TYPE 5 WIND TURBINE TECHNOLOGIES: THREE MAIN CANDIDATES COMPARED

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Abstract

Type 5 wind turbines drive synchronous generators which are directly grid-connected, just like conventional power plants. The generator is the self-exciting electromagnetic type controlled by an automatic voltage regulator (AVR), capable of the same amount of system strength (being fault current at more than 3 times rated (3 pu) for fault and post-fault conditions) as thermal and hydro turbine-generators. Historically, system strength from conventional power plants has ensured system stability.

However, the mainstream of the wind industry is dominated by Type 3 and Type 4 wind turbines, with inverters capable of typically only 0.4 pu and 1 pu current respectively. The degradation of system strength because of wind and solar inverter-based resources (IBRs) is a major concern facing the zero-carbon transition. As renewables' penetration increases, synchronous condensers are increasingly being required to avoid curtailing IBRs.

The directly-connected synchronous generator of Type 5 wind turbines avoids the need for separate synchronous condensers. There are three main Type 5 designs, which use different mechanical variable-speed (VS) systems so the generator can run at synchronous speed. This paper describes recent research into these three systems and compares their levelized cost of energy (LCOE) against Type 3 and 4 systems, and against each other.

1 Introduction

Type 5 wind turbines drive synchronous generators which are directly grid-connected, 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 smaller and more efficient than most generators used in Type 3 and 4 wind turbines.

The combination of a synchronous generator and AVR represents the "mainstream" of the power industry since the 19th century. It is a major source of system strength because the generator can feed more than 3 times rated (3 pu) current transiently into fault and post-fault conditions. This keeps all the synchronous generators synchronized and on-line both during and as the system is recovering from the fault.

However, the mainstream of the wind industry is (for historical reasons) dominated by Type 3 and Type 4 wind turbines, which have inverters rated at 0.4 pu (typically) and 1 pu respectively. The degradation of system strength because of wind and solar inverter-based resources (IBRs) is a major concern facing the zero-carbon transition. Without system strength, cascading power outages will cause widespread, prolonged blackouts. IEEE Standard 2800 for "Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems" [1] sets out mitigation options which range from adding synchronous condensers (sync-cons) to curtailing IBRs. Such mitigation options are a growing problem, causing significant financial pain and planning uncertainty in Australia and elsewhere.

Type 5 wind turbines essentially enable the sync-con mitigation option to be built into every turbine's generator, so that the benefit of system strength is available as part of the basic wind turbine architecture. Benefits relating to power factor and synchronous inertia are also provided.

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.

Since the early days of the modern wind industry (1970s onwards) there have been some Type 5 wind turbine designs alongside the prevailing Types 1-4. Three main candidates remain, which have in common a mechanical variable-speed (VS) system so the generator can run at synchronous speed set by the grid frequency (eg 1500 or 1800 rpm for 4-pole 50 and 60 Hz generators), while turbine speed varies. They are differentiated by the design of their mechanical VS systems:

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

This paper describes recent research into these three systems and compares their levelized cost of energy (LCOE) against Type 3 and 4 systems, and against each other.

2 SyncWind's TLG-LVS System

2.1 Description of the System

Henderson [2] and [3], and Henderson and Gevorgian [4] informed the 2017, 2021 and 2022 Wind Integration Workshops of the history since 1990 of SyncWind's synchronous wind turbine power-train, but focussed more on what it does rather than what it is and how it works. In summary, this is a mechanical VS system which has over 1000 turbine-years track record in its original configuration called the torque limiting gearbox (TLG).

2.1.1 Description of the TLG System: This is set out below:

- It uses the hydrostatic torque reaction of a radial piston pump, which is integrated into the main turbine gearbox, reacting the final (high speed, low torque) stage, which is a differential epicyclic stage (one input and two outputs).
- This is combined with a simple pressure-relief valve circuit for torque limiting (TL) in order to set the torque rating of the wind turbine (which can be varied remotely if desired). Torque limitation is achieved because the torque on a fixed displacement hydrostatic pump/motor is directly proportional to the pressure differential across its ports.
- It enables a synchronous generator directly on-line, which runs at constant speed (set by the grid). Since power equals torque times speed, the torque control provided by the hydrostatic circuit also keeps the generator power constant at the turbine's nominal rated power, or some other set-point varied remotely.
- The constant speed of the generator also means the generator is not accelerated during wind gusts, which protects the gearbox from transient torque overloads. Furthermore, the relief valve provides robust mechanical protection against torque transients on the generator shaft due to electrical faults, enabling the gearbox to be designed with a lower application factor (Ka).
- With a torque duty of 100% of turbine rating but a narrow-band VS range which is only 5% above synchronous (sufficient for speed control purposes above rated), the radial piston pump and the TL circuit only handles a maximum of 5% of turbine power.
- It has no inverters and used a mass-produced, efficient generator (zero slip), thus eliminating sources of losses that reduce the efficiency of Type 3 and 4 turbines.
- The instantaneous energy balance of the TLG (neglecting gearbox losses) is described by the equation $P_{WT} = P_G + P_{TL}$, where P is power and the subscripts refer to the wind turbine, generator and TL pump shafts respectively. This explains how the power on the generator shaft can be kept constant when the relief valve opens; the TL circuit then absorbs fluctuations of turbine shaft power due to gusts (which are themselves ameliorated by 'flywheel' energy storage in the turbine). Newton's 3rd Law applied to gearing explains how the torque can be held constant on all three shafts – power fluctuations on two of them are experienced as speed (not torque) fluctuations.
- The power in the TL circuit, which is up to 5% of rated, and typically 3% +/- 2% when running in above-rated winds, is dissipated as heat in an external cooler. This is of no consequence, because in above-rated winds there is surplus wind energy being spilled for control purposes (including by feathering the turbine blades). Below rated, it dissipates only 1% of power, giving overall losses similar to Type 3 and 4 generators. On the contrary, energy capture is improved because some energy storage occurs both in the flywheel effect of the turbine rotor and a high pressure (HP) accumulator stores energy which is returned to the power-train during wind lulls.
- Wind farm electrical connection requirements are reduced because the generator-AVR combination provides power factor control, dynamic VAR compensation, and high short circuit current capacity.

Figure 1 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).

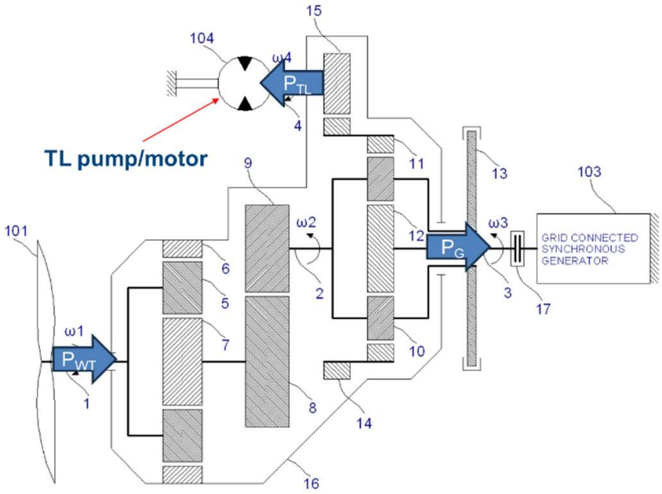


Figure 1 - The TLG (Figure from US Patent 9,835,140 B2)

Figure 2 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).

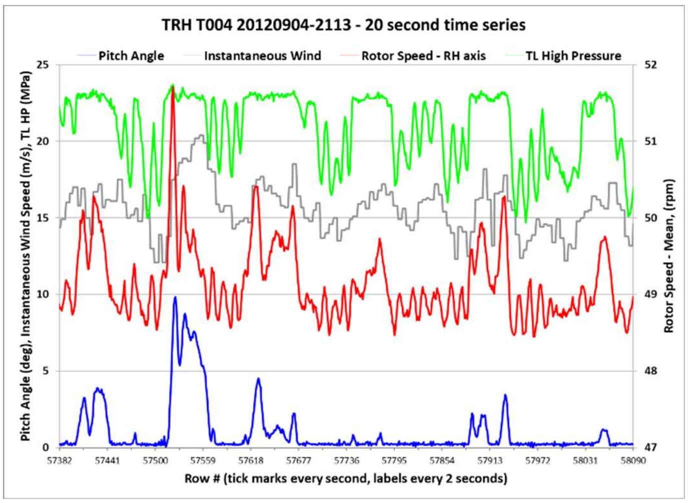


Figure 2 - 20 seconds of TLG operation showing how pressure, hence torque and generator power, are limited

- 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, 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.

2.1.2 Description of the LVS System: the current configuration of SyncWind's system is called the low-variable-speed ("LVS") system, which adds broad-band VS capability to the original TLG system. This is enabled while keeping the rating of the radial piston pump and hydraulic circuit at 5% of turbine rating. The LVS hydraulic circuit (shown schematically in Figure 3) enables the turbine VS range to be 60-105%. "Synchronous" speed is defined as occurring when the TL pump/motor is stationary (0 rpm) and is defined as the 100% reference. So the LVS range can be expressed as +5%, -40% relative to synchronous.

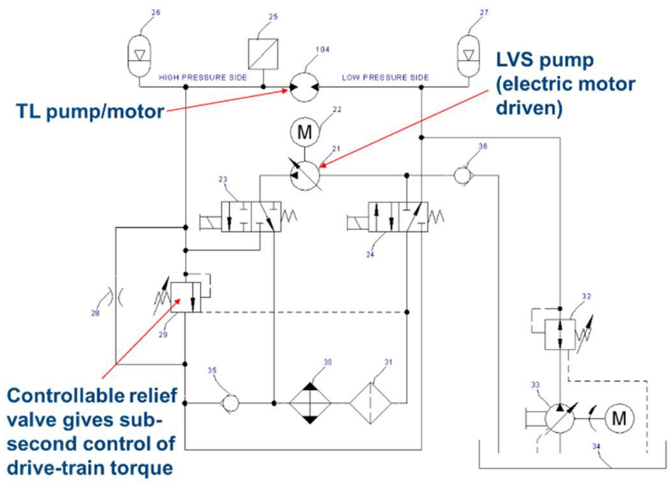


Figure 3 - The TLG-LVS Hydraulic Schematic (Figure from US Patent 9,835,140 B2)

For LVS operation, a second hydrostatic machine is added external to the gearbox which is called the LVS pump. The LVS pump is driven by an electric motor and drives the TL motor so as to make up the difference in generator shaft speed when the turbine is running slowly in low winds. Increased energy capture (from the improved aerodynamic efficiency) more than compensates for the electrical energy required to drive the LVS pump. This enables the turbine to have a low cut-in wind speed (3-4 m/s) and follow the point of maximum Cp when operating in low winds. Both these attributes increase the turbine's energy capture and running hours relative to the TLG which is a narrow-band VS system.

A sophisticated control algorithm manages the hydraulic speed control in the LVS mode for low wind running, and then the transition to TLG mode in high winds (hydraulic torque control, blade pitch for speed control). Figure 4 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.

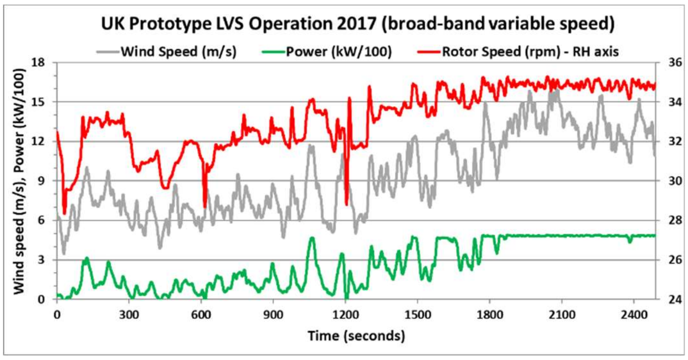


Figure 4 - 41 minutes of data showing broad-band LVS operation in below-rated winds, then TL operation

2.1.3 Scalability of the TLG-LVS System: A preliminary design has been developed for retrofit to a 2.3 MW Type 3 turbine. This is shown in Figure 5 alongside the 0.5 MW TLG.

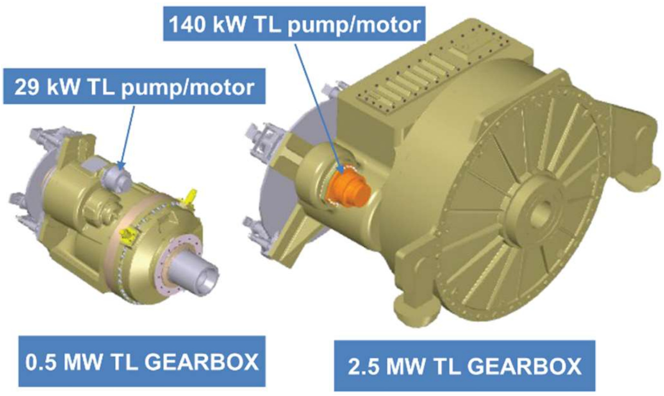


Figure 5 - Preliminary Design for a 2.3 MW gearbox retrofit with the TLG system

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. Note in particular the small size of the TL pump/motor relative to the main gearbox, in contrast to the relative size of the Voith Windrive in Figure 6. 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.

2.2 Thirty-four year history, more than 1000 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 [2] 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 sync-con.
- 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 pu instantaneous fault current followed by 'no-bother' 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 100 synchronous Windflow 500 turbines, accumulating more than 1000 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.

3 Voith's Windrive

3.1 Description of the System

The Windrive is a separate hydrodynamic torque converter which is mounted on the drive-train between the main gearbox (typically a two-stage unit) and the generator. As such it handles all the mechanical power from the wind turbine and is a comparable size to the generator and gearbox (Figure 6).

Figure 6 - WinDrive mounted at front of 2 MW generator (Credit: Renewable Energy World [5])

The hydrodynamic torque converter has:

- a hydraulic circuit consisting of a pump, turbine, and a guide wheel with adjustable guide vanes,
- two differential epicyclic gear stages, the first being a planetary epicyclic and the second being a star epicyclic, which are connected by a rotating compound annulus.
- These are combined in a common housing filled with hydraulic oil.

The output from the sun gear of the first stage is the output shaft to the generator, but it also drives the pump, which hydraulically drives the turbine, which feeds power at variable speed through the second stage back to the first (Figure 7).

The adjustable vanes of the guide wheel regulate the mass flow in the circuit. At closed guide vanes (small mass flow) the power transmission is at its minimum. With the guide vanes completely open (large mass flow), the power transmission is at its maximum. Because of the change in mass flow (due to the adjustable guide vanes), the pump speed (driven by the turbine through the main gearbox) can be adjusted to give variable speed on the wind turbine.

The instantaneous energy balance of the Voith Windrive (neglecting Windrive losses) is described by the equations:

- $P_S = P_{WT} + P_T$
- $P_G = P_S - P_P$
- $P_T = P_P$
  where P is power and the subscripts refer to the **s**un (1st stage), **w**ind **t**urbine, (Windrive) **t**urbine, **g**enerator and (Windrive) **p**ump shafts respectively.

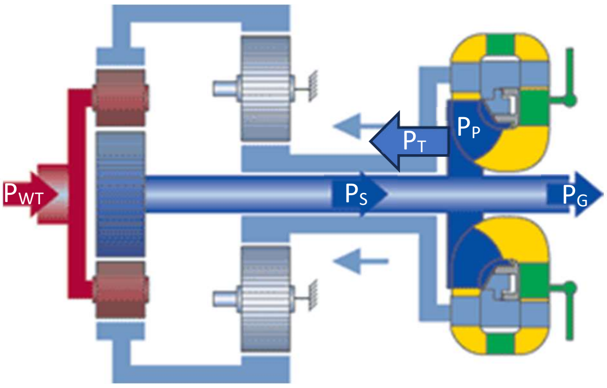


Figure 7 - WinDrive operating principle (Credit: Renewable Energy World [5])

With Windrive losses being neglected, these equations simplify to $P_G = P_{WT}$. The main operating principle is to recycle some power through the torque converter and two epicyclic stages to enable variable speed on the wind turbine while generator speed stays constant, set by the grid. Some issues with this system are that:

- It lacks the ability to limit torque at rated power independently from the speed control function.
- The significant mass of the Windrive's rotating components means that referred inertia will cause torque transients during wind gusts which accelerate the wind turbine rapidly. By contrast the TL pump/motor in the TLG-LVS system has negligible inertia (about 0.1% that of the generator rotor, which is responsible for significant inertial transients in Type 3 and Type 4 drive-trains).
- With the Windrive handling all the wind turbine's power, a large proportion of which is recycled through the torque converter, losses are important to the analysis of the Windrive.
- The weight and cost of the Windrive add significantly to the nacelle capital cost.
- The Windrive is vulnerable to damaging torque transients if a pole-slip event occurs, which would require the Windrive unit (and perhaps other drive-train elements) to be replaced at considerable expense.

3.2 History of the Voith Windrive

Dewind is the main company associated with the commercialization of the Voith Windrive. Their 2 MW Type 5 turbine has been installed in:

- 30 turbines in three 20 MW wind farms in Texas,
- 5 turbines at Wind Energy Institute of Canada, Prince Edward Island,
- 2 turbines in Minnesota,
- A single turbine in the Chilean Andes.

Of these 38 turbines, about 6 are still running (mainly the 5 on Prince Edward Island).

4 Full Hydrostatic drive

4.1 System Description

Type 5 hydrostatic wind turbines (HSWTs) use a continuously variable hydrostatic transmission (HST) to transmit power from the (variable-speed) turbine rotor to the grid-connected synchronous generator, Figure 8. In this arrangement, both hydraulic machines (the fixed-displacement radial piston pump and the variable displacement axial piston motor) are rated for 100% of the wind turbine power. The turbine rotor drives the pump, which converts mechanical power into hydraulic power, in the form of a pressurised fluid, which is fed to the motor, and the hydraulic power is converted back into mechanical power. Finally, the synchronous generator converts the mechanical power into electrical power. By adjusting the motor displacement, the fluid pressure and pump speed can be controlled, allowing a variable turbine rotor speed while maintaining a constant speed for the generator [6].

In addition, a hydraulic accumulator can be easily integrated through a variable displacement pump/motor, that can store and release energy, thus enabling a short-term energy storage capability (of the order of seconds), helping to reduce output variability and mechanical stress, and improve controllability [7]. Type 5 HSWTs can operate in synchronous condenser mode (since they are synchronous machines) by disengaging the shaft clutch, allowing them to regulate reactive power and stabilise local voltage levels, even under non-windy conditions.

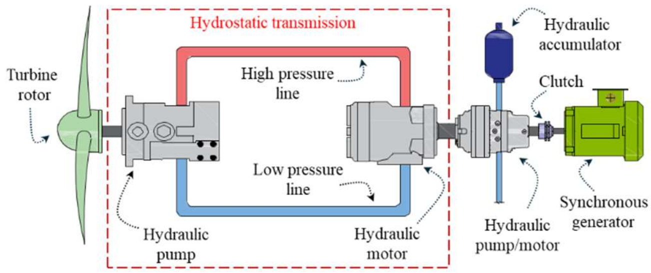


Figure 8 - HSWT schematic, incorporating an accumulator and a variable displacement pump-motor

Using a HST, instead of the traditional mechanical drivetrain and power converter of Type 3 and 4 wind turbines, offers greater flexibility and allows for lighter turbine structures, facilitating easier component placement and access to electrical systems. As a result, the generator can be placed either in the nacelle or even at the tower base. The in-nacelle approach requires a much lower volume of hydraulic fluid compared to the on-ground design, while the latter also results in higher fluid pressure losses [8]. In addition, for multi-MW wind turbines, pendant cables across the yawing nacelle-tower interface are generally considered preferable to a rotary hydraulic connection. Type 5 HSWTs do, however, have their drawbacks, such as lower efficiency, particularly at part-load, due to hydro-mechanical and volumetric losses in hydraulic components, as well as fluid properties (viscosity and compressibility), which lead to energy losses, pressure fluctuations, and reduced performance. However, efficiency can be enhanced by refining design, implementing digital HSTs, and using advanced controls and high-performance fluids [9].

4.2 History of the Full Hydrostatic drive

The concept of HSWTs dates back several decades. For example, Sir Henry Lawson-Tancred of Yorkshire [10] built and patented a 100 kW wind turbine in the 1970s which used a full hydrostatic drive. However, their initial development was limited by the inefficiencies of early hydraulic and fluid power technologies, making them impractical compared to traditional mechanical systems.

The early 2000s saw pioneers such as Artemis Intelligent Power (now part of Danfoss) begin developing digital displacement technology, which greatly enhanced the efficiency and control of hydrostatic systems, making the concept more feasible for wind energy applications [11]. More recently, the Norwegian firm ChapDrive developed HSTs for large multi-MW wind turbines, aiming at reducing the weight at the top with floating wind turbines. Similarly, WindSmart in Canada and Windera in the U.S. developed HST systems, demonstrating their ability to handle wind fluctuations more effectively than traditional gearboxes [12]. In addition, RWTH Aachen University developed and tested a HST capable of achieving a constant efficiency of 85% at partial loads [13], while Artemis, in collaboration with Mitsubishi Heavy Industries, successfully applied their digital displacement transmission (DDT) technology to a 7 MW "Sea Angel" turbine, tested in Yokohama, Japan [14]. System designs and control algorithms have also been refined for mid-sized HSWTs [15], while Eaton have managed to reduce installation and maintenance costs for mid- and small-scale HSWTs by locating the most critical components at the turbine base [16].

5 NREL Recent Research

National Renewable Energy Laboratory (NREL) is conducting a project funded by the Wind Energy Technology Office of the U.S. Department of Energy to evaluate the impacts of synchronous wind power on the grid [17], [18]. This work is done in collaboration with the Idaho National Laboratory (INL) [19], [20]. The project includes theoretical analysis based on modelling and simulations, and testing with power-hardware-in-the-loop (PHIL). The test setup is shown in Figure 9. It includes a 2.5 MVA /13.2 kV synchronous generator with rotating exciter and automatic voltage regulator (AVR). The generator is connected to a 7 MVA power electronic grid simulator, or controllable grid interface (CGI). CGI allows creating any type of grid condition on the generator terminals, including dynamic and transient events, voltage faults, phase jumps, etc. CGI is also capable of measuring the test article impedance by using a frequency scan technique. The mechanical power to the generator is provided by 5 MW dynamometer which consist of an induction motor operated by variable frequency drive. A full real time model of a Type 5 wind turbine (wind rotor, pitch control, gearbox, torque converter and torque limiting system) was developed in Real-Time Digital Simulator (RTDS) and implemented in closed loop setup as shown in Figure 9.

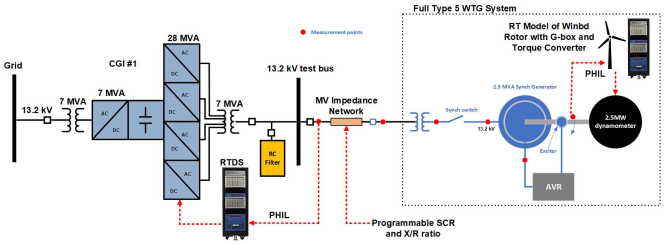


Figure 9 - NREL test platform

The system can operate using historic wind speed series as an input (example test results are shown in Figure 10). After wind speed increases to rated, the turbine pitch control and torque limiter become active to limit the power at 2 MW level.

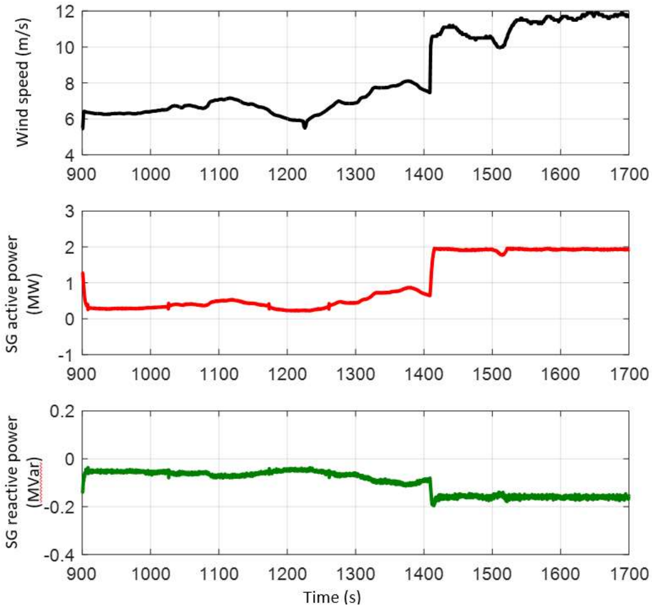


Figure 10 - Variable wind speed operation

The torque limiter helps arrest the torque oscillations during low voltage ride-through (LVRT) operation of Type 5 wind turbines. Test results shown in Figure 11 demonstrate robust ride-through after 50% voltage drop with torque converter limiting power oscillations keeping it within the MVA rating of the generator. The torque limiter is important to avoid pole slip which is one of the most destructive conditions for any synchronous machine. It allows ride-through and maintenance of synchronism in case of weak grid or islanded operation of Type 5 wind turbines.

At present, NREL is conducting power system level studies to demonstrate the stability benefits of Type 5 topology to the grid. In particular, the ability of Type 5 topology to provide grid strength and short circuit current is the focus for these simulations.

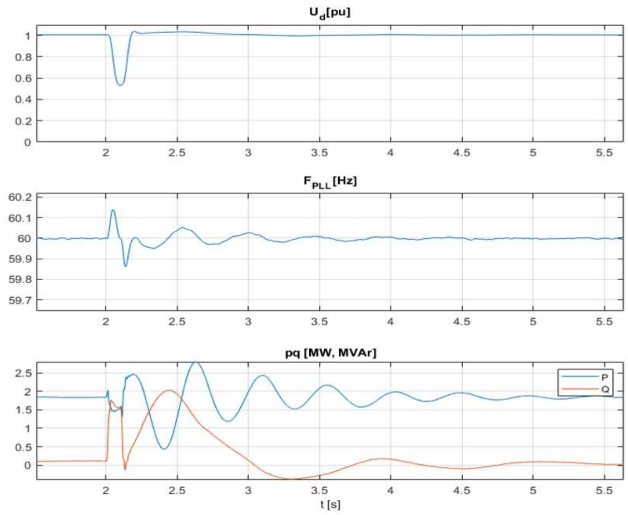


Figure 11 - LVRT during 50% voltage drop with torque limiter

Contrary to the impedance characterization of Type 3 wind turbines, which involves complex controls, the impedance response of a Type 5 wind turbine generator is dominated by the SG's winding inductance. The comparison between the measured impedance characteristics of a Type 3 wind turbine in grid following (GFL) and grid forming (GFM) modes, with those of a Type 5 wind turbine is shown in Figure 12.

Unlike Type 3 GFL operation, Type 5 torque and excitation controls modify the impedance response only around 60 Hz, making stability properties of Type 5 machines easy to interpret and predict. Type 5 turbines have less risk of high frequency resonances but still can be prone to sub-synchronous instability if the phase response crosses 90º threshold at around 30 Hz.

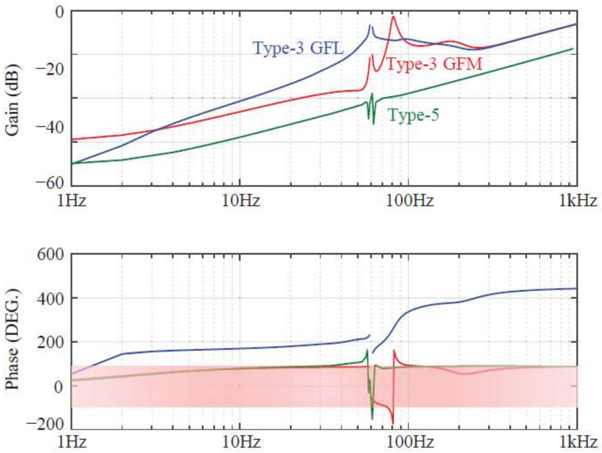
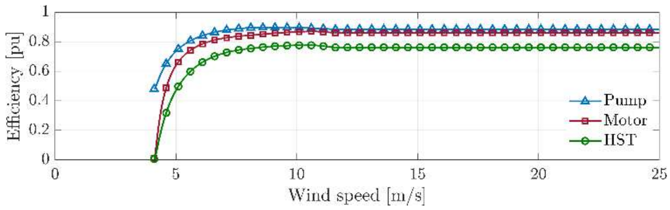


Figure 12 - Comparison of impedance characteristics between Type 3 and Type 5 wind turbine topologies

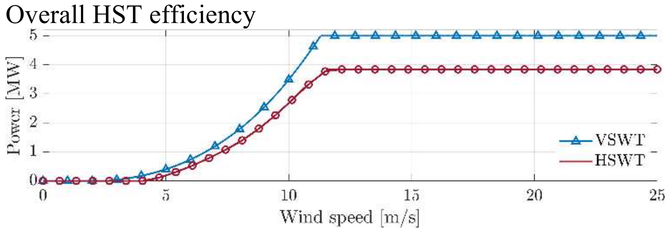
6 UCD Recent Research

Research on Type 5 HSWTs at University College Dublin (UCD) has predominantly focused on how this turbine technology interacts with the electrical grid, particularly when implemented at scale. Electro-mechanical models of Type 5 HSWTs and their control systems have been developed, with comparisons made against Type 3 and 4 (converter-based) wind turbines. In particular, the ability of HSWTs to meet grid code requirements and provide system services, such as a fast frequency response, has been investigated.

The HSWT design studied is a modified version of the NREL 5 MW VSWT, which incorporates fluid-to-mechanical power conversion, including variable loss coefficients that adjust with operating conditions. In the HST system, the pump operates most efficiently within a moderate speed range and at mid to high pressures, but its efficiency drops significantly outside these conditions. Conversely, the motor peaks in efficiency at full displacement and medium to high pressures, with a sharp decline at lower displacement and pressure, particularly during partial load operation, as shown in Figure 13. Compared to the reference VSWT, which delivers 5 MW, the HSWT—using the same turbine rotor—delivers only 3.94 MW due to its lower HST efficiency.



Overall HST efficiency



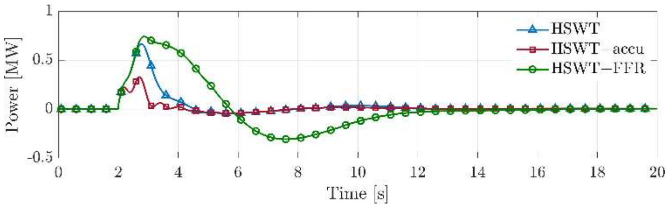
Power curve comparison

Figure 13 – Efficiency and power output characteristics of an HSWT in comparison to a VSWT

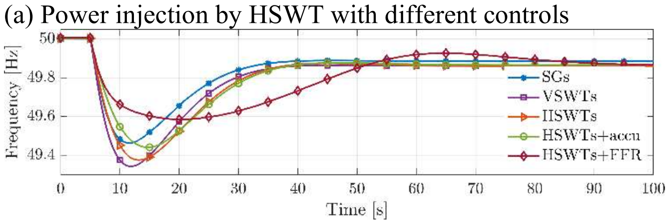
For a power system with high wind shares (and other converter-based RES options), synchronous inertia is typically reduced due to fewer synchronous generators on the grid, affecting the system's ability to manage frequency disturbances. Consequently, effort has focused on developing controls to enable frequency service provision by HSWTs [7], [16]. Unlike VSWTs, the synchronous generator in a HSWT naturally provides an inertial response. Additionally, an accumulator can further improve the frequency response by controlling the rapid exchange of energy with the system, effectively supporting the inertial response. Further fast frequency response (FFR) controls augment power injection during the initial stages of frequency events, employing controls to release rotational energy from the turbine rotor.

For example, Figure 14(a) illustrates the additional active power injected during a frequency event with different HSWT controls: i) inertial response (HSWT), ii) inertial response + accumulator (HSWT+accu), iii) inertial response + FFR (HSWT+FFR). In Figure 14(b), these controls are tested on a Type 5 HSWT power plant connected to the IEEE 14-bus system. For a 80% renewables scenario, a 10% load increase is introduced to assess the system frequency response. Without frequency controls, replacing synchronous generators with VSWTs leads to a higher rate of change of frequency

(RoCoF) and lower frequency nadir due to reduced system inertia. HSWTs improve the frequency response but don't match the base case, as their inertial contribution is lower than large thermal plants. Despite HSWT accumulators releasing additional energy during events, the frequency nadir may still be lower due to limited power exchange capacity. The accumulator improves the RoCoF and delays the frequency nadir, giving primary frequency controls more time to act. Activating the FFR controls in HSWTs significantly improves the frequency nadir by temporarily extracting rotational energy from the turbine rotors, leading to a better overall response.



(a) Power injection by HSWT with different controls

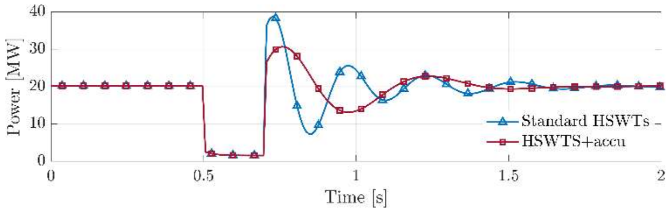


(b) Frequency response with high wind share

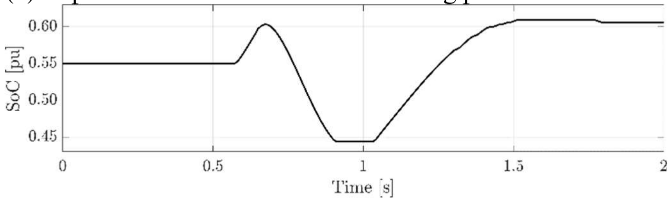
Figure 14 – Impact of HSWT control strategies on frequency response

Ensuring stable operation of Type 5 HSWTs during grid faults is crucial, requiring effective fault ride-through (FRT) controls. During faults, power oscillations can cause abrupt changes in turbine output, risking turbine integrity and pole slipping. Hydraulic accumulators can enhance the dynamic response by quickly responding to grid faults, improving FRT capabilities. UCD research has explored the ability of accumulators to reduce turbine stress during faults, based upon a Type 5 wind power plant, consisting of three strings, each with five HSWTs and its own transformer. A 200 ms bolted 3-phase fault is introduced at the low-voltage side of the collector transformer, and Figure 15 shows the impact of the accumulator on reducing power oscillations in string 1, by acting as a temporary energy buffer. This reduction in power oscillations not only enhances the stability and reliability of the wind power plant but also mitigates stress on generator components, leading to improved operational performance and extended equipment lifespan. Also shown is the state of charge (SoC) of one of the HSWT accumulators, which confirms that the accumulator is charged/discharged as the power oscillates, but without hitting its operational limits. Consequently, it offers a simple and inexpensive solution, instead of costly energy storage devices or complex controls used with VSWTs.

As previously mentioned, the efficiency of an analogue HSWT drops significantly, especially in the motor, at lower displacements due to internal leaks and friction. This inefficiency is problematic for wind turbines, which often run at partial loads, leading to hydraulic losses and reduced performance. However, to improve efficiency and control, the analogue HST can be replaced with digital displacement machines (DDM) that use computer-controlled valves. Each cylinder in a DDM is independently activated, allowing for adjustable displacement and greater efficiency across a wider range of conditions. Additionally, DDMs enable precise control of the transmission ratio, eliminating the need for a power converter to match grid frequency and enhancing power extraction under partial loads. As a result, DD-HSTs are gaining interest as a high-efficiency alternative to traditional systems [9].



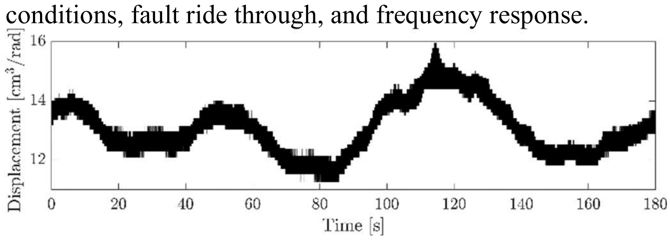
(a) Impact of the accumulator on reducing power oscillations



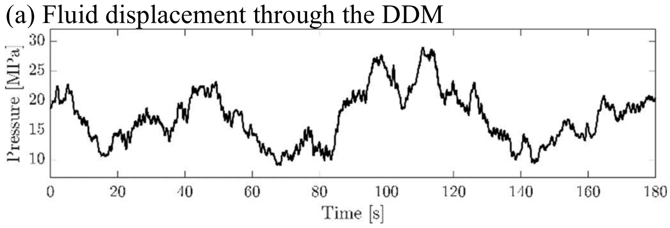
(b) SoC of an accumulator during power oscillations

Figure 15 – Accumulator's role in controlling power oscillations during faults

UCD research has developed a model and control system for DD-HST-based wind turbines, which addresses turbulent wind conditions, fault ride through, and frequency response.



(a) Fluid displacement through the DDM



(b) Fluid pressure in the DD-HST

Figure 16 – Operation of DD-HST based wind turbine in turbulent wind speed conditions

For example, the upper figure in Figure 16(a) illustrates fluid displacement in the DD-HST under a turbulent wind speed profile, showing how the number of active cylinders dynamically adjusts to balance pump torque with aerodynamic input. This process, inherent to digital displacement technology, creates flow ripples due to the precise activation and deactivation of individual cylinders. Figure 16(b) shows the resulting pressure variations in the HST high-pressure line, due to volumetric flow pulsations from the digital displacement mechanism. The accumulator is crucial here, dampening flow and pressure ripples by absorbing (releasing) energy during peaks (and troughs), in support of stable and efficient HSWT operation.

7 Capital, O&M Costs in LCOE Analysis

Table 1 sets out the main cost-driving engineering characteristics of the three candidates described in sections 2, 3 and 4 above.

Table 1 - Type 5 system characteristics affecting LCOE

Type 5 System	Sync Wind	Voith drive	Full Hydro
Number of gearboxes in drive-train	1	2	0
Inverters removed from standard turbine design	Yes	Yes	Yes
Hydraulics added to standard turbine design	Yes	Yes	Yes
Power rating of added system(s) (% turbine rating)	5%	100%	100%
Overall effect on energy capture (% Type 3 turbine)	+0%	-5%	-10%
Net effect on O&M costs	0 – 2%	0-10%	0-20%

7.1 Baseline Values for LCOE

Stehly et al [21], [22] have set out details of the build-up of wind energy LCOE for 2021 and 2022. Their model is as follows:

$LCOE = (CapEx * FCR + OpEx) * 1000 / AEP_{net}$

where:

- LCOE = levelized cost of energy ($/MWh)
- FCR = real (net of inflation) fixed charge rate (%)
- CapEx = capital expenditures ($/kW)
- AEP_{net} = net annual energy production (MWh/yr/MW)
- OpEx = operational expenditures ($/yr/kW)

There were significant variations (up and down) between the results for the two years. Therefore, we have taken average values for "utility-scale, land-based" projects for 2021 and 2022, which are assumed to be based on Type 3 turbines (the most common and least-cost of the mainstream turbines). These are presented below in Tables 2 and 3 to the level of detail which is relevant for comparing different power-trains.

Table 2 – Baseline Type 3 LCOE (2021-22 average [21], [22])

Utility-Scale Land-Based Values		Notes
Wind turbine rating (MW)	3.15	
CapEx ($/kW)	$1,626	
Real fixed charge rate (FCR)	6.31%	per annum
Annualised CapEx ($/yr/kW)	$102.5	= $26.3/MWh (72% of LCOE)
OpEx ($/yr/kW)	$40.5	= $10.1/MWh (28% of LCOE)
AEPnet (MWh/yr/MW)	3,938	= 45% capacity factor
LCOE ($/MWh)	$36.4	

Table 3 - Type 3 Capex Breakdown (2021-22 av'ge [21], [22])

Capex Breakdown	$/kW	$/MWh	% of LCOE
Drive-train	210	3.4	9%
Nacelle Electrical	146	2.3	6%
Other turbine components	644	10.4	29%
Total Turbine Capex	1000	16.1	44%
Electrical Infrastructure	98	1.6	4%
Other Balance of System Costs	528	8.6	24%
Total Balance of System Capex	626	10.2	28%
Total Capex	1626	26.3	72%

Henderson [3] included a Table 1 which shows SyncWind's analysis of the capex 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 is loosely equivalent to "Drive-train" plus "Nacelle Electrical" in Table 3. In Table 1 of [3], the Type 3 power-train total cost was set at 100 units (i.e. 100%) and the TLG-LVS sub-systems were estimated relative to that base case, showing that power-train cost would realise a net reduction of about 5%.

Table 4 combines the information in Table 1 of [3] with similar estimates for the Voith Windrive and full hydrostatic systems, along with Tables 1-3 above. In addition, a further column is added showing the effect on Type 3 LCOE if sync-cons are required at wind farm level. This would increase LCOE by 9%:

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

These assumptions and other estimates in Table 4 are intended to enable illustrative values to be calculated. These show the fundamental relativities that are expected based on the hardware increments and energy losses associated with each candidate.

Table 4 - Type 5 system vs Sync-con effects on LCOE

LCOE Effect	SyncWind TLG-LVS	Voith Windrive	Full Hydrostatic	Sync-con
Drive-train	0 x 9%	0.2 x 9%	1 x 9%	0 x 9%
Inverters	-0.3 x 6%	-0.3 x 6%	-0.3 x 6%	0 x 6%
Hydraulics	0.1 x 9%	0.2 x 9%	0.5 x 9%	0 x 9%
Sync-con	0	0	0	9%
AEPnet	0%	5%	10%	1%
O&M	1% x 28%	5% x 28%	10% x 28%	1% x 28%
LCOE	-0.62%	8.2%	24.5%	10.3%

8 Conclusion

Type 5 wind turbines have been used since the early days of the wind industry since at least the 1970s when Sir Henry Lawson-Tancred developed his full hydrostatic turbines [10]. However, this Type 5 candidate has had to overcome the capex and efficiency burdens of a high power radial piston machine and associated hydraulics. Recent deyelopments have addressed these issues and research is ongoing, stimulated by concerns over the impact of IBRs on system strength and inertia.

There are now three established candidates for Type 5 power-trains. In contrast to the full hydrostatic drive, the other two Type 5 candidates retain the main features of conventional wind turbine drive-trains, including the main gearbox. Differential epicyclic gearing is added along with a reduced fraction of the power transmission being handled hydraulically.

Of these, Table 4 shows that SyncWind's Type 5 power-train is economically competitive with Type 3 turbines under present settings which do not generally penalise IBRs. 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.

If sync-cons become generally required, the Voith Windrive could also become competitive. It remains to be seen whether the full hydrostatic drive will be able to overcome the capex and efficiency burdens of a high power radial piston machine and associated hydraulics.

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