Pitch-Teeter Coupling and the Torque Limiting Gearbox: Cost-Effective Methods of Fatigue Load Reduction

Geoff Henderson, Managing Director
Wind Torque Limited

Abstract

The nascent New Zealand wind industry faces a very stringent cost target of 5-6 c/kWh. Meeting this target in New Zealand's high wind regimes requires a particularly cost-effective and reliable windmill design. This paper outlines the main features of such a design, the Windflow 500, which is based on two advanced technologies which have been proven to remove major categories of fatigue loads:

* a two-bladed teetering rotor with full-span pitch control and pitch-teeter coupling
* the patented torque limiting gearbox (TLG) system of power control.

These technologies are compared with leading wind power technologies and found to provide major advantages. The paper concludes that these technologies, necessary for the lean and mean market in New Zealand, can also provide the basis for a profitable export industry.

Introduction

In recent years, the cost of energy from the latest wind power technology has frequently been quoted as 6-8 c/kWh. This is based the use of imported windmills on sites with 10 m/s annual mean wind speed or greater and is similar to the delivered cost of electricity. Thus wind power has now established itself among the least cost renewable options. However the value of new embedded energy is around 5 c/kWh plus or minus 0.5 c/kWh. This is due to the short-term availability of low-cost gas resources and the absence of environmental cost internalisation or incentives for wind power to recognise its lack of environmental costs.

Therefore there remains a gap between the commonly quoted cost of wind power and its market value. Wind Torque Ltd has consistently argued that a key to closing this gap is to adopt the most cost-effective and reliable technologies and combine them in a locally manufactured windmill design. This paper outlines the main features of such a design, the Windflow 500 (see Figure 1), which is to be developed in New Zealand. The Windflow 500 is based on two advanced technologies which were originally developed in Britain while the author was employed as project engineer with the leading UK wind power R&D firm, Wind Energy Group Ltd (WEG). One of the technologies, the rotor, is the same as that embodied on WEG's successful MS3 series of windmills. The other is a system of power control invented by the author, who holds patents in the New Zealand, Australia and the USA.

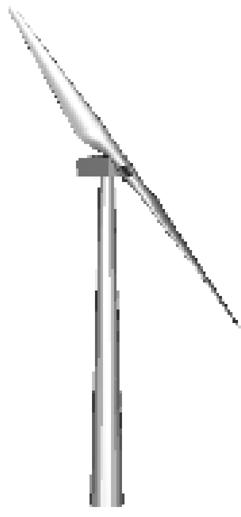


Figure 1 - The Windflow 500

The Design Problem

The basic windmill design problem is to convert wind energy to electrical, with minimum installation and running costs. For minimum installed cost, weight per unit output is an important indicator, i.e. kg/kW or kg/(kWh/yr). For minimum running costs, reliability must be high (greater than 95%), and the design life must be long (20 years typically). These two requirements are conflicting in the classic manner of engineering problems. Correct engineering practice requires that weight reduction should only be made

if robustness and durability are not compromised. This means that the applied loads must be fully understood and quantified, in particular the aerodynamic fatigue (operating) loads.

The Teetering 2-Bladed Rotor

The Windflow 500, like the WEG MS3, uses a 2-bladed teetering rotor with full-span pitch control and mechanical pitch-teeter coupling. The principal advantage of a 2-blader is that it can be mounted on a teeter hinge. This eliminates the large overturning moments caused by asymmetrical rotor loading, which are experienced by fixed-hub three-bladers. These overturning moments are a major source of fatigue loads on the entire windmill structure.

The advantages of teetering have long been recognised, but a major drawback has deterred many manufacturers. Simple teetering is a resonant phenomenon (Ref. 1). "Simple teetering" means that blade pitch does not change as the rotor teeters, for example if the teetering 2-blader is fixed-pitch, stall-regulated. For such machines the resonance become unstable when the blades stall, as they are designed to do in above-rated winds. In these conditions the teeter motion will have a theoretically infinite amplitude, causing violent teeter excursions and destructive restraint loads as the windmill literally bangs itself to pieces.

From a conservative engineering point of view, it would be preferable to find an alternative method of teetering which takes the system away from resonance entirely.

Pitch-Teeter Coupling

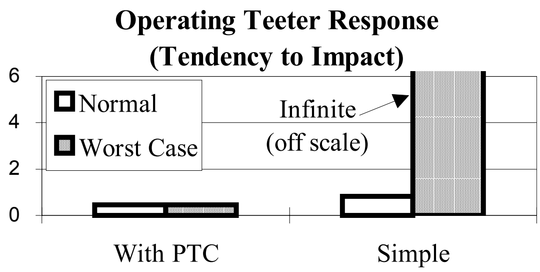
Pitch regulation provides two benefits with respect to the problem of unstable teeter resonance:

a) if the design allows pitching while retaining simple teetering, the motion will still be resonant, but not unstably so because pitch-regulation prevents the blades from stalling

b) if the pitch and teeter motions are coupled because of the geometry of the pitch-change mechanism, a powerful restoring force proportional to teeter displacement is created which changes the natural frequency of teetering <u>away from resonance</u>. This minimises the teeter restraint loads in all conditions.

<u>Figure 2 - Benefits of Pitch-Teeter Coupling</u>

This shows the teeter response at the normal and worst case operating points for a teetered rotor with and without pitch-teeter coupling.



The advantages of mechanical pitch-teeter coupling (PTC) were first analyzed by Henderson et al (Ref. 1) during the development of the WEG MS3 in 1988. Measurements of operational, start-up and shut-down teeter restraint loads vindicated the design. For example it was found that fatigue overturning moments on the main shaft from this 33 m rotor were lower than those experienced with the 3-bladed, 25 m, MS-2 windmill which was the MS3's predecessor.

The TLG System of Power Control

The TLG system is a narrow-band variable speed (VS) system which uses simple, well established hydraulic concepts and components. It includes a differential stage in the gearbox to allow the windmill rotor speed to vary independently of the generator speed. The torque on the differential stage, and hence the entire transmission, is controlled by a hydrostatic torque reaction circuit, with the two main components being a radial piston pump and a relief valve. In addition the control system is simplified from the conventional configuration, with blade pitch being varied in response to speed, not power, variations.

A basic prototype of the TLG system was installed in a three-bladed, 25 m, 200 kW windmill in Devon, England under a research project largely funded by the UK Department of Energy. It has been running successfully, with high reliability, since mid-1990. The system has been patented by the author in New Zealand, Australia and the U.S.A.

Like other VS systems the TLG system solves the problem of power control. Conventional windmills in the 1980's and early 1990's used fixed ratio transmissions (simple industrial gearboxes) to convert the windmill rotor speed (typically 50 rpm) to the generator speed (typically 1500 rpm). The speed of the generator is set by the 50 or 60 Hz grid to which it is connected. So with a fixed ratio gearbox, fluctuations in wind power input can not be accommodated by speed fluctuations, except for some small compliance provided by the slip characteristic of induction generators. This results in high power and torque fluctuations (typically 50-70% above and below rated). Among other things this means that the gearbox must be significantly over-designed (with a service factor generally at least 2.0). The gearbox, the single most expensive component, becomes twice as heavy and expensive as it might otherwise be.

It has long been recognised that VS operation solves this technical problem, because instantaneous wind power fluctuations can be absorbed by speed variations and the pitch control system has time to respond to mean wind variations. However the main focus of VS development has been on electrical methods, using power electronics to allow the generator speed to vary. The problems here are:

a) cost of power electronics
b) inefficiency as the power electronics handle all the generator power all the time
c) reliability concerns because of heating effects and the novelty of some of the latest semi-conductor devices being used
d) generator- and line-side harmonics (Ref. 4).

Compared to electronic VS systems, the hydraulic torque-limiting pump is light, compact and inherently suits low speed, stationary and reversing applications. The TLG system solves all of the commercial and technical problems associated with electronic VS systems (Ref. 2). It is:

a) low cost because it handles only 3% of the power
b) efficient because it handles less than 1% of the power in below rated winds (when efficiency is important)
c) reliable because it uses hydraulic components with a long track record in normal industrial applications
d) not a source of generator- or line-side harmonics.

A major additional benefit is that the TLG system enables the use of a standard synchronous generator directly on line (conventional windmills use induction generators in order to provide some torsional compliance). The synchronous generator is considerably less expensive at 500 kW rating and has better electrical characteristics than the induction generator.

The system is clearly cost-effective because it will enable a 60% uprating of the gearbox (by reducing the service factor to around 1.25) for an incremental cost of 20% of the gearbox cost, 25% of the hydraulic system cost and a saving of about 33% on the generator cost. To achieve the same uprating conventionally, those sub-systems would normally cost an extra 60%, whereas the TLG system results in only a 10% increase. This is about $20/kW compared to electronic VS systems at $75-150/kW (Ref. 3).

Conclusion

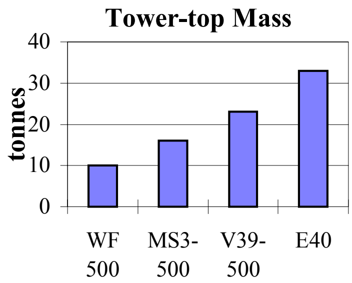
With such high mean wind speeds in New Zealand, any windmill design must be robust against fatigue loads, providing high reliability and low maintenance costs. A robust design which is cost-effective and reliable necessitates technologies which <u>fundamentally reduce fatigue loads</u>. This is the only way to reduce machine weight without compromising reliability. In such an arduous economic climate as prevails in New Zealand, the machine must be able to achieve 95-99% availability with a minimum of maintenance costs. Heavyweight technologies which achieve high availability while taking high fatigue loads "on the chin" have little future because of inherently high capital costs. At the same time, the semi-routine retrofits or rebuilds following mechanical failure which characterise a lot of light-weight designs can not be tolerated because of high maintenance costs.

The Windflow 500 combines two proven technologies for reduction of fatigue loads:

* 2-bladed rotor with mechanical PTC
* TLG system of power control.

Well-established, conservative design procedures can be maintained and reliability is not compromised. The design has also been optimised for New Zealand's high wind conditions by matching the 33 m rotor to the 500 kW rating. The overall result is a windmill design which is about <u>half the weight of comparably reliable 3-bladers</u> as shown by the following comparison.

	Diameter (m)	Power (kW)	Tower-top mass (t)
2-bladers with PTC:			
Windflow 500	33	500	10
WEG MS3-500	39	500	16
3-bladers:			
Vestas V39-500	39	500	23
Enercon E40	40	500	33



These design economies are the result of fundamental fatigue load reduction. The benefits of teetering are achieved without incurring the penalties of teeter resonance. The benefits of VS operation are achieved without incurring the high costs, complexity and inefficiencies of power electronic systems.

By getting these fundamentals right, a technology platform is provided for local manufacturing for the New Zealand market. Importantly the reduced material costs will enable profitable manufacturing at prices which can compete with established European designs, even when the latter are being marketed with diminishing profit margins. Once local manufacturing is established, it will serve as a platform for the establishment of an export industry which could one day be as important to New Zealand as it presently is to Denmark.

References

1. Henderson, G.M., Haines, R.S. and Quarton, D.C. 1989 - "The Analysis and Design Implications of Pitch-Teeter Coupling", pp 799-803, *Proceedings of EWEC '89 European Wind Energy Conference and Exhibition*, Glasgow, Peter Peregrinus Ltd

2. Henderson, G.M., Bossanyi, E.A., Haines, R.S. and Sauven, R.H. - "Synchronous Wind Power Generation by means of a Torque-limiting Gearbox", pp 41-46, Wind Energy Conversion 1990, *Proc. 12th BWEA Conference*, Norwich, Mechanical Engineering Publications Ltd, 1990

3. Follings, F.J. 1989 - "Economic Optimization of Wind Power Plants", pp 983-987, *Proceedings of EWEC '89 European Wind Energy Conference and Exhibition*, Glasgow, Peter Peregrinus Ltd

4. Carlson, O. and Hylander, J. 1989 - "Electrical System with Frequency Convertors for Variable Speed Operation of Wind Turbines", pp 774-778, *Proceedings of EWEC '89 European Wind Energy Conference and Exhibition*, Glasgow, Peter Peregrinus Ltd