Final Report

Demonstrating the Value of Wind Farm Inertial Response Functionalities to the Alberta Transmission System

ENERCON

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Executive Summary

Globally, there is a transition underway to shift towards more renewable forms of electricity generation. In 2018, the Canadian government announced regulations to phase-out traditional coal-fired electricity by 2030 as well as greenhouse gas regulations for natural gas-fired electricity.

With this shift away from fossil fuel powered generation come challenges for the Alberta electric network. One of these challenges is the reduction of traditional frequency response functionalities that are currently provided by conventional power plants in the province. This can have a negative impact on the ability of the power system to overcome the immediate imbalance between power supply and demand. As a result, a severe grid fault might translate into the frequency dropping so fast and to such low levels that connected loads and generation cannot tolerate it anymore. The risk of power system outages increases significantly. Part of the solution could be to use the Inertia Emulation capability of modern Wind Turbines. Inertia Emulation allows Wind Turbines to respond to a drop in grid frequency by temporarily increasing their active power output by extracting energy stored in the rotating masses.

A prominent example for a market that is already going through a transition as described above is Ireland. The local government is following ambitious targets for greenhouse gas emission reductions. Based on the goal of achieving generation of 40% of electricity annually from renewables by 2020, the relevant grid operators EirGrid and SONI have identified, amongst others, the need for additional frequency response functionalities. The solution to this challenge is a technology agnostic system services market that will allow all kinds of generators, including wind farms, to offer inertial response against an availability based remuneration. EirGrid has completed a trial process and as an outcome thereof WTs with IE enabled can now receive contracts to provide system services which will allow WF operators to create additional revenue streams on top of the existing remuneration per kWh produced. Hence, important technical challenges can be overcome in a cost-effective manner by procuring services from existing assets.

As Inertia Emulation from Wind Turbines is a relatively new technology, most system operators do not have access to realistic and reliable data from manufacturers about the performance of such features. Therefore, ENERCON partnered with Alberta Innovates to demonstrate the Inertia Emulation capability of ENERCON’s Wind Turbines at the ENMAX Taber wind farm. The Alberta Electric System Operator, as well as the wind farm owner, ENMAX, were also partners on the project. The two main objectives of the demonstration were:

1. Enabling the exchange of knowledge between Alberta Electric System Operator, ENERCON and ENMAX technical staff with the goal to optimize grid integration of wind power in the province of Alberta;
2. Educate the Alberta renewables industry about frequency response capabilities of modern Wind Turbines to demonstrate that an energy transition in the province does not impose a risk for a stable and reliable supply of electricity to Albertans.

The Taber wind farm has been in operation for more than ten years and some hardware as well as software retrofits were necessary to enable the Wind Turbines to be ready to provide Inertia Emulation. Based on ENERCON’s experience with deploying Inertia Emulation in other markets and with the collaboration with the Alberta Electric System Operator, eight different test scenarios were defined to investigate the performance of Inertia Emulation during active power activation and recovery.

Final results demonstrate that provision of Inertia Emulation from existing Wind Turbines is possible. All performance criterion with regards to Inertia Emulation behavior, Wind Turbine retrofit as well as impact on annual yield were met. Solutions like these can provide the Alberta Electric System Operator additional tools to manage the grid as Alberta shifts to increased renewable and variable generation. Unlocking the enhanced system services that can be provided by wind farms through technologies like this, yield several benefits for the Alberta market.

For developers, owners and operators of wind farms:

- The overall share of renewables can be increased which will lead to more project opportunities
- In case of an ancillary service market additional revenue streams can be accessed which will support the trend of falling energy prices (kWh)

For the Alberta Electric System Operator:

- Cost competitive provision of reliability services without need for installation / connection of additional assets
- Opportunity to introduce performance based ancillary service market where remuneration depends on quality of provided functionality

In conclusion, it is recommended that the Alberta Electric System Operator works on quantifying the technical and commercial benefit that Inertia Emulation can provide to its electrical system and to explore the possibility of enabling wind farms operators to derive additional value from their assets by providing frequency response to the grid through the ancillary service market.

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1 Introduction

Globally, there is a transition underway to shift towards more renewable forms of electricity generation. In 2018, the Canadian government announced regulations to phase-out traditional coal-fired electricity by 2030 as well as greenhouse gas regulations for natural gas-fired electricity. In Alberta, this could result in about 5000 MW of additionally installed renewable energy, most of it being wind power. With this shift away from fossil fuel-powered generation come challenges for the Alberta electric network. One of these challenges is the reduction of inherent inertia in the system.

The frequency within a power system will immediately fall upon a contingency event such as a major loss of generation. A very fast increase in power output from generating resources is required to stop the fall and stabilize the frequency [1]. An indication for an electric network's capability to restore the frequency to its nominal value after such a contingency event is the inertia constant. Power systems need a minimum inertia constant for safe and reliable operation.

The inherent inertia constant of Wind Turbines (WTs) is zero, which is one of the reasons why system operators limit wind penetration in their network to a certain percentage of total generation. However, this is neglecting the fact WTs can be equipped with advanced controls allowing them to respond to a drop in grid frequency by temporarily increasing their active power beyond the available power from the wind [2]. ENERCON offers this functionality as Inertia Emulation (IE).

Understanding current capabilities and limitations of modern WTs is essential for the Alberta Electric System Operator (AESO) in order to be able to perform proper system planning. This is especially true when anticipating major changes in the generation portfolio and when facing new challenges such as a significant reduction of inherent inertia in the electrical system. However, it is usually difficult to obtain realistic and reliable data from component manufacturers about their products. This increases uncertainty in system planning studies which can result in technical and financial risks.

ENERCON has partnered with Alberta Innovates (AI) to prove out and demonstrate the second generation of ENERCON's Inertia Emulation controls at ENMAX's Taber Wind Farm (WF). The two main reasons for seeking AI's support are to allow the proposed demonstration to be executed in the province of Alberta and to facilitate the involvement of AESO. This enables gaining and building up knowledge locally in the province which is instrumental for developing solutions specific to the province's electric network.

The main role for AI in the project was to ensure that the outcomes of the demonstration support the current climate change strategy in the best way possible from a technical and public perception perspective.

The remainder of this report is structured as follows:

- Chapter 2 puts the topic of inertial response from WTs into context of international grid connection requirements and discusses the current status of ENERCON's IE technology;
- Chapter 3 introduces basic information about the Taber WF
- Chapter 4 provides an overview about activities related to planning and preparing the demonstration such as definition of the measurement setup, the test scenarios as well as the WT parameter settings used
- Chapter 5 summarizes the executed activities on site and explains testing conditions
- Chapter 6 presents measurement results and assesses them based on predefined technical performance criteria
- Chapter 7 and Chapter 8 discuss learnings from the demonstration and the resulting proposal for additional work

2 International Context for Inertial Response from Wind Turbines

The present chapter puts the topic of inertial response from WTs into context of international grid connection requirements and discusses the current status of ENERCON's IE technology.

2.1 Existing Grid Connection Requirements

Requirements for WTs to provide IE functionalities exist in several jurisdictions today. The most prominent example is the province of Québec, where the grid codes and validation programs of both the distribution as well as the transmission system operators have been including IE sections since 2006 [3] – [6]. As a result, more than 2000 MW of WTs that are currently in commercial operation in Québec respond to large, short-duration under-frequency conditions in the grid with an increase in their active power output. The Independent Electric System Operator (IESO) in the Canadian province of Ontario followed Hydro-Québec's lead by mentioning speed / frequency regulation requirements for WFs with an installed capacity greater than 50 MW in their Market Rules [7] – [8]. SaskPower, the system operator in Saskatchewan, is also requesting for upcoming wind farms to be equipped with the IE functionality. Other examples for existing or anticipated future requirements are Brazil and Europe, where the European Requirements for all Generators (RfG) allow Power System Operators to require IE from WFs [9].

The above examples show that several system operators have identified the need for new providers of IE based on the retirement of conventional power plants and the resulting reduction of inherent physical response from classical synchronous generators. Inverters are capable of responding in a timely fashion if their controls are designed appropriately. As such, all inverter-based power generation units are capable of IE. WTs in particular are very favorable for this application, since they contain a substantial amount of energy stored in their blades, generator and drive train. This typically amounts to several rated power seconds of energy, depending on the operating point.

In addition to ENERCON, some other major manufacturers such as GE and Senvion offer IE functionalities for their wind turbines today [10] – [11]. The basic concept of the functionalities is similar. The WTs include controls that detect under frequency conditions in the electric network and trigger an increase in active power above the available power from the wind for an adjustable time period. However, differences exist between the actual implementation of the controls, the trigger conditions, the shape and duration of the active power response as well as the levels of freedom for parameterizing the controls.

ENERCON WTs can provide a significant amount of energy for IE without the need for dedicated storage, and without significant wear and tear. With the latest version of the controls, they also provide a configurable and very power system-friendly way of reaccelerating the WT rotor following the power increase phase.

Therefore, integrating WTs into the overall frequency control scheme represents an opportunity for using existing and future assets more efficiently. The need for additional frequency control equipment can be deferred, limited or even avoided. Furthermore, the electrical behavior of modern WTs largely depends on control algorithms, rather than on the inherent physical characteristics of e.g. a generator. Hence, the exact frequency response features of WTs in terms of speed, duration and magnitude could be adapted relatively easily to the specific needs of an electric network.

The competitiveness and reliability of response from IE provided by WTs compared to other technologies has been demonstrated in Ireland through a trial coordinated by the Transmission System Operator from March 1st to August 31st 2017. The Irish electricity system operators EirGrid and SONI have identified the need for additional inertia in their system based on the goal of generating 40% of electricity annually from renewable sources by 2020. This translates into instantaneous wind penetration levels of up to 75%. To achieve this, they are currently introducing a technology agnostic ancillary service market for Fast Frequency Response (FFR) instead of adding mandatory requirements to their grid code. FFR is defined as an active power rise in the event of a sudden power imbalance. EirGrid has completed the trial process and released a paper on their Outcomes and Learnings [12] which has been followed by a paper on System Services Contracts procurement process [13]. As an outcome from the trial process, WTs with IE enabled can now receive contracts to provide both FFR and Primary Operating Reserve (POR) with a total IE response time of 15 seconds. This will allow WF operators to create additional revenue streams on top of the existing remuneration per kWh produced.

2.2 Status of the Proposed Technology

ENERCON has been offering IE functionalities for its WTs for more than five years. Originally, the ENERCON Inertia Emulation feature was developed in response to Hydro-Québec TransÉnergie's grid code requirements. Today, more than 1000 MW of ENERCON WTs are equipped with the IE and are in commercial operation in the province of Québec.

ENERCON IE is implemented using a control system that responds to a drop in grid frequency by temporarily increasing active power beyond the available power from the wind. The energy for this power increase is drawn from the inertial power of the rotating masses of the WT such as the annular generator, the rotor hub and the blades. The system frequency is constantly measured by the ENERCON WT control system. A value of the system frequency below a certain threshold or trigger level $f_{inertia,trigger}$ is indicative of a contingency event on the electrical network like the loss of a large generation unit. IE reacts to a frequency $f < f_{inertia,trigger}$ by commanding a pre-defined power increase for the period $t_{inertia,max}$.

Figure 1 shows the idealized IE response to an under-frequency event with $f_{inertia,trigger}$ set to 59.7Hz and $t_{inertia,max}$ set to 10s.

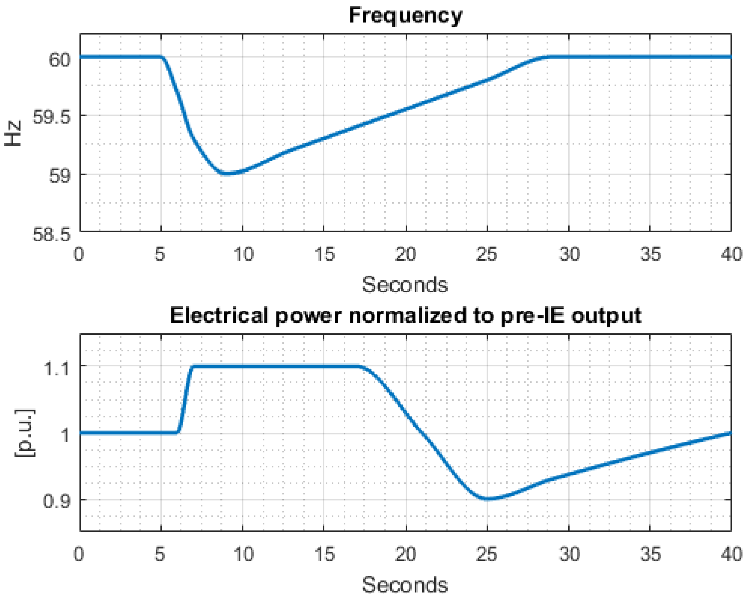


Figure 1, idealized IE response to an under-frequency event

Since commissioning of ENERCON's first project in Québec in 2012, measurement data of real network events has been collected and analyzed. Results have shown that the IE fulfills the Hydro-

Québec grid code. The first generation of the ENERCON IE controls emphasizes a fast return of the WTs rotational speed to the optimum value during the recovery period. As a side effect, this results in significant power output reductions during the recovery phase. From a power system's perspective, this could be interpreted as an additional disturbance affecting the system several seconds after an initial severe contingency. Therefore, ENERCON has developed a second generation of the IE with an improved recovery period and the controls are in a pre-commercial stage. Figure 2 shows simulation results comparing the performances of the first generation IE controls (blue) to the second generation (green) for varying wind speed conditions. The black dashed line shows the simulated active power without IE.

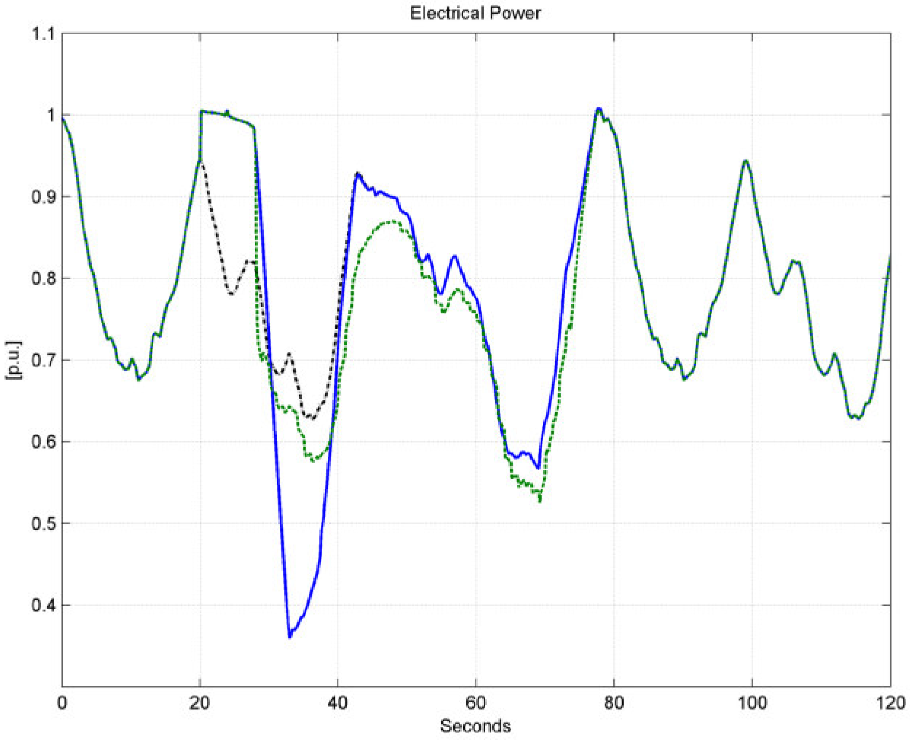


Figure 2, simulation results comparing first generation (blue) to second generation (green) IE controls and to performance without IE controls (black)

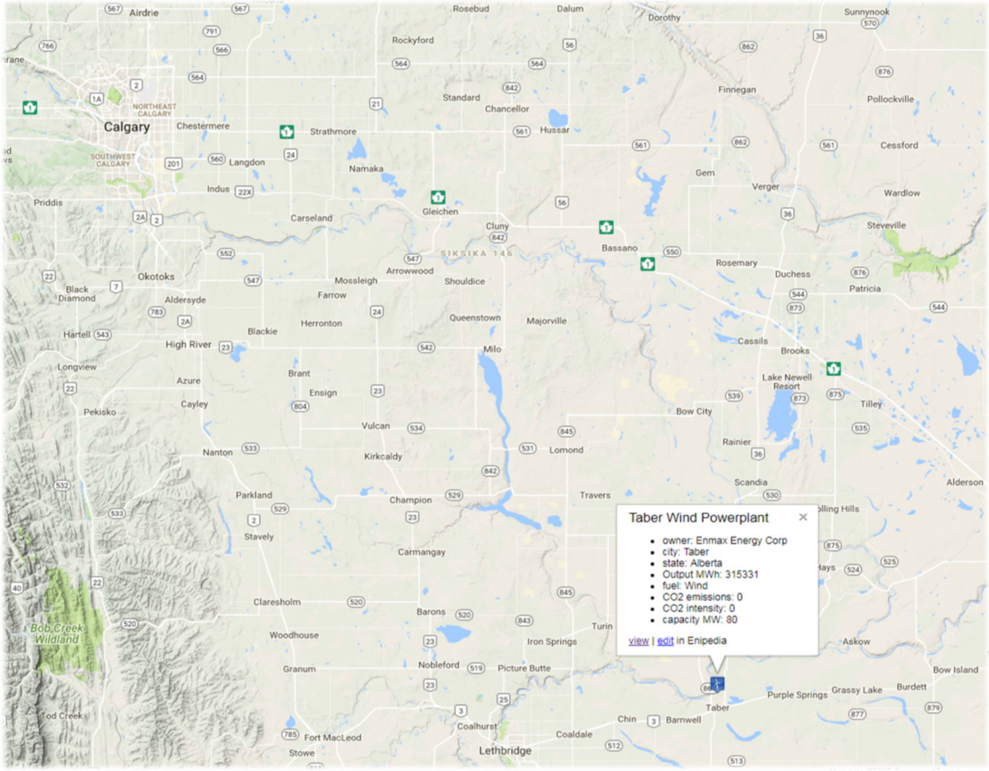
3 Test Wind Farm Information

Table 1 shows basic information about the WF.

Table 1, basic project information

Parameter	Value
Project name	Taber
Country, province	Canada, Alberta
Project operator	ENMAX Generation Portfolio Inc.
ENERCON project number	W-02534
Number of Wind Turbines	37
Wind Turbine model	ENERCON E-70 E4
Wind Turbine nominal active power	2200kW
Collector system voltage	25kV
Voltage level at Point of Connection	138kV

Figure 3 shows where the wind farm project is located in Alberta.



Taber Wind Powerplant

- owner: Enmax Energy Corp
- city: Taber
- state: Alberta
- Output MWh: 315331
- fuel: Wind
- CO2 emissions: 0
- CO2 intensity: 0
- capacity MW: 80

view | edit in Enipedia

Figure 3, approximate location of the Taber Wind Farm[1]

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[1] http://enipedia.tudelft.nl/maps/PowerPlants.html?enipedia_country=Canada

4 Planning and Preparation of the Demonstration

The present chapter provides an overview about activities related to the planning and preparation of the demonstration such as information on the measurement setup, the test scenarios as well as the WT parameter settings used.

4.1 General Measurement Setup

Two measurement systems were used for the demonstration.

1. A WF measurement system connected to 138kV High Voltage (HV) Voltage Transformers (VT) and Current Transformers (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. A measurement system connected to 400V Low Voltage (LV) CT and voltage connection in the WT number 36 to measure the total instantaneous values of the three phase-to-earth voltage signals and the instantaneous values of the three phase currents.

Furthermore, additional signals such as the wind speed measured by the WT 36 were recorded. All raw data were analyzed, stored and processed by an ENERCON measurement computer. Figure 4 shows a simplified overview of the above described setup including the imc iMEAX measurement devices that are specified in more detail in section **Error! Reference source not found.**.

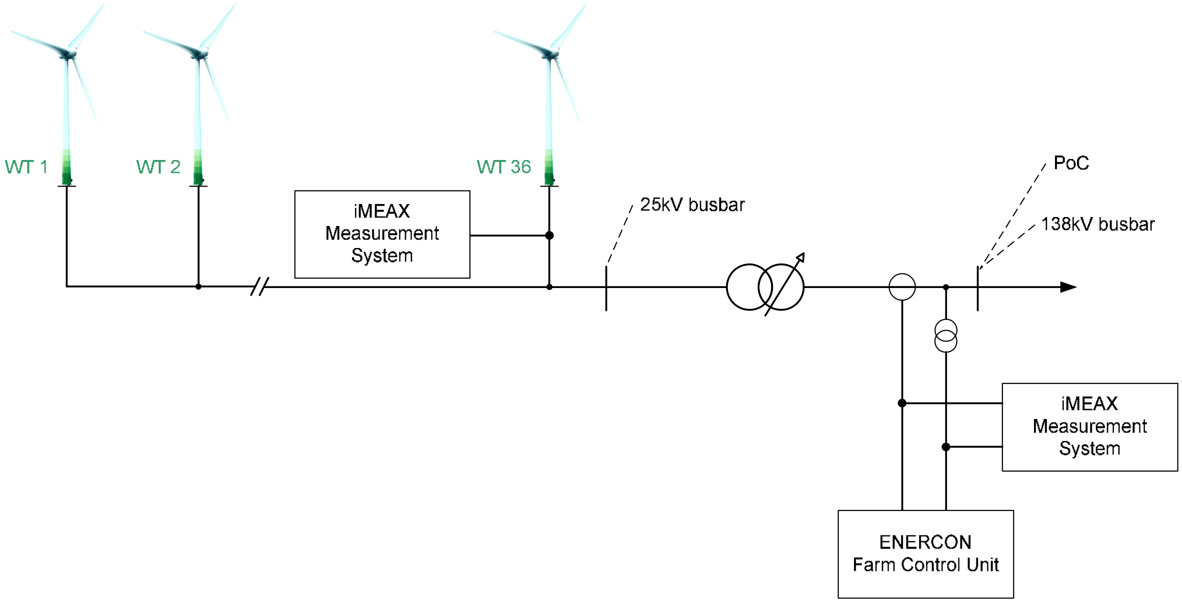

Figure 4, simplified overview of the measurement setup

4.1.1 Recorded Signals

Table 2 shows the voltage and current signals that were recorded during the demonstration as well as their sampling rate.

Table 2, recorded voltage and current signals

Signal	Reference	Signal Description	Unit
I_{1_FCU}	PoC, 138kV	Instantaneous line current, phase 1	A
I_{2_FCU}	PoC, 138kV	Instantaneous line current, phase 2	A
I_{3_FCU}	PoC, 138kV	Instantaneous line current, phase 3	A
V_{1_FCU}	PoC, 138kV	Instantaneous line to ground voltage, phase 1	kV
V_{2_FCU}	PoC, 138kV	Instantaneous line to ground voltage, phase 2	kV
V_{3_FCU}	PoC, 138kV	Instantaneous line to ground voltage, phase 3	kV
$I_{1\_WT\_36}$	WT 36, 400V	Instantaneous line current, phase 1	A
$I_{2\_WT\_36}$	WT 36, 400V	Instantaneous line current, phase 2	A
$I_{3\_WT\_36}$	WT 36, 400V	Instantaneous line current, phase 3	A
$V_{1\_WT\_36}$	WT 36, 400V	Instantaneous line to ground voltage, phase 1	V
$V_{2\_WT\_36}$	WT 36, 400V	Instantaneous line to ground voltage, phase 2	V
$V_{3\_WT\_36}$	WT 36, 400V	Instantaneous line to ground voltage, phase 3	V

4.2 Test Program

The most significant frequency disturbances that occur in Alberta result from unplanned outage of the interties when pre-event interchange is high. Therefore, the signal used to test WT frequency response was generated by performing a transient simulation of an intertie outage. The simulation output was scaled to represent an event of unusually large magnitude so the WT would have their maximum response. The model was validated by simulating events that occurred in the real system and comparing the results with recorded data. The model was adjusted by blocking governors, for example until its behavior was similar to that of the real system. Figure 5 shows the artificial frequency signal injected into the WT control systems during the tests to trigger IE. It should be noted that only the first 90 seconds are of relevance. The last 30 seconds consist of an arbitrary recovery that could be modified for testing purposes.

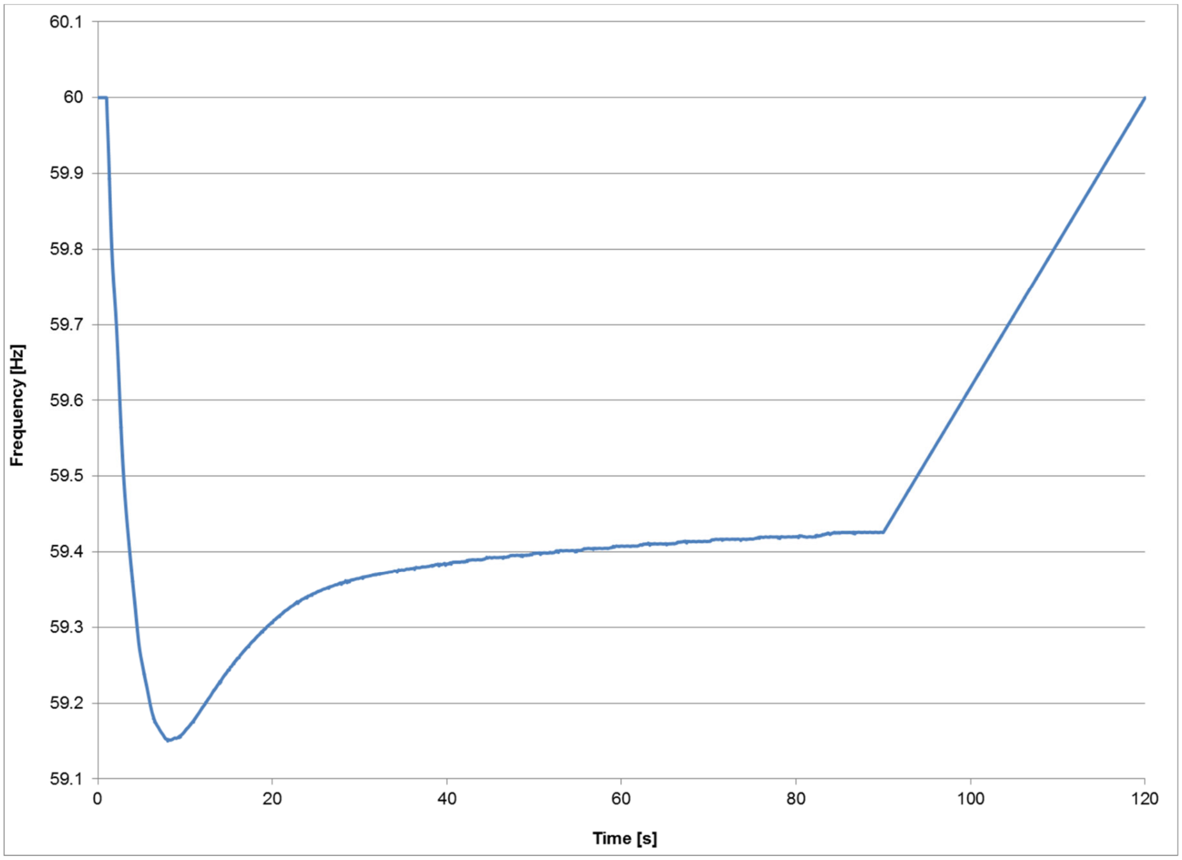

Figure 5, simulated frequency signal used during the tests

ENERCON's experience with previous on-site testing of IE shows that the overall characteristic of the WF active power response depends on many factors such as the parameter setting and wind conditions. In order to demonstrate the impact of the active power output level prior to activation of the IE as well as the duration of the recovery period, ENERCON and AESO agreed on in total eight test scenarios. They consisted in applying the above frequency curve at four operating points for two different settings of the IE parameter *Inertia Torque Recovery*. Table 3 shows an overview of the tests performed for the demonstration.

Table 3, overview of the test scenarios performed

#	**WF active power [p.u.]**	**Inertia Torque Recovery [s]**
1	0.1 - 0.4	40
2	0.1 - 0.4	80
3	0.4 - 0.7	40
4	0.4 - 0.7	80
5	0.7 – 0.95	40
6	0.7 - 0.95	80
7	>0.95	40
8	>0.95	80

Prior to executing the above shown demonstration, ENERCON, ENMAX and the AESO agreed on a detailed procedure to be followed during the tests. This included, but was not limited to, communications between ENERCON testing staff, ENMAX site manager and AESO system operations.

4.3 Wind Turbine Parameter Settings

All parameters that can be adjusted for the IE, including their setting ranges, are described in the IE Technical Description [14].

4.3.1 AESO Simulations

The AESO has investigated the impact of inertial response from WTs on the system frequency following a supply and demand disturbance in the system based on dynamic simulations in power system modeling software PSS/E. One of the main objectives of the study was to determine whether the wind farm technical requirements [15] should be amended to require synthetic inertia. The following preferences in terms of a desired IE characteristic can be found in the report [16]:

"*Considering the practical limitations of inertia emulation and the system frequency response that is typically observed today, the targeted aggregate response is the contribution of a fixed amount of power for 10 seconds immediately after an under frequency event, followed by withdrawal of a fixed amount of power for the next 1 minute, with an equal amount of energy contributed and withdrawn. Settings should be coordinated so that the actual aggregate response matches the targeted response reasonably closely.*"

The above was taken into consideration for the parameter setting as per section 4.3.7, especially for the *inertia control mode*, *max. Inertia time*, *inertia recovery mode* and *inertia torque recovery*.

4.3.2 Parameter Setting Overview

Table 4 shows the IE parameter settings used during the demonstration. Those values are based on the AESO's preferences in terms of desired IE characteristics on the one hand and on ENERCON's experiences with IE in Québec on the other hand [17].

The *inertia torque recovery* parameter was altered during the demonstration in order to identify the optimal setting for the Alberta transmission system. It is important to note that the objective was to achieve 4.8% of additional active power at the PoC. In order to compensate for active power losses in the collector system between the WECs and the PoC the parameter *Inertia factor* was set to 6%.

Table 4, IE settings used for the demonstration

Parameter	Internal Reference Number	Unit	Value
Inertia control mode	1051	Text	constant
Inertia trigger frequency	1052	Hz	59.8
Inertia min. frequency	1053	Hz	59.2
Inertia factor	1054	%	6
Max. inertia time	1055	s	10
Inertia recovery time	1056	s	N/A
Inertia return frequency	1057	Hz	59.9
Inertia boost	1058	%	0
Inertia factor base	1060	-	00
Inertia recovery mode	1061	-	01
Inertia torque recovery	1062	s	40 and 80
Inertia recovery delay	1063	s	0
Inertia hold constant	1064	-	00

5 Summary of the Activities Executed on Site

Table 5 shows a high-level overview of the activities performed prior and during the demonstration.

Table 5, summary of on-site activities

Date	Activity
12 October 2017	Preparation of measurement equipment for shipping from ENERCON's warehouse in Boucherville, Québec
13 October 2017	Installation of measurement devices in WT 36 and at the ENERCON Farm Control Unit (FCU)
16 October 2017	Commissioning of measurement systems including quality insurance checks
17 October 2017	Retrofit of the FCU and update of the WT's software
18 October 2017	34 IE tests with 80 s recovery time (8-74 MW), 34 of 37 WTs in service. Change of recovery time to 40 s
19 October 2017	19 IE tests with 40 s recovery time (16-34 MW), 34 of 37 WTs in service
20 October 2017	Measurement device in WT 36 damaged, transmission system faults prevented further IE testing
23 October 2017	Installation of a new measurement device in WT 36. Two IE tests performed with 40 s recovery time (< 7MW), 34 of 37 WTs in service
24 October 2017	2 out of 4 feeders tripped. 19 of 37 WTs in service, tests temporarily stopped by ENMAX
25 October 2017	3 IE tests with 40 s recovery time (38 MW), 18 of 37 WTs in service, P set point > P_available 1 IE test with 40 s recovery time (32 MW), 15 of 37 WTs in service, P set point > P_available (3 WTs stopped) 11 IE tests with 40 s recovery time (20-32 MW), 16 of 37 WTs in service, P set point > P_available (2 WTs stopped)
26 October 2017	Revert the FCU to the conditions found before the test.

5.1 Force Majeure Events

The following events occurred during the project which delayed or affected the execution of the planned tests.

- Lost data communication to WT 33, 34 and 35 due to a fiber optic cable cut by the WT's transformer fan
- Lost feeders due to an equipment problem at the substation
- Grid events on the AESO electric systems hindered the work
- Wind conditions varied during the test
- Curtailment orders received from AESO required the tests to be performed with fewer WTs

6 Assessment of Results

The results of the demonstration were assessed on the following technical metrics:

- Behaviour of Inertia Emulation
  - Response delay of active power increase after detection of under frequency
  - Duration of additional active power contribution
  - Amplitude of additional active power contribution
  - Maximum subsequent active power drop below pre-disturbance level
- WT retrofit
  - Time for implementation
  - Impact of implementation on annual availability
- Impact of IE activation on annual yield

6.1 Behaviour Of Inertia Emulation

Based on the proposed WT parameter settings, the frequency curve provided by the AESO and the above described test scenarios, the expected outcome of the demonstration was to see on average the following behavior of Inertia Emulation:

- Response delay of active power increase after detection of under frequency of less than 1s;
- Amplitude of additional active power contribution of 4.8% of the nominal power;
- Duration of additional active power contribution of 10s;
- Maximum subsequent active power drop of less than 25% of the nominal power;

Table 6 shows an overview of how the tests were distributed amongst the eight originally defined scenarios. It should be noted that the assessment of the results is normalized based on the respective maximum available active power at the time of the test. For example, if 18 WTs were online, the results will be based on 39.6MW versus 81.4MW if all 37 WTs were online.

Table 6, overview of the tests executed

#	WF active power [p.u.]	Inertia torque recovery [s]	WTs online	Number of tests executed
1	0.1 - 0.4	40	34	12
2	0.1 - 0.4	80	34	12
3	0.4 - 0.7	40	34	7
4	0.4 - 0.7	80	34	7
5	0.7 – 0.95	40	16	3
6	0.7 – 0.95	80	34	3
7	>0.95	40	15 16 18	1 8 3
8	>0.95	80	34	12
			TOTAL	**64**

The results of the measurements have been analyzed and divided into the original eight defined scenarios. The results of the IE tests measured at WF level are presented in Figure 6 to Figure 13 and show the average response of the different tests performed for each scenario. At the top of each figure the frequency curve is presented in blue to show the simulated frequency signal observed by the WT. This simulated frequency curve is identical for all test scenarios. The corresponding IE response P_FCU measured at the PoC is shown in red for each figure and depicts how the active power varies during the event, as a proportion of the rated power of the WF. For ease of visualization, the axis was adjusted so that the value of 0 pu represents the power of the WF at the time that the IE was triggered.

From these results, the following can be observed:

a) Response delay of active power increase after detection of under frequency of less than 1s

The response delay can be calculated from the time when the frequency drops below the trigger frequency of 59.8 Hz to the time when the active power increase is measured. It is important to understand that the active power increase provided is calculated dynamically according to the frequency observed. With the parameters used in these tests, the active power increase is expected to vary linearly between a 0% increase at the trigger frequency of 59.8 Hz and a 100% power increase at the minimum frequency of 59.2 Hz. From the results of all scenarios, it can be observed that the active power increase starts ramping up almost immediately when the frequency drops below 59.8 Hz, faster than the 1 second response expected. We can also see that the targeted power increase of 4.8% of rated power could be achieved by the time the frequency has dropped to 59.2 Hz, the value at which the maximum power increase is expected to be reached.

b) Amplitude of additional active power contribution of 4.8% of the nominal power

The goal of the demonstration was to observe a maximum additional active power increase of 4.8% of the WF rated power. According to the measurement results, we can conclude that this performance criterion was generally met. However we have learned that further improvements could be realized. For example

- The parameter defining the active power increase used for the test was set to 5% of the nominal power and hence 0.2% above the desired level. ENERCON will further investigate why it was still challenging for the WTs to achieve the prescribed power increase.
- It was observed for scenario 8 that the FCU, in its attempt to enforce a maximum power at the point of interconnection, can fight against the IE activation. Hence, forcing the WTs to reduce the active power production in the middle of the IE power increase. WF are required to respect curtailment orders and maximum power levels. As such, it will be important for system operators to decide if the inertia power increase should be allowed to go beyond these prescribed limits.

c) Duration of additional active power contribution of 10s

The duration of the active power increase during IE is calculated from the time when the trigger frequency of 59.8Hz is exceeded to the time when the active power increase subsides. It could be seen from the results of the different scenarios that an active power increase was still observed at the 10 seconds mark following the activation of the IE, therefore meeting the performance criterion. As discussed earlier, it was observed however that achieving the sustained full inertia increase was challenging for the WF and on this regards there could be room for further improvement.

d) Maximum subsequent active power drop of less than 25% of the nominal power

The demonstration tested the performance of the second generation ENERCON IE software. One of the main goals for the development of this software is to reduce the active power drop found during the recovery period of the IE event. On this regard, it could be clearly observed from the average results of all scenarios that the worst active power drop measured during recovery was less than 20%.

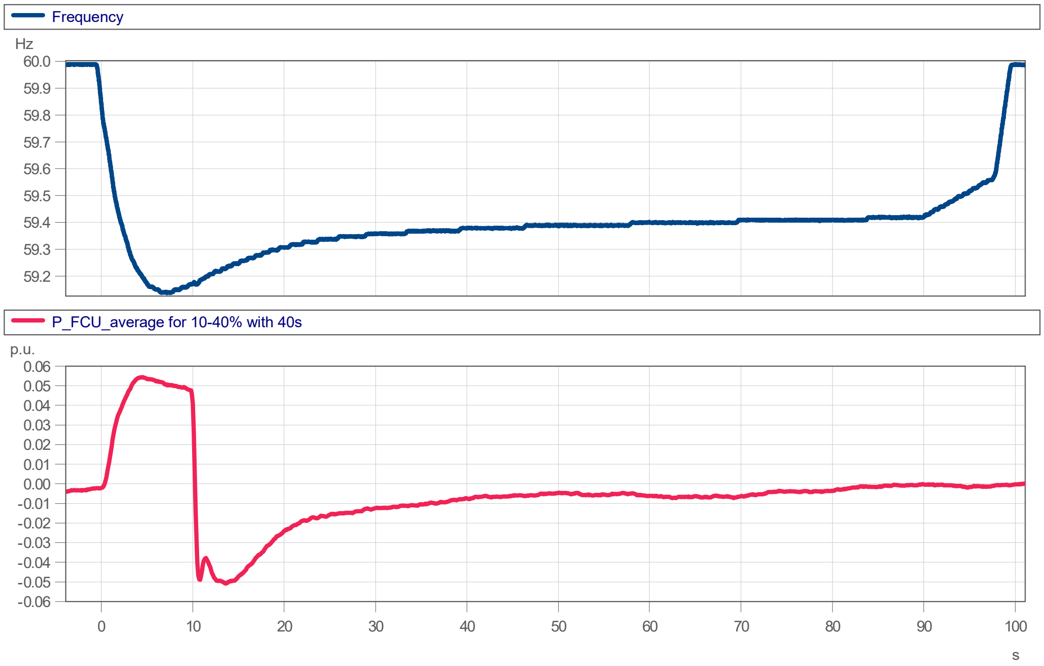

Figure 6, average measurement result for test scenario 1, 10-40% active power and recovery of 40 s

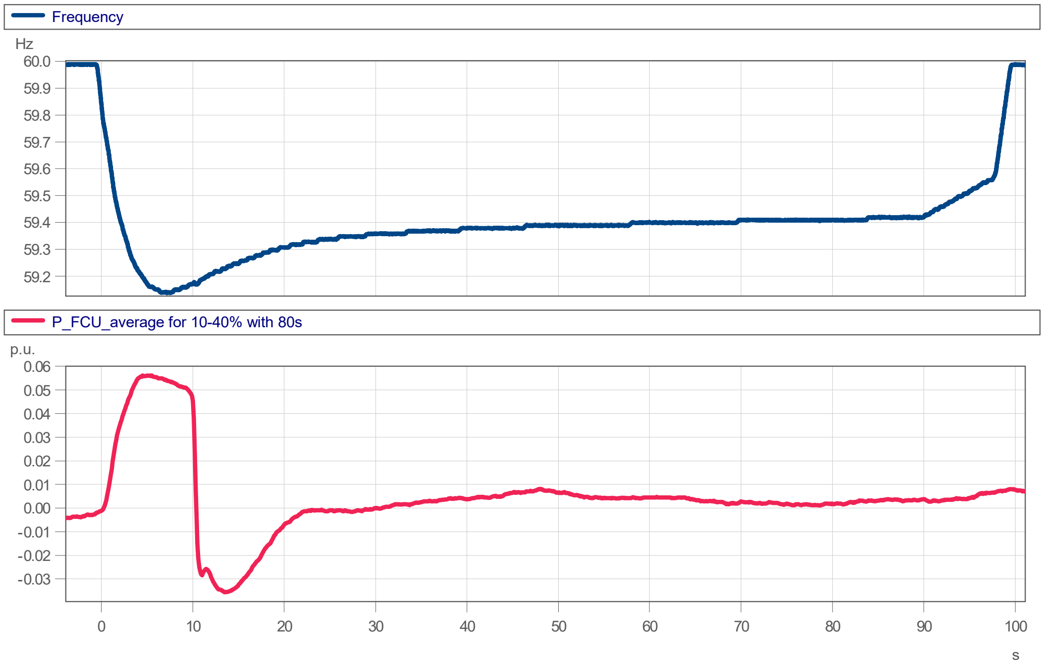

Figure 7, average measurement result for test scenario 2, 10-40% active power and recovery of 80 s

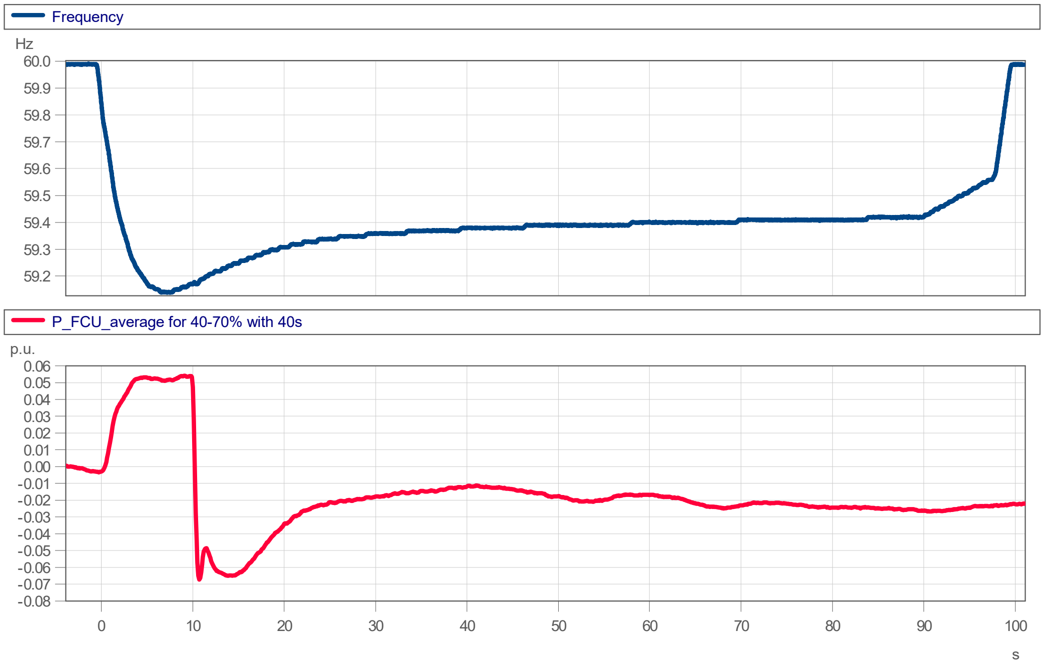

Figure 8, average measurement result for test scenario 3, 40-70% active power and recovery of 40 s

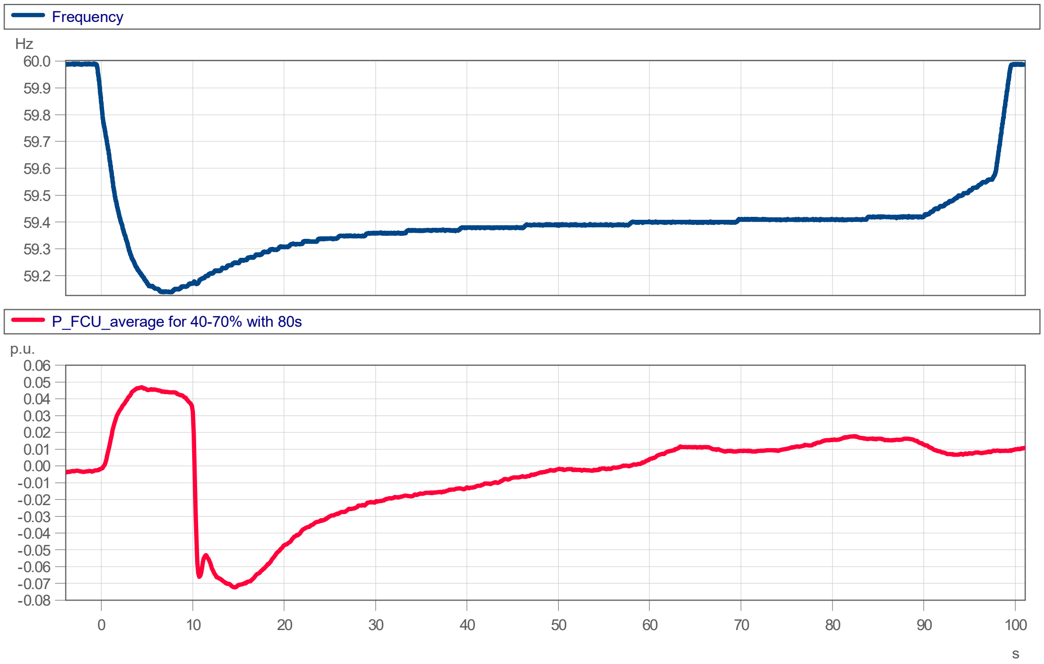

Figure 9, average measurement result for test scenario 4, 40-70% active power and recovery of 80 s

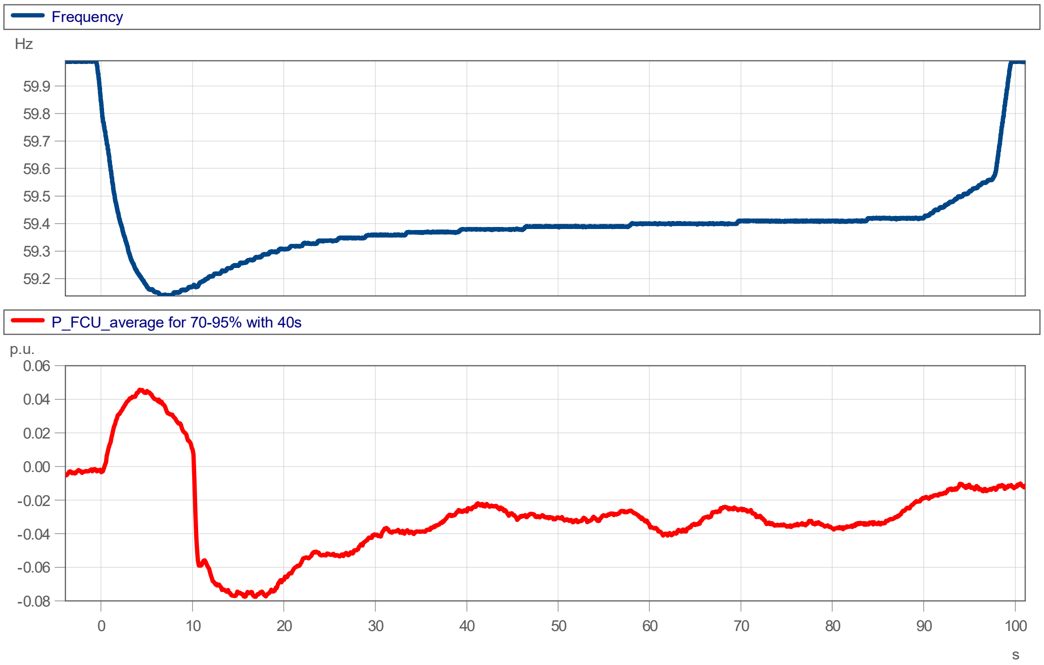

Figure 10, average measurement result for test scenario 5, 70-95% active power and recovery of 40 s

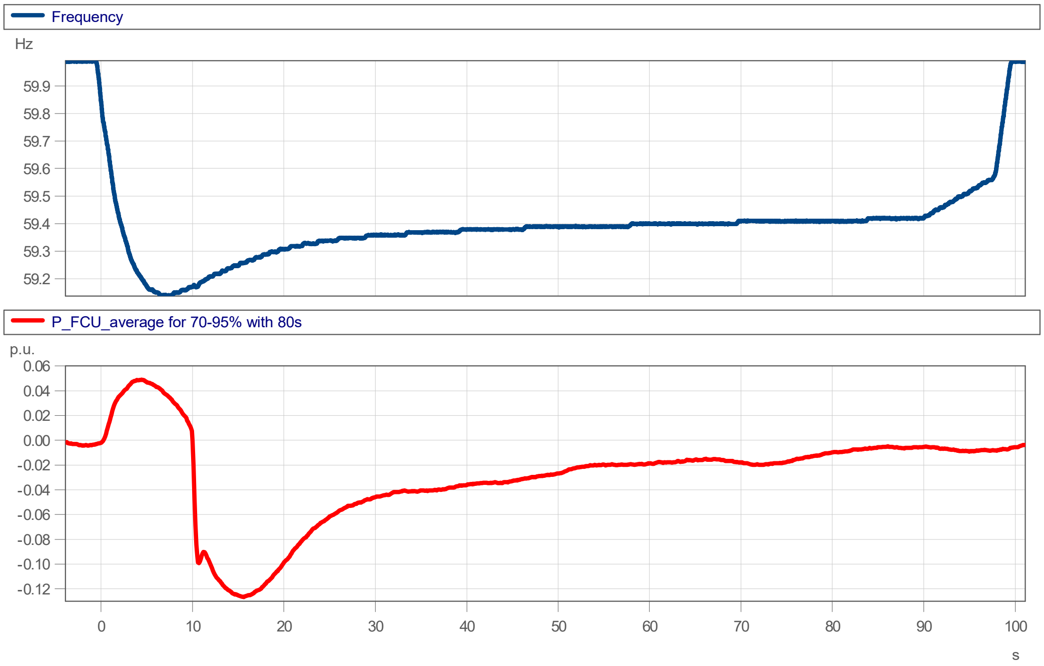

Figure 11, average measurement result for test scenario 6, 70-95% active power and recovery of 80 s

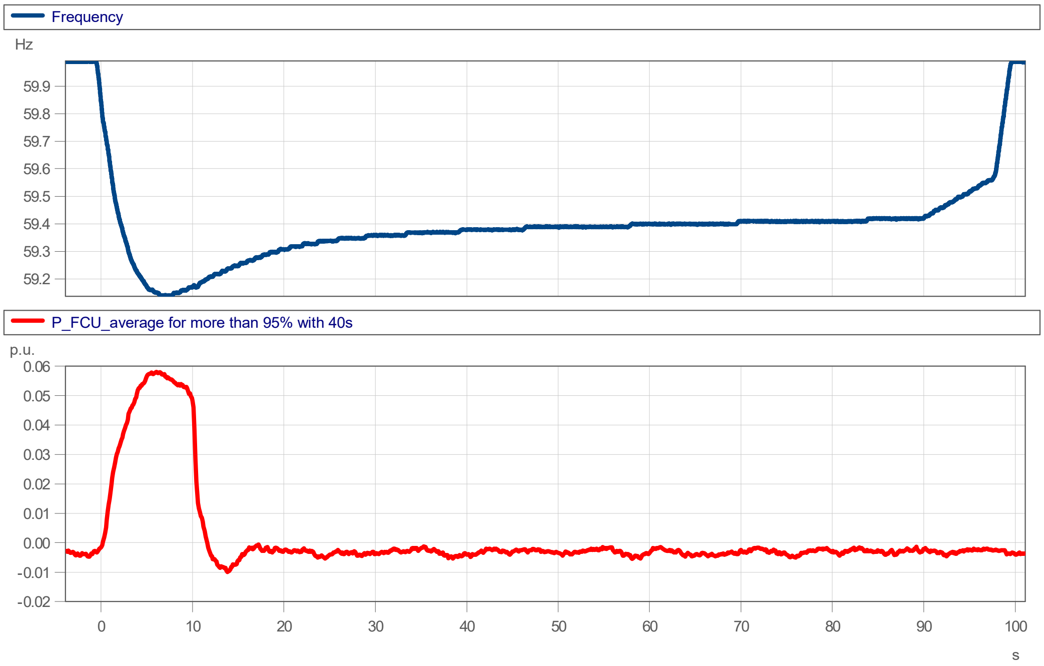

Figure 12, average measurement result for test scenario 7, >95% active power and recovery of 40 s

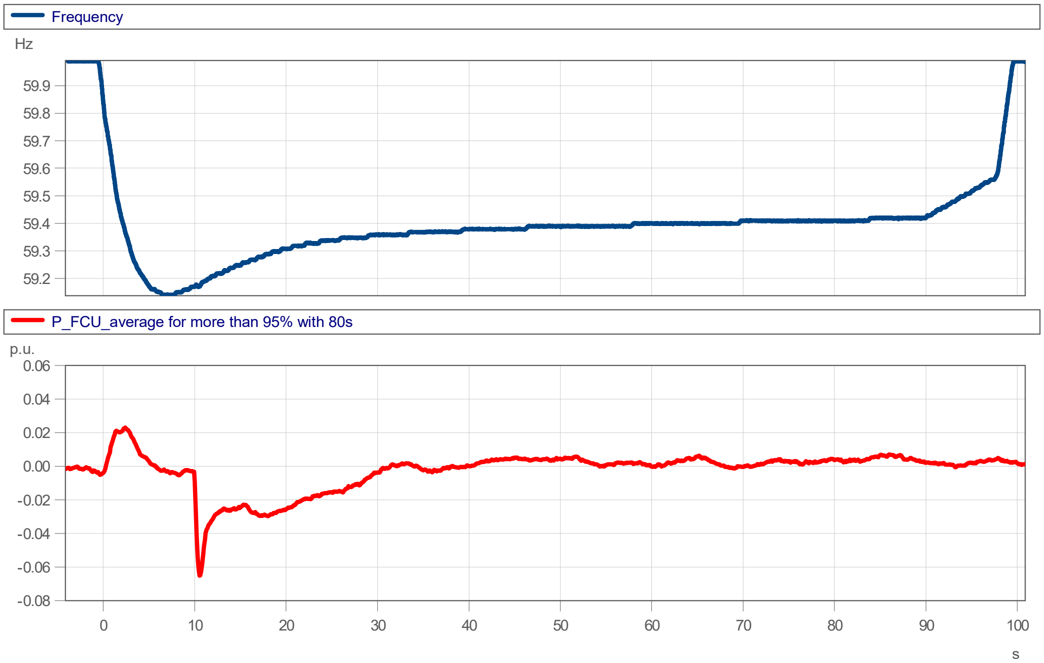

Figure 13, average measurement result for test scenario 8, >95% active power and recovery of 80 s

6.2 Wind Turbine Retrofit

The performance criteria for time for implementation was met. The impact of the retrofit on the annual technical availability of the project are neglectable.

A further reduction of WT downtime could be achieved by performing the retrofit as part of a scheduled maintenance. In case of the demonstration this was not possible due to time constraints.

6.3 Measurements at Wind Turbine Level and Effect of Wind Speed Variations

During the demonstration, measurements were also taken at WT 36 in order to observe the performance of the IE software at WT level. The goal of performing WT measurement was to observe how wind variations may affect the IE response for a single WT. This is a phenomenon which cannot be observed easily at WF level as a fast wind speed measurement representing the instantaneous average of the conditions for the whole WF is not available. Figure 14 and Figure 15 show the results of single measurements performed at WT level for different wind conditions. In Figure 14 it can be seen that the wind speed increased significantly shortly after the end of the IE activation, which allowed for a quick recovery of power after the event. On the other hand, for Figure 15, the drop in wind speed caused the power to continue falling during the recovery phase up to the 45 s mark. This illustrates well that wind speed variations can be fast enough to greatly influence the minimum active power level reached during the recovery period and the length of time needed before recovering to the pre-event power.

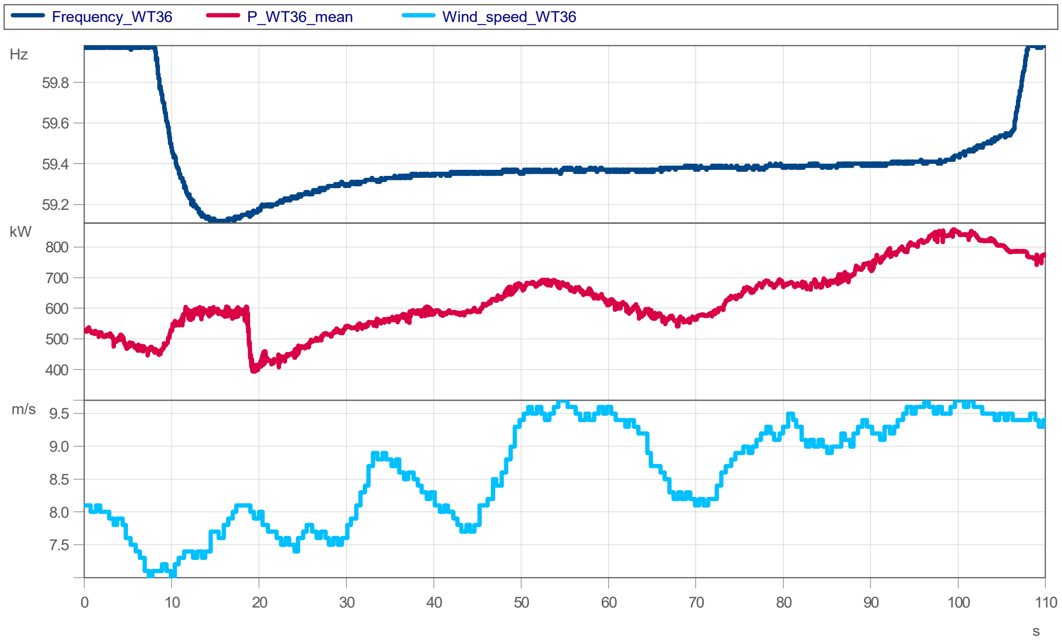

Figure 14, example of the measurement of the IE activation at wind turbine level with increasing wind speed

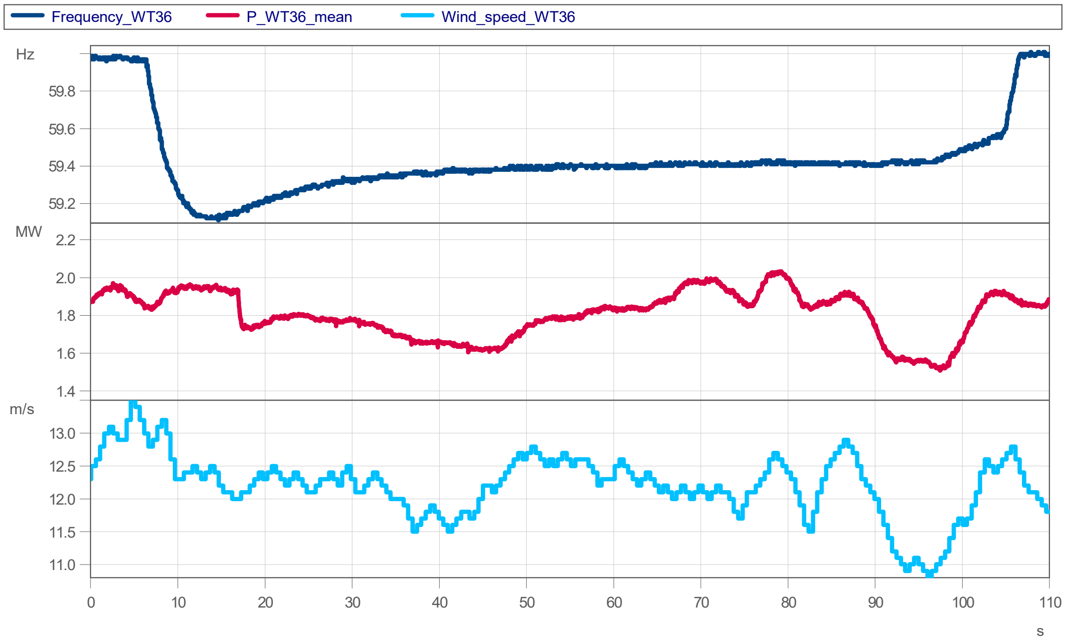

Figure 15, example of the measurement of the IE activation at wind turbine level with decreasing wind speed

7 Discussion of Learnings

This IE demonstration covered many aspects that are new to the wind industry in general and the project partners in particular. The learnings that are related to retrofitting WTs that have been in operation for ten years and to performing WF level tests of IE functionalities are summarized below.

For the Alberta Electric System Operator:

- Characteristics of the IE response such as activation delay, magnitude and duration of power increase and recovery phase are all important factors which can be customized according to the needs of the system
- Parameters defining the behavior of the IE response are interdependent on each other and should be defined carefully on a project specific basis
- The following improvements to the existing IE are expected to increase the attractiveness of the functionality:
    - Allow system operator to remotely enable / disable IE by sending digital command signal. Combined with a load / generation forecast this option could enable system operators to optimize coordination of IE from wind with frequency response from conventional resources (penalty free IE)
    - Prevent the WF from exceeding its maximum authorized real power during an Inertia Emulation response
    - Provision of total available IE volume from an entire WF, given in MW, as a status signal

For WF operators:

- Feasibility and costs of retrofitting existing WFs with IE has to be investigated project-specifically by the WT manufacturer
- Impact of IE activation on annual yield can be neglected
- Impact of IE activation on annual availability is insignificant
- WF downtime can be optimized by including the WT retrofits in scheduled maintenances
- Ancillary service markets allow accessing additional revenue streams in addition to energy payments

8 Conclusion and Additional Work

This demonstration project was successful in illustrating the feasibility of IE provision from existing WTs. All performance criterions were met and the factors that have an impact on IE behavior were highlighted.

The characteristics of every power system are unique. Main influencing factors are location, type and number of generators and loads, local geographic and climatic conditions, available interconnections to neighboring networks as well as electricity market mechanisms. Therefore, the specific technical needs of every grid are different. Solutions that work well in one market do not necessarily have a positive impact on another market. Executing the IE demonstration at a WF in Alberta provided reliable and realistic data about functionalities of modern WTs which were optimized for the needs of the AESO electrical grid. This will help AESO understand how new technologies (e.g. wind, solar, storage, etc.) can provide IE and other services and hence be an important contribution to the power system planning and design that will lead to optimizing the maximum allowed wind generation on the network. Final results of the project demonstrate that provision of IE from existing WT is possible. All performance criterion with regards to IE behavior, WT retrofit as well as impact on annual yield were met. This is just one out of several system services that can be provided by WF, but are currently not used in Alberta. Changing that would yield several benefits for the Alberta market.

For developers, owners and operators of WF:

- The overall share of renewables can be increased which will lead to more project opportunities
- In case of an ancillary service market additional revenue streams can be accessed which will support the trend of falling energy prices (kWh)

For the AESO:

- Cost competitive provision of reliability services without need for installation / connection of additional assets
- Opportunity to introduce performance based ancillary service market where remuneration depends on quality of provided functionality

Additional work is recommended mainly in two areas:

- The AESO is encouraged to work on quantifying the technical and commercial benefit that IE can provide to its electrical system and to explore the possibility of introducing an ancillary service market similar to the one in Ireland.
- All partners to the demonstration educate the Alberta renewables industry about technical capabilities of modern WT by presenting the results of the demonstration at workshops and conferences such as CanWEA or at events that are hosted and organized by any of the participants to the project

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