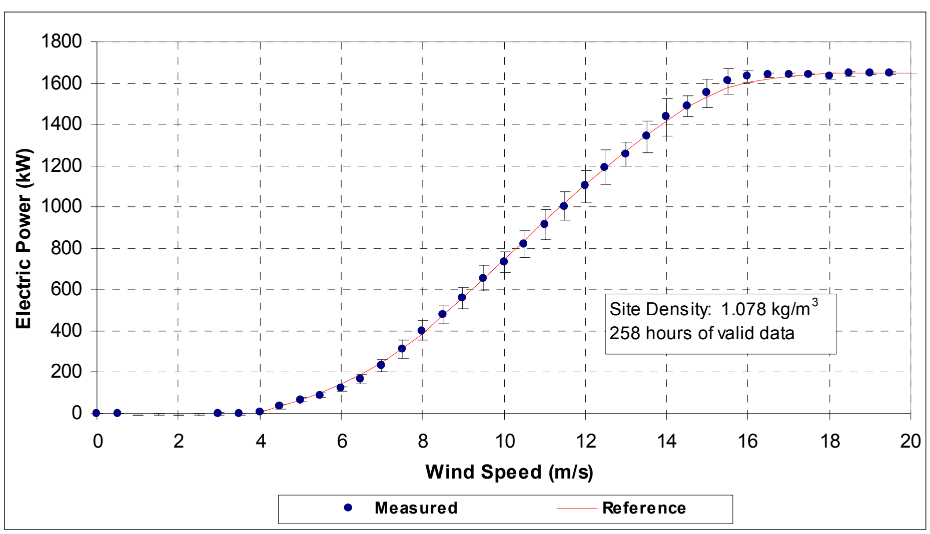


FIGURE 5. RESULTS OF POWER PERFORMANCE TEST OF VESTAS V66 AT BIG SPRING, TEXAS

Springview, Nebraska, Update

Initial testing of the Zond Z-50 Turbine 1 in Springview, Nebraska, was conducted between April 19 and May 25, 2000. The test results indicated that the turbine did not perform according to the manufacturer's specifications—the turbine regulated power output at 744.8 kW (approximately 1% below nominal rated power) and the body of the measured power curve was 10% to 20% below the manufacturer's reference power curve.

To improve turbine performance, the blade pitch set point was adjusted by 1 degree and the software configuration on the turbine was changed during the summer of 2000. Additional test data were collected from October–November 2000 as part of ongoing TVP monitoring to quantify the effects of the turbine modifications. Figure 6 presents the reference and measured power curves before and after the modifications. As shown, the power levels measured after the turbine modifications remain below the reference curve over the range of operating wind speeds. Some improvement in power production is seen around 11-13 m/s. TVP will work with the project operator and manufacturer to determine whether or not further turbine modifications are necessary.

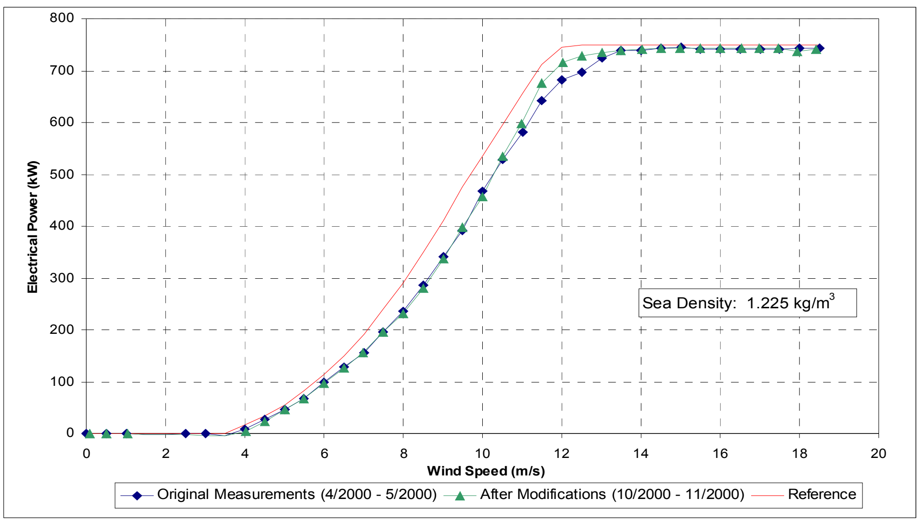


FIGURE 6. RESULTS OF POWER PERFORMANCE TESTS OF ZOND Z-50 AT SPRINGVIEW, NE

Kotzebue, Alaska, Update

Initial testing of the AOC 15/50 Turbine 8 in Kotzebue, Alaska, was conducted between Nov. 1, 1999, and May 31, 2000. The test results indicated that the turbine did not perform according to the manufacturer's specifications—the maximum 10-minute average power output of the turbine exceeded the 66 kW rated power by about 10 kW. The turbine was re-pitched from 1.15 degrees to -0.60 degrees to reduce the maximum power output. Additional test data were collected from January– April 2001 as part of ongoing TVP monitoring and a new power curve was generated to quantify the effects of re-pitching the blades. Figure 7 presents the power curves generated before and after blade re-pitching. As shown, the pitch change reduced the maximum power output within the expected range.

The test turbine still appears to exhibit slow starts that were apparent during the initial test. In some cases, the turbine remains off-line at wind speeds in excess of 7 m/s. These slow-start events lower the measured power curve from cut-in wind speed up to 10 m/s. Similar slow-start behavior is seen with other AOC 15/50 turbines at the Kotzebue site. TVP will continue to investigate this issue further with the project operator and manufacturer.

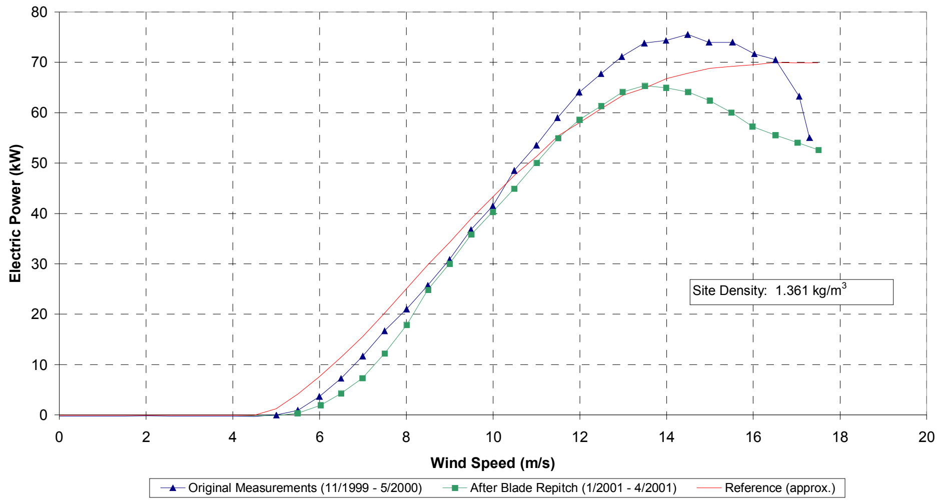


FIGURE 7. RESULTS OF POWER PERFORMANCE TEST OF AOC 15/50 AT KOTZEBUE, AK

Lessons Learned

Over the past year, TVP has refined its knowledge of the IEC standard and provided additional experience in its application on different turbine types at a variety of sites. The following items of interest were noted during the power performance tests conducted by TVP this year.

Terrain Effects

As noted in other TVP power performance tests, one of the major sources of uncertainty is in the estimation of wind speeds at the turbine. Although the V47 and V66 test sites failed to meet the topography requirements of the IEC standard, no site calibrations were performed. The standard allows two methods for site calibration: an experimental test site calibration or a test site analysis using a three-dimensional flow model validated for the site terrain. Both methods were impractical for the Big Spring test. Since the turbines were placed into commercial operation before the tests were planned, it was unrealistic to install temporary meteorological towers on the turbine foundations and stop turbine production to collect the required meteorological data. In addition, there are no validated wind flow models for the complex terrain at Big Spring. Consequently, an exception was taken to the standard by assuming that the wind speeds measured at the meteorological tower were the same as those at the turbine despite the complex terrain.

In an attempt to quantify the effects that the complex terrain may have on the power curve measurements, the data for the V47 test were segregated by wind direction into 30-degree sectors. Power curves and AEP estimates were performed for each sector to determine if the turbine appeared to over- or under-perform when the winds were from certain directions, which could indicate that terrain effects influenced wind speed measurements from those directions. Power curves and AEP estimates for each sector are presented in Figure 8 and Table 3, respectively. The results do not show a significant difference in the power curves or estimated AEP between the wind direction sectors. Overall, the complex terrain does not appear have a large effect on the wind speeds at the test turbine, and using the default 3% uncertainty value provided in the standard appears to be reasonable.

TABLE 3. COMPARISON OF V47 AEP ESTIMATES FOR 30-DEGREE WIND DIRECTION SECTORS

Wind Direction	AEP-Extrapolated (from extrapolated power curve) (MWh/yr)	Deviation from Average AEP (%)
63-90 degrees	2,227	1.6
90-120 degrees	2,204	0.5
120-150 degrees	2,156	-1.7
150-180 degrees	2,176	-0.7
180-208 degrees	2,196	0.2
Average	2,192	

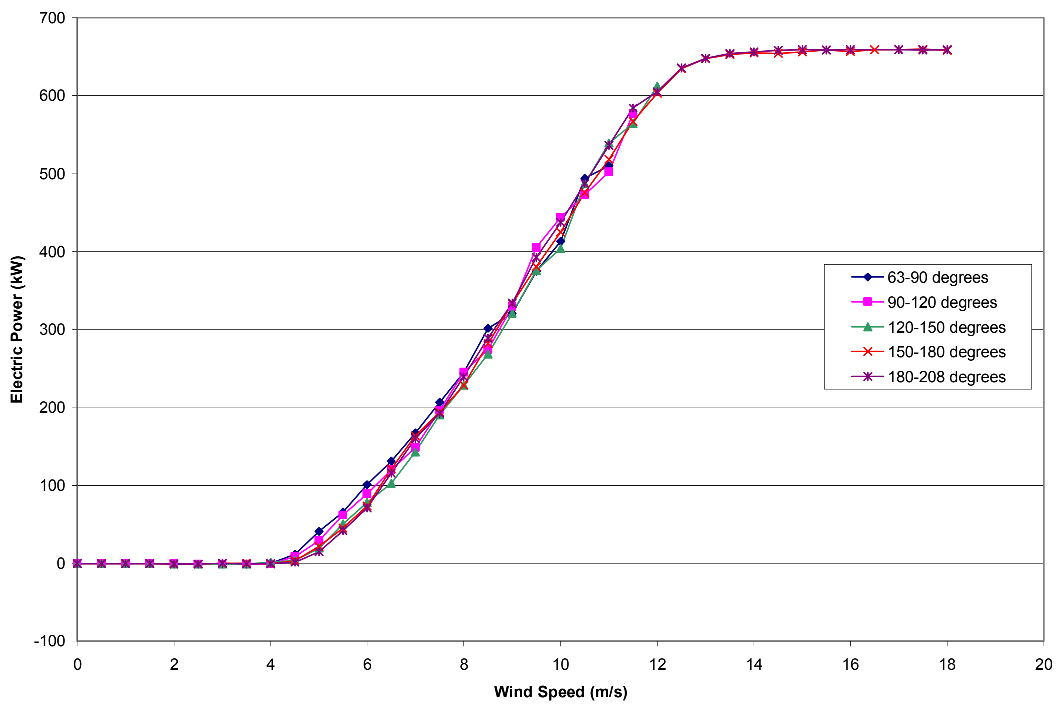


FIGURE 8. COMPARISON OF V47 POWER CURVES FOR 30-DEGREE WIND DIRECTION SECTORS

Turbine Power Measurements

According to the IEC standard, a calibrated reliable power transducer is required to measure power output from the turbines. Power measurement devices used by the turbine controllers typically do not meet the accuracy or calibration requirements of the IEC standard. As a result, Phaser power transducers were used to measure power on all recent TVP power performance tests.

During the V47 power curve test, power measurements were recorded from both the Phaser and the Vestas turbine controller through the SCADA. A comparison of these measurements is presented in Figure 9. The two measurements are essentially identical, with an average difference of less than 1 kW at rated power, and a slope of the regression line that varies from unity by less than 0.05%. This variation is well within the estimated uncertainty on the Phaser measurements, based on the manufacturer's specifications, and the small observed differences may be a result of slight differences in measurement times or averaging intervals. Similar results were seen when comparing the V66 turbine power measurements to the Phaser measurements.

These results are particularly important to the project operator in developing a valuable O&M tool. The project operator now has added confidence in using turbine controller data recorded by the SCADA for accurately monitoring and tracking changes in turbine and wind farm power output over time without needing to install additional equipment.

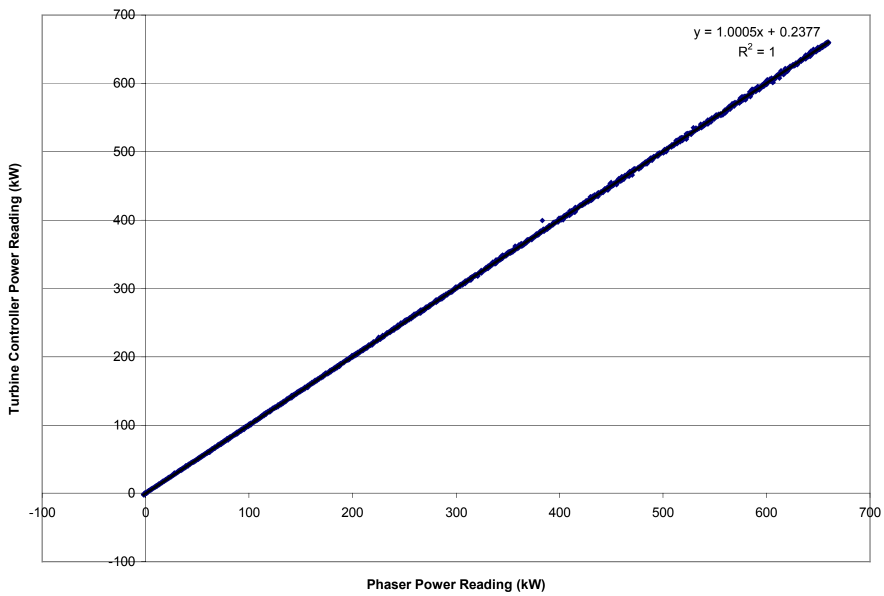


FIGURE 9. COMPARISON OF PHASER POWER TRANSDUCER AND VESTAS V47 TURBINE CONTROLLER POWER MEASUREMENTS

Availability Determination

One of the difficulties with the V66 test was determining when the turbine was available. As specified in the test plan, the status code recorded by the SCADA was the primary mechanism used to determine availability. However, the status code designed for the Big Spring turbines was a 10-minute "average" status; e.g., if a turbine was on-line for 6 minutes and faulted for 4, the status was recorded as available for the entire 10-minute period.

While this status code was adequate for the V47 test, because the turbine infrequently faulted, it was problematic for the V66 test, because the turbine often faulted, particularly at high wind speeds. Since many of these faults were "soft" faults, they automatically reset within a few minutes. As a result, there were many 10-minute data records in which the status code indicated the V66 was producing power, but the turbine was actually unavailable for some of the data record. Filtering out these data records while determining the measured power curve was time-consuming and required manual effort. For future power performance tests, it would be preferable to automate this process by recording a cumulative availability record that counts the amount of time in each 10-minute period that the turbine is available.

One aspect of the V47 test that proved easier than expected was removal of data for icing. Because the Vestas controller records faults when the nacelle anemometer or vane is iced, all data collected during icing events were removed based on the SCADA status code.

Power Coefficients

The IEC standard recommends the calculation of the power coefficient (C_p) for the test turbine and presenting the results as a function of wind speed. In addition to indicating measured turbine efficiency, the C_p graph is also a useful data analysis tool to check data quality and understand different operating characteristics of the turbine that may not be apparent in the power curve. As an example, the measured C_p curve for the V66 turbine is shown in Figure 10, and C_p reaches a peak of 43% at 8 m/s. The C_p curve has an abrupt change in slope near 5 m/s and the test engineers questioned whether this was a problem with data quality or a real characteristic of the machine. Initial study showed that the change was caused by the turbine switching from the small 300 kW generator, which operates at low wind speeds, to the large 1650 kW generator. Further analysis confirmed this by comparing the C_p curve from the performance test with two C_p curves generated from two earlier periods: one period when the turbine was believed to be operating well and another period where the large generator was not operational. The power performance test curve is nearly identical to that from the earlier period when the turbine was operating properly. During the period when the small generator was not in use, the C_p curve is smoother.

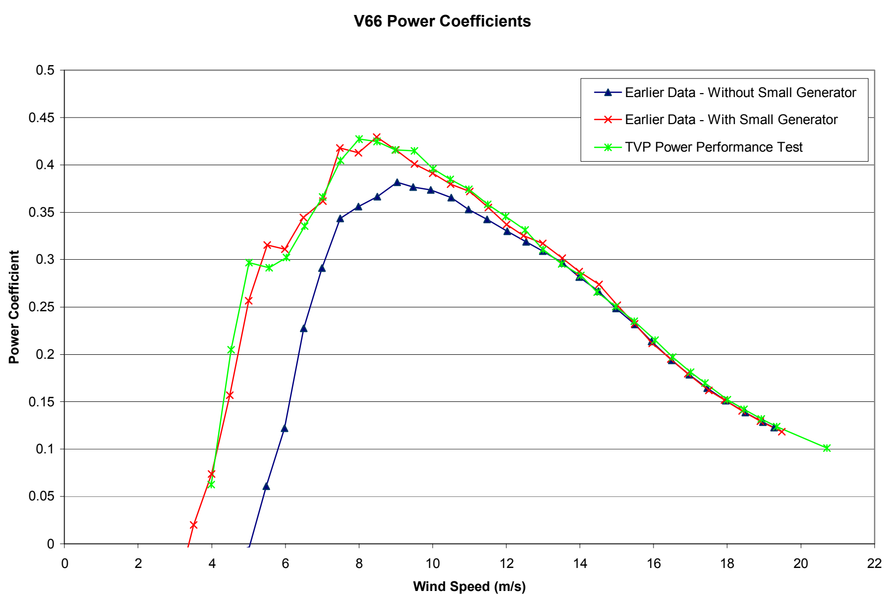


FIGURE 10. COMPARISON OF V66 C_P CURVES WITH AND WITHOUT SMALL GENERATOR

Conclusions and Recommendations

TVP has completed power performance tests on seven turbine types at six facilities in accordance with the IEC 61400-12 standard. The following conclusions and recommendations can be made based on TVP's experience with power performance testing.

- The IEC power performance standard is generally easy to follow for tests on commercial wind projects as long as the planning and testing process is conducted thoroughly and diligently. However, strict compliance with the standard may not always be possible. The standard could be improved by providing more guidance on handling issues that prevent exact implementation of the procedures.

- Commercial SCADA systems can be used as data acquisition systems for IEC power performance tests with minimal effort and expense. This capability must be designed into the SCADA system and the required SCADA data must be identified and considered carefully while preparing the test plan. If possible, turbine availability should be recorded by the SCADA as cumulative time during 10-minute periods.
- Site wind speed calibration can be critical in obtaining an accurate power performance measurement. If a site calibration cannot be performed as specified in the standard, terrain effects on the power curve measurements should be closely examined using data collected from different wind direction sectors.
- The experimental site calibration section of the standard is difficult to apply in complex terrain and impractical for operating commercial wind projects. The use of a mathematical model as an acceptable alternative to an experimental calibration is also difficult to apply in complex terrain because the standard requires model validation for the relevant type of terrain. The standard could be improved by providing more guidance on practical site calibration methods for complex terrain.

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