ABSTRACT

Researchers at the National Wind Technology Center have identified a need to acquire data on the rotor of an operating wind turbine at precisely the same time as other data is acquired on the ground or on a non-rotating part of the wind turbine. The researchers will analyze that combined data with statistical and correlation techniques to clearly establish phase information and loading paths and insights into the structural loading of wind turbines. A data acquisition unit has been developed to acquire the data from the rotating system at precise universal times specified by the user. The unit utilizes commercial data acquisition hardware, spread-spectrum radio modems, and a Global Positioning Satellite receiver as well as a custom-built programmable logic device. A prototype of the system is now operational, and initial field deployment is anticipated this summer.

KEY WORDS

Time synchronization, data acquisition, remote systems

INTRODUCTION

Wind-energy researchers at the National Wind Technology Center (NWTC), representing Sandia National Laboratories (SNL) and the National Renewable Energy Laboratory (NREL), are developing a better understanding of the environment in which a wind turbine operates. Until quite recently, like other wind-energy researchers around the world, they have been content to record long-term summary data (averages, minimums, maximums, cycle counting, etc.) from wind turbines, supplemented with representative ten-minute duration time-series data. The assumption underlying this mode of data acquisition is that this information is sufficient to define the wind-generated turbine loads and the
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turbine response. Continuing problems with premature turbine failures and measurements of loads far in excess of predictions have forced reexamination of that assumption. Obviously, some of the significant but infrequent events that drive turbine fatigue lifetimes have been and continue to be missed with traditional data acquisition techniques. We need to gather continuous long-term time-series data so we can capture and analyze those very infrequent events. How long should these time series be? We don’t know, but researchers in Europe have found that ten minutes is not long enough. In addition, numerous new turbines require the use of small, lightweight data acquisition systems to obtain truly accurate data. Recent advances in electronics enable us to now assemble a cost-effective, real-time, small, lightweight data acquisition system, capable of acquiring continuous time-series data over periods of days or weeks, something which would have been extremely expensive, if not impossible, just a few years ago.

This system is the next evolutionary step in the ongoing NWTC effort to provide a consistent set of hardware using common software that is specifically designed for use in a wind turbine environment. The primary objective continues to be the development of a data system that is easy to use, accurate, and operates reliably in a wind-turbine environment, thereby decreasing the time and effort required to instrument a field experiment, collect data, validate that data, and do preliminary data analysis. An important secondary objective is the development of a more cost-effective data system by decreasing the overall life-cycle costs (including the initial purchase costs, user training costs, and the on-going maintenance/modification costs) and by making it more versatile so it can be used in more applications.

WIND TURBINE DATA ACQUISITION SYSTEM

A complete wind-turbine data acquisition configuration will contain several data acquisition subsystems (DAS), as shown in Figure 1. A normal configuration will utilize at least one rotor-based DAS unit (RBU), at least one ground-based DAS unit (GBU) and one ground-based computer unit (GBCU). The RBU will be mounted on the rotor, rotating with and in close proximity to the blade- and main shaft-mounted strain gauges and other sensors and indicators. The GBU would be any data acquisition unit that doesn’t mount on the rotor--it could be mounted in the nacelle, on the turbine tower, or on the meteorological tower. All units will be located close to the sensors and indicators from which they are acquiring data, in order to minimize contamination of the data by electrical noise picked up by analog signal wires. The GBCU will control the operation of the data acquisition systems and display, store, and post-process the data. Since the RBU is mounted on the turbine rotor and thus must meet the toughest operating requirements in terms of small size, light weight, robustness, immunity to vibration and rotation, etc., it is the first unit we have developed. Four distinct subsystems are combined to perform the function of the RBU: the data acquisition subsystem (DAS), the data communication subsystem (DCS), the time synchronization subsystem (TSS), and the programmable logic device subsystem (PLDS).

Additional information on the RBU, including system requirements, hardware components, and early integration work, may be found in the papers by Berg, Robertson, Rumsey, Kelley, McKenna, and Gass and Berg, Robertson, and Ortiz. A summary of each of the components of the RBU is given below.
Data Acquisition Subsystem (DAS)

The RBU utilizes a commercially available data acquisition system known as the MicroPro,™ marketed by Nicolet Instrument Technologies4 of Madison, Wisconsin. The MicroPro is a small, rugged, modular, lightweight data acquisition system with a relatively low power consumption that is designed for remote operation in harsh environments—its operational temperature range is from -40° to +85° C (-40° to +185° F), and it will withstand 100g shock loads. The unit utilizes nominal 12 VDC power (input power must be between 9 and 36 VDC), and power consumption can range from 5 to 20 watts, depending on the numbers and types of data channels being sampled. A six-slot MicroPro is shown in Figure 2.

![Figure 1. Schematic of Typical Wind Turbine Data Acquisition System](image)

Data is acquired simultaneously from all channels utilizing a separate 12-bit analog-to-digital converter on each channel, and the acquisition time can be precisely specified by an externally supplied synchronization pulse. The data encoder module in the mainframe controls the MicroPro and outputs the acquired digital information in a pulse-code-modulated (PCM) serial data stream. The PCM stream can be transmitted to the data acquisition computer over an RS-422 cable, a fiber optic link, or a telemetry link, in any of a large number of PCM formats.

The MicroPro is programmable from a remote computer—the data channel selection, data sampling rates, filter cut-off frequencies, channel gains and offsets, bridge excitation voltages, and PCM format can be set on a ground-based computer and that information transferred via telemetry or cable to the RBU at any time.

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4 Company names and specific product information given throughout this paper are given for information only and do not imply endorsement by SNL or NREL.
Data Communications Subsystem (DCS)

Data must be transferred from the RBU to the computer concurrent with data acquisition to enable us to acquire data continuously over a period of hours, days, or weeks. Although we may be able to utilize wires and slip rings to effect this transfer on some turbines, many of the turbines on which this system will be used will not be equipped with slip rings, and telemetry will be required. We have utilized conventional single-frequency telemetry systems to transmit data off an operating wind turbine in the past, but we had to resort to a diversity combiner/receiver arrangement in that application in order to overcome the severe multi-path environment created by the many rotating blades in the surrounding wind farm. That was a very expensive, complicated means of communication, and we do not wish to utilize it for this data system. For this application, we don’t need a high-power telemetry system, as we only need to transmit the data a few hundred yards. The system we’ve selected for initial application is a low-cost, commercially available, frequency-hopping, spread-spectrum radio modem. These units from Digital Wireless Corporation operate in the 2.4 Ghz band and achieve data rates up to 115 kbps. A transparent error-correction feature automatically requests a re-transmission of any data that is not received properly. The modems can operate in either asynchronous or synchronous modes, enabling us to perform all the communication functions with a single set of modems. The asynchronous mode is required for programming the DAS and the PLDS, monitoring the Global Positioning Satellite (GPS) receiver status, and other tasks, while the synchronous mode is required for transferring the PCM data.

Highly robust transfer of the PCM data to the ground computer is essential for our application--the long-duration data records are required for detailed analysis, and loss of data during transmission will invalidate those analyses. Initial testing of the DCS on an operating wind turbine revealed that the error detection/retransmission capabilities of the modems are essential to achieving reliable data transfer at higher rotational speeds and higher data transfer speeds.

Timing Synchronization Subsystem (TSS)

In order to obtain the precise time sequence and phase information needed to understand the turbine load and response phasing, the loading sequences, and the load paths of the turbine, data must be simultaneously acquired by the RBU and the GBUs. The length of the long-duration time-series tests may well run into several days, and over that entire time period we need to maintain very accurate synchronization between the RBU and GBUs.

The DAS units that we are using feature simultaneous acquisition on all channels, and the data acquisition may be initiated by external clock, so the time synchronization problem becomes a problem of maintaining synchronous clocks on the units. If all units are connected by cable, this is not a problem, for we can slave all units to the same clock. If, however, the RBU communications are via telemetry, it becomes a problem, for telemetry is not adequate for maintaining time synchronization, due to the time delay inherent in that process. Independent clocks are clearly inadequate, as the drift of even a highly accurate, temperature-stabilized clock is on the order of one part per million. This corresponds to a drift of as much as 86ms per day per clock, for a drift of up to 172 ms per day between two clocks. This is nearly one-fifth of a second! At sample rates of 10 Hz or higher, two independent systems could be out of synchronization by more than one sample interval at the end of a single day. This is unacceptable for most applications.
This cumulative clock drift can be eliminated if the data acquisition clocks in the systems are continually resynchronized. The device that is used to accomplish this synchronization must be small, rugged, and capable of running on battery power. We have been unable to locate a commercial product that will accomplish this task, so we have developed our own.

![Figure 2. Six-Slot MicroPro Data Acquisition System](image1)

![Figure 3. Rockwell Jupiter® GPS Receiver Card](image2)

The GPS system is ideally suited for this type of application. GPS receivers not only determine their location very accurately; they also track the time very precisely, resynchronizing their internal clock to the Universal Time Coordinated (UTC) time every second. Typical variation from UTC time for commercial GPS units is ±1 μs or less, over any time period, so the clocks of two GPS receivers will vary with respect to each other by a maximum of 2 μs over any time period. GPS technology is relatively mature, and small, inexpensive receivers are readily available. The synchronization system that we have developed utilizes the single-card Jupiter system from Rockwell International shown in Figure 3, which has been developed for the automobile navigation system market. This system maintains synchronization with UTC time to within ±1 μs (as long as it can acquire signals from at least three GPS satellites) and generates a one pulse-per-second (1 pps) clock signal, with the rising edge occurring precisely on the UTC second.

**Programmable Logic Device Subsystem (PLDS)**

The three subsystems that have been described above (the DAS, the DCS, and the TSS) sample the data channels, communicate with the ground-based computer, and output a one pulse-per-second clock signal synchronized to UTC time. However, another system is needed to generate the clock trains necessary to drive data acquisition at user-defined times, to acquire the UTC time from the GPS, and to pass data back and forth between the subsystems. We have developed a programmable logic device subsystem (PLDS), utilizing an ALTERA 10K70 from Altera Corporation, to perform these functions.

The ALTERA® 10K70 is a RAM-based programmable logic device (PLD) with extremely fast cycle speeds, and it is programmed at power-up via an external ROM. It contains 70,000 programmable logic
gates, requires low power, and can be programmed using a combination of AHDL (Altera Hardware Design Language) and traditional schematic-based digital design. As illustrated in the block diagram in Figure 4, the PLDS contains the PLD and includes the hardware required to interface with the TSS (the GPS receiver, mounted as a daughter card on the PLDS) and with the DAS (the MicroPro) bus, and to communicate with the DCS (the modem). Power to the DAS, the DCS, and the TSS is controlled by the PLDS. An eight-layer printed circuit board was designed and built to supply the power and provide the necessary input and output connections for the PLD. The first working prototype of this board was demonstrated in December 1997. Figures 5 and 6 illustrate the relatively complex PLDS device.

![Figure 4. Schematic of Programmable Logic Device Subsystem](image)

One of the major tasks of the PLDS is the generation of the synchronization clock and bit-rate clock timing signals. The synchronization clock triggers the DAS data acquisition cycle, and the bit-rate clock establishes the rate at which PCM data is transferred out of the DAS. The bit-rate clock must be fast enough to transfer all of the acquired data out of the DAS prior to the occurrence of the next sync clock. The sync clock and bit-rate clock speeds are specified by the user. The GPS-generated 1 pps signal initializes a sync clock at the user-specified rate, precisely aligned with the 1 pps signal. The sync clock then initializes the bit-rate clock at the user-specified rate. The bit-rate clock is re-initialized by every sync clock pulse, and the sync clock, in turn, is re-initialized by the occurrence of the 1 pps signal. Since the 1 pps signal is aligned with the UTC second, the sync clock, and thus the data acquisition time, is kept synchronized to the UTC time.

The PLD card also reads and decodes the UTC time that is output as a serial stream by the GPS card. The PLD then places that time into RAM registers which are read by the DAS as part of the normal data acquisition process.
With the current version of the software, the PLDS performs the following functions:

1. Generates the data-synchronization and bit-rate clock pulse trains at the user-specified rates. These clock trains are precisely aligned to the GPS one pulse-per-second pulse train.
2. Latches the GPS time when data is acquired and places that time (accurate to the microsecond) in the DAS PCM output stream.
3. Transfers user-generated programming commands to the DAS.
4. Transfers GPS receiver card status messages to the ground and user-generated commands to the GPS card.
5. Converts the synchronous MicroPro PCM data to asynchronous form and transmits it to the ground via an asynchronous 2.4 GHz spread-spectrum modem. A second PLDS on the ground is used to recreate the original PCM data stream.
6. Places the system into a "sleep" mode in which the TSS, PLDS, and DAS are either shut off or placed into an low power state to draw a minimum current and thus conserve battery life. The PLDS checks the modem input line once every 10 seconds. If the appropriate message has been received, the PLDS will power up the entire system and it will be ready to start full-power data acquisition within 2 seconds.
7. Monitors the status of the GPS receiver (including satellite lock and UTC lock), input power voltage, and the current data synchronization and bit-rate clock settings, and returns this to the user in response to the appropriate inquiry.
8. Switches between functions 3, 4, and 5, above, in response to user command, enabling the system to operate with a single modem.

Figure 5. GPS/PLD Front View; SCSI Connector Shown on Front Panel, MicroPro Bus Connector at Rear.  
Figure 6. GPS/PLD Unit with GPS Board Removed; ALTERA 10K70 PLD Visible
SYSTEM FIELD TESTING

In March and April of this year we tested the prototype RBU on an operating wind turbine at the USDA Agricultural Research Service location in Bushland, Texas, with encouraging results. The Bergey Excel turbine is an upwind, variable-speed machine that operates between 120 and 300 rpm. The MicroPro (with the PLDS installed in it) and two modems (one for PCM data and one for RS-232 communication), together with a sealed lead-acid battery to power the system, were placed in a waterproof box. The antennas for the modems and the GPS (placed on a 12-inch mast extending along the axis of rotation) were mounted on the outside of the container. The entire system was then attached to the upwind side of the rotor hub, at the centerline of rotation. The system is shown mounted on the turbine in Figure 7--the white bulb in the center of the photograph is the GPS antenna and the four-inch stubs at the upper left and the lower right of the box are the 2.4 GHz modem antennas.

FIGURE 7. RBU Mounted on Bergey Turbine

When we tested the TSS operation on the turbine, the turbine rotation rate was slightly above 200 rpm. The Jupiter receiver card continuously received signals from a minimum of six GPS satellites over the 20-minute testing period. Only three satellites are required to maintain synchronization of the on-board clock to UTC time, so the clock remained locked to UTC time during rotation. Additional tests on a turbine simulator show that, at speeds of 350 rpm or so, the receiver may receive only one satellite signal for time periods of a second or so, but that is not sufficient to cause the receiver to lose time synchronization or lock. As long as signals from three or more satellites are received every few seconds, time sync is maintained. However, loss of time sync would not be catastrophic--the receiver clock will continue to provide time and the 1 pps signal, although the time will gradually drift with respect to UTC time. As soon as the receiver receives data from three or more satellites, the receiver clock will again be synchronized to UTC time.

We also ran tests to examine the robustness of the PCM radio link. The receiving radio/modem was placed about 100m directly downwind of the rotor, so the radio signals had to propagate around or
through the hub, the blades, and the tower to reach the receiver. Close monitoring of the received data for ten minutes, using diagnostic software, showed no loss of data for data transfer rates below 6 kbps. Test results for higher data transfer speeds were ambiguous, and we do not yet know if any data is lost at the higher transfer speeds. Further testing of the telemetry system will be conducted in the next two months on a 350-rpm turbine simulator system. We will monitor the time at which each data sample is taken, store the data received by the ground computer to disk, and then post process the data file. Any missing data records will be easily located, and we will also be able to determine how much data is lost.

FUTURE PLANS

The first field application of the RBU will occur this summer on a turbine at the USDA site at Bushland, Texas. In this application, a second MicroPro will be utilized to obtain turbine drive-train data and a third MicroPro will be used to obtain turbine tower and meteorological data. The PCM data from the RBU will be transmitted via radio to the ground-based radio/modem, where it will be merged with PCM data from the other two MicroPros, and the composite PCM stream will be decoded and placed into computer memory. A National Instruments LabVIEW® program, currently under development, will retrieve the data from memory and merge the rotor data with data from the other DAS units by time of acquisition. At this point, the data will look just like the data acquired from other hardware systems and we can use existing LabVIEW software routines to write the data to disk, view it, and post process it.

Over the next few months, this LabVIEW software will be developed into a virtual instrument, or VI, software module to communicate with both the RBU and the GBUs. This module will program the RBU and/or GBU and retrieve the decoded PCM data from the ground-based computer unit. It will be merged into existing wind-turbine data acquisition software to yield a complete, user-friendly software system that will accomplish everything from hardware setup, to data storage, to post-test data reduction and analysis, for both old and new hardware.

Finally, we plan to transfer the PLDS technology to industry so that it becomes more readily available for alternative applications in the future. We feel that the small size, low power consumption, flexibility, and low cost will make it attractive for numerous data acquisition applications such as missile flights, remote sensing, and general aerospace testing. Also, having it available as a commercial product may free us of the need to provide ongoing hardware and software support for it.

SUMMARY

The need to gather detailed, long-term time-series data on the rotors of highly dynamic and/or small wind turbines has led to the development of a new-generation, lightweight, rotor-based data acquisition unit (RBU), which comprises four distinct subsystems. The data acquisition subsystem (DAS) consists of a small, rugged, lightweight commercially available data acquisition system. This device simultaneously acquires data on all input channels in response to an external clock pulse, and outputs the resultant digital data as a PCM data stream for transmission to a computer.
Commercial spread-spectrum radio/modems are utilized as the data communication subsystem (DCS) to transmit control and programming information and data between the RBU and the ground. The error correcting, spread-spectrum technology makes the radio link much less susceptible to interference than conventional, single-frequency radio technology.

Data acquisition times and rates are synchronized with a ground-based data acquisition unit (GBU) through the use of a time synchronization subsystem (TSS). The TSS utilizes the one pulse per second signal generated by a GPS receiver to generate pulse trains that are precisely synchronized to UTC time. These pulse trains are used to drive the data acquisition of both the RBU and the GBU units, enabling them to acquire data within two microseconds of each other.

Finally, a custom-built programmable logic device subsystem (PLDS) has been developed to coordinate the operation of the DAS, the DCS, and the TSS. This unit fits inside the DAS and handles all communications with the user and all communications and data interchange between the DAS, the DCS, and the TSS. Field tests have demonstrated the capability of the unit, and initial field application is anticipated to occur this summer.

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ACKNOWLEDGEMENT

Significant contributions to this project have been made by Jose Zayas, Michael Ortiz, and Karl Gass, all of Sandia National Laboratories.