DOE AWARD # DE-FG36-06GO86105

PRIME ENERGY CORPORATION

FINAL REPORT

POWERJET WIND TURBINE

Integration of a Generator with an Electronic Controller and Mechanical Controls
to Optimize the Production of Electricity from Wind Power

30 November 2008

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EXECUTIVE SUMMARY

PROJECT OBJECTIVE

The PowerJet wind turbine overcomes problems characteristic of the small wind turbines that are on the market today by providing reliable output at a wide range of wind speeds, durability, silent operation at all wind speeds, and bird-safe operation. Prime Energy's objective for this project was to design and integrate a generator with an electrical controller and mechanical controls to maximize the generation of electricity by its wind turbine.

The scope of this project was to design, construct and test a mechanical back plate to control rotational speed in high winds, and an electronic controller to maximize power output and to assist the base plate in controlling rotational speed in high winds. The test model will continue to operate beyond the time frame of the project, with the ultimate goal of manufacturing and marketing the PowerJet worldwide.

Increased Understanding of Electronic & Mechanical Controls Integrated With Electricity Generator

The PowerJet back plate begins to open as wind speed exceeds 13.5 mps. The pressure inside the turbine and the turbine rotational speed are held constant. Once the back plate has fully opened at approximately 29 mps, the controller begins pulsing back to the generator to limit the rotational speed of the turbine. At a wind speed in excess of 29 mps, the controller shorts the generator and brings the turbine to a complete stop. As the wind speed subsides, the controller releases the turbine and it resumes producing electricity. Data collection and instrumentation problems prevented identification of the exact speeds at which these events occur. However, the turbine, controller and generator survived winds in excess of 36 mps, confirming that the two over-speed controls accomplished their purpose.

Technical Effectiveness & Economic Feasibility

Maximum Electrical Output

The output of electricity is maximized by the integration of an electronic controller and mechanical over-speed controls designed and tested during the course of this project. The output exceeds that of the PowerJet's 3-bladed counterparts (see Appendix).

Durability

All components of the PowerJet turbine assembly—including the electronic and mechanical controls designed, manufactured and field tested during the course of this project—proved to be durable through severe weather conditions, with constant operation and no interruption in energy production.

Low Cost

Materials for the turbine, generator, tower, charge controllers and ancillary parts are available at reasonable prices. Fabrication of these parts is also readily available worldwide. The cost of assembling and installing the turbine is reduced because it has fewer parts and requires less labor to manufacture and assemble, making it competitively priced compared with turbines of similar output manufactured in the U.S. and Europe.

The electronic controller is the unique part to be included in the turbine package. The controllers can be manufactured in reasonably-sized production runs to keep the cost below \$250 each. The data logger and 24 sensors are for research only and will be unnecessary for the commercial product.

Benefit To Public

The PowerJet wind-electric system is designed for distributed wind generation in 3 and 4 class winds. This wind turbine meets DOE's requirements for a quiet, durable, bird-safe turbine that eventually can be deployed as a grid-connected generator in urban and suburban settings.

Results

As described more fully below and illustrated in the Appendices, the goals and objectives outlined in 2060 SOPO were fully met.

Electronic and mechanical controls were successfully designed, manufactured and integrated with the generator. The turbine, tower, controllers and generators operated without incident throughout the test period, surviving severe winter and summer weather conditions such as extreme temperatures, ice and sustained high winds. The electronic controls were contained in weather-proof electrical boxes and the electrical wires were fully contained inside the control arm, which prevented water damage to the electrical system during heavy rains. The wind conditions exceeded the Class 2 average for the test site, and there were episodes of high winds, including 3 10-minute periods of winds that exceeded 35 mps (80 mph). Electricity generation was constant throughout.

There were no technology transfer activities during the project period, and there are no patents or property certifications pending as a result of this project.

Field testing and data collection are continuing.

Figure 1: 0.91-m PowerJet & Meteorological Tower in Field Test

PROJECT ACTIVITIES

The scope of work consisted of 4 primary tasks:

- Task 1.0 Development of Over-Speed Controls**
- Task 2.0 Integration of Turbine, Generator, & Over-Speed Controls**
- Task 3.0 Testing**
- Task 4.0 Project Management & Reporting**

TASK 1 – DEVELOPMENT OF OVER-SPEED CONTROLS

Task Objective (2006 SOPO)

“While the turbine exhibits properties of self-limiting speeds relative to wind speed, the turbine may need electrical or mechanical means of limiting peak speed, and to stop the turbine for maintenance. This test will be conducted with a 1-meter diameter rotor cage (without a generator) in a wind tunnel. The rotor assembly will be instrumented to measure wind velocity and rotor speed (rpm’s) to determine the relationship between velocity and speed. A data logger will be used to record the data. The assembly will be operated in a wind tunnel to obtain the data. Our subcontractor will analyze the results at their offices. The aerodynamics of the rotor will be tested at high speeds to determine the need for over-speed controls. Once the problem is clearly identified, alternative mechanical and/or aerodynamic control mechanisms will be designed and tested. The mounting bracket, yaw bearing assembly, and slip ring assemblies to transmit power and electronic controls through the yaw bearing will be designed and tested.”

Task Activities

The aerodynamic feature of the wind turbine indicated that at some high wind speed, the rotational speed of the turbine would stop increasing as the wind speed increases. Testing was conducted in a wind tunnel to determine at what speed that occurs, and whether the speed is low enough to be controlled dynamically through the electrical controller or if a mechanical device would be necessary.

Approaches Used

Initially, we had arranged to use a truck-mounted fully instrumented wind turbine and to run the truck either on a rented airport runway or on the Black Rock Playa. Both of these alternatives were quashed. The airport runway was too short to hold speeds long enough to do the testing. The Playa use-approval requirements were too onerous to be practical.

As an alternative, we arranged to use Colorado State University’s high-speed wind tunnel to test the PowerJet at speeds in excess of 80 mph (35 mps.)

Problems Encountered

When the PowerJet entered the wind tunnel, the University limited the turbine to 20 mps. As a result, we could not determine whether the turbine's rotational speed would reach a maximum before it spun in excess of the generator's rpm limit. The data up to 20 mps indicated a linear relationship up to 20 mps—each 1 percent increase in wind speed produced a 1 percent increase in rotational speed. In the end we could not determine the wind speed that results in the turbine achieving a constant rotational speed relative to high wind speeds. However, it did not appear that the rotor would self-regulate at a reasonable wind speed.

Departure from Planned Methodology and Assessment of Impact on the Project Results

Due to lack of reliable wind tunnel results, a dynamic breaking function was integrated into the electrical controller. When the turbine's rpm reaches a critical level, the controller increases the load on the generator through the use of a diversion resistive load. If the rpm's continue to increase, the controller shorts out the generator, causing the turbine to come to a complete stop. As a secondary brake, Prime Energy designed a back plate that begins opening at a prescribed wind speed. As the wind speed increases the back plate opens, reducing the air pressure inside the turbine rotor cage, thereby reducing the air flow across the blades and slowing the turbine's rotational speed. Once fully open, the rotational speed of the turbine is controlled exclusively by the electronic brake, described above. This phase of testing was inconclusive because there were not sufficient high wind events (> 15 to 20 m/s) during this testing phase to evaluate the turbine's ability to properly shut down during high wind events.

Summary

The aerodynamics of a 1-meter rotor (without generator) was tested in a wind tunnel at high wind speeds to determine the need for over-speed controls. Following testing, two mechanisms were designed: (1) a dynamic breaking function built into the electrical controller; and (2) a back plate that begins opening at a prescribed wind speed.

The Task 1 objective was met.

TASK 2 – INTEGRATION OF TURBINE, GENERATOR, & OVER-SPEED CONTROLS

Task Objective

2006 SOPO

“In Task 2, all of the components of the wind-electric generator will be assembled into a performing wind-electric generator. This task will involve several iterative steps to design the component placement to provide a mechanically efficient and coordinated turbine, and prepare it for testing. Once assembled, the wind-electric turbine will be tested in a wind tunnel up to a wind speed of 35 mph. The turbine will then be modified or changed as appropriate. The final turbine will be prepared for field testing.”

Task Activities

Approaches Used

The turbine was assembled with ease. The wiring initially included connection to two 12-volt batteries, and later changed to one 12-volt battery. The completed assembly was mounted on a dynamic balancing machine and spun to 1,000 rpm's. The generator was balanced by its manufacturer prior to installation. The turbine cage with the blades, front and back rings, and back plate were fabricated from materials with constant density. The balancing machine was fabricated from a digital truck-wheel balancing machine. The final integrated turbine was in balance and did not require any supplemental weights.

A meteorological tower was installed in accordance with the IEC standards for testing. The instruments were installed at hub-height to the turbine and 10 meters horizontally from the turbine and upwind of the prevailing wind. Data loggers were installed on both the turbine and the met tower.

As tested in this project, the turbine has an outside diameter of 0.91 meters—the maximum size possible in the wind tunnel used to perform design testing. As shown in Figure 1 (page 3), the controller and data logger are contained in the small electrical box at the base of the PowerJet tower. The large box contains the battery charge controller and a resistive bank. The batteries are in the cabinet on the ground. The hub height is 10 meters and the turbine is in a downwind configuration relative to the tower. The anemometer on the adjoining tower is at hub height to the PowerJet.

The over-speed controls begin at about 13.5 mps when the back plate begins to open. As the back plate opens, it relieves air pressure in the turbine and reduces the flow of air over the airfoils, resulting in a constant rotational speed. The back door fully opens at wind speeds of 29 mps, and the controller begins to regulate rotational speed by pulsing back to the generator. At approximately 36 mps the controller shorts the generator, bringing the turbine to a complete stop.

Problems Encountered

The original contractor could not meet deadlines, so a new contractor was retained to build the controller. We also expanded the contract to include more over-speed control features. At one point the controller shorted out due to an accident that occurred while trying to coordinate the data loggers. Prime Energy had to send the controller back to the factory to diagnose and repair the damage. This resulted in further delay, loss of data, and unexpected cost.

Departure from Planned Methodology and Assessment of Impact on the Project Results

The basic methodology for this task did not change.

Summary

The turbine cage was easily integrated with the generator, and assembly took place without incident. The wiring from the generator was contained inside the control arm, through the yaw bearing, down the tower and into the power controller. Batteries were installed as planned.

Prime Energy installed an opening back plate that was minimally designed with a spring-loaded shaft so that at approximately 15 mps the plate would begin to open and thereby reduce the aerodynamic lift on the

blades. It worked in conjunction with the controller to limit the maximum rotational speed of the generator. This design was not expected to be a permanent feature, but would later need to be refined for manufacturing. The action of deceleration and acceleration eventually worked the securing nuts loose, causing the back plate to fly off. This was solved by placing a pin through the nut and shaft.

The Task 2 objective was met.

TASK 3 – TESTING

Task Objective

2006 SOPO

“Field testing will occur over a 6-month period at a site with variable wind and climactic conditions. The turbine will be instrumented and attached to data loggers for monitoring and performance analysis. All testing will be carried out following either the IEC 62400-12 standard or the AWEA/UL standard (if available at the time of testing).

“The 0.91-meter PowerJet assembly will be instrumented and operated for up to 6 months next to a hub-height meteorological tower that will record wind speed and direction, air temperature, barometric pressure, precipitation, and time. The instruments on the turbine tower will record the turbine’s rotational speed, power output, battery performance, and twenty-four variables recorded about the performance of the controller. The testing will allow the controller to optimize the speed of the turbine to achieve the optimum tip speed ratio. The controller was designed to control the rotational speed of the turbine to achieve a set tip speed ratio at all wind speeds to maximize electrical power output. It is also programmable so that we could experiment with different settings to optimize the integrated turbine-controller / over-speed controls.”

Task Activities

Approaches Used

Test Site Selection

The field testing site was selected and approved by the DOE project team. The US EPA issued a NEPA Determination of No Significant Impact on 27 June 2007, contingent on obtaining the appropriate Washoe County building permits.

Field Testing

Field testing took place over a 6-month period, during which time the tower and turbine assembly survived severe winter and summer climactic conditions without damage or interruption of power production. Data logging instruments were to record performance at all levels of wind speed. The intermediate data was to be used to change the programmable settings in the controller to eventually optimize the turbine assembly, and to develop final specifications for the manufacture of the controller, with fewer programmable elements.

Each visit to the site included a survey of the site for bird kills. No birds were found. The site is inhabited by several species of birds and seasonally by water fowl. When the turbine is spinning at any speed, the turbine cage appears to be a solid object. The gap between the blades is narrow enough that at even slow speed, the blades appear to be connected and the gap disappears, making it easily visible to birds in flight.

Problems Encountered

Zoning & Building Code Requirements

Local zoning code requirements resulted in higher costs than expected for installation of the turbine tower. The zoning and building departments required that a local, licensed engineer be retained to review and professionally stamp the tower-manufacturer's recommended design and installation instructions. The engineer recommended several changes to the manufacturer's specifications, the most significant of which was the use of reinforcing steel and nearly doubling the amount of concrete for the base and guy-wire anchors—8 cubic yards vs. the 4.5 cubic yards required by the manufacturer. The PowerJet also weighed about 10 lbs less (160 lbs including the control arm and yaw bearing assemble) than the 175-lb turbine the tower was designed to support (not including the yaw mechanism.) Permitting was a significant problem and delayed the project by nearly 4 months. The cost of installation and permitting increased project costs considerably.

Data Collection

Data collection from the data logging instruments was problematic and never fully resolved. Two data loggers were to be synchronized to the same internal clock. However, repeated attempts to electronically connect the two failed. This failure resulted in loss of a significant amount of data, and significant time to correlate the two data sets. As a result, intermediate analysis of the data to adjust the programmable controller never occurred.

Climactic Conditions

The average annual wind speed at the site is Class 2. In winter, when most of the testing was done, the wind speed was often in excess of 10 mps. Wind events often produced peak wind speeds in excess of 35 mps (80 mph), which is well above the level of optimal power production. In 3 10-minute periods, winds averaged 35 mps. Moderate wind speeds in the range of 5 mps to 10 mps were rare while the data loggers were functioning. As a result we could not obtain sufficient data to adjust each of the 24 programmable variables in the controller to optimize the power output.

In winter, the site is prone to long periods of sub-zero weather coupled with still air. The controller constantly drew power from the batteries, which periodically caused the batteries to be drained of power and freeze. Batteries were not charged due to insufficient wind. Two batteries were lost to these conditions.

Departure from Planned Methodology and Assessment of Impact on the Project

There was no change in basic methodology for this task.

Summary

The turbine and tower assembly survived several wind events of greater than 35 mps, sub-zero temperatures, snow build-up and icing conditions without damage to the turbine or tower. The assembly also experienced temperatures above 100 degrees and wind-driven rains without damage or interruption of power production. Having the electrical wires fully contained inside the control arm and tower prevented any damage to the electrical system. The controller and charge controllers were contained in weather-proof electrical boxes.

Data was collected according to the IEC guidelines. However, the problems with data loggers prevented collection of enough data to fully achieve the objectives for this task.

The Task 3 objective for durability and constant energy production through high winds was met.

TASK 4 – PROJECT MANAGEMENT

Budget Summary

The amount of the DOE award was \$309,375 with DOE contributing \$247,500 and Prime Energy contributing \$61,875. Total expenditures, however, were \$360,331, exceeding the award by \$50,956. DOE reimbursements totaled \$247,500—100% of its contribution to the project. Prime Energy absorbed the overage. Quarterly Reports were submitted as required by the terms of the award. Any further requirements extending beyond the project period will be met.

APPENDIX

Appendix A: 0.91-m PowerJet Specifications

0.91-Meter PowerJet

PowerJet Test Turbine Configuration & Operational Data	
General Configuration	
Make, Model	Prime Energy, PowerJet
Rational Axis (H/V)	Horizontal
Orientation (Upwind/Downwind)	Downwind
Number of Blades	16
Rotor Diameter (m)	0.91
Hub Height as Tested (m)	10
Operation	
Rated Electrical Power (W)	360 (projected)
Rated Wind Speed (m/s)	13.4 (30.0 mph)
Cut-in Wind Speed (m/s)	2.25 (5.0 mph)
Cut-out Wind Speed (m/s)	29 (65.0 mph)
Rotor	
Swept Area (m ²)	0.72
Direction of Rotation	Counter-clockwise

Appendix B: Estimated Annual Energy Output for the 0.91-m PowerJet

Average Annual Wind Speed 5.8 m/s

Wind Speed Bin (m/s)	Instantaneous Power (W)	Rayleigh Frequency Distribution	Hours / Year	Annual Energy Production (Wh/yr)
0.5 - 1.5	0.00	0.064	565	-
1.5 - 2.5	0.03	0.105	916	31.3
2.5 - 3.5	0.14	0.135	1186	166.7
3.5 - 4.5	0.64	0.147	1287	824.2
4.5 - 5.5	3.34	0.141	1234	4,116.8
5.5 - 6.5	8.59	0.122	1070	9,189.8
6.5 - 7.5	20.11	0.097	851	17,117.4
7.5 - 8.5	34.05	0.071	625	21,292.9
8.5 - 9.5	48.84	0.049	426	20,819.4
9.5 - 10.5	61.89	0.031	271	16,747.1
10.5 - 11.5	78.46	0.018	160	12,576.9
11.5 - 12.5	100.90	0.010	89	8,959.1
12.5 - 13.5	133.42	0.005	46	6,143.4
13.5 - 14.5	158.98	0.003	22	3,557.6
14.5 - 15.5	225.84	0.001	10	2,303.7
15.5 - 16.5	226.54	0.000	4	988.6
16.5 - 17.5	0.00	0.000	2	-
17.5 - 18.5	0.00	0.000	1	-
18.5 - 19.5	0.00	0.000	0	-
19.5 - 20.5	0.00	0.000	0	-
>20.5	0.00	0.000	0	-

Annual Energy Output (W/yr)

124,834.9

Appendix C: 0.91-m PowerJet Performance Curve