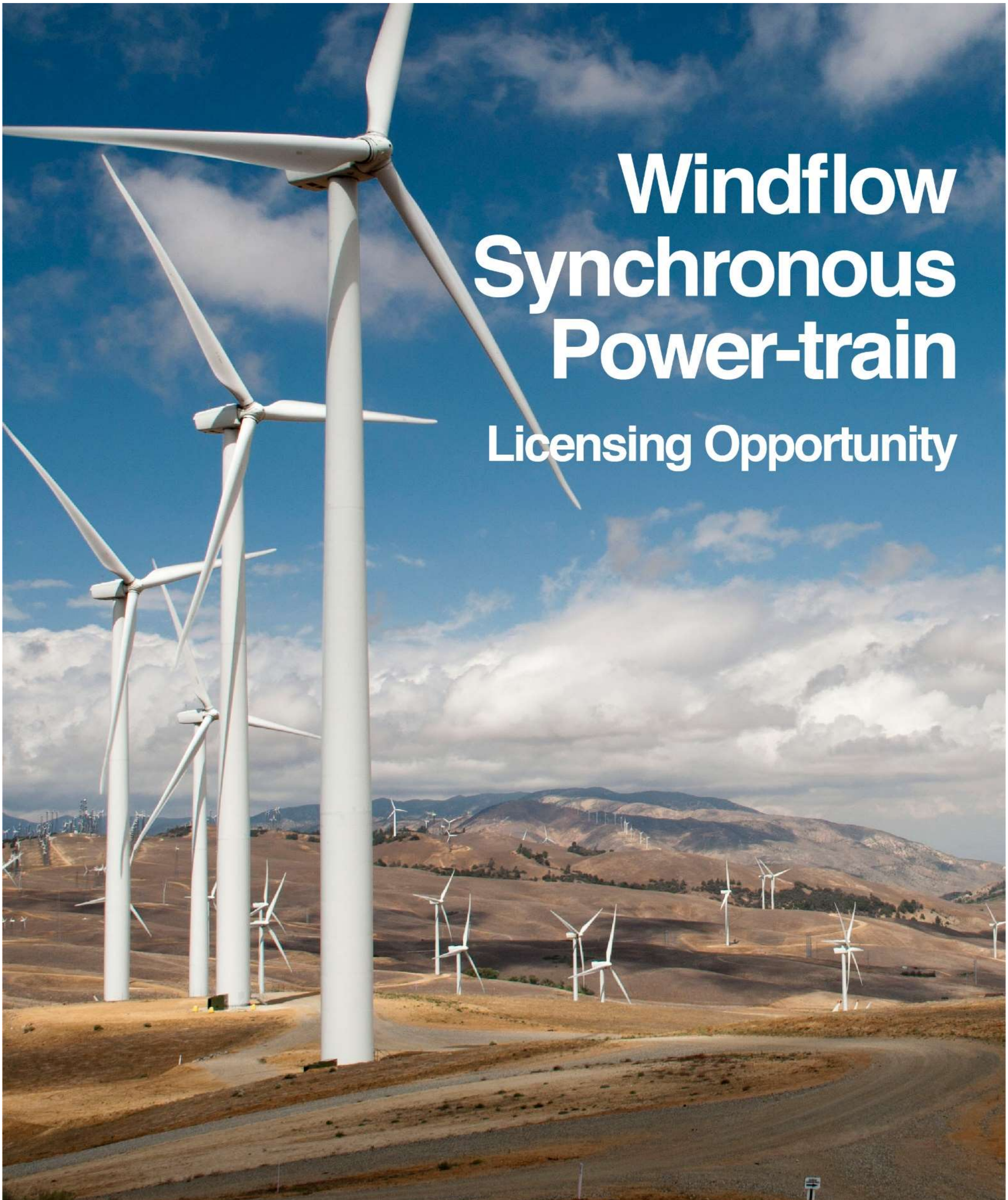
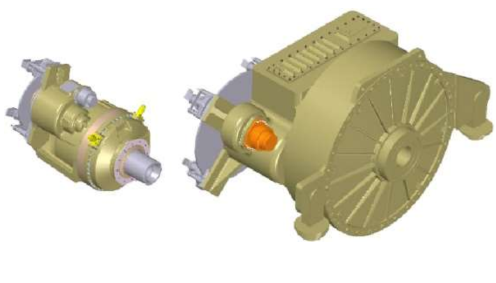
Windflow Synchronous Power-train

Licensing Opportunity





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Synchronous generation improves system stability in voltage faults and provides inertia, essential in frequency faults.

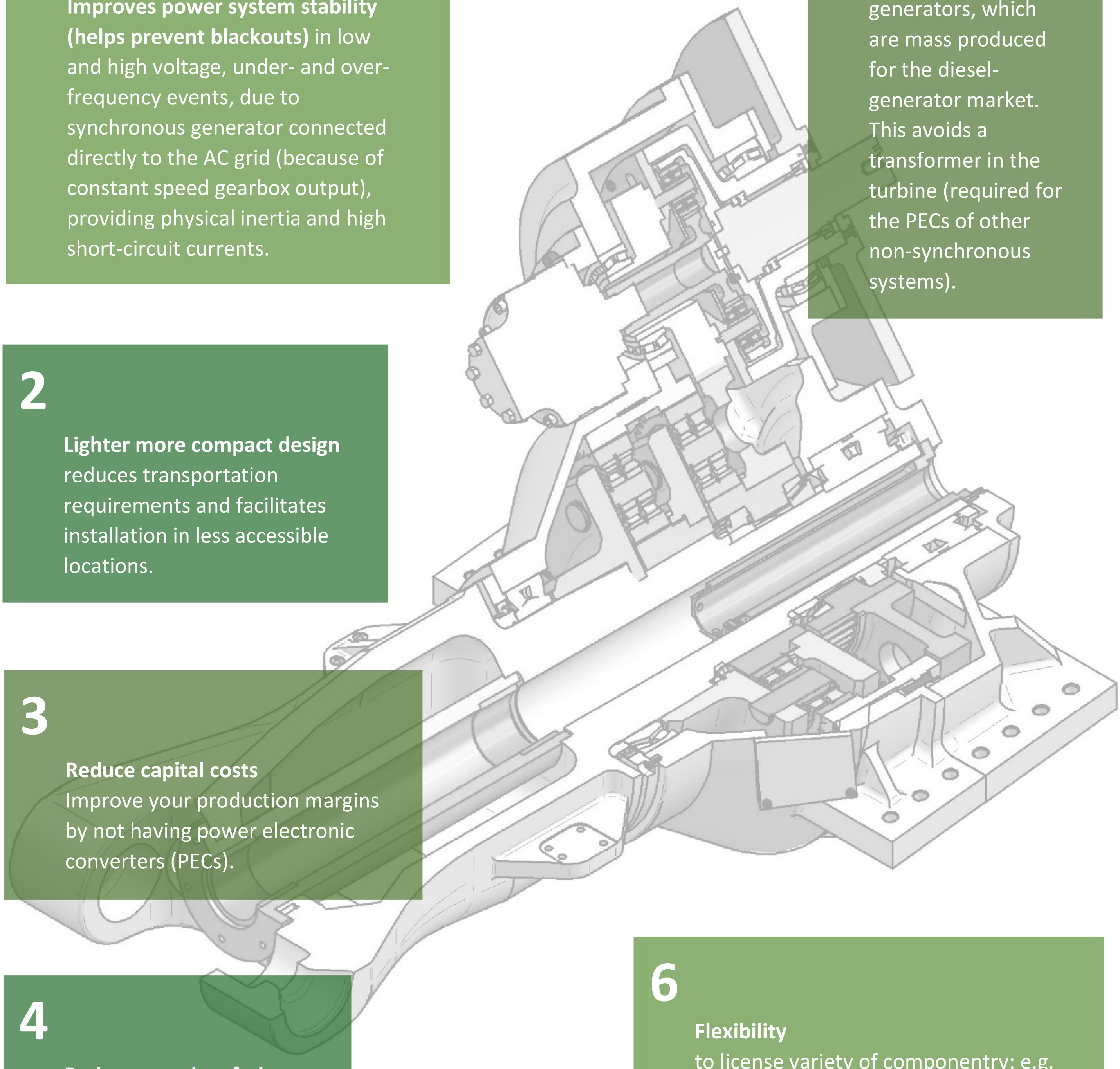
Few challenge the logic and global trend towards renewable energy generation. However, whilst harnessing Mother Nature's gifts, turbines need to assist grids to retain their in-built resilience and system strength to withstand wild weather, and system events or faults which can cause sudden fluctuations in voltage and/or system frequency.

What does physical inertia do?

It enables grid frequency to be stable. Any device or system with physical inertia has the momentum to "ride through the bumps", without slackening speed. By contrast, controlling a system with little inertia involves working very fast with the "gas pedal" to alternatively squirt in more power, or reduce the amount squirted in, depending on whether the system has slowed down or sped up. In an electricity system, inertia normally comes from synchronous generators, which inherently (through electro-magnetic reaction) combine their physical inertia in an instantaneously co-ordinated way, even when hundreds of kilometres apart. But most wind turbines' generators are not synchronous like this, so the increase of renewable energy is causing system inertia to reduce. With a low inertia electricity system, multiple generators would have to "work the gas pedal" in an instantaneously co-ordinated way, to maintain a steady frequency. This is unproven with current power electronic converter (PEC) wind turbine technology, which has zero inertia connected to the grid (shown for example in this background photo) and has a good chance of undershooting, overshooting, or getting out of rhythm and losing control, causing blackouts. ***By contrast, Windflow's system enables wind turbines to drive synchronous generators.***

Licensing opportunity

Introducing Windflow Technology's synchronous power-train system



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Improves power system stability (helps prevent blackouts) in low and high voltage, under- and over-frequency events, due to synchronous generator connected directly to the AC grid (because of constant speed gearbox output), providing physical inertia and high short-circuit currents.

2

Lighter more compact design reduces transportation requirements and facilitates installation in less accessible locations.

3

Reduce capital costs
Improve your production margins by not having power electronic converters (PECs).

4

Reduces gearbox fatigue
Extends life and reduces service costs/downtime due to mechanical variable speed input.

5

Scalable
for 2 and 3 bladers, for 1.5 MW and larger turbines, for up to 15,000 volt generators, which are mass produced for the diesel-generator market. This avoids a transformer in the turbine (required for the PECs of other non-synchronous systems).

6

Flexibility
to license variety of componentry: e.g. discuss applying a conversion to your own gearbox.

Partner with Windflow Technology:

- Synchronous wind turbines are trusted and understood by electricity system operators, because of the physical inertia and system strength (high currents) that they provide.
- Avoid the prospect of future constraints by electricity system operators resulting in additional costs for power electronic converters/inverters (PECs).

Speed to market
Reduce R&D costs. Get to market quickly with existing, patented technology.

Proven performance
10% of New Zealand's wind power is synchronous. The 48 MW wind farm using Windflow turbines is the last to be curtailed if the system needs to curtail wind power. 600 turbine-year track record in NZ, UK, Scotland and Texas. The first TLG synchronous power-train was installed in a 3-blader in Devon, England in 1990.

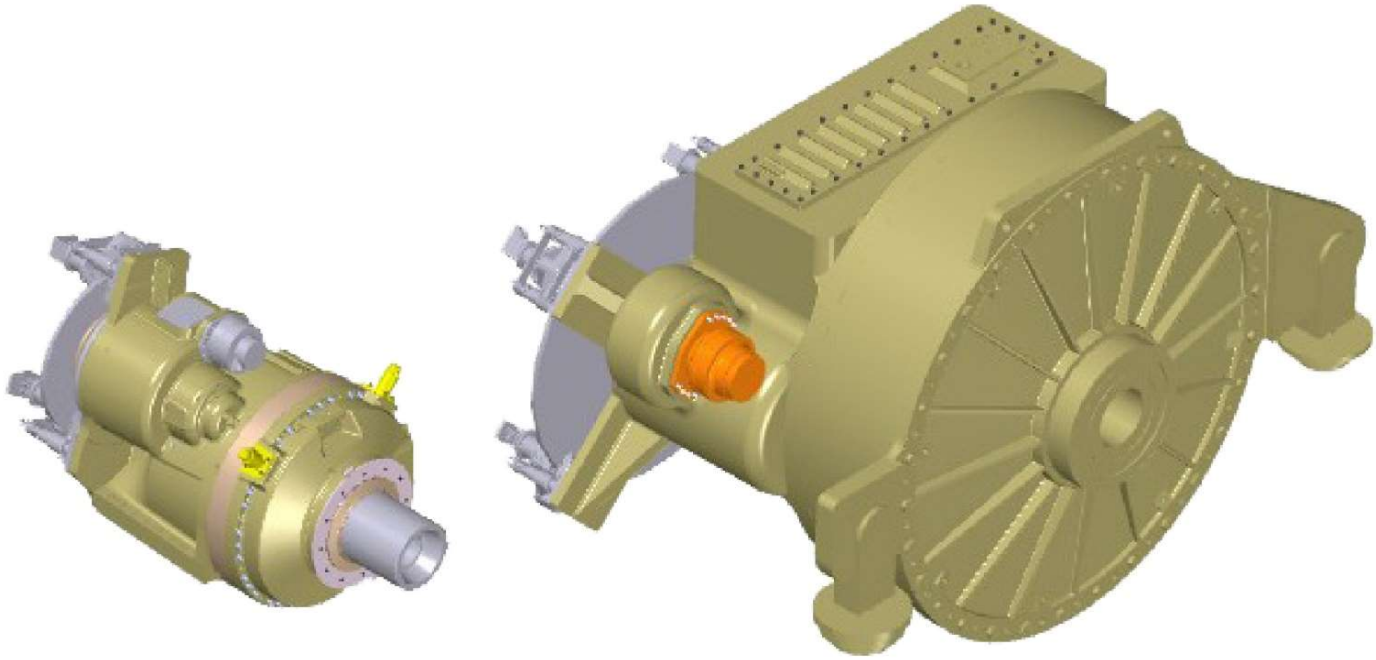
Support
Get the backup and support of Windflow's experienced engineers.

Non-competitive
Licensing proven patented technology complements your manufacturing capability. Windflow does not plan to manufacture 3-bladed turbines and is yet to develop a turbine larger than 500 kW.

Confidence
Provide buyers the reassurance of IEC-certified machines.

Intelligent solutions
Spearhead the industry with forward-thinking solutions from wind industry veteran Geoff Henderson. Access unrivalled depth and breadth of experience in wind turbines from over 30 years in the industry.

Windflow's TLG/LVS synchronous Power-train suits 3-bladers as well as 2-bladers



Facilitates grid stability

The torque limiting gearbox (TLG) and low variable speed system (LVS) enable synchronous generation. Available for licensed manufacture in mid to large-sized wind turbines.

Delivers broad-band variable speed capability

The LVS feature enables broad-band variable speed for better energy capture, reduced cut-in wind speed and reduced noise.

Eliminates costly power electronic systems

Windflow's synchronous Power-train eliminates the need for power electronics. We integrate the TLG & LVS hydraulics into the overall hydraulic system.

Reduces gearbox downtime

Gearboxes are very sensitive to torque fluctuations. Grid faults can put torque spikes through systems. These and other momentary overloads cause damage to gearboxes. Windflow's patented torque limiting gearbox protects the system from overloads and ensures gearbox reliability by controlling peak loads mechanically. It allows wind turbine rotor speed to vary while generator speed stays constant.

Lighter, more compact design

Enjoy a significant saving in production costs. For the same reliability and life, the Windflow system delivers a modern gearbox that weighs 10-15% less than equivalent PEC machines.

A gearbox can be the single most expensive component in a wind turbine. A lighter gearbox means lower mass throughout, transportation costs can be reduced, and the machine will be cheaper to produce.

Low-cost hydraulic system

For every 1 MW of turbine in PEC systems, you need 1 MW of power electronics, whereas the hydraulic TLG/LVS system has only a 5% rating.

Power electronics might be cheaper per kilowatt, but the hydraulic TLG/LVS which replaces power electronics has 5% of the kilowatt rating, so it's a fraction of the cost. For a 1 MW machine, we have a 50 kW hydraulic add-on, not a 1000 kW power electronic add-on.

PECs … Power electronic converters are used to connect asynchronous generators to the grid.

Power-Train Advantages

1. TLG removes torque spikes, makes gearbox lighter and more reliable.
2. LVS enables broad-band variable speed.
3. The TLG/LVS utilizes a low power (5% of rated) hydraulic sub-system:
   - Keeps cost low.
   - Reacts torque hydrostatically using power-splitting differential stage.
4. Enables synchronous generation (constant generator speed, only varies if grid frequency varies).

Synchronous Generator Advantages

1. Synchronous generator enhances grid stability relative to asynchronous generation:
   - Voltage stability (LVRT/HVRT) enhanced by high short-circuit currents.
   - Frequency stability enhanced by mechanical inertia.
2. No additional hardware required to have all attributes (not only inertia) that grid traditionally gets from synchronous generators:
   - Inertia (2.5 s at 0.5 MW, more at multi-MW).
   - High short-circuit current.
   - Reactive power.
   - Synchronous condenser mode (small extra motor to do this with no wind).
   - Frequency keeping (load following).
3. No power electronics (lowers purchase cost and long-term cost).

Lower Overall Power-Train Costs

Power-Train Component	Conventional	TLG/LVS	Notes
Gearbox	60	60	Lighter vs more complex
Generator	20	15	Mass-produced for diesel generators
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**

Note: Numbers are estimates of relative cost within turbine build. Operating and maintenance (O&M) costs are separate and support elimination of power electronics. All other components (tower, rotor etc) unchanged.

Lower Overall Cost

- Power-train costs are lower (per above table), plus
- O&M costs are lower (no power electronics), plus
- No need for auxiliary services equipment for grid connection (SVC, storage, etc.) or reduced need in high penetration

Thus lower overall societal cost of renewable future due to:

- lower turbine cost
- lower wind farm auxiliary costs
- larger wind farm potential/less curtailment

So wind power will cost less and be better for grid – why wouldn't the industry opt for synchronous wind turbines?

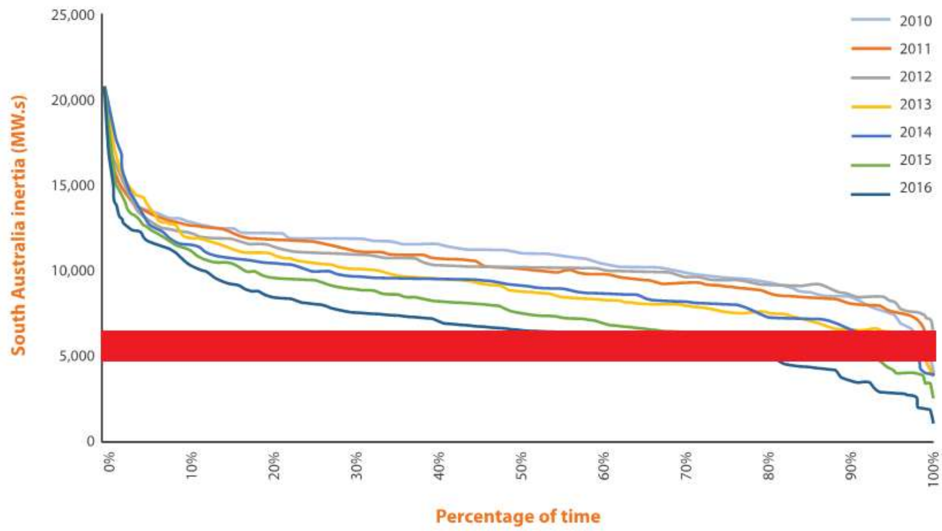
Inertia is Critical for Grid Stability

Inertia is critical for stability in power grid systems, which almost always use alternating current (AC) of 50 Hz or 60 Hz frequency. Power grids rely on the mechanical inertia of synchronous rotating power plant to maintain grid integrity and stability during load fluctuations and electrical disturbances.

The level of inertia in power grids has been in steady decline as power electronics connected (PEC) renewable energy has displaced conventional synchronous generators.

Australia has hit this issue before most nations, because of its combination of low population density and large-scale displacement of coal-fired power by renewables. The graph shows that the growth in connections of wind and solar power between 2010 and 2016 has led to inertia levels reducing significantly, by a factor of three or four at the 95%-ile level.

Figure 1: Reducing system inertia in South Australia – exceedance lines for 2010-16

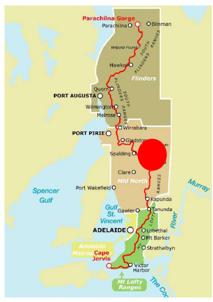


The thick red line is inserted on this exceedance graph (a form of cumulative probability diagram) to indicate that, at some time between 2010 and 2016 inertia levels became unacceptably low. It is not a thin, precise line, because the issue is probabilistic.

Figure 2: Maps relating to the September 2016 Blackout in South Australia (SA)

Map 1 – Australia

Map 2 – Adelaide (capital of SA)



Map 3 - Fault area

Map 4 - State-wide Blackout area

Lessons from the South Australian blackout

The blackout in South Australia in September 2016 highlighted the weakness of PEC generation. The voltage fluctuations experienced by South Australia's PEC generators caused half the wind farms to shut down.

Investigations showed there were many control systems errors inherent in the wind farms' controls setup. When the wind farms curtailed their contribution, the connector to Victoria picked up the resulting deficit and tripped out on overload blacking out the entire state.

The remaining PEC wind farms provided no inertia. When the Victoria connector tripped, only 300 MW of synchronous generation remained.

What conclusions have come from AEMO's investigations?

From its analysis of the Black System event, many of AEMO's conclusions provide valuable guidance for improving the management of extreme conditions in SA:

BLACK SYSTEM SOUTH AUSTRALIA 28 SEPTEMBER 2016 – FINAL REPORT

AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

- The following factors must be addressed to increase the prospects of forming a stable SA island and avoiding a Black System:
  - Sufficient inertia to slow down the rate of change of frequency and enable automatic load shedding to stabilise the island system in the first few seconds. This will require increases in SA inertia under some conditions, as well as improvements to load shedding systems combined with reduced interconnector flows under certain conditions.
  - Sufficient frequency control services to stabilise frequency of the SA island system over the longer term. This will require increases in local frequency control services under some conditions.
  - Sufficient system strength to control over voltages, ensure correct operation of grid protection systems, and ensure correct operation of inverter-connected facilities such as wind farms. This will require increases in local system strength under some conditions.

Figure 3: Progress of the South Australia Blackout

1

South Australia's power supply before and during first 82 seconds of voltage faults …

2

The next 6 seconds …

3

The next 2 seconds …

Total load was 1800 MW. Voltage fluctuated due to tornado damage to lines, but the PEC wind farms did well, staying on line for first 82 seconds.

Half the wind farms shut down over next 6 seconds, Victoria interstate connector tried to pick up the load but tripped on overload. 1800 MW of load now fell on 750 MW of generation (300 MW thermal and 450 MW wind).

Until then frequency had not fallen, but then fell abruptly at over 6 Hz/s. This was too fast for 1050 MW of interruptible load to be tripped to restore frequency balance. The final AEMO report suggests that more inertia would have reduced the rate of change of frequency, though this may not have avoided the complete blackout of the whole state which occurred within 2 seconds.

Synchronous generators would be more likely to ride through the South Australia system disturbances that caused half of the wind farms to shut down.

Physical inertia and large amounts of short-circuit current are two attributes, in terms of which PEC systems cannot compete with synchronous generators.

Synchronous generators would have provided inertia for frequency stability, slowing down the system collapse sufficiently to allow load shedding to reduce excessive load. Synchronous generators could have contributed to frequency and voltage control.

Synchronous generators increase system strength through their ability to contribute significant short-circuit current, enhancing system stability, voltage control and the operation of protective devices.

Synchronous wind power is proven and cost-effective.

Synchronous generators enhance system security, reliability and resilience.

The primary determinant of system reliability is knowledge:

- Proven performance, that is easily modelled and well understood.
- Classical frequency and voltage controls.
- Classical short-circuit characteristics.
- Conventional protection systems.

The primary requirement for knowledge is predictability:

- Windflow's 106 wind turbines – all synchronous - have accumulated more than 600 turbine years of track record.
- Assembled from proven subsystems and components (including off-the-shelf generators for the diesel genset market) which have individually, demonstrated millions of satisfactory operating hours.

The primary requirement for reliability is simplicity:

- Simple to set up, operate and control.
- Electrical and mechanical maintenance practices and knowledge are transferable from maintenance of conventional power plant.

Grids need physical inertia

The final report in June 2017 by the Australian Government's Chief Scientist, Dr Alan Finkel, 'Independent Review into the Future Security of the National Electricity Market' states that:

> **'Security and reliability have been compromised by poorly integrated variable renewable electricity generators, including wind and solar...**
>
> **Security should be strengthened through Security Obligations for new generators, including regionally determined minimum system inertia levels...**
>
> **Technologies that provide a fast frequency response (FFR), including 'synthetic inertia' from wind turbines, can partially compensate for a decrease in physical inertia. However, international experience shows that at present, in large power systems, FFR cannot provide a complete substitute for physical inertia. That is, a minimum level of physical inertia from synchronous technologies is required.'**

The Finkel Report then goes on to make numerous recommendations as to how Australia can continue to make a transition to achieving increasing levels of renewable electricity generation.

Windflow's synchronous wind turbines exactly fulfil the recommendations in this Australian Government Review on how to avoid adverse effects from increasing amounts of wind power on the grid. This is because they enable the use of synchronous generators directly grid-connected, and thus identical in all respects to the synchronous machines that have kept the lights on before the advent of wind turbines.

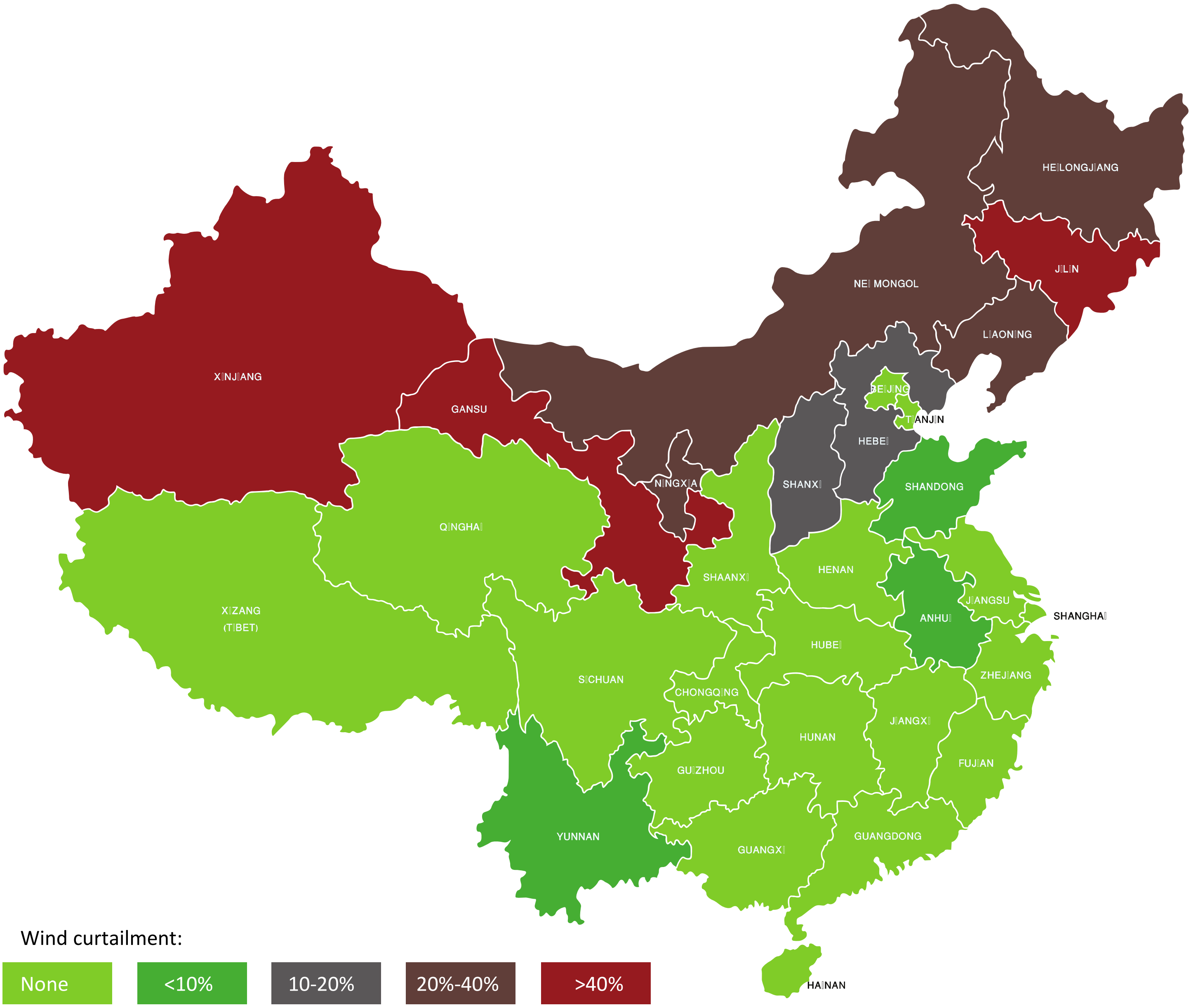
China Grid Issues

Currently, wind turbines are mainly erected and connected to the grid in the north-western provinces. This poses problems, as the electricity generated there cannot be transported to the load centres in the East of China.

How much is due to stability concerns? A lack of ultra-high-voltage lines can result in the curtailment of up to almost 50% of the potential electricity generated by wind in some provinces e.g. Gansu.

Stability is a matter of degree. Faults can be caused by many external events (weather and non-weather) and can cause low-voltage, high-voltage, over- and under-frequency events at different parts of the system.

Synchronous generators improve system stability in voltage and frequency faults.



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Short Circuits and Power Swings

The most common events that can disrupt a power system are short circuits and power swings.

Short circuits

The most common disturbance on a power system is insulation failure which results in a short circuit. During short circuits, synchronous generators predictably contribute up to ten times rated current ensuring rapid detection and clearance of the fault by conventional protection relays.

Synchronous wind turbines are not just riding through, keeping the wind farm online, but they also contribute large amounts of short-circuit current, which helps support the system voltage during the short-circuit event. Large short-circuit current capability is a key definition of "system strength".

The grid voltage can become low during a short circuit, temporarily disrupting the balance between the power generated and the power that can be delivered to the system load. A synchronous generator can "ride through" such a fault event, staying in synchronism with the system by virtue of a combination of its rotational inertia and reactive power capabilities, meaning it survives the event to be ready to deliver power again the instant the short circuit has been cleared by the system protection.

The PEC wind industry has invested in developing electronic controls and capacity to ride through low voltage events. This attribute is not inherent in the technology, but involves a certain level of complexity which is not predictable at the system level, as shown by the Australian experience. Nor can it provide the strong (up to 10 x rated) short-circuit current, as PEC systems will fail if they deliver such over-currents.

Power Swings

Synchronous generators assist in keeping the power system in synchronism by generating and absorbing large quantities of synchronising "reactive" power. Synchronising power is able to flow readily between generators in parallel operation on-line, helping the rotors stay locked in synchronised operation, and absorbing rotor oscillations by the inherent damping available from rotor eddy currents or from built-in amortisseur windings.

PEC wind turbines have no such characteristics but must rely on complex control strategies to try and achieve a performance that is comparable to the synchronous machine.

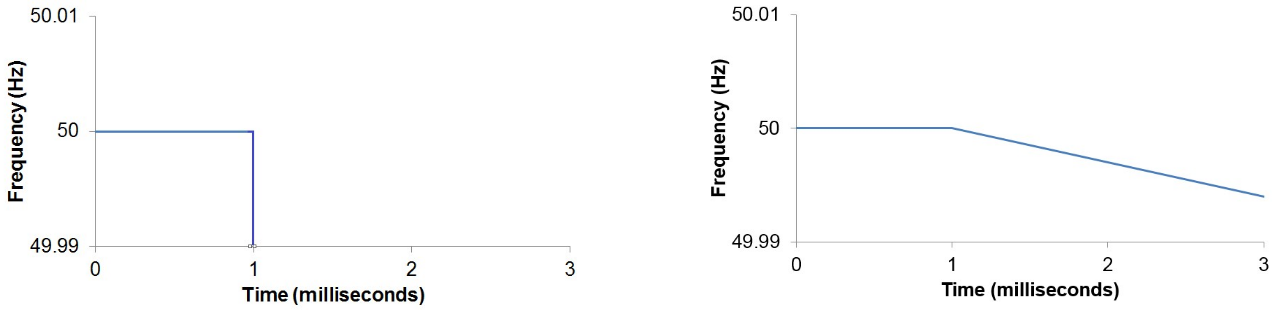
Frequency Stability

The inertia within synchronous generators continually absorbs and releases kinetic energy to smooth and stabilise the system frequency in the very shortest time frame for both, small, routine, and occasionally large, step changes in system load. This smoothing effect is instantaneous, direct and inherent, independent of any generator controls.

PEC generation – as used by most wind farms and all solar photovoltaic generation - provides zero inertia and so cannot stabilise the system frequency in the face of loading shocks. This shortcoming was brought out in the AEMO Final Report on the investigation into the causes of the September 28th 2016 blackout.

Figure 4 below sets out the basic principles.

Figure 4: Fundamental PEC versus Synchronous generator frequency response



PEC generator on its own has no inertia so frequency can change abruptly on a millisecond timescale

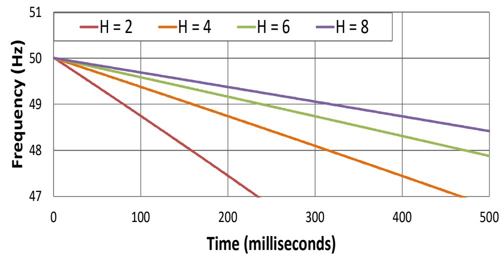
Synchronous generator contributes to frequency stability

An AC grid made up entirely of PEC systems would not be able to control frequency stably to connect remote generators and loads. All systems would become stand-alone.

If PEC generators are significant in the generation mix, the system has low inertia, and so frequency jitter increases. In the event of a sudden large change in system demand, the frequency governors have insufficient time to respond before the magnitude of the frequency deviation is too large to correct and the power system must shut down.

The number of PEC generators that are on line varies from one hour to the next, making it difficult for system operators to be confident that the system has sufficient inertia to be stable for a large contingency, which could happen at any time.

Figure 5: Effects of Inertia (H) with power imbalance 100% of rated



All the synchronous generators on a grid (and coupled turbines etc) slow down together instantaneously in the event of a power imbalance. The slope is more gradual with more inertia, expressed as MW.s/MW. With maximum reduction of 3 Hz allowable, decreasing inertia reduces system control stability by reducing time available to measure and respond.

When synchronous generators supply the grid, inertia is inherent in all the synchronous generators on line. During a change in system demand, electromagnetic effects make all of the synchronous generators on a grid slow down together instantaneously at a rate that is determined by the total system inertia.

Providers of "fast frequency response" services (FFR, aka "synthetic inertia") employ power electronic control systems to approximate the inertial power contribution of synchronous generators. This has proved to be a workable approximation for large-scale power connection such as HVDC inverters, which control 100s – 1,000s of MW from a single control source. The same cannot be said for 100s – 1,000s of individual small-scale inverter-connected DER facilities, each employing its own controller, with diverse designs and settings, which taken together must provide a secure and reliable, unified response if the responsibility for system stability is to be placed in their domain. Current thinking is that a secure power system will always need some classical inertia on the grid to provide assurance of a reliable frequency response to contingencies.

Frequency fluctuations caused by routine changes in load are smoothed by their inherent inertial response allowing time for the governors to respond to correct the situation. If that is not possible in sudden large changes in load, inertia provides time for under-frequency load shedding systems (UFLS) to shed load in an orderly fashion to restore the balance between generation and the load. Because the inertia component comes as part of the generation, system operators can be confident of understanding the inertial capability of the system for any generation mix or magnitude of system demand.

A power system needs to have sufficient inertia at all times to respond to both small and large fluctuations in the balance between generation and demand, which cause under- or over-frequency events. The inertia is required to keep the rate of change of frequency slow enough, so the system governors can respond and minimise the effect of any foreseeable disturbance. Effective system security planning depends on the absolute assurance that sufficient inertia is present on the system for any combination of generation, transmission and connected demand.

Example of fault contribution & ride-through of a Windflow 500 synchronous turbine

Data from an event recorded at the Te Rere Hau wind farm (shown in photo above) on 8 September, 2012.

Figure 5: A system voltage dip to 60% of normal voltage that lasted around 100 ms (0.1 seconds).

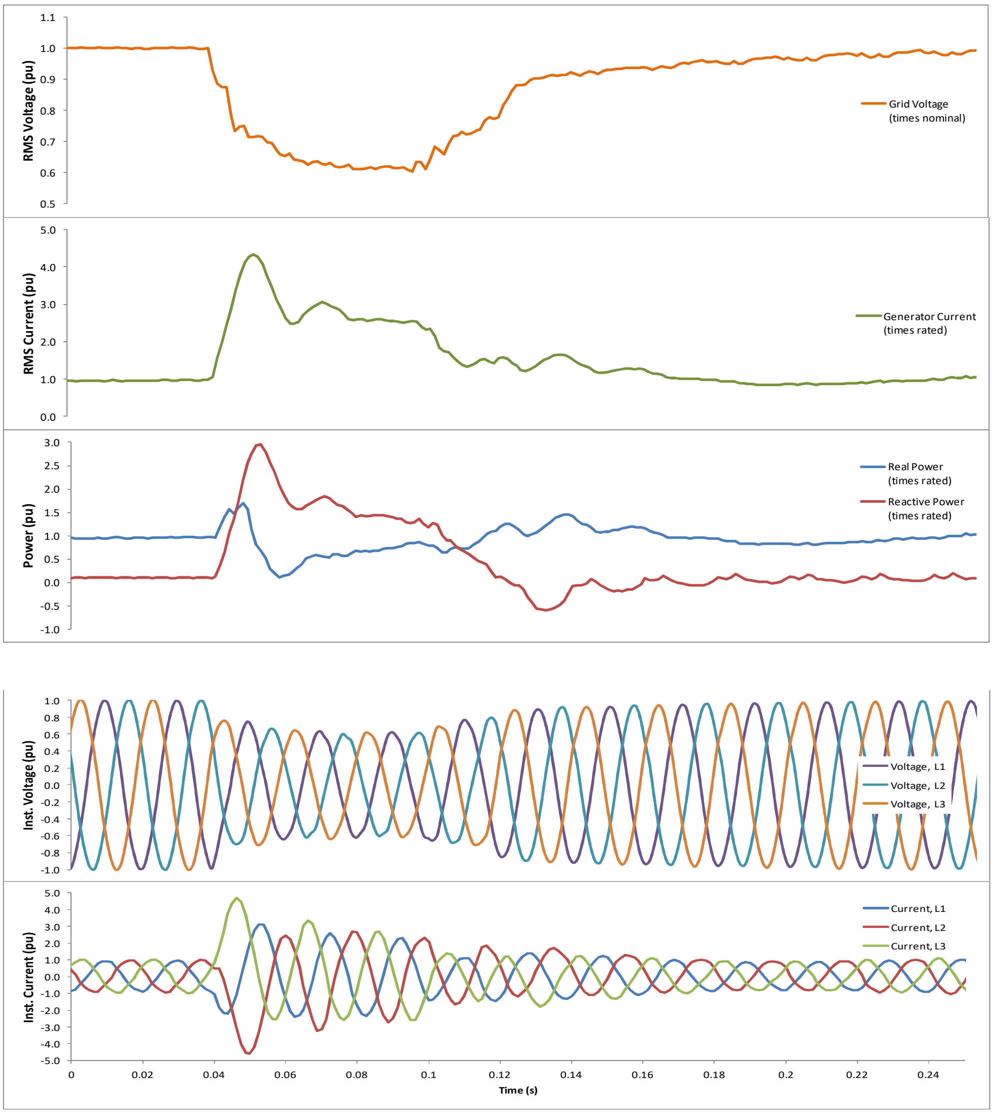
The voltage dip

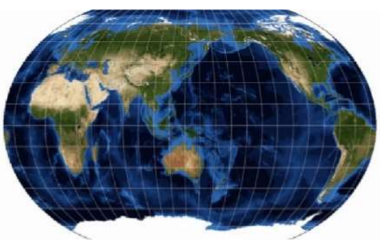
The short-circuit current response. Note that it is many times rated current (the 1.0 pu level). This cannot be provided by PEC systems, which are limited to 1.0 pu or a little above.

***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.*

***3-phase instantaneous voltage trace** - the turbine remains online during the system event & returns to pre-fault levels*

***3-phase instantaneous current trace** - the peak current on one phase is nearly five times the rated current. This peak precedes the maximum voltage dip. By opposing the voltage dip, it reduces its magnitude.*





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