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DEVELOPMENT OF A LIGHT-WEIGHT, WIND-TURBINE-ROTOR-BASED DATA ACQUISITION SYSTEM*†

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ABSTRACT

Wind-energy researchers at Sandia National Laboratories (SNL) and the National Renewable Energy Laboratory (NREL) are developing a new, light-weight, modular system capable of acquiring long-term, continuous time-series data from current-generation small or large, dynamic wind-turbine rotors. Meetings with wind-turbine research personnel at NREL and SNL resulted in a list of the major requirements that the system must meet. Initial attempts to locate a commercial system that could meet all of these requirements were not successful, but some commercially available data acquisition and radio/modem subsystems that met many of the requirements were identified. A time synchronization subsystem and a programmable logic device subsystem to integrate the functions of the data acquisition, the radio/modem, and the time synchronization subsystems and to communicate with the user have been developed at SNL. This paper presents the data system requirements, describes the four major subsystems comprising the system, summarizes the current status of the system, and presents the current plans for near-term development of hardware and software.

INTRODUCTION

For the past several years, wind energy researchers around the world have been content to record long-term summary data (averages, minimums, maximums, cycle counting, etc.) from research wind turbines, supplemented with representative ten-minute duration time-series data, assuming that this information would be sufficient to define the wind-generated turbine loads and the 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 missed. We need to gather 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 ten minutes is not long enough. Researchers in Europe have started collecting long time-series records and find that the results obtained from them differ significantly from the results obtained from ten-minute records[1].

Several small and/or highly dynamic wind turbine rotors will be tested at the National Wind Technology Center (NWTC) or in the field over the next few years, and wind energy researchers at NREL and SNL want to obtain long-term time-series data from many of them. Existing NREL/SNL data systems are not well suited for this application. The Combined Experiment Rotor (CER) data system, which NREL has developed, incorporates a high channel count, fairly high data rate, simultaneous data acquisition on all channels, and continuous data acquisition. However, it is fairly bulky, it utilizes slip rings to transfer commands and data between the rotor and the ground computer, and it consists largely of custom-built equipment, which is relatively fragile and for which few spares and little documentation exists. The costs to maintain and repair it are quite high. Developing this system into a ruggedized system that can be mounted on a variety of

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turbines and used by personnel who are not intimately familiar with it would be very costly.

Another NREL research rotor data acquisition system, the SoMat 2100 Field Computer System,[2*] is relatively small, rugged, and modular; quite flexible on number/type of channels measured; acquires data at a fairly high data rate; and utilizes telemetry to transfer the data to a ground-computer for storage and analysis. However, it has a relatively low channel count, all channel gains and filter settings must be set manually, and while it can acquire long-term summary data, such as rainflow cycle counting matrices, it cannot acquire long-term time-series data-the amount of data is limited to what will fit in 16Mbyte of on-board memory. In addition, data acquisition must be terminated in order to transfer any data to a ground-based computer for storage and analysis.

The Advanced Data Acquisition System,[3] or ADAS, a field data acquisition system developed for NREL by Zond Systems (now Enron Wind Corporation), is not well suited for this application, either. The ADAS is modular, rugged, quite flexible on number/type of channels measured, fully computer programmable, has a moderate data acquisition rate, and can use either telemetry or slip rings to transfer data to a ground computer. However, an ADAS unit can only acquire relatively short continuous time-series records at reasonable data acquisition rates (the amount of data is limited to what will fit in 4Mbyte of on-board memory), and it must terminate data acquisition to transfer data to the ground. The ADAS units are also quite heavy-each eight-channel module weighs about 25 pounds. The size and weight of the ADAS restricts its use to relatively large rotors that are not particularly dynamic.

At the maximum data acquisition speed of 160Hz for each channel of data for the ADAS system or 3000 Hz for each channel for the SoMat system, transfer of time-series data from the internal memory to ground can take significantly longer than the actual acquisition time for that data-perhaps as much as 3 to 4 times as long. The actual transfer time depends on a number of factors and is much slower for a radio link than for a hard-wire or slip-ring connection. Since no data can be acquired during the transfer of data to ground, the chances of missing a significant event during testing may be as high as 80%. This is simply not acceptable for some test programs. In addition, lack of continuous data transfer to ground results in much longer test times. In fact, it may completely preclude acquiring data under some rare meteorological conditions (i.e., wind direction changing very rapidly, etc.), simply because data is being transferred when those conditions occur and therefore no data can be acquired.

While multiple ADAS units can be programmed to synchronize the start of data acquisition, each unit subsequently runs off its own internal clock, so they quickly lose synchronization. Multiple SoMat Field Computers can be networked together for precise synchronization, but at the present, this can only be done via hard-wired connections. Only one SoMat unit is presently owned by NREL, and it cannot be slaved to an external clock, so it cannot be time-synchronized with a ground-based data system. This lack of ability to synchronize multiple data systems has not been considered a serious limitation in the past, but it is now, at least in some applications.

Numerous turbines will be tested at the NWTC and in the field over the next few years, and, while the ADAS and SoMat systems may be adequate for acquiring data from some of them, the inability to acquire continuous, long-term, time-series data with time synchronization across all channels will be a serious deficiency.

Although there will always be wind-turbine applications that require very specialized data acquisition systems, we felt we could develop a system that would meet the requirements for a large number of the wind-turbine testing applications at the NWTC over the next few years, one that would be suitable for use on turbines ranging in size from 10kW to 1MW or larger. The new system should incorporate a rotor-mounted unit that is small, light-weight, and robust; that communicates with ground-based computers via telemetry; that is capable of synchronizing data acquisition times; and that is capable of essentially continuous data acquisition. Such a system, although it might be quite expensive initially, would result in significant savings over a period of time, as it would reduce the number of hardware types and software packages that must be developed and maintained.

SYSTEM REQUIREMENTS

The first stage in this development consisted of a number of meetings with Wind Energy Program management and the NREL and SNL staff who will be the initial users of these systems. We quickly concluded that long-term synchronization between the various units is essential-the system must faithfully capture the relative temporal or phase relationships

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[*] Company names and specific product information are given for information only and do not imply an endorsement by SNL, NREL, or Utah State University.

between measured variables, as well as their magnitudes. In addition, we concluded that the new systems would consist of three units with significantly different requirements-a rotor-based data acquisition unit (RBU), a ground-based data acquisition unit (GBU), and a ground-based controller/display/data-storage/post-processor unit (GBCU). Figure 1 illustrates an application where three ground-based units are used - one to acquire data in the nacelle, one to acquire tower data, and one to acquire meteorology data. The RBU would be mounted on the rotor, rotating with and in close proximity to the blade- and shaft-mounted strain gauges and other sensors and indicators. This makes size, weight, and ability to withstand the rotor rotation of critical importance. Since size and weight considerations and the ability to operate in a rotating frame are not, in general, of great importance for the ground-based units, we concluded that the RBU would have to meet the most stringent requirements and thus would be the most difficult of the three units to acquire. Therefore, we focused our attention on defining and developing that unit.

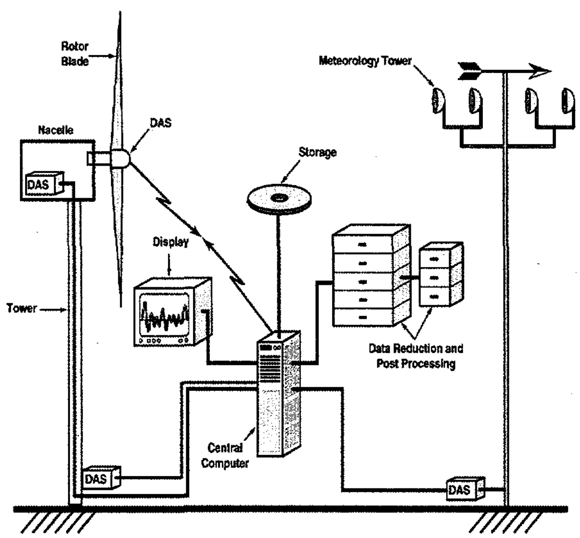

Figure 1. Wind Turbine Data Acquisition and Analysis System

From these meetings we compiled the following requirements for the RBU:

1. It must be small, highly modular, and light-weight, with the ability to acquire data from at least 20 channels of high-level analog and strain-gauge signals. Twenty channels will allow for the monitoring of, say, four main shaft strain gauges, four strain gauges on each of three blades, and four additional sensors to measure things such as blade twist and tip deflection. While "light-weight" is a relative term, with a 50-pound system meeting that criteria for a 1MW turbine, but not for a 10kW turbine, we decided to aim for a unit weight of less than 10 pounds (without batteries).
2. It must be computer controlled and/or computer programmed.
3. It must supply programmable filtering and gain on each analog channel, together with strain-gauge-bridge excitation and bridge completion circuitry for all strain-gauge channels.
4. It must merge all acquired data into a single, high-level, digital, serial data stream for transmission to a ground-based computer system, in order to minimize electrical noise problems.
5. It must acquire data simultaneously on all channels or scan through all the channels very quickly, with only a few microseconds delay between the acquisition of data from the first data channel and the acquisition of data from the last data channel.
6. The time at which data is acquired must be synchronized with the other data acquisition units, to ensure that critical phase information between the various signals is maintained. This synchronization must be maintained over data acquisition periods of days or weeks.
7. It must be capable of acquiring data from all channels at rates of at least 100 Hz/channel continuously for days or weeks, to enable us to identify and characterize the rare events that are the driving events in turbine failures. One hundred Hz is adequate to achieve 18° azimuthal resolution on a 300 rpm rotor. Maximum acquisition rates for short periods of time should be significantly higher (say 200-500 Hz per channel) to support various time-domain analysis techniques. These data rates are very easily achieved with current technology. These rates and acquisition times mandate transfer of the data to a ground computer as it is acquired, in order to permit near real-time data monitoring and not require massive amounts of memory or disk storage in the RBU itself.
8. It must communicate with the ground computer via telemetry, to avoid the expense, installation, and noise problems inherent in using instrument-quality slip rings, and to minimize the space required by the system. While slip rings that are suitable for serial communication may be available on a few turbines and they can be added to others, they would be extremely difficult and expensive to install for many turbines. Some machines simply have no space for them. In addition, slip rings are normally tailored to each specific application and cannot be transferred from machine to machine. The cost of purchasing and installing them on just a few machines will quickly exceed the cost of purchasing a suitable telemetry system. If suitable

slip rings are available on a turbine, they can be used in place of the telemetry. The telemetry units must be highly resistant to the normal wind-turbine environment of vibration, high-level electrical interference, multi-path interference and constantly changing orientation.

9. It must consume a relatively small amount of power, to minimize the current that will be supplied to it through slip rings or a rotary transformer, or from a battery. The unit should be capable of operating for several hours on battery power. The unit must be resistant to power surges and short power interruptions, and it must include lightning protection.
10. Its major components should be supplied by commercial vendors, to avoid the maintenance expense of custom-built hardware.
11. It must be packaged so that it can withstand the extremes in environment that may be encountered during wind turbine testing - blowing sand, driving rain, 0% to 100% relative humidity, and -40° to 75°C temperature range.

Although an early use of the new RBU will be to collect data on small (10-50 kW) wind turbines, the initial application for it has been identified as the 300 kW Cannon Wind Eagle prototype turbine already installed at the NWTC. This machine (shown in Figure 2) has an innovative, light-weight nacelle with a very flexible rotor and is a very dynamically active turbine. While the size of the data acquisition system is not a major concern in this application, researchers are very concerned about the effects on the machine dynamics of adding a system as heavy as the ADAS. Continuous time-series data will be acquired over periods of several days. The phase relationships between the various data signals must be maintained in the sampled data to permit researchers to understand the dynamics of the system. Data will be acquired at 200 Hz in order to get a flat magnitude response up to 40 Hz (5X oversampling). The 200 Hz data rate yields a sample time of 5 ms. According to Crochiere and Rabiner,[4] at 5X oversampling, a time offset between two data signals causes a linear phase shift of 72° at 40 Hz for a time offset of one sample time (5 ms for the Wind Eagle). Researchers working on the Wind Eagle wish to restrict the phase shift to 5°, implying that the time offset between any two data signals must be limited to 0.35 ms. Thus, for this application, the data from the RBU must be synchronized with the data from any GBU to within 0.35 ms over the longest duration data acquisition period during testing. Future applications may impose a more stringent time synchronization requirement.

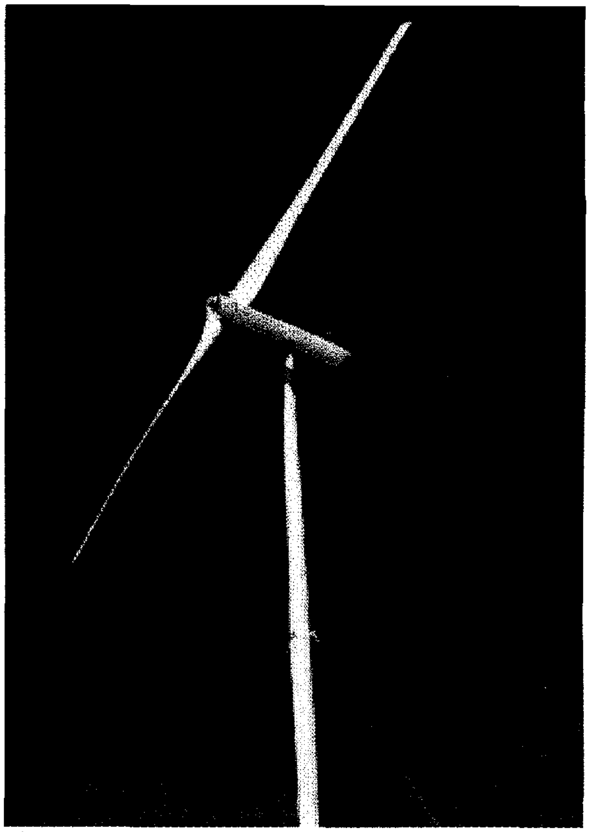

Figure 2. Cannon Wind Eagle Turbine at the National Wind Technology Center

SYSTEM COMPONENTS

The list of RBU requirements was sent to a number of companies that specialize in data acquisition systems. None of these companies could meet all of our requirements. Several of the companies could furnish units that met many or most of the data acquisition requirements, and a few could furnish telemetry systems, but none of them could offer a solution to the long-term time-synchronization requirement or provide a complete, integrated system. As a result, we decided to break the system into four distinct subsystems; a data acquisition subsystem (DAS), a telemetry or data communication subsystem (DCS), a time synchronization subsystem (TSS), and a programmable logic device subsystem (PLDS) which will integrate the other three subsystems into a complete rotor-based unit. Figure 3 illustrates the relationship of these subsystems. The DAS and DCS equipment is commercially available, but the TSS and the PLDS hardware/software must be developed, either by SNL/NREL or by a contractor. This violates our requirement for utilizing only commercially available components, but it appears to be the only way we can satisfy our other requirements.

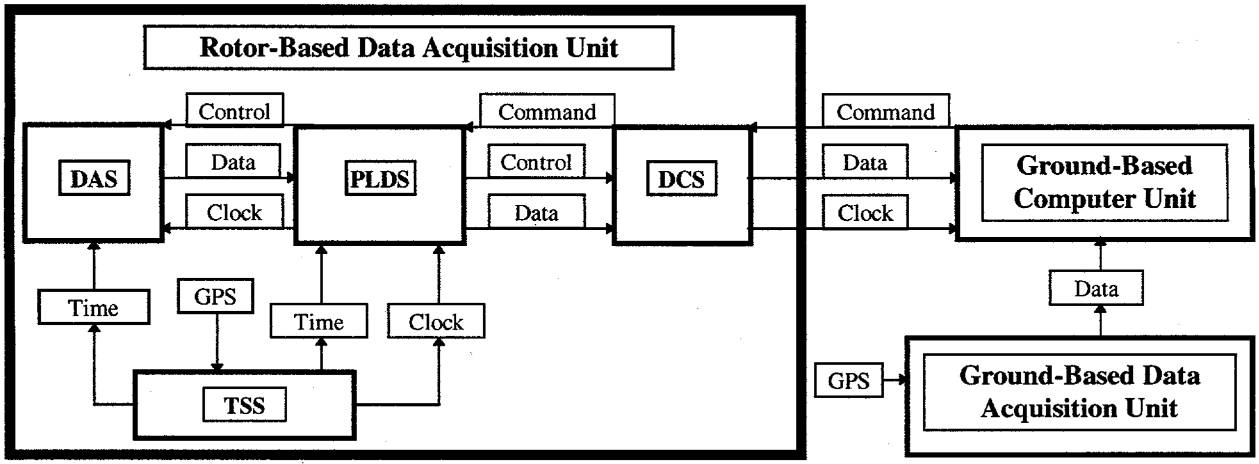

Figure 3. Rotor-Based Data Acquisition Unit Schematic

Data Acquisition Subsystem (DAS)

The list of DAS requirements were furnished to several data acquisition companies with a request for proposal (including price quote and technical information) for a basic system that could acquire 16 channels of strain gauge data (with power excitation, bridge completion, and filtering), eight channels of high-level analog data, and 32 lines of digital data. The most promising six responses (from Nicolet, Optim, Lockheed-Martin[two different systems], Campbell, and MetraPlex) were then evaluated in depth, considering things such as size, power consumption, data sample and transfer rates, types of measurements that can be made, programmability of sampling modules, software availability, remote programming capability, ability to acquire simultaneous data, ability to slave to an external clock (perhaps another system), filter flexibility, price, delivery date, company interest in our project, and company willingness to furnish us with detailed technical information.

The Nicolet MicroPro™[5] unit emerged as the one best suited to our application. It is very cost competitive with the other systems considered, with a small size, good acquisition speed, and moderate power consumption. Although it is sold by Nicolet in the U.S., it is actually built in Ireland by ACRA Control, Ltd.,[6] and is known in Europe as the ACRA KAM 500.

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 basic unit or mainframe includes one or more power supplies and a data encoder module which controls the MicroPro and formats the output digital data stream. MicroPro units are available in four configurations, with 3, 6, 9, or 13 slots available for the insertion of sampling modules. The 3-slot unit has dimensions of 3.15"x3.39"x4.65", with a weight of 2.2 pounds, and the 13-slot device has dimensions of 3.15"x3.39"x10.7", with a weight of 5.7 pounds. A 9-slot unit is shown in Figure 4. The unit is not weatherproof, so it must be enclosed in an environmental box.

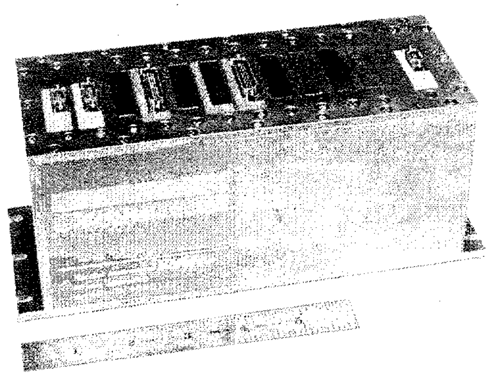

Figure 4. Nine-slot MiroPro Data Acquisition System

Each slot of the MicroPro mainframe accepts a single sampling module, supplies that module with power and control information, and reads input data from that module. Data is acquired simultaneously from all channels on all modules, and the acquisition time can be precisely specified by an externally supplied synchronization pulse. Analog and strain-gauge modules accept eight channels of input each, with programmable filtering, signal conditioning, and a separate 12-bit analog/digital converter for each channel. The strain gauge modules (shown in Figure 5) also contain bridge excitation and completion circuitry for each of the channels on the module. A digital input module is available to monitor the status of up to 48 input lines and to perform timer/counter functions. Additional modules include accelerometer, thermocouple, and digital serial data input units.

All sample and signal-conditioning parameters, including sample frequency, filter roll-off, gain, and offset, are controlled via Nicolet-supplied software. That software also controls the data acquisition, display, and storage of the data, in any of a variety of binary or ASCII formats, for easy access by additional data analysis software packages. Software drivers, compatible with National Instruments' LabVIEW® and other programming languages, are available for user software development.

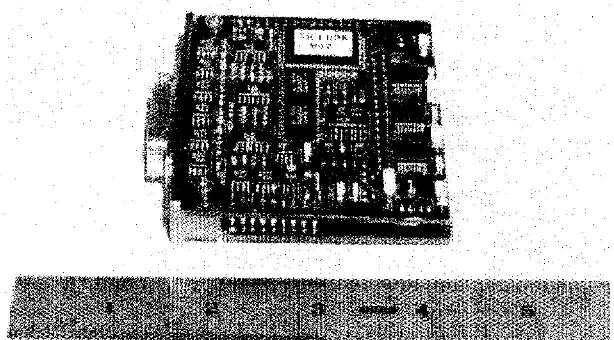

Figure 5. MicroPro 8-Channel Strain Gauge Data Module

The MicroPro formats the output data into a pulse code modulated (PCM) digital serial stream for transmission to the host computer. The PCM stream consists of a series of data blocks or frames. Each frame contains one 12-bit data word for each channel, together with a single data synchronization word to ensure data integrity. The PCM stream can be transmitted to the computer over an RS-422 cable, a fiber optic link, or a telemetry link, in any of a large number of PCM formats. The data is decoded at the receiving computer and placed into computer memory for further manipulation by MicroPro or custom-written software.

The MicroPro can either run off its internal clock or it can be slaved to an external clock. Each channel can be sampled at up to 100k samples/second, with a maximum system throughput rate of 167k samples/second. A maximum system throughput rate of 500k samples per second can be realized with the use of a higher data rate, third-party decoder.

Wind-energy researchers at the Center for Renewable Energy Systems (CRES)[7] in Greece have used a MicroPro system to acquire wind turbine rotor data for the past three years. They are very satisfied with the system performance and the company support, and have just recently purchased a second system.

The two MicroPro units that we have purchased for checkout and system development contain nine module slots, to provide plenty of slots for a variety of sampling modules and extras for use by our custom-built PLDS and TSS modules (to be discussed below). The modules which will initially be used in these systems are:

1. One module with eight channels of high-level analog input. The gain (which may be set to 1, 2, 4, or 8) and offset on each channel may be individually programmed utilizing the furnished software. Each channel passes through a 2nd-order anti-aliasing active filter with a fixed 3 dB point of 5kHz, followed by a programmable 5th order Butterworth filter, with a cut-off frequency that is set by the user. The cut-off frequency is the same for all eight channels on the module. The supplied software includes the ability to check and adjust offset voltage and to accomplish a shunt calibration of each channel.
2. Two modules with eight channels of strain-gauge input per module. Each strain-gauge module consists of a high-level analog module as described above, with a daughter board that supplies an additional fixed amplification (gain of 500) and bridge excitation and completion per channel. The bridge excitation is set by the user and can be up to ±7.5 volts. Each module is factory configured for full, half, or quarter bridge operation-they cannot be reconfigured in the field. Again, the software includes the ability to check and adjust offset voltage and to accomplish a shunt calibration of each channel.
3. One module containing 48 bits of digital input with eight on-board counters per card. Each bit can be used to monitor the status of an input line, and each of the counters can be programmed to count period, frequency, events, elapsed events, time, etc.

The MicroPro utilizes 12 VDC power. Power consumption is about 18 watts for 16 channels of 350 ohm strain gauge, with 8 channels of high-level analog (no excitation), and 48 channels of digital. For 8 channels of 1000 ohm strain gauges, 8 channels of high-level analog (no excitation), and 48 channels of digital input, the power consumption drops to about 8 watts. For the Wind Eagle application, 110 VAC power is available on the rotor. That power will be used to charge a 12 VDC battery which will then power the

MicroPro. This will provide protection against both surges and short-term interruptions in the AC power.

While cost-competitive, the MicroPro is not cheap. The cost of a single prototype system that will measure 16 channels of strain gauge data, 8 channels of high-level analog data, and 48 bits of digital data is about $31,600. However, if we eliminate the digital module, the cost for the 24 channels of analog data drops to $27,700, less than $1,200 per channel (the DCS, TSS, and PLDS will add costs of $100-200 per channel, total). We certainly expect these costs to decrease in the next few months as we buy additional units and additional marketplace competition appears. For comparison, the cost of the five-year old ADAS system was approximately $1,000 per analog channel or eight bits of digital input. Keep in mind that the MicroPro is the main component of the system, and its cost is far greater than the cost of any of the other system components.

Data Communication Subsystem (DCS)

The wind turbine environment is a rather difficult one for most conventional telemetry systems, which transmit data at a single radio frequency. While telemetry units work very well for many applications, they are quite susceptible to severe signal degradation in wind-turbine applications. The rotating blades, other turbines in the vicinity, and the constantly changing orientation all contribute to multi-path interference problems. These problems can frequently be resolved with the use of multiple receivers and associated electronics to identify and use only the strongest signal (known as diversity combiner/receiver systems). However, these systems tend to be very expensive, with a cost of $30,000 to $40,000 for a single system. A relatively new radio technology known as spread-spectrum modulation appears to be superior for wind-turbine applications.

Spread-spectrum radio modulation originated in military communications systems that required high immunity to jamming, electro-magnetic interference, multi-path distortion and signal interception, while still maintaining very high level data transmission integrity. Data signals are spread over a frequency band and radiated power is lowered to a level where the signal appears to be just noise. The reconstruction techniques make the signal relatively immune to interfering signals. Over the past few years, integrated circuits have been developed which integrate many of the complex functions required to implement spread spectrum. They are now extensively used for wireless networks inside buildings, as they eliminate the need to run expensive cabling throughout the building. As a result, the cost of these systems has declined rapidly over the past few years.

A number of spread-spectrum systems have previously been used in wind-turbine applications, with a fair amount of success. The NREL Somat and ADAS units both utilize spread-spectrum systems, but their data transfer rates of 9600 to 19,600 bits per second (bps) are significantly less than the 38kbps that is required for the Wind Eagle application.

During the development stage of this data system, two different spread-spectrum systems are being used; one to transmit data from the MicroPro to the ground using synchronous operation, and a second to program the MicroPro from the ground using full-duplex asynchronous operation (the "Commands" link to the DCS in Figure 3).

The transmission of data from the MicroPro to a ground-based computer is accomplished with a wireless modem system from Digital Wireless Corporation[8] that utilizes spread-spectrum frequency-hopping technology in the 2.4 GHz band to achieve data rates, with built-in transparent error correction, of up to 115 kbps. The error correction means that, in case of interference problems, the data is transparently re-transmitted up to two times before it is lost. This system is operated in the synchronous mode, with the MicroPro data clocked into the radio/modem by the MicroPro data clock, but it may also be operated in the asynchronous mode. The clock and data are reconstructed by the receiving radio/modem on the ground and fed into the MicroPro PCM decoder card where the data is decoded and stored into memory. The radio system requires no license for operation, and the maximum transmit power is 100 mW, so it should not interfere with other radio systems. The radio/modem is 2.4"x2.0"x0.6" in size and consumes a maximum of 1.5 watts of power. The cost is $600 per unit or $1200 for the pair that is required for this application.

The Digital Wireless system, which we intend to continue using with the system, has been tested on an operating AOC (Atlantic Orient Corporation) wind turbine at the USDA Agricultural Research Station in Bushland, Texas, with encouraging results. The radio unit, attached to a MicroPro system, was placed on the downwind side of the rotor hub on the AOC. The 4-inch antenna was placed parallel to the rotor shaft and pointed directly downwind. The receiving radio/modem was then placed about 100m directly upwind from the rotor, so the signal had to go around or through the hub, the blades, and the lattice tower to reach the receiver. Monitoring the test channel for several minutes did not reveal any data loss. Additional tests will be run in the next few months.

A FreeWave Technologies[9] wireless modem system is now used to send commands from the ground-based computer to the RBU to remotely program the MicroPro. This system also utilizes spread-spectrum frequency-hopping technology and has a maximum data rate of 115 kbps, but it operates in the 900 MHz band, does not include error correction, and operates only in the asynchronous mode. Again, the radio system requires no license, but it has a maximum transmit power of 1 watt. The cost for this pair of radio/modems was $2500. The FreeWave modems have not been tested on a wind turbine, as we do not intend to use them once the DCS and the PLDS are developed. However, we do not yet have the ability to easily switch the Digital Wireless units from synchronous mode to asynchronous and back again, so we will utilize this system for the asynchronous mode communications, which are used only to program the MicroPro prior to turbine operation.

Timing Synchronization Subsystem (TSS)

Data must be acquired by the RBU and GBU simultaneously, in order to retain time-order or phase information. With a hard-wired system, we could slave the data acquisition clocks from all of the units together to accomplish this requirement, but a hard-wire link to the RBU will not usually be available. We have been unable to locate a commercial product that will accomplish this task, so we have developed our own.

One way to achieve this simultaneity would be to place a clock on each system and then sample precisely on the second or millisecond, but to achieve the simultaneity that's needed for the Wind Eagle application (0.35 ms or less between RBU and GBU samples for any scan), the two clocks must remain in time synchronization to within 0.35 ms over a period of days. Even highly accurate, temperature-stabilized (and therefore expensive) clocks have an accuracy of only one part per million. This corresponds to a drift of as much as 86 ms/day, per clock, or a drift of up to 172 ms/day between two clocks. One way to avoid this drift is to continually re-synchronize the clocks. However, all communications between the two systems will be via radio/telemetry, which introduces variable-duration delays, so re-synchronizing the RBU clock from the ground would be very difficult. On the other hand, the Global Positioning System (GPS) provides a very accurate time anywhere in the world. GPS receivers contain a clock, which is synchronized to the GPS time frequently, typically once every second. Moreover, these receivers can be used to generate a pulse train at a desired frequency, with the rising edge of the pulse train exactly aligned on the second or some subinterval of the second. Typical time variation for commercial GPS units is ±1 μs or less, over any time period, so two of these units will vary with respect to each other by a maximum of 2 μs. Figure 6 illustrates the alignment that is maintained between pulse trains from two GPS systems, even after they have been running independently for 20 hours. GPS technology is relatively mature, and small, inexpensive receivers are now readily available, so we have decided to utilize it to time-synchronize our systems. As illustrated in Figure 3, we will place GPS units both on the RBU and the GBU.

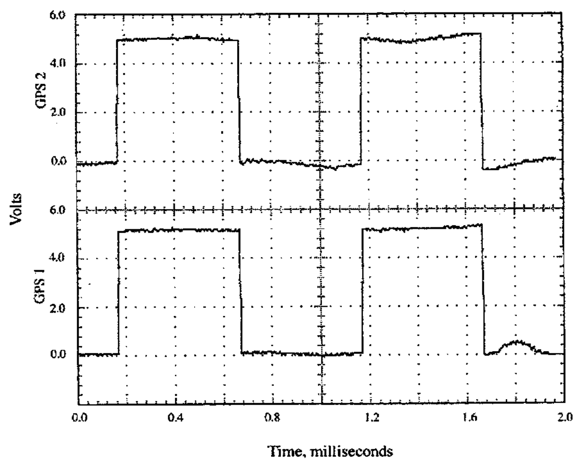

Figure 6. Alignment of Timing Pulses from Two Independent GPS Receivers

Even after establishing time synchronization, however, we will experience some additional timing problems due to the delay in transmitting the rotor data to ground. For example, assume we wish to acquire data at 200 Hz from 20 channels, with a resolution of 12 bits/channel, and transfer that data to the ground-based data system at a rate of 50kbps. This results in a minimum delay of about 5 ms between the time that an RBU data acquisition cycle begins and the time that data is received by the ground computer. In addition, there is the possibility of additional down-link delays from communication drop-outs and re-transmissions due to errors in reception by the ground station. In spite of these delays, this rotor data must be accurately merged with data from the GBU that's taken at exactly the same time. Therefore, each scan of data will be tagged with the time at which it was acquired, accurate to within a millisecond (accurate enough to resolve ambiguities at data rates below 1 kHz). The GBU will have a similar time stamp associated with each scan of data, and the two corresponding scans of data can be easily identified by the GBCU and merged together as a single record on a data disk. This method will also enable us to readily utilize multiple RBUs and/or GBUs.

Two commercial GPS receiver units were purchased to enable us to gain experience with their operation and to evaluate the feasibility of accurately synchronizing data acquisition on multiple data systems. The cost of these units was fairly high - $2500 for a rack-mounted unit and $4600 for a robust unit to be used in the rotor. Although these units have worked quite well, they contain many features that are not required for this application, they are quite large and heavy, and acquiring similar units for each data system would be very expensive. A small (2.8"x1.6"x0.5"), single-card Jupiter® GPS receiver system has recently been obtained from Rockwell International[10]. This system (shown in Figure 7) appears to satisfy all of our timing requirements at a cost of about $185 each in small quantities. The time accuracy of the system is advertised as ±1 μs. It consumes a maximum of 1.2 watts of power and is small enough to be integrated with the PLDS and housed inside the MicroPro. Testing of one of these devices with its supplied antenna reveals that it does maintain lock on multiple satellites and it does continue to synchronize its clock with the GPS clock while rotating as it will on a wind turbine. We will gain further experience with this system on the Wind Eagle data system.

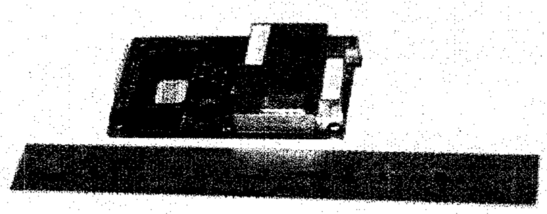

Figure 7. Rockwell Jupiter® GPS Receiver Card

Programmable Logic Device Subsystem (PLDS)

The three subsystems that have been described above will acquire the digital data, cause that acquisition to take place only at precise times and at the user-selected rate, and communicate with the ground-based computer. However, some technique is needed to pass data back and forth between the subsystems and to coordinate subsystem activities in order to meet the system requirements. A programmable logic device (PLD) from Altera Corporation[11] will be used to perform this function.

The particular device that we're using is an ALTERA® 10K70. It is a RAM-based unit, with extremely fast cycle speeds, and it is programmed at power-up with an external ROM. It contains 70,000 programmable logic gates, requires low power, and can be programmed in VHDL (Visic Hardware Design Language), a common language for hardware design. Costs for this device run about $275 in single-unit quantities. More or less powerful devices are available, at correspondingly higher or lower prices. The customized aspect of this project is to design a board for mounting the PLD, to supply the power and provide the necessary input and output connectors for the PLD, and to program the actual functioning of all those logic gates. Although several organizations at SNL are sharing the board development costs, the RBU application is the driver for the design, so the board is being sized to fit into a slot of the MicroPro, draw power from it, and communicate directly with its internal control and data lines. The PLDS will also share data and control lines with the DCS and the TSS units and will have additional lines available for direct monitoring of board activities. A schematic of the PLDS subsystem is shown in Figure 8. We have completed the design and fabrication of this board, and we will have working prototypes in early November, 1997.

The PLD device must be programmed before it can perform any useful functions, and the development of that software is currently underway. The hardware can be simulated in software, so we can develop and debug the software even before the board design is complete. When it is complete, the software will add considerable intelligence and flexibility to the system, enabling us to, among other things:

1. Use a single telemetry system to both program the data acquisition, time synchronization, and data communications subsystems from the ground and also to down-load data from the rotor to the ground.
2. Acquire data from the turbine rotor at very precisely known acquisition times and sample rates. This will include inserting a highly accurate time stamp into each PCM data frame.
3. Turn the rotor-based data acquisition and timing synchronization subsystems power on and off to perform power-on resets and to permit a power conservation mode of operation.
4. Directly monitor the acquired data, via direct connection.
5. Place the rotor-based data into a large, on-board buffer and implement additional data detection and correction protocol to eliminate or minimize data loss. The data could be transferred as many times as necessary to correct corrupted or incomplete data.

6. Set error flags to inform the user of problems such as loss of data due to radio transmission error or loss of GPS satellite lock.
7. Optionally format the PCM data through a UART (Universal Asynchronous Receiver/Transmitter) unit to enable the asynchronous radio transfer of that data to ground. This asynchronous data could then be fed into a PC serial port and decoded to yield the data words, eliminating the need for the relatively expensive PCM decoding hardware. PC-based software will have to be written to perform the necessary decoding.

The PLDS will be designed to mount inside the MicroPro and receive power from that unit. Power consumption is expected to be about 3 watts.

data obtained from GBUs and to subsequently view and process these merged data on the GBCU.

The Wind Eagle application of this system will integrate it with an existing data acquisition system. We will use the Nicolet-supplied software to program the MicroPro. Data from the MicroPro will be transmitted to the ground-based radio/modem and then decoded and placed into computer memory. At this point, a C-language program will utilize MicroPro drivers to retrieve the resultant data from memory and output it as digital words to the existing data system. That data system will merge this digital input with data acquired from ground-based instrumentation and write it all to disk for later analysis utilizing existing software.

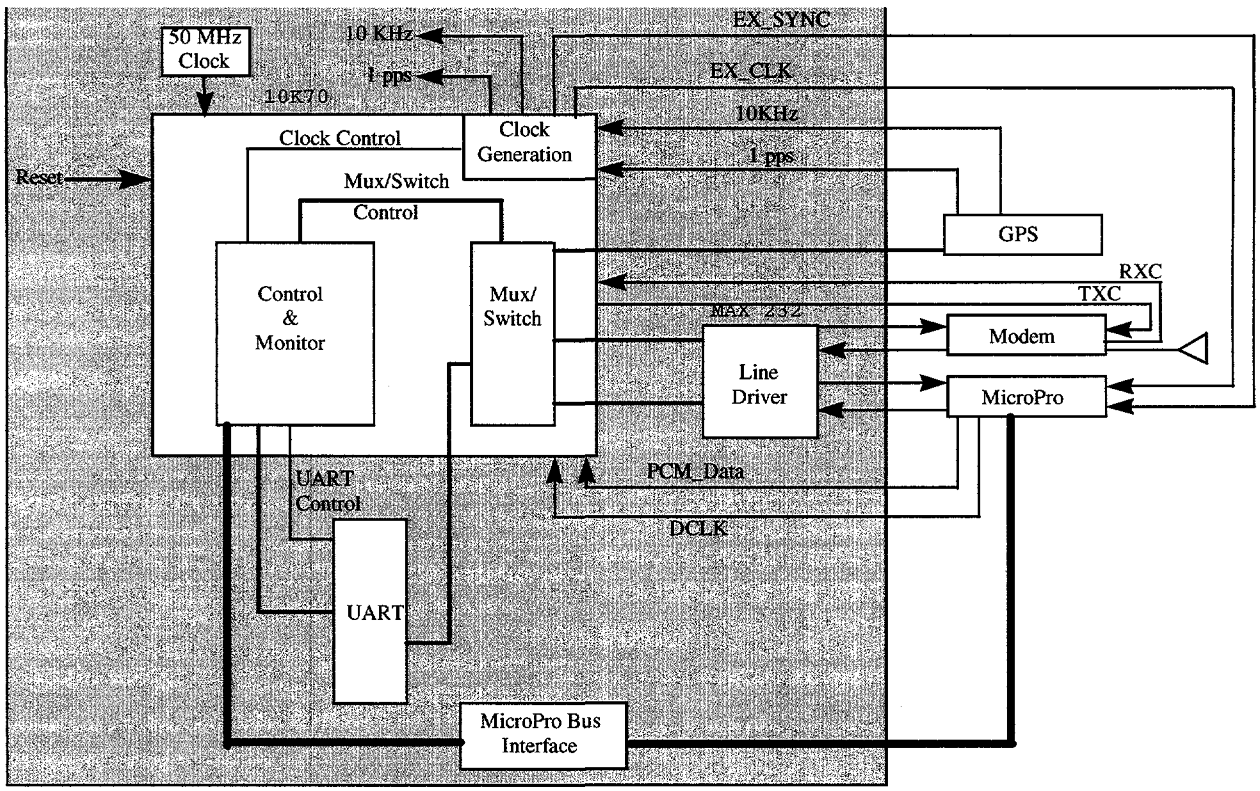

Figure 8. Programmable Logic Device Subsystem Schematic

FUTURE PLANS

Software Development

The RBU described above has the basic capability to acquire data at a user-specified data rate from user-specified channels, with user-specified gain, offset, and frequency roll-off on each channel. These data can be viewed and stored on the ground-based computer using the Nicolet-supplied software. Specialized application software will be developed to merge these data with

The next step in development of a software environment will be the adaptation of National Instruments LabVIEW®-based software that is currently being developed for the ADAS hardware. In this case, a virtual instrument, or VI, software module will be developed to communicate with both the rotor system and the ground system. It will program the RBU, retrieve the decoded rotor data from the ground-based computer, and merge it with the appropriate data from one or more GBUs. At this point, the data will look just like the data acquired from the ADAS systems and we can use the existing ADAS routines to write the data to disk, reduce it, and post process it. The result will be a complete, user-friendly software system that will accomplish everything from hardware setup to data storage to post-test data reduction and analysis, for the price of developing one hardware-specific software module.

Some future applications may require not only data acquisition and analysis, but also real-time feedback control to control turbine output and blade loadings. These may involve some custom software written in a lower-level language to optimize system response capabilities. We have no plans to address these applications at this time.

Additional System Development

In addition to the software, some additional hardware capabilities will be added to improve the performance of this system. First, we intend to specify and acquire a GBU, designed specifically for use with this RBU. The system will have 12-bit accuracy and must accept an external clock pulse to trigger simultaneous data acquisition (or sample and hold, followed by sequential acquisition) on all channels. It will include a full complement of signal-conditioning cards, including amplification, filtering, bridge excitation and completion, that are all computer controllable. The resultant system could be much cheaper than the rotor-based system discussed here, since there are fewer restrictions on size or power consumption. We may, however, decide that the advantages of having identical systems for the RBU and GBU are worth the additional cost that would be incurred. We will also specify and acquire the ground-based computer unit, which will actually control both the RBU and GBU and merge the data before storing, displaying, and post processing it.

The existing radio/modems are adequate for the Wind Eagle application, but faster units may be needed for some future applications. Efforts to locate such units are already underway.

As mentioned above, 110VAC power is available on the rotor of the Wind Eagle turbine, and that will be used to charge a battery which will actually power the RBU. Future tests will require a means of inductively coupling power from the tower up to the rotor, as many of the light-weight machines will not have power available on the rotor. Work on developing such a system has begun.

In addition, we intend to develop system-level software to permit the GBCU to receive the PCM data through a computer serial port and directly decode the data stream with software, rather than using the relatively expensive PCM decoder card to accomplish this function. This would eliminate the need for purchasing a decoder card for each RBU and could well save a few thousand dollars on each new system that we buy.

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, light-weight, modular, rotor-based data acquisition unit or RBU. Initial efforts to procure a commercial system that contained all of the needed features were unsuccessful, so we elected to separately procure or develop the major system components and then integrate them into a system that meets our needs.

The commercially-available Nicolet MicroPro data acquisition subsystem has been selected as the basis upon which to build the RBU. This is a small, rugged, modular, lightweight device that is designed for remote operation in harsh environments. The device can acquire data simultaneously on over 100 strain-gauge or analog channels at up to 500k samples per second, and the time at which the data is sampled can be precisely defined by an external clock pulse. The resultant digital data is output as a digital serial data stream for transmission to a receiving computer located on the ground.

Commercial spread-spectrum radio/modems will be used to transmit control and programming information to the RBU and to retrieve data from it. The spread spectrum technology makes the radio link much less susceptible to interference than conventional, single-frequency radio technology.

Data acquisition times and rates will be synchronized with a ground-based data acquisition unit (GBU) through the use of a GPS receiver card set on each unit. This receiver contains a clock that is continually updated by satellite to keep it within one microsecond of the Universal Time, and it generates a pulse train that is precisely aligned on each second. This pulse train will be used to drive the data acquisition of both units, enabling them to acquire data within two microseconds of each other. A timestamp on each data record will be used to associate the RBU data with the corresponding GBU data.

Finally, a custom built and programmed programmable logic device is being developed to coordinate the operation of these three subsystems. This unit will fit inside the MicroPro data acquisition device and will handle all communications with the user and all communications and data interchange between the data acquisition, the data communications, and the timing synchronization subsystems. Initial application of the system is expected to occur in late 1997 on the Cannon Wind Eagle turbine at the National Wind Test Center near Boulder, Colorado.

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