Grid-forming Wind Turbines:
without the inverters!

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Type 5 Wind Turbine Technologies:

Three Main Candidates Compared

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Contents

Why does the industry need Type 5?

- Type 5 turbines drive directly grid-connected synchronous generators, which are **grid-forming** just like conventional power plants
- Historically, **system strength** from conventional power plants (>3 pu current capability, inertia etc) has ensured system stability
- Type 3 and Type 4 wind turbines have inverters capable of typically only 0.4 pu and 1 pu current respectively, and no synchronous inertia
- System strength has degraded because of wind and solar inverter-based resources (IBRs)
- As renewables' penetration increases, synchronous condensers etc are increasingly being required in order to avoid curtailing IBRs
- Type 5 wind turbines avoid the need for separate sync-cons etc

IEEE 2800:2022: a driver for Type 5 wind power

- Fundamental problem arises because of "complex inter-dependencies between IBR and power system characteristics".
- IEEE 2800:2022 calls sync-cons: *"presently the primary solution for adding system strength because of multifaceted benefits including large capability to supply fault current, inertia and voltage support capability"*.
- Such mitigation options have been required by the TSO in Australia, causing significant financial pain and planning uncertainty to wind farm developers there
- Type 5 wind power provides a low-cost grid-forming option

Sync-con Mandates: Early Adopters

- Early adopters still rare - market characteristics:
  - high penetration of non-synchronous wind and solar
  - low interconnector strength
- South Australian experience - following the 2016 black-out and despite the much-publicised Tesla battery installation:
  - 250 MW of gas turbines were installed in South Australia, then
  - 516 MW (continuous rating) of sync-cons were installed at cost of A$169 million (~US$200/kW)
- Irish experience – EirGrid and SONI earlier this year contracted to procure “10,000 MVA.s” of grid support services including inertia, reactive power and short-circuit contribution
- Other examples exist of such projects, generally (to date) at expense of the grid company, not (yet) the wind and solar farms

The three Type 5 candidates - history

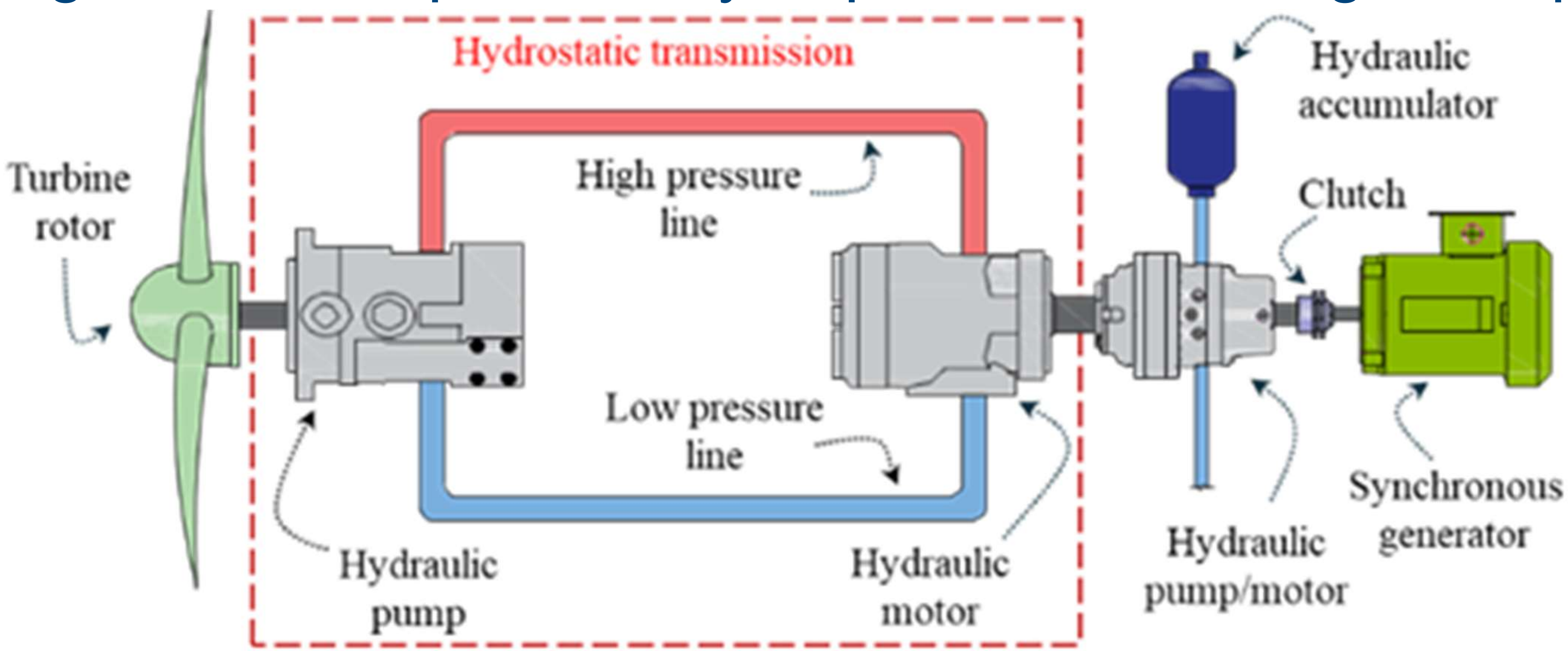
- Full hydrostatic drive
  - Sir Henry Lawson-Tancred's 100 kW unit in 1970s
  - renewed interest since 2000 by hydrostatic system suppliers enhancing efficiency and control
- SyncWind TLG-LVS
  - 34 years since 1990 TLG prototype in Devon, England
  - >1000 turbine-years at 0.5 MW scale, 46 MW farm still runs in NZ
  - demonstrated system strength in grid fault, steady VAR export and import, fast frequency control, benign "sacrificial element" in pole-slip event and broad-band VS ability of new LVS system
- Voith Windrive
  - Dewind commercialised at 2 MW scale in 2000s
  - 38 turbines in North and South America, 6 still running

General Features of Type 5 Grid-forming Turbines

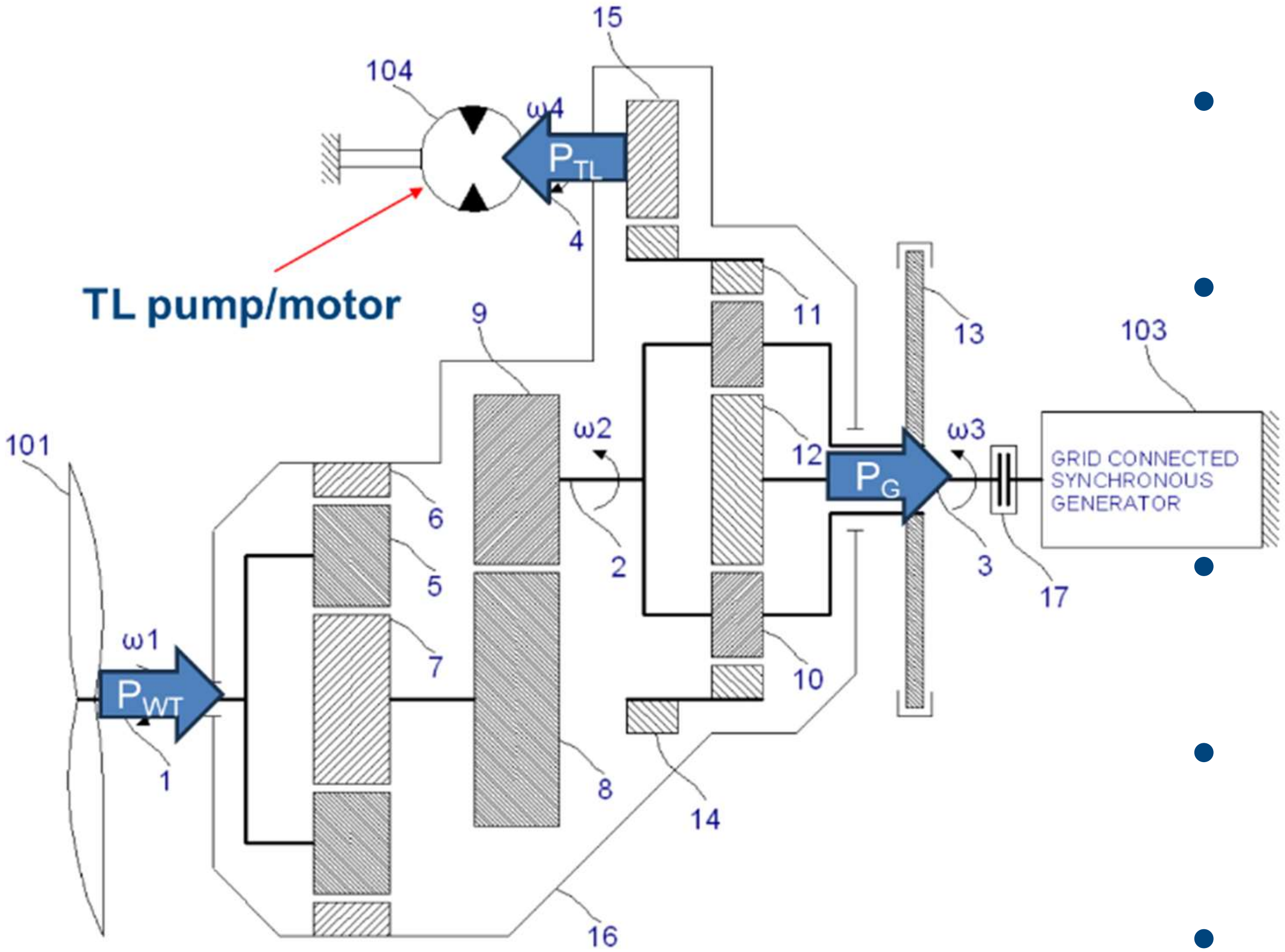
- Features in common:
  - no inverters
  - mechanical VS so turbine speed can vary
  - generator speed is locked to grid frequency
  - constant generator speed reduces drive-train torque transients (no generator accelerations hence no inertial term)
- Distinguishing features of the three candidates:
  - number of gearboxes (0, 1 and 2)
  - power rating of hydraulics (100%, 5% and ~50%)
  - hydraulic machines (two use hydrostatic, one hydrodynamic)
  - torque limiting throughout drive-train (one does, two don't)

Full hydrostatic drive description

- Continuously variable hydrostatic transmission, no gearbox
- Fixed displacement radial piston pump and variable displacement axial piston motor both rated 100% wind turbine power
- Accumulator to smooth power output and turbine loads
- Higher losses, particularly at part-load, and higher capital cost

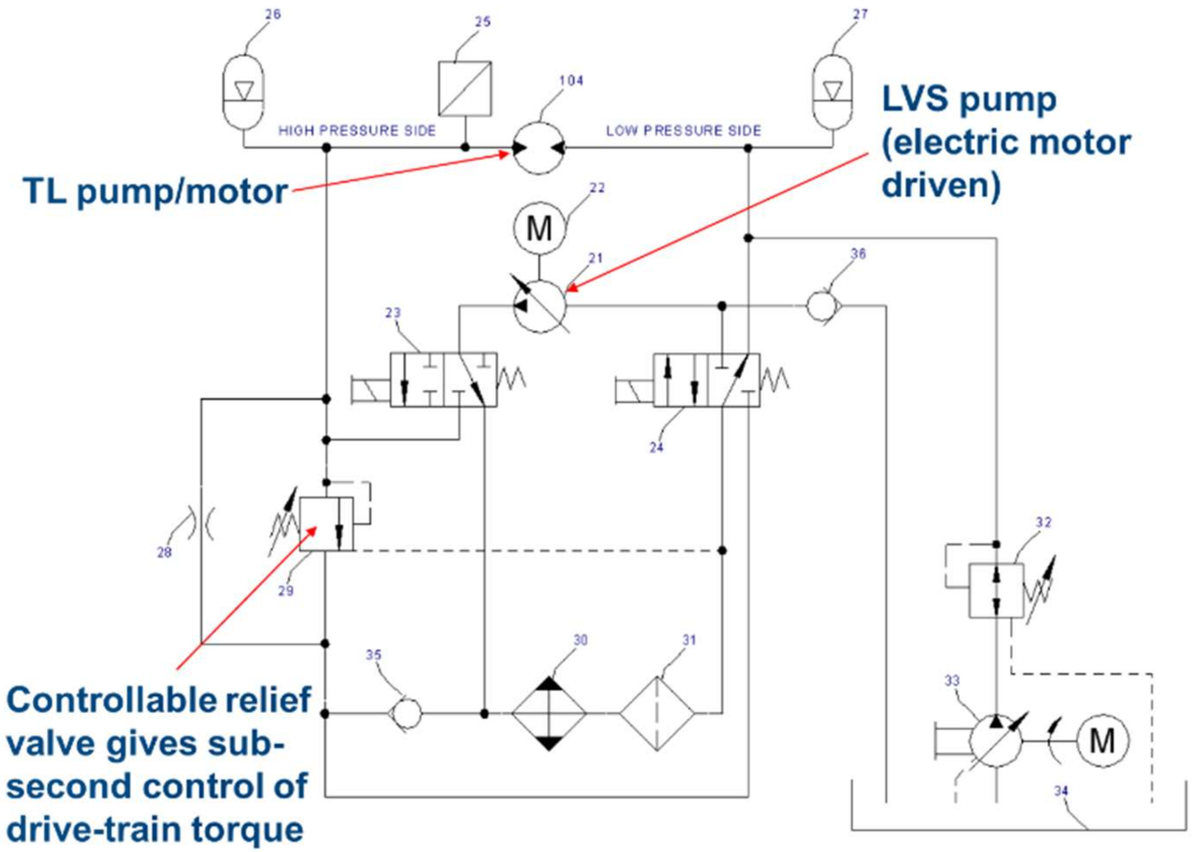


SyncWind's TLG-LVS System



- Hydrostatic torque reaction at final differential stage of main gearbox
- Torque limiting (TL) pump/motor is fixed displacement radial piston
- Small TL pump can be sacrificial item, protecting main gearbox from electrical faults, pole-slip etc
- Torque limiting is provided by a relief valve with controllable setpoint
- LVS pump is variable displacement axial piston, electric motor driven
- Both rated 5% wind turbine power
- Accumulators to smooth power output and turbine loads

SyncWind’s TLG-LVS System



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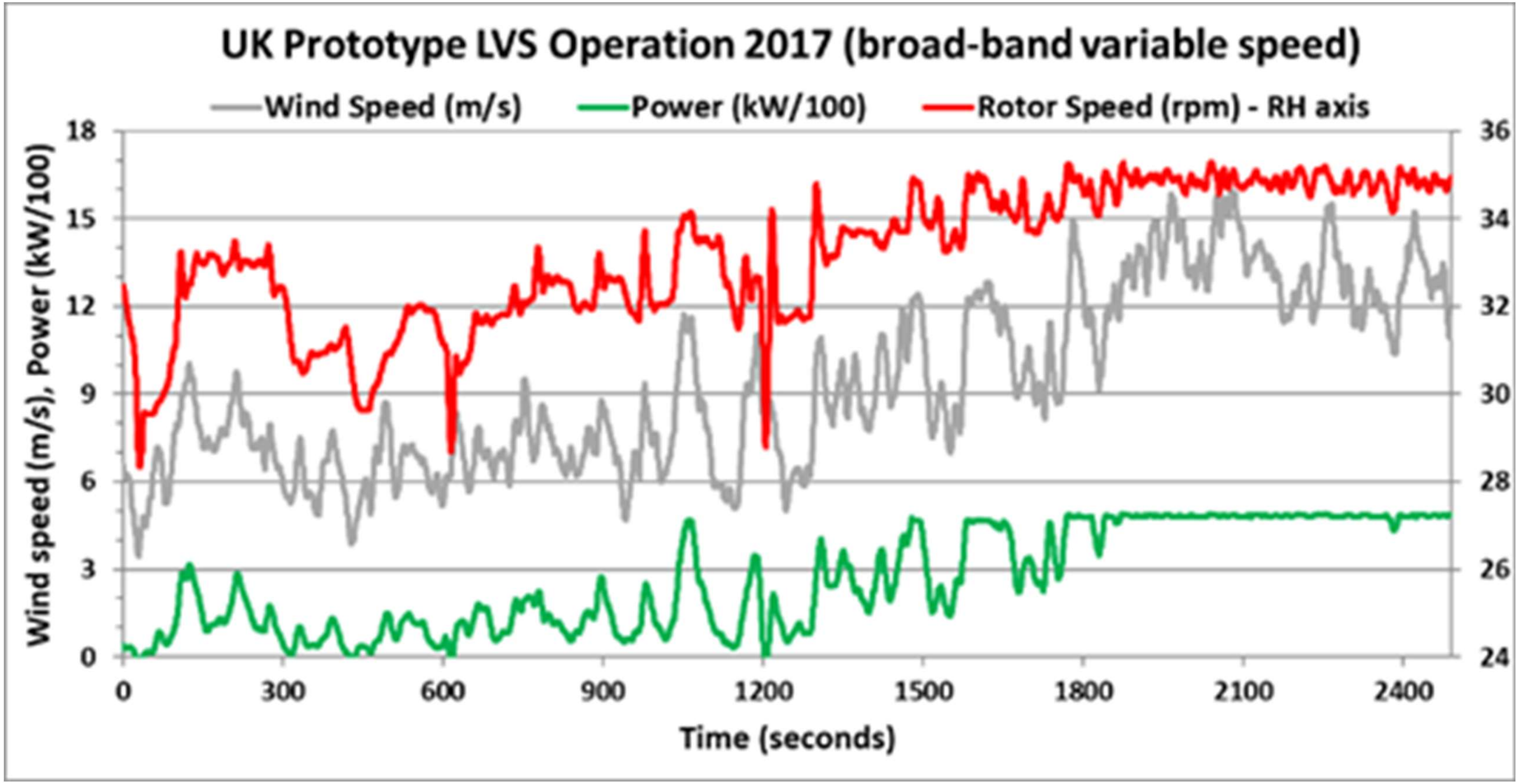
46 MW Synchronous Wind Farm

- Proven design at high wind New Zealand site
- 18 years operation and still going
- >1000 turbine-years track record
- Type certification
  - IEC 61400-1:2008 (Edition 3)
  - Class 1A

TRH List
14/02/2023 08:25:24
Net Power: 36.76 MW
Net Energy: 1505.10 GWh
Number Available: 86
Number Generating: 81
MeanWindspeed: 18.5 m/s
Wind Dir: SSE (154.6 degrees)
High Windspeed (TRH_T007): 28.5 m/s
PSDs: Yes (6). (with RunFlag: 0)
Controller: Pete Darke

Txxx Run Status PSD Power
T001 ON AutoGen PSD:No 500 kW
T002 ON AutoGen PSD:No 487 kW
T003 ON AutoGen PSD:No 425 kW
T004 ON AutoGen PSD:No 530 kW
T005 ON AutoGen PSD:No 511 kW
T006 ON AutoGen PSD:No 349 kW
T007 ON AutoGen PSD:No 526 kW
T008 ON AutoGen PSD:No 526 kW
T009 ON AutoGen PSD:No 517 kW
T010 ON AutoGen PSD:No 541 kW
T011 ON AutoGen PSD:No 428 kW
T012 ON AutoGen PSD:No 432 kW
T013 ON AutoGen PSD:No 517 kW
T014 ON AutoGen PSD:No 546 kW
T015 ON AutoGen PSD:No 407 kW
T016 ON AutoGen PSD:No 493 kW
T017 ON AutoGen PSD:No 462 kW
T023 OFF Standby PSD:No 0 kW
T024 ON AutoGen PSD:No 432 kW
T025 ON AutoGen PSD:No 548 kW
T026 ON AutoGen PSD:No 348 kW
T027 ON Standby PSD:No 0 kW

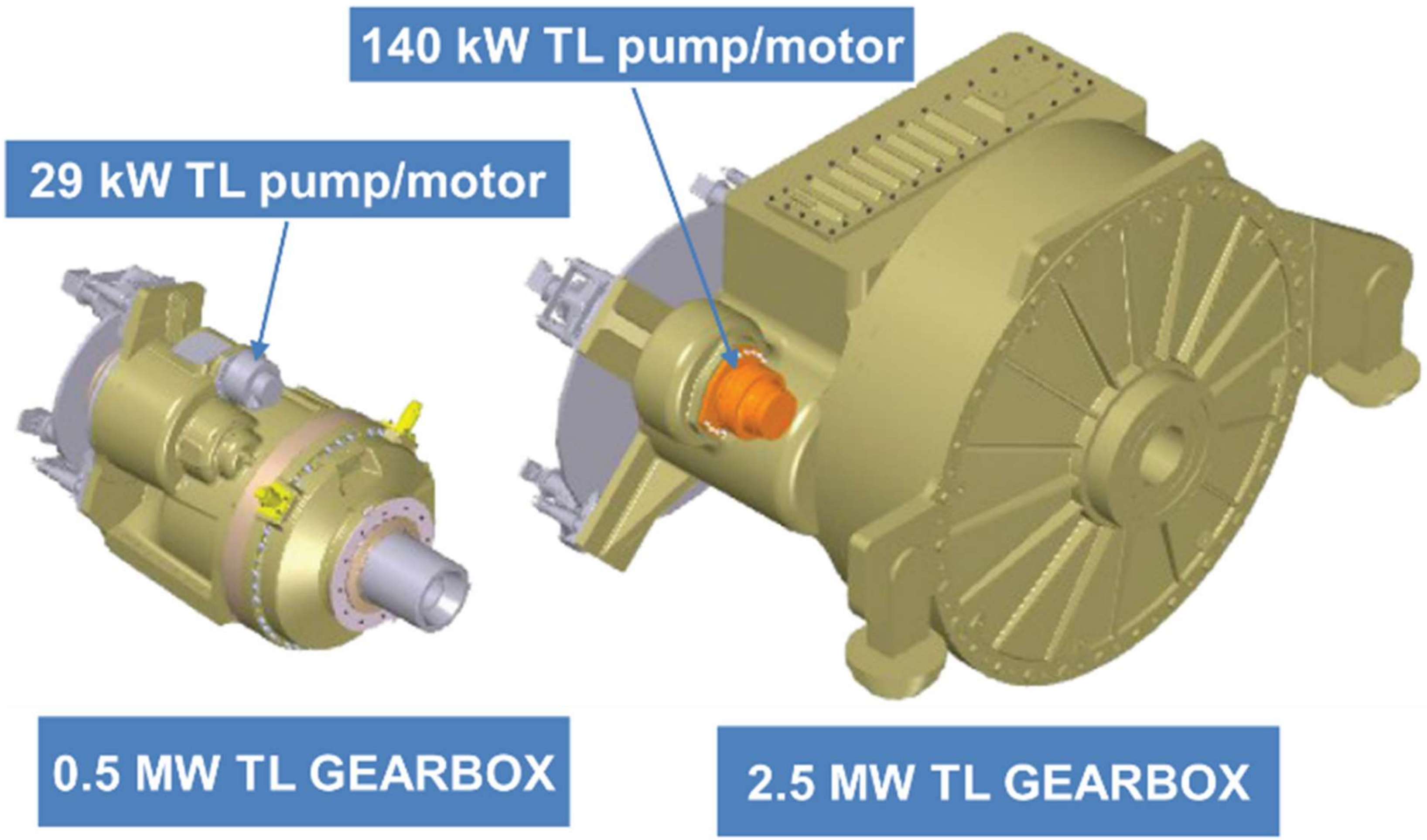
LVS System enables broad-band VS



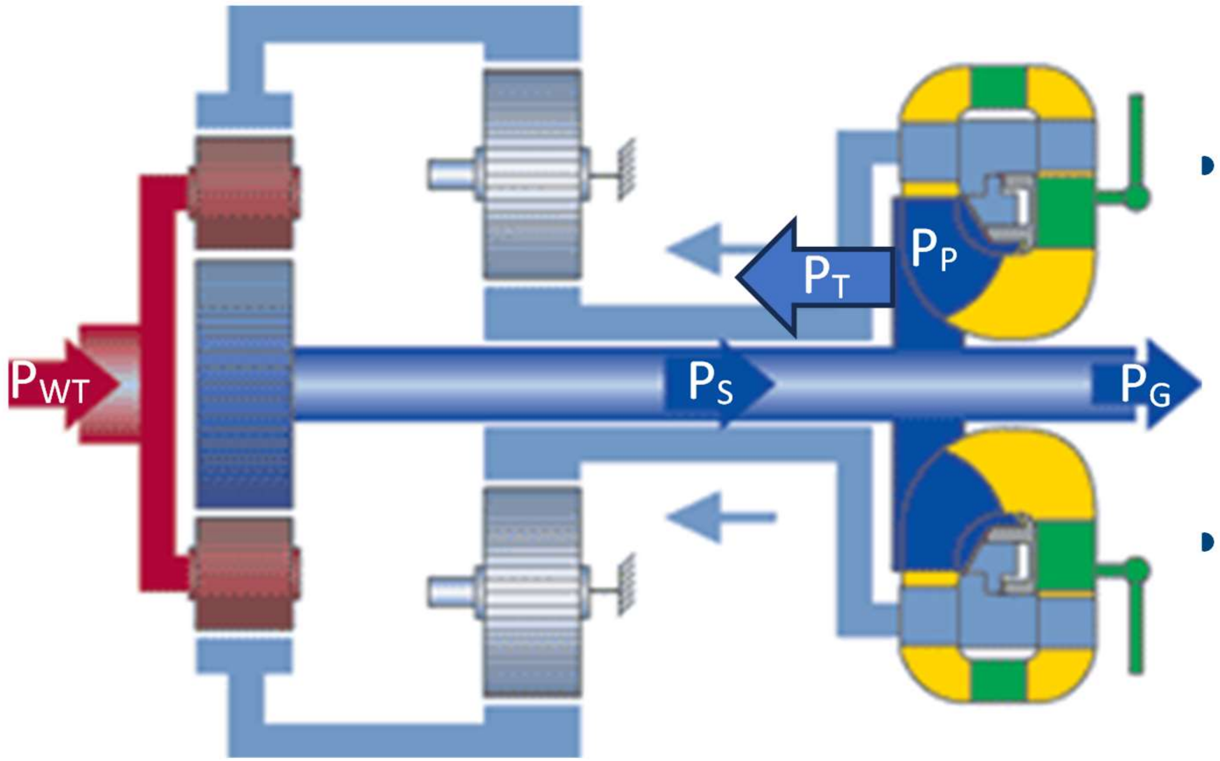
Time-series showing broad-band LVS operation in below-rated winds, then TL operation

TLG-LVS System
Cost-Competitive with Type 3

Small hydraulic machines are key (low losses, low capital cost)



Voith Windrive



- Separate hydrodynamic torque converter mounted on the drive-train between main gearbox and generator
- Two differential epicyclic gear stages and a hydraulic circuit which recycles a large part of the power to provide variable speed on the wind turbine
- Handles all the turbine’s mechanical power and comparable in size to the generator and gearbox
- Significant losses, weight and capital cost

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NREL/INL Recent Research

- National Renewable Energy Laboratory (NREL) has current project:
  - funded by the U.S. Department of Energy's Wind Energy Technology Office
  - to evaluate the impacts of synchronous wind power on the grid
  - in collaboration with the Idaho National Laboratory (INL)
  - includes:
    - theoretical analysis based on modelling and simulations
    - testing with power-hardware-in-the-loop (PHIL)
    - focus on ability of Type 5 turbines to provide system strength
- Test setup includes:
  - 2.5 MVA /13.2 kV synchronous generator with rotating exciter and AVR
  - 7 MVA power electronic grid simulator ("controllable grid interface", CGI)
  - 5 MW dynamometer, an induction motor operated by variable frequency drive
  - dynamic model of a Type 5 wind turbine (wind rotor, pitch control, gearbox, torque converter and torque limiting system) implemented in closed loop setup

NREL/INL Results

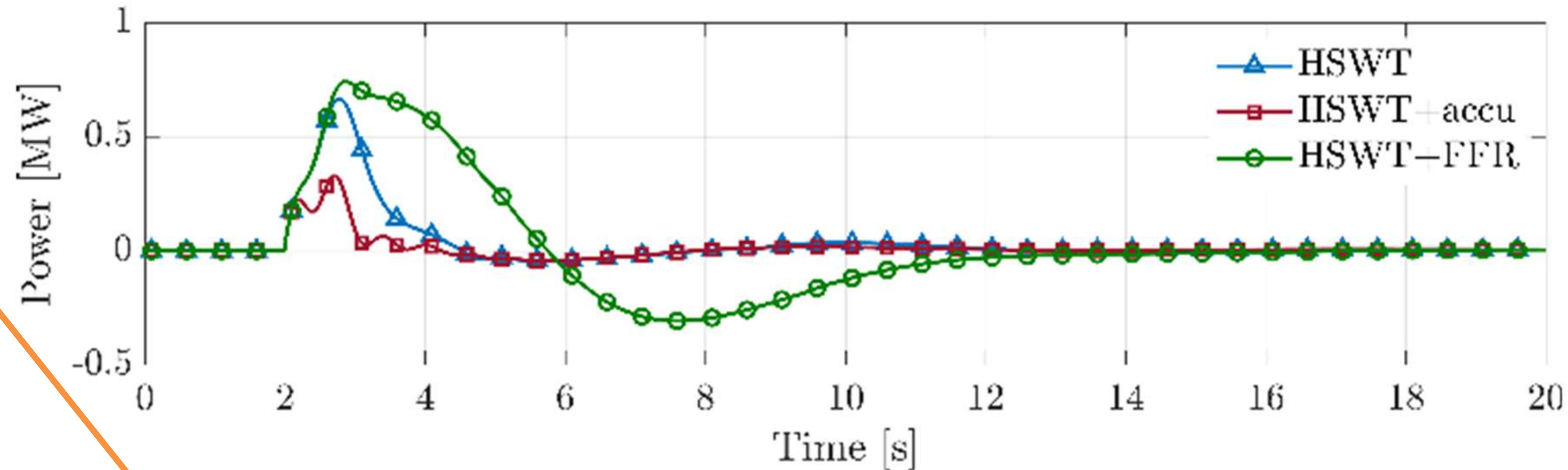
- Torque limiter :
  - helps arrest torque oscillations during LVRT
  - protects against pole slip (very destructive synch generator condition)
  - allows ride-through and maintenance of synchronism in weak grids
- Type 5 torque and excitation controls modify the impedance response only around 60 Hz (unlike Type 3), making Type 5 turbine’s:
  - stability properties easy to interpret and predict
  - risk of high frequency resonances much reduced
- These build on previous reported results:
  - Significant, helpful levels of short circuit current at beginning of LVRT events
  - Superior voltage stability in “weak” (low short-circuit ratio) grids, relative to Type 4, both grid-following and grid-forming
  - Type 5 offers unique characteristics unmatched by any IBRs

UCD Recent Research

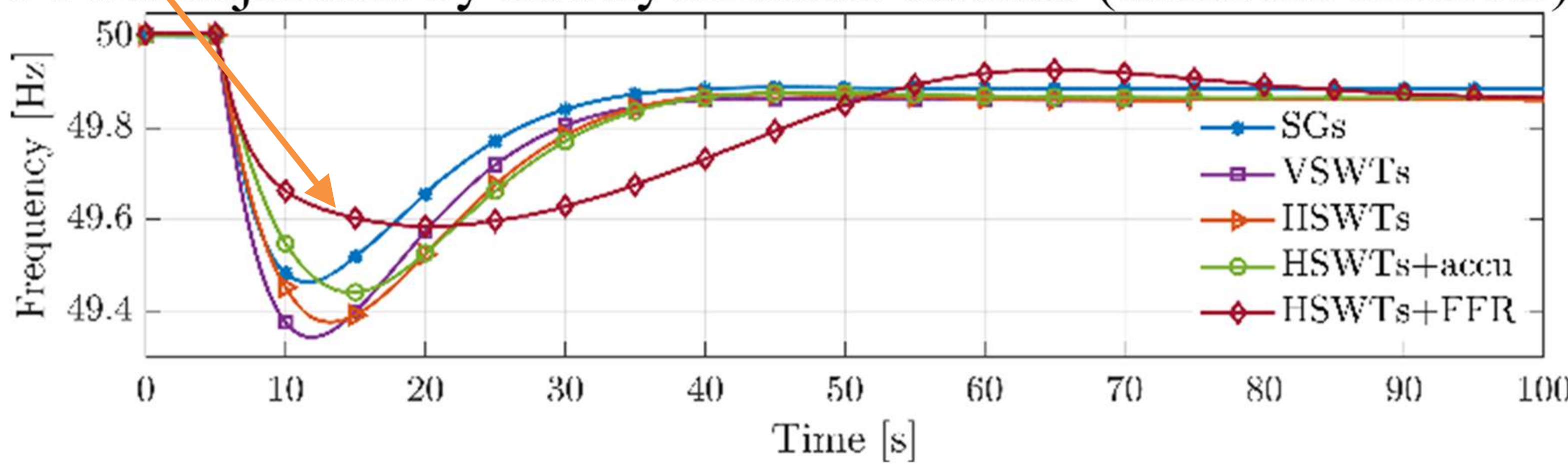
- Full hydrostatic Type 5 turbines have been focus
- Predominantly how they interact at scale with grid
- Electro-mechanical models of full hydrostatic turbines & their control systems have been developed, and compared with Type 3 and 4
- Ability to meet grid codes and provide system services, such as fast frequency response, has been investigated:
  - generator has synchronous inertia, whereas Type 3 and 4 have none
  - this alone improves response to a frequency transient, but not as well as conventional synchronous power systems, because turbine inertia decoupled
  - adding hydraulic accumulator provides some very fast frequency response
  - and as with Type 3 and 4 turbines, main energy is stored in the turbine "flywheel" and can be extracted for fast frequency response

UCD Results

Taken together, the red line with diamonds shows Type 5's inertia, accumulator and flywheel energy improve the response to be better than the blue line (conventional synchronous systems). Also applicable to SyncWind and Windrive systems.



Power injection by full hydrostatic turbine (different controls)



Frequency response with high wind share

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Type 5 features and effects on LCOE

based on NREL model of LCOE (Stehly et al) – details in paper

Type 5 Grid-forming 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%
Overall estimated effect on LCOE	-0.62%	8.2%	24.5%

Conclusions

- Degradation of system strength because of IBRs is a major concern
- Early examples of sync-con mandates have occurred, likely to increase with costs being imposed on the wind and solar industries. Based on South Australia figures this could be a 10% LCOE increase
- Three Type 5 wind turbine systems, inherently grid-forming, have been developed with different track records and cost implications
- NREL, INL, UCD and others are studying these options:
  - Full hydrostatic is being developed to address cost and efficiency
  - Voith Windrive could be cost-competitive with a sync-con mandate
  - SyncWind's system is cost-competitive without sync-con mandate
- Type 5 represents a prudent grid-forming alternative to IBRs