

Abstract:

Windmills are pleasing to the eye, but the size, violence, and expense of these mega-machines make them even more impressive. They are standalone power plants, 40 to 80 meters above the ground, costing more than a \$1 million USD each with 20+ year life spans, meaning they require maintenance. This article describes the need for a machine monitoring system in wind turbines, how the requirements for a music studio network are similar to a wind turbine's machine monitoring system, and how a FireWire™ music studio networking system has been used to create a condition based maintenance system for wind turbines.

Of Windmills and Recording Studios

by Burke Henehan



Figure 1 Windmills and Recording Studio¹⁰

Wind turbines are deceptive. There is something pleasing about the clean streamlines of the blades, the spindly looking tower, and the steady, seemingly slow rotation pumping out clean power (Figure 1). But the size and expense of these mega-machines make them even more impressive. Anyone who has met the longest tractor-trailer rig they will probably ever see on the road in the USA can attest to the size of the blades, smoothly curved 35 to 50 meter long composites, streaming by in a convoy. The towers, while not as beautiful as the blades have a brutish power about them, requiring extra axles on the trailers that haul the steel beasts. The rotation may seem slow, but that is an illusion of scale, while rotating at 20.4rpm¹, the tips of GE's 1.5MW wind turbines will be traveling at 82m/s, 184mph. Yes, the ends of those blades are going NASCAR speeds. Remember centripetal force ($=MV^2/R$) from physics? If you need a not so gentle reminder, search for "windmill explosion" on youtube.com to see the brutal real world physics.⁷ Then there is the nacelle, where the tower connects to the energy collecting blades. This is where the linear power of the wind the blades transform to rotation is in turn transformed into electrical power. The nacelle contains the shafts, bearings, gearbox, generator, hydraulics, electrical controls, and mechanical controls for this standalone power plant (Figure 2). It houses these in a school bus sized container 40 to 80 meters above the ground.

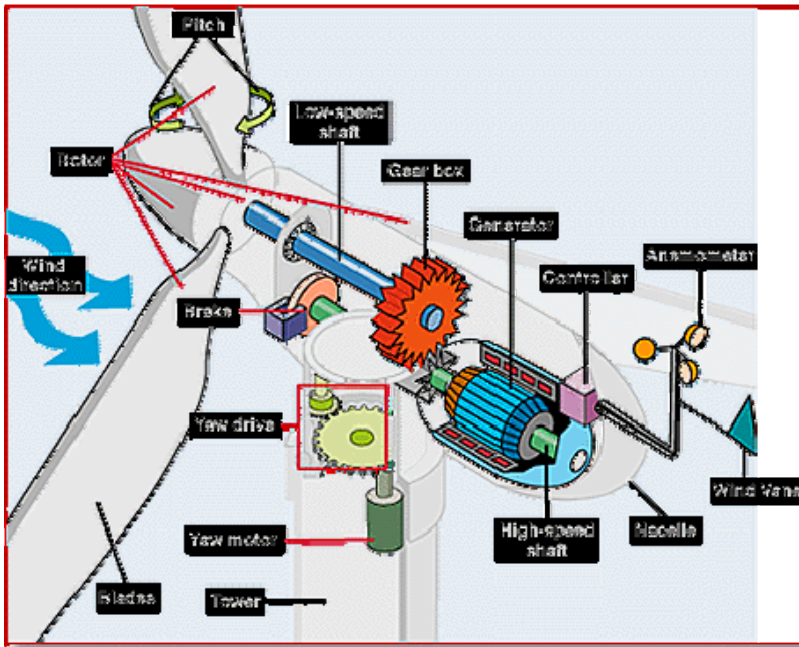


Figure 2 Wind Turbine Components⁹

Since the nacelle must be hoisted so high and the entire assembly moves to point into the wind, the nacelle components are chosen with the minimal weight to do the job, i.e. the “over-design” margins are as small as the designers dare. In total these rotating machines can cost in excess of \$1 Million USD, a large investment in a machine typically located a significant distance from repair facilities and replacement parts. These machines have a 20+ year lifetime, so it is not a matter of if they will require maintenance, only a matter of when and how much. Their installation requires skilled people using a very large, very expensive crane.⁸ Maintenance that requires the same operators and crane is also expensive.

What does this have to do with recording studios? Before I answer that I would like you to think of a more familiar rotating machine – your car engine and transmission. Much of the time the first indication we have of a problem with our car is a new vibration or noise that is not “normal.” Wind turbines are the same, when something is wearing out or starting to go wrong there is a vibration signature which the magic of the fast Fourier transform can turn into numbers easily computer analyzed. Over 80% of maintenance costs (parts, skilled labor, and lost production) are expended on wind turbine blades, generators, gearboxes, and the shaft and bearing³. All of it is rotating machinery, so listening to the vibrations is important. Another word for vibration in the human audio range is of course sound. Therein lies the connection to recording studios. The conversion to digital capture, recording, and transmission has already swept through music recording studios and it has direct applicability to wind turbines. Both have multiple sensors several meters apart, both require precise timing to achieve their goals, and the frequency range of interest is remarkably similar, since music studios are now recording at up to 192KHz sampling rates. TC electronics took the FireWire-based TCD2220 System on Chip (SoC) they created to enable the networking of digital music recording studios and built a smaller “digital music LAN” for the specialized purpose of recording and diagnosing the music of wind turbines (music at least to us engineers). The TCD2220 will packetize the samples to be transported across FireWire along with a time stamp from the local cycle timer clock (more about that later) to precisely recreate the sample clock. IEEE 1394-2008 was chosen because it supports all the usual networking requirements:

1. Market proven with millions of nodes incorporated into shipping consumer, automotive, industrial, and aerospace applications
2. Based on international layered protocol standards (IEEE, IEC, IETF, etc.)
3. Multiple vendors for silicon and software with highly integrated SoC's available with little or no firmware development required
4. Peer to peer capability to eliminate single points of failure
5. Highly reliable with a Bit Error Rate $< 10^{-12}$
6. Available in industrial and military temperature ranges
7. Cable lengths up to 100m
8. Flexible choices of cabling:
 - a. cheap UTP5e in nominal environments
 - b. shielded twisted pair or coax for noisy environments
 - c. optical fiber (glass and plastic) for explosive, corrosive, or high EM field environments. We are talking about megawatt generators often located at sea.
9. Power over the cable that eliminates the need for a power supply for every node

But more importantly FireWire has specific unique functionality that makes it the best choice for this industrial task:

- #1. Precise network-wide time, i.e. a hardware clock in each node
- #2. Alignment of sample clocks network wide
- #3. Bounded latency of data sample packets
- #4. Standardized transport of time sensitive sampled data using IEC61883-6
- #5. Standardized allocation of available bandwidth to prevent over subscribing
- #6. Hardware guaranteed delivery of control packets
- #7. Flexible cabling topologies including tree, star, ring, daisy-chain, etc. (Figure 3)
- #8. Automatic hardware cable redundancy using loop-free build and loop healing hardware
- #9. Very efficient, utilization of over 90+% of bandwidth possible

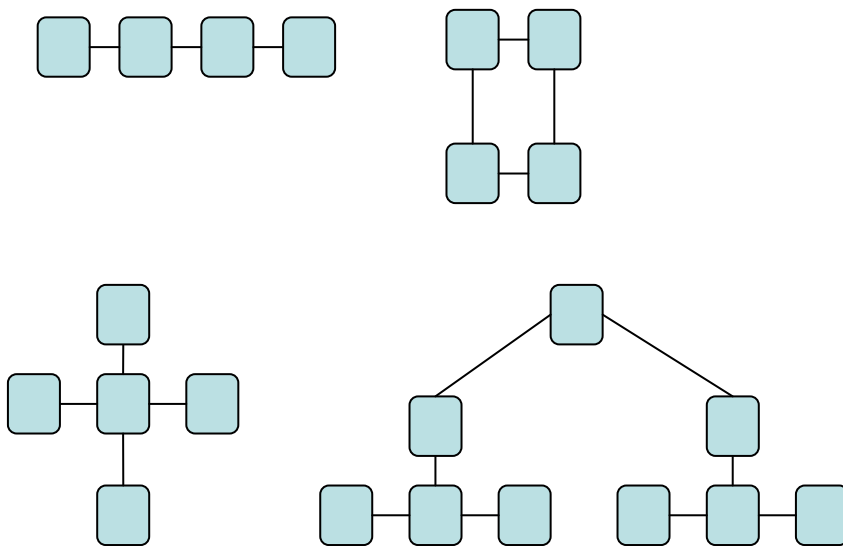


Figure 3 Cable Topologies: Clockwise from upper left, Daisy-Chain, Ring, Tree, Star

In order to do system level analysis of sampled data it is important that the data is sampled at all nodes at the same time using the same sample clock having approximately the same phase. The

design of FireWire has the concept of precise network time (#1), guaranteed bounded latency (#3), and guaranteed delivery (#6) built into the lower hardware layers. These features were not tacked on afterthoughts; they are fundamental building blocks. The cycle timer coupled with the cycle start packet mechanism synchronizes every node's local cycle timer clock to the cycle master's 24.576MHz cycle timer clock every 125us. This enables a precise time stamp to be associated with each sample and for there to be a precise correlation between the time stamps at every node (#1,#2). This clock synchronization allows analysis not only in the frequency domain, but also in the time domain to isolate when an event occurred with 40.69ns resolution. Theoretically that 40.69ns resolution would allow a precision of less than a millimeter in steel (5790m/s)⁵, and less than 0.1mm in air (343m/s)⁵, though the practical limitations of the sensor and analog to digital converter can degrade this substantially. Advanced techniques from the music studio industry, which has a thing about perfect reproduction, allow the sample clocks of the sensors to be reproduced with jitter less than 30ps^3 RMS (#2, #4). This prevents aliasing errors in the sampled PCM data and enables exquisite sensor recording to be done. The isochronous service gives hardware guaranteed bounded latency enabling the sensor node to transport the sampled data on time, every time (#3). This allows small defined buffer requirements, typically less than 300us worth of data at a maximum. The BOSS (bus owner supervisor selector) arbitration does hardware arbitration in parallel with the data transmission. BOSS allows very fast handoff to the next node to transmit, making for high efficiency (#9), no collisions, no back-offs, no slowdowns. The automatic cable redundancy happens in the physical layer silicon. For example, when a ring topology is connected, the hardware senses that a "closed loop" has been formed using the loop-free build mechanisms and automatically electrically disables one of the connections. Since the topology is a ring all nodes are still connected and can still communicate. Now if one of the active connections is disconnected, the hardware senses the disconnect and uses the loop healing mechanisms to rebuild the topology and re-enable the previously electrically disabled connection (Figure 4). So any one cable can be broken, but all nodes will still be able to communicate. Additional redundancy is as simple as connecting more cables, though certain topologies are better than others.

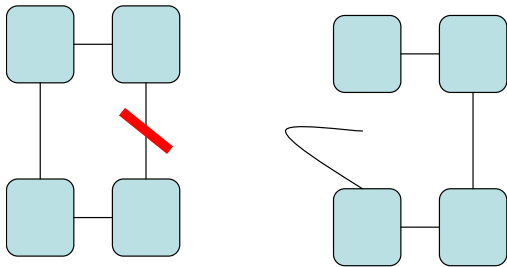


Figure 4 Ring topology with one leg electrically disabled, then restored if left most cable disconnected.

These are the reasons FireWire was chosen to network the music industry. And what was developed and optimized in the music industry has spread to other industries as Moore's law continues its push on silicon unit prices, i.e. into wind turbine diagnostics.

Diagnosing what is wrong before it goes terribly wrong and fixing it is called Condition Based Maintenance. CBM saves money, time, and logistics by allowing preventative maintenance to just be done when required, based on a closed loop feedback system, rather than simple scheduled "open-loop" replacement. So rather than replace expensive components based on hours of service, whether needed or not, they are replaced when they need to be. Maintenance is then done before anything catastrophic happens (looked at the video yet?). It allows a finite number of maintenance technicians with a finite number of spare parts to use their time and parts for the

machines most in need. Wind farm operators use CBM to limit catastrophic failure costs, lost energy production, and reduce the damage to components (Figure 5). It allows more latitude to choose when to do the maintenance, allowing the scheduled use of expensive equipment for multiple tasks. And in the case of ocean based machines, it allows maintenance to be scheduled at a convenient, safe time instead of being forced out into the Godforsaken Sea⁶.

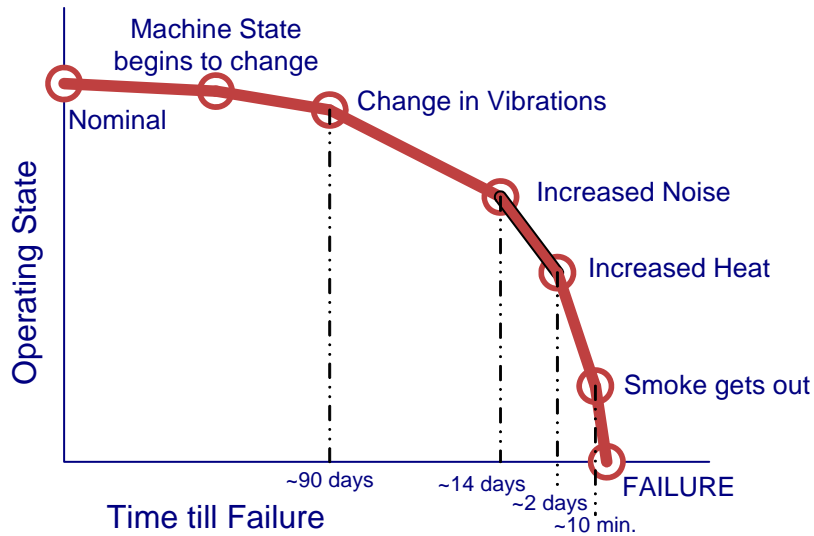


Figure 5 Vibrations/noise may provide days to weeks of lead time before the actual failure⁴

FireWire is as natural for implementing condition-based maintenance as it is for music studios. Its precise network wide clock, large bandwidth, guaranteed delivery, bounded latency, ability to handle long cable runs with a wide variety of cables, cable redundancy, etc, make it a natural fit for many types of machines that benefit from CBM. It may not be as sexy as Sade¹¹, but listening to and understanding the music of the machines saves time and money we can spend on new music, listened to in our warm dry living room.

- 1 GE 1.5MW Wind Turbine Brochure
http://www.gepower.com/prod_serv/products/wind_turbines/en/downloads/ge_15_brochure.pdf
- 2 ASSESSMENT AND OPTIMISATION OF OPERATION AND MAINTENANCE OF OFFSHORE WIND TURBINES by L.W.M.M. Rademakers, H. Braam, M.B. Zaaier, G.J.W. van Bussel
- 3 Advantages of using IEEE1394 for Industrial Condition Monitoring System by TC Applied Technologies.
http://www.tctechnologies.tc/index.php?option=com_content&view=article&id=30&Itemid=29
- 4 Based on data from National Instruments Machine Condition Monitoring Technical Library web page
- 5 Handbook of Chemistry and Physics, 65th ed., Chemical Rubber Company.
- 6 Godforsaken Sea by Derek Lundy

- 7 Youtube Wind Turbine Explosion <http://www.youtube.com/watch?v=7nSB1SdVHqQ>
- 8 Youtube Wind Turbine Construction
<http://www.youtube.com/watch?v=DxOYwWu7Xcc>
- 9 United States Department of Energy, Energy Efficiency and Renewable Energy, Wind and Hydropower Technologies web site.
http://www1.eere.energy.gov/windandhydro/wind_how.html
- 10 Courtesy of United States Department of Energy, Credit Corey Babcock
http://www.nrel.gov/data/pix/searchpix.php?getrec=10629&display_type=verbose&search_reverse=1
- 11 Sade official web site. <http://www.sade.com/>

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