

SYNCWIND'S TYPE 5 WIND TURBINE POWER-TRAIN: A GRID-FORMING ALTERNATIVE TO INVERTER-BASED RESOURCES

Geoff Henderson^{1*}

¹*SyncWind Power Ltd, Liguria, Italy*

^{*} *Geoff@windflow.co.nz*

Keywords: (TYPE 5, SYSTEM STRENGTH, SYNCHRONOUS, GRID STABILITY)

Abstract

Degradation of system strength because of inverter-based resources (IBRs) is a major concern facing the zero-carbon transition. Blackouts like the one in Iberia on April 28 highlight this. They are generally followed by:

- Uninformed conservative voices calling for an end to investment in renewable energy;
- Optimistic solar and wind power advocates claiming that IBRs were not the problem and can totally replace synchronous machines;
- Transmission system operators requiring new investments in synchronous compensators.

This paper will attempt to inform the debate and explain clearly why synchronous machines cannot be totally replaced. At the same time, this does not mean that investment in renewable energy should end, nor are new investments in synchronous compensators the economic way forward.

The author has previously presented work on Type 5 wind turbines, i.e. those that drive a synchronous generator, without inverters, through one of three variants of hydraulic variable speed system. In their 2024 paper he and co-authors presented to this workshop, they explained that the SyncWind Type 5 power-train is the most cost-effective and proven of these three. This paper will detail the various control sub-systems of the power-train, to enable high-level comparison of its control systems with the IBR approach to grid-forming.

1 Introduction

Degradation of system strength because of inverter-based resources (IBRs) is a major concern facing the zero-carbon transition. Lack of synchronous inertia, generally just referred to as “inertia”, is most often cited as if it is the problem. However, “inertia” as defined by electrical engineers is more correctly described as rotational kinetic energy (RKE), and lack of RKE is a “real power” problem for which there are many solutions in the form of fast-frequency response. Though not an immediate inertial response like synchronous inertia, short term energy stores, ranging from the RKE of an asynchronous wind turbine rotor to a DC battery, can respond very quickly to reduce rates of change of frequency (ROCOF) and help return to normal frequency.

Less focus has been given to the “reactive power” aspect of system strength. What keeps synchronous inertias synchronised is a form of “strength” in the mechanical sense of the word, i.e. strong reaction torques which hold the rotors of an AC system in synchronism. During a fault, high currents can be generated because of the electromagnetic torques required, and these can be 10 times the rated current of the generator. To use a mechanical metaphor, when things start rocking and it's hard to stay upright, is the problem the speed of the rocking motion due to the lack of inertia, or the lack of strength and quick reflexes in your arms to hold on? The correct answer is that all three are involved: inertia, strength

and quick reflexes that respond correctly as the shaking changes back and forth. Synchronous generators and their automatic voltage regulators (AVRs) provide all three.

Another aspect of the reactive power capabilities of synchronous generators is voltage control. Many voltage faults do not involve frequency changes and hence do not involve inertia. However, if these faults are not cleared smoothly, which can require large transient fault currents, they can propagate and develop into frequency faults. Similarly, slow voltage oscillations can build up over time to the point where more significant voltage faults occur, which in turn can develop quickly into frequency faults. Synchronous generators and their AVRs provide a proven, trusted way to inject fault currents many times the rated current of the generator, ensuring that voltage and frequency faults are cleared smoothly and stably with fast post-fault active power recovery (FPFAPR).

2 Synchronous Machines cannot be Replaced

Blackouts like the one in Iberia on 28 April, 2025 highlight these issues. While the final ENTSO-E report on this event is yet to be produced, voltage stability has been identified as a key issue [1] [2] and the initial response of the system operator has been to require increased amounts of synchronous generation and reduce the dispatch of wind and solar power [3].

The short-circuit current (or “fault current”) capacity of synchronous machines is a powerful voltage stabiliser because the stator windings of synchronous generators (or compensators¹) in an AC grid are electro-magnetically coupled to each other in short-circuit across large geographic distances.

This enables them to respond to system voltage and frequency changes, and holds the inertial energy of their rotors together, at microsecond timescales. Figure 1 shows an example of SyncWind’s system at Te Rere Hau wind farm in New Zealand providing instantaneous fault current to counter a voltage fault.

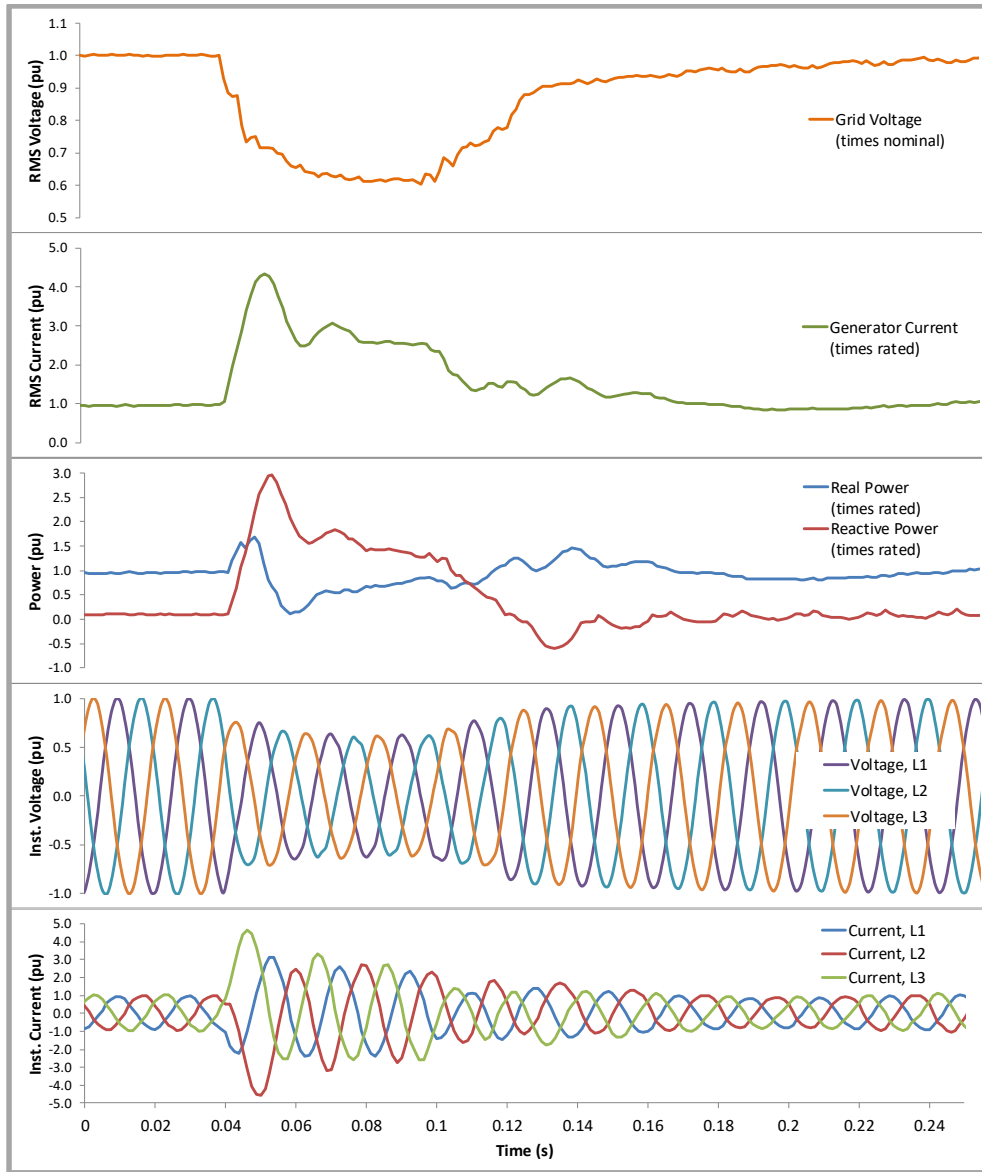


Fig. 1. Fault response of Windflow 500 synchronous wind turbine during voltage sag event, 8 September 2012, at the 48 MW Te Rere Hau wind farm, New Zealand. This shows an example of short-circuit current contribution and ride-through of a Windflow synchronous turbine during a system voltage disturbance that lasted around 100 ms (0.1 seconds). Note in particular:

- the red trace in the third pane, which shows reactive power immediately being exported to oppose the dip in voltage. This is initially at about 0 kVAr but shoots up to 3 times rated before settling as voltage recovers;
- the turbine remains online and the output power (blue trace in the third pane) returns to pre-fault levels shortly afterward;
- the peak current on one phase (green trace in the fifth pane) is nearly five times the rated current (it was at rated before the disturbance) and that this peak precedes the maximum voltage dip.

¹ Also commonly called synchronous condensers, although this implies only reactive power export, whereas they can both import and export reactive power.

It is this immediate fault current capacity of synchronous machines which is irreplaceable for system stability, more so than the inertia. For example, IEEE 2800:2022 [4] states that adding synchronous compensators is “presently the primary solution for adding system strength because of multifaceted benefits including large capability to supply fault current, inertia and voltage support capability”. ABB [5] reports that “After decades out of favour, utilities and industrial operators around the world have started to place major orders for synchronous condensers to address grid stability issues associated with the increased penetration of renewables”.

Without these, IBRs in South Australia, Ireland and other places have had to be curtailed, causing significant financial pain and planning uncertainty to wind farm developers there.

Where synchronous compensators have been installed, to date it has been at the expense of the network companies. However, it is foreseeable (if not already happening in some places) that solar and wind farms will be required to pay for some degree of synchronous compensation.

There are only two alternatives to the installation of synchronous compensators for voltage regulation:

- Grid-forming inverters (a possibility that has been identified by RED Electrica [1]);
- Type 5 power-trains can be installed in existing wind turbine designs, so that each turbine has a synchronous generator which can be run for synchronous inertia, voltage stability and system strength with “quick reflexes”, whether or not the wind turbine is generating power.

The first of these is perhaps the easiest for the wind industry to adopt in the short term, given the current dominance of IBRs. However, it is not economically feasible that this will provide the same fault current capability as synchronous machines. **Nor does it seem a serious prospect that synchronous machines can be completely replaced by grid-forming IBRs.** IBRs cannot provide the inherent synchronisation created by the low-impedance circuits between the stators of synchronous generators.

After two decades of the wind industry mastering the ability to ride through faults, it is arguable that the challenge of true grid-forming (for which synchronous generators are the reference point) is to contribute to overall grid stability, not merely each generator’s ability to ride through.

If the second alternative (Type 5) is cost-competitive with existing wind turbine power-trains, it should have a strong business case in the coming decades to avoid the cost of synchronous compensators.

3 SyncWind’s Torque Limiting Gearbox-Low Variable Speed (TLG-LVS) Type 5 System

Type 5 wind turbines drive synchronous generators which are directly grid-connected, without inverters, just like thermal and hydro power plants. The generator used is the traditional self-exciting electromagnetic type controlled by an AVR. At

wind turbine scale (smaller than large thermal and hydro plants), generators that are mass-produced for the diesel generator market can be used. These are more efficient, and thus smaller, than most generators used in Type 3 and 4 wind turbines.

Type 5 wind turbines essentially enable the synchronous compensator option to be built into every turbine’s generator, so that the benefits of synchronous inertia, voltage stability and system strength are available as part of the basic wind turbine architecture.

Type 5 wind turbines also avoid the need for significant power electronic inverters, other than the micro-electronic inverters in their AVRs which are rated at typically less than 1 kW.

The author has previously presented work on Type 5 wind turbines [6] [7] [8] [9]. The 2024 paper he and co-authors from the USA and Ireland presented to this workshop [9] compared three variants of Type 5 hydraulic variable speed system:

- SyncWind’s TLG-LVS system
- Voith’s Windrive, and
- full-hydrostatic drive systems.

They explained that the SyncWind Type 5 power-train is the most cost-effective of these three, because its hydraulics are only rated at 5% of turbine power, giving it a total turbine cost less than that of a Type 3 turbine.

SyncWind’s Type 5 system has been running successfully in a 46 MW wind farm in a high wind site in New Zealand for nearly 20 years, accumulating more than 1500 turbine-years track record.

3.1 Description of the System

Henderson [6] and [7], Henderson and Gevorgian [8], and Henderson et al [9] informed the 2017, 2021, 2022 and 2024 Wind Integration Workshops of the history since 1990 of SyncWind’s synchronous wind turbine power-train, what it does, what it is, how it works and how it is scalable to 10 and 20 MW turbines. Henderson et al [9] described the mechanical-hydraulic system in significant detail, an abbreviated version of which is as follows:

There is the TLG System which:

- uses the hydrostatic torque reaction of a radial piston pump, integrated into the main turbine gearbox, reacting the power-train torque through a differential epicyclic stage;
- has a simple pressure-relief valve circuit for torque limiting (TL) to protect the gearbox from torque transients. This sets the torque rating of the wind turbine and can be varied remotely;
- enables a synchronous generator directly on-line, running at constant speed (locked to grid frequency);
- has a narrow speed band for power control at rated of only 5% above synchronous, so the radial piston pump and the TL circuit only handles a maximum of 5% of turbine power;

- dissipates up to 5% of rated power in above-rated winds (when there is surplus wind energy being spilled for control purposes) as heat in an external cooler;
- dissipates only about 1% of power in below rated winds, while also improving energy capture because some energy storage occurs both in the flywheel effect of the turbine rotor and a high pressure (HP) accumulator;
- reduces wind farm electrical connection requirements because the generator-AVR combination provides power factor control, dynamic VAR compensation, and high fault currents.

Figure 2 shows the mechanical layout of the TLG with its differential epicyclic final stage reacted by a hydrostatic TL pump, which is rated at only 5% of the turbine power. (It also acts as a motor during wind lulls and in the LVS system described below).

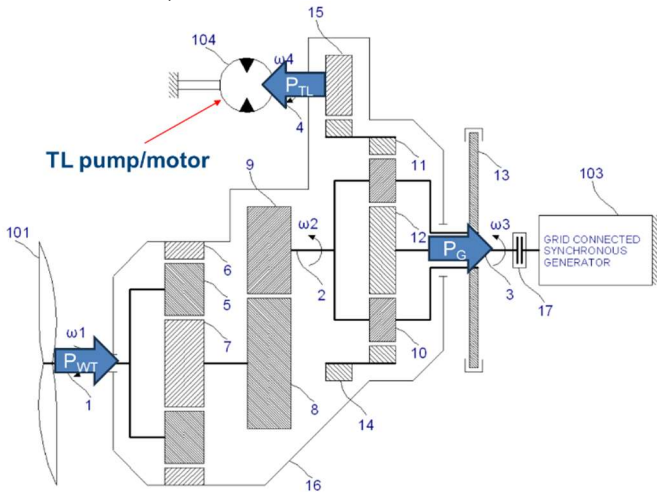


Figure 2 - The TLG (Figure from US Patent 9,835,140 B2)

Figure 3 shows the behaviour of the TLG system in a 20 second time series of monitored data from a Windflow 500 running in 12 – 20 m/s winds (the grey line).

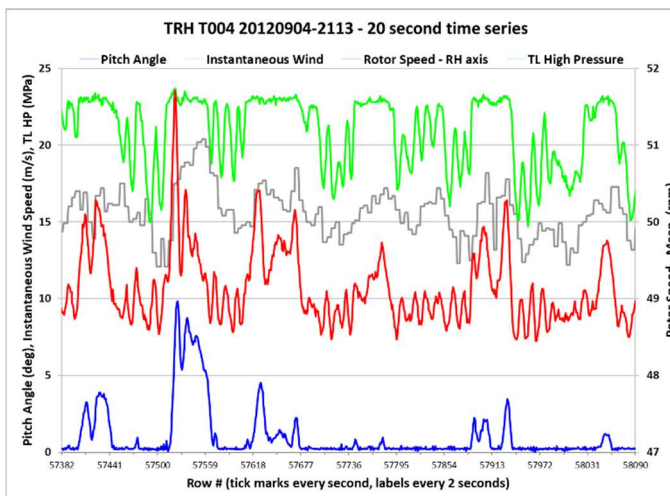


Figure 3 - 20 seconds of TLG operation showing how pressure, hence torque and generator power, are limited

The green line shows the TL high pressure (MPa) which is kept constant within a range of less than 3% in above rated winds, hence the torque on all 3 shafts and the generator power is kept constant also.

The red line shows turbine rotor speed (rpm per right-hand axis) which varies in a 5% range in above rated winds, and a 1% range (due to hydraulic slip) in below rated winds.

The blue line shows the blade pitch (degrees) which is active in above rated winds (controlling turbine speed) but inactive in below rated winds to maximise energy capture.

Note that, when torque limiting, torque is kept constant on all 3 shafts by the principle of equal and opposite reactions (Newton's 3rd Law), while power varies on the turbine and TL pump shafts as their speeds vary. The TL pump power is analogous to the slip power of an induction generator. However, power remains constant on the generator shaft because its speed is tied to grid frequency.

There is the patented LVS system which:

- adds a second hydrostatic machine external to the gearbox which is called the LVS pump;
- provides broad-band VS capability to the original TLG system while keeping the rating of the radial piston pump and hydraulic circuit at 5% of turbine rating;
- enables the turbine to have a low cut-in wind speed (3-4 m/s) and follow the point of maximum C_p when operating in low winds, increasing the turbine's energy capture and running hours relative to the TLG;
- has a turbine VS range of 60-105% of "synchronous speed", N_s , which is defined as occurring when the TL pump/motor is stationary (0 rpm).

Figure 4 shows the hydraulic circuit of the combined TLG-LVS system.

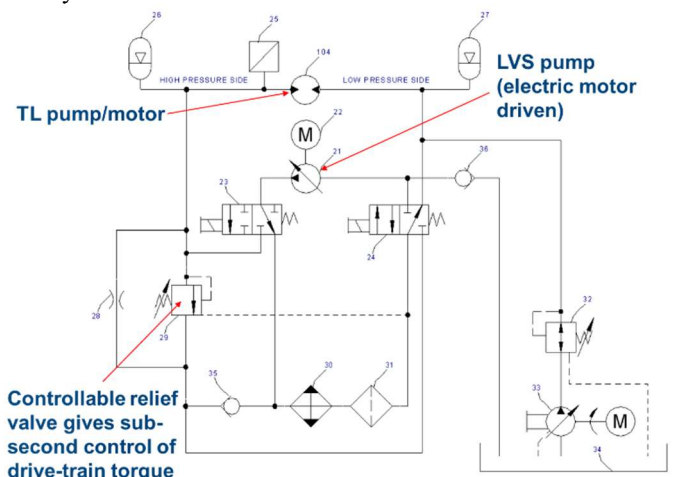


Figure 4 - The TLG-LVS Hydraulic Schematic (Figure from US Patent 9,835,140 B2)

Figure 5 shows the behaviour of the LVS system in a 41-minute time series of monitored data from a Windflow 500 running in 4 – 16 m/s winds (the grey line).

The green line shows the electrical power output across the full range from 0 to 500 kW

The red line shows turbine rotor speed (rpm per right-hand axis) which varies in a 5% range in above rated winds, and a 20% range (due to the LVS system) in below rated winds. Note that, for reasons to do with constraints on the allowable speed range of the Windflow 2-bladed design, the prototype had a narrower LVS range of operation than would be the case for commercial 3-bladers. These would have a 40% range in below rated winds, while keeping the power rating of the LVS pump and TL pump/motor at 5% of turbine rating.

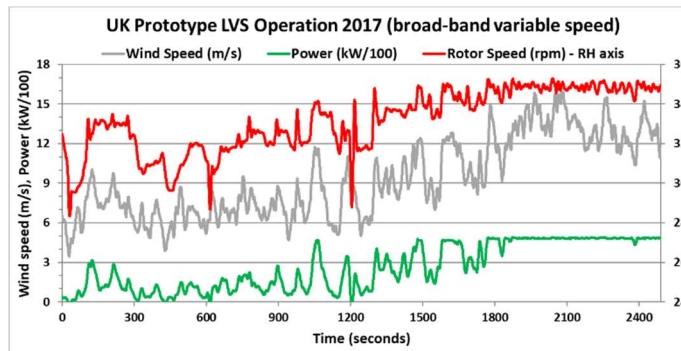


Figure 5 - 41 minutes of data showing broad-band LVS operation in below-rated winds, then TL operation

3.2 Thirty-five year history, more than 1500 turbine-years

The TLG system was first prototyped in a 250 kW 3-bladed turbine (the WEG MS2) in England in 1990. This was a research prototype, funded by the UK Department of Energy. The TLG system operated successfully and was retained in the prototype turbine for several years until it was decommissioned in the late 1990s when WEG (Wind Energy Group Ltd) was bought by NEG Micon.

Henderson [6] set out the track record of the TLG system in the Windflow 500 turbine, which has been successfully running in New Zealand (NZ) since 2006 and Scotland since 2013. Some illustrative experiences were set out:

- 550 kVAr steady export from the prototype Windflow 500 kW turbine for 11 kV voltage support (Christchurch, NZ). This was enabled even in calm wind conditions with the turbine stationary and the generator online as a synchronous compensator;
- 0.5 Hz maximum sag and 1 second recovery to 50 Hz after a 30% step in load during an islanded demonstration of the prototype Windflow 500's ability for frequency control using a combination of:
 - very fast hydraulic control of reaction torque, with
 - turbine inertia which helps speed excursions be managed by pitch control;
- 1500 kVar steady import for voltage control when the first five Windflow 500s at Te Rere Hau wind farm (Manawatu Saddle, NZ) were required to be derated to 200 kW each (1000 kW total) for two years because the initial 11 kV connection was weaker than expected;
- 4 to 5 pu instantaneous fault current followed by FPFAPR settling to rated power output 100 ms later when the full 46 MW Te Rere Hau wind farm (connected via a 33 kV cable and 220 kV substation to New Zealand's main transmission backbone) experienced occasional fault events (typically 0.6 pu voltage faults) from the grid;
- Pole-slip on a Windflow 500 installed on the Orkney Islands in Scotland after an islanding event on a 33 kV network, which lasted 300 ms. This provided experience of the benefit of the TLG in protecting the drive-train (generator and gearbox) from torsional shocks in such electrical fault events, while sustaining only low-cost damage to the TL pump itself.

In summary, the TLG system has been running in over 100 synchronous Windflow 500 turbines, accumulating more than 1500 turbine-years of track record that is ongoing at high wind sites in New Zealand (a 46 MW wind farm) since 2006 and Scotland since 2013 (several single turbines). The patented LVS system, which has been demonstrated in a prototype in Scotland, adds the important feature of broad-band VS while keeping the hydraulic system rated at 5% of turbine rated power.

4 Control Sub-Systems

The control sub-systems of the TLG-LVS system, being mechanical-hydraulic rather than power electronic, are necessarily different from mainstream wind turbines. The power control problem is separated into speed and torque control, and the generator speed is locked to grid frequency while the wind turbine rotor runs with VS. As a result it:

- achieves very fast torque control to protect the drive-train and adjust output power using an hydraulic relief valve;
- maintains turbine efficiency cost-effectively with its LVS sub-system;
- exports or imports real and reactive power control during normal operation, with and without wind;
- imports or exports reactive power during fault conditions;
- stabilises voltage;
- provides synchronous inertia from the generator rotor during frequency excursions;
- provides fast-frequency response from the wind turbine rotor's RKE.

Table 1 on the following page sets out the main characteristics of the SyncWind Type 5 control sub-systems. Several of the abbreviations set out in the table and footnotes are taken from Eirgrid and SONI [10].

The LVS mode applies for wind speeds between cut-in and part-way up the power curve. "Between modes" applies for the top part of the power curve below rated.

The TLG mode applies at "rated" - noting that this can dynamically "re-rated" between (typically) 10% and 120% of normal turbine rating.

Table 1 – SyncWind Type 5 control sub-systems

Controlled Parameter	Actuator	Type of control	Notes
1. Wind turbine speed (rpm)			
a) LVS mode (60-100% N_s^2)	LVS pump flow	PI & notch filter	Flow varied with pump displacement or speed. Hydraulics damped for 1% slip characteristic. “Infinite” slip limited in range 1-5%, PI loops for rpm and power ramp rate.
b) Between modes (100-101%)	None	None	
c) TLG mode (101-105% N_s)	Blade pitching	Double PI	
2. Wind turbine torque (N.m)			
a) LVS mode	None	None	Blade pitch fine, torque varies with wind speed. As above, passive hydraulic damping per 1b). Set point of relief valve is remotely adjusted.
b) Between modes	None	None	
c) TLG mode	TL relief valve	Force balance	
3. Wind turbine power (W)			
a) LVS mode	None	None	Turbine speed set per 1a) to maximise power. Passive hydraulic damping & transient storage. Generator power constant, TL power to cooler. Curtailing output possible if reserves value high. Fast response (10-100% in ~1 s).
b) Between modes	None	None	
c) TLG mode	See 1c) & 2c)	See 1c) & 2c)	
d) Operating reserves	TL relief valve	Set point step	
e) Ramping performance	TL relief valve	Set point step	
4. Grid frequency (Hz)			
a) synchronous inertial response (SIR)	Electromagnetism	Grid connection	Low-impedance circuits between stators of all synchronous generators maintain synchronism. Even at rated power, 10-20% torque overloads can be accommodated for 10 s, extracting energy from the wind turbine’s inertia and aerodynamic torque characteristic.
b) fast frequency response (FFR)	TL relief valve	Set point step	
5. TL pump/motor speed (rpm)			
a) LVS mode	LVS pump flow	PI & notch filter	See notes for wind turbine speed control 1a)-c). When grid frequency is steady, TL pump/motor speed is related to wind turbine speed by a constant rpm/% slip and 0 rpm at N_s .
b) Between modes	None	None	
c) TLG mode	Blade pitching	Double PI	
6. Voltage (V)			
a) LVRT ³ and FPFAPR ⁴ (DRR ⁵)	Electromagnetism	None	Typical AVRs control the generator’s exciter for steady power factor ($\cos\phi$), steady VAR export or import, or terminal-voltage control with droop. Regardless of control mode, the DRR is such that, in LVRT events, the inherent electromagnetic response of the generator provides immediate transient reactive current responses to support the voltage and help to maintain synchronism. Post-fault, the elevated field enables rapid voltage recovery and FPFAPR.
b) steady pf ($\cos\phi$)	AVR	Set point step	
c) steady VAR export/import (SSRP ⁶)	AVR	Set point step	
d) terminal-voltage control with droop.	AVR	Set point step	

² N_s denotes the wind turbine’s “synchronous speed”, i.e. when the generator is synchronised to the grid at its nominal speed (eg 1500 rpm for 50 Hz) and the TL pump/motor is stationary.

³ LVRT – low-voltage ride-through

⁴ FPFAPR – fast post-fault active power recovery

⁵ DRR – dynamic reactive response

⁶ SSRP – steady-state reactive power

5 Implementing SyncWind's Type 5 System

5.1 Scalability of the TLG-LVS System

A preliminary design has been developed for retrofit to a 2.5 MW Type 3 turbine. This is shown in Figure 6 alongside the 0.5 MW TLG.

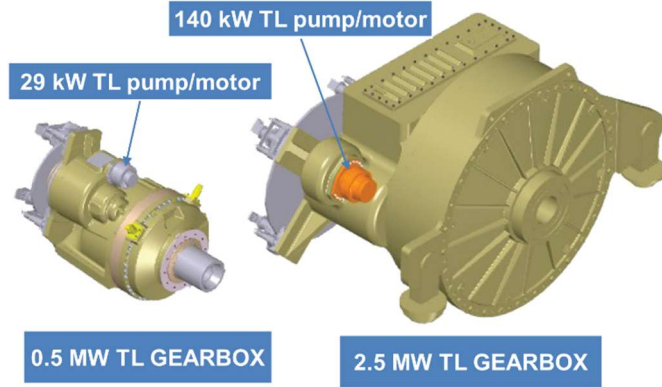


Figure 6 - Preliminary Design for a 2.5 MW gearbox retrofit with the TLG system

This retrofit design retains the front (high torque, low speed) end of the gearbox unchanged, so that the gearbox can be fitted into its original nacelle. Similarly, the synchronous generator, which is smaller than the DFIG which it would replace, can be fitted into the original nacelle.

The radial piston pump/motor used in the TLG is a standard catalogue design for various industrial applications and is available in power ratings up to 500 kW. Using the design rule of keeping its power rating at 5% of turbine rating, this means that a single such unit would enable a 10 MW turbine to have a TLG. Two such units reacting the annulus of the gearbox's output differential stage would enable a 20 MW TLG.

Therefore, the SyncWind power-train is scalable to wind turbines up to 20 MW rating. Ratings beyond that (if required in future) would be possible if either: higher rated radial piston pump/motors are developed for industrial supply; or a custom design for such a wind turbine is implemented.

5.1 The Business Case for the TLG-LVS System

Henderson et al [9] included an analysis which shows the capex and opex effects of changing from a “conventional” Type 3 power-train to the SyncWind power-train. “Power-train” was defined as 4 sub-systems: gearbox, generator, hydraulics (which most turbines have for pitch control, brake release etc) and power electronics.

This was based on a published NREL LCOE analysis produced by Stehly et al [11], [12]. Table 2 shows the results of this analysis of LCOE in terms of:

- the TLG-LVS system relative to a Type 3 turbine;
- adding a separate synchronous compensator relative to a Type 3 turbine.

The estimate of the effect of adding a synchronous compensator:

- is based on the costs of South Australia's recent synchronous compensator project (~A\$300/kW = US\$200/kW of continuous machine rating), and
- assumes synchronous compensators are required at a rate of 1 MW (continuous machine rating) per MW of asynchronous wind turbines.

Table 2 – SyncWind Type 5 system and synchronous compensator effects on LCOE

LCOE Effect	SyncWind TLG-LVS	Separate synchronous compensator
Drive-train	0 x 9%	0 x 9%
Inverters	-0.3 x 6%	0 x 6%
Hydraulics	0.1 x 9%	0 x 9%
Sync-con	0	9%
AEPnet	0%	1%
O&M	1% x 28%	1% x 28%
LCOE	-0.62%	10.3%

The middle column of Table 2 shows that, because of the small increment to the capital cost (due to the 5% rating of the hydraulics) and the savings in inverter costs, the TLG-LVS system is expected to have a slightly lower LCOE than a standard Type 3 turbine. Modifying an existing Type 3 or 4 turbine design, building a demonstrator, then certifying and commercialising the design will entail some development costs. Depending on the magnitude of these and the expected manufacturing volume, the business case of this slightly lower LCOE will be more or less attractive.

However, if the wind industry is asked to bear the costs of adding synchronous compensators to new wind farms, comparison with the last column of Table 2 shows that the TLG-LVS system will provide a significant reduction in LCOE. This will make for a compelling business case.

6 Conclusion

Degradation of system strength because of inverter-based resources (IBRs) is a major concern facing the zero-carbon transition. Synchronous machines are trusted to provide system strength for fundamental reasons arising from the electromagnetic connections between the stators of geographically widespread machines in a grid. Major orders are being placed for synchronous compensators “to address grid stability issues associated with the increased penetration of renewables”.

To date, system operators have been bearing the cost of synchronous compensators but it is foreseeable (if not already happening in some places) that solar and wind farms will be required to pay for some degree of synchronous compensation.

SyncWind’s Type 5 power train for wind turbines offers a significantly lower-cost solution for the provision of a synchronous generator, without inverters, that can provide the system strength of a synchronous machine when the wind is blowing, and even when it is not (through the provision of a clutch on the generator shaft). This paper has detailed the various control sub-systems of the power-train, to enable high-level comparison of its control systems with the IBR approach to grid-forming.

SyncWind’s Type 5 power-train is economically competitive with Type 3 turbines under present settings which do not generally require synchronous compensation. This follows from its minimalist design in terms of adding hydraulics and epicyclic gearing to the standard wind turbine power-train, handling only 5% of turbine rated power. This means that the costs and any energy losses of those items are more than offset by savings in gearbox rating, elimination of inverters and use of a light, mass-produced, more efficient synchronous generator.

It also means that, if the wind industry is asked to bear the costs of adding synchronous compensators to new wind farms, the TLG-LVS system will provide a significant reduction in LCOE which will make for a compelling business case.

A preliminary design has been developed for retrofit to a 2.5 MW Type 3 turbine, and the system is scalable to 10 and 20 MW power-trains. It is recommended that this system be demonstrated by retrofit/modification of an existing 2.5 MW turbine design, so that the mainstream wind industry has a synchronous option for removing the concern that IBRs cause about the zero-carbon transition.

7 References

- [1] RED Electrica – ‘Report on the incident of 28 April’, <https://www.ree.es/en/press-office/news/press-release/2025/06/red-electrica-presents-report-incident-28-april-and-proposes-recommendations>, June 2025
- [2] ENTSO-E – ‘28 April 2025 Blackout’, <https://www.entsoe.eu/publications/blackout/28-april-2025-iberian-blackout/> Sep. 2025
- [3] Davi-Arderius, D. and Graf, C. – ‘Iberian Peninsula Blackout: A Trade-Off Between Operational Risk and Consumer Cost’, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=5429395, Sep. 2025
- [4] IEEE 2800: ‘Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems’, 2022
- [5] ABB – ‘Synchronous condensers rediscovered – a new way to strengthen grids’ https://library.e.abb.com/public/c8adfa0169c44de3b6ed8ba186121922/Synchronous_condensers_rediscovered_Jun_2021.pdf, May 2021
- [6] Henderson, G.M. – ‘Field Experience with Synchronous Wind Turbines in New Zealand and Scotland: Instances of short-circuit current contributing to system stability, and an instance of frequency instability’, Proc. Wind Integration Workshop, Berlin, 2017
- [7] Henderson, G.M. – ‘The Latest Development in Synchronous Wind Turbine Technology: how the LVS System can deliver low cost, broad-band variable turbine speed and Type 5 grid connection’, Proc. Wind Integration Workshop, Berlin, 2021
- [8] Henderson, G.M. and Gevorgian, V. – ‘Type 5 Wind Turbine Technology: How Synchronised, Synchronous Generation Avoids Uncertainties About Inverter Interoperability under IEEE 2800:2022’, Proc. Wind Integration Workshop, The Hague, 2022
- [9] Henderson, G.M., Gevorgian, V., Yan, W., Flynn, D., Mendieta, W. and Alam, S.M.S. – ‘Type 5 Wind Turbine Technologies: Three Main Candidates Compared’, Proc. Wind Integration Workshop, Helsinki, 2024
- [10] Eirgrid and the System Operator of Northern Ireland (SONI) – ‘DS3 System Services Protocol – Regulated Arrangements’, <https://cms.soni.ltd.uk/sites/default/files/media/documents/DS3-SS-Protocol-v4.1.pdf>, Oct. 2024
- [11] Stehly, T. and Duffy, P. – ‘2021 Cost of Wind Energy Review’, NREL, December 2022
- [12] Stehly, T., Duffy, P. and Hernando, D. M. – ‘2022 Cost of Wind Energy Review’, NREL, December 2023