Technical Report

October 2002 • NREL/TP-500-32879

Controls Advanced Research Turbine (CART) Commissioning and Baseline Data Collection

Fingersh, L.J. and Johnson, K.

National Renewable Energy Laboratory

1617 Cole Boulevard
Golden, Colorado 80401-3393

NREL is a U.S. Department of Energy Laboratory
Operated by Midwest Research Institute • Battelle • Bechtel

Contract No. DE-AC36-99-GO10337

October 2002 • NREL/TP-500-32879

Controls Advanced Research Turbine (CART) Commissioning and Baseline Data Collection

Fingersh, L.J. and Johnson, K.

Prepared under Task No. WER2.1410

National Renewable Energy Laboratory

1617 Cole Boulevard
Golden, Colorado 80401-3393

NREL is a U.S. Department of Energy Laboratory
Operated by Midwest Research Institute • Battelle • Bechtel

Contract No. DE-AC36-99-GO10337

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: reports@adonis.osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

Contents

Figures

Tables

Introduction

The Controls Advanced Research Turbine (CART) began as a Westinghouse WTG-600 wind turbine installed at Kahuku Point on the island of Oahu, Hawaii (Figure 1). The turbine was operated commercially for about 10 years.

Figure 1 - Kahuku Point, Oahu, Hawaii

In 1996 two such turbines and their spare parts were removed from the wind farm and shipped to the National Wind Technology Center in Golden, Colorado. One was erected as the Advanced Research Turbine (ART) and used in an experiment called Long-term Inflow Structural Test (LIST). This machine was, except for some new instrumentation, essentially in its original configuration (Figure 2).

Figure 2 - ART, LIST turbine

The second turbine became the CART. This machine was significantly modified to be a state-of-the-art test bed for controls research (Figure 3).

Figure 3 - Controls Advanced Research Turbine (CART)

System Description

The turbine, especially the pitch system, was extensively modified to make it suitable for controls testing. The original hydraulically actuated pitch system (Figure 4) was replaced with a high-speed electromechanical pitch system (Figure 5). The electromechanical system consists of a servo drive electronics box that drives a three-phase permanent magnet servo motor. This motor is connected to a gearbox that in turn drives the blade through a pinion and bull gear system. This new system enables high bandwidth independent pitch control of the blades.

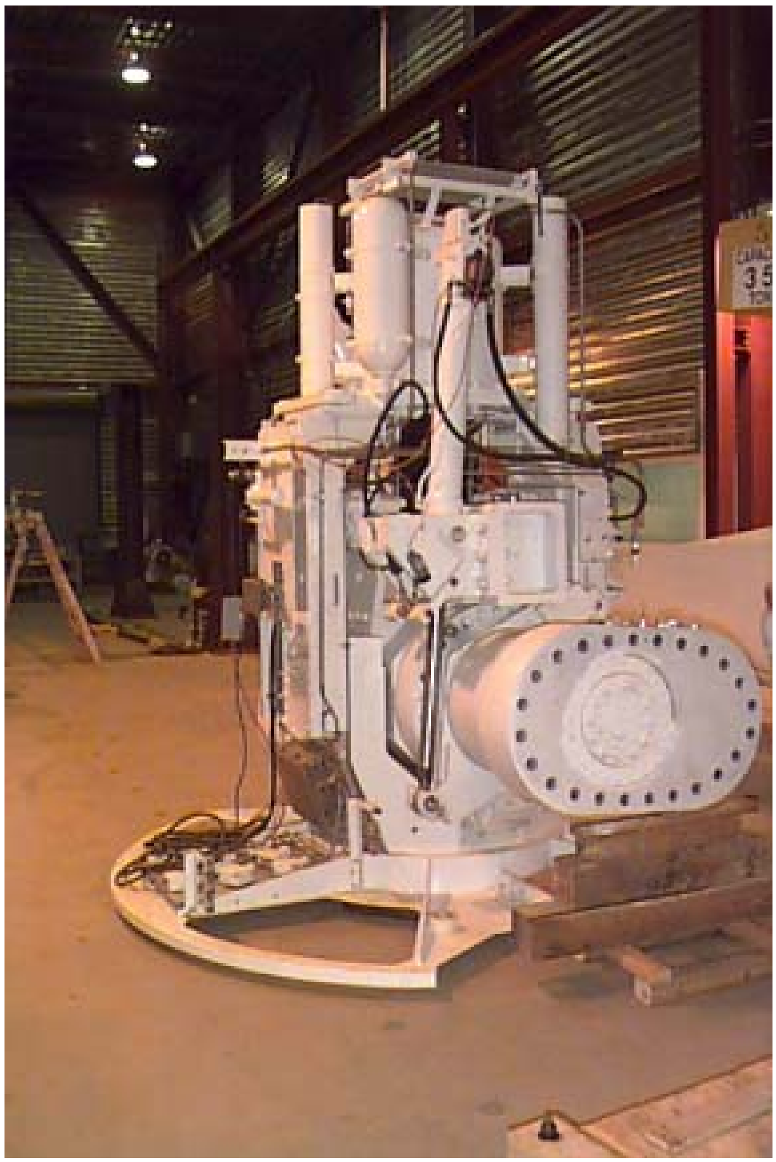

Figure 4 - ART hub with original hydraulic pitch system

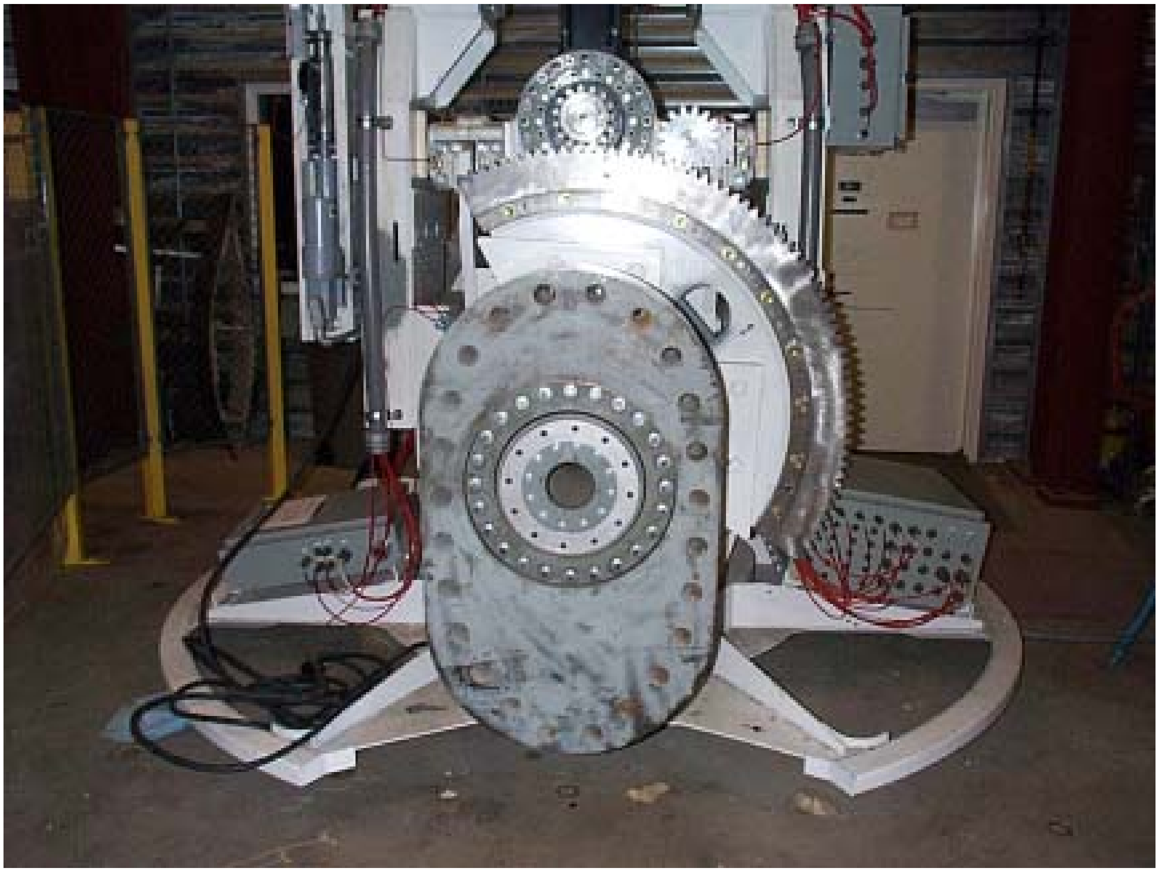

Figure 5 - CART hub with new electromechanical pitch system

A completely new generation system was also added to the CART. The original system consisted of a synchronous 4160 VAC generator directly connected to the grid by an auto synchronizer (Figure 6). This generator (white cylindrical object on the left) was connected to the gearbox through a fluid coupling (silver disk shaped object in the center). This coupling was necessary to provide slip and damping to the stiff, un-damped system. The new generator is a squirrel-cage induction generator directly connected to the gearbox (Figure 7). It is connected to the grid through full processing power electronics that can directly control generator torque (Figure 8). The power electronics also have a special feature consisting of a group of contactors that are linked to the controller. The contactors make up a bypass system that can short out the power electronics system. Essentially, this enables the generator to be directly connected to the grid as though the power electronics were not available. The power electronics system makes it possible to control the turbine in either full variable-speed mode or, by activating the bypass system, as a constant-speed machine.

Figure 6 – Original synchronous generator and fluid coupling

Figure 7 – New CART induction generator being installed

Figure 8 – Power electronics and bypass system for controlling induction generator

A completely new control system was also designed and constructed for the CART. This system has a personal computer (Figure 9) that enables nearly complete flexibility in the type of control that can be implemented. All the data and control systems are connected to the computer through a series of interface systems. Software is written in ANSI C and has nearly unlimited capabilities. Because this software has access to all the data channels and controllable components of the turbine, a nearly infinite combination of control systems can be developed. The control loop runs at 100 Hz which enables the controller to control the turbine with a high bandwidth.

Figure 9 – Operation screen for new control system

A wide variety of custom instrumentation was also added to the CART. It was designed to allow a high degree of flexibility in the type of control algorithm that can be implemented. Most of the sensors are designed to measure properties in one of three categories: Performance (torque and power sensors), loads (strain gauges, accelerometers and position sensors) or meteorological (wind speed, direction, temperature and pressure). A summary of CART capabilities is in Table 1 and a data acquisition and control summary is in Table 2. Note that the turbine control outputs are channels 79 and higher.

Pitch system maximum speed	19° per second
Generation system electrical power	650 kW
Maximum rotor torque	162 kNm at 41.7 RPM
Maximum rotor speed	58 RPM
Yaw rate	0.5° per second
Control system cycle time	10 ms
Data acquisition rate	100 Hz

Table 1 – CART capabilities

Chan #	Name	Chan #	Name
1	Teeter Brake Pressure	46	Tower Bending E/W
2	Pitch System Digital Outputs	47	Tower Bending N/S
3	Blade 1 Analog Output 1	48	Tower Bending E/W Poisson
4	Teeter Angle	49	Tower Bending N/S Poisson
5	Blade 1 Analog Output 2	50	Windspeed 58.2 m
6	Blade 1 Pitch	51	Wind Direction 58.2 m
7	Blade 2 Analog Output 1	52	Temperature 58.2 m
8	Blade 2 Pitch	53	Windspeed 36.6 m
9	Blade 2 Analog Output 2	54	Wind Direction 36.6 m
10	Teeter Brake Limit Switch	55	Windspeed 15.0 m
11	LSS Torque	56	Wind Direction 15.0 m
12	Blade 1 Edge Bending	57	Windspeed 3.0 m
13	Blade 1 Flap Bending	58	Temperature 3.0 m
14	Blade 2 Edge Bending	59	Sonic U 36.6 m
15	Blade 2 Flap Bending	60	Sonic V 36.6 m
16	Gear Box Oil Temperature	61	Sonic W 36.6 m
17	HSS Position	62	Barometric Pressure
18	HSS Prox Sensor	63	GPS Year
19	Yaw Position	64	GPS Month
20	HSS Torque	65	GPS Day
21	LSS Position	66	GPS Hour
22	Yaw Brake Pressure	67	GPS Minute
23	Nacelle Digital Outputs	68	GPS Second
24	X Accelerometer Port	69	GPS Tenths of Milliseconds
25	Y Accelerometer Port	70	GPS Validity
26	Z Accelerometer Port	71	HSS RPM
27	X Accelerometer Starboard	72	Yaw Rate
28	Y Accelerometer Starboard	73	LSS RPM
29	Z Accelerometer Starboard	74	Air Density
30	Nacelle Windspeed	75	HSS Power
31	Nacelle Wind Direction	76	LSS Power
32	IMU - Roll	77	LSS RPM Rate of Change
33	IMU - Pitch	78	HSS RPM Rate of Change
34	IMU - Yaw	79	Blade 1 Pitch Rate
35	IMU - X	80	Blade 2 Pitch Rate
36	IMU - Y	81	Torque Demand
37	IMU - Z	82	Torque Command
38	Generator Power	83	Digital Outputs 1
39	PE Digital Outputs	84	Digital Outputs 2
40	Generator Current	85	Normal Stop Bits 1
41	Generator Frequency	86	Normal Stop Bits 2
42	Generator Voltage	87	Emergency Stop Bits 1
43	PE Power	88	Emergency Stop Bits 2
44	PE kVA	89	Warning Bits 1
45	PE Power Factor	90	Warning Bits 2

Table 2 – CART data and control channel list

Commissioning

Commissioning a new turbine and control system is a long and difficult process. Hardware must be installed and checked out, instruments calibrated, sensors and control outputs checked, and software written and validated.

Because this is not just a large turbine that must be controlled and protected but also a test bed, this process becomes even more complex. With many instruments and many possible control paradigms a near infinite combination of failures can occur. Therefore, the protection system must be intelligent and flexible.

The protection system is written almost entirely in software to enable the use of more sophisticated protection and detection algorithms. However, software is difficult, if not impossible, to fully validate.

Several strategies have been employed to mitigate this effect.

One of the most important strategies is to test and debug any new control algorithm with a simulator before allowing it to control the machine. A simple wind turbine simulator was written into the control code on the machine. Using this simulator, the control code can be exercised with simulated inputs before it is allowed to operate the machine.

Simulations are inherently inaccurate because they always produce only a subset of possible field conditions. As a result, simulations of the control code can identify only certain types of errors. Ultimately, the code must be tested on the machine. Because this process can damage the machine, an operator must closely monitor the algorithm's performance to ensure the system performs properly.

To facilitate this close monitoring, real-time displays of data are available to the operator (Figure 9). Data are continuously streamed to disk and can be quickly analyzed in Matlab® using functions and scripts specifically developed by the CART team for this experiment. In this way, control changes can be quickly tested and difficulties eliminated.

Before data collection could be collected in bulk, the controller had to function properly. Because this turbine can be operated in both constant and variable-speed modes, two controllers had to be tuned.

A known difficulty of a constant-speed wind turbine is the method of starting the machine and connecting the generator to the grid: soft start, hard start, wind start, etc. For this test a wind start was used and the generator connected to the grid after synchronous speed was reached. Two examples of this type of start are shown in Figure 10. The trace labeled "Hard Start" is an early example wherein the pitch system failed to appropriately damp oscillations in torque after generator connection was initiated at approximately one second on the plot. The trace labeled "Good Start" is a later example in which this problem was corrected. This is an example of the type of control problem that must be solved during the commissioning of a new machine and control system. Others are when to start and stop, how to perform a high-wind shut down, how to perform an emergency stop and how to control power in high winds. These problems have been solved in the CART's control system.

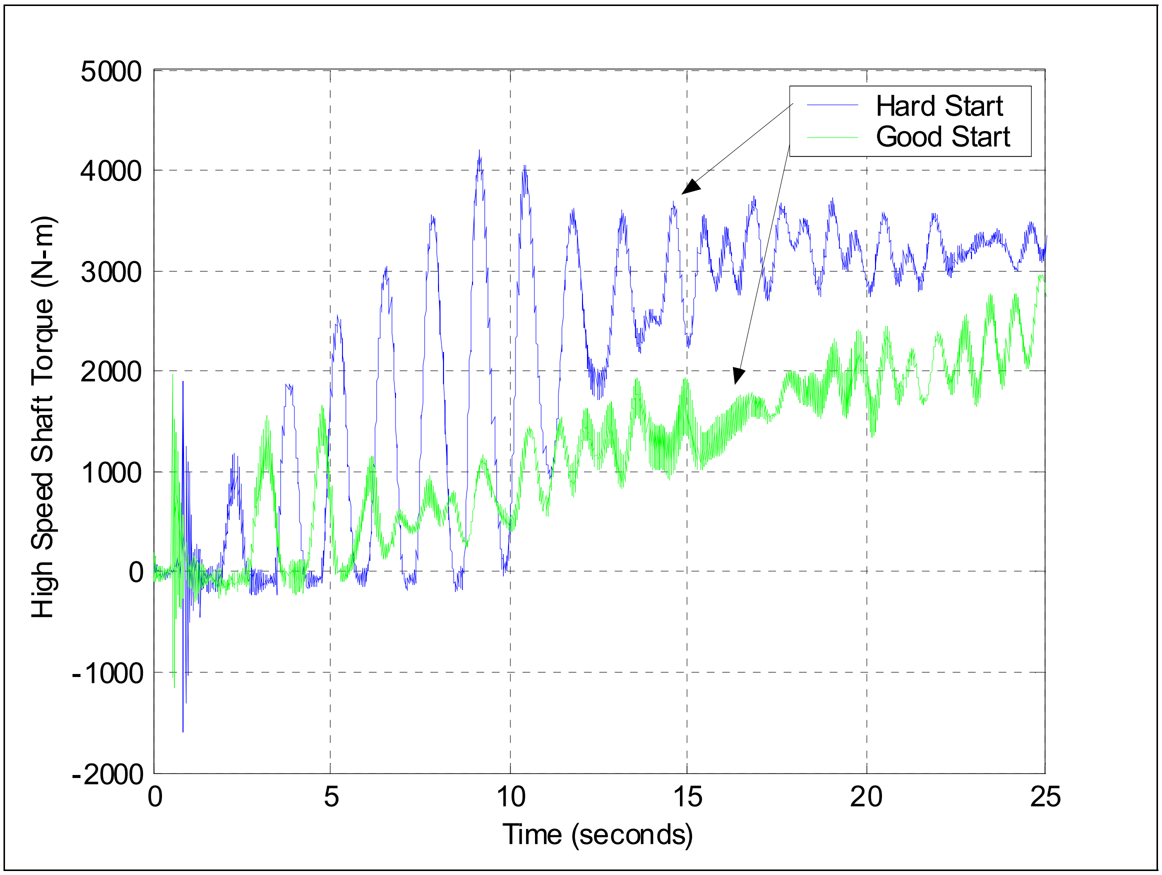

Figure 10 – Two constant-speed starting examples

When the wind reaches a certain value, called the rated wind speed, the generator can no longer absorb any additional rotor power that additional wind would provide. The method of controlling this power is critical to the turbine designer. When this machine is in the constant-speed mode, power is controlled by collectively pitching the blades to feather in response to the output of a PID (proportional, integral, derivative) controller. Figure 11 and Figure 12 are examples of two controllers used during constant-speed testing. The newer controller does not allow the large excursions above 600 kW that the earlier controller permitted. This is another example of the continuous improvement that is necessary during the commissioning process.

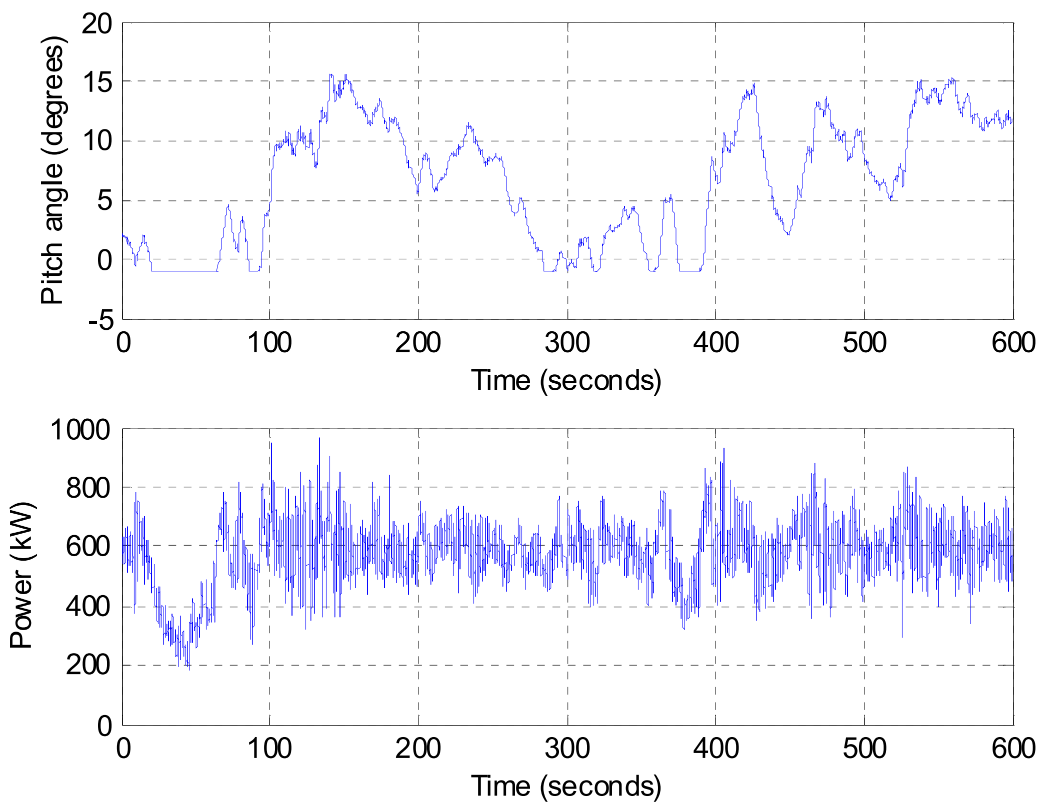

Figure 11 – An early constant-speed power controller

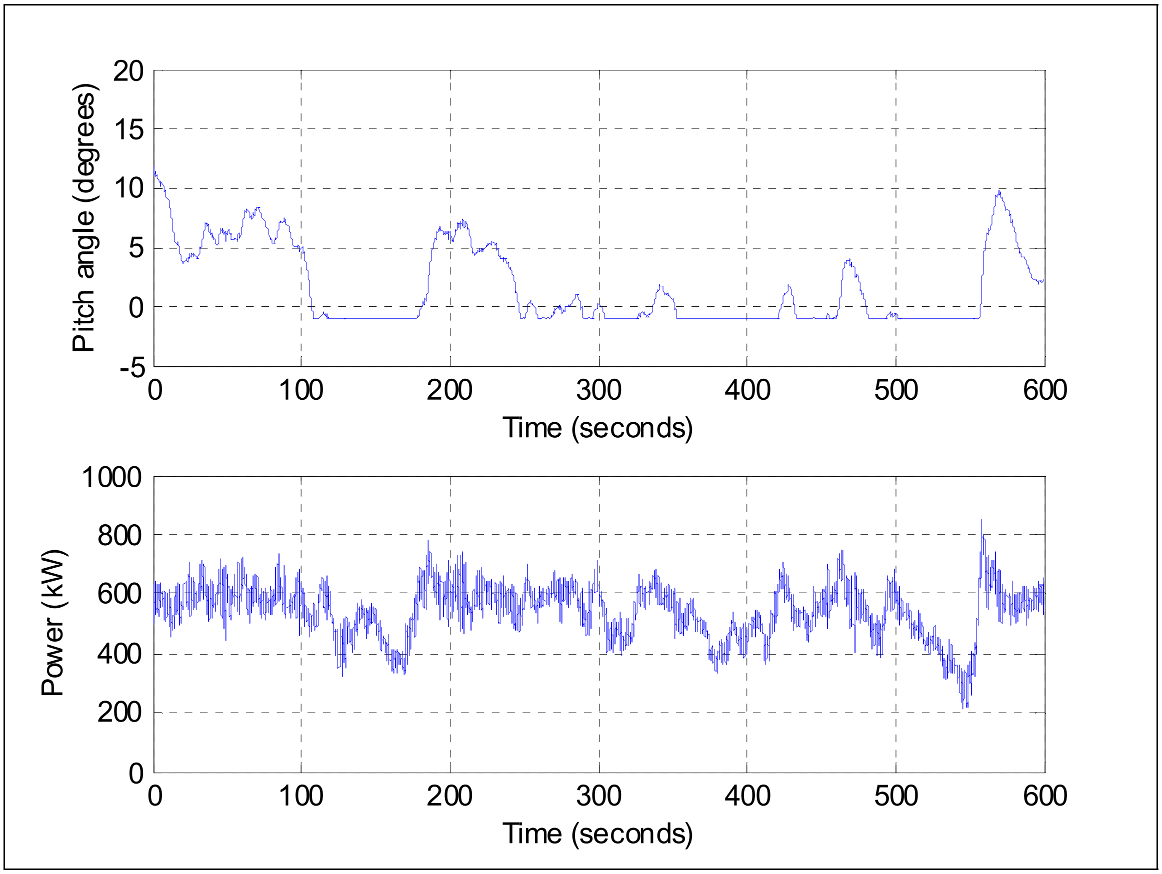

Figure 12 – An improved constant-speed power controller

When the turbine is operated in variable-speed mode, placing the turbine on line is not a problem because torque can be controlled via the power electronics. This enables the control system to transition smoothly from not operating to operating with none of the discontinuities associated with closing a contactor (an issue with constant-speed mode).

Although pitch angle control is still used, the turbine (when it is operating at or near rated power) is controlled differently in variable rather than constant-speed mode. Because generator power cannot be independently controlled in constant-speed mode, pitch is used to control aerodynamic power and hence generator power. In variable-speed mode, generator power can be precisely controlled. This is done by sending a command to the power converter for the torque required at rated power. Since torque times speed is power and speed can be separately controlled by the pitch system, a request for torque is essentially a request for power. Figure 13 is an example of this type of control. Note how well power is controlled in this mode in comparison to the control in Figure 12. Additionally, the figure shows that rotor speed is also being tightly controlled at the same time.

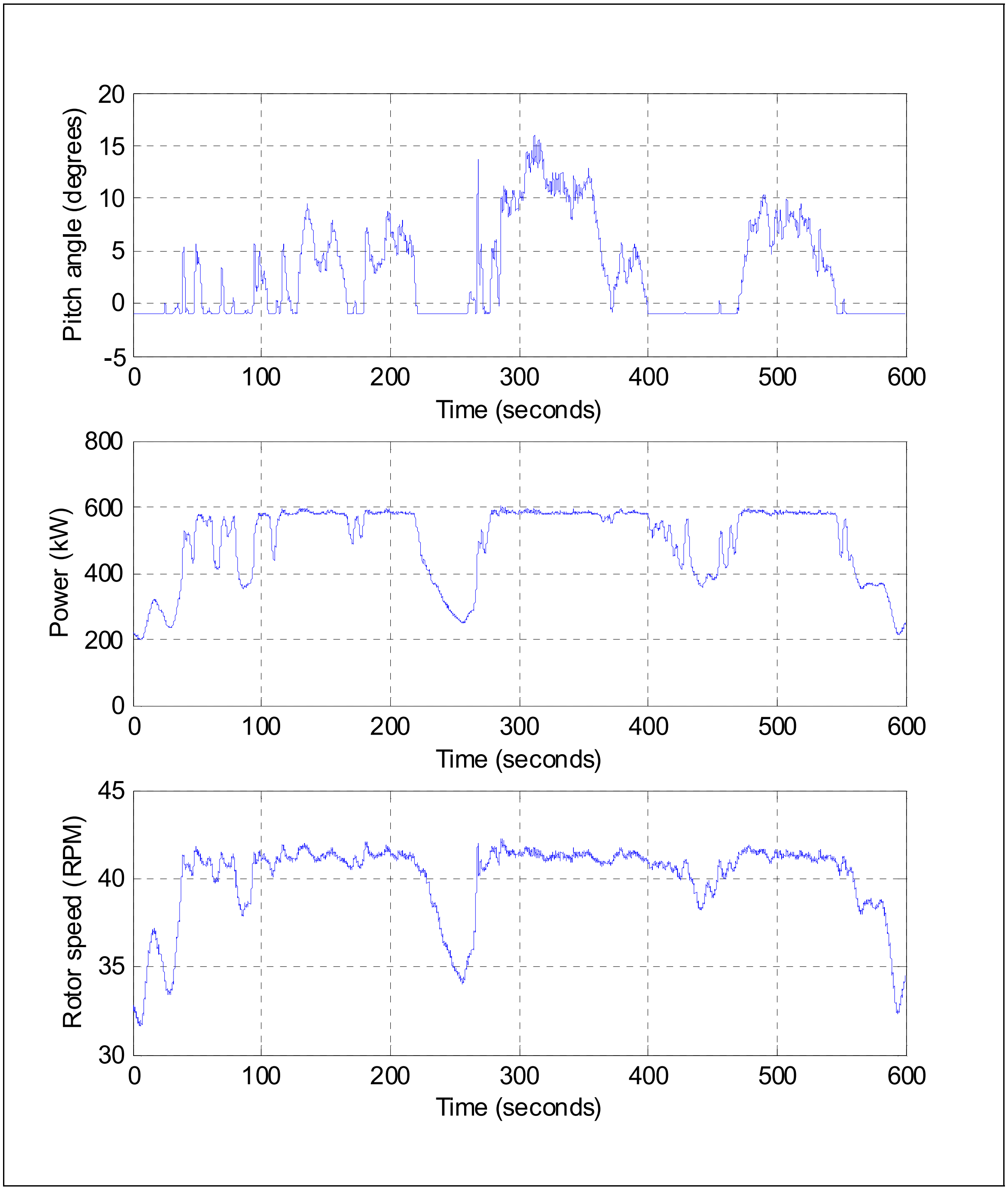

Figure 13 – Power and speed control in variable-speed mode

Data Collection

Aside from turbine and control system commissioning, the primary purpose of the testing during FY 2002 was to acquire baseline data for comparing all other control systems. Because this turbine can be operated in either a constant or a variable-speed mode, two complete data sets – one for each type of control – had to be collected. These data sets needed to be long enough to perform statistically significant analyses. The results of previous tests indicated that at least 50 hours of data in each mode would be enough if a wide range of conditions were experienced during that time.

Table 3 contains a list of the ten minute constant-speed data sets that were collected during this phase. The format is month, day, hour, minute. For example, 12141516 was collected on December 14 at 1516 UTC (Coordinated Universal Time). Table 4 lists the variable-speed data collected. More than 50 hours of data were collected in each mode of operation.

12141516	01082108	01212007	02141512	02200238	03052034	03201914
12141526	01082118	01292207	02141535	02200248	03052044	03201924
12141536	01082128	01292217	02141545	02200258	03052054	03201934
12141546	01082138	02081813	02141555	02200308	03052104	03201944
12141556	01082148	02081823	02141606	02200318	03052114	03201954
12141606	01082206	02081833	02141616	02201555	03052124	03202004
12141616	01082216	02081843	02141626	02201605	03052134	03202014
12141626	01082226	02081853	02141636	02201615	03052144	03202024
12141702	01091443	02081903	02141646	02201625	03052154	03202034
12141712	01091453	02081925	02141656	02202043	03052204	03202100
12141722	01091650	02081935	02141711	02202053	03052214	03202110
12141732	01091717	02081945	02141739	02202103	03052224	03202120
12141742	01091733	02081955	02141813	02202113	03052234	03202130
12141752	01091743	02082005	02141842	02202123	03052244	03202140
12141802	01111433	02082015	02141852	02202133	03071456	03202150
12141812	01111647	02082025	02141902	02202143	03071506	03202200
12141822	01111657	02082035	02141912	02202153	03071516	03202210
12141832	01111707	02082045	02192057	02202203	03071526	03202220
12141842	01111717	02082055	02192107	02202213	03071536	03202230
12141852	01111727	02082105	02192117	02202223	03071546	03202240
12141902	01112118	02082115	02192127	02202233	03071556	04012133
12141912	01112128	02082125	02192137	03041449	03071606	04012151
12141922	01112138	02082135	02192147	03041514	03071616	04012201
12141943	01112148	02082145	02192157	03041531	03071626	04012211
12141457	01112158	02111422	02192207	03041541	03121713	04012221
12171436	01112208	02111432	02192217	03041551	03131804	04091314
12171446	01131644	02111442	02192227	03041601	03192206	04091324
12171500	01131658	02111507	02192237	03041611	03201434	04091334
12171510	01131711	02111517	02192247	03041621	03201444	04091344
12171539	01131724	02111527	02192257	03041631	03201454	04091354
12182156	01131738	02111537	02192307	03041641	03201504	04091404
12191839	01131751	02111547	02192317	03042234	03201514	04091414
12212111	01131804	02111557	02192327	03042244	03201524	04091424
12212121	01131818	02111607	02192337	03051453	03201534	04091434
12212150	01211512	02111617	02192347	03051503	03201544	04091444
12212238	01211522	02111627	02192357	03051513	03201554	04091454
12212252	01211532	02111637	02200007	03051523	03201604	04091504
01081820	01211542	02111647	02200017	03051546	03201614	04091514
01081857	01211552	02111717	02200027	03051556	03201624	04091524
01081907	01211602	02112003	02200037	03051606	03201634	04091534
01081917	01211612	02112013	02200047	03051616	03201644	04091544
01081927	01211622	02112023	02200057	03051626	03201654	04091554
01081937	01211740	02141412	02200107	03051636	03201704	04091604
01081947	01211750	02141422	02200117	03051646	03201714	
01081957	01211800	02141432	02200127	03051656	03201724	
01082022	01211810	02141442	02200208	03051706	03201734	
01082032	01211842	02141452	02200218	03051716	03201853	
01082042	01211852	02141502	02200228	03052024	03201903	

Table 3 – Constant-speed 10 minute data sets collected

04151413	04172110	04232135	05031650	05141951	05220053	05222137	05231421	06061621
04151423	04172120	04271824	05031700	05142001	05220103	05222147	05231431	06061631
04151433	04172130	04271834	05031710	05142011	05220113	05222157	05231441	06061641
04151443	04172140	04271844	05031720	05142021	05220123	05222207	05231451	06061651
04151453	04172150	04271854	05031730	05142031	05220133	05222217	05231501	06061701
04151503	04172200	04271904	05031740	05142041	05220143	05222227	05231511	06061711
04151513	04172210	04271914	05031750	05142051	05220153	05222237	05231521	06061721
04151523	04172220	04271924	05031800	05142101	05220205	05222247	05231531	06061731
04151533	04172230	04271934	05031810	05142111	05221453	05222257	05231541	06061741
04151543	04172240	04271944	05031820	05142121	05221503	05222307	05231555	06061751
04151719	04172250	04271954	05031830	05142131	05221513	05222317	05231619	06061801
04151729	04172300	04272004	05031840	05142141	05221523	05222327	05231630	06061811
04151739	04172310	04272014	05031850	05142151	05221537	05222337	05291739	06061821
04151749	04231452	04272024	05031900	05152151	05221547	05222347	05291749	06061831
04151759	04231504	04272034	05031910	05152201	05221557	05222357	05291759	06061841
04151809	04231516	04272044	05031920	05161324	05221607	05230007	05291809	06061851
04151828	04231526	04272054	05031939	05211905	05221617	05230017	05291819	06061901
04151838	04231536	04272104	05031949	05211931	05221627	05230027	05291829	06061911
04151939	04231546	04272114	05031959	05211941	05221637	05230037	05291841	06061921
04151949	04231556	04272124	05032009	05211951	05221647	05230047	05291851	06061931
04151959	04231606	04272134	05032019	05212001	05221657	05230057	05291901	06061941
04152009	04231616	04272144	05032029	05212011	05221707	05230107	05291911	06061951
04152019	04231626	04272154	05032039	05212021	05221717	05230117	05291921	06062001
04152029	04231647	04272204	05032049	05212031	05221727	05230127	05291931	
04152039	04231657	04272214	05032059	05212041	05221737	05230137	05291941	
04152049	04231707	04272224	05032109	05212051	05221747	05230147	05291951	
04152059	04231717	04272234	05032119	05212101	05221757	05230157	05292001	
04152118	04231727	04272244	05032129	05212111	05221807	05230207	05292011	
04152128	04231737	05031330	05032139	05212121	05221817	05230217	05292021	
04152138	04231747	05031340	05061627	05212131	05221827	05230227	05292031	
04161340	04231757	05031350	05061637	05212141	05221837	05230237	05292041	
04161656	04231826	05031400	05061647	05212156	05221847	05230247	05292051	
04161709	04231836	05031410	05061657	05212206	05221857	05230257	05292101	
04161723	04231846	05031420	05061707	05212216	05221907	05230307	05292111	
04161733	04231900	05031430	05061717	05212226	05221917	05230333	05292121	
04161743	04231914	05031440	05061727	05212236	05221927	05230343	05292131	
04161753	04231924	05031450	05061737	05212246	05221937	05230353	05292141	
04161803	04231934	05031500	05061750	05212301	05221947	05230403	05292151	
04161818	04231955	05031510	05061800	05212311	05221957	05230413	05292201	
04161828	04232005	05031520	05061810	05212321	05222007	05230423	05292211	
04161838	04232015	05031530	05061820	05212331	05222017	05230433	05292221	
04172000	04232025	05031540	05061830	05212342	05222027	05230443	06061333	
04172010	04232035	05031550	05061840	05212353	05222037	05230453	06061343	
04172020	04232045	05031600	05061850	05220003	05222047	05230503	06061353	
04172030	04232055	05031610	05061900	05220013	05222057	05230513	06061403	
04172040	04232105	05031620	05061914	05220023	05222107	05231351	06061413	
04172050	04232115	05031630	05141931	05220033	05222117	05231401	06061423	
04172100	04232125	05031640	05141941	05220043	05222127	05231411	06061611	

Table 4 - Variable-speed 10 minute data sets collected

06071709
06071719
06071729
06071739
06071749
06071759
06071809
06101415
06101507
06181813
06181823
06181833
06181843
06181910
07171526
07171612
07191419

Table 5 – Data collected to test the tower resonance avoidance algorithm

After 50 hours of data were collected in each configuration, extra time was still available during the wind season. This time was used to experiment with a slight control system modification to the variable-speed controller (Table 5). This turbine has a particular dynamics issue with the first tower natural frequency. This mode of vibration can be excited by rotor 2P when the high-speed shaft is rotating at or near 1,112 RPM. This equates to a low-speed shaft speed of 25.76 RPM. Because this speed is within the normal operational range of the variable-speed controller, this mode can be excited quite often during normal operation.

There are many ways to handle such a resonance problem but we decided to try to avoid this speed while operating. Generator torque was used to hold the speed just below or above this resonance point, or to rapidly transition through the resonance. An example of this strategy is shown in Figure 14. The speed that would cause tower resonance (represented by the horizontal line) is avoided or passed through at a high rate.

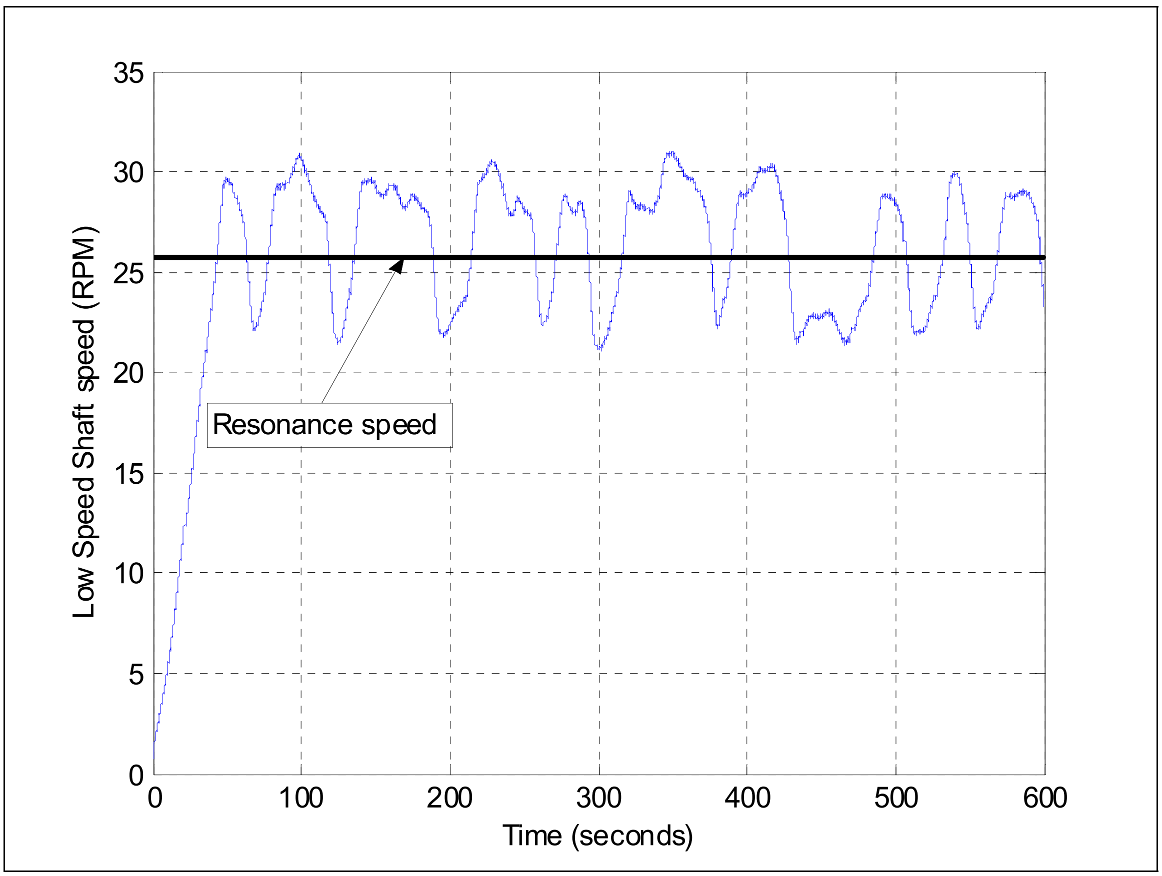

Figure 14 – Tower resonance avoidance example

Conclusion

During FY2002, the CART turbine and controller were developed and commissioned. This included developing and checking out the protection and operational control systems. More than 50 hours of data were collected in constant and variable-speed modes. A new strategy, which underwent limited testing on the machine, was created for avoiding tower resonance. All the data from the checkout through the operational periods were organized, archived, and backed up.

A new round of testing is planned for the FY 2003 wind season. The tests include post- and pre-calibrations, modifications to the control and data systems, and software upgrades. Control and protection systems have been sufficiently developed that the turbine may be allowed to operate in fully unattended mode. New controllers have been developed and are ready for testing during the FY 2003 wind season. Finally, negotiations have been initiated to acquire a three-bladed hub that is planned for installation and testing during the FY 2004 wind season.

Future Work

The turbine was prepared for the FY 2003 wind season. The first two control paradigms that will be tested are the tower resonance avoidance system and an optimally tracking rotor system. Other controllers under final development include a system for optimal rotor tracking and blade load reduction with full state feedback, a system designed to operate the machine optimally without advance knowledge of the rotor's performance characteristics and a system for reducing extreme loads while parked. Several other control systems are in various stages of development and will be implemented when feasible.

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	October 2002	Technical Report for Fiscal Year 2002

4. TITLE AND SUBTITLE
Controls Advanced Research Turbine (CART) Commissioning and Baseline Data Collection

5. FUNDING NUMBERS
WER2.1410

6. AUTHOR(S)
Fingersh, L.J. and Johnson, K.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NREL/TP-500-32879

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
During FY2002, the CART turbine and controller were developed and commissioned. This included developing and checking out the protection and operational control systems. More than 50 hours of data were collected in constant and variable-speed modes. A new strategy, which underwent limited testing on the machine, was created for avoiding tower resonance. All the data from the checkout through the operational periods were organized, archived, and backed up.

14. SUBJECT TERMS
Wind energy, turbine, commission, data collection, research

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102