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.

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***Abstract*— Synchronous wind turbines, directly grid-connected, provide about 10% of New Zealand's wind power at a 48 MW wind farm that has been running since 2006. A further 4 MW of these turbines have been installed in Scotland since 2013. In these turbines, the generator runs at constant speed (set by grid frequency) while the turbine rotor runs at variable speed (VS). This is achieved by having a differential stage in an otherwise conventional 3-stage gearbox, combined with a hydrostatic torque reaction system. Unlike other VS designs (hydraulic or electronic), this has the great virtue that the sub-system that it adds (hydraulic in this case) handles only 5% of the turbine power, and thus does not significantly increase the capital cost of the wind turbine. The net effect on wind turbine cost is neutral or a saving because the considerable cost of power electronic conversion (PEC, rated at up to 100% of turbine power) is eliminated.**

As grid-connection requirements become more demanding of synchronous attributes (system strength and inertia), synchronous wind turbines offer significant cost savings through elimination of the need for ancillary plant to meet these requirements:

- **each wind turbine's generator can be used as a synchronous condenser, with short-circuit current capacity of 5-7 times rated supporting local system strength, thus avoiding major costs of ancillary grid strengthening in grids weakened by the high penetration of PEC renewables like South Australia's. Such grids are becoming more prevalent as the renewable transition progresses, and system operators are increasingly requiring synchronous condensers to be added to ensure secure operation of their grids.**

- **each synchronous wind turbine's generator provides some physical inertia, and the inertia of the wind turbine itself is available for fast-frequency response, promising to eliminate the need for ancillary forms of inertia - flywheels or other rapid-discharge energy storage systems**

- **ancillary voltage/VAR compensators can be dispensed with, as these functions are provided by the synchronous wind turbine's classical reactive power capability and automatic voltage regulator (AVR).**

As well as cost-savings, synchronous wind turbines provide significant reliability improvements for the grid. Fault ride-through occurs natively, because of the well-known characteristics of the synchronous generator-AVR combination, which provides instant, "analogue" response to system disturbances.

These characteristics, along with the system strength and physical inertia of synchronous generators, are well-understood and desired by grid operators around the world. For example, in New Zealand, the grid operator ranks the 48 MW wind farm of synchronous wind turbines ahead of asynchronous wind farms, as regards keeping it on-line in fault events.

A new development in synchronous wind turbine technology is SyncWind's low-variable-speed (LVS) system. This is an enhancement of the hydrostatic torque reaction system, which hitherto enabled only a narrow band of VS. By enabling broad-band VS operation of the wind turbine, the LVS system can bring synchronous wind power to all classes of global wind farm sites. IEC class 2, 3 and less windy sites require broad-band VS operation to enable low cut-in wind speed, whereas the original VS system was optimized for high wind, New Zealand sites (IEC class 1 and above). The LVS system achieves this flexibility while retaining the virtue that the hydrostatic sub-system handles only 5% of the turbine power. By eliminating the cost of power electronics that conventional wind turbines use to achieve broad-band VS, the LVS system gives an attractive net saving on the capital cost of the wind turbine. This is noteworthy because it makes the economic case for the LVS system even before the savings in ancillary plant are considered.

The first 0.5 MW LVS synchronous wind turbine has been running in Scotland since 2017 and has validated the novel elements of the design. A preliminary design for a multi-megawatt turbine has been developed since then. This paper outlines that operational experience and the main parameters of the multi-megawatt design.

***Key Learnings*— Synchronous wind power generation is functional, durable and well-proven in New Zealand and Scotland. It is scalable, eliminates power electronics and provides system strength and physical inertia. Thus, ancillary reactive power and inertial devices to bolster system strength can be omitted from wind farm grid connections, even on grids with high levels of renewables penetration, and on weak parts of any grid.**

Keywords—synchronous, wind turbine, powertrain, fault current, short-circuit current, inertia, VAR support, system strength, renewable transition

I. INTRODUCTION

Reference [1] informed the 2017 Wind Integration Workshop in Berlin of the history to date with the synchronous powertrain which is the subject of this paper. That experience dated back to the original torque limiting gearbox (TLG) system prototyped in England in 1990, for which the main purpose was protecting the gearbox from above-rated torque transients. The ability to run a synchronous generator (SG) directly on-line was regarded as a side-benefit, and one of uncertain value at a time. As colleagues pointed out in the late 1980s, "wind power will always be a small part of the generation mix and anyway Britain has a massively stiff electricity grid". There is some irony in this, viewed with the benefit of hindsight.

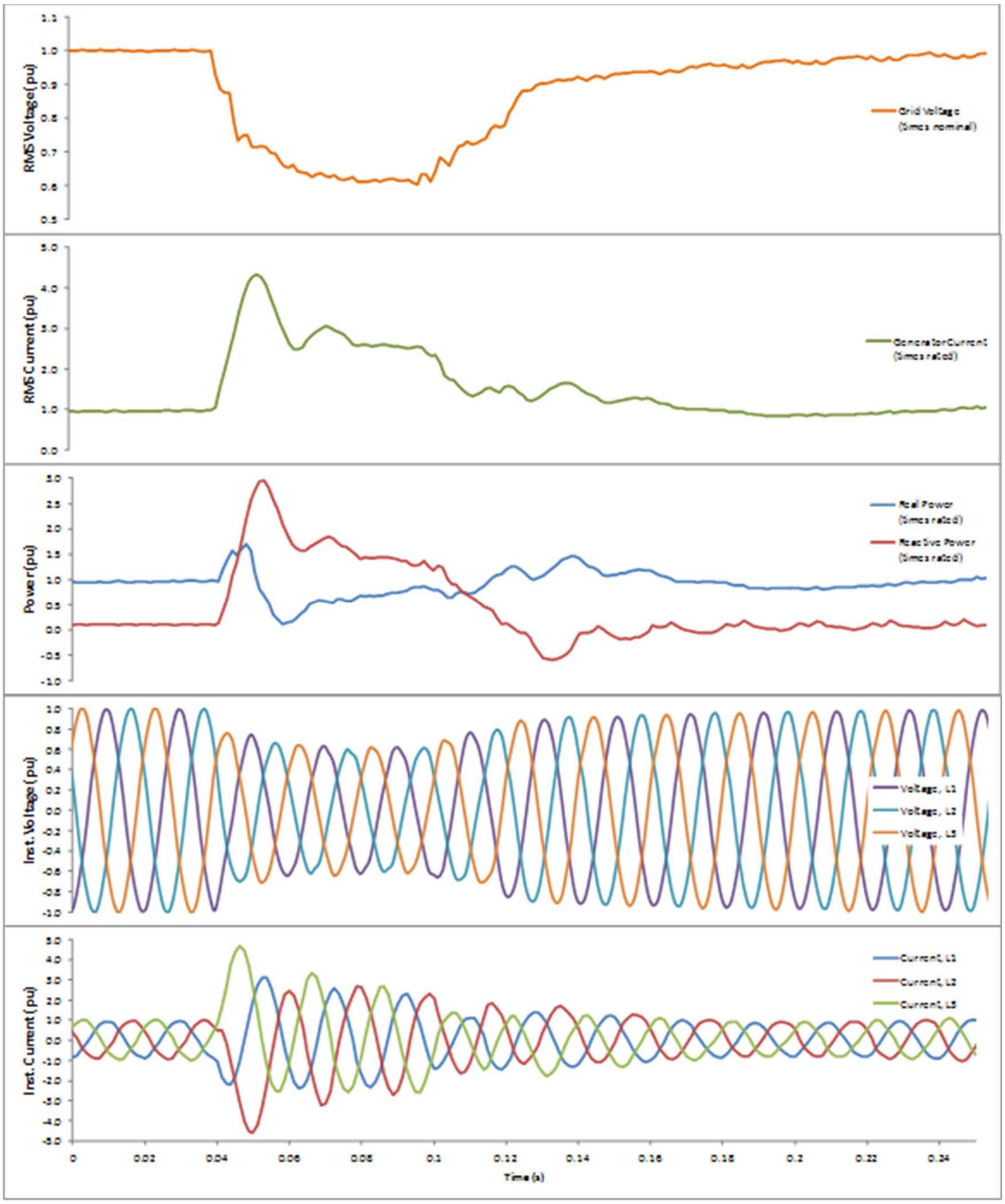

Fig. 1. Fault response of Windflow 500 synchronous turbine during voltage sag event, 8 September 2012, at the 48 MW Te Rere Hau wind farm, New Zealand. This shows an example of short-circuit current contribution and ride-through of a Windflow synchronous turbine during a system voltage disturbance that lasted around 100 ms (0.1 seconds). It is the same basic response as any other "conventional" generating plant on the grid.

- The top pane shows the voltage dip on the grid.
- The second pane shows the short-circuit current response.
- The third pane show the real and reactive power response, and in particular the red trace 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. By responding to the voltage dip effectively instantaneously, the 48 MW synchronous wind farm played its part alongside the larger generators on-line at the time (typically totalling 4000 MW) in ensuring the national grid could achieve rapid and stable return to normal operation.
- The bottom two panes show instantaneous voltage and current from the generator and show the turbine remaining online and returning to approximately pre-fault levels shortly afterward. Note that the peak current on one phase is nearly five times the rated current (it was at rated before the disturbance) and that this peak precedes the maximum voltage dip.

Reference [1] set out the track record of the TLG system in the Windflow 500 turbine, which has been successfully running in New Zealand since 2006 and Scotland since 2013. Some illustrative experiences were set out:

- The prototype 500 kW turbine near Christchurch, New Zealand, earned considerable revenue by provided up to 550 kVAr reactive power to support network voltage during periods of high demand
- The pilot 2.5 MW Te Rere Hau wind farm in the Manawatu Saddle, New Zealand, was required to be derated to 1.0 MW for two years because the initial 11 kV connection was weaker than expected. To prevent unwanted voltage rise, the five turbines ran at 200 kW rating and 0.6 power factor, importing kVArs while running on each generator's stability limit
- The full 48 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 which operationally nearly passed unnoticed but for the event-recording function of the SEL relay installed at each turbine. Figure 1 illustrates one event.
- A Windflow 500 installed on the Orkney Islands in Scotland experienced an islanding event on a 33 kV network, which lasted 0.3 s. A total of 10 MW of PEC wind turbines were also islanded with the Windflow 500. Rapid and chaotic high-frequency voltage transients were experienced, illustrating what an inertialess system might look like. A pole-slip occurred. This provided experience of the benefit of the TLG in protecting the drive-train from torsional shocks in such electrical fault events, while sustaining only low-cost damage at the "scheduled maintenance" level. Such events are known to have caused extensive damage to other types of synchronous wind turbine drive-trains which have been tried (but found wanting) over the years.

Reference [1] concluded by introducing the newly prototyped LVS synchronous wind turbine, as perhaps an idea whose time has come. By adding broad-band VS capability to the proven TLG system at a time when there is growing need for grids to maintain system strength, a new source of system strength can be added to the grid as it transitions to renewable energy.

II. Developments since 2017

A. *Growing track record with the prototype LVS turbine*

Following commissioning in early 2017, the prototype LVS Windflow 45-500 has built a successful track record at its site near Edinburgh, Scotland. Prototyping issues were addressed during 2017 and 2018 such as:

- Determining stable parameters for the new, low-slip control loops involved in providing broad-band VS capability in low winds
- A cooling issue, due to operating in low winds when the original Windflow design relied on the wind correlating with cooling requirements, was addressed by supplementing with a small fan cooler
- Tuning the start-up parameters to achieve desired cut-in wind speed of 4 m/s while producing positive net power output.

The turbine, along with the other Windflow turbines in Scotland, was sold to a third party in 2019 and it has continued to run since then, building up positive track record. Pleasingly, this successful prototyping experience has been achieved with an even lower rated LVS system (3% of turbine rating) than the 5% of turbine rating that would normally be recommended for economic optimisation.

B. *Emphasis on system strength in Australia*

In September 2017, a year after a much-publicized blackout in South Australia, a new system strength framework was introduced by the Australian Energy Market Commission (AEMC) [2]. The following month, the Australia Energy Market Operator (AEMO) issued a notice to the South Australian network operator, Electranet [3]. The notice declared a "shortfall in system strength". This resulted in Electranet undertaking a A$166 million project to install 516 MW (continuous machine rating) of synchronous condensers at two sites in South Australia. The project is nearing completion in August 2021 [4].

The effect of that project will be to bring the South Australian network into compliance (without relying on surplus fossil-fired power) with the new AEMC framework in respect of historical asynchronous renewable generation. However, the new framework has created an obligation for new generation projects to meet the cost of maintaining system strength, if such projects are located at an insufficiently stiff part of the grid.

C. *Regulatory uncertainty in Australia delaying renewable transition*

Multiple regulatory bodies (AEMO, AEMC, and the overarching Australian Energy Regulator (AER) at the Federal level as well as many others at the state level) have issued multiple documents in recent years, for example [2], [3], [4], [5], [6], [7], [8]. In August, 2019 AER commenced court proceedings against four wind farm operators in South Australia, relating to the 2016 blackout, for "*not maintaining continuous uninterrupted operation to ride-through low voltage disturbances*" [9].

Such issues over electrical connection requirements have resulted in "big delays for even already built projects" [10], [11].

D. *East England blackout of August 2019*

On 9 August 2019, near simultaneous faults at the Hornsea offshore wind farm and a thermal power station triggered a significant blackout in east and south-east England. While power was restored in about 15 minutes, the impact of the blackout was prolonged with some train passengers being stranded for several hours.

Like the South Australia blackout of October 2016, an issue with the offshore wind farm was the fact that certain controller parameters were incorrectly set or had remained at inappropriate factory defaults.

It is of interest to try to compare the fault ride-through characteristics of this wind farm of modern PEC turbines with the behavior of the SGs of the Windflow 500 turbines at Te

Rere Hau. Figure 2 shows such a comparison, taking the data from Figure 1 and plotting it on a common scale with published data from the August 2019 blackout in England [12].

Figure 2 compares the fault response of:

- one of the Windflow 500 synchronous turbines at a 48 MW wind farm during voltage sag to 0.6 pu on 8/9/2012, New Zealand, with
- Hornsea 737 MW wind farm during voltage sag to 0.92 pu before a blackout on 9/8/2019, SE England.

The bottom graph shows the synchronous Windflow turbine provides massive and immediate reactive power export opposing the voltage sag stably. By contrast the Hornsea wind farm delayed more than 50 ms before providing an inadequate amount of reactive power. Subsequently, this graph shows "*unexpected large swings*" which "*should not have occurred*", according to [12]. The middle graph shows the synchronous turbine resuming power versus Hornsea tripping.

While this comparison is not a rigorous "apples to apples" comparison in terms of the scale of the wind farm, the national grid, or the fault itself, consideration of the synchronous turbine graphs illustrates how Type 5 fault current provides system strength, helping to keep a system "in sync" and generation "on-line".

E. Preliminary design of multi-megawatt LVS gearbox

Given the scale of modern wind turbines, it is clear that the LVS system needs to be implemented at multi-megawatt scale. In order to progress this prospect, a preliminary design for a LVS gearbox has been prepared. The gearbox chosen was one commonly used by several turbine manufacturers, being a 2.3 MW rated, 3-stage (planetary plus two parallel) for a 4-pole DFIG generator, which remains the most common drive-train in the wind industry.

The gearbox, which would most conveniently be retrofitted in the event of a gearbox repair, would leave unchanged the main planetary stage internals, front housing and its mounting to the nacelle. These are the largest parts of the gearbox, reacting the largest torques imposed by the turbine rotor. Thus, it is beneficial to leave them unchanged, either for retrofit or original equipment manufacture.

The rear housing is best converted to the TLG/LVS design by redesigning it in a similar fashion to the existing design, with a split housing. The split is inclined at a different angle, in order that the output shaft is kept in the same alignment with the generator shaft. The gearing inside this housing is changed to have one parallel stage and one planetary epicyclic stage, the latter having its annulus reacted hydrostatically by a radial piston pump.

Other work to complete the LVS system in a wind turbine would be:

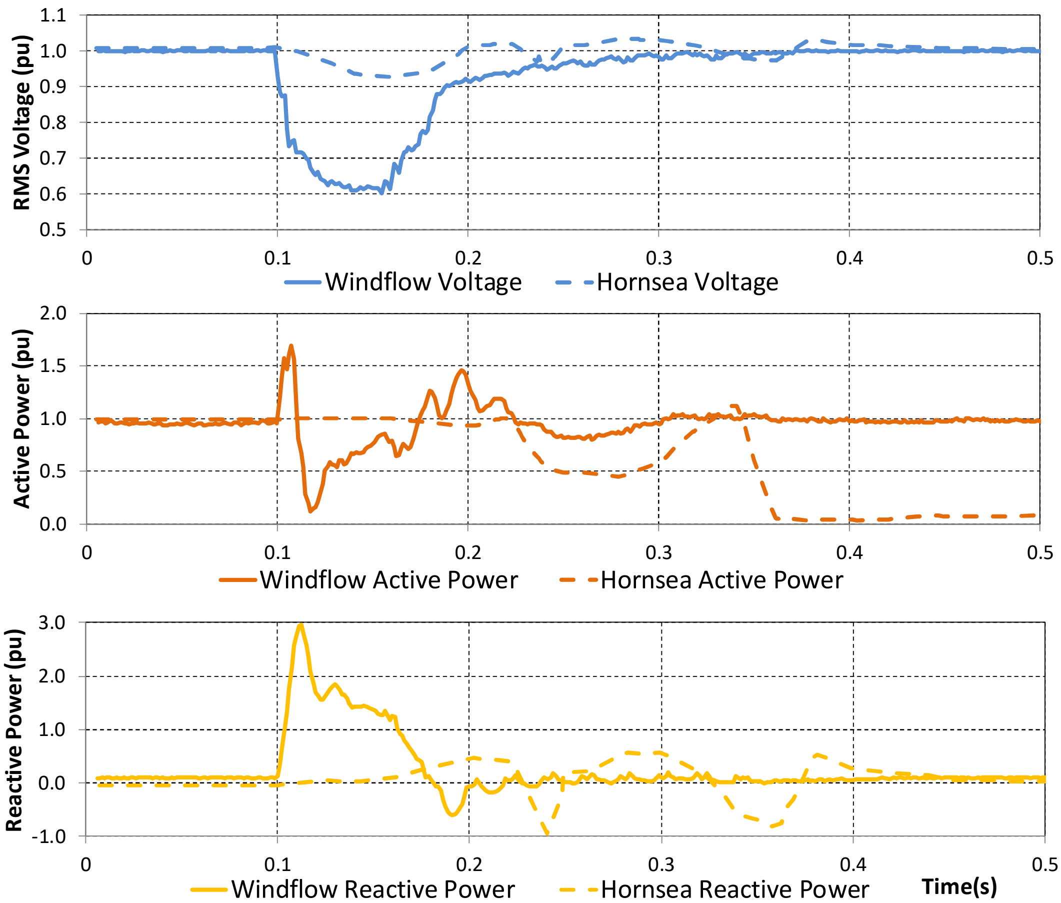

Fig. 2. Comparison of fault response of Windflow 500 synchronous turbine at 48 MW wind farm (8/9/2012) and Hornsea 737 MW wind farm (9/8/2019).

- Replacement of the generator with a multi-megawatt SG (there are several manufacturers of these for the diesel-genset market)
- Removal of the PEC interface with the turbine's grid connection
- Modification of the turbine's hydraulic system to integrate the TLG/LVS hydraulics
- Modification of the turbine's controller code to disable the PEC controls and enable the TLG/LVS controls along with changes to the turbine rotor speed control algorithm.

While these are not trivial changes, they can be shown to be cost-effective in volume manufacturing. If wind-farm scale requirements for synchronous condensers are introduced as in Australia, the economic case for the LVS system will be more than cost-effective: it will be compelling.

III. The Need For System Strength

A. What is System Strength?

Reference [5] gives the following definition for system strength, which this paper uses:

"*the ability of the power system to maintain and control the voltage waveform at any given location in the power system, both during steady state operation and following a disturbance.*

…Synchronous machines are a source of system strength".

System strength can be understood in terms of an analogy with mechanical/structural strength and stiffness. Mechanical/structural systems need to be strong enough to withstand external static and dynamic forces imposed on them without falling apart. Structures do this by developing adequate internal "reactive" forces to oppose the external ones. They also need to be stiff enough that they do not lose shape and vibrate excessively. Structures do this by having surplus strength, especially if they span large distances.

Power systems need to withstand sudden dynamic events without falling apart or losing shape. Like structures, power systems fall apart if their components are unable to develop integral forces (electromagnetic in this case) sufficient to be able to oppose the forces imposed on them by dynamic system events. Transmission grids contribute to system strength by being "stiff" enough to span large distances while conveying the forces that hold the system together.

B. The Role of SGs in Providing System Strength

SGs contribute to system strength by exerting large stabilizing forces to keep the rotors of the generator fleet "in step" with each other. They do this inherently by inducing "reactive" current flows between the collective system and the individual machines, whenever the system is being squeezed or bent out of shape by sudden external events. In this case, the right "shape" is when all generator rotors are in step and spinning at synchronous speed.

In conjunction with an adequately stiff grid, the collective synchronization of each generator's spinning rotor with the others is constantly tended to by adequate reactive electromagnetic forces. Any perturbation causes sufficient reactive currents to develop to restrain any generator rotor which may have moved out of alignment with the collective during the event. These so-called "fault" or "short-circuit" reactive currents can be up to 7 times rated current.

An important application of SGs' high fault currents is to keep the system in sync in the fractions of a second immediately following the clearance of a short circuit fault. They also feed high currents during the fault which have an important role informing the grid protection system and thus enabling it to isolate the fault and keep as many "lights on" as possible.

But what keeps SGs in sync with each other during the short circuit? In that brief period (typically 0.1 s), the system voltage is depressed to a level that makes it impossible for the collective to exert any collective stabilizing influence, or to achieve any kind of balance between the "prime mover" power being injected into the generators and the power able to be delivered by them to the system load.

The answer is – nothing! They are left to their own devices to keep in line, shut off from any collective restraint. They can only stay together as a pack for a very short time before the unbound rotational energy being input by their prime movers accelerates their rotors to positions so out of keeping with each other that stability is no longer possible. An analogy with a Grand Prix start is appropriate. On the starter's signal, each driver puts their car's accelerator to the floor, but even though each car is unconstrained by the others in the line, the cars remain more or less in line with each other for at least the first second of the race. This is because the power to weight ratios of all the cars are similar and so they gain speed at similar rates.

In this power to weight analogy, the "power" of a generator is the surplus power being input by the prime mover, which cannot be exported to the load during the short circuit. The "weight" is the inertia of the generator rotor (and any rigidly connected turbine and drive-train components). Classical SGs have similar "power to weight ratios" (referred to as their "H" constants[1]). This limits the mismatch in rotor angles that accrues during the fault until it is cleared by the transmission system. Thus, after typically 0.1 s, the mismatch is low enough that reactive currents flowing between the machines can "muscle" the rotors back into line without incurring a damaging "pole slip" event, which otherwise can cause widespread chaos in the system[2].

In summary, SGs provide system strength by having similar "H" values, which minimizes any mismatch of rotor

[1] The "H constant" of a generator is the ratio of the kinetic energy stored in the rotating mass of the rotating parts of a powerplant, to its rated power.

[2] This requirement is not confined only to recovery from a short circuit. Every kind of sudden disturbance on the power system such as the switching of an intertie transmission line, or the tripping of a generator, requires the system vector to adjust to the new requirements in an orderly way.

angles, and by having the high fault current capability to muscle the rotors back into line.

IV. Can Power Electronics Provide System Strength?

A. Inertia Maybe, but not High Fault Currents

PECs can be designed as voltage sources able to set and control system frequency. As a result, so-called "grid forming" PECs may (in principle) be able to be programmed to simulate an inertial response during faults. The active control of the voltage waveform may thus be able to minimize the mismatch of "rotor angle" accruing during a fault, with similar resulting mismatch as achieved with SGs. It is unclear from the literature [13], [14], [15], [16] whether this so-called "virtual inertia" has been shown to achieve successful resynchronization after a fault is cleared, autonomous of any grid information during the fault.

In the future, such grid-forming software may be able to improve the robustness of PEC systems to ride through a wider range of faults than they have to date been able. Table 16 of the important IEEE standard 1547:2018 [17] regarding Class III inverters seems to envisage this technical potential.

However, some mismatch will be inevitable, generating large currents immediately after the fault is cleared. PECs do not inherently have high current capacity many times rated. If required to carry (say) 3 times rated current for even a few milliseconds, PECs will overload. Thus, the only way to get high current capacity is to increase the investment in PECs by the required factor, for example 3 times the rating of the power transistors in the PECs.

Therefore, to the extent that power systems with high wind power and PV penetration are required to exhibit system strength in the form of high current capacity, it appears to be prohibitively expensive to do this using PECs. The recent developments in Australia, including Electranet's investment of A$166 million in 516 MW of synchronous condensers (A$0.3/W) suggests that this deficiency in PECs incurs a high cost in the ancillary plant required to make up the missing system strength.

B. Limited Life and Reliability

PECs "have high failure rates" [18]. They have not delivered the life and reliability of the SG-AVR combination. A new generation of grid-forming PECs may be able to be developed with superior life and reliability. These are likely to be more expensive than today's PECs.

C. Can Grids be Inertialess or 100% PEC-based?

The development of grid-forming PECs seems to raise the prospect that future grids may be either completely inertialess or at least with 100% of generators being PEC-based. However, either outcome can be ruled out, even if theoretically possible, on the grounds of prohibitive expense:

- An inertialess grid would require not only all generators to be 100% PEC-based, but also all electromagnetic loads (motors etc)
- Even if just generators are envisaged to be 100% PEC-based, this assumes that no thermal power stations will remain when the renewable transition is complete. But solar thermal power and biofuel power are likely to be important components of a 100% renewable future, not least because they both provide longer-term energy storage (hours, days, weeks). Adding PEC systems to such power stations will add expense which would otherwise be not required.

Such considerations raise the question as to how grids will maintain system strength during the transition, when there will be a mixture of an increasingly large proportion of PEC-based generation operating with existing SGs. Will "grid-forming" PECs be contributing everything that is needed for forming a stable grid? A conclusion of [19] is *"that the fully reactive current injection during severe grid faults may cause the loss of synchronization of converter-based resources"*. In this case, PECs will not contribute system strength, thus will effectively be free-riding on the system strength provided by the SGs, together with increasingly reinforced grids.

This raises the question as to whether society, acting through its regulators, will allow such free-riding to persist. As in Australia, will PEC-based renewables increasingly be required to pay the cost of synchronous condensers and/or other enhancements of system strength?

D. Can Software achieve Grid-scale Coordination?

Blackouts or other grid events involving large-scale renewable generation have occurred in recent years, for example in South Australia in September 2016 and East England in August 2019. A common factor was that software settings caused unexpected and undesirable behavior.

Renewable energy is inherently a distributed form of generation. A positive aspect of the coming renewable transition could be the accompanying reliability through diversity and geographic distribution. However, this will be undermined if distributed renewable generation uses increasingly complex software and communication systems to attempt (less than 100% reliably) to provide the rotor angle synchronization required by an AC grid.

Reference [19] makes this point: "*the unique challenge with converter-based resources is that their synchronization dynamics are highly dependent on their control structure and controller parameters, and hence, a design-oriented analysis plays a critical role in stabilizing converter-based resources. Such design-oriented analysis works well in single converter systems, yet tends to be complicated in power systems with multiple converters*".

Keeping the lights on is a very risk-averse, politically sensitive business. This is perhaps the most cogent argument in favor of synchronous wind turbines. The simplicity, reliability and well-understood robustness of the SG provides a safe bet for the coming zero-emissions transition.

V. SyncWind's Synchronous Powertrain Benefit

SyncWind's synchronous powertrain is cost-effective and proven. Historically there have been a few other synchronous powertrain designs for wind turbines. However, these have failed to catch on. In general, the problem has been that their mechanical VS systems (generally hydraulic) have involved adding a sub-system which handles 100% of the turbine's rated power. This has added considerable capital cost. It has also made those designs vulnerable to costly maintenance issues.

For example, one synchronous powertrain design that was tried in recent decades involved an additional gearbox "in series” between the main gearbox and generator. The additional gearbox included a hydrodynamic transmission system and handled 100% of the turbine’s power. Thus, any failure (due perhaps to torsional shocks in grid fault conditions) could cause that additional gearbox to need replacing at considerable expense. For this or other reasons, that design did not achieve successful commercialization.

By contrast, SyncWind’s synchronous powertrain embodies a hydrostatic torque-reaction system into the turbine’s main gearbox. Rated at only 5% of the turbine’s rated power, it inherently protects the main drive-train from torsional shocks by diverting that small amount of power into a parallel mechanical path. In the event of a mechanical failure of that sub-system (either due to normal wear and tear or an infrequent severe electrical fault), it is an inexpensive maintenance item.

The 5% rating of the hydrostatic torque-reaction system is the major advantage of SyncWind’s synchronous powertrain, because it ensures the system gives a net cost saving, both on the initial capital cost and (as explained above) maintenance costs. Table 1 illustrates how this comes about. The numbers are estimates of relative cost within the powertrain costs, being part of the total wind turbine build. Note that conventional turbines have hydraulic sub-systems for brake release, pitch control and/or yaw control. Therefore, the TLG/LVS hydraulics become an addition to those existing sub-systems rather than a full, new sub-system being added. All other turbine components (tower, rotor etc) are unchanged; hence it is valid to consider only the costs listed in Table 1.

Eliminating the need for the PEC is a major benefit of the synchronous powertrain. PECs are rated at either 100% of the turbine rated power (Type 4), or a large (30-40) percentage (Type 3). Either way they are a significant capital cost. PECs are also known causes of maintenance costs, seldom lasting 10 years in the field [18].

In summary, SyncWind’s synchronous powertrain can deliver Type 5 grid connection at Type 3 cost.

TABLE I. LOWER OVERALL POWERTRAIN COSTS

POWER-TRAIN COMPONENT	Conventional	TLG/LVS	Notes
Gearbox	60	60	Lighter vs more complex
Generator	20	15	Mass-produced for diesel gen’rs
Hydraulics	10	20	Low cost because only 5% of power
PE Converter, SVC	10	0	Big saving because 100% of power
OVERALL	**100**	**95**	**Lower overall cost**

VI. CONCLUSION

The patented LVS system has been successfully prototyped in a Windflow 500 turbine in Scotland. This has added broad-band VS capability to the proven TLG system, enabling the synchronous powertrain to compete directly in all wind regimes in the global wind power market.

There is growing need for grids to maintain system strength because PEC-connected solar and wind power are increasingly displacing SGs. Reference [19] raises serious questions whether new “grid-forming” PEC systems will technically be able to meet this need. In any event, the associated costs will be significant, certainly if supplementary synchronous condensers are required as in Australia.

Wind turbines using SyncWind’s synchronous powertrain offer a new, cost-effective source of system strength to the grid as it transitions to renewable energy.

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