# Synchronous and Synchronised Wind Power Generation

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**Abstract**
In July 2003 New Zealand's first indigenous grid connected wind turbine was officially opened at Gebbies Pass, Christchurch. The Windflow 500 differs from traditional windmills in several important ways, not the least of which is its ability to run a synchronous generator directly online.

The synchronous generator has many inherent cost and electrical advantages when compared with induction generators. Even induction generators fitted with sophisticated power electronics are struggling to meet the requirements of utility companies around the world. These benefits will be explored by considering Windflow's connection arrangement with Orion Ltd.

As a synchronous generator is self-exciting, it is feasible that the Windflow system could also be adapted to generate in islanded mode and enable diesel generators to be completely shut down, thus maximising fuel savings in the system. This has significant implications for the remote communities and networks found throughout the South Pacific, as well as demonstrating its superior characteristics in grid-connected applications.

## 1.0 Introduction

Over the last decade installed wind power generation has increased dramatically and is now considered a mainstream form of generation. This growth has forced the electrical transmission industry to start looking at wind power generation in a more serious light.

With increasing wind energy penetration, wind power generators using induction technology are beginning to have a significant affect on the stability and quality of grid operation. As a result regulations are being set for WTG's so that the reliability of the grid will be maintained.

This paper demonstrates the differences between the generation system of the Windflow 500 from other commercially available WTG's and to highlight its advantages. A brief introduction to the technology that allows the use of a synchronised synchronous generator is given to provide the reader with an understanding of the patented Torque Limiting Gearbox (TLG) and why it is central to the Windflow design. The advantages of a synchronous generator are then highlighted and the implementation of those advantages is explained. It is then shown how a synchronous generator in a WTG will affect grid security and power quality.

A brief explanation is presented of how the TLG system and a synchronous generator may be able to be used in conjunction with diesel generator sets, fuel cells or any other controllable off grid generation. Finally a case study of the Windflow 500 connection agreement at Gebbies Pass with the Orion Network is given.

## 2.0 The Torque Limiting Gearbox

Table 2.1 below summarises the comparison between the TLG system and four competing electrical VS systems. This paper will focus on one of those benefits, the synchronised synchronous generator.

| | **TLG System** | **Singly-fed VS Generator** | **DFIG** | **Variable Slip IG** | **Electrical/ Mechanical VS** |
|---|---|---|---|---|---|
| Example | WEG MS2, Windflow | Enercon | Kenetech/ Enron/GE, Vestas et al | Vestas et al | WEG LS1 |
| Track Record | 1990-96, 2003-2004 | 1992-2004 | 1998-2004 | 1995-2004 | 1989-95 |
| VS System Power Rating (% of windmill power rating) | 5%[1] | 100% | 40% | 10% | 10% |
| Synchronous Generator: | Yes[1] | Yes | No | No | Yes |
| If Synchronous, Synchronised? | Yes | No | N/A | N/A | Yes |
| "Off-the-shelf" Generator | Yes[1,2] | No | No | No | No |
| "Off-the-shelf" VS System Components | Yes[1,3] | No | No | No | No |
| VS System simplifies control system | Yes[1,4] | No | No | No | No |
| VS System introduces new sub-systems? | No[1,5] | Yes | Yes | Yes | Yes |
| Power Electronic System | No | Yes | Yes | No | Yes |
| Slip rings | No | No | Yes | No | No |
| Stationary/low speed electric machine | No | No | No | No | Yes |
| Rotating slip controller/optical comms | No | No | No | Yes | No |
| Associated Losses in below-rated Winds | No[1] | Yes[6] | Yes[6] | Yes | Yes[6] |
| Low inertia VS system | Yes[1,7] | No | No | No | No |
| Electrical Faults affect Torque Limiting? | No[1,7] | Yes | Yes | Yes | Yes |
| Generator-side Harmonics? | No[1,7] | Yes | Yes | No | Yes |

TABLE 2.1 – COMPARISON OF TLG SYSTEM WITH COMPETING VS SYSTEMS

The TLG allows for a constant speed output shaft while the input shaft speed may vary. This is achieved by having mechanical slip introduced by a hydraulic pump reacting part of a differential epicyclic stage in the gearbox. The mechanical slip gives variable speed on the wind turbine rotor, with speed excursions being governed by the pitch control system. The torque level at which slip occurs is fully adjustable via a relief valve and under normal operating conditions would be set at a level equivalent to the MW rating of the generator. As a result of having no speed transients on the gearbox output shaft it is possible to use a synchronous generator as the electromechanical energy converter.

1 All these factors provide capital and running cost benefits to the TLG system.
2 Off-the-shelf synchronous generators cost about NZ$20,000 less than standard (let alone non-standard) induction generators at 500 kW scale. This is because they are mass-produced for the standby and mobile diesel generator markets.
3 TLG hydraulics use proven industrial components (radial piston pump, relief valve etc).
4 Control system for TLG has only to control blade pitch to regulate windmill rotor speed (a function already required).
5 TLG is just an extension to existing gearbox and hydraulic sub-systems.
6 Increased aerodynamic energy capture below rated may or may not offset these losses.
7 Referred generator inertia, electrical faults and/or generator-side harmonics undermine the fundamental torque-limiting benefit (with respect to gearbox duty) for all options except the TLG system.

By controlling the torque level that the TLG slips at, the output power of the wind turbine is controlled. To stop the generator from motoring the blades during a wind lull, a one way sprag clutch is fitted in the drive train. See Refs 1-3 for further details and advantages of the TLG system.

## 3.0 Generator Types

It is important to distinguish between different types of generator technology currently available in WTG's.

### 3.1 Synchronised Synchronous

A synchronous generator rotates at a fixed speed determined by the frequency of the supply it is connected to and the number of poles wound onto the stator. These generators are the standard topology used in power stations and can be considered the power industry norm. This is the generator topology installed in the Windflow 500.

A synchronous generator is self exciting and can be configured to run in either VAR import or export modes that are fully controllable and do not require heavy duty power electronics.

### 3.2 Unsynchronised Synchronous

These generators are found in the ABB Windformer, Enercon, etc. This topology is termed synchronous as the generated frequency is synchronous with the rotor rotation. But because the generated frequency is not synchronised with the grid frequency, power electronics are necessary to rectify and then invert the generated power to be grid compatible. Excitation is either provided with rotor windings or permanent magnets.

### 3.3 Asynchronous – Induction

An induction generator rotates at a speed asynchronous to grid frequency which is determined by grid frequency and load. These machines are not self exciting and require reactive power to either be supplied from the grid or supplied separately by static or dynamic VAR compensators. Most wind turbines utilise the induction generator technology (or variations thereof) because the slip provides torsional compliance. Combined with various methods of controlling the rotor's electrical characteristics, it can provide narrow- or broad-band variable speed capability.

Variations to the induction generator include the doubly fed induction generator DFIG (which requires associated power electronics) and the variable slip generator (e.g. Vestas Optislip), but these are still characteristically induction machines.

| Manufacturer | Generator Type |
|---|---|
| Vestas | Opti-Slip, DFIG |
| GE | DFIG, but moving to unsynchronised synchronous |
| Enercon | Unsynchronised Synchronous |
| NEG Micon | DFIG, Standard Induction |
| Lagerwey | Unsynchronised Synchronous |
| Windflow Technology | Synchronous Synchronised |

Table 3.1: WTG Manufacturer and Generator Type

## 4.0 Advantages of Synchronous Generators

4.1 VAr Capability

Synchronised, synchronous generators are inherently able to control kVAr import and export (in other words they can control power factor) by using the excitation on the generator rotor. The other generation technologies described in Section 3.0 either require separate excitation systems or have excitation capability built into their necessary power electronics.

Figure 4.1 shows the capability curve of the generator used in the Windflow 500. This shows the amount of kVArs that can be imported or exported at any operating real power.

The generator may be dynamically controlled to run in one of three modes:

- Voltage control (keeping terminal voltage constant at a fixed level).
- Power factor control (allowing power factor of the generator, or plant, to be controlled, usually set to near unity).
- VAr control (allowing VAr export/import to be set at a level or maximised within the capacity of the generator).

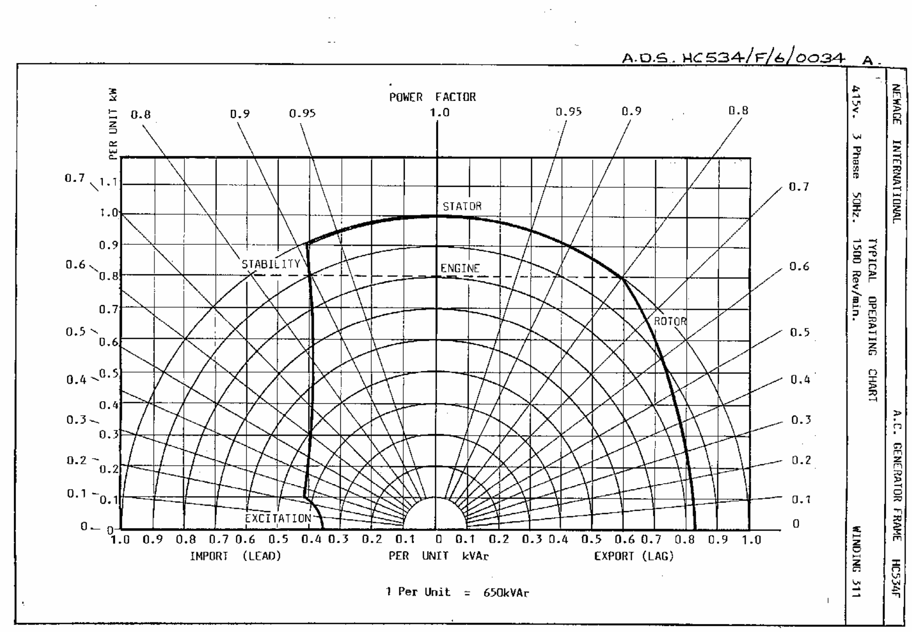


Figure 4.1: Capability curve of the Windflow 500 generator.

Other WTG types are now being required to provide VAr generation capability. These topologies all require sophisticated and expensive electronics to achieve this. Some topologies require power electronics rated to the full load current of the WTG and thus need sophisticated cooling designs. As no significant power electronics are used with a synchronised synchronous generator, harmonic issues associated with high frequency switching are not a concern.

By being able to import and export kVArs the number of potential wind farm (or individual sites) increases. This is because VAr control supports voltage and many wind farms face restrictions with the available local grid connection with respect to voltage rise. The following is an example of one such real life situation.

Example:

Load flow studies for the connection of six Windflow 500 kW wind turbines into an 11 kV distribution network showed that there were likely to be voltage rise problems. As a result more existing line was required to be upgraded to larger conductor. Or the option of generating at 0.86 pf was proposed.

By generating at this pf, more reactive current flows in the line hence increasing voltage drop and suppressing the voltage rise. This option is attainable without adding any extras onto the Windflow 500 topology and without affecting the real power generation.

4.2 Other Advantages

- Available "off the shelf" from a number of suppliers
- Well understood by power system engineers and is the generation "norm"
- Size and weight advantages
- No soft start requirements or flicker problems during start-up
- Readily available in 400 V – 15 kV output voltages
- Self excited and doesn't need a fixed grid to generate

4.3 Disadvantages

- Requires fixed speed input
- Needs synchronising with the grid which requires a sync relay ($800) which may delay reconnection times in the event of a grid fault which causes WTG isolation.

## 5.0 Grid Stability and Power Quality

As wind power is gaining more and more penetration, its intermittent nature and unconventional generators are beginning to concern system operators. Internationally there is growing need for WTG's to provide an acceptable calculable risk for grid stability and power quality. Any compliance measures necessary will be at the expense of the WTG.

5.1 Grid Stability (Fault Ride Through)

It is a requirement of the system operator that a generator shall endeavour to support the grid under fault conditions. This means that if there is a fault on the grid, a generator is to remain connected (within certain limits) and try to support the grid by generating VArs to maintain voltage. Normally expected faults are 1, 2 and 3 phase faults to earth (Ref. 4). The worst of these faults is a 3 phase to earth (or line) at a location near to the generator. This type of fault is reasonably rare (Ref. 5). Figure 5.1 shows the minimum network voltage characteristics that WTG's are required to ride through as required by Transpower (Ref. 4).

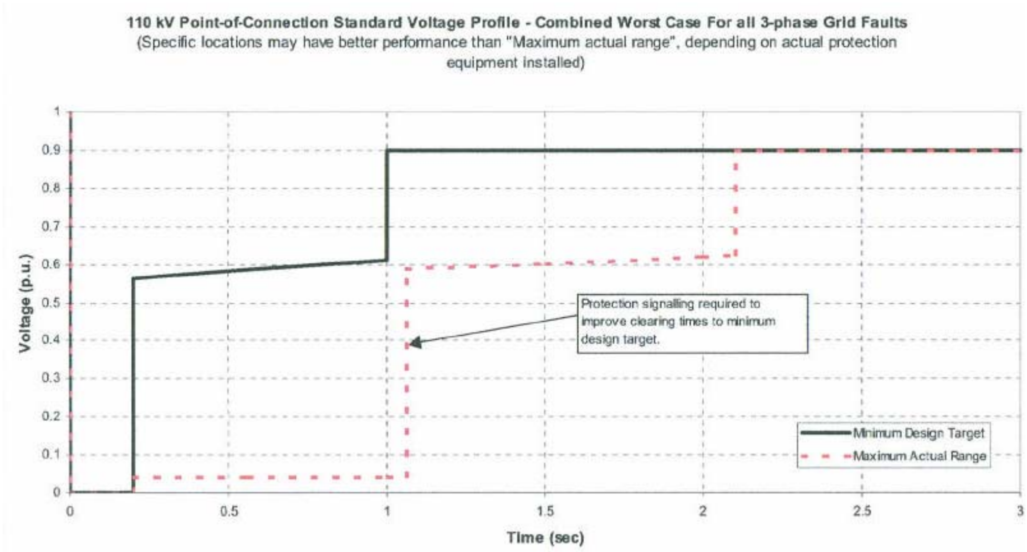


Figure 5.1: Transpower minimum fault ride through requirement.

In NZ, the generator and system operator work together to ensure that the level of fault ride through is known so that appropriate control actions may be taken for different faults. The required capability of fault ride through is mainly determined by the injection point to the grid, proximity to other generation, proximity to constrained lines and the type/probability of certain faults occurring. To determine this, power system modelling is required. Results of the modelling may show that protection or system changes for either (or both) the grid or generator are needed. The cost of these changes would be passed onto the generator. Therefore the broader the fault ride through capability of a generator, the more grid injection points become economically viable.

Synchronised synchronous generators are inherently able to ride through a large range of faults. The risk however is that during a prolonged fault, when there is no electrical torque, the wind accelerates the wind turbine enough that it loses synchronism with the grid.

Studies on fault ride through for the Windflow 500 are due to start shortly. It is expected that the fault ride through capability will be good enough to ride through faults equivalent to those of standard synchronised synchronous generators. If necessary fault ride through capability can be increased by simple control of the torque limiting system which would reduce the chance of loss of synchronism. This would be accomplished by using the TLG to effectively isolate the generator from the blades and therefore eliminate any acceleration due to the wind. Pitch control of the blades would then immediately act to control any potential turbine over-speed.

There will always be potential faults that would require any form of generation to disconnect. For a synchronised synchronous generator, this situation can be protected for using loss of synchronisation and under voltage relays. These take the generator offline until system voltage is restored. At this time the generator will then synchronise with the grid, which may take 5 – 30 s. This would be no worse than many other WTG topologies.

Induction generators are not able to supply VArs to the grid during a fault and therefore without sophisticated power electronics do not comply with system operator regulations.

DFIG's are able to supply VARs during a grid fault until the system voltage drops to a level outside of the tolerance of the power electronics. At this point a crowbar type protection is activated on the rotor which in effect shorts the rotor thus turning the generator into an induction generator until the system voltage is restored (Ref. 6). This is not supporting the grid.

Some synchronous unsynchronised generators (principally Enercon of the major WTG manufacturers but now GE as well) are meeting the requirements of some foreign system operators by utilising their necessary power electronics (Ref. 7). Whilst this is a technical solution, it is not as cost-effective as the use of a synchronised synchronous generator.

<u>5.2 Frequency Support</u>

The Electricity Governance Rules (EGRs) require generators to make maximum possible injection contribution to maintain frequency within certain bounds of frequency deviation. In under-frequency excursions, the WTG should maintain its pre-event output (this would obviously depend on the wind regime). In over-frequency excursions the WTG should remain connected and possibly respond to the over-frequency.

In under- or over-frequency events the TLG (as configured presently) will tend to maintain constant torque in above-rated winds. In below-rated winds torque will vary with wind speed. Thus there are two possibilities depending on whether operating above- or below-rated:

- Below rated, power will vary with wind speed, but across a wind farm will remain steady during a short-term transient
- Above rated, power will reduce or increase proportionately to the frequency excursion (since torque remains constant).

As a small refinement to this, power can instead be maintained constant by introducing active control of the TL relief valve setting.

Furthermore, if required or incentivised to do so, the Windflow turbine could be configured in a similar mode to its islanded operation mode (see section 6 below) so as to respond to under- or over-frequency excursions. If configured to respond to under-frequency events, the Windflow turbine could in principle be run with some reserve capacity in hand (i.e., with blades feathered) so that it could increase its power output to try to restore grid frequency. However because this would entail routine spilling of available wind power, it is unlikely that this would be economic.

If configured to respond to over-frequency events, the TLG would tend to reduce its torque setting and hence power output, (while staying grid-connected) until the generator speed returns to normal frequency.

In summary, in either event:

- the TLG (as configured presently) will tend to maintain constant torque in above-rated winds. In below-rated winds torque will vary with wind speed (the blue line in Figure 5.2).
- A minor hardware modification to the TLG system will enable it to maintain constant power in above-rated winds (the red line in Figure 5.2).

- Further software modifications will enable it, in any winds above cut-in, to increase power in under-frequency events or decrease power in over-frequency events (the green line in Figure 5.2). The former would carry an energy capture penalty in below-rated winds and is likely to be uneconomic, but the latter is readily achievable.

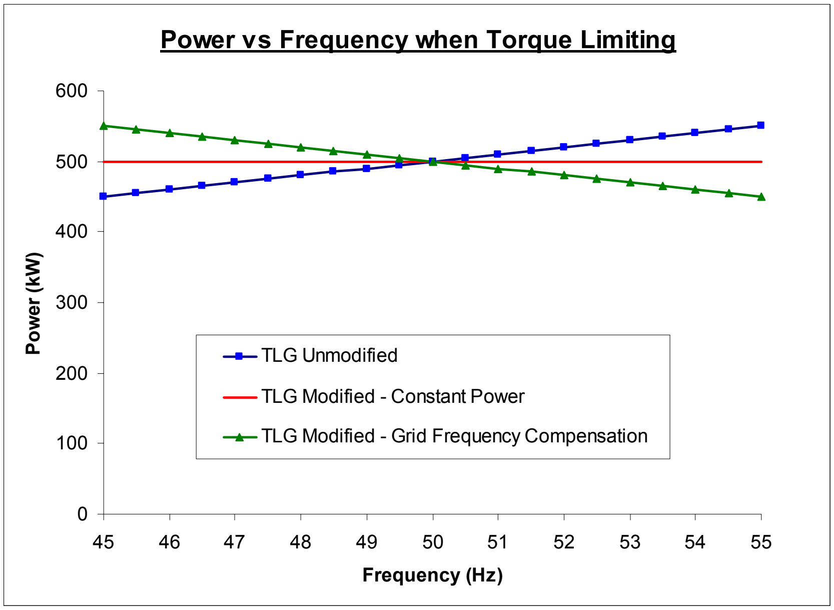


Figure 5.2: Graph depicting power excursion due to frequency changes while torque limiting in three different configurations.

5.3 Voltage Support

The EGRs require that all grid connected generators must be able to operate over the full voltage range of the grid. It also requires that while the voltage at the grid connection point is within the nominal range that the generator be able to export 50% or import 33% reactive power of the continuous MW rating of the generator. This easily falls within the capability curve of a synchronous generator which is not surprising as this is what these codes have been designed around.

## 6.0 Islanded Generation

Islanded generation is generating to a load that is not connected to the national grid. In this case the load requires voltage and frequency to be controlled as if it were connected to the grid. This is a problem for wind turbine generation due the variable nature of the energy source.

A synchronised generator is well suited for islanded generation and is in fact the exact same type of generator as used in diesel generator sets which are the primary generation type for islanded loads.

WTL plan to test the feasibility of using the Windflow 500 in conjunction with a standby diesel generator set for islanded generation. To achieve this, the torque limiting function of the Windflow 500 will need to be controlled by the WTG control system. This will require feedback of either generator rotor speed or grid frequency.

## 7.0 Case Study: Gebbies Windflow 500 Connection to Orion Ltd

The first Windflow 500 is connected to the Orion Network in Christchurch under a standard connection agreement. Orion has a policy of paying generation connected to their network for generating at times of high load. This helps to:

- reduce peak loads and hence equipment wear and tear
- reduce the half hourly peak charges from Transpower
- allows Orion to defer capital expenditure on network upgrades

Figure 7.1 shows a trace of kVAr generated for a period when the Windflow 500 gearbox and blades had been removed. The spike in the trace is due to a tap change on a tap changing transformer at the local substation.

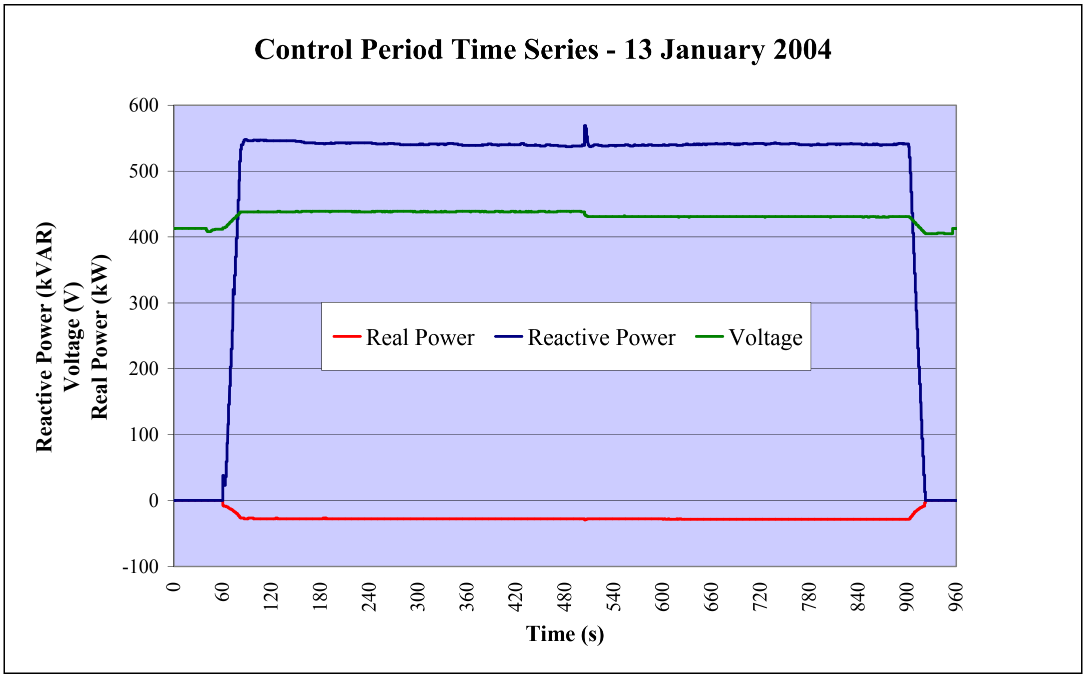


Figure 7.1: Trace showing reactive power generated during an Orion CPD.

This all has value to Orion who pay on a network wide basis. In the Windflow case Orion will pay 95% the line charge for the average real power exported during a Control Period Demand (CPD) and 31% for the average reactive power exported. Based on a 10 m/s mean wind speed (which equates to 200 kW and therefore 550 kVAr) the Orion agreement would have a value of $29,532 per annum or 1.69 c/kWh.

Even if the wind was not blowing this agreement would still have a value of $13,967 due to 550 kVAr of generation, achieved by operating the generator as a synchronous condenser (this is what has been happening during the first half of 2004).

The only costs incurred to fully utilise the benefits of the Orion connection agreement are tabulated in Table 7.1.

Assuming the worst case scenario of no wind blowing the Orion agreement will have a payback time of 0.38 years for this equipment. The potential dual purpose of the remote PFC

interface has not been considered. It is also possible that the VSD may be made redundant in the future.

| ITEM | PURPOSE | PRICE ($) |
|---|---|---|
| Induction motor | Runs generator up to synchronous speed when used as a synchronous condenser. | 1500 |
| Belt and Pulley | Provides a drive between motor and generator. | 250 |
| VSD | Achieves accurate enough speed to synchronise. | 2200 |
| Remote PFC interface | Allows a standard industrial signal to control the VAr generation. | 1400 |
| | **Total** | **5350** |

Table 7.1: Additional costs for kVAr generation

**8.0 Conclusions**

The wind power industry is struggling to meet the demands of transmission grid system operators all over the world largely due to generator types that do not inherently have full range reactive power capability. Synchronous generators do have this capability and the difficulties associated with using synchronous generators in WTG's have been overcome with the Windflow 500. Using a synchronous generator with the TLG gives the Windflow 500 huge flexibility and features that are economically provided for little more than the basic cost of an already low-cost generator. For small additional costs, these features can be enhanced to provide three different modes of frequency support, three different modes of VAr support (including voltage control for fault ride through) and full VAr output even when the wind is not blowing.

**9.0 References**


1. 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
2. Henderson, G.M.: - "Pitch-Teeter Coupling and the Torque Limiting Gearbox: Cost-Effective Methods of Fatigue Load Reduction", *Proceedings of 1st NZWEA Conference*, EECA, Wellington, 1996
3. Henderson, G.M. – "Referred Generator Inertia: a new and decisive advantage for the Torque Limiting Gearbox (TLG) system", *Proceedings of NZWEA Conference*, Wellington, 2002
4. Transpower New Zealand Limited - "Connection and Dispatch Guide", Version 3.0, Wellington, March 2004.
5. Grainger, J.J. and Stevenson, W. D. - "Power System Analysis", pp 380-381, McGraw Hill, Singapore, 1994.
6. Poller, Markus A. - "Doubly-Fed Induction Machine Models for Stability Assessment of Wind Farms", *Power Tech Conference Proceedings*, Bologna, 2003.
7. De Vries, Eize - "Grid Failure Test: Enercon E-66 is world's first to be certified", Renewable Energy World p. 37, James & James (Science Publishers Ltd), May-June 2004.