UTILITY FORUM – TASK 1

WIND FARM ENHANCED CAPABILITY DEMONSTRATION PROJECT

PERFORMED AT NOVA SCOTIA POWER'S NUTTBY MOUNTAIN WIND FARM

Prepared by
Eldrich [dot] rebello@weican.ca
Marianne [dot] Rodgers@weican.ca

WIND ENERGY INSTITUTE OF CANADA
21741 ROUTE 12
NORTH CAPE, PEI C0B 2B0

MAY 21, 2021

Revision History

Version	Issued on	Created/Modified	Reviewed	Summary
Draft	01-Mar-21	ER	MR, MA, MF	Interim draft with Fast frequency response, power-frequency response data
Draft	21-Apr-21	ER	MR, MA, NSPI	Added AGC data
R1	21-May-21	ER	MR	Comments from Enercon, NSPI. First release.
R1.1	17-Aug-21	ER		Enercon comments

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This work was carried out under contract from Natural Resources Canada, Contract number 3000695333. More information about this contract can be obtained from Natural Resources Canada's website or a Freedom of Information request.

Acknowledgements
The authors would like to thank all parties involved in this project for their efforts at coordinating this work through the challenges posed by the COVID-19 pandemic. We thank Natural Resources Canada for their financial support. We thank Enercon Canada and their team for their co-operation, for proposing the project idea, for their technical support and their in-kind support. We thank Nova Scotia Power and their team for allowing the use of their Nuttby Mountain wind farm, for their coordination efforts and for their in-kind support.

Citing this work
Please cite this report as:
E Rebello, M Rodgers, 'Wind Farm Enhanced Capability Demonstration Project', Wind Energy Institute of Canada, North Cape, Prince Edward Island, Canada, 2021

Questions and feedback
Feedback, questions, or comments should be directed to the report authors. Alternatively, use one of the methods below:

@windenergycan

@ info@weican.ca

REPORT REVIEW TEAM

WEICan

Marianne Rodgers

Enercon Canada

Markus Fischer
Mouhcine Akki

Nova Scotia Power Inc

John Charlton
David Stanford
Bill Oakley
Peggy Green
Amy Campbell
Robert Creighton

NB – The intended audience for this report is power system operators or those in closely related areas such as manufacturers of electrical generation equipment. As such, this report assumes a basic understanding of power system concepts such as energy, power, inertia and a basic understanding of NERC or related standards. Advanced knowledge is not required though this report is not intended to cover all relevant details.

SYMBOLS, ABBREVIATIONS AND GLOSSARY

AGC	Automatic Generation Control
f	Frequency (Hz)
FCU	Farm control unit
I, i	Current
IE	Inertia emulation
LV	Low voltage
MEC	Maximum export capacity (max. active power of the wind farm)
MV	Medium voltage
P	Active power
PoC	Point of connection
Q	Reactive power
S	Apparent power
SCADA	Supervisory Control and Data Acquisition
V, v	Voltage
WEC	Wind energy converter
WF	Wind farm
WFCS	Wind farm control system
NSPI	Nova Scotia Power Inc
WEICan	Wind Energy Institute of Canada

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EXECUTIVE SUMMARY

Power grids have traditionally been operated with several, large synchronous generators running in parallel. In addition to energy, synchronous machines contribute to grid stability in numerous other ways such as ancillary services examples of which include inertia, voltage regulation, frequency support etc. The growth of inverter-based generators such as wind and solar, particularly in terms of their share of generated energy represents a significant change. Generators such as wind and solar typically contribute only energy and not ancillary services hence their growth and consequent displacement of synchronous generation capacity has led to the need for alternate sources of these ancillary services.

Nova Scotia Power Inc (NSPI) seeks to examine the technical ability of the provinces' wind generator fleet in providing various grid ancillary services. The services examined in this report are fast-frequency response, power-frequency response (similar to droop-frequency control) and automatic generation control (AGC). Tests are carried out on NSPI's 50.6 MW Nuttby Mountain Wind farm located in central Nova Scotia. This work was a collaboration between NSPI in the role of system operator and wind farm owner, Enercon Canada Inc in the role of wind turbine OEM and the Wind Energy Institute of Canada in the role of project co-ordinator in addition to providing independent data analysis.

Fast-frequency response is a means of contributing to grid stability in a manner similar to inertia from synchronous machines. It arrests sudden drops in grid frequency by injecting active power for a fixed duration. Fast-frequency response results demonstrate the wind farm's ability to increase active power output by a constant amount, for a pre-determined duration, independent of active power levels. The only requirement is that the wind farm be operational and generating power as the energy required is obtained from the rotational energy of the wind turbine rotors. This demonstration shows that the measured active power rise time to 63% of the peak is 1 s which is as expected. The peak power boost value is greater than the expected value of 5 MW and the response duration was close to the expected value of 10 s.

Power-frequency response is similar to droop-frequency control in a synchronous generator where an increase in grid frequency causes a drop in generator active power output. A wind generator is limited in that the maximum possible power is dictated by prevailing wind speeds and consequently, increasing active power output requires constant power curtailment. This is not economically sound hence only the response to grid frequency increases is tested. This requires a reduction in active power output which is achievable without power curtailment. The power-frequency demonstration was performed on a single wind turbine. Results are in line with expectations and the mean error between measured and expected response is approximately 50 kW.

AGC is a means of balancing grid supply and demand via small changes in the power outputs of generators. An AGC test was run where the wind farm accepted active power targets from the system operator. These targets changed every four seconds. Although gathered data was limited, results are positive and in line with similar work. A performance score of around 90% is reported and the mean error between power target and measured value was approximately 0.2% of rated farm power.

1. PROJECT PARTNERS AND CONTEXT

1.1. PROJECT PARTNERS AND ROLES

1. Natural Resources Canada's Utility Forum

Natural Resources Canada (NRCan) has constituted a Utility Forum which brings together all ten Canadian provincial transmission system operators to discuss issues of shared importance specific to the planning and operation of power systems with high penetrations of variable generators (solar, wind). The Utility Forum has budget allocated for field demonstrations, research work or pilot projects in collaboration with equipment manufacturers and provincial utilities. This project is Task 1 of three planned projects.

2. Wind Energy Institute of Canada

The Wind Energy Institute of Canada (WEICan) is a not-for-profit research institute located at North Cape, Prince Edward Island (PEI) that advances the development of wind energy across Canada through research, testing, innovation, and collaboration. WEICan owns and operates its own 10 MW wind farm in North Cape, PEI in addition to a 100 kW solar PV array and a 200 kWh battery storage system. WEICan's previous work includes funded research for field demonstrations focused on examining ancillary services provided by wind generators. Past project collaborators include Maritime Electric (PEI), the Alberta Electric System Operator, SaskPower, the University of Calgary, and the Saskatchewan Research Council (SRC) among others. WEICan's demonstrations of wind ancillary services involved WEICan's own 10 MW wind farm and SRC's 800 kW single turbine at Cowessess First Nation, SK.

WEICan provides secretariat services to the Utility Forum and co-ordinates the execution of each task in addition to interpreting results, drawing conclusions, and managing documentation including this report.

3. Enercon Canada

Enercon Canada are the turbine manufacturer for Nuttby Mountain's wind turbines and provide maintenance and operational support to the wind farm owner. Enercon Canada's role as relevant to this project includes proposing possible tests, preparing associated documentation, co-ordinating & performing necessary turbine hardware retrofits, gathering high-speed data during the demonstration, preparing the wind farm for the demonstration, planning the demonstration with NSPI, and finally providing data to WEICan for analysis.

4. Nova Scotia Power Inc

Nova Scotia Power Inc. (NS Power or NSPI) are a vertically integrated utility in the province of Nova Scotia. NSPI use a fuel mix of hydro, wind, coal, oil, biomass, and natural gas to provide electrical power to over 520,000 customers across the province. NS Power own and operate the Nuttby Mountain wind farm [1] used in this project. The wind farm consists of 22 wind turbines (Enercon E-82 E2) with a combined power output of 50.6 MW.

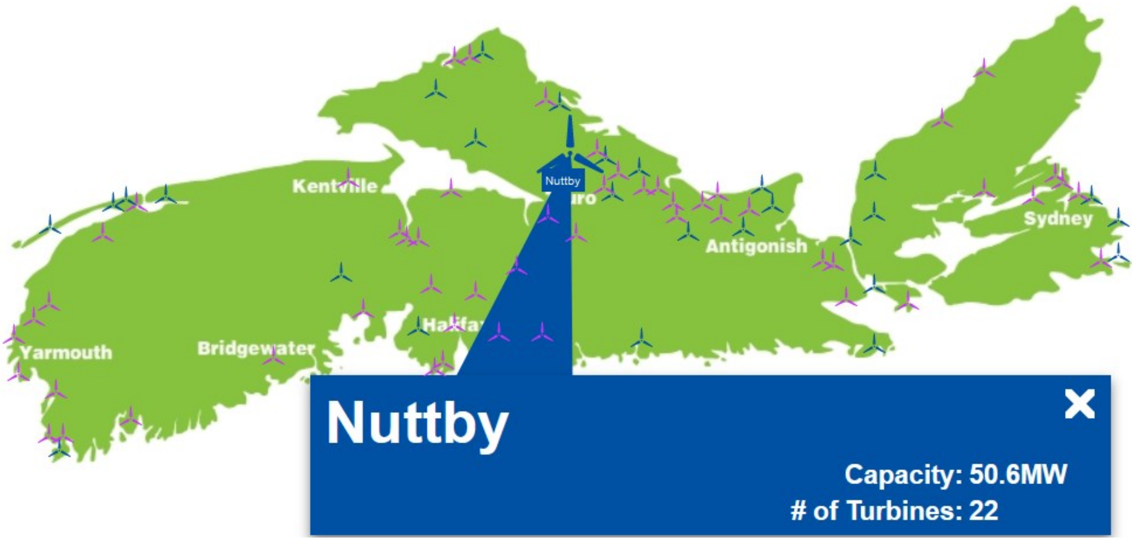


Figure 1: Location of Nuttby Mountain wind farm in Nova Scotia [1]. NB - Map rotated to save space.

Each wind turbine has a rated power of 2.3 MW. The wind farm's collector system voltage is 34.5 kV and interconnects to NS Power's transmission system at 69 kV.

NSPI's role as relevant to this project spans the operation of the wind farm's point of connection to the transmission system, coordinating wind farm operation and dispatch during this project, project management, setting test goals and expected outcomes, collaborating with Enercon in establishing the approach to the demonstration for optimal results, coordinating SCADA system enhancements in addition to providing data for WEICan's analysis.

1.2. PROJECT CONTEXT

In any power grid, there exists a continuous balance between supply and demand i.e., between generation and load. The two must be always equal. Maintaining this balance requires several services provided by generators on the power grid. Operational requirements are imposed by the North American Reliability Council (NERC), the Northeast Power Coordinating Council (NPCC) and Nova Scotia Power, in its role as system operator, is bound to maintain reliable and stable operation of its power grid. As is the case on several power grids around the world, the amount of electrical energy generated by renewable energy sources has been increasing and this is no different in Nova Scotia. NSPI's grid has (2019) approximately 600 MW of wind generation providing approximately 18% of annual supplied energy. The share of energy supplied from wind has steadily increased starting from around 1% in 2007. In contrast to traditional generation technologies, renewable generators are often relatively small in capacity, numerous, spread over large geographical areas and tend to connect to the power grid with some level of power electronics. Increasing energy contributions from these generators displaces traditional generators which tend to be large, synchronous machines. The generation patterns of renewable generators such as wind and solar tend to be uncertain and forecasts are never perfect. All of this combines to create a set of challenges for any system operator. NSPI aim to examine the ability of a wind farm to provide a range of services and supports to the grid in addition to simply generating energy. This work is therefore a collaboration between Nova Scotia Power Inc. and Enercon Canada to examine possibilities such as providing frequency regulation from wind generators and examining the ability of a wind farm to contribute to grid dynamic stability.

2. PLANNED DEMONSTRATIONS AND EXPECTED OUTCOMES

Three demonstrations are planned viz.
1. Fast frequency response, sometimes called inertia emulation.
2. Power-frequency response
3. Automatic generation control (AGC) or secondary frequency response

The planned wind farm power levels for each of the tests are shown below. Note that the per unit (p.u.) scale is a fraction of the rated farm power (50.6 MW).

#	WF active power [p.u.]
1	0.1 - 0.4
2	0.4 - 0.6
3	>0.6

The technical aspects of each and their effects are examined below.

2.1. SITE SINGLE LINE DIAGRAM AND MEASUREMENT SETUP

NSPI's Nuttby Mountain wind farm is in the central part of the province of Nova Scotia (Figure 1). Owned and operated by Nova Scotia Power [1], the farm has been operational since 2010 and consists of 22 Enercon wind turbine generators each rated at 2,300 kW. The wind turbines are classified as IEC Type 4 machines. They use a direct-drive, separately excited synchronous generator, and a full converter (AC-DC-AC) to interface with the grid. The full converter changes the variable frequency AC power from the synchronous generator to fixed frequency (60 Hz) power injected to the grid. Note that this power electronic interface means that there is no AC electrical connection between the grid and the generator of the wind turbine.

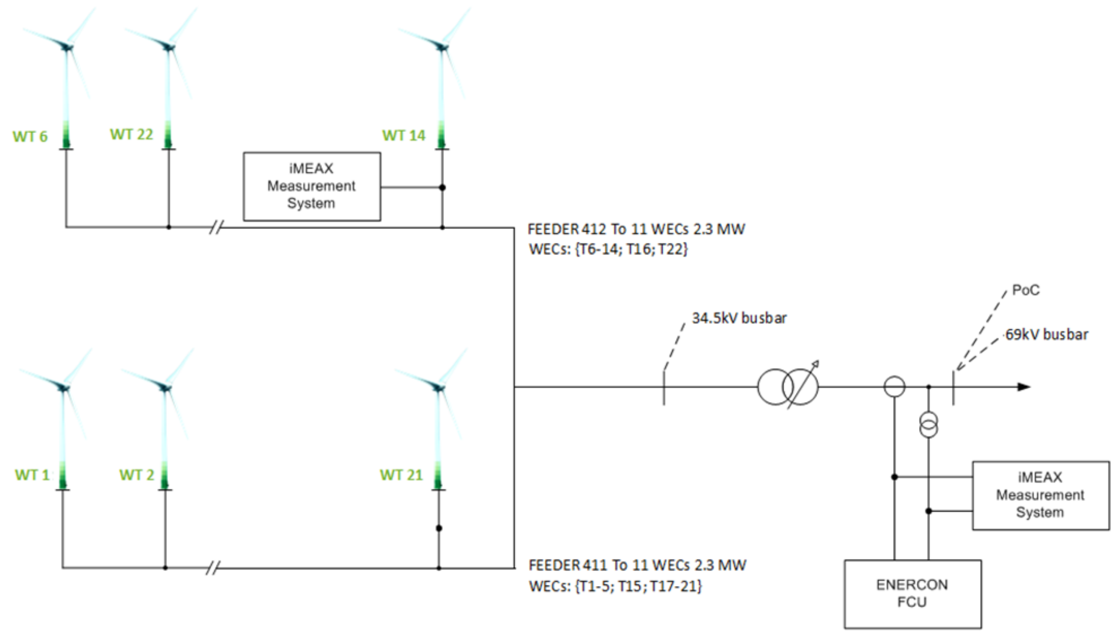


Figure 2: Simplified farm SLD and measurement setup. Enercon gather data at two locations – one at the PoC for farm-level data and one at turbine #14. Note - Not all turbines are shown. Source - Enercon Canada

High-speed data are gathered by Enercon at the locations shown in Figure 2. Some demonstrations are performed on the wind farm as a whole and others are performed on individual turbines, here turbine WT 14. Two measurement systems will be used for the demonstration as described below.

1. Wind farm-level measurement connected to 69 kV High Voltage (HV) Voltage Transformers (VT) and Current Transformer (CT) to measure the total instantaneous values of the three phase-to-earth voltage signals and the instantaneous values of the three phase currents at the Point of Connection (PoC).
2. Measurement connected to 400 V Low Voltage (LV) CT and VT in WT 14 to measure the total instantaneous values of the three phase-to-earth voltage signals and the instantaneous values of the three phase currents.

In addition to this data, NSPI will gather SCADA data using their equipment at the wind farm's point of connection to the grid. NSPI's data are lower frequency (slower than 0.5 Hz) but serve as a check. For reference, data logged by Enercon's equipment is detailed below.

Table 1: Data logged locally by Enercon's high-speed equipment. Source: Enercon Canada

Signal	Reference	Signal Description	Unit	Sample Rate
I_{1_FCU}	PoC, 69 kV	Instantaneous line current, phase 1	A	5 kHz
I_{2_FCU}	PoC, 69 kV	Instantaneous line current, phase 2	A	5 kHz
I_{3_FCU}	PoC, 69 kV	Instantaneous line current, phase 3	A	5 kHz
V_{1_FCU}	PoC, 69 kV	Instantaneous line to ground voltage, phase 1	kV	5 kHz

Signal	Reference	Signal Description	Unit	Sample Rate
V_{1_FCU}	PoC, 69 kV	Instantaneous line to ground voltage, phase 2	kV	5 kHz
V_{1_FCU}	PoC, 69 kV	Instantaneous line to ground voltage, phase 3	kV	5 kHz
$I_{1\_WT\_14}$	WT 14, 400 V	Instantaneous line current, phase 1	A	5 kHz
$I_{2\_WT\_14}$	WT 14, 400 V	Instantaneous line current, phase 2	A	5 kHz
$I_{3\_WT\_14}$	WT 14, 400 V	Instantaneous line current, phase 3	A	5 kHz
$V_{1\_WT\_14}$	WT 14, 400 V	Instantaneous line to ground voltage, phase 1	V	5 kHz
$V_{1\_WT\_14}$	WT 14, 400 V	Instantaneous line to ground voltage, phase 2	V	5 kHz
$V_{1\_WT\_14}$	WT 14, 400 V	Instantaneous line to ground voltage, phase 3	V	5 kHz
$P_{available\_FCU}$	PoC, 69 kV	Available active power at PoC	kW	100 Hz
$P_{available\_WT\_14}$	WT 14, 400 V	Available active power of WEC 14	kW	100 Hz
$f_{simulated\_FCU}$	PoC, 69 kV	Simulated frequency of the WFCS at the FCU*	Hz	100 Hz
$P_{setpoint\_FCU}$	PoC, 69 kV	Active power control set point at the FCU*	kW	100 Hz
V_{WT_14}	WT 14, 400 V	Wind speed of WEC 14	m/s	100 Hz

* FCU refers to the Farm Control Unit which is the central controller for the wind farm. It is located at the point of connection to the grid and is responsible for distributing control targets across all wind turbines.

2.1. Fast- frequency response or Inertia emulation

Fast-frequency response is an electrical control function that behaves in a manner similar to the inertial response of a synchronous machine. NERC defines inertial response and fast frequency response as primary frequency responses [2] [3]. In essence, the rotational inertia of a synchronous machine acts as a counter (or damper) against grid frequency changes. When grid frequency falls, some stored rotational energy is converted to electrical energy and the synchronous machine increases its active power output. The reverse happens in case of a frequency increase with the machine consuming power and increasing rotational speed. This response is only possible due to electromagnetic coupling between the stator and the rotor in a synchronous machine. Inertial response is important as it slows the rate of change of frequency (ROCOF[1]) on the grid providing the system operator with more time to respond and counter the frequency change [4].

An IEC type 4 WTG connects to the grid with a power electronic converter and so lacks an equivalent electromagnetic coupling. Fast-frequency response from such a converter can act similar to synchronous inertia. Additionally, the converter's response, though slower than electromagnetic inertia, can be parameterised and controlled. The inertial response of a

[1] ROCOF is a measure of how quickly frequency changes following a sudden imbalance between generation and load. This is the definition in the 2018 LBNL Frequency Control Requirements for Reliable Interconnection Frequency Response Report: https://certs.lbl.gov/project/interconnection-frequency-response.

synchronous generator is an inherent feature and depends primarily on the rotating mass of the machine – a fixed parameter.

Fast frequency response is a form of Primary Frequency Response (PFR) that is triggered automatically in response to measured frequency changes. As detailed in NERC's 2020 white paper on Fast Frequency Response [2], this report avoids using the label "inertia" in any form when referring to this response from a WTG. For clarity, fast-frequency response as documented in this report is not a substitute for electromechanical inertia. Although both behave in a similar manner and operate on similar time scales, their fundamental nature differs. Inertia from a synchronous machine is due to rotational inertia and is an entirely electromechanical response. Fast-frequency response from Enercon's Type 4 WTGs is based around power electronics as there is no direct AC connection between the WTG generator and the grid.

Fast-frequency response from a Type 4 WTG involves extracting kinetic energy from the WTG rotor and using it to provide a momentary boost in active power output. In physical terms, the torque on the WTG's synchronous generator is momentarily increased thus reducing rotor rotational speed. Provided that the wind turbine is above a certain output level, around 5-10% x $P_{nominal}$ of additional active power can be injected [2]. The magnitude of this response does not generally depend on prevailing power output levels but requires that the wind turbine power level be non-zero. Due to the rotor speed reduction, the period of active power increase is followed by a recovery period where the WTG rotor is brought back up to speed. The energy required for this comes from the wind and thus the duration of the recovery period depends on the prevailing wind speed. More details can be found in Appendix B of reference [2]. See also Enercon's grid integration brochure [5].

In the context of increasing generation levels of non-synchronous generation, this part of the demonstration is important for several reasons. Increasing levels of non-synchronous generation reduce the inertia[2] on the power grid thus reducing the ability of the grid to arrest frequency changes i.e., this has the effect of reducing grid stability. Further, the nature of the response from some wind generators can be modified (or tuned) and this provides response time for the system operator and slower-acting controls or generators. This aspect is particularly important during moments when non-synchronous generation is the majority of generation. Frequency reductions due to a loss of generation can sometimes cause under frequency protections to operate.

Test setup

To simulate the effect of fast frequency response, an artificial grid frequency signal, as shown in Figure 3, will be injected into the control system of each WTG to trigger a response.

[2] See Chapter 3: Concept of Critical Inertia in [2]

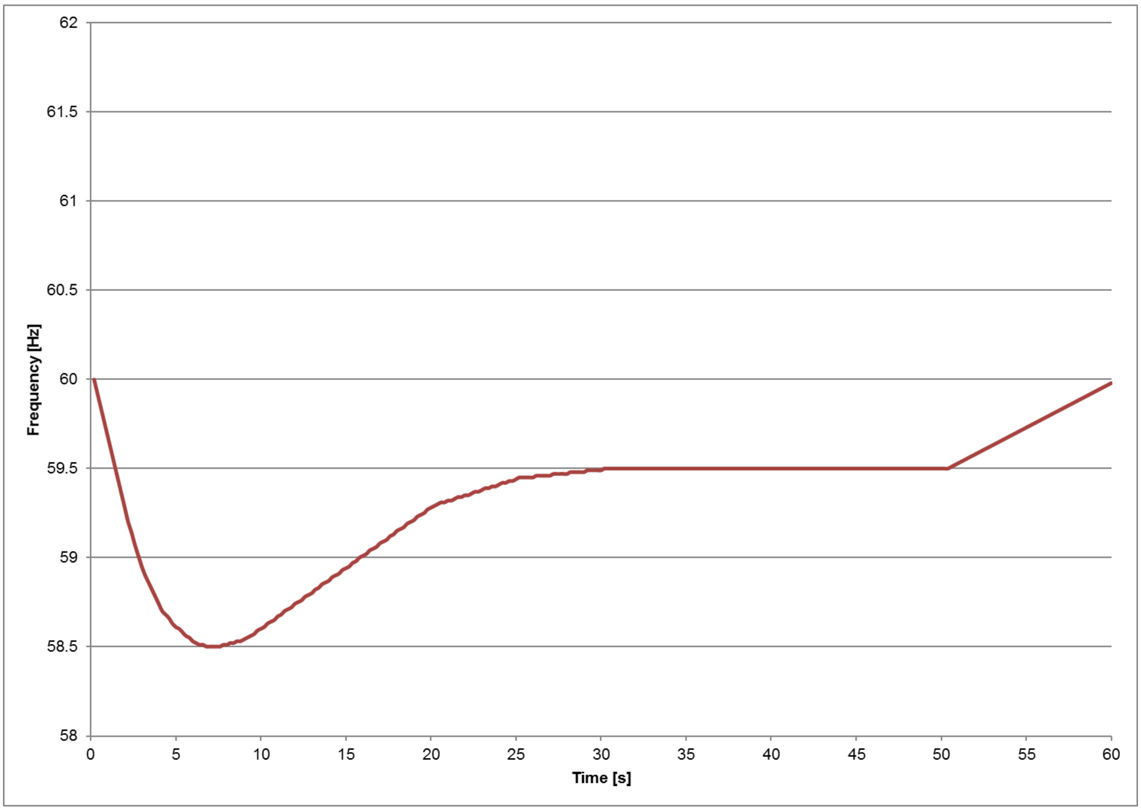


Figure 3: Artificial grid frequency signal injected into each WTG to test fast frequency response. Source: Enercon Canada

2.2. Power frequency control

Power frequency control refers to a change in the wind turbine active power output in response to a measured grid frequency change. Grid frequency must be outside a pre-determined dead-band. If grid frequency rises, WTG active power output is reduced and if grid frequency falls, WTG active power output increases provided headroom is available. This is analogous to droop speed control in a synchronous machine.

Note that power-frequency control is distinct from fast-frequency response in that the response time is slower. Fast-frequency response activates within milliseconds of sudden frequency changes while power-frequency response activates within seconds. Further, fast-frequency response uses rotor kinetic energy to provide a temporary increase in power while power-frequency response uses headroom i.e., curtailment to provide a power increase. Responding to frequency increases is simple and does not require continuous active power curtailment. This is the only mode of power-frequency control tested in this work. Although possible, the WTG's power-frequency response to frequency reductions is not tested.

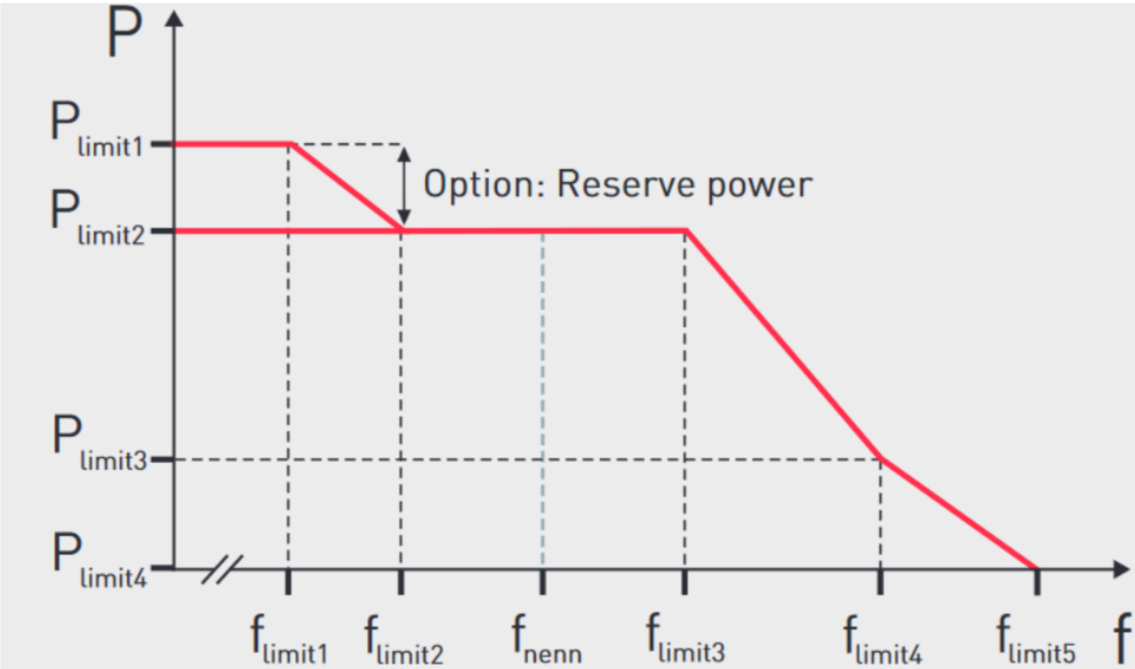


Figure 4: Frequency limits and power changes for power-frequency control. Source: Enercon [5]

In the context of the increasing levels of non-synchronous generation on the grid, this response is important as a wind turbine's power output is dependent primarily on prevailing wind speeds. Type 4 WTGs with a full converter electrically decouple the generator from the grid so the generator itself is unable to respond to grid frequency changes without control system intervention. Power-frequency control contributes to grid stability by increasing grid frequency's recovery rate after a change in load or generation (See figure B.1 in [2]).

Test setup

Modifying grid frequency is not possible in an operational power system hence an artificial measured frequency is read into the WTG control system (Figure 5). The frequency value increases steadily above 60 Hz and triggers the power-frequency response at 60.5 Hz. The expected response is that the WTG reduces its active power output in proportion to the frequency value.

Note on triggering Power Frequency Control versus Fast Frequency Response
Fast frequency response is designed to be fast-acting and typically triggers within 120 ms of a frequency event being detected. In contrast, Power frequency control is slower and responds only when grid frequency is outside a predetermined dead band. FFR is designed to arrest sudden frequency declines and thus is able to increase turbine power output above what is possible with prevailing wind speeds. Power frequency control is designed to counter slower frequency changes. Here, active power is controlled based on frequency deviation. Power values are calculated as a function of frequency deviation. Further, PFR requires headroom via active power curtailment in order to respond to a reduction in grid frequency. On the flip side, responding to a grid frequency increase is trivial and requires only a decrease in active power output.

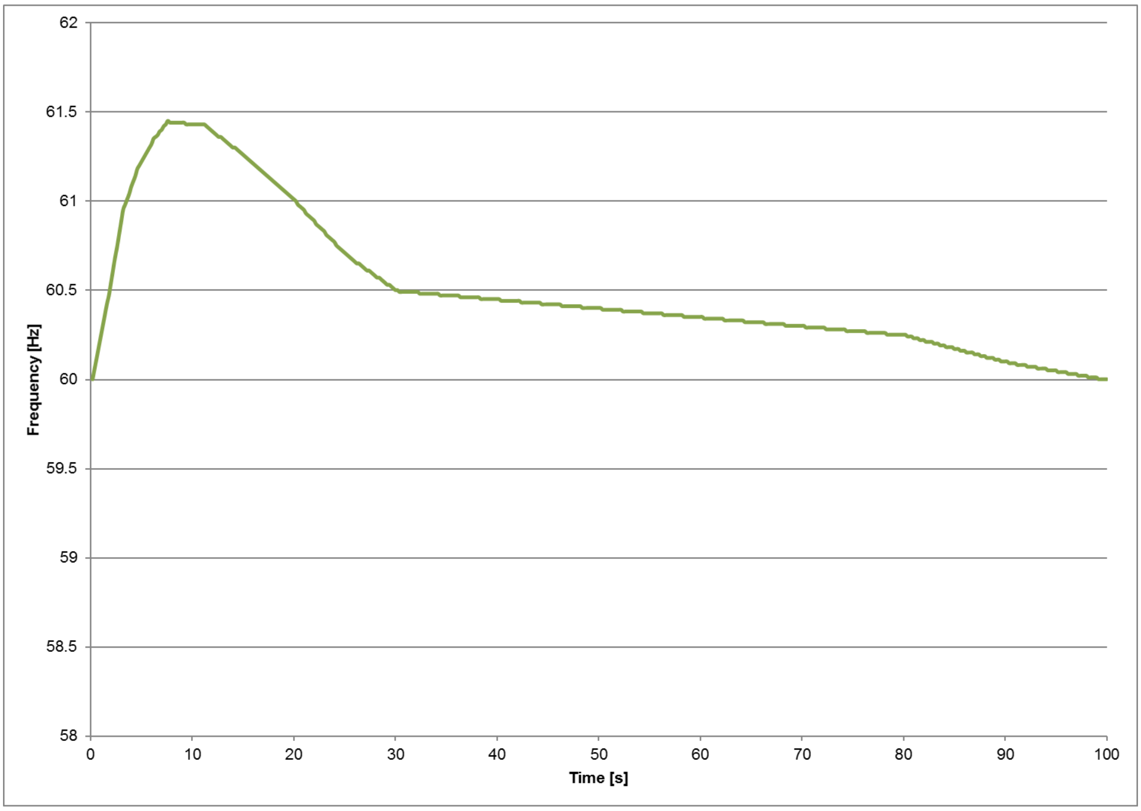


Figure 5: Artificial frequency signal injected into a single WTG. Source: Enercon Canada

2.3. AUTOMATIC GENERATION CONTROL (AGC)

Following NERC's definition [3], Automatic Generation Control (AGC) is the most common method of secondary regulation and operates on the order of seconds, typically 2 – 4 s. It is a controlled response with the aim of addressing short-term (seconds) imbalances in the demand-supply equation. AGC is computed by the system operator using inputs such as Area Control Error (ACE) and frequency error [3] and is distributed among several generators that are commanded to make small changes in their active power outputs.

AGC can command a generator to either increase or decrease active power production. For a WTG, reducing active power output is a matter of simple curtailment however active power output cannot be increased above the level permitted by prevailing wind speeds. Providing a power increase in response to AGC therefore requires some level of continuous curtailment.

Test setup
Testing the wind farm's response to providing AGC involves normal operation with the addition of an external AGC signal for the wind farm to follow. NSPI expect to use 20 MW (40%) of the available 50 MW capacity to provide AGC however the precise range tested depends on prevailing wind speeds.

2.4. PREPARATORY SIMULATIONS CARRIED OUT BY NOVA SCOTIA POWER & SIMULATION RESULTS

NSPI performed simulations to examine the effect of enabling Nuttby's fast frequency response on the rest of their power system. Simulations were done only for fast frequency response as this has the potential for the greatest impact on system dynamic response and stability. The need for and effects of AGC are well understood and the demonstration seeks to examine the performance of a wind farm in providing AGC – the demonstration being easier to examine in detail as opposed to a simulation. Additionally, a field demonstration provides data that a simulation cannot provide such as power error and wind speed changes. The text, plots and parameter values below are taken from an NSPI simulation report.

Power system model

To simulate the effects of significant under-frequency events, the detailed NS system model was extracted from the full 2017 NERC dynamics model and updated to 2020. A shoulder peak (fall) load of around 1350 MW was chosen to represent the potential conditions during the proposed field test. However, to avoid modelling issues in dynamics, all user-written models except for the Enercon models described above were eliminated. Thermal units were either taken off-line or operated near full rated capacity to limit the unrealistic generation pick-up that is seen in standard PSS®E governor models. This ensured that under-frequency load shedding (UFLS) would be activated as intended, and frequency dip would be within the range for the FFR models to operate without Nuttby frequency protection operating.

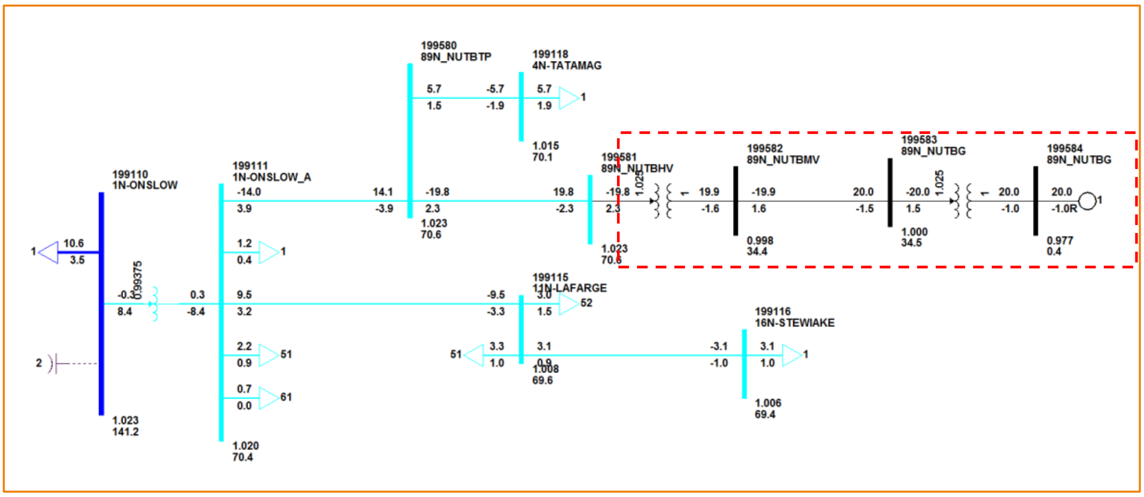


Figure 6: Grid interconnection for the Nuttby Mountain wind farm (dotted). All WTGs are represented as a single, lumped equivalent. Source – NSPI

The outside world was represented by an equivalent machine on the New Brunswick (NB) side of the NS-NB border to allow up to 300 MW of import from NB. The classical dynamic model (GENCLS) of this equivalent machine was sufficient to initialize the case, but the unit was tripped to represent the loss of source in the islanded NS system, therefore the model for that unit was immaterial.

System response without fast frequency response on Nuttby wind farm

Figure 7 shows the Nova Scotia islanded frequency for a loss of 22.2% of net system requirements (load plus losses) without FFR activated on Nuttby (IE-CTRL = 0). We can detect three stages of UFLS operation, starting at 59.5 Hz (with a 300 ms delay). Because frequency fails to recover within 10 s, the anti-stall stage trips a fourth stage at 11.5 s. Figure 8 shows how the Nuttby model responds to the frequency excursion, with very minor power (0.1 MW) excursions whenever a block of load is shed. Without IE implemented, Nuttby controls keep the plant at pre-disturbance output of 20 MW through the 20 second simulation.

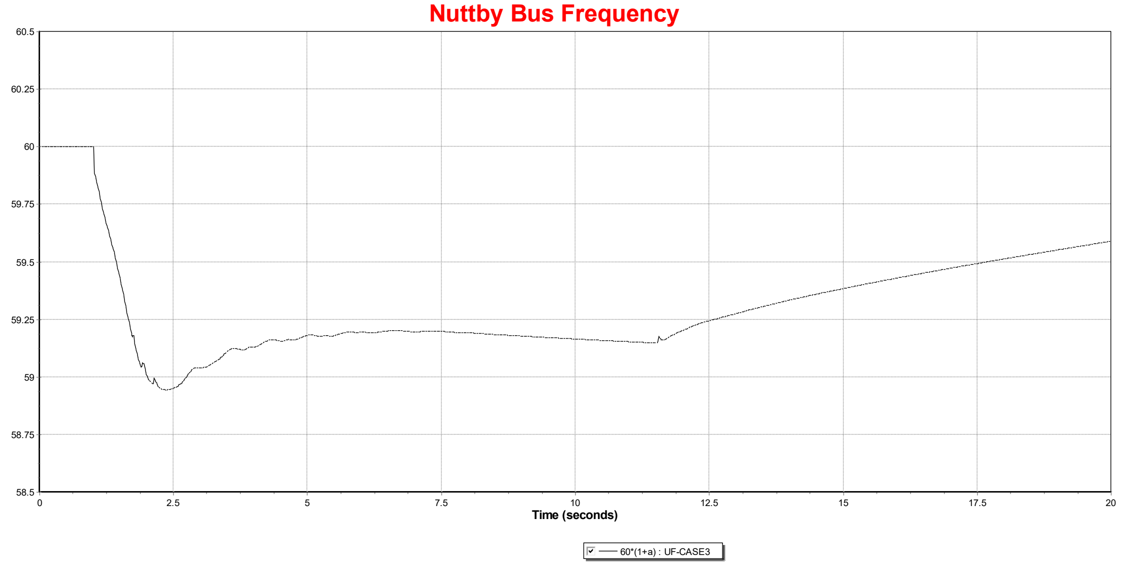


Figure 7: Islanded grid frequency during grid frequency dip event as measured at Nuttby wind farm point of connection. Farm dispatch = 20 MW & FFR was not active. Source - NSPI

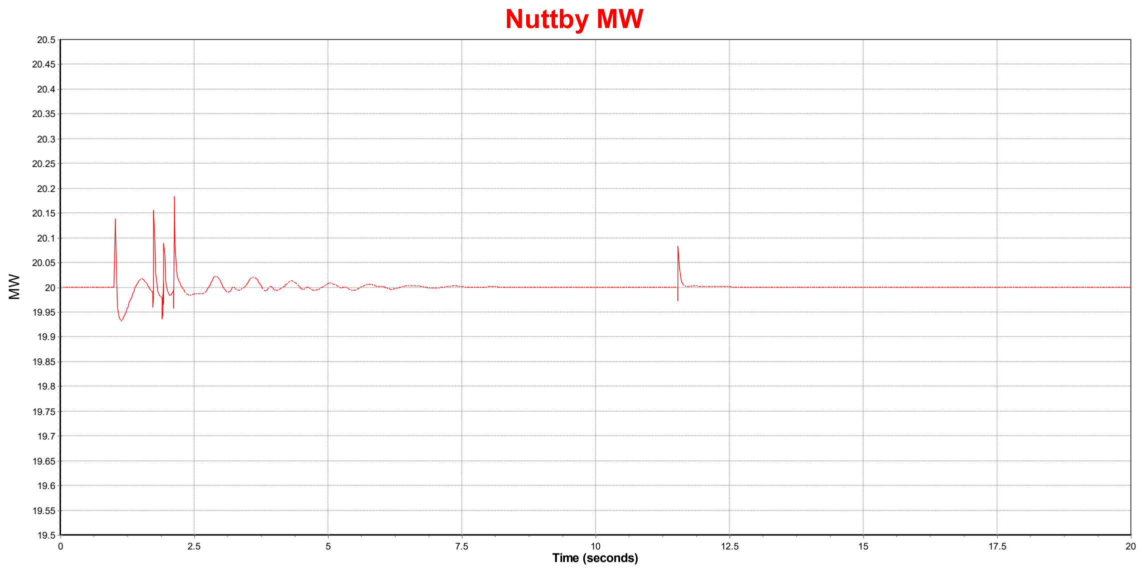


Figure 8: Simulated active power output of Nuttby wind farm without fast frequency response active. Note that the output spikes correspond to grid loads being shed. Wind farm output remains almost constant (20 MW) throughout. Source – NSPI

System response with fast frequency response active on Nuttby wind farm

The response of Nuttby is shown in Figure 9. The plant responds to the drop in frequency at a rate of about 0.8 MW/s picking up 1 MW (2% of rated capability) for a period of about 10 s. It then reverts to recovery mode where it extracts 1 MW from the system to bring the WEC units back to nominal speed. This characteristic is the shape that was expected, so parameters were modified for additional cases as shown in Table 2, with response curves as noted. Case 11 has the same IE parameters as Case 10, but Nuttby is dispatched at 40 MW, demonstrating that the response is independent of wind conditions. Cases 11-14 use a base case dispatch of 40 MW.

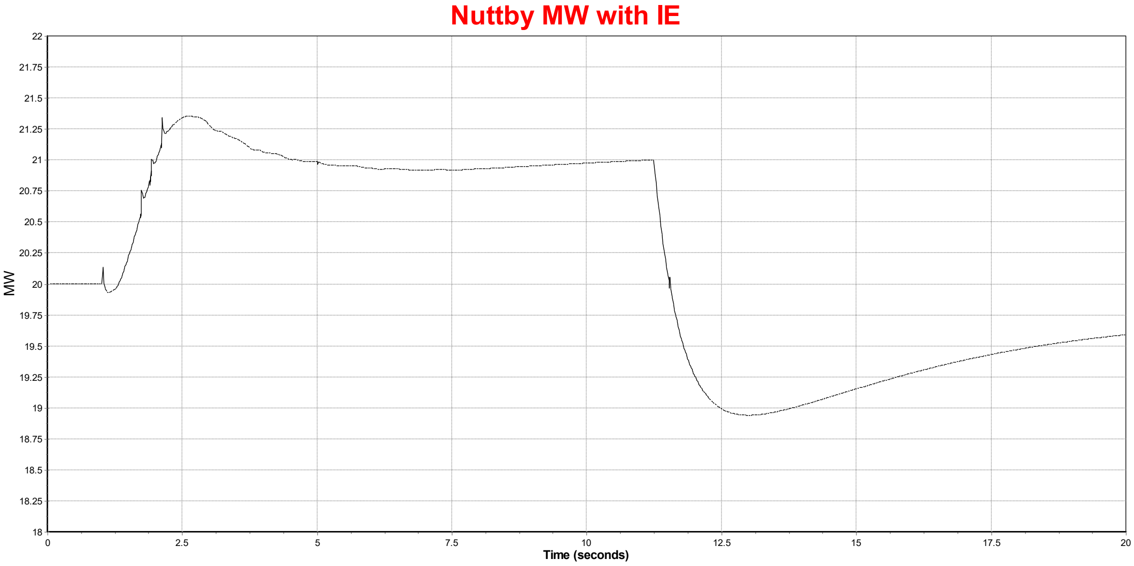


Figure 9: Case 10 - Nuttby POC active power with FFR active. See Table 2 for parameters.

Table 2: Parameter summary for NSPI's fast frequency response simulations

Parameter	Case 10	Case 11	Case 12	Case 13	Case 14
Plant MW	20	40	40	40	40
Trigger frequency in Hz (FIETG)	59.7	59.7	59.7	59.7	59.7
Inertia factor in % of Pnominal (PIEST)	10	10	30	30	30
Boost in % (IEBST)	0	0	0	0	20
Hold factor 0 = OFF (IEHLD)	0	0	0	1	0
Results Figure	Figure 9	Figure 10	Figure 11	Figure 12	Figure 13

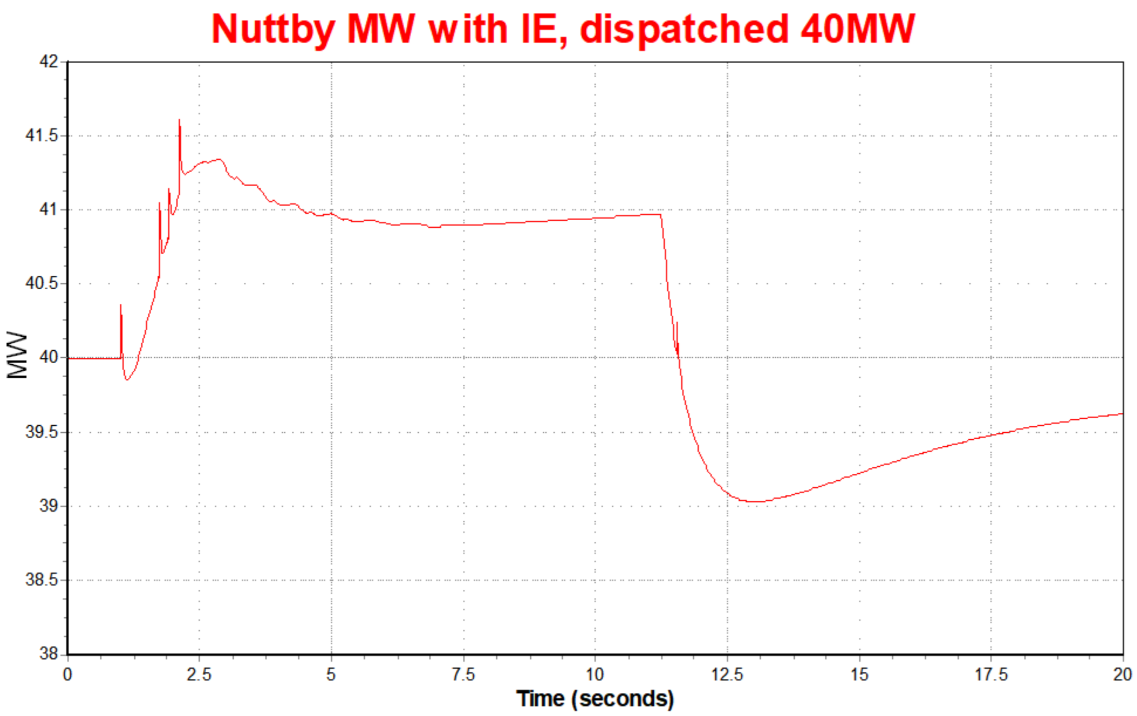


Figure 10: Case 11 - Nuttby POC active power with FFR active. See Table 2 for parameters.

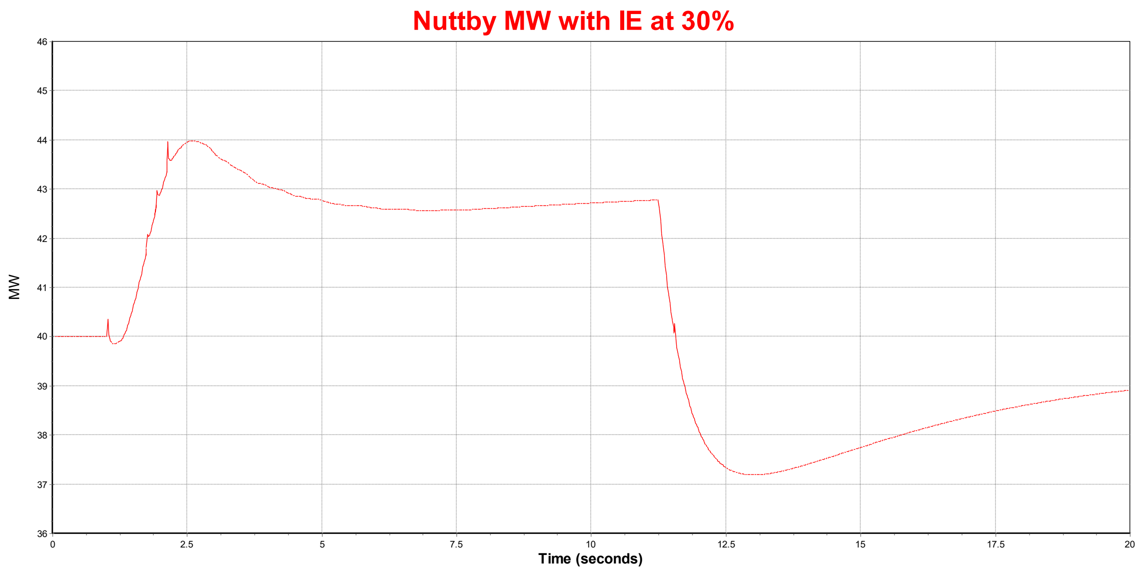


Figure 11: Case 12 - Nuttby POC active power with FFR active. See Table 2 for parameters.

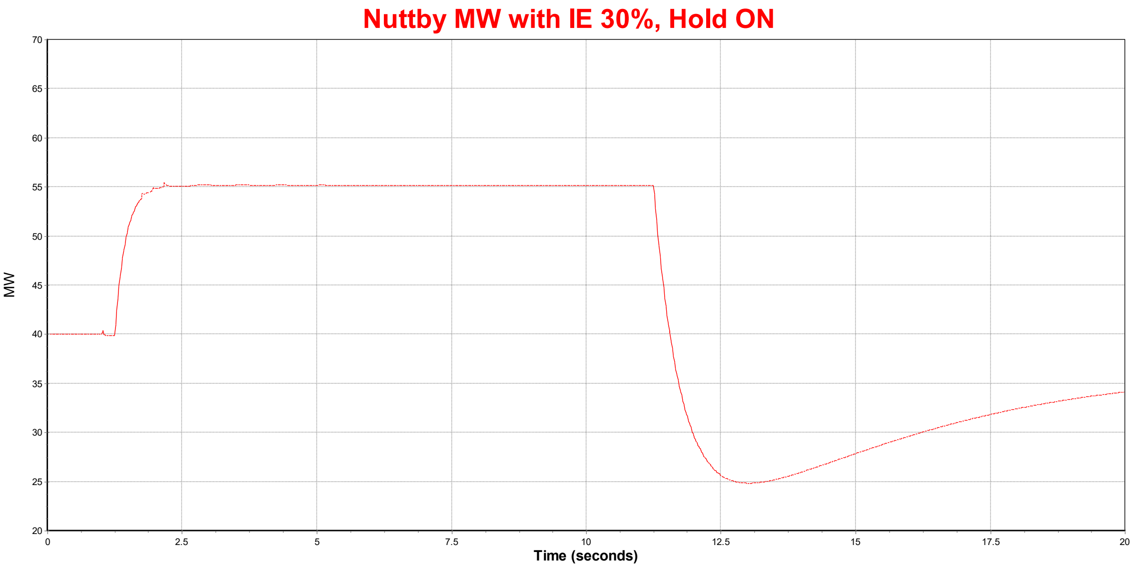


Figure 12: Case 13 - Nuttby POC active power with FFR active. See Table 2 for parameters.

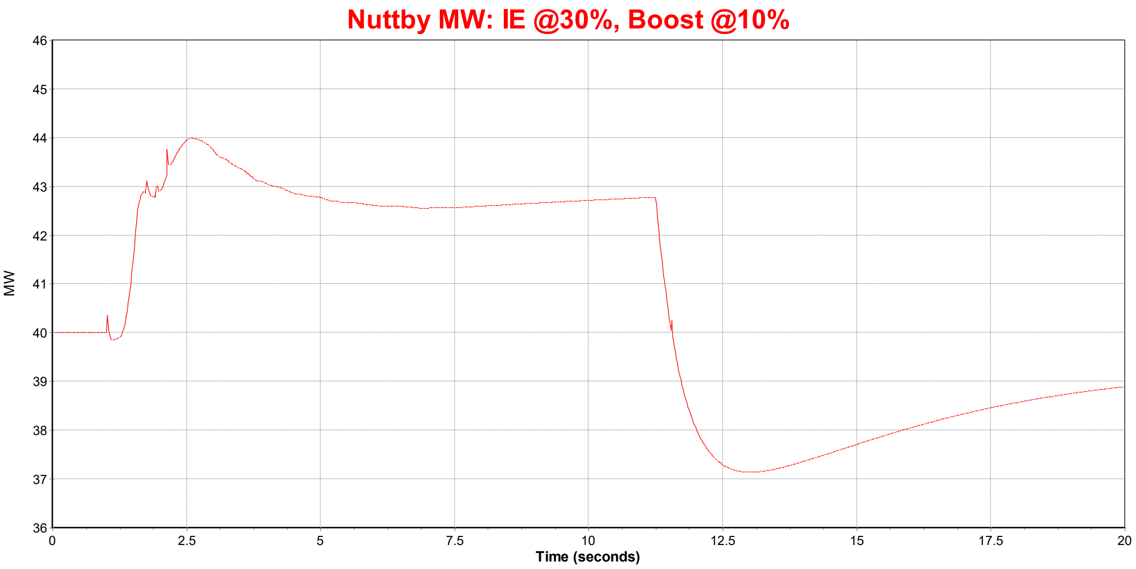


Figure 13: Case 14 - Nuttby POC active power with FFR active. See Table 2 for parameters.

Table 3: Simulation parameters, labels, and recommended values

Value	Label	Description
59.7	FIETG	IE: Inertia trigger frequency in Hz
10	PIEST	IE: Inertia factor in % of P_N
10	IEBST	IE: Inertia boost in % (see IEBAS)
0	IEHLD	IE: Inertia factor hold, 0 = off, 1 = on

Figure 14 and Figure 15 compare the response with various parameters of the IE model. Obviously, a setting of IEHLD=1 (kW magnitude held constant for duration of response) with PIEST=30% of nameplate gives significantly higher energy extraction (15 MW) compared with the other trials, but at a significant cost in energy recovery, which will hinder system frequency recovery. A reasonable compromise would be Case 14, which does not use IEHLD mode, but gives an initial boost of 10% (IEBST=10%) and limits IE energy extraction to 30% of nameplate.

System frequency response in this test model made a very small change to the RoCoF since only one wind farm on the NS system operating at 40/1350 = 3% with a pickup of 0.3% of generation. The benefit of the IE would come from a much higher penetration of wind generation similarly equipped with the IE feature.

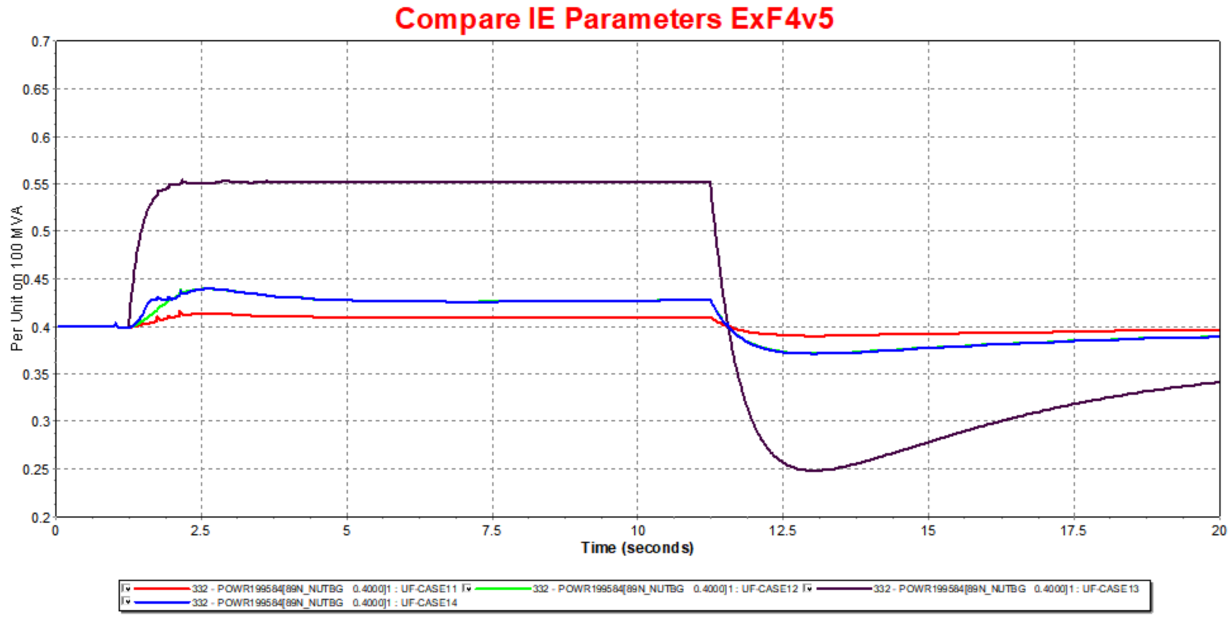


Figure 14: Comparison of parameter effects on active power output. See Table 2 for parameters.

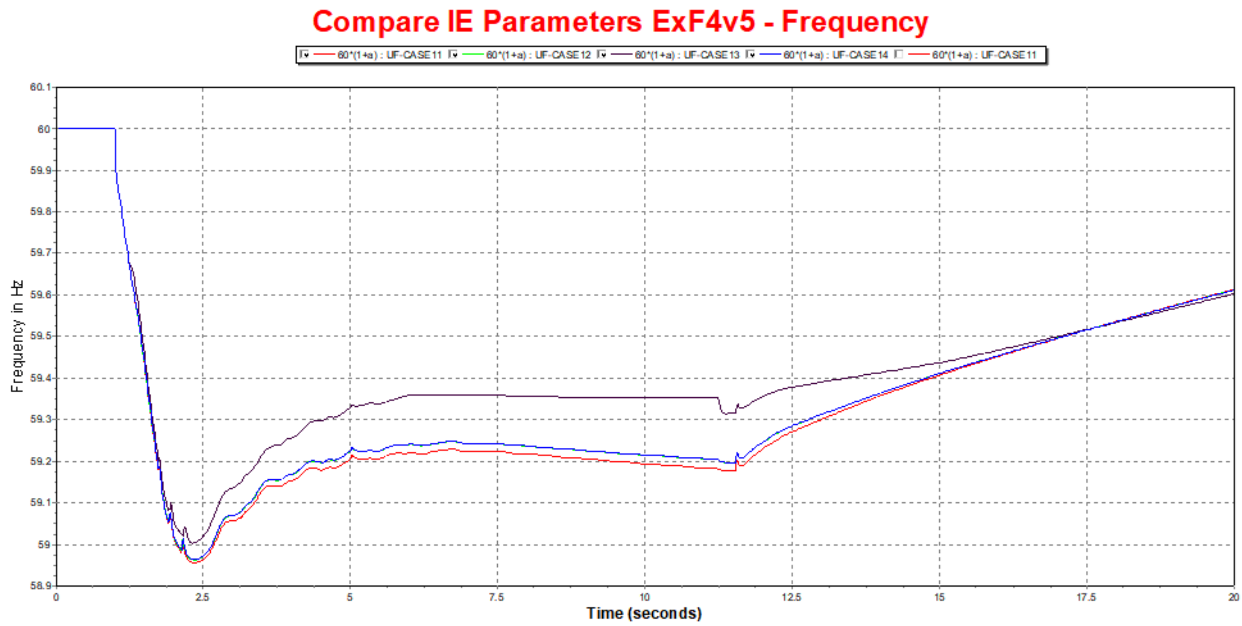


Figure 15: Comparison of parameter effects on system frequency response. See Table 2 for parameters.

Based on the results above, NSPI recommend a trigger frequency of 59.7 Hz, a 30% active power boost with a 10 s response duration.

2.5. RECORDED DATA

Data was provided by Enercon and NSPI and was gathered at different locations –

1. Fast frequency response – logged at the farm control unit, single point for the entire wind farm.
2. Power frequency response – logged at a single turbine – WT14.
3. AGC – Recorded by NSPI via their remote SCADA system.

Data is logged at different frequencies however all data is resampled and reported at 100 Hz. Active power data is not logged directly but is calculated via three-phase current and voltage data (V_1, V_2, V_3) using the a-b transformation equations below:

$$V_a = \frac{\sqrt{2}}{3}(V_1 - \frac{1}{2}V_2 - \frac{1}{2}V_3)$$

$$V_b = \frac{1}{\sqrt{6}}(V_2 - V_3)$$

$$I_a = \frac{\sqrt{2}}{3}(I_1 - \frac{1}{2}I_2 - \frac{1}{2}I_3)$$

$$I_b = \frac{1}{\sqrt{6}}(I_2 - I_3)$$

Active power is then calculated as:

$$P = 3(V_a.I_a + V_b.I_b)$$

3. RESULTS AND INTERPRETATION

3.1. FAST FREQUENCY RESPONSE

A total of thirty eight runs were carried out at various power levels as shown in the plot below. All responses are documented and plotted however, for clarity, not all are shown in this report. Only summary analyses are presented.

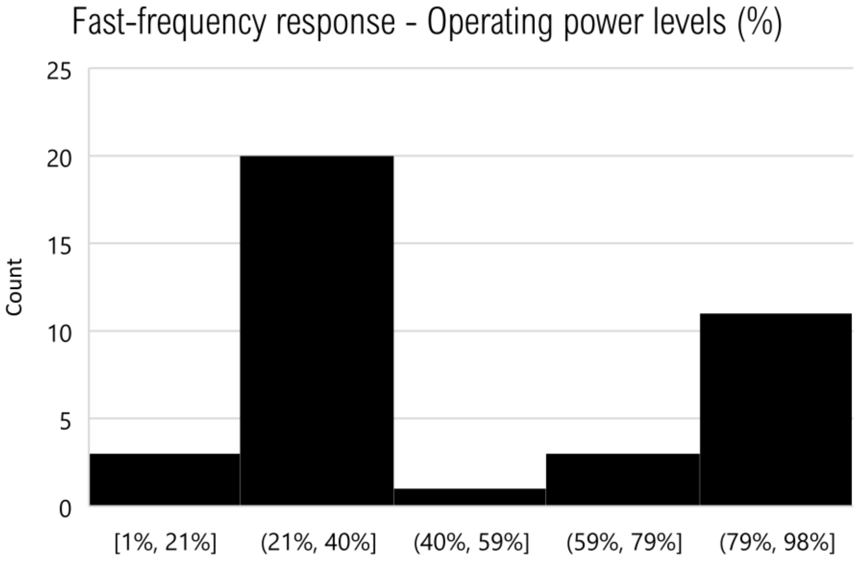


Figure 16: Wind farm operating power levels for fast-frequency response

Definitions and calculations

Refer to Figure 17 and the definitions below. In the result plots, line colour follows axis colour.

1. Response start time – this is the value of time (s) where the injected grid frequency signal is ≤ 59.7 Hz *for the first time.*
2. Response start power – the value of wind farm active power at `time = response start time`
3. Response end time– This is the value of time (s) at which the fast frequency response ends. The expected value is 10s as set in the wind farm's control system however a calculation is performed to verify the value. The slope of the power time series is used and the point at which its 5-cycle mean is maximum is the event end time. Observe from Figure 17 that the black power curve around the point "Response end" is nearly vertical i.e., the absolute value of its slope is high.
   Some error is introduced by averaging slope values. The maximum value of error is 5 times the sampling interval or ±50 milliseconds.
4. Recovery drop value – This is the minimum value of wind farm active power in the interval `[response end time, response end time + 10 s]`. This represents the active power dip required to accelerate the wind turbine rotors. The maximum value of the drop in power is 50% of wind farm rated power or 25.3 MW. The drop magnitude is calculated relative to the response start power.
5. Boost peak MW – this is the maximum value of measured wind farm power in the time interval `[response start time, response end time]`. The expected value is `response start power + 5 MW`.
6. Boost magnitude – this is the MW difference between `response start power` and `boost peak MW`.
7. 63% response MW – Once the fast frequency response is triggered, this is the time taken for wind farm active power output to reach 63% of `boost peak MW`. The expected value is 1 s.
8. Response duration – this is the time difference between `response end time` and `response start time`.

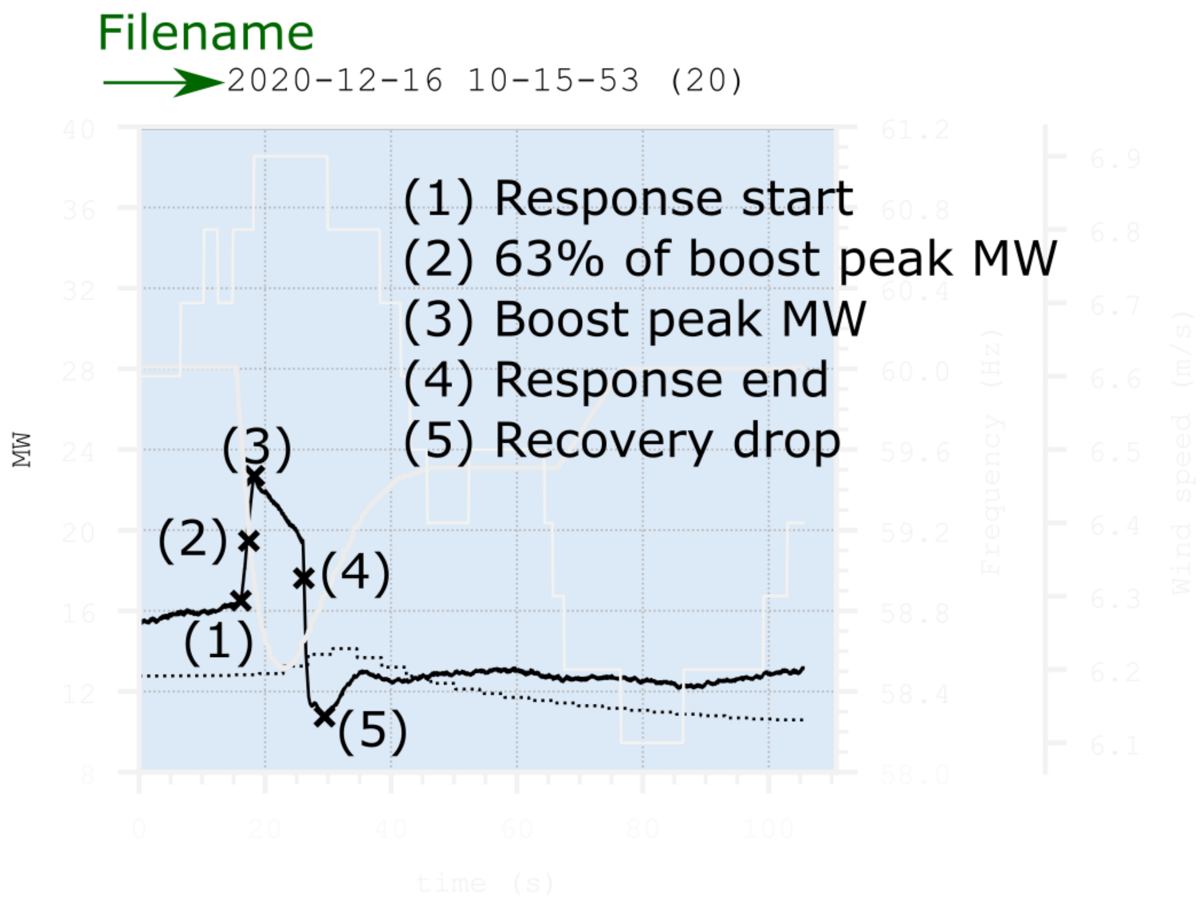


Figure 17: Fast-frequency response - Result plots explained. Sections are greyed out for clarity.

Results

Calculated values for the definitions in the previous section are presented in the attachments to this report. Summaries are presented below.

Rise time to 63% - Refer to Figure 18 that shows the calculated rise times for all fast-frequency runs. The one response in red is the only outlier. All other responses are close to the expected 1 s value with deviations accounted for by measurement error, control system delay and calculation error. It is safe to say that should the fast-frequency response be triggered by a grid event, the boost rise time to 63% of peak is 1 s and to the maximum boost is 2 s.

In the highlighted response (filename: 2020-12-15 10-36-37 (10)), a communication failure occurred During test, a remote trigger command is sent to all wind turbines, triggering a simulated frequency injection at each turbine (Figure 3). During the communication failure, the wind farm continued normal operation, as the wind turbines did not receive the remote trigger command.

Enercon feedback: In the event of an actual change in grid frequency, the response would be triggered by each turbine independently. Such a communication error would not prevent the wind farm from responding to a real grid frequency change

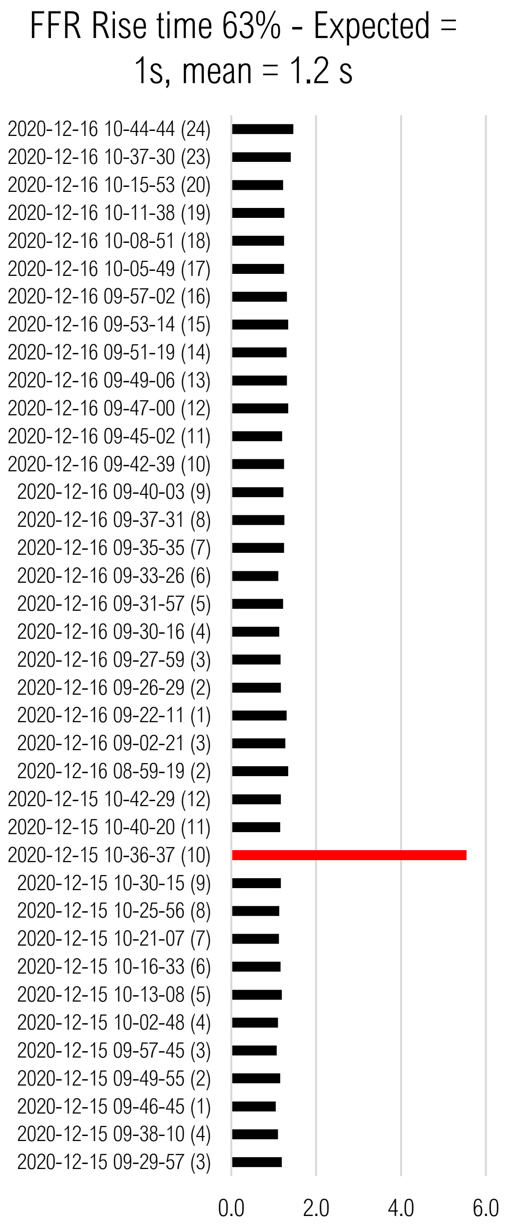


Figure 18: Fast-frequency response - Rise time to 63%. Axis values are data file names.

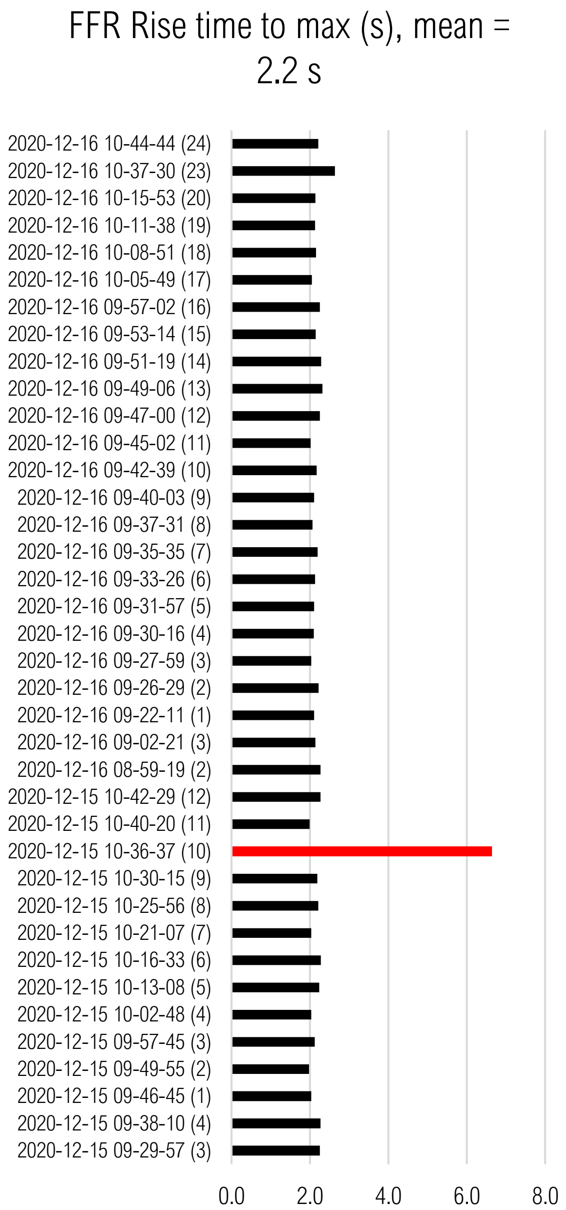


Figure 19: Fast-frequency response - Rise time to peak. Axis values are data file names.

Boost magnitude – The expected boost in active power is 10% of the wind farm rated power or 5.06 MW. Observe from Figure 20 that there are two instances where the boost magnitude is less than the expected 5 MW. In all other cases, the boost magnitude is ≥ 5 MW with a mean of 6 MW.

The explanation for the lowest value (filename: 2020-12-15 10-36-37 (10)) is the same as in the previous case – a communication error prevented the response from triggering.

In the second case (filename: 2020-12-16 10-37-30 (23)), the prevailing wind speed was low with a mean value of 5.1 m/s. This is the lowest mean wind speed among all recorded data and consequently, the mean active power generation was 0.8 MW for the entire wind farm. This meant that almost all wind turbines were not generating power and did not have sufficient energy stored in their rotors to generate a response. Despite this, the turbines that were operational did respond and raised active power output by 3 MW.

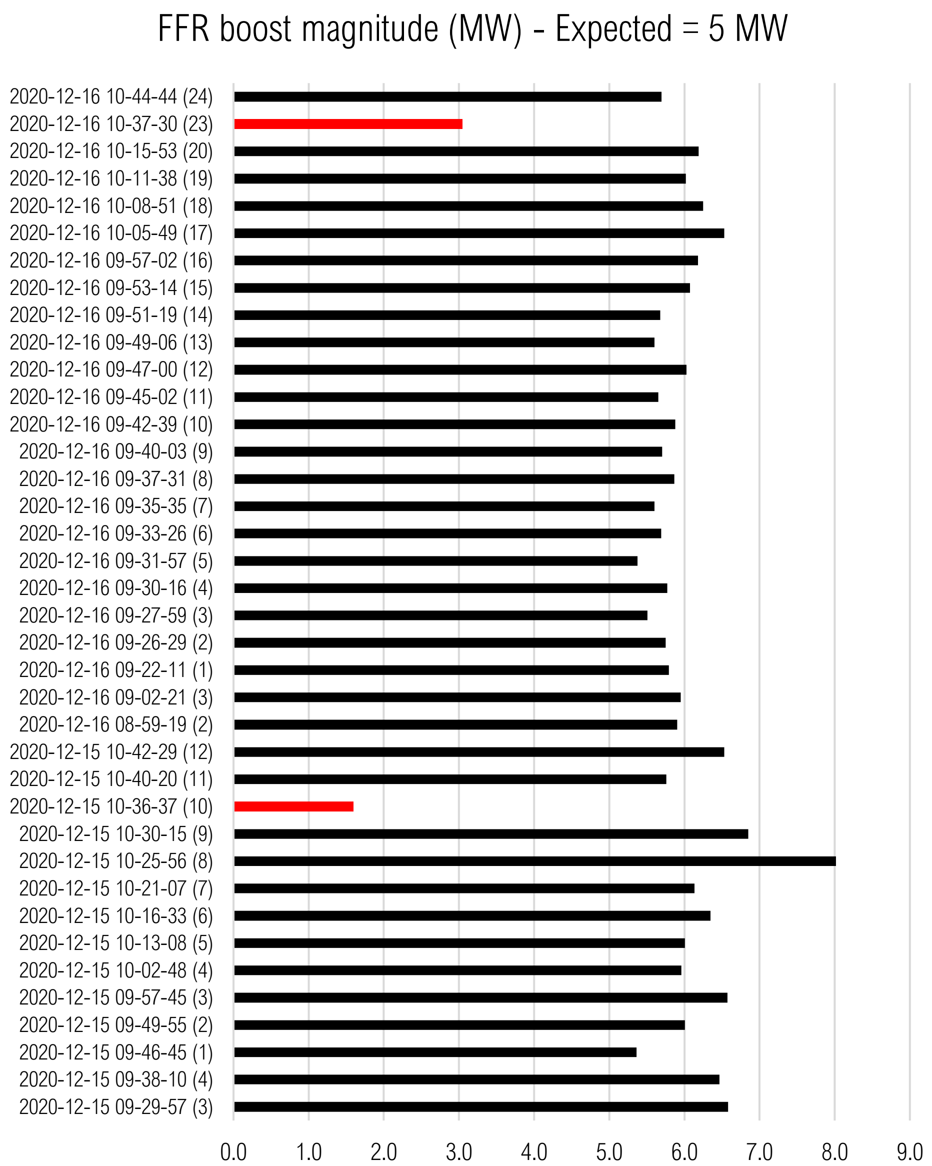
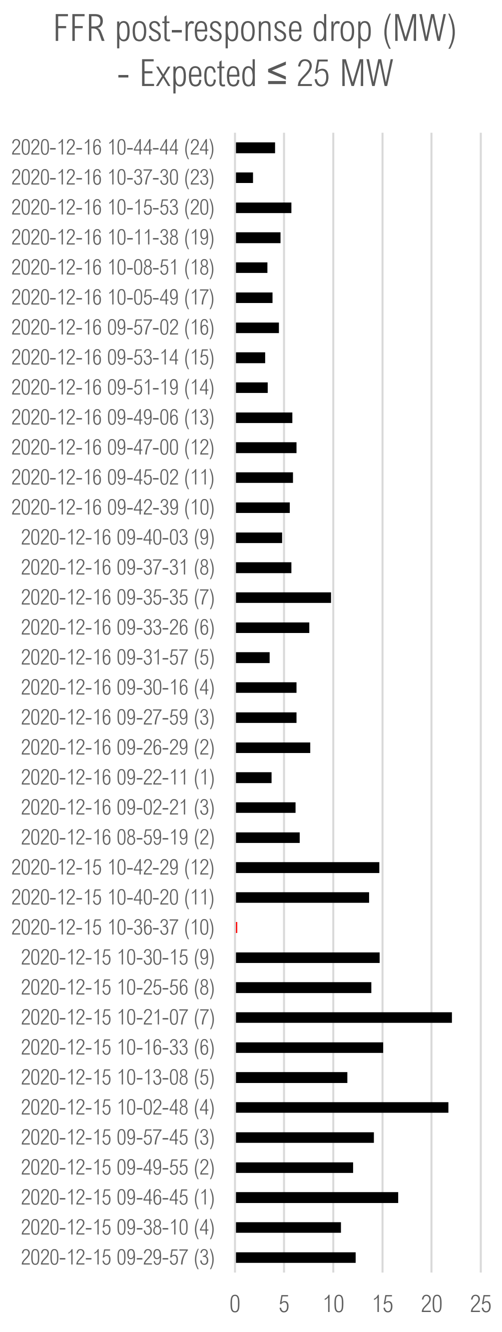


Figure 20: Fast frequency response - Boost magnitude. Axis values are data file names.

Post-response (recovery) drop – In order to provide an active power boost, energy is extracted from the wind turbine rotors. This causes a drop in rotor rotational speed. Once the boost duration has elapsed, the turbine rotors must accelerate to their optimal speed. The energy for this acceleration comes from the wind and during this period, turbine active power output drops. This drop is the referred to as the recovery period drop. Enercon's design claims that the maximum magnitude of this drop is 50% of rated farm power or 25.3 MW. Observe from Figure 20 that the recovered drop is below 25 MW in every instance.

An important component here is the prevailing wind speed trend. A falling wind speed trend causes a higher recovery drop. When operating near rated wind speeds, recorded data shows that the recovery drop is around 15 MW which is well below the maximum of 25 MW.



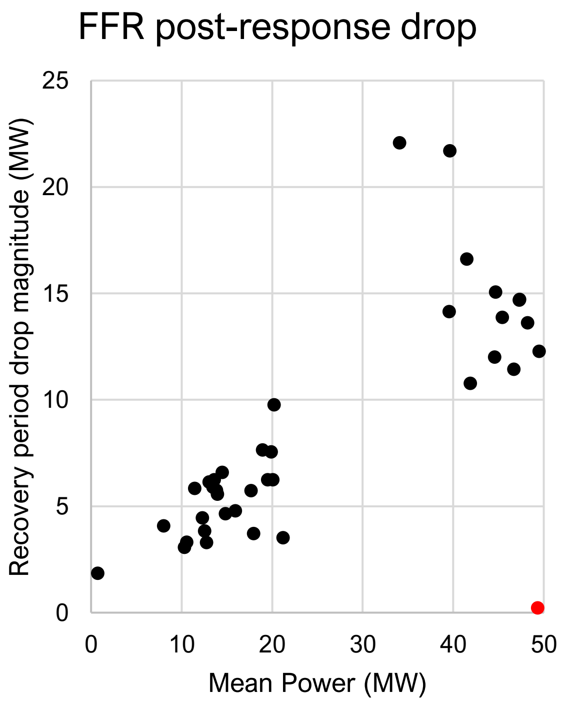


Figure 21: Relation between mean power and magnitude of recovery period drop. The two are proportional with the gap being due to limited data.

Expected use cases – Comment from NSPI

In practical applications NSPI can see the impact of Inertia in an under frequency scenario and how the expected behaviour of this enhanced technology will help to limit Under Frequency Load Shedding, prevent over shedding, and enhance customer reliability during system disturbances.

Fast-frequency response is an important component of grid stability as the share of inverter-based generation such as wind and solar continues to grow. The evaluation of Enercon's fast-frequency response shows that the magnitude of the power boost achievable is largely independent of prevailing wind speeds and is injected so long as the wind turbines are generating power. Performance after the boost peak power depends on prevailing wind speeds and the wind speed trend.

3.2. POWER FREQUENCY CONTROL

A total of 39 runs of the power-frequency response were carried out at various power levels. The power-frequency response in this report only examines this response when grid frequency increases. This requires a reduction in active power output or a power curtailment – relatively simple for a wind generator. On the other hand, the response to a grid frequency decrease is an increase in active power output. This requires power headroom i.e., the wind turbine must be operating below the maximum possible power or in simpler terms, an increase in power output requires a constant power curtailment. A wind turbine cannot continuously increase its power output beyond what is available in the prevailing wind.

As before, only summary results are presented here. Refer to the attachments for results from all runs. Note that this demonstration was performed on a single wind turbine in contrast to the fast frequency response demonstration which was performed on the entire wind farm.

Expected use cases: Comment from NSPI - Under-frequency events, while rare, occur more regularly than over-frequency events. NSPI would leverage this operation as a form of curtailment by using blade feathering to back off energy taken out of the wind in a controlled manner. Having this capability enabled would have assisted NSPI in past system disturbance events in that it may have helped to prevent conventional generating units from tripping. NSPI can see future use cases during system disturbances, often caused by extreme weather events, to assist with maintaining system stability.

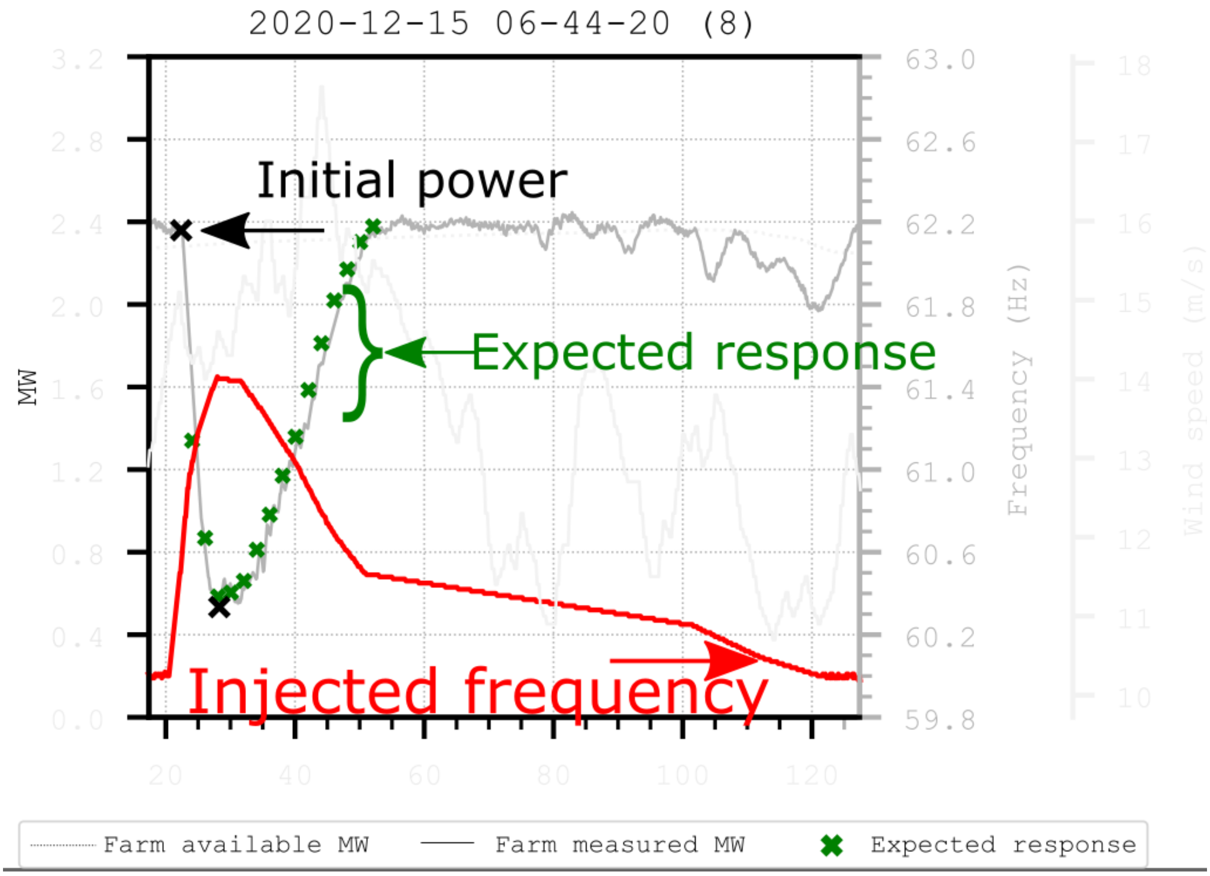


Figure 22: Power-frequency - Plots explained. Sections are greyed out for clarity.

Definitions and calculations

1. Trigger frequency – This is the value of frequency above which the power-frequency response is activated. The set value is 60.5 Hz.
2. Initial power level (P_{start}) – the value of turbine active power at the point when f = 60.5 Hz *for the first time*
3. Expected response – The expected power-frequency response depends on the initial power level and the relative change in grid frequency from 60 Hz.
   The expected response is calculated as:

$$P_{Expected}\ p.u. \ = \ P_{Start}\ p.u. - 0.8 P_{Start}\ p.u. (f_{Grid}\ Hz - 60.5\ Hz)$$

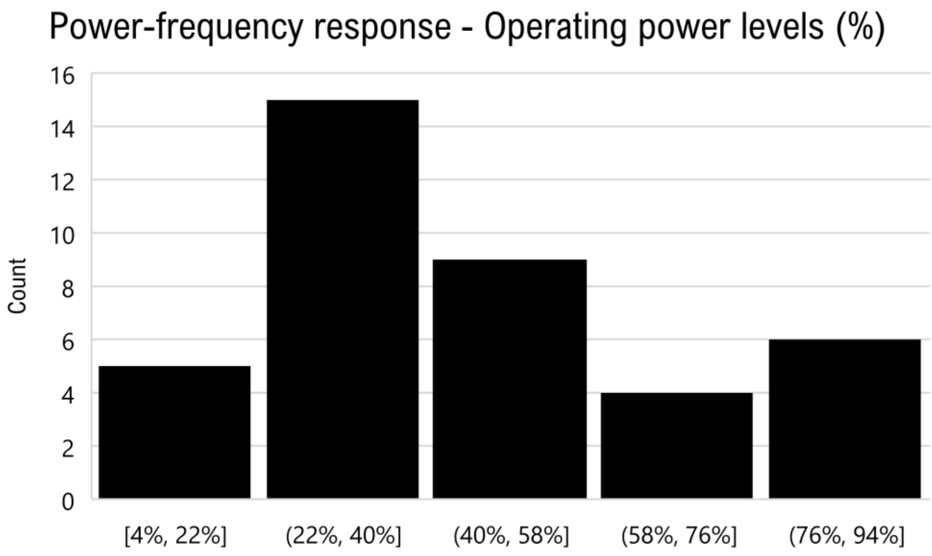


Figure 23: Wind farm operating power levels during power-frequency demonstration

Results

Power-frequency response is proportional to the deviation in grid frequency from the trigger frequency (60.5 Hz). As such, the only meaningful metric is the difference between the measured and expected responses. Note that because the response is calculated using active power at the response start time, a drop in wind speed means that the power during the response may not reach the initial level.

Mean error for each recorded data set is shown in Figure 24. The one outlier (filename - 2020-12-15 07-02-29 (13)) is explained by a decreasing wind speed trend which did not allow the wind turbine power to follow the rising part of the expected response curve. Mean error across all data is 50 kW.

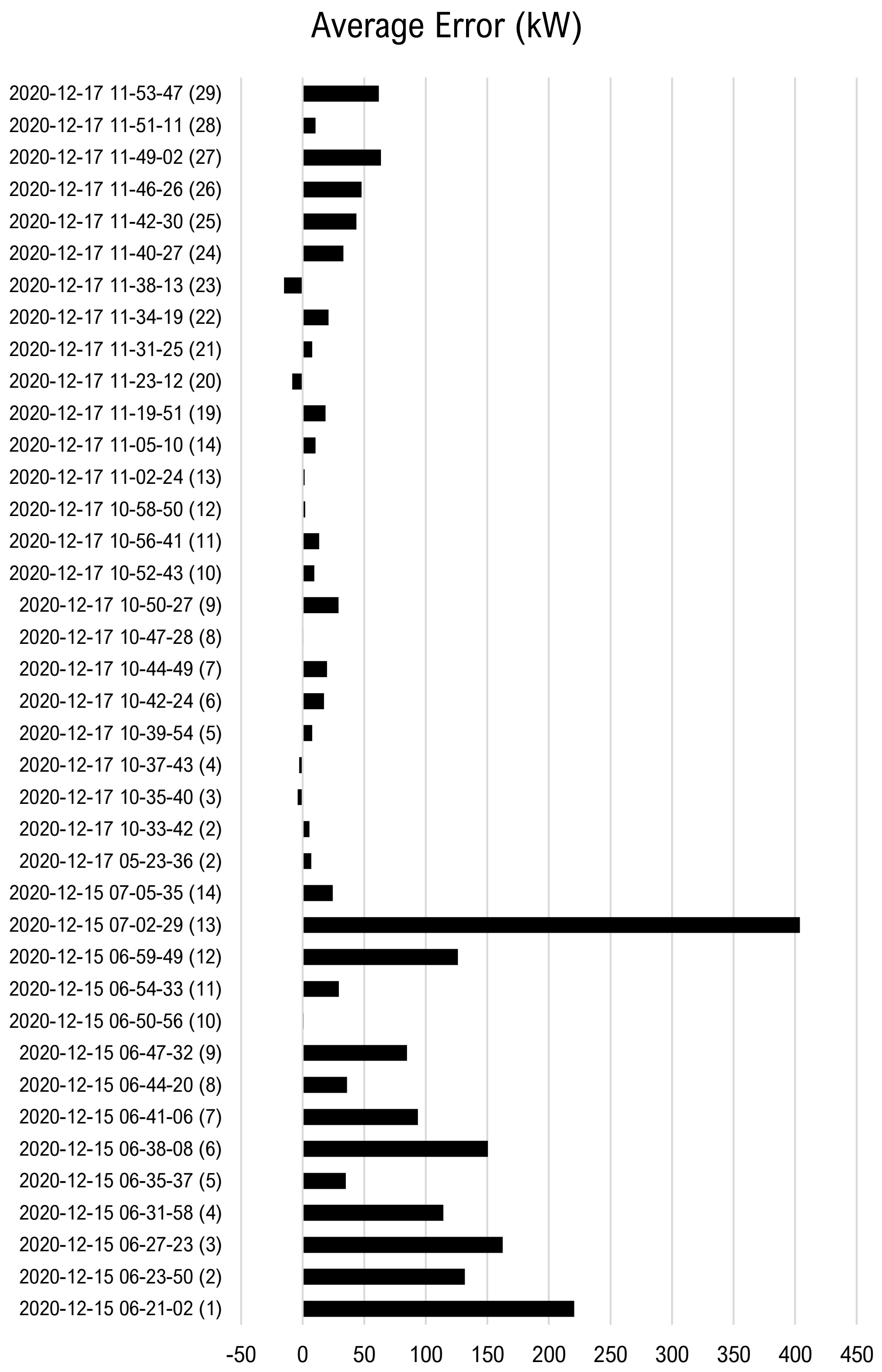


Figure 24: Power-frequency response - Mean error. Axis values are data file names.

3.3. AUTOMATIC GENERATION CONTROL

AGC testing was performed in April 2021 during a period of sufficiently high winds allowing for operation near farm rated power. The test was run on a live power system with AGC dispatch coming from the system operator. The AGC target was calculated based on the

Area Control Error (ACE). A total of forty five minutes of data was gathered and the available power from the wind farm remained between 40 and 45 MW for the duration of the test.

Result data is shown in Figure 25. The shaded region is the possible regulation region. The upper limit of this region is determined by the available power in the wind i.e., the maximum possible generation value from the wind farm. The lower limit of the regulation region is the upper limit less the regulation range. Three values of regulation range were tested – 20 MW, 30 MW and 35 MW. The changes in the lower limit in Figure 25 correspond to changes in the regulation range. The wind farm's power follows changes in the lower regulation limit. The ACE signal is not shown here for the sake of clarity.

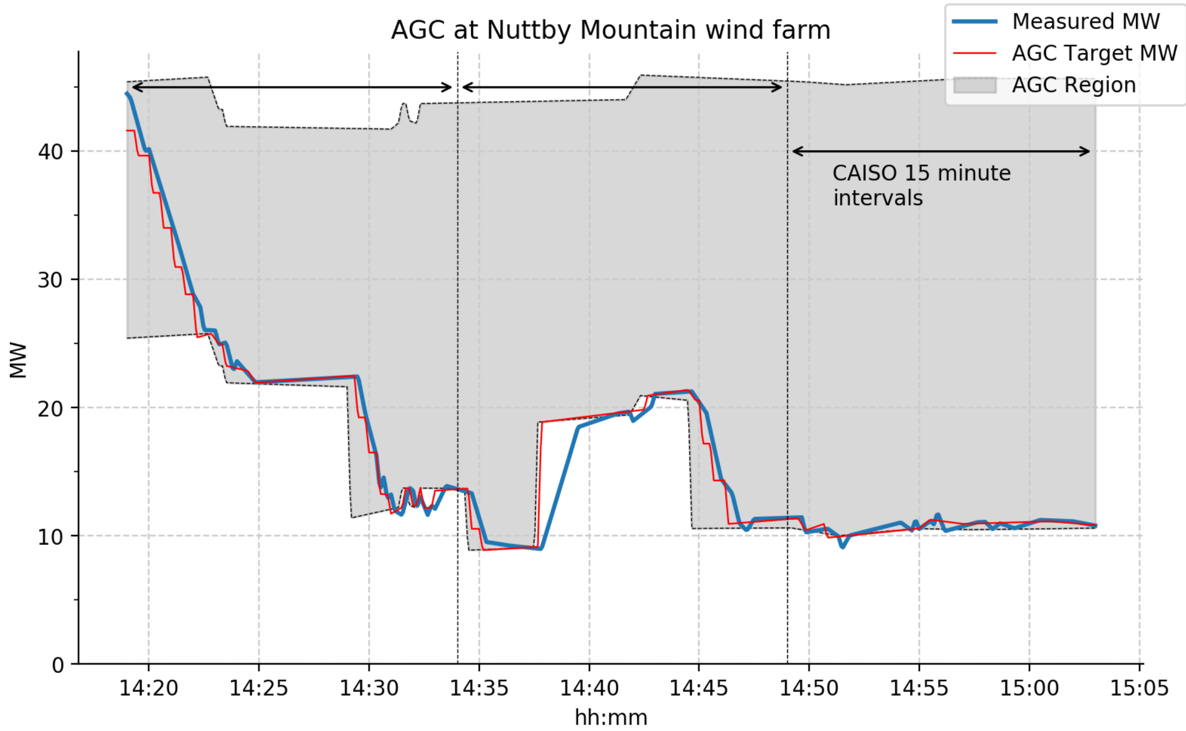


Figure 25: AGC at Nuttby Mountain wind farm. Shaded region is the allowed regulation region and vertical lines represent AGC score calculation intervals used in the CAISO calculations.

Performance can be measured by mean error or by various regulation performance metrics developed by ISOs. Examples include scoring metrics from PJM (Pennsylvania-Jersey-Maryland), CAISO (California), MISO (Midcontinent ISO), NRC in Canada, among others. As a basic metric, the absolute mean error across the test duration was 0.12 MW between the AGC power target and the measured value. This can be confirmed visually in Figure 25. Note that the entire dataset here is in a situation where prevailing wind speeds are well above the target AGC power levels. As such, this data proves that a full-converter wind turbine (IEC Type 4) is able to accurately curtail power output.

For simplicity, only the CAISO and MISO performance scores are reported below. The calculation methods are sourced from [6]. CAISO performance scores are calculated for 15-minute intervals and the test data has three such intervals. The three intervals are marked in Figure 25. The CAISO performance score for the overall data is around 99% and is to be expected as the error between target and measured power is small, around 0.2% of rated farm power. This is in line with data from the Tule wind farm [7] that reported an AGC error of around 2% of rated power. The difference can be explained by the limited data presented here and the fact that available power was significantly higher than target power.

The MISO method [6] calculates a performance score for 5-minute intervals however, due to the nature of data here, scores greater than 100% are sometimes reported. This is due to the limited movement of the regulation signal over five minute intervals. To avoid this, we report a MISO performance score for the entire 45 minute dataset.

Table 4: Summary of AGC performance scores. Refer to Figure 25 for various time regions.

Scoring Method	Time region	Performance Score (%)
CAISO Performance score	Interval 1 (15 minutes)	97.8
CAISO Performance score	Interval 2 (15 minutes)	97.1
CAISO Performance score	Interval 3 (15 minutes)	99.9
MISO Performance score	Overall (45 minutes)	87.9

Observe from Table 4 that the performance scores are good i.e., better than most conventional generators. The authors are unable to draw conclusions based on limited data however past experience and related works such as [7] and [8] indicate that a high performance score is expected. For comparison, CAISO regulation performance scores [7] are shown in Figure 26. This shows that CAISO regulation performance scores of > 90% are expected with full-converter technology such as in a solar PV farm and a Type 4 wind turbine.

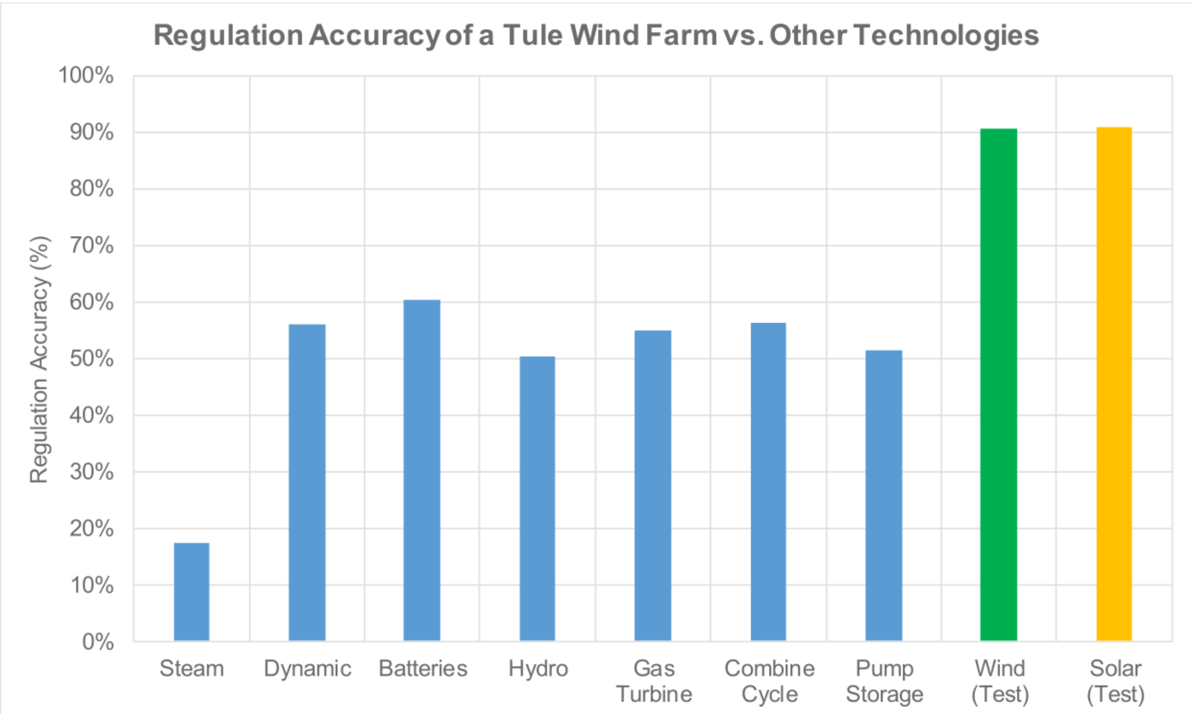


Figure 26: Examples of CAISO regulation performance scores from different generation technologies. Source: Figure 18 in [7]

4. Conclusions

The responses from fast-frequency and power-frequency are largely as expected. Fast-frequency response is able to deliver active power for a fixed duration via extracted energy from the wind turbine rotors. The magnitude of boost power is found to be independent of the prevailing wind farm power level. Rise times and response durations were as expected although the remainder of the response depends on wind speed and the wind speed trend.

Power-frequency response was found to operate as expected with an average error between the calculated and measured responses of 50 kW.

AGC was found to track an external power target accurately with a mean error magnitude of 120 kW or around 0.2% of rated farm power. Performance scores of >90% were calculated and are in line with similar work however due to the limited data available, more examination is required.

NSPI Comment - NSPI found the wind farm very responsive on AGC. NSPI's AGC calculates its own Performance Factor (PF, calculated as MW response / MW requested) and Nuttby's PF was 1.09. Values between 0.3 and 0.6 are typical for NSPI's traditional steam and hydro units. All these values line up well with the performance scores calculated by WEICan.

While ACE was predominantly sending the wind farm in the downward direction, NSPI did manage, with some manipulation of the Low Regulating Limit, to get AGC to send about half as many raise pulses as it did lowers. We feel this gave us a good representation of performance in both directions.

In conclusion, we felt the test was a great success and that using a wind farm as a regulating resource definitely seems feasible. NSPI's next step is to continue testing to determine under what scenarios we can best utilize it.

Overall, NSPI is pleased with the results and the potential this pilot has revealed. These enhancements move us much farther ahead in our ability to respond to certain system impacting events. NSPI is currently reviewing opportunities to leverage this new technology to expand development of these ancillary services.

5. References

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[6] A. Sadeghi-Mobarakeh and H. Mohsenian-Rad, "Performance accuracy scores in CAISO and MISO regulation markets: A comparison based on real data and mathematical analysis," *IEEE Transactions on Power Systems ,* vol. 33, no. 3, pp. 3096-3098, 2018.

[7] California ISO, Avangrid Renewables, GE, NREL, "Avangrid Renewables Tule Wind Farm - Demonstration of Capability to Provide Essential Grid Services," California ISO, March 11 2020.

[8] E. Rebello, D. Watson and M. Rodgers, "Performance analysis of a 10 MW wind farm in providing secondary frequency regulation: Experimental aspects," *IEEE Transactions on Power Systems,* vol. 34, no. 4, pp. 3090 - 3097, 2019.

6. ATTACHMENTS

1. Fast frequency response calculation summary spreadsheet- Calculation results Fast frequency response 20210210-155049
2. Fast frequency response plots - Nuttby_fast_freq_20210210-155049
3. Power-frequency response plots - Power Frequency_20210203-111359
4. Power-frequency response – Calculation summary spreadsheet - Calculation results Power Frequency 20210201-124440