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REPORT

Enhanced Frequency Control Capability (EFCC)

Wind Package Report

Frequency Support Outlook

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3. Nomenclature

- AP Active Power
- AVG Average
- BBW01 Burbo Bank Wind Power Plant
- CAPEX Capital Expenditures
- EFCC Enhanced Frequency Control Capability
- EIR Extended Inertial Response
- IR Inertial Response
- (L)FSM (Limited) Frequency Sensitive Mode
- NGET National Grid Electricity Transmission
- Ofgem Office of Gas and Electricity Markets
- PCT Percentage
- SGRE Siemens Gamesa Renewable Energy
- GB Great Britain
- Ørsted Company name of "DONG Energy" as per 06.11.2017.

4. Executive Summary

Frequency Sensitive Mode (FSM) was tested on Ørsted Burbo Bank wind power plant with droop settings from 1 to 20 percent and deadbands ranging from 0.015 Hz to 0.4 Hz to prove the capability for both low and high magnitude response. In addition, the wind power plant was subject to a step active power reduction, testing maximum active power ramp rate. The expected ramp rate of 20 percent of active power per second was achieved, and the FSM tests verified that the combined wind power plant control system and turbines respond correctly with dead bands and droop specifications needed to participate in sub second frequency support. These tests confirm the current ability of wind power to perform frequency support.

An Inertial Response (IR) function which taps into the kinetic energy of the rotational mass of the wind turbine was tested at Østerild field test facilities. The resulting turbine IR profile data provided by Siemens Gamesa Renewable Energy (SGRE) was analysed on a portfolio level based on fleet wind speed data for 2016. The turbine profile used a 10 second delivery duration, a wind speed dependent magnitude between 4 and 8 % of pre-activation active power per turbine and a 100% confidence in delivery. Aggregated response magnitude was scaled according to the rated power of the entire wind power plant portfolio, and illustrated by the probability of delivering a specific % of portfolio power, directly as a function of historical turbine wind speeds at each wind power plant. The analysis showed a 68% probability of being able to increase the power output by 1% of the entire portfolio rating at any point in time throughout the year, and 17% for 4%. The IR function showed a lower than expected performance at rated power attested to the converter current limitation of the specific turbine type under test. Assuming a turbine type with ample converter current headroom and thereby 10% boost at all active power levels results in a 75% probability of 1% of the entire portfolio capacity, and 25% for 6 %. With ratings in the gigawatt range for new plants, 1-6 % active power increase from multiple combined plants is a substantial amount of energy injected into the system. The analysis does not consider the recovery period as the data provided is from simulation, and to utilize the IR function, the response must be part of a broader control strategy. The initial results are promising and with concept maturation to a predictable response, the IR product can provide upward faster than Primary frequency response (‘pre-primary’),

The report documents that wind power can contribute to fast acting upward, and downward system stability services. Utilization of wind power services requires the frequency support market to be more inclusive, i.e. be structured in a way that accommodates renewable energy sources and the inherent limitations. Wind power can already offer substantial quantities of sub second high frequency response in a market with for instance day ahead terms and with IR additionally offer short term upwards response for up to 10 seconds. This fast upward and downward response does not require expensive capital expenditures (CAPEX), and uses infrastructure that will be an increasingly large part of the GB system over the coming decades.

5. Introduction

This report is a part of the wind package of the Enhanced Frequency Control Capability project. The report summarizes the current and near-future capabilities of wind power with respect to fast acting frequency support. Current capabilities including Frequency Sensitive Mode and Limited Frequency Sensitive Mode were tested at the Ørsted Burbo Bank (BBW01) wind power plant, and an Inertial Response (IR) function was tested at SGRE facilities in Østerild. A summary of the wind package, conducted tests, their purpose, settings and conclusions are presented. Where relevant, market mechanisms hypothesized to be required for wind power to participate in markets are presented.

5.1 Purpose

Wind energy, and in general non synchronous renewable energy, penetration is expected to increase in Great Britain (GB) over the next decade. Many renewable sources such as solar and wind are intermittent in nature and increased penetration requires careful planning and high-level control. One of the challenges identified is a lack of system inertia. Power electronic device based grid-connected generation decouples the high inertia parts of the generation system from the grid lowering the inertia of the system. A low inertia system is more vulnerable to a loss of production as frequency fluctuations are damped by the inertia of the total mass of rotating machines in the system. The low inertia system changes the nature of the system requirements and needs for frequency support in GB. The system needs solutions to ensure that the frequency can be arrested far more quickly for a large loss of generation that has been the case previously. This report demonstrates how wind energy can contribute to grid frequency stability and be a part of the solution, allowing better integration of power electronic generation devices and higher shares of renewables in the energy system.

5.2 Ørsted Wind Power Assets in Great Britain

Ørsted is currently operating twelve wind power plants in GB, and three are in the construction phase. The capacity of the wind power plants in construction, and recently constructed, have increased due to innovations in wind turbine technology and economics of scale. As illustrated in Figure 1 certain areas have a large feed in from renewable energy, which further provides incentive to use wind power for ancillary services incl. frequency support services.

Figure 1 – Ørsted activity in the Great Britain.
In operation (blue), under construction (turquoise) and in planning (purple)

6. Inertial Response

This chapter presents the SGRE IR report [1] conclusions that are applied in a later chapter to a portfolio wide assessment of the function impact.

6.1 Introduction

Wind power plants are normally operated to run at maximum output and only curtailed in exceptional circumstances, there is usually no headroom available to inject additional power to counteract under-frequency events on the grid. However, even while at maximum output, a new functionality allows wind turbines to temporarily increase active power to support the frequency events on the grid by tapping into the kinetic energy of the rotational mass. In standard operation, the turbine seeks a rotor angular velocity for which the power capture is optimal relative to the wind speed. If the generator-converter system at any point of operation is controlled to increase the power output, the torque opposing the rotor torque applied by the wind is increased and the rotor angular velocity decreases unless the rotor system can feather in the blades to achieve additional torque, which is possible given adequate wind speeds. Any function that has the potential to deaccelerate the turbine system from its optimal rotor angular velocity in a time interval will result in a need for subsequent acceleration of the rotor to achieve optimal power capture. The period and magnitude of this subsequent acceleration and thereby decreased power output varies with pre-and concurrent trigger conditions, most significant are pre-trigger rotor angular velocity and the rise or fall of wind speeds in the activation interval. If the turbine operates at wind speeds exceeding the max-power knee point of the power curve, the post-activation decrease in active power output is close to zero.

The results and assumptions in this report are based on a type of Inertial Response (IR) function at an early stage of development by SGRE. A summary of the performance of this specific IR function as tested by SGRE and presented in the SGRE report [1] is shown in this chapter.

6.2 Test setup

A series of trials were run at different wind speeds on a SWT-7.0-154. Trial results were binned into four pre-test active power ranges relative to rated power of the turbine,

- 20 to 40 %
- 40 to 60 %
- 60 to 80 %
- 80-100 %.

The resulting duration, increase in active power output, time to reach maximum power output and the average active power output were recorded for three modes with different desired magnitudes relative to pre-activation active power output, chosen to investigate the response to different requests,

- 5%,
- 8%,
- 10%.

while the desired duration of the response was kept constant at ten seconds to allow time for other sources of frequency support to activate. The results from each bin are aggregated to estimate an average response profile from a wind power plant.

6.3 Results

Results from the SGRE report [1] are summarized below. All powers are expressed in percent relative to the rated power of the turbine and detailing of the average power and power increase can be found in the SGRE report [1]

Mode	Bins	Pre-test Power	Peak	Time to peak (s)	Avg. Power	Power increase
10%	20-40%	33	36	9	35,5	8.23
10%	40-60%	45	51	1	48	6.67
10%	60-80%	65	74	1	72	10.77
10%	80-100%	99	104	5	103	4.04
8%	20-40%	30	33	1	32	6.56
8%	40-60%	46	52	1	51	9.68
8%	60-80%	68	74	4	73	7.35
8%	80-100%	92	98	4	96	4.89
5%	20-40%	33	36	8	35	6.06
5%	40-60%	46	50	6	49	6.45
5%	60-80%	73	80	7	78	6.95
5%	80-100%	97	102	1	101	4.12

Table 1 – SWT 7.0-154 IR Profiles [1]

Table 1 illustrates that the three modes show few general tendencies of an overall IR response profile. A lack of general tendencies indicates a result pool with a small sample size and a function which performance is highly dependent on the initial conditions. The limited response at rated power indicates a power converter output current limitation.

6.4 Conclusion

In the SGRE report [1] conclusions are drawn based on detailed single turbine and aggregated responses not presented here; notably SGRE were unable to test this function at a wind power plant level. Some of the core conclusions from the report follow:

- If the wind speed is increasing *right before* IR, the desired response is going to a reach higher peak in a shorter time.
- If the wind speed is increasing *during* the IR event, the desired response is going to be sustained throughout the period or even exceeded.
- The higher the rotor speed, the more likely it is that the desired response is obtained.
- In some circumstances, the energy lost during the recovery can be much higher than energy delivered during IR for a single turbine, though this is expected to be less pronounced at an aggregate level across many turbines in a large wind power plant.

Energy lost in the recovery period was not quantified in the SGRE report [1], and quantifying lost energy due to triggering of IR requires a prediction of the possible output power given no activation of IR. This could be accomplished to some degree of certainty by for instance comparison with adjacent turbines or using wind speed measurements.

A sustained delivery time of up to ten seconds suggests a use of the function as a ‘pre-primary’ response, i.e. a quick response that ramps up within a second, and lasts until the Primary response is active. The indicative commercial benefits of this (considering that there will be some recovery time after the initial power injection) are outlined later in the Commercial Section (Section 7) of this report. Overall, the IR function shows promise based on the conducted tests, but requires further development, quantifiable recovery period and a wind power plant level testing to demonstrate its full potential.

7. Inertial Response in Great Britain

Presented in the section is an aggregated estimation of the current generation IR functionality impact assessed using a wide range of wind power plants in GB. The assessment is based on historical site data.

7.1 Turbine Inertial Response Profile

Inertial Response was tested on a single turbine type, the SWT-7.0-154. A portfolio assessment requires a general and consistent plant wide performance profile. The results presented in chapter 6 were divided into bins per current production as a percentage of rated power, and a general turbine profile is created from the average response for each bin.

Active power bin	IR magnitude %
0-20%	0
20-40%	6.95
40-60%	7.60
60-80%	8.36
80-100%	4.35

Table 2 – Assumed generic turbine IR profile

The IR magnitude percentage shows the increase in active power proportional to the pre- activation generation. It should be noted that the numbers of Table 2 are used as a general response profile for SGRE turbines, and the IR function could show different performance across turbine types.

7.2 Assumptions

The following assumptions have been included in the portfolio analysis,

1. Energy lost in the recovery period is not considered.
2. Energy lost due to ramp up time is not considered.
3. Energy gained as part of the ramp down period is not considered.
4. The average additional power is sustained throughout the entire IR period.
5. SGRE turbines of different model show similar IR performance.

Assumptions one through five are grounded in a lack of specific data from the SGRE report [1]. The sixth assumption is included to show a broad spectrum of responses across the portfolio, and assumed valid since IR already exists for an earlier turbine type.

7.3 Portfolio Assessment

Wind power is a stochastic resource and from system stability perspective the key interest is certainty in delivery of the offered service. The desired curve is thus a combined IR active power contribution probability distribution.

The approach used originates from the lack of a defined market mechanism for this type of product. Possible market structures are suggested in the commercial section (Section 7) of this document. Section 7 also outlines strategies that would increase availability of response as the market reforms.

7.3.1 Results

The calendar year 2016 was chosen for wind power site data due to completeness of data history, and the method detailed in the appendix was applied to data from the entire wind power plant portfolio. The results are summarized in Table 3, and illustrated graphically in Figure 8 in the appendix. To present a relatable figure for extrapolation to additional wind power plants in the portfolio, the active power generation increase is shown relative to the total registered capacity of the combined wind power plant portfolio.

Wind being a stochastic resource is reflected in the results as the possible magnitude of IR depends on the wind available, even with distributed wind power plant locations. The IR can deliver a significant injection of energy into the grid in a very short time, key figures are shown in Table 3.

IR magnitude relative to portfolio capacity	Probability
1%	68 %
2%	50 %
3%	35 %
4%	17 %

Table 3 – IR magnitude probabilities.

It should be noted that the scaling used is the maximum capacity of all wind power plants, and not the current production at the time of IR activation. Scaling with current active power generation yields figures closer to Table 2.

7.3.2 Impact of IR magnitude

Key figures of IR are magnitude percentage, duration and recovery period. Duration is for this analysis locked at 10 seconds to provide a window for substituting generation to ramp up, and the recovery period impact is a function of IR implementation and usage. The intent of IR is to minimize the rate of change of frequency and following nadir in response to a critical frequency event, which is best done with a high magnitude and a quick response. Comparing the percentages of the pre-activation power bins of Table 2 to the probability of that bin, shown in Figure 9, shows that the lower performance of IR at 80 to 100 percent of rated power has a significant effect on the overall response magnitude comparable to lower pre-activation bins. The performance of IR in the '80-100' range is attested to the converter current limited for this specific turbine type. The converter current limitation impact on the overall response is estimated by redoing the analysis with the performance in range '80-100' equal to '60-80', shown in Table 4 (1). Additionally, the impact of having a constant IR magnitude percentage of seven and the original intended ten is shown in Table 4 (2) and (3).

Because of the low correlation between wind speeds at the east and west coast, the modified IR magnitude percentage does not have a large influence on the probability of low magnitude responses.

IR magnitude relative to portfolio capacity	(1) Probability (8.36% for 60-100)	(2) Probability (7% for all bins)	(3) Probability (10% for all bins)
1%	68 %	68 %	75 %
2%	55 %	51 %	61 %
3%	42 %	38 %	51 %
4%	32 %	28 %	40 %
5%	24 %	17 %	33 %
6%	16 %	7 %	25 %

Table 4 – IR magnitude probabilities.

To maximize grid support value, the IR function must be optimized for wind conditions that statistically results in the most frequent and critical frequency events, e.g. when conventional power plants are offline. Thoughts on IR function optimization can be found in the appendix.

7.4 Inertial Response Conclusion

The energy stored in the rotating masses in wind turbines can be used for IR and gives wind energy an advantage compared to other renewable generation with respect to providing a fast increase of generation in response to critical low frequency events. As depicted in Figure 8 the additional infeed of power varies between 0-5 percent of the entire portfolio rating with the current implementation, and a mature IR function will show higher probabilities for similar or larger magnitudes. For widespread implementation, the response profile at different pre-trigger production levels and the recovery period energy loss must be fully understood and be predictable. Furthermore, the function activation must be thought into a system wide operation procedure handling the stochastic nature and recovery energy loss. It is the view of the author that IR represents an opportunity as it scales well with wind power penetration. However, to harness this opportunity IR should be predictable and must be an integrated part of a common response due to the recovery period.

As the shape of the market for an IR product becomes clearer, the analysis can be adjusted to reflect new market realities.

8. Frequency Response

This chapter summarizes the testing conducted at the Ørsted Burbo Bank (BBW01) wind power plant. A summary of the conducted tests, their purpose, settings and conclusions are presented. The functionality tested exists on most offshore wind power plants.

As part of the Grid Code compliance, all wind power plants must be able to support the grid frequency by modulating the active power output proportional to the frequency deviation from nominal. Two modes exist: Frequency Sensitive Mode and Limited Frequency Sensitive Mode (LFSM). FSM enables up- and downregulation while LFSM only enables downregulation. The modes are detailed in the appendix.

8.1 Purpose of tests

The tests aim to demonstrate existing wind power frequency support capabilities. BBW01 is comprised of 25 SGRE turbines with a nameplate capacity of 3.6 MW, totalling 90 MW. The SGRE 3.6 MW turbine mechanical structural safety imposes an active power ramp rate limit of 20% of rated capacity per second. A full transition from rated production to zero would thus take approximately 5 seconds from command acknowledgement.

8.2 Tests

Tests parameters were selected to represent a broad spectrum of possibilities, and show different dead bands, droops and the effect of a decrease in wind speed. To show upregulation, the wind power plant was curtailed to around 33% of rated capacity and tests were executed with an active power setpoint of 30 MW and with 24 turbines connected to the grid, totalling a capacity of 86.4 MW In tests 7 and 8, an artificial frequency measurement was added to the control system, forcing a response. Note that a droop of 1% might cause additional turbine mechanical wear.

Number	Mode	Droop	Deadband (Hz)	Injection
1	FSM	3.3333	0.015	-
2	FSM	3.3333	0.015	-
3	FSM	1.0000	0.015	-
4	FSM	20.0000	0.015	-
5	FSM	3.3333	0.100	-
			0.200	-
6	FSM	3.3333	0.300	-
			0.400	-
7	FSM	3.3333	0.015	49.50 Hz
8	FSM	3.3333	0.015	50.50 Hz
9	N/A	N/A	N/A	0 MW

Table 5 – BBW01 Tests (tests in gray are shown in the appendix)

8.3 Results

In all graphs, the hatched area represents the dead band area for the frequency control. When the available power far exceeds the active power set-point of a test it is omitted to preserve details in the figure.

8.3.1 Test 1

The first test runs for around 6 minutes. 20 seconds into the test, an active power curtailment set-point and the frequency control are activated. The now output limited plant decreases the active power output from the maximum available 65 MW to the scheduled curtailment of 30 MW, plus the active power delta contribution from the under-frequency response. The variation in frequency and the following change in active power aligns with the FSM mode settings for an under-frequency event. Note that the initial curtailment set-point is subject to different time-constraints than the frequency control and thus slower than 20% of rated power per second.

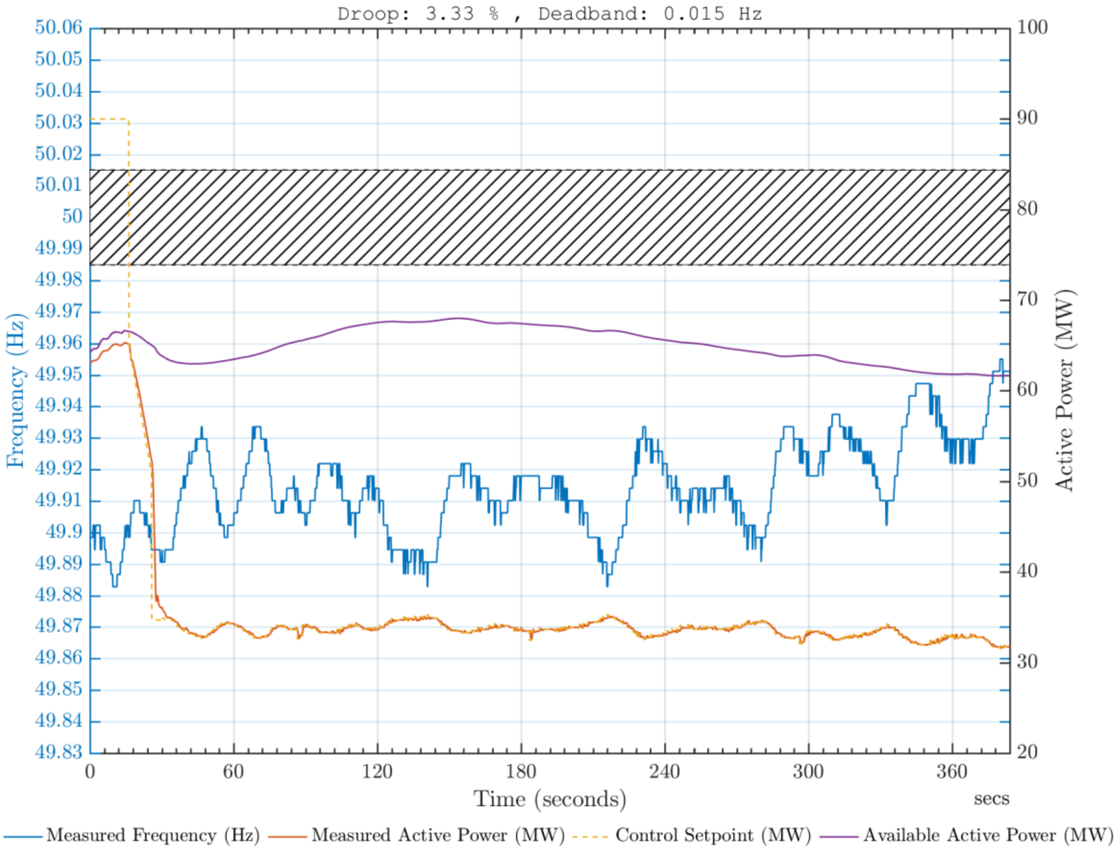

Figure 2 – BBW01 Test 1

8.3.2 Test 2

Test two runs for three hours, and shows standard FSM control. As the frequency exceeds the dead band, the system responds with appropriate magnitude. It is important to note that the control set point is a real-time calculated value for the turbines to track given adequate wind resources. 2 hours and 20 minutes (8400s) into the test the wind speed decreases, and the available active power follows. The calculated control set-point remains the ideal value to track, but the active power output is resource limited. At the subsequent rise in wind speed, the active power tracks the set point once again.

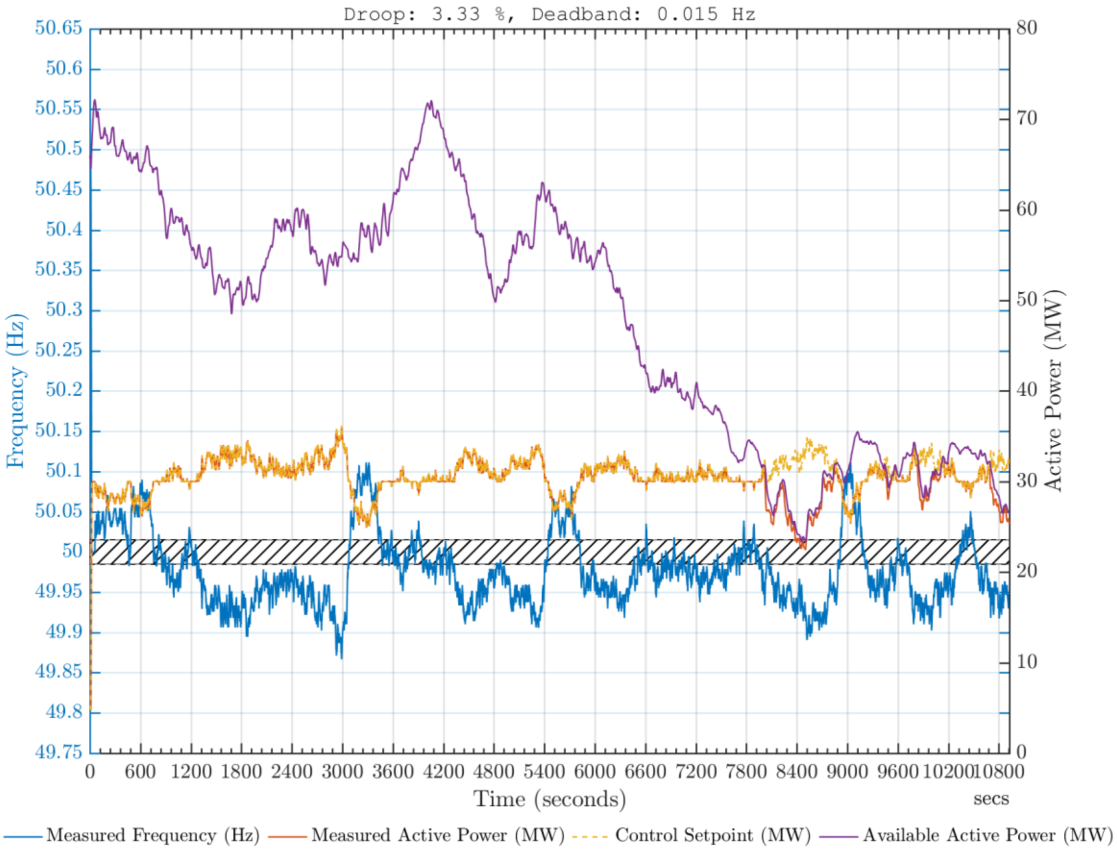

Figure 3 – BBW01 Test 2

8.3.3 Test 3

In test 3, the droop was set to 1% and a dead band of 0.01 Hz. The droop of 1% and a narrow dead band results in a response profile with larger magnitude and frequent activation. The active power control system accurately tracks the desired response, and shows fast acting performance.

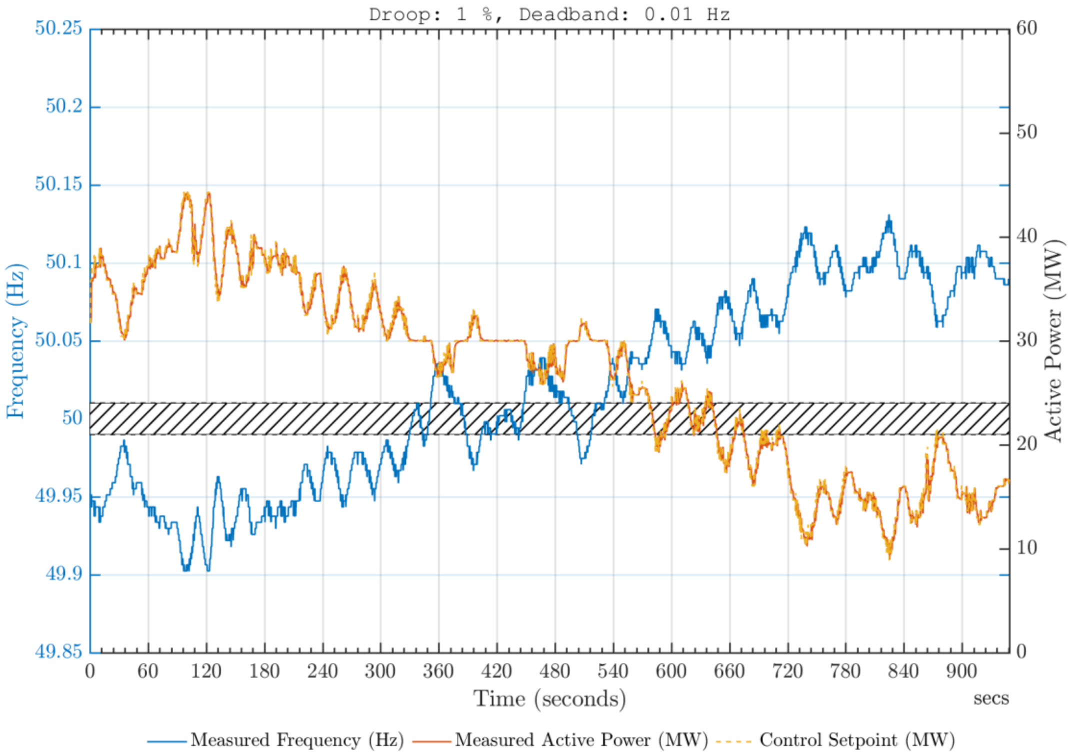

Figure 4 - BBW01 Test 3

8.3.4 Test 7

To show the response profile for a large frequency deviation, an artificial frequency measurement is injected. The figure below shows that the system operates exactly as expected when the frequency exceeds the dead band, and provides the correct proportional positive active power response.

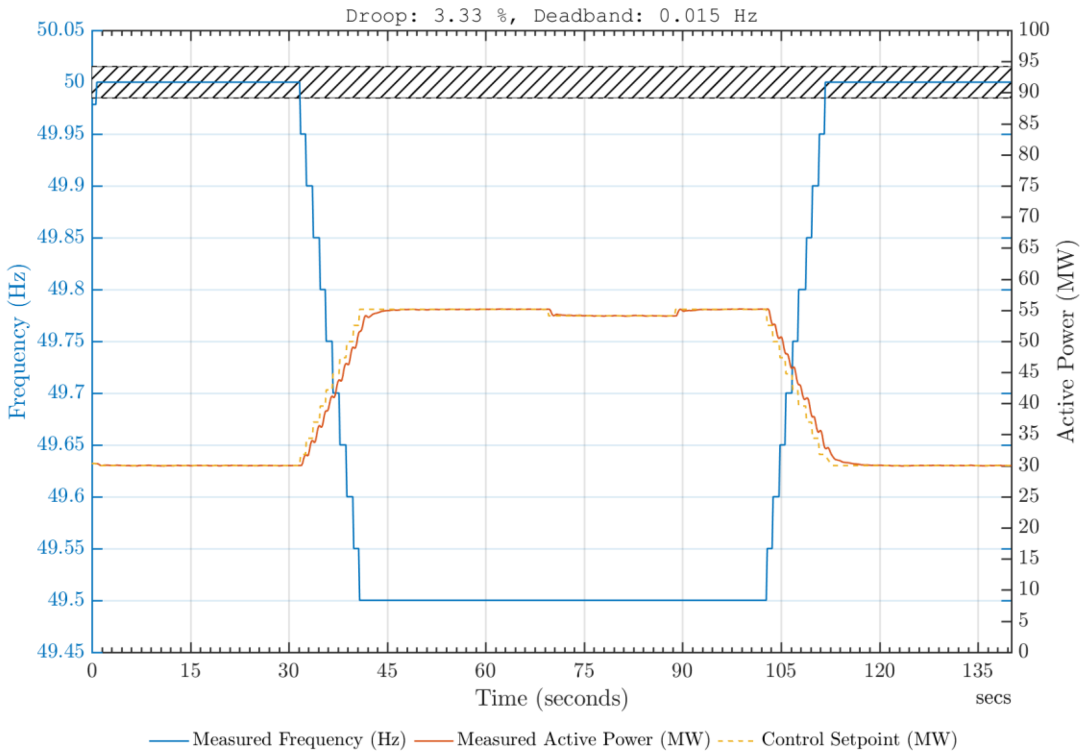

Figure 5 – BBW01 Test 7

8.3.5 Test 8

Test 8 is the inverse of test 7, and a rising frequency is injected into the control system. Again, the system gives the correct proportional active power response, which is now negative as the frequency deviation is positive.

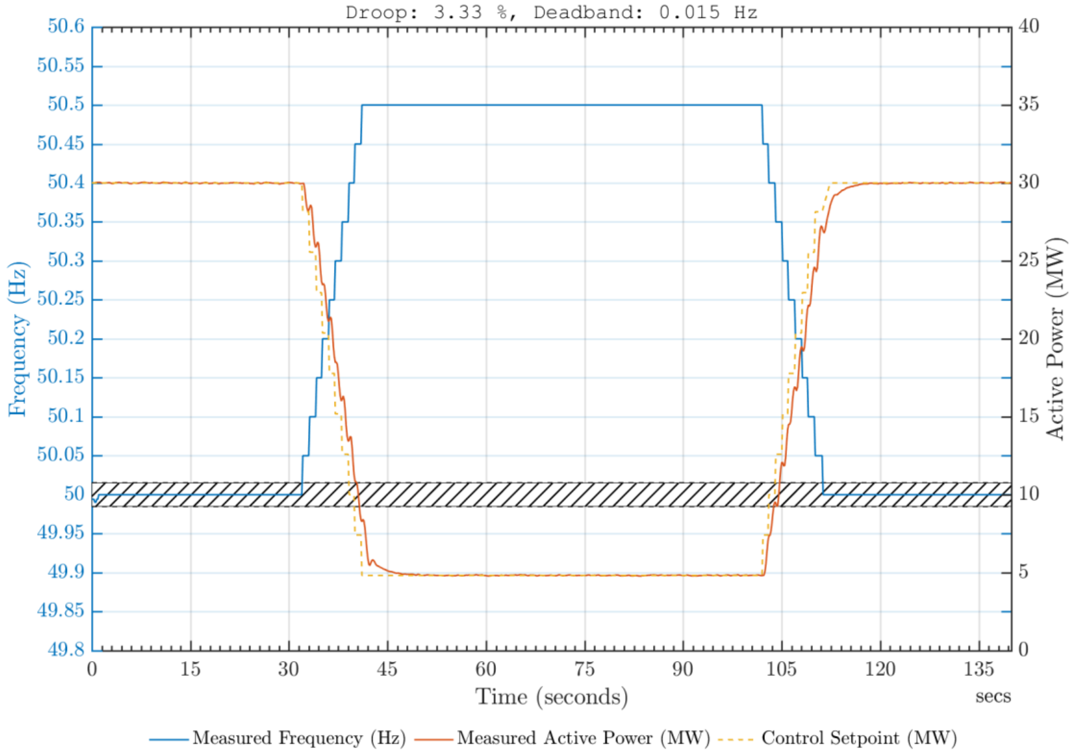

Figure 6 – BBW01 Test 8

8.3.6 Test 9 –Performance test

Test 1 to 8 showed various droop and dead band settings successfully, but the direct performance limit of the turbine was never reached. Test 9 shows the execution of a curtailment from full production to 0 MW conducted at Grid Code compliance testing with a large enough droop to be limited by the turbine mechanical ramp rate. Each green dot represents a one second sampling and it takes just under five seconds to get to zero production. The time required to complete the curtailment aligns with the turbine ramp limit of 20% per second.

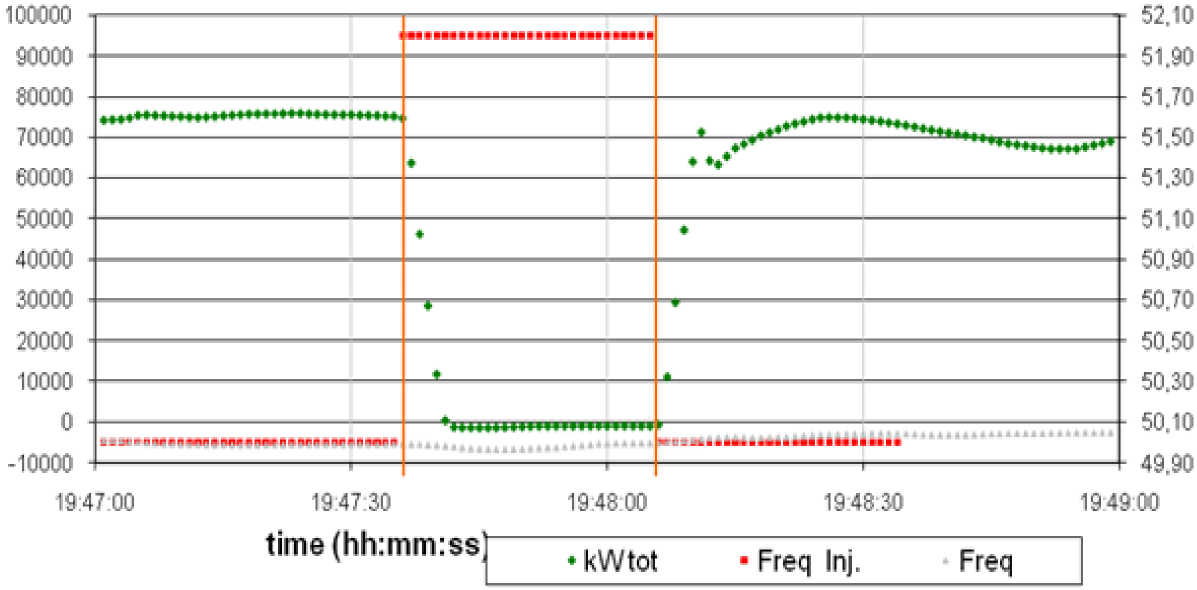

Figure 7 – BBW01 Test 9

8.4 Frequency Response Conclusion

This chapter has proven that current generations of wind power plants *already have* specific frequency response capabilities, that may even outperform traditional generators in some areas. This is not surprising, as frequency response service requirements for wind power plants are included in the grid code requirements, where these capabilities are routinely demonstrated at compliance testing. Test 9 illustrates the active power ramp of 20 percent of active power per second, and Test 1 to Test 8 verifies that the system supports dead bands and droop specifications that are needed to participate in fast acting frequency support. The central controller is fast enough for the plant to have a sub second response.

Currently the grid code requires the plant to be able to partake in frequency support through LFSM and FSM modes. The specified performance requirements for wind turbines with regards to magnitude and response time are like the requirements for other types of generators. As spelt out in the following section, given adequate market mechanisms, wind power can offer a high-speed response.

9. Commercial Potential

Existing frequency response capabilities can provide downward response, and a product like Inertial Response could provide upward response to the GB System Operator (SO). Wind power plants can currently provide up-regulation, but need to be in a curtailed state to offer this. Since wind power plants typically do not normally operate in a de-rated or curtailed state, Ørsted would use a product like IR to provide upward response.

It is the view of Ørsted that wind has a significant role to play in both upward and downward fast frequency response with three core benefits to the GB system:

1. The speed of the response will reduce the deviation of the frequency from the 50 Hz target
2. This response does not require expensive CAPEX.
3. The response uses infrastructure that will be an increasingly large part of the GB system over the coming decades – this infrastructure will persist long after many conventional plants are phased out

Current market structures do not allow wind power to truly harness the upward and downward response potential. Below, market changes believed to be required to unlock these services are presented.

Both upward and downward response would be encouraged by an inclusive market that values response speed. Most wind power plants can offer sub-second upward and downward response. Current market mechanisms (e.g., Fast Frequency Response High and Primary products) do not distinguish between slow assets that take up to 10 seconds to respond, and faster assets such as wind. This puts faster, and therefore more valuable, response at a disadvantage to slower responding providers. Fast responders are not paid for the first 10 seconds of response in current Primary and High markets. A market that reflects the additional value of this response, instead of penalising this fast response would encourage Ørsted to participate in the upward and downward Frequency Response markets.

Similarly, a day ahead market, perhaps with defined time intervals such as the four-hour time periods prevalent in the German MRL and SRL[1] markets would allow offshore wind to bid into the market with larger, more predictable quantities. Day ahead forecasts tend to be largely correct (reducing the need for expensive back-up in case the wind is not blowing), and short time periods allow wind to bid in large amounts in forecasted high wind periods, and less in forecasted low wind periods. Making this change does not discount any current players in the market, but allows renewables to play in this market, increasing service supply and reducing the cost to the end customer.

Upward Fast Frequency Response, using a product like IR, would be enabled by the creation of a fast response ‘Pre-primary’ product. Initial discussions suggest that the ratio of energy provided by IR to energy lost (in the recovery period after response) is optimised with turbines providing power for up to 10 seconds [1]. Assuming these preliminary technical findings to be true, wind can offer upward response for the first 10 seconds after a frequency event, and allow Primary response to take over after. A predictable profile of response and recovery time will allow the System Operator to

[1] Minute and Secondary Control Reserve

integrate the energy output and recovery time of this new product into existing models of Primary response requirements. Ørsted believes that fast response is worth more to the system than slower response as faster response leads to a lower overall deviation of frequency from the target, as response kicks in before frequency hits its low point. Therefore, the benefits of this response in terms of reduced slower response should be higher than the costs in terms of Primary response required to make up for the recovery period[2].

Ørsted is continuously working to overcome challenges posed by the stochastic nature of wind to fit into the current market structure. First, Ørsted is working to provide limited quantities of High response within the current market structure by aggregating our assets from across GB. This guarantees a minimum quantity of wind production that can be downregulated as assets are distributed across relatively uncorrelated wind areas (e.g. South East and North West). Second, Ørsted is working with National Grid to increase selection of wind power plants in the Mandatory markets for activation for a short period based on actual production. These solutions can help increase availability for an upward 'Pre-primary' product too, allowing the role wind can play to be more predictable.

To realise the full potential of offshore winds capabilities would require frequency response market design parameters to be updated. More inclusive products parameters are necessary signals for the industry to commit further investment needed to fully commercialise functions like the Inertial Response product. As spelt out above the three major changes we recommend are rewarding fast response, procuring services closer to real time, and creating a 'Pre-primary' upward response product. Ørsted believes that these suggestions will create a more inclusive market, - in no way excluding current providers – but instead simply increasing competition. Ørsted urges National Grid's System Needs and Product Strategy (SNAPS) consultation to consider the recommendations as it maps out a path towards a future market. In parallel Ørsted continues to trial innovative solutions (e.g., aggregation of assets, Extended IR) that help reduce the inherent uncertainty offshore wind faces with fluctuating wind speeds.

10. Future works

The future works in relation to LFSM and FSM is influencing the market design to utilize the existing functionality and integrate wind power plants into the market.

IR is still a function in development and has room for optimization, e.g. ahead of time confidence in a minimum delivery. Depending on market design, the compromise between magnitude, duration and recovery period must be evaluated per the requirements of the grid. Extended IR functionality, detailed in the SGRE Technical Report [2], apply wind power plant closed loop control to ensure a predictable response when subject to different wind conditions, increasing the commercial applicability of the function.

Currently the challenge is to decide on the way forward to influence the market design for stochastic energy sources, and determine the type of optimization that provides the most value to NGET.

[2] This hypothesis can be tested when SGRE releases more information about Extended IR.

11. Conclusion

The EFCC project aims to show the frequency support capabilities of wind power, both current, near future and outlook. This report has presented tests of FSM as an existing capability ready for integration into a future smart power system, and IR as a function that has potential to alleviate critical events. The outlook of wind power in frequency support is market driven and dependent on stochastic resource control integration on a grid level. Integration of stochastic energy resources such as wind energy must be accommodated to utilize the already available functions and achieve a lower cost of energy.

12. Acknowledgements

Ørsted would like to thank the Office of Gas and Electricity Markets (Ofgem) and National Grid Ltd for funding the Enhanced Frequency Control Capability project.

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[1] I. G. Szczesny, “Siemens Wind Turbines, Tests of SWT-7.0-154, Inertial Response,” Siemens Gamesa Renewable Energy, 2017.

[2] M. Stoettrup, “Siemens Wind Turbines, Tests of SWT-7.0-154, Inertial Response,” Siemens Gamesa Renewable Energy, 2018.

14. Appendix

The appendix includes descriptions of the applied methods and illustrations of results already listed in the report. Furthermore, data from additional FSM tests of low importance to the reader, i.e. low response settings, are included.

14.1 Portfolio analysis

14.1.1 Method

The calendar year 2016 serves as representative of wind power yield. One-hour time-based averaged samples are used for wind speed (m/s), active power (MW) and number of available turbines. The available number of turbines is included to account for availability impact. If the wind power plant is under construction, a nearest neighbour approach is applied. The wind speed and availability are based on the neighbouring wind power plant and the active power output is estimated from the turbine power curve.

The probability distribution can be generated in at least two ways,

1. Generate histograms for each wind power plant and show the combined bin probability.
2. Summation of additional active power production and calculate histogram.

Using method (1), incomplete datasets are overcome by combining multiple histograms, but it suffers from the amount of possible combinations for which the set of wind power plants can achieve a specific active power output. Method (2) works with multiple intersected incomplete datasets to obtain a comparable dataset. The reader should note that the average missing data partition is 0.11 percent.

Method (2) is applied on a wind power plant level, and the applied IR magnitude is estimated from the mean wind speed of the plant, measured active power export at the transmission interface point and the turbine curve for both power and IR.

14.2 Graphical illustration

The hatched area in Figure 8 represents the probability domain for which IR can deliver a certain amount of increase in active power export for ten seconds.

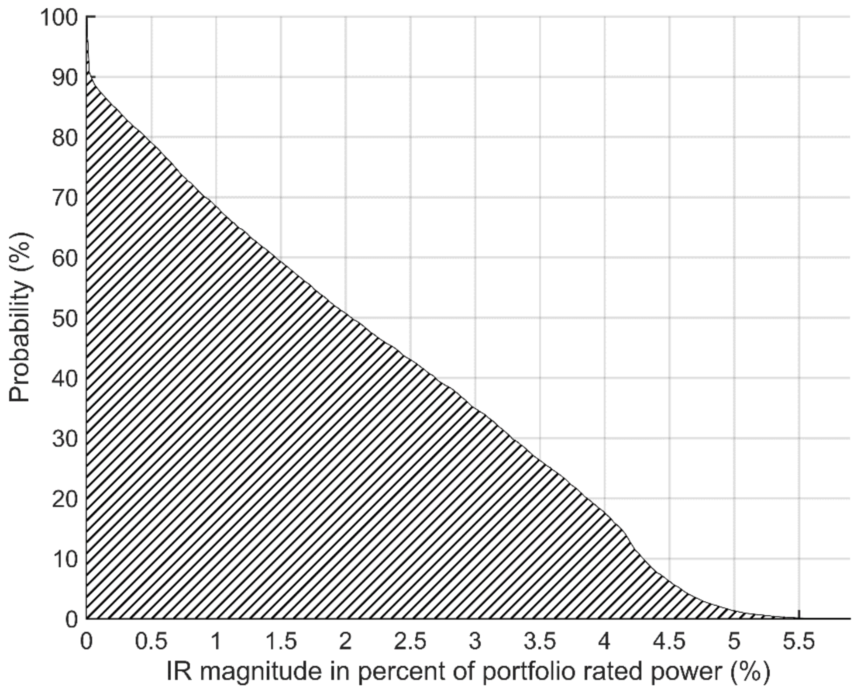

Figure 8 – Aggregated wind power plant IR magnitude probability distribution using values from Table 2.

14.2.1 Optimization

Figure 9 illustrates the challenge of segmenting the IR magnitude into bins given the narrow range of wind speeds that designate each bin due to the high gradient of the turbine power curve prior to rated generation. To maximize grid support value, the IR function must be optimized for wind conditions that statistically results in the most frequent and critical frequency events, e.g. when conventional power plants are offline, and the average wind conditions on each site. Response magnitude, duration and recovery period are linked parameters and depending on grid requirements, the order of optimization will follow.

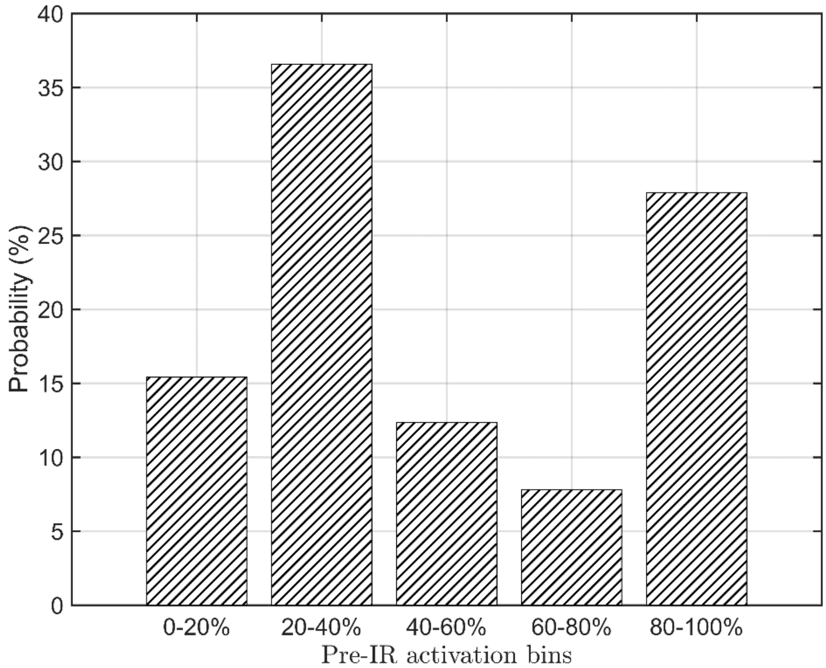

Figure 9 – Probability of turbine in activation bin.

14.3 Frequency response tests

14.3.1 Control modes

All tests in this report are done in FSM mode. FSM implements a droop control, with a default deadband of 0.015Hz around nominal, and reacts to both under (if curtailed) and over frequency events.

The response profile required from the plant is determined from a specified linear relationship between frequency and active power (droop), and the dead band, f_{db}, as,

$$\Delta P(f_m) = \begin{cases} \dfrac{f_m + sgn(f_m - f_{nom})f_{db} - f_{nom}}{Droop \cdot f_{nom}} P_{rated}, & |f_m - f_{nom}| \leq f_{db} \\ 0, & otherwise \end{cases},$$

where f_m is the measured frequency. The droop is defined as $\Delta f / \Delta P_{rated}$ and represents how much active power changes in response to a change in frequency. Typical values range from 3 % to 5 %, such that for a 3-5% frequency deviation relative to nominal, the plant must up or downregulate 100% of its rated capacity. FSM and LFSM are continuously acting system functions that react to frequency errors relative to nominal. At deadband boundary crossing, the active power set-point in charge is locked. The frequency control power delta is added to the locked active power set-point until a second deadband boundary crossing has occurred.

14.3.2 Additional tests

14.3.2.1 Test 4

With a droop setting of 20 %, and a dead band of 0.015 Hz, test 4 aims to show the capacity to operate even at high droop settings. The test follows directly from Test 3 by adjusting the droop setting online at 55 seconds. Note that the system returns to 28.6 MW and not 30 MW. This is a consequence of the continuous testing as the last deadband boundary crossing happened at 530 seconds in Test 3, and the control set-point was 28.6 MW at the time of crossing. When the frequency enters the deadband region again, the locked set-point of 28.6 MW is superseded. It is evident that a 20 % droop setting correctly results in small variations in active power.

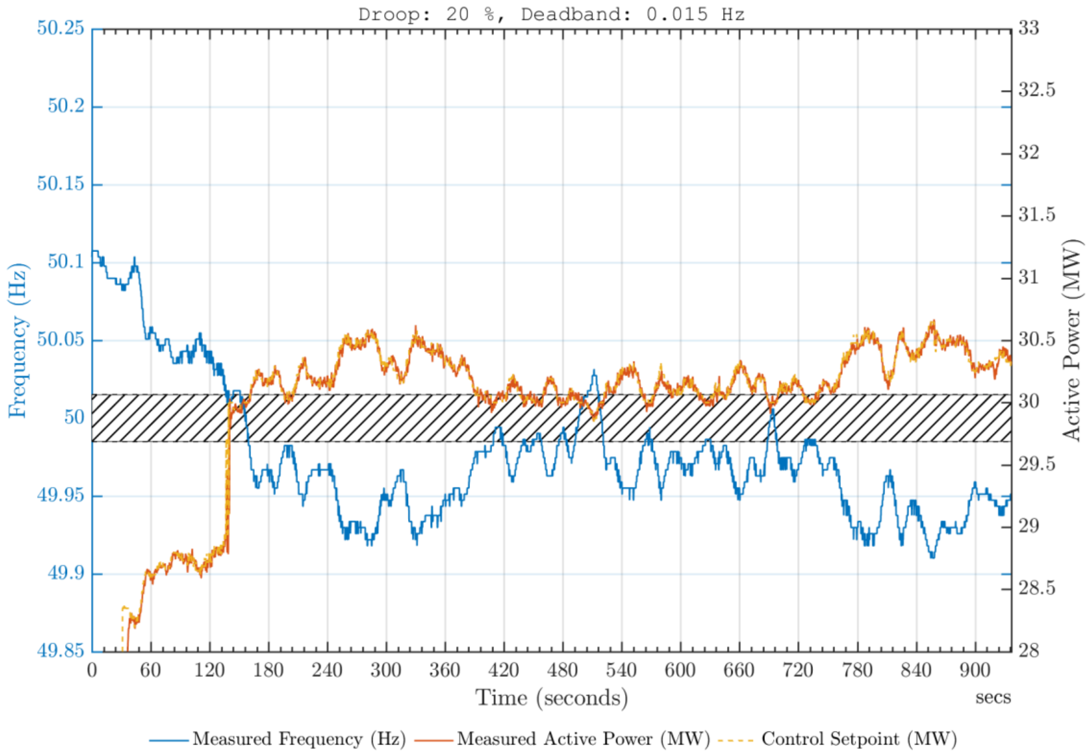

Figure 10 – BBW01 Test 4

14.3.2.2 Test 5 & 6

Tests 5 and 6 operate with a droop of 3.33% and dead bands of 0.1 Hz and 0.2 Hz respectively. The purpose of these tests is to validate the behaviour of the system with FSM enabled, but not triggered. The frequency never exceeds the dead band, and consequently the frequency response is not triggered.

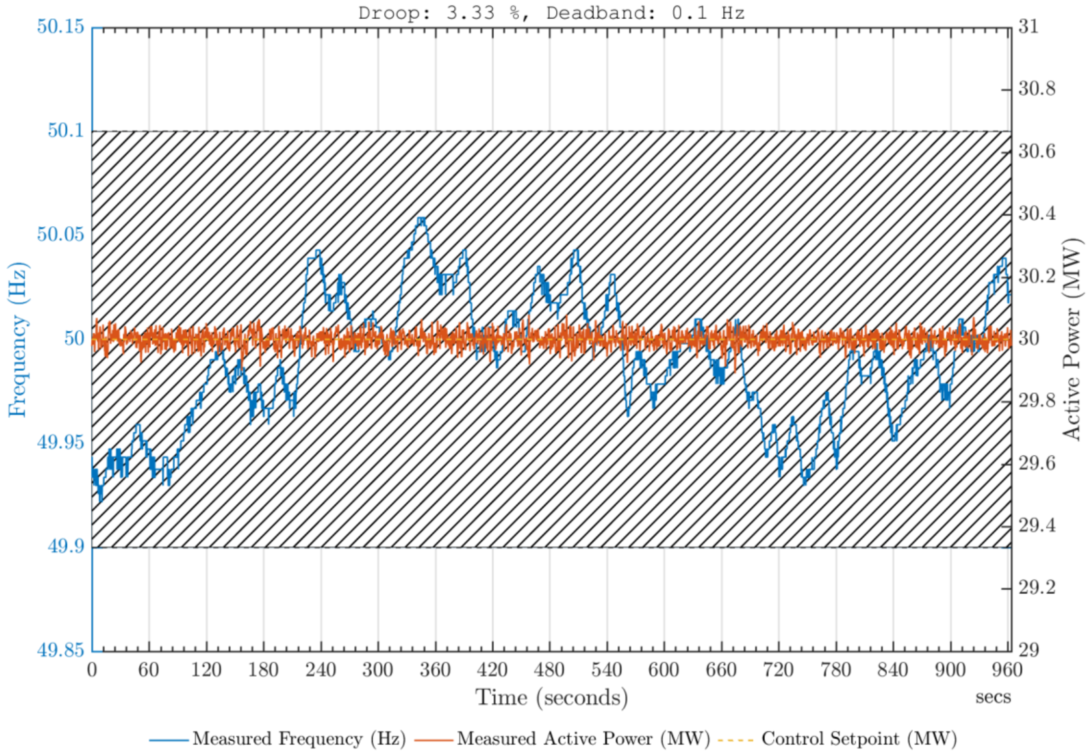

Figure 11 – BBW01 Test 5

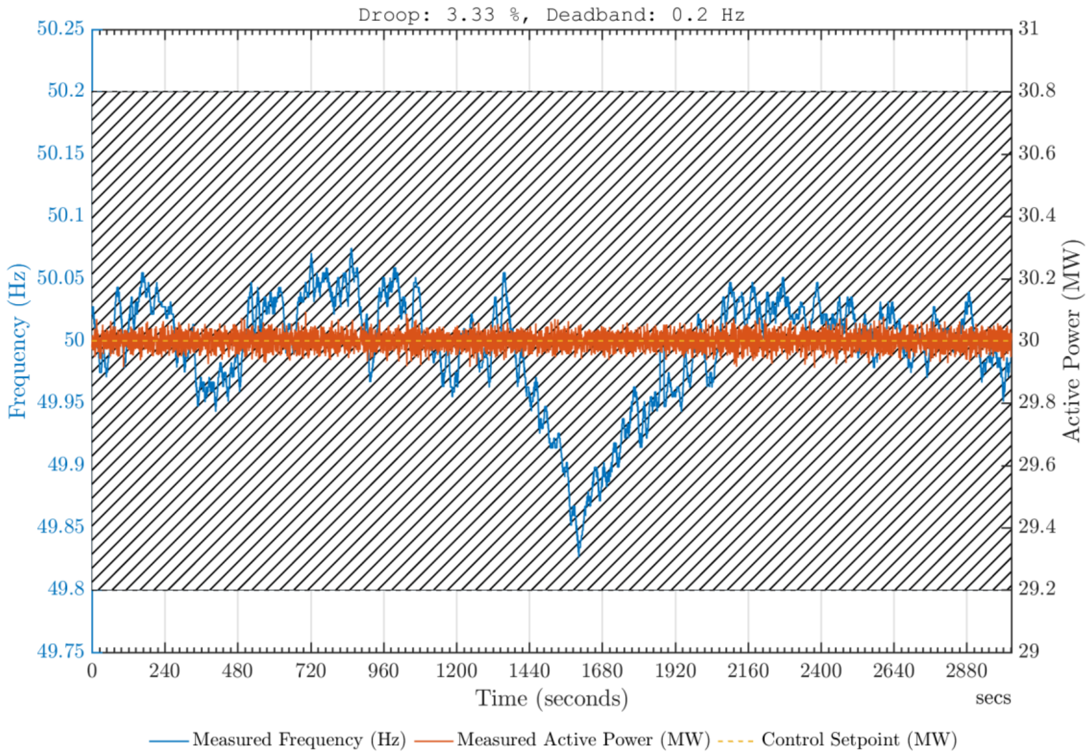

Figure 12 – BBW01 Test 6