TYPE 5 WIND TURBINE TECHNOLOGY: HOW SYNCHRONISED, SYNCHRONOUS GENERATION AVOIDS UNCERTAINTIES ABOUT INVERTER INTEROPERABILITY UNDER IEEE 2800:2022

Geoff Henderson[1*], Vahan Gevorgian[2]

[1]SyncWind Power Ltd, Genoa, Italy
[2]NREL, 16253 Denver West Parkway, Golden, Colorado, 80401 USA
** Geoff@windflow.co.nz*

Keywords: (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. A new standard released this year, IEEE Standard 2800, attempts to codify the relationship between IBRs and the Transmission System Operator (TSO).

It is apparent from IEEE 2800:2022 that there remain fundamental problems with quantifying whether source impedance (the measure of "system strength" with which the standard is concerned) will present a problem for allowing an IBR to connect. This is "because of complex interdependencies between IBR and power system characteristics". So developers are increasingly required to adopt mitigation options such as adding synchronous condensers or curtailing IBRs.

A proven Type 5 (synchronous) wind turbine exists and has been running at 0.5 MW scale in a 46 MW wind farm in New Zealand since 2006 and eight turbines in Scotland since 2013. The US National Renewable Energy Laboratory (NREL) is conducting a study of the impacts on grid reliability, stability, and resilience of Type 5 wind turbines. The project has both simulation and testing tasks and will result in proposing a variable generation solution that will help system operators and utilities address all reliability and most resilience challenges in the evolving grid.

1 Introduction

Henderson [1] informed the 2017 Wind Integration Workshop in Berlin of the history to date with the synchronous wind turbine power-train. 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.

The degradation of system strength because of IBRs is now a major concern facing the zero-carbon transition and a recurring theme at these Workshops.

Henderson [2] updated the 2021 Workshop in Berlin with recent experience with the broad-band variable speed version of this power-train, called the low variable-speed (LVS) system. It described how the LVS system fundamentally achieves cost lower than the industry-standard Type 3 power-train and that preliminary multi-megawatt designs have been produced. It also highlighted recent experiences of blackouts in Australia and England and discussed the fundamental need for system strength to maintain grid synchronism after a fault, and whether IBRs can fundamentally provide it. It cited numerous papers, including Wang et al [3] which raised serious questions whether new "grid-forming" IBR systems will technically be able to meet this need.

Four fundamental issues were identified:

- Grid-forming IBRs may prove able to provide "virtual inertia" (although it was unclear whether this concept can achieve successful resynchronization after a fault is cleared, autonomous of any grid information during the fault) but they cannot economically provide high fault currents (say 3 x rated).
- Inverters have high failure rates and thus have not delivered the life and reliability of the SG-AVR combination.
- An inertialess grid (100% IBR-based) would theoretically resolve some problems of grid-stability, but this is not a realistic prospect, especially during the transition.
- IBRs will rely on software to manage grid-scale co-ordination. This is quite different from the robust electro-mechanical behaviour of SGs that has provided grid stability since the late 19th century.

In this paper, we will further examine these issues in the context of IEEE 2800:2022 [4].

2 IEEE 2800:2022

A new standard released this year, 'Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems' (IEEE 2800:2022 [4]), attempts to codify the relationship between IBRs and the Transmission System Operator (TSO).

It is apparent from IEEE 2800:2022 that there remain fundamental problems with quantifying, before an IBR is connected, whether system strength will present a problem for ensuring system stability after that IBR is connected. As IEEE 2800:2022 states, this is "*because of complex interdependencies between IBR and power system characteristics*".

2.1 Definition of system strength

IEEE 2800:2022 defines "system strength" as one of two things:

- System inertia, which is a measure of frequency stability
- Source impedance strength, whereby a "weak" system has a high source impedance relative to the generation connected at that point.

IEEE 2800:2022 states that "for the purposes of this document *system strength* refers to the latter".

2.2 Quantification of system strength problematic

IEEE 2800:2022 provides various metrics for system strength, including the formula for short-circuit ratio (SCR) which it calls "*the most basic and easily applied metric to determine the relative strength of a power system*". However the standard cautions that these metrics:

> "*should be used judiciously. In general, the best that these metrics may provide is a highly conservative threshold below which additional study should be conducted to help ensure stability. The value for these thresholds can vary from one system to another, or even from one operation condition to another. It is therefore generally not good practice to consider mitigation or redesign based solely on the value of these system metrics….*
>
> *For these reasons, the quantitative value of SCR is limited … 'high' and 'low' SCR values are not clear or unique, and there is generally a large range between the 'high' and 'low' values in which SCR essentially provides no guidance.*"

ERCOT's weighted short circuit ratio (WSCR) has been proposed in recent years as a metric for weak grids to account for interactions between generating resources located in electrical proximity from each other. In addition, a composite SCR metric was proposed by Achilles et al [5] as a metric for weak systems with high levels of IBRs. These modified SCR calculation methods, although used in many studies, still provide limited guidance on IBRs' impact on system stability.

Consequently, developers are recommended to use "*more rigorous studies such as electromagnetic transient (EMT) study tools … as a more reliable means to help ensure that the IBR operates as intended*".

2.3 IBR stability "impossible to guarantee"

The preceding paragraphs describe how IEEE 2800:2022:

a) defined *system strength* for its purposes as "source impedance strength",
b) then provided various metrics to quantify it while cautioning that there is a large range of the most basic and easily applied metric which essentially provides no guidance,
c) therefore recommended EMT tools as a more reliable way to ensure the IBR operates as intended.

Uncertainty about grid stability is compounded when IEEE 2800:2022 goes on to state:

> "*General requirements for IBR to prevent any control interactions with the network are impossible to guarantee by manufacture or developer, since it is originated not in the control, but in the combination of control and rest of the grid.*"

Thus IEEE 2800:2022 seems to rule out the prospect of IBRs alone being able to guarantee grid stability. This is in line with the findings of Gevorgian et al [6], which explained in some depth the limitations of the various topologies of grid-forming inverters.

Therefore IEEE 2800:2022 sets out mitigation options which range from adding synchronous condensers (which it calls "presently the primary solution for adding system strength because of multifaceted benefits including large capability to supply fault current, inertia and voltage support capability") to curtailing IBRs. Such mitigation options have been required by the TSO in Australia, causing significant financial pain and planning uncertainty to wind farm developers there.

3 Advantages and Limitations of Different IBR Technologies

The increasing need for power grids to maintain minimum levels of system strength needed for reliable operation is becoming a main concern for grids in transition. Degrading grid strength is considered a main stability "deteriorator" in the evolving grid, along with decreasing inertia and short-circuit ratio. Droop-controlled grid-forming (GFM) power converters, as first-order nonlinear systems, have potential to improve stability better than conventional phase-locked loop (PLL)-based grid-following (GFL) power converters, which act as second-order nonlinear systems. However, both GFM and GFL converters have limited overcurrent capability. This fact establishes another constraint to the transient stability of IBR-based grids. Limited overcurrent capability can be addressed either by oversizing the GFM converters or by large-scale deployments of synchronous condensers to maintain system strength. However, both solutions are costly. Furthermore, another challenge with GFM IBRs is how to determine the optimal control structure and how to control them for the best grid stability [6].

3.1 Droop-controlled grid-forming (GFM) converters

In GFM operation, the wind turbine converter itself is controlling the PCC voltage magnitude and phase. Therefore, in this particular control implementation, there is no need for the PLL to measure the voltage phasor (unless it is needed for the provision of certain frequency response services or grid resynchronization). However, in this case too, like GFL operation, it is possible to use outer loops to control the levels of the injected active and reactive power when operating in grid-connected mode. In islanded mode, the GFM wind turbine will operate as a "swing bus," adjusting its active and reactive power to follow the load. The benefit of PLL-free operation is better stability and avoidance of various interactions with the power controller. In certain cases, a PLL-free GFM controller offers a relatively simpler method that allows the converter to synchronize with the grid and operate on active power-frequency droop and reactive power–voltage droop. However, stable GFM operation can be achieved even using a PLL, depending how the PLL is used.

3.2 Phase-locked loop (PLL)-based grid-following (GFL)

In a GFL operation, the wind turbine converter controls the level of injected current depending on the active and reactive power set points with a specific phase angle difference from the voltage at the point of common coupling (PCC) interconnection. Therefore, to inject the desired levels of power, the turbine controller needs to calculate the reference current, which, in turn, requires knowledge of the grid voltage fundamental phasor. For this purpose, a PLL is used to measure the phase angle of the grid voltage at the point of interconnection. Using additional outer control loops, it is possible to control the active and reactive power injections to provide additional frequency- and voltage-responsive services.

3.3 Impact of SCR on transient performance (offshore wind power plant example)

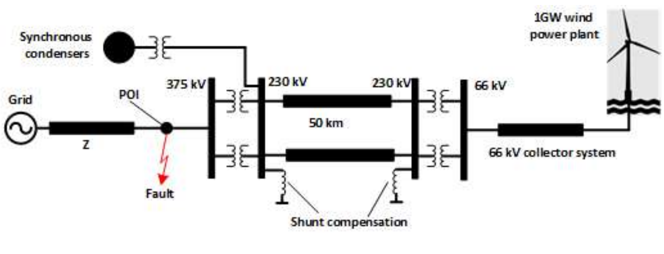

Figure 1 - Modelled system

In spite of the fact that voltage-fault ride-through behaviour and control of GFL wind generation is well-understood and has been required globally for almost two decades now, the impact of weak grids on transient performance of IBRs is still on-going research. IEEE 2800:2022 considers use of synchronous condensers as a mitigation method to improve transient stability in weaker grids.

Figure 2 and Figure 3 show results of PSCAD simulations for a 1 GW HVAC-interconnected GFL Type 4 offshore wind power plant to explain the impact of grid strength on transient performance. The modelled plant (shown schematically in **Figure 1**) is interconnected with the onshore grid using 50 km of 230 kV transmission with SCR = 3 at the onshore point of interconnection (POI). This is a relatively weak grid assumption. 250 MVAR of shunt compensation is used in both sending and receiving ends of the submarine line. The plant is exposed to a single phase to ground 200 ms fault at POI upstream of the onshore substation transformer. In the first case (Figure 2), the plant rides through the fault but recovery from the transient is accompanied by significant voltage and current transients at POI despite the wind turbines at the sending end not seeing such significant transients. The lower graph shows the total current at 66 kV offshore collector bus (inverters limit turbine currents during the fault).

The reason for such severe transient behaviour at POI is because of weak POI (SCR=3) in combination with the impedance characteristics of the transmission line and shunt compensation.

In the second case (Figure 3), synchronous condensers (200 MVA total) were connected to onshore POI when the plant was exposed to the same fault. It can be seen in Figure 3 that synchronous condensers have significant mitigating impact on voltage and current transients. Synchronous condensers are operating in voltage control mode improving voltage stability at POI, and in the same time help increasing the SCR of POI. This example explains why IEEE 2800:2022 leans towards mitigation with synchronous condensers. The other solution can be increasing the POI SCR by additional onshore transmission build-up which may not always be possible.

For comparison, we ran a simulation for Type 5 offshore wind power plant using the exact same transmission model and fault scenario as for previous two cases. The results of simulations are shown in **Figure 4**. With no synchronous condensers, the Type 5 wind power plant demonstrates fault ride-through without significant overvoltage and fast recovery compared to the GFL case shown in **Figure 2**.

RMS voltage at the 230 kV POI bus for all three cases is compared as a function of SCR in **Figure 5**. The mitigating effect of synchronous condensers on voltage stability of Type 4 GFL wind plant is obvious by comparing traces for cases 1 and 2. Type 5 wind power plant demonstrates stable operation for very low SCRs without synchronous condensers (Case 3 trace).

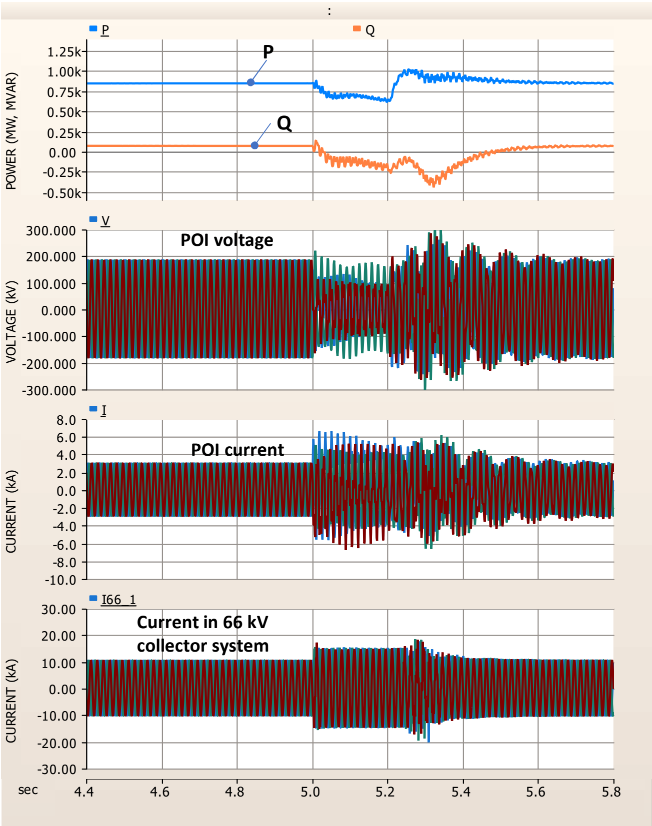

Figure 2. 1 GW Type 4 GFL wind power plant ride through 200 ms L-to-G fault (no synchronous condensers)

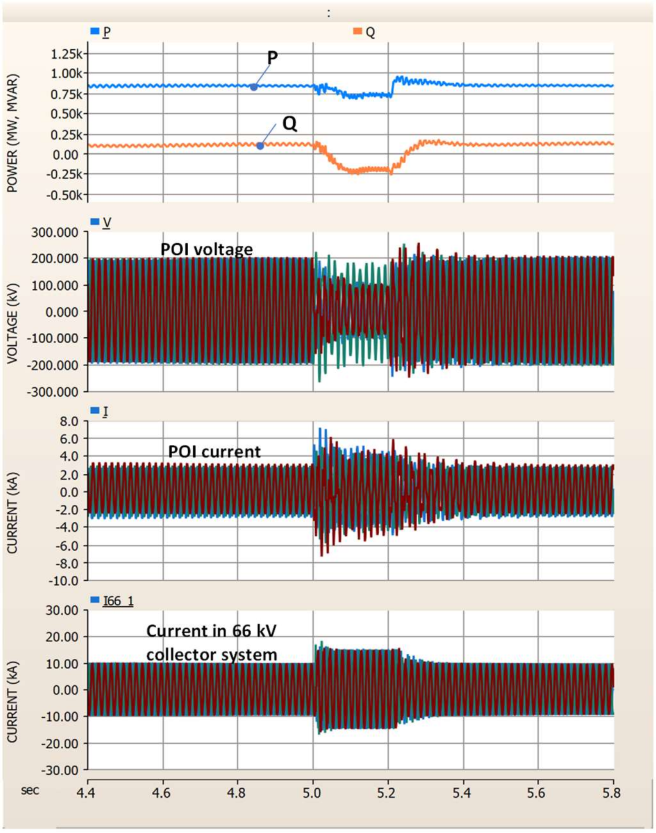

Figure 3, 1 GW Type 4 GFL wind power plant ride through 200 ms L-to-G fault with synchronous condensers

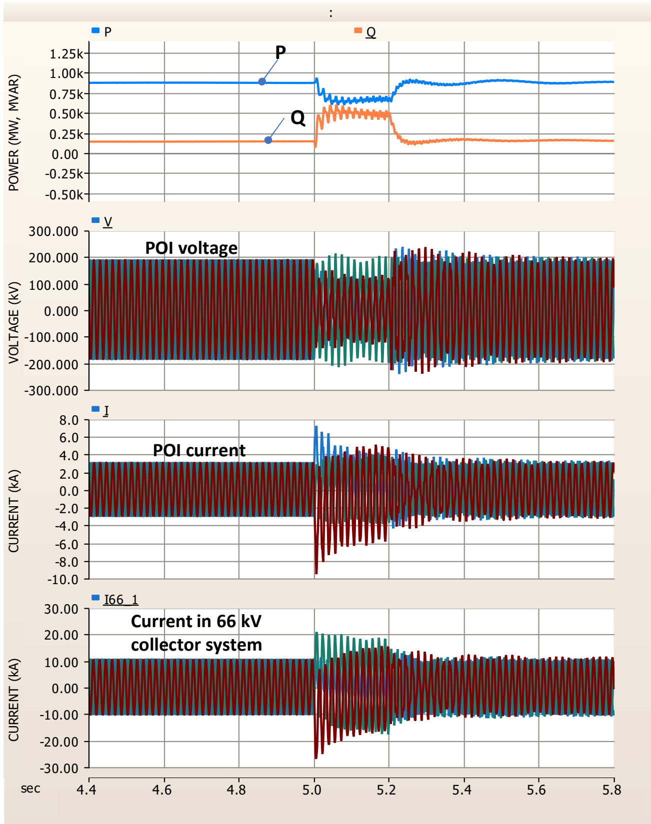

Figure 4. 1 GW Type 5 wind power plant ride through 200 ms L-to-G fault (no synchronous condensers)

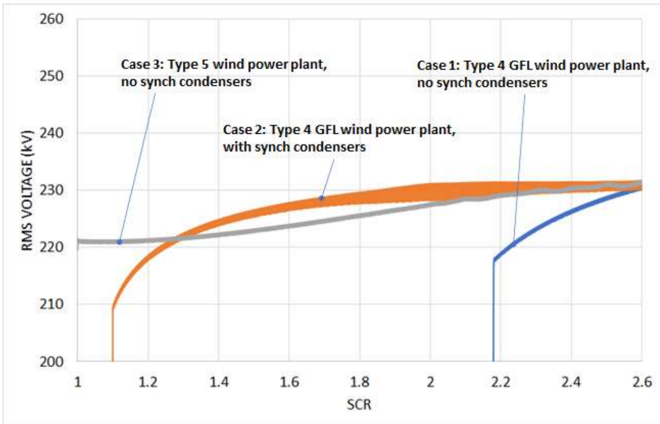

Figure 5. Voltage stability at POI as a function of SCR

4 NREL synchronous wind project

NREL is conducting a study of the impacts on grid reliability, stability, and resilience of Type 5 wind turbines. The project has both simulation and testing tasks and will result in proposing a variable generation solution that will help system operators and utilities address all reliability and most resilience challenges in the evolving grid. Type 5 wind power generation offers unique characteristics that cannot be matched by any inverter-based resources (wind, solar PV, storage). With Type 5 wind turbines, industry's most fundamental challenge – "How to transition reliably and economically from the present largely synchronous grid to the future asynchronous grid?" – will have new answers and solutions that may impact on a global scale the whole future of evolving power systems.

The NREL project is now in the modelling stage to characterize the performance of Type 5 turbines under various conditions including fault-ride through. Some preliminary simulation results of Type 5 wind turbine with variable torque limitation exposed to 3-phase nearly zero-voltage 600 ms fault are shown in **Figure 6**. Generator speed increases during the initial phase of the fault due to turbine unloading. However, that speed increase is quickly arrested by controlling the hydraulic torque limiting system. There is mechanical torque increase observed during recovery which is contained by the torque limiting system at 1.5 p.u. The turbine is producing a significant level of short circuit current during the beginning of the fault. This is helpful for maintaining the adequacy of power system protection since IBRs are not able to produce high levels of fault current. The rotating exciter's voltage and current during the fault are shown in **Figure 6** as well. These preliminary modelling results are encouraging and will be validated during the testing stage of the project.

5 SyncWind's Type 5 Power-train

5.1 Thirty-two year history and more than 1000 turbine-years

Henderson [1] and [2] informed the 2017 and 2021 Wind Integration Workshops in Berlin of the history since 1990 of SyncWind's synchronous wind turbine power-train. In summary, this is a system which:

- eliminates the inverter rated at 40-100% of turbine power in Type 3 and 4 turbines
- instead uses a mechanically variable speed (VS) gearbox which includes a differential stage and adds some hydraulics rated at only 5% of turbine power, in order to keep the power-train cost less than that of a Type 3 turbine
- originally provided only narrow-band VS (torque-limiting) capability, but has recently been enhanced (while keeping the hydraulic rating at 5% of turbine power) to provide also broad-band VS (the patented LVS system)
- has been running in 100 "Windflow 500" turbines that continue to run at high wind sites in New Zealand since 2006 and Scotland since 2013, accumulating more than 1000 turbine-years of track record that is ongoing
- is readily scalable to multi-megawatt turbines (1-20 MW) by modifying the 3-stage gearbox architecture for a 4-pole DFIG generator, which remains the most common drive-train in the wind industry
- has demonstrated its ability to act as a synchronous condenser for steady reactive power support (even when the wind is not blowing)
- has demonstrated its ability for islanded (i.e. black-start) operation
- has demonstrated its ability for frequency control using a combination of:
  - o very fast hydraulic control of reaction torque, with
  - o large rotor inertia to limit turbine speed excursions.

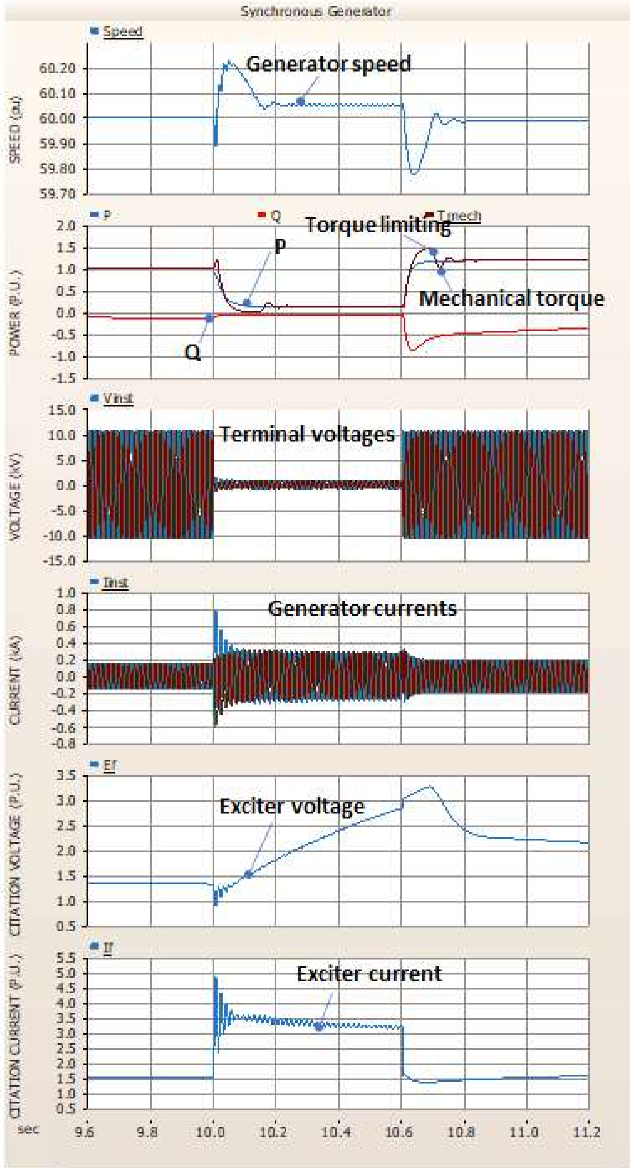

Figure 6. Modelled 3-phase voltage fault ride-through by Type 5 wind turbine with variable torque limitation

5.2 Real world examples of system strength during faults

Most importantly, it has demonstrated its ability to feed high levels of short-circuit current into transmission system faults in just the same way as any other "conventional" generating plant on the grid.

The simulations presented above in sections 3 and 4 show computer modelling results of the calculated Type 5 system behaviour, compared to best expectations of a correctly controlled GFL system with and without synchronous condensers.

Real-world data from grid fault events is, of course, not able to be "dialled up" to match the grid code prescriptions of such simulated events. However, a very good example of the Type 5 response was captured for a transmission system voltage sag event on 8 September 2012, at the 48 MW Te Rere Hau wind farm, in New Zealand. Figure 7 on the next page shows the short-circuit current contribution from one of more than 90 Windflow synchronous turbines running there during a system voltage disturbance that lasted approximately 100 ms:

- 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.

5.2 A real-world comparison of Type 4 and Type 5 behaviour

As mentioned above, real-world data from grid fault events is not able to be "dialled up" to match the grid code prescriptions of simulated events. Much less is it feasible to have two identical real-world faults to enable a comparison of Type 5 behaviour with IBRs.

The best such comparison available is shown in Figure 8 thanks to data provided by Reference [7]. This contrasts the behaviour shown in Figure 7 with that of another real-world event, being the Hornsea wind farm behaviour in the lead-up to a significant blackout in East England on 9 August, 2019. A lightning strike was followed by loss of 737 MW from Hornsea offshore wind farm and 244 MW from Little Barford thermal power station, leading to a blackout of part of the UK grid. While (unlike South Australia in September 2016) a black-start was not required and power was restored in 15 to 45 minutes, many train passengers were stranded for several hours due to software flaws on some trains. While most blame was on a rare combinations of events, the operators of Hornsea and Little Barford each paid £4.5 million to OFGEM's voluntary redress fund for not remaining connected.

The comparison in Figure 8 is not a rigorous "apples to apples" comparison in terms of the scale of the wind farm, the national grid, or the fault itself. However, it should be noted that:

- The first pane shows that the Type 5 turbines in 2012 experienced a sag to 60% voltage whereas the Type 4 turbines in 2019 experienced a much smaller sag to 92% voltage
- The second pane shows that the Type 5 turbines in 2012 experienced significant real power fluctuations (presumably due to short-circuit loads) which decayed stably and returned to full rated power. By contrast the Type 4 turbines in 2019 tripped off-line after 350 ms, possibly due to "unexpected" reactive power swings as mentioned below
- The third pane shows that the Type 5 turbines in 2012 immediately output large, helpful amounts of reactive power (short-circuit current) that decayed quickly after the voltage sag. By contrast the Type 4 turbines in 2019 did not output any reactive power until the voltage sag event was almost at the end of the normal 100 ms clearance time (when voltage was returning to the 100% level) and then produced "unexpected large swings" [which] "should not have occurred" according to Reference [7]. This presumably caused the voltage instability to be prolonged, leading to the wind farm tripping off-line.

There were software settings on the Hornsea turbines which were responsible for at least some of this unhelpful behaviour. Obviously, such events do not always occur and most IBR wind farms display good ride-through behaviour.

However, it should be noted that most of the helpful aspects of Type 5 turbine behaviour are not software dependent or otherwise reliant on how the generator and AVR are set up. This is because the high short-circuit current response is fundamental to the synchronous generator architecture. By directly connecting the synchronous generator to the grid (rather than through inverters), system strength is ensured. Type 5 turbines embody a synchronous condenser into each turbine's generator, with obvious cost benefits.

Table 1, condensed from Gevorgian et al [6], summarises the attributes of Type 3, 4 and 5 wind turbines.

6 Conclusion

Degradation of system strength because of IBRs is a major concern facing the zero-carbon transition. A new standard, IEEE 2800:2022 [4], provides little comfort to developers using IBR wind turbines, but rather explains why they are increasingly required to adopt mitigation options such as adding synchronous condensers or curtailing IBRs.

A proven synchronous wind turbine power-train exists and has been running at 0.5 MW scale in a 46 MW wind farm in New Zealand since 2006 and eight turbines in Scotland since 2013. This embodies a synchronous condenser into each turbine's generator and eliminates the costs associated with inverter systems. This has obvious cost benefits relative to the option of adding synchronous condensers at wind farm scale, especially since the synchronous power-train (from first principles) is expected to cost less than a Type 3 power-train.

NREL is conducting a study of the impacts on grid reliability, stability, and resilience of Type 5 wind turbines. The project has both simulation and testing tasks and will result in proposing a variable generation solution that will help system operators and utilities address all reliability and most resilience challenges in the evolving grid.

With Type 5 wind turbines, industry's most fundamental challenge – "How to transition reliably and economically from the present largely synchronous grid to the future asynchronous grid?" – will have new answers and solutions that may impact on a global scale the whole future of evolving power systems.

The voltage sag

The short-circuit current response - note that this instance is many times rated current (the 1.0 pu level). This cannot be provided by IBRs, which are limited to 1.0 pu or a little above

The real and reactive power response - the red trace shows reactive power immediately being exported to oppose the dip in voltage before settling as voltage recovers

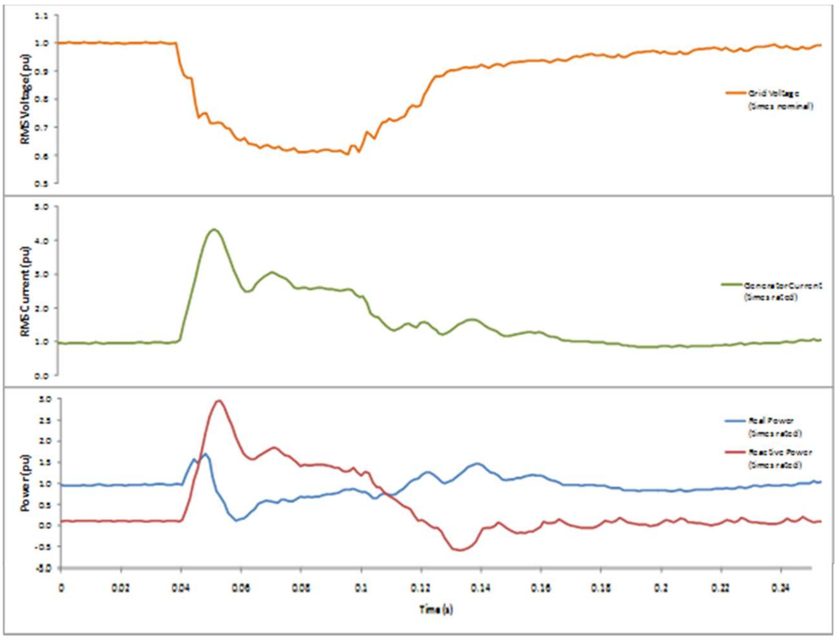

Figure 7 Example of fault contribution & ride-through (8/9/2012):
A system voltage sag to 60% of normal voltage that lasted approximately 100 ms.

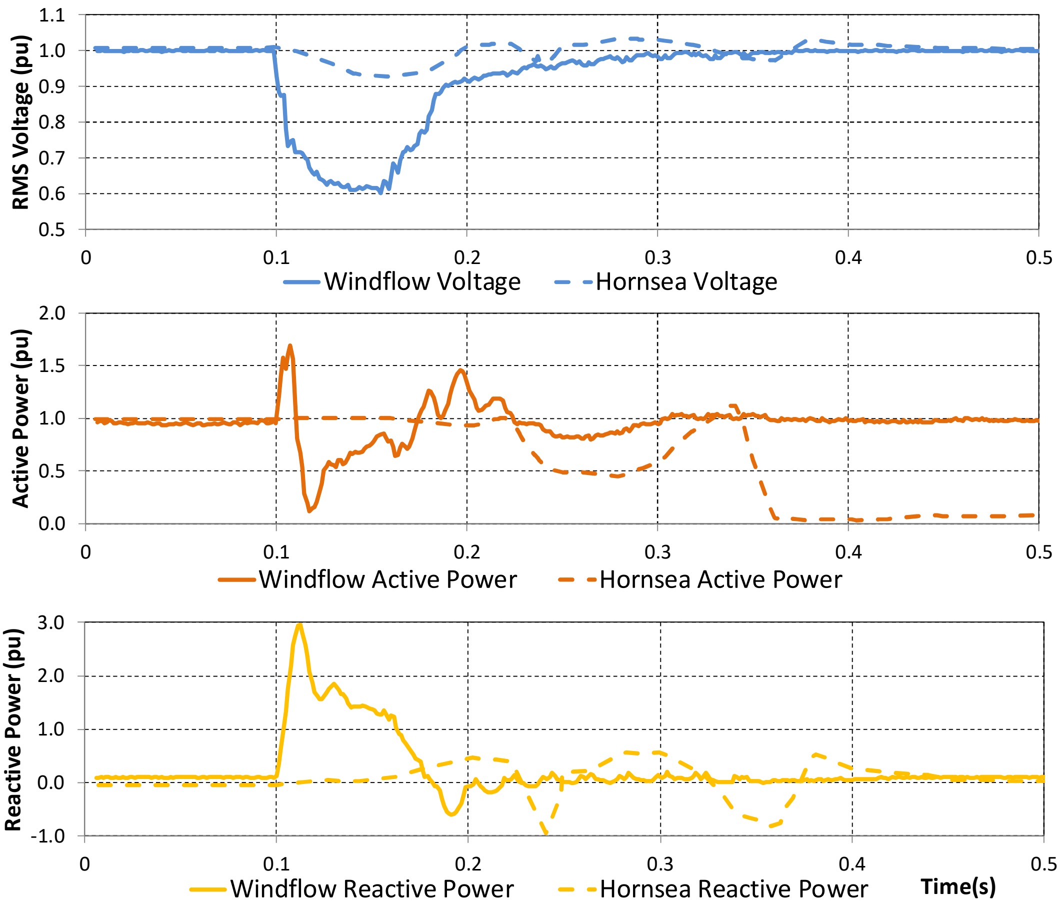

Figure 8 Comparison of fault response of Windflow 500 synchronous turbine at 48 MW wind farm (8/9/2012) and Hornsea 737 MW wind farm (9/8/2019) based on data from National Grid [7].

Table 1 Comparison of wind turbine power-trains in context of grid integration challenges

Grid integration challenge	Type 3	Type 4	Type 5
Weak grid operation	Yes, with controls		Yes, no controls needed, tends to make grid stronger.
Short-circuit current contribution	Limited	Limited	High, no controls needed
Contribution to system inertia	Fast-frequency response only	Fast-frequency response only	Yes, no controls or curtailment needed
Fast frequency response	Yes, with special controls, curtailment, and/or transient uprating		
Independent control of active and reactive power	Yes, with controls		Yes, with controllable AVR
Transient performance and ride-through	Yes, with special controls		Yes, same as conventional synchronous generator/AVR
Voltage control	Yes, with special controls		Yes, same as conventional synchronous generator/AVR
GFM operation	Yes, with controls		Yes, no controls (default operation mode)
Black-start & islanded operation	Yes, with controls and energy storage		Yes, no controls
Medium-voltage operation	Yes, with step-up transformer.		Yes, up to 20 kV no Xformer
Protection impacts	Yes, but Type 3 has more SCC capability than Type 4		No change in the existing protection framework
Wind-free voltage support	Yes, with special controls (voltage control only, no inertia)		Yes, with clutch to disconnect generator from gearbox
Brushless operation	No	Yes	Yes
Generator	Special design	Special design, depends on rare earths for PMGs	Mass produced, global maintenance network and workforce, no rare earths
Cybersecurity	Yes	Yes	Fewer controls means fewer targets for external attacks

7 References

[1] 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

[2] 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

[3] Wang, X., Taul, M.G., Wu, H., Liao, Y., Blaabjerg, F.& Harnefors, L. – 'Grid-Synchronization Stability of Converter-Based Resources: An Overview', IEEE Open Journal of Industry Applications, https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=9181463, September 2020

[4] IEEE 2800: 'Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems', 2022

[5] Achilles, S., Miller, N., Larsen, E., MacDowell, J. –'Stable Renewable Plant Voltage and Reactive Power Control', Presented to NERC ERSTF, June 11-12, 2014

[6] Gevorgian, V., Shah, S., Yan, W. & Henderson, G. – 'Grid-Forming Wind: Getting Ready for Prime Time with or without Inverters', IEEE Electrification Magazine, Vol. 10, No.1, pp 52-64 doi: 10.1109/MELE.2021.3139246, March 2022

[7] National Grid – "Technical Report on the events of 9 August 2019", 6 September 2019 https://www.nationalgrideso.com/document/152346/download