RHODE SYSTEM SERVICE FACILITY

EirGrid Demonstration Project: Flywheel/Battery Hybrid Project Report

TABLE OF CONTENTS

TABLE OF FIGURES

EXECUTIVE SUMMARY

The power system of Ireland and Northern Ireland faces significant change due to a large increase in renewable generation driven by government objectives to reach 40% renewable generation by 2020. EirGrid and SONI have the responsibility to enable increased levels of renewable sources, such as wind and solar, to generate on the power system whilst also ensuring secure electricity supply. The system operators have identified grid challenges relating to high penetrations of variable non-synchronous renewables in advance of other large systems. The Delivering a Secure Sustainable Electricity System (DS3) programme was initiated by EirGrid and SONI to address the challenges of integrating renewable generation on the power system. One of the key activities that the operators have undertaken is to investigate the capabilities of new technologies to address the challenges of integrating high levels of renewable generation. Schwungrad Energie Limited, an Irish based company has developed Flywheel/Battery Hybrid on the grid at Rhode, Co. Offaly and have engaged in a demonstration project with EirGrid to trial the technology. The demonstration enabled performance validation in preparation for commercial deployment of the solution in Ireland and subsequently Great Britain and mainland Europe as their grids realise similar levels of non-synchronous renewable penetration. This was a Demonstration Project in conjunction with EirGrid (TSO in Ireland) who provided a Disturbance Recorder to validate the performance.

This report presents the results from the demonstration project, showing how the Flywheel/Battery Hybrid solution responded to real frequency events over a period of nine months. The metrics used to classify the quality of performance are: response time and sustainability of power output, both of which are time based measurements.

The Flywheel/Battery Hybrid achieved the required performance targets. For events (defined as when the system frequency fell below 49.5Hz) both the flywheels and batteries achieved full output within 500ms from t=0 (defined as when the frequency fell through 49.8Hz). The flywheels can sustain full output for 5 min and the batteries for more than 20 min.

The results indicate that the Flywheel/Battery Hybrid would be suitable for providing fast responding services to grids. The demand for such fast responding services is expanding, driven by the transition to renewable based power systems.

BACKGROUND – NEED FOR ADDITIONAL SYSTEM SERVICES

TECHNICAL BACKGROUND

Ireland is an island electricity system with a peak demand of 6,878 MW, which is relatively small on a global scale. The Irish grid has a limited interconnection capacity of 1000 MW (2 x 250 MW Moyle and 500 MW EWIC) representing an import/export capability of 15% of peak demand. All the interconnection is DC and there is no synchronous AC interconnection. In addition to this the grid is undergoing significant change due to a large increase in renewable generation driven by government objectives to reach 40% renewable generation by 2020. The majority of this will be delivered from wind generation, which currently accounts for 21% of Ireland's electricity demand. The combination of low interconnection capacity and high renewables results in periods of very high system non-synchronous penetration (SNSP). The Delivering a Secure Sustainable Electricity System (DS3) programme was initiated by EirGrid and SONI to address the challenges of managing a power system with high levels of SNSP. Challenges include, controlling system frequency and voltage for adverse system events and maintaining overall stability of the grid.

Traditionally the grid frequency was set by the rotational speed of electrical machines spinning in synchronisation at 3,000 rpm. The output of these machines is controlled to accurately match the instantaneous system demand, which is relatively predictable. The deployment of non-synchronous machines, such as wind turbines whose output is dependent on the volatile wind speed, introduces two issues 1) lack of system inertia and 2) unpredictable power generation, the combination of which results in an imbalance between power supply and demand.

New sources of fast acting frequency response, are required to continue maintaining the grid frequency at a nominal 50 Hz (± 0.20 Hz). Fast acting frequency response can be delivered as a rapid injection of Real Power (MW) from a non-synchronised source, of a magnitude dependent on the change in grid frequency, quickly reconciling momentary any imbalance between the supply and demand for electricity.

The DS3 Programme (Delivering a Secure Sustainable Electricity System) is designed to address the challenges of operating an electricity system with a high penetration of variable non-synchronous renewable generation. System (Ancillary) Services are a key part of this programme and are designed to support the transmission of power from generator to consumer through the electricity system, while ensuring stability and reliability of supply. The DS3 Programme has defined fourteen system service products which in general are categorised in sequential timeframes.

The demand for System Services is increasing as a consequence of the transition to renewables which is largely driven by European Renewables Targets for 2020. A limit to the maximum allowable instantaneous penetration of non-synchronous generators – system non-synchronous penetration (SNSP) – is in place to ensure that system stability can be maintained at any instant. This metric also provides a proxy to ensure that there is a sufficient quantity of System Services. The SNSP limit, currently 55%, is a constraining factor which at times leads to the curtailment of renewables and substitution with conventional plant. In order to realise our renewable targets the electricity system will need to be capable of operating securely at a higher limit, expected to be 75%. Achieving this 75% SNSP limit would assist unlocking the potential of Ireland's abundant wind resource.

Table 1: System Service Products defined by DS3 Programme in various timeframes

New Services			Existing Services		
SIR	Synchronous Inertial Response		**SRP**	Steady-state reactive power	
FFR	Fast Frequency Response	2s - 10s	**POR**	Primary Operating Reserve	5s - 15s
DRR	Dynamic Reactive Response		**SOR**	Secondary Operating Reserve	15s – 90s
RM1	Ramping Margin 1 Hour	1h - 3h	**TOR1**	Tertiary Operating Reserve 1	90s – 5min
RM3	Ramping Margin 3 Hour	3h - 8h	**TOR2**	Tertiary Operating Reserve 2	5min - 20min
RM8	Ramping Margin 8 Hour	8h - 16h	**RRD**	Replacement Reserve (De-Synchronised)	20min - 1h
FPFAPR	Fast Post-Fault Active Power Recovery		**RRS**	Replacement Reserve (Synchronised)	20min - 1h

This project was set up to demonstrate the capability of flywheels and batteries to provide system services in the timeframe of 500ms to 20min without participating in the energy market. In this way batteries and flywheels can contribute to providing the required stability to the grid to allow SNSP to rise towards 75% while not displacing any renewable generation as would be the case with conventional plant running at minimum generation just to provide system services. The plant can also provide voltage control.

COMMERCIAL BACKGROUND

Schwungrad Energie undertook this demonstration to develop a solution to a growing problem and to demonstrate its performance and validate the benefits that the Flywheel/Battery Hybrid can provide. The demonstration plant is a showcase for Schwungrad where potential customers can witness the Hybrid system in operation.

INTRODUCTION

DESCRIPTION OF PLANT – TECHNICAL DETAILS

The plant has been designed specifically as a research facility which has added features to enable testing and monitoring.

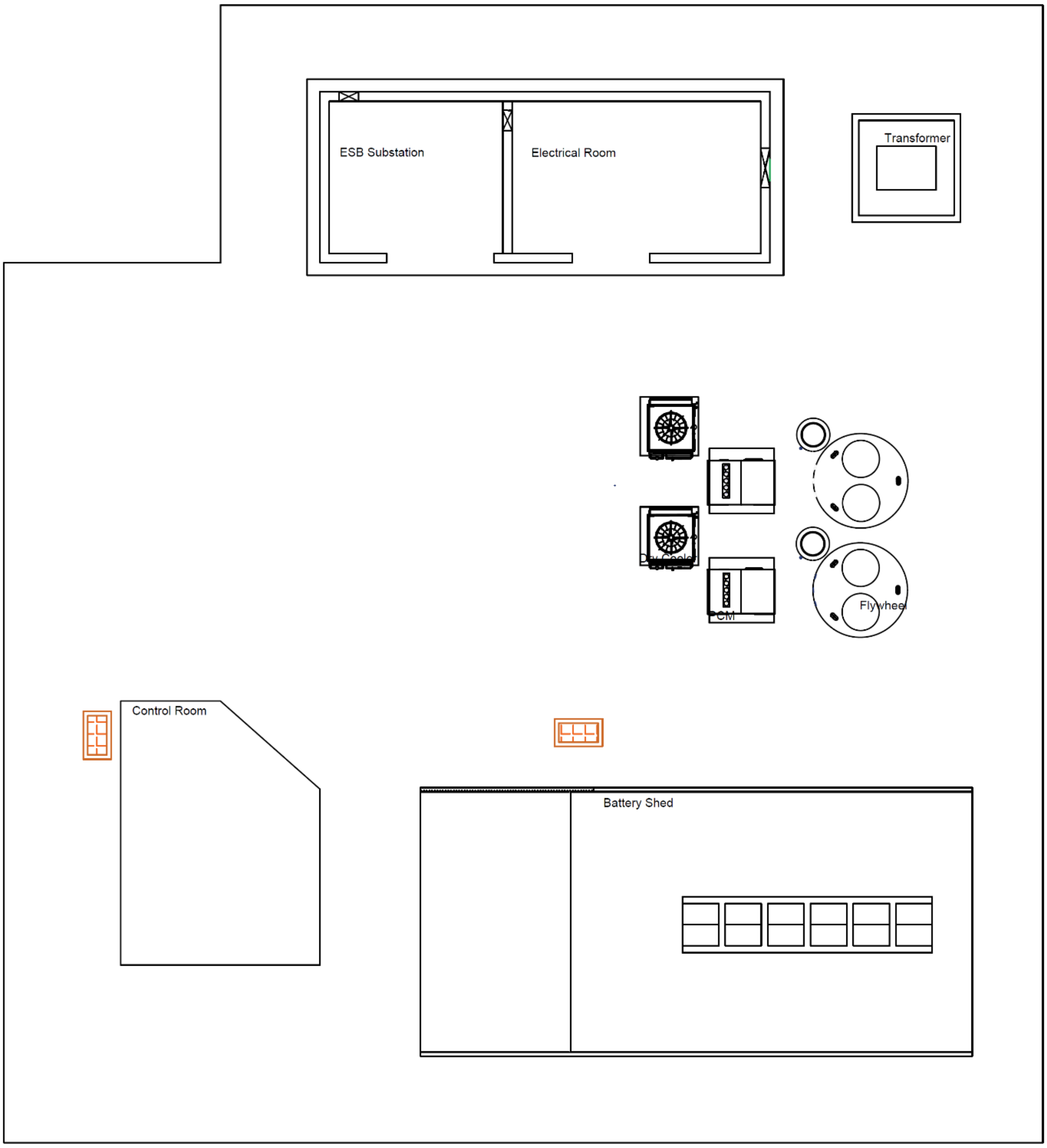
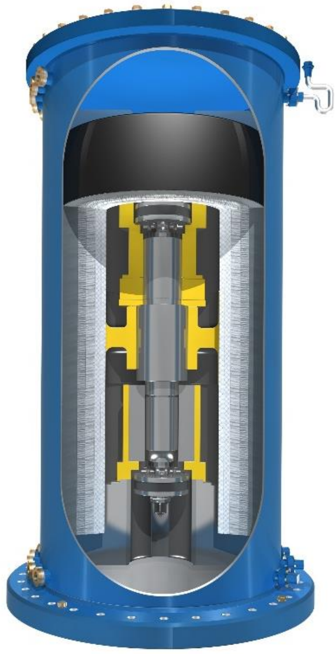


Figure 1: Rhode demonstration plant layout. Clockwise from top: ESB Substation/Electrical Room, Transformer, 2 x flywheel units with PCM and cooler, Battery housing with PCS, and Control Room.

FLYWHEEL TECHNOLOGY



- Manufacturer: Beacon Power, LLC.
- Flywheel Model: Gen. 400 FESM
- Design life: 175,000 cycles (20 years)
- Supply Voltage: 480 VAC
- Power rating: 160 kVA
- Storage capacity: 30 kWh
- Response time: 100 ms
- Roundtrip efficiency: > 85%
- Power Control Module (PCM): Converts variable speed motor output into a clean and stable source of AC power.
- Dry Cooler: Fan power 480 VAC

BATTERY TECHNOLOGY

- Manufacturer: Hitachi Chemical Co., Ltd.
- Battery model: LL1500-WS
- Battery type: Valve Regulated Lead Acid (VRLA)
- Design life: 4,500 cycles (17 years)
- Number of cells: 192
- Number of parallel strings: 1
- Power rating: 160 kVA
- Battery capacity: 1500 Ah (576 kWh)
- DC voltage: 400 V
- Weight: 195 kg

POWER CONVERSION SYSTEM

- Manufacturer: Freqcon
- Model: NGC 160kW Converter
- IGBT type SKiiP 603 GD123-3DUW V3
- Rated AC voltage (Vr) 400 V, 3-phase system
- Rated AC current 232 A
- Rated power (Pr) 160 kW
- DC link voltage ±450 V (working range 200V to 700V)

CONTROL SYSTEM

- Manufacturer: Yokogawa
- FAST/TOOLS SCADA
- Exequantum data historian

COMMUNICATIONS

As the demonstration project involved a combination of technologies a number of communication protocols were used to communicate between the various technologies. Initially, the communication path chosen for the Flywheels proved to be faster than that used by the batteries. However, as a result of optimisation during the demonstration project the reaction time of the batteries was reduced resulting in an equally fast response from both batteries and flywheels.

CONTROL ALGORITHMS

EirGrid and Schwungrad collaborated to develop four frequency control modes based on likely future system requirements. Schwungrad designed and implemented the algorithms to deliver these control modes using inputs based on grid frequency and voltage to determine an optimum combination for active and Reactive Power output from the flywheels and batteries. The algorithms have a number of variable set points and slopes for both power and frequency which define the plant output curve.

These algorithms were reviewed and approved by EirGrid prior to implementation. Feedback from EirGrid was incorporated into the algorithms.

The inputs for the control system are provided by a high resolution frequency monitoring equipment. This is used to provide a dynamic and smooth response, in all operational Modes: enabling a different power output for every 10 mHz. In addition to dynamic response, the plant can deliver full power in two situations: 1) when the frequency dips below a particular threshold, typically 49.80Hz or 2) on detection of a RoCoF event. On detection of a high rate of change of frequency (RoCoF) event the plant delivers full power for 5 seconds after which it reverts to monitoring the grid frequency and adjusts the power output accordingly. The injected/used energy is replaced during the normal periodic equalisation charge or, in some cases following frequent usage, the system is charged when the frequency is within the ± 0.05 Hz deadband. This maintains the State of Charge within preset limits. For the Demonstration these limits were set to 87% - 90%.

FREQUENCY RESPONSE

Imbalances in the power system, between generation and consumption can increase or decrease the desired nominal frequency of 50Hz.

The primary function of the Hybrid is to provide frequency response. The plant will inject power as the frequency of the grid falls and can also absorb excess power if it rises.

MODE 1: STATIC RESPONSE

This mode is the least complex operational mode and was designed primarily for test purposes, minimising the processing and calculation requirements on the control system. This mode delivers a triggered MW response once a frequency threshold has been breached. The mode includes a deadband where the device will provide no frequency response and a droop characteristic between the edge of the deadband and the static trigger response. A frequency recovery trigger point is also included to trigger the device back down to the droop line. Recharging the flywheels and batteries after an event to return them to a preset State of Charge occurs only when the frequency has sufficiently recovered i.e. is within the deadband.

If the frequency rises above the deadband (set at 50.05Hz for the Demonstration) the control algorithm causes the flywheels and batteries to absorb power to reduce the frequency back towards 50Hz.

MODE 2: FEEDBACK RESPONSE

Feedback Response mode is the most intelligent mode and is designed to deliver an enhanced performance from the plant. It has been designed to gradually reduce the power output as the frequency recovers from its nadir.

This mode delivers a triggered MW response once a frequency threshold has been breached. The mode includes a deadband where the device will provide no frequency response and a droop characteristic between the edge of the deadband and the triggered response point. The device then provides a droop response on frequency recovery. Recharging the flywheels and batteries after an event to return them to a preset State of Charge occurs only when the frequency has sufficiently recovered i.e. is within the deadband.

If the frequency rises outside the deadband the control algorithm causes the flywheels and batteries to absorb power to reduce the frequency back towards 50Hz.

MODE 3: DROOP

In Droop Mode the plant provides an output that is similar to that provided by large traditional generators. The slopes get more pronounced as the frequency falls away from 50Hz.

In Droop Mode there is no large step in power output. Power output increases gradually based on two slopes, which cover the full range of frequency becoming steeper as grid frequency deviates further from nominal. The mode includes a deadband within which the device does not provide frequency response. Outside the deadband the device provides a proportional droop response to frequency. Once the frequency breaches a pre-set threshold, the device provides a proportional droop response on a more aggressive droop slope. The slopes of both droop characteristics are settable.

Recharging the flywheels and batteries after an event to return them to a preset State of Charge occurs only when the frequency has sufficiently recovered i.e. is within the deadband.

If the frequency rises outside the deadband the control algorithm causes the flywheels and batteries to absorb power to reduce the frequency back towards 50Hz.

VOLTAGE RESPONSE

In the Voltage response modes, the plant absorbs or injects Reactive Power as the ESB Network voltage increases or decreases. The voltage is referenced to the medium voltage distribution network and is currently set at 20kV (variable).

The hybrid plant is able to deliver Reactive Power in any point of the quadrant of the Apparent Power i.e. it can provide any combination of active and Reactive Power which means it can separately provide frequency and voltage control.

The control system prioritises the delivery of Real Power over Reactive Power, as determined by EirGrid. For example, if the frequency drops and Active Power is required, this reduces the Reactive Power available to control the voltage.

MODE 4: POWER FACTOR CONTROL MODE

In Power Factor Control Mode, the Power Factor can be set between 0.95 and 1. The plant is capable of both leading and lagging but as it is connected at medium voltage to the distribution network there is a restriction that the plant is not allowed to export Reactive Power. This restriction would not apply if the plant was connected to the transmission grid.

The Reactive Power is calculated to give the required power factor at the Active Power output at that moment. This algorithm also determines an offset if the voltage is outside a range between a minimum and maximum voltage setpoint. It adds/subtracts that offset to the Reactive Power needed, only when the voltage deadband thresholds are breached. It should be noted that the algorithm calculates a Reactive Power command which provides the required power factor for the Active Power command at that time i.e. the Active Power and Reactive Power commands to the flywheel and batteries yield the desired power factor. The actual Active Power and Reactive Power at the point of connection will be slightly different because of the effects of the transformer and also any house load.

MODE 5: VOLTAGE CONTROL MODE

Voltage Control Mode is designed to bring the local voltage to the desired set point, based on a droop characteristic. If the local voltage is below the set point, the plant will export kVAR to increase the voltage. Conversely, if the local voltage is above the set point, the plant will absorb kVAR to reduce the voltage.

In a commercial plant connected to the transmission grid, EirGrid would send the voltage set point, to the plant as a command. As this was a demonstration plant of less than 0.5MW connected into the local distribution network, it was determined to be uneconomical to set up such communications with EirGrid's DCC. Instead the set point was adjusted manually with the control system.

MODE 6: REACTIVE POWER CONTROL MODE

A third Reactive Power control mode would be for EirGrid's NCC to send a command to the plant to provide kVAR exporting or importing. Again this was deemed unfeasible for a small demonstration plant. Instead such commands were given locally through the control system GUI.

The Reactive Power control algorithms were tested offline during commissioning but Reactive Power response was not recorded as part of the demonstration due to the network limitations on the export of Reactive Power. Although the plant is equipped with this capability the Reactive Power control was disabled for the duration of the demonstration.

TEST METHODOLOGY

RESPONSE TO REAL EVENTS

It was decided that the plant should operate in each mode for a number of months in order to observe the performance of each mode in response to actual system events. After realising an adequate quantity and range of representative frequency events the plant was manually switched from one mode to the next.

The hybrid is a 422kW demonstration plant connected to the distribution network in a rural area. In conjunction with the Distribution Network Operator it was decided that the operation of the plant would only include the Active Power capabilities of the plant to minimise the risk of breaching power quality standards. However, during commissioning, the algorithms for the 3 modes of voltage control were tested and verified.

MANUAL/SIMULATED TESTING

A series of manual tests were designed to monitor the response of the plant to simulated normal grid conditions, low frequency events and simulated RoCoF events. Manual control overrides the automated control system, stopping it from monitoring live grid conditions.

The plant delivers Real Power to the grid when manual response is selected, providing a physical response to a simulated input. This was typically used to validate any modifications to the plant or the control algorithms.

RATE OF CHANGE OF FREQUENCY (ROCOF)

Before any events were experienced a test signal was generated to simulate a rapid change in the system frequency. The RoCoF simulation was programmed into the control software and can be simulated at any time.

A grid induced RoCoF trigger occurs when the frequency suddenly drops as a result of the loss of a large generator. The frequency transducer provides a frequency signal every 2 cycles (40ms). The Yokogawa control system monitors this frequency and the rate of change of frequency. If the rate of change of frequency exceeds a threshold the control system generates a “full blast” command. This “full blast” remains for a set period, after which if reverts to the normal control algorithm in whatever mode has been selected. A set period of 5 sec was used for the Demonstration but this is a parameter which can be changed. The Yokogawa system takes less than 10ms to process the frequency signal and send the “full blast” command to the Beacon and Freqcon inverter controllers.

LOW FREQUENCY SIMULATION

A typical frequency curve for a frequency event was generated and programmed into the control software as a hard coded event which can be simulated at any time. This simulation is designed to test the plant output over a broad frequency range. The curve can be seen in Figure 2. It was useful during the early commissioning and testing phase and also as a demonstrator for visitors to show how the plant performs under a frequency event.

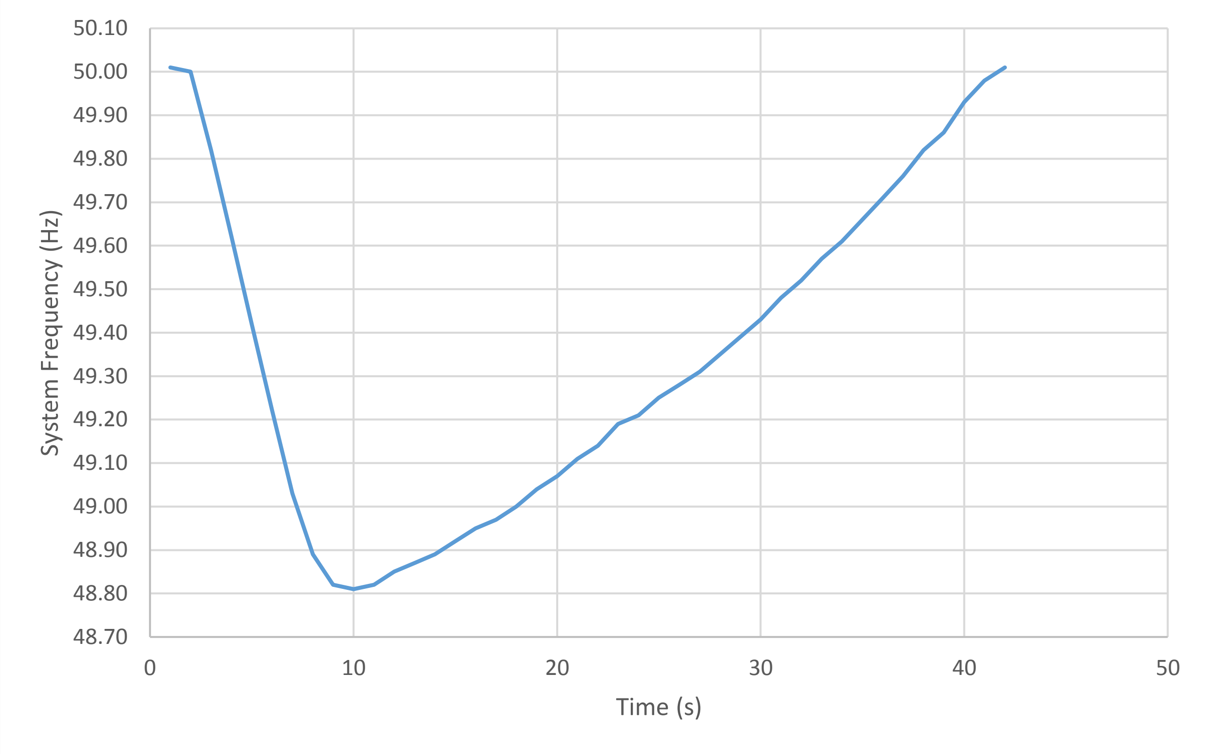


Figure 2: Low Frequency Curve

PERFORMANCE RESULTS

TARGET PERFORMANCE

Schwungrad Energie plans to deploy the hybrid technology pending the results of the demonstration. For a commercial installation the target is to deliver the following DS3 products: FFR, POR, SOR, TOR1 and TOR2. In order to maximise revenue generation, the following performance metrics were set:

- Response time: 0.5 s
- Output Sustainability: Flywheels 5 min, Batteries 20 min

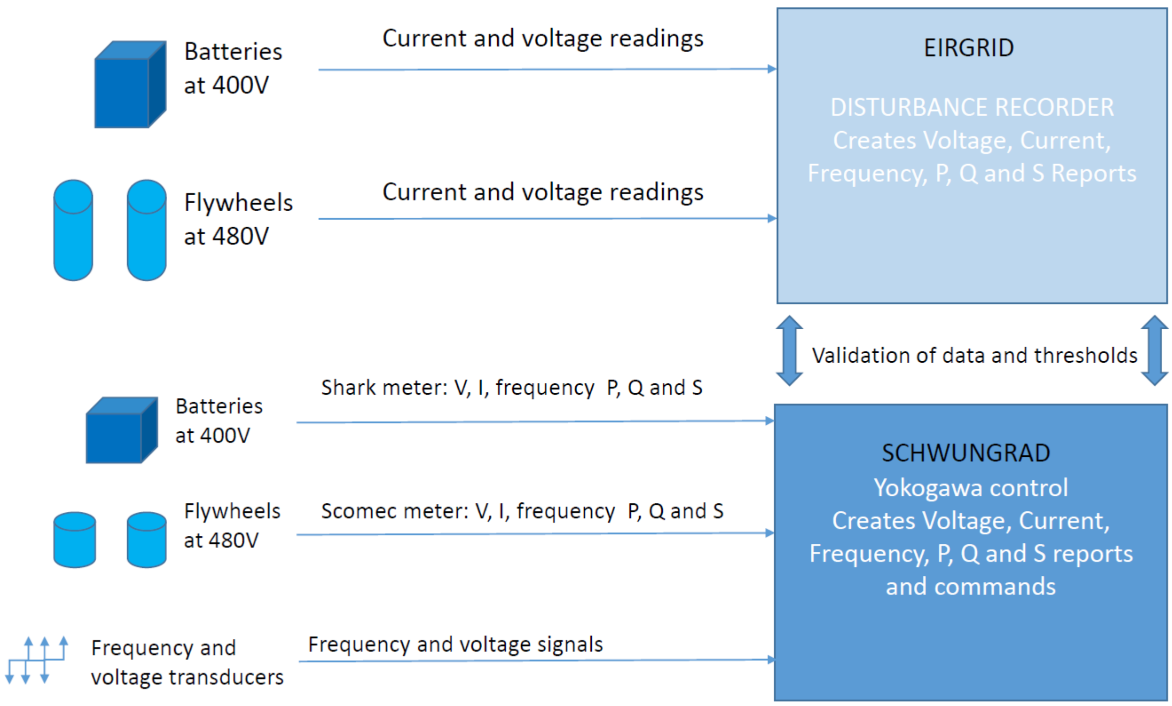
Meeting these performance metrics will deem the technology commercially viable. Voltage control will also be provided.

VALIDATION OF RESULTS

The plant has high accuracy frequency and voltage transducer to permanently monitor the grid. They are used to feed into the algorithms and determine the Hybrid's output at any given time.

The plant performance is monitored and recorded by the Yokogawa Plant Information Management System - Exaquantum and also independently by EirGrid's Disturbance Recorder. The performance results presented in this report have been recorded by EirGrid's Disturbance Recorder.

MONITORING AND MEASUREMENT



The Disturbance Recorder monitors the frequency, current and voltage. The readings are used to generate reports that demonstrate the reaction time and performance provided by the hybrid; similarly Schwungrad uses frequency and voltage transducers that feed into the master controller and determine the commands send to the flywheels and batteries. In addition Schwungrad has two high accuracy meters (one at the batteries circuit and other at the Flywheels circuit) to generate reports. Currently the health and accuracy of the readings is validated by the different sensors, meters and the independently managed disturbance recorder.

All the events shown below have been recorded by Eirgrid's Disturbance recorder and validated by Schwungrad meters and sensors.

OUTPUT SUSTAINABILITY TESTS

FLYWHEEL

The Flywheels have proven their capability of sustaining full output for over 5 minutes after which the output power reduces gradually as the flywheel loses its remaining kinetic energy over an additional period of 10 minutes.

BATTERY

The batteries demonstrated a capability of sustaining full output for 20 minutes, stop for 5 minutes go into full output for another 20 minutes, repeating the process 3 consecutive times and still remain available to assist the grid if necessary.

The battery recharges by absorbing power from the network. Recharging is achieved in two ways 1) during normal operation the battery will receive a periodic equalisation charge, this is a low current charge sustained over a long duration and occurs every couple of weeks and 2) if the State of Charge of the battery falls below a set point, as a result, for example of discharding for a frequency event, the controls will recharge the batteries at 10% of nominal power capacity if the frequency is healthy and is in the 0.05Hz deadband.

HYBRID

The output from the hybrid is the combined output from the two technologies. The result is the plant can deliver full power for 5 minutes and sustain an output from the batteries for a further 15 minutes.

REACTION TIME TESTS

Real data obtained from the Disturbance Recorder provided by Eirgrid for the demonstration to monitor and validate the hybrid performance is analysed below.

The events displayed are real frequency events where the frequency changed due to a mismatch between generation and demand, probably due to a trip of a generator or the interconnector.

The Analysis section demonstrates that the system is able to go into full output in under 0.5 seconds. This is measured from the time of system frequency falling through 49.80Hz until the flywheels and battery first reach 320kW and 160kW respectively.

ROCOF TESTS

The example below shows a physical response to a simulated RoCoF command. Both flywheels and batteries go into full blast and sustain that for 5 seconds.

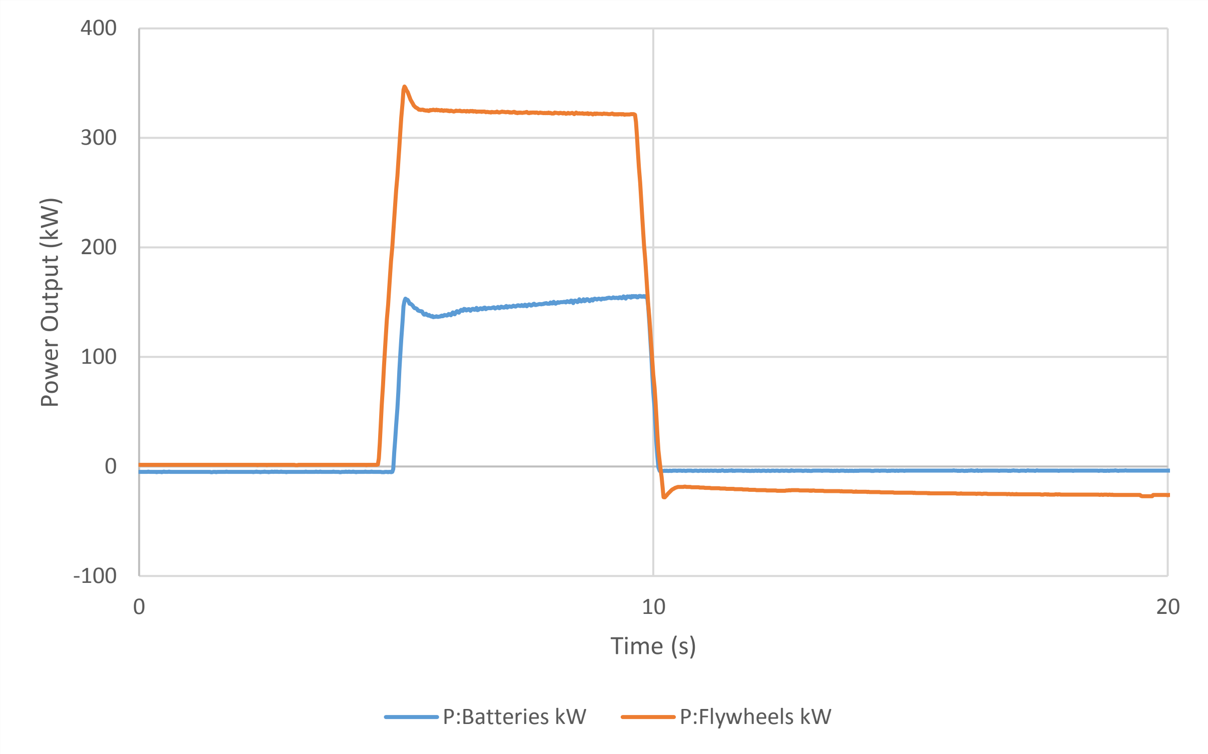


Figure 3: Hybrid response to simulated RoCoF event

During the demonstration different communication protocols and technologies were tested. The results show that the command reaches the Flywheel inverter sooner that the battery. However, once received the batteries ramp up more quickly than the Flywheels and both reach maximum power output at approx. the same time.

During the course of the demonstration the controls were modified to optimise the performance of the hybrid system. Optimisation included the minimisation of power output undershoot having reached full power output. The implementation of these modifications resulted in an improved response from the batteries.

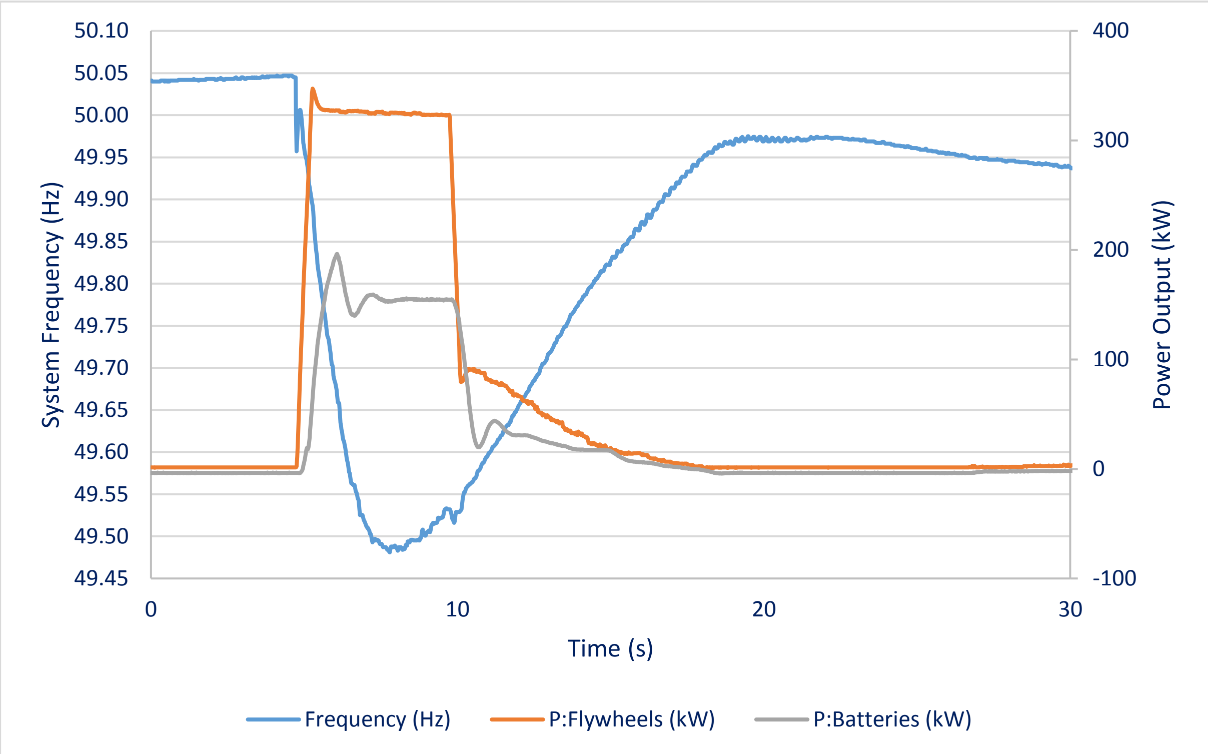


Figure 4: 03/09/2016 at 14:27:42.035 - Plant response to RoCoF event and reverting to Droop mode

The controller was in Droop mode when this event occurred, shown in Figure 4. It detected a sudden change in the frequency. As the RoCoF was detected, the hybrid was requested to deliver full power: 320kW from Flywheels and 160kW from batteries. Once the system triggered back into droop mode the reaction time for each individual frequency is approximately 2 cycles. The flywheels discharged by 0.75% for the event and the batteries by approximately 0.038%.

On detection of a RoCoF the Master Controller predicted that a frequency event was starting, and commanded the plant to deliver full power. The flywheels achieved full power output within 0.5 seconds time the ROCOF signal was set and achieved full power before the frequency went below 49.80Hz, which is time 0. The batteries achieved full power rapidly after the frequency fell through 49.80Hz. Full power output was maintained for 5 seconds, as per RoCoF command, after which the control system reverted to monitoring the grid frequency and adjusted plant power output accordingly.

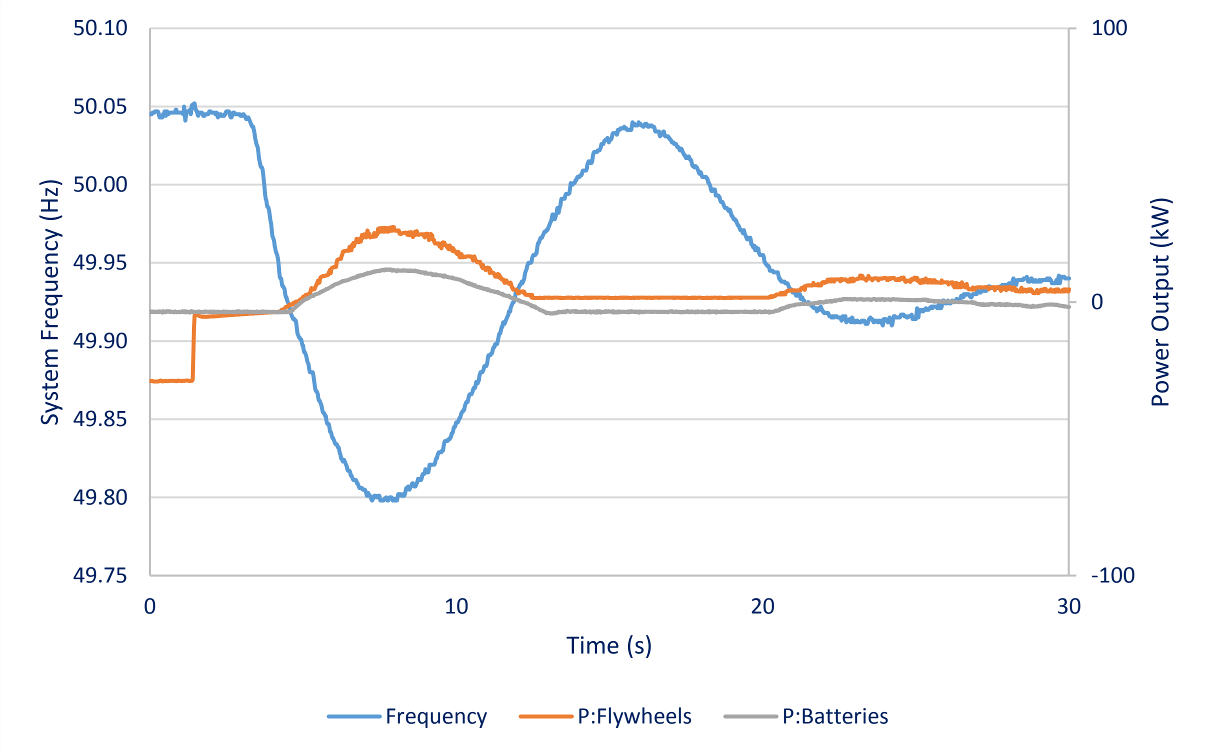


Figure 5: 04/08/2016 at 14:00:12.190 - Plant response in Droop mode

In this example, Figure 5, the system was in Droop mode when the system frequency fell from 50.05Hz to 49.80Hz over a period of approximately 5 seconds. Both flywheels and batteries adjusted their power output according to Droop Mode, precisely adjusting to the fall and rise of grid frequency. This provided a very smooth output from the plant as the frequency recovered but then fell again.

For each value of frequency the system delivered a certain amount of Active Power, processing, communication and ramping time in droop mode is almost instantaneous as the steps are very small. In this occasion both flywheels and batteries were discharged by a negligible amount.

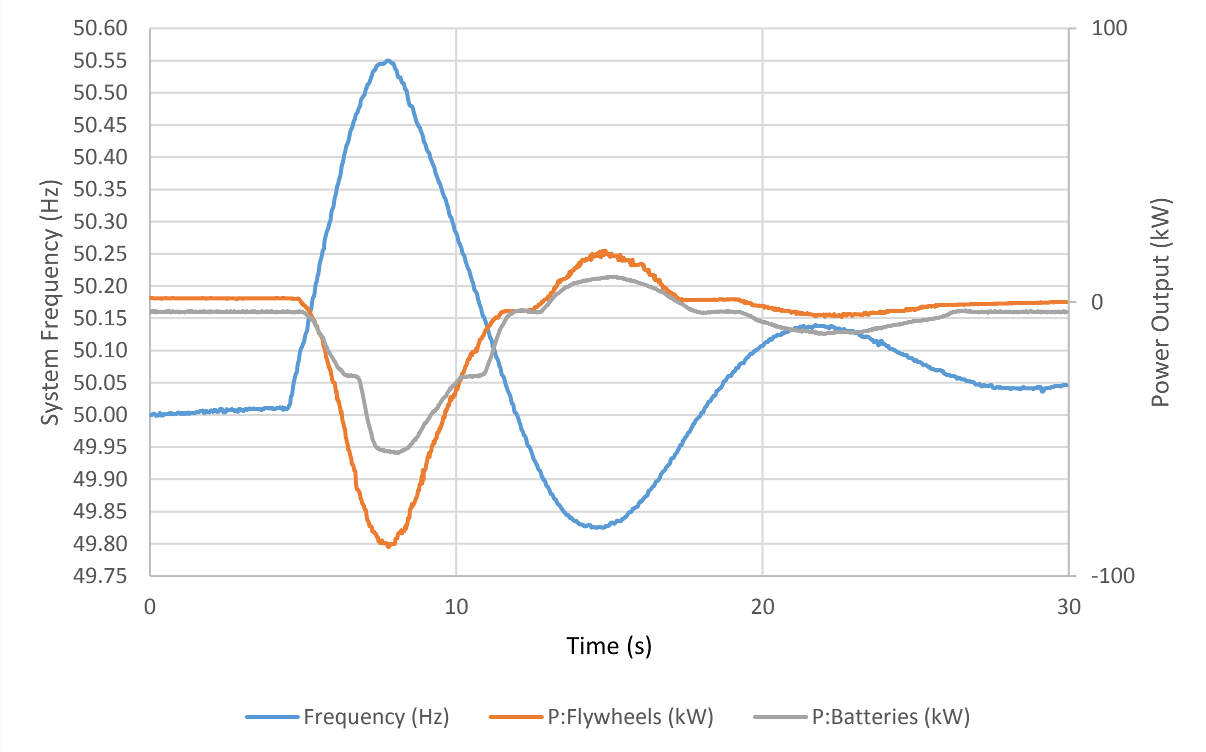


Figure 6: 09/08/2016 at 12:11:01.379 - Plant response an over frequency in Droop mode

In this example, Figure 6, it is believed that the interconnector tripped while Ireland was exporting energy into the National Grid.

As a result there was an over frequency event, followed by a small under frequency event. The hybrid system is also able to assist the grid in this type of situations, by absorbing the excess power while the frequency is high and releasing it while the frequency is low.

The hybrid was in droop mode during this over frequency event, flywheels and batteries started absorbing power when the frequency reached 50.05Hz and changed the slope at 50.40Hz.

For each value of frequency the system absorbed a certain amount of Active Power, processing, communication and ramping time in droop mode is almost instantaneous, as the steps are very small, rapidly reaching each desired output. In this occasion both flywheels and batteries were charged by a negligible amount, smaller than 0.5% of the State of Charge.

This example shows the output from the battery with shoulders at a particular frequency (50.20Hz). This was a result of it being the first test for power absorption and following this the controls were modified.

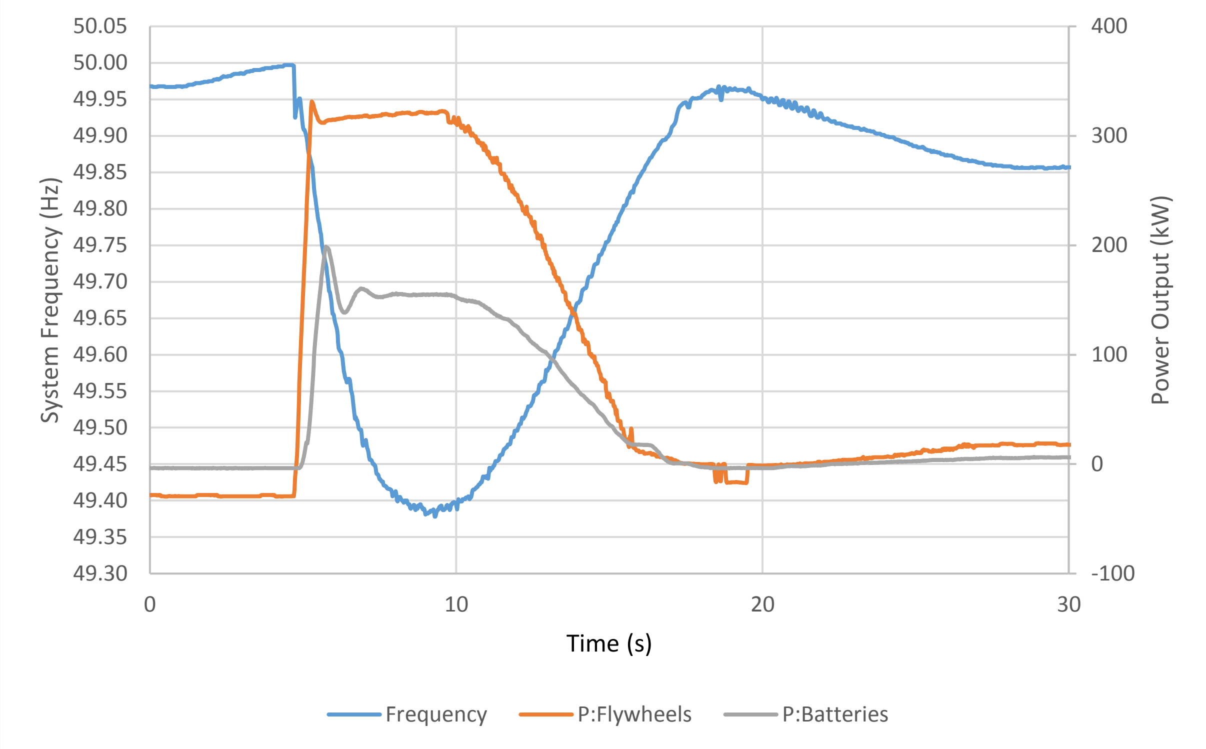


Figure 7: 17/07/2016 at 10:46:19.390 - Plant response to RoCoF event and reverting to Feedback Response mode

This system Frequency Event, Figure 7, is believed to be a consequence of the loss of a large generator.

In this system Frequency Event the plant is in Feedback Response mode, again the system detected a sudden change in the rate of frequency and sent the full blast command anticipating the dip in frequency before it passed below 49.8Hz. Full blast was then maintain for 5 seconds, after that, the system reverted into Feedback Response mode. As the frequency recovered, the output of the hybrid decreased.

On detection of a RoCoF the Master Controller predicted that a frequency event was starting, and commanded the plant to deliver full power.

Once the system reverted back to Feedback Response mode the frequency was already recovering so the hybrid calculated a droop from full blast to the total recovery of the frequency assigning a value of power output for each value of frequency; under this circumstances the flywheels reach the desired output rapidly.

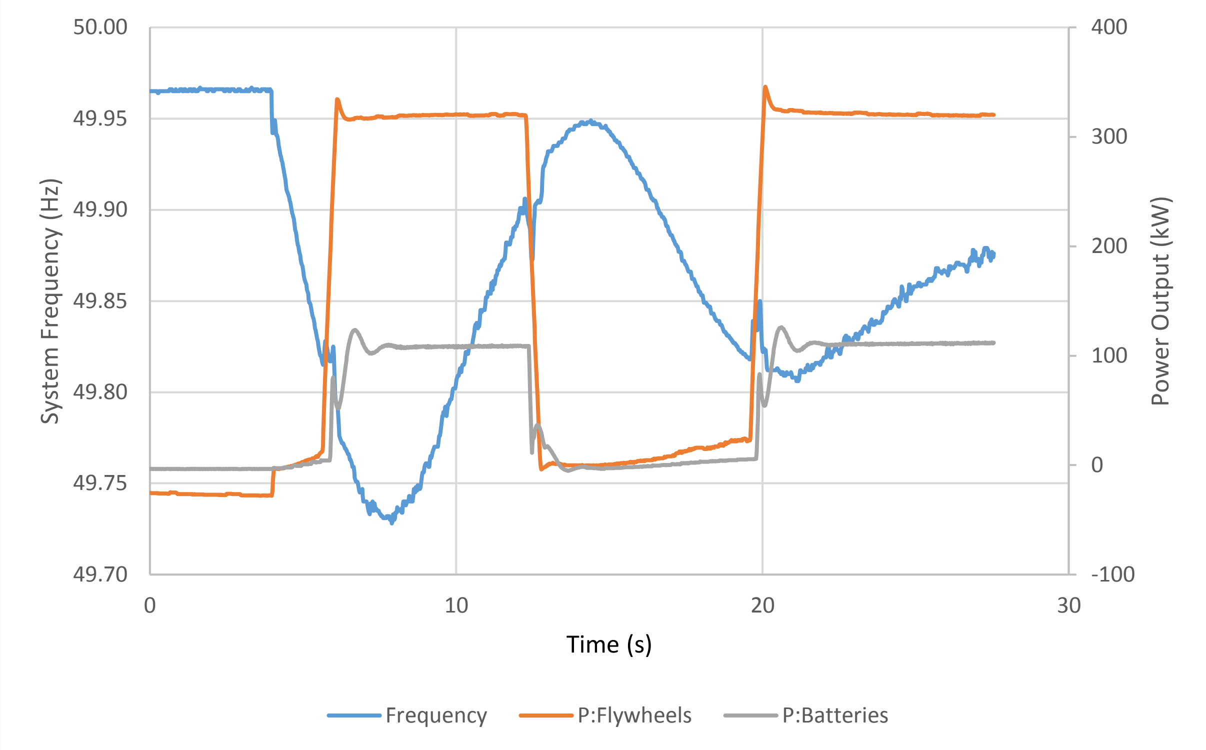


Figure 8: 07/11/2016 at 06:17:06.451 – Plant response to frequency event in Static Response mode

In this example the plant was in Static Response Mode, Figure 8.

During the event, the frequency fell gradually and when the frequency fell below 49.80Hz the controller sent the full blast command to both flywheels and batteries. The sudden change in power output created some momentary disturbance in the frequency readings provided by the disturbance recorder. However the device recovered in a few cycles and continued to provide accurate readings after that.

It is very difficult in this case to clearly establish time 0, and ramping time of the batteries as the Power exported by the flywheels affected the frequency and power output of the batteries readings in the disturbance recorder. In a commercial size plant a GPS antenna in the disturbance recorder would cross correlate the values of frequency in different points of the Irish grid.

The flywheels were recharging prior of the start of the frequency event, once the frequency reached 49.95Hz, the flywheels stopped charging and started to gradually increase the power export as the frequency continued to fall, as mentioned earlier, once the frequency reached 49.80Hz the system sent the full blast command.

The ramping time of the flywheels was < 500 ms, the full output was sustained until the frequency recovered above 49.90Hz.

The hybrid is designed to be available to assist the grid given that it has enough energy to do so, there is no recovery time needed, as soon as the frequency recovers from a frequency event the plant is ready again.

GENERAL OPERATIONAL PERFORMANCE OF PLANT

FLYWHEEL OPERATION

As with the battery, the flywheel has operational constraints which were specified by Beacon Power. These constraints are very different for the flywheel than the battery as they are mechanical as opposed to chemical but refer to the same parameters such as State of Charge, charge/discharge rates etc. For example the State of Charge of the flywheel needs to be continuously conditioned, consuming power, as it has higher losses than the battery. To achieve this, a different control strategy was developed.

BATTERY OPERATION

The Valve Regulated Lead Acid battery supplied by Hitachi Chemical Co., Ltd. has specific operational constraints for the battery. The constraints include maximum power output/input, maximum and minimum State of Charge and maximum depth of discharge etc. These were taken into account when designing the control system to ensure the optimum balance between conservation of battery life and delivery of DS3 system services.

Figure 9 shows the profile of power delivery during a four week period. It indicates that for the vast majority of the time the battery remained in standby mode where the power output was nearly zero (<5kW). The impact of this on the power system is that it can operate with a high penetration of renewables without the need for curtailment as the battery is a non-energy source of reserve. The graph also shows that the battery delivered full power during the course of the month but for a very short time, a fraction of a one hour.

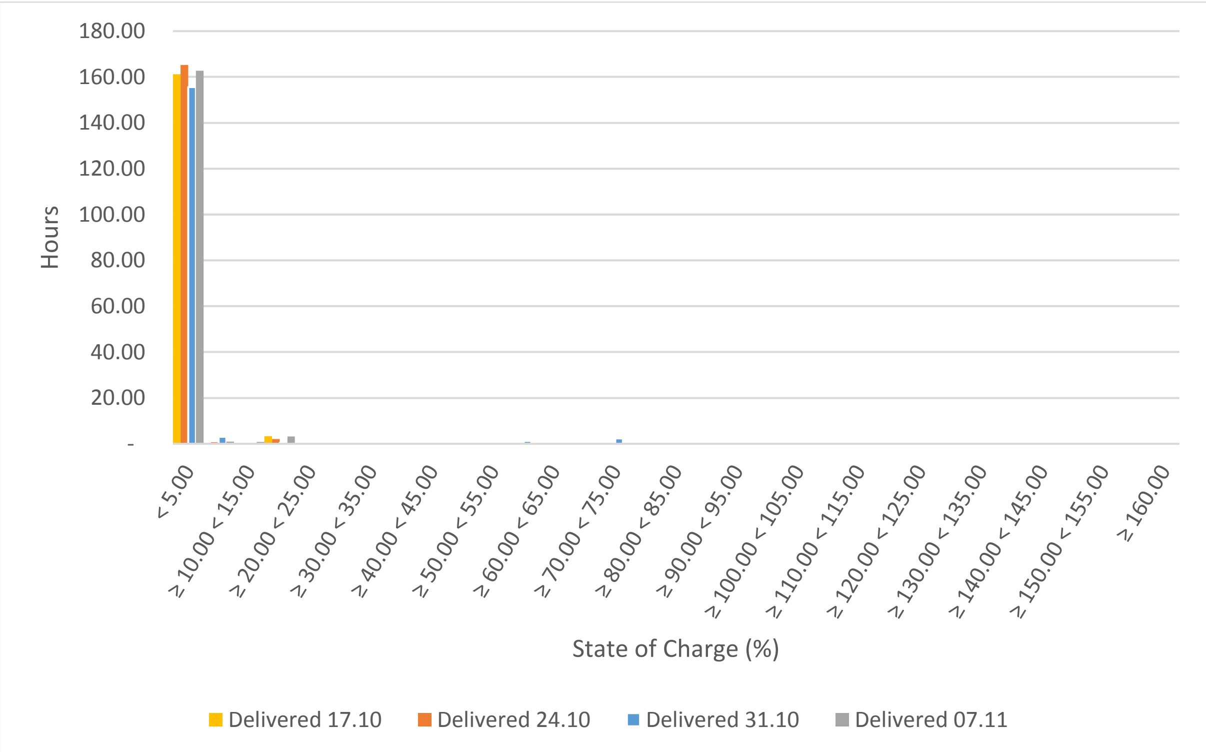


Figure 9: Battery Delivered kW Distribution (17/10/2016 to 14/11/2016)

Maintaining a high State of Charge ensures that the plant availability is maximised allowing for multiple successive responses to system frequency events without the need to recharge. The State of Charge of the battery is shown in Figure 10 to be between 85% and 90%. This is within the design specification of Lead Acid battery technology and also very suitable for the demands of unidirectional system services i.e. provision of additional power output.

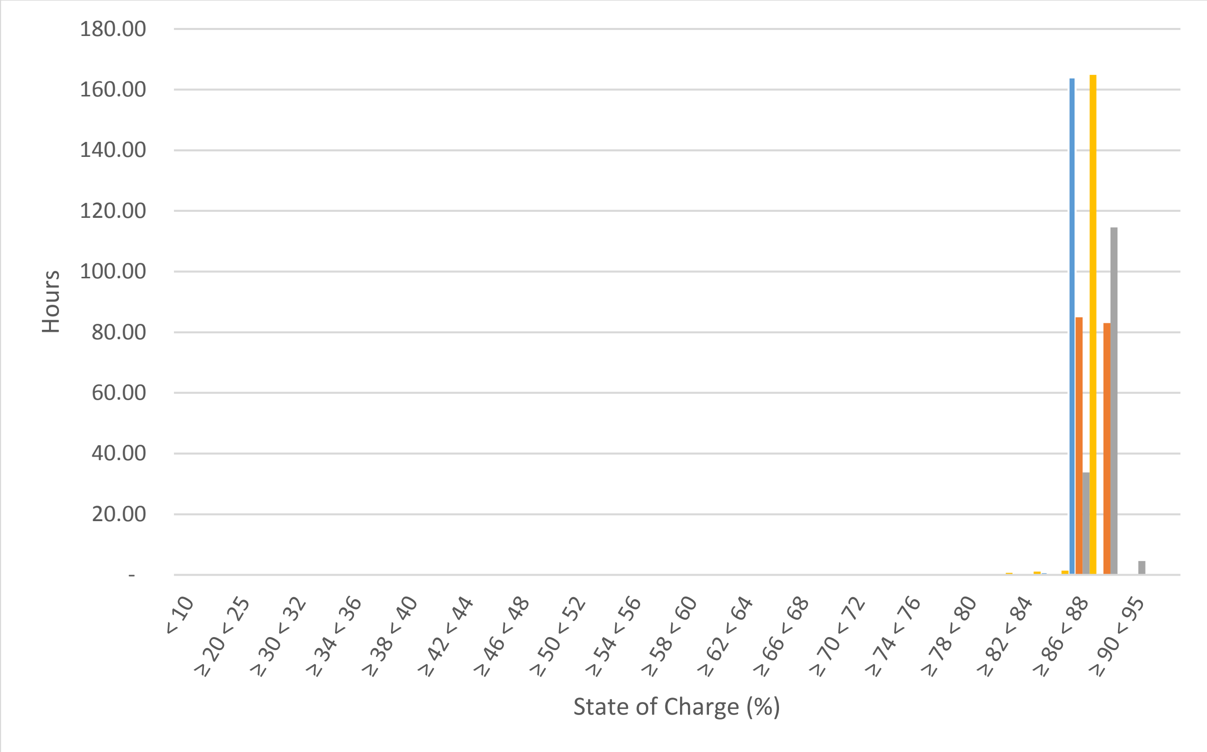


Figure 10: Battery State of Charge Distribution (17/10/2016 to 14/11/2016)

LEARNINGS/ OUTCOME

The communication protocols used for the flywheel commands are better and faster than the ones used with the batteries. This was quantified using a manual RoCoF trigger which sends a signal to both technologies simultaneously: the flywheels started ramping after 4.5 seconds and the batteries shortly after that, although the ramping time is clearly quicker for the batteries than for the flywheels, the flywheels achieved full power faster than the batteries. When moving this technology into a full size commercial plant, the learnings from this demonstration will be applied to the batteries communication control architecture with the intended result being a reduction in reaction time.

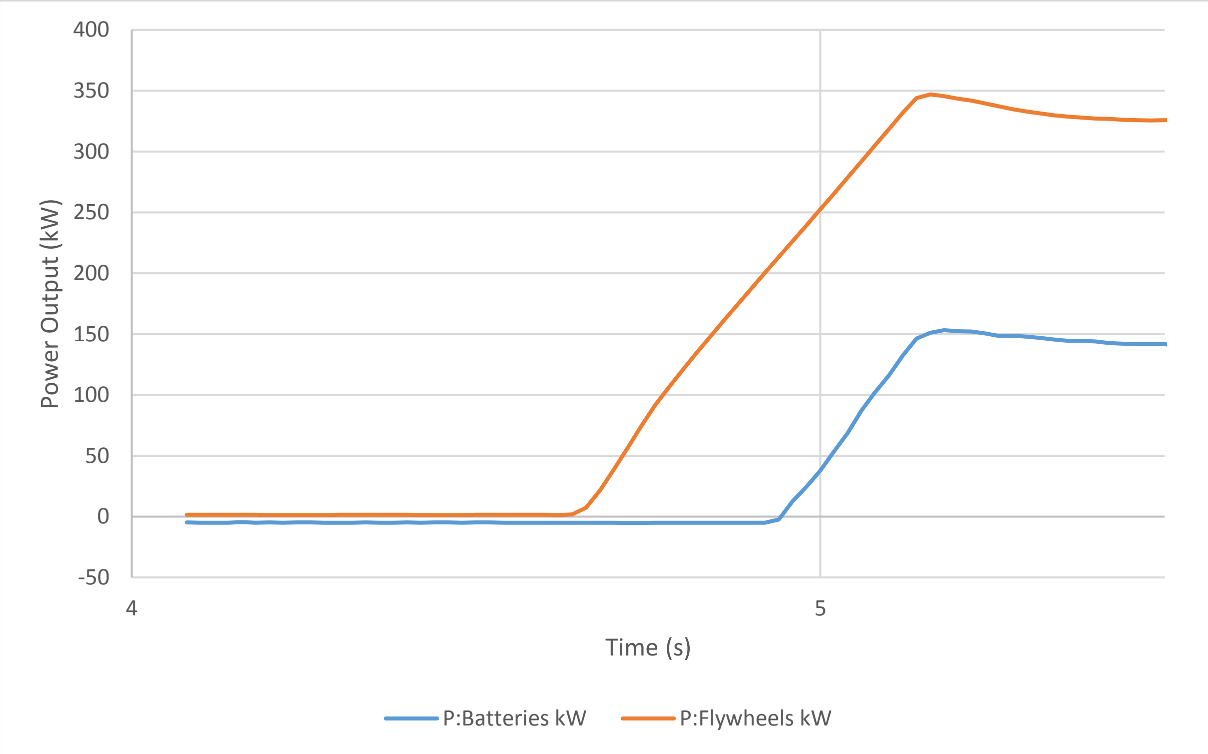


Figure 11: Signal processing/communication delay

The demonstration plant is connected to the Distribution Network in a rural area with customer demand loads. That has created power quality challenged and the impossibility of testing voltage control.

With some alterations to the controls of the Hybrid system, there are a range of additional applications which could benefit from rapid power injection e.g. wind power plants, pump hydro, and Waste to Energy plants. These applications were not part of this Demonstration project.

CONCLUSIONS

The power system of Ireland and Northern Ireland is currently undergoing significant change due to the increased penetration of non-synchronous renewable generation. The system operators are currently undertaking a programme of work to deliver solutions to address the operational challenges associated with these changes. One area that the TSOs are investigating is the deployment of new technologies to help address these challenges. This project investigated the application of a flywheel and battery solution developed by Schwungrad Energie. The plant performed well and we demonstrated that, over a number of events, it consistently had a very fast response time of the order of 500ms, either by using ROCOF detection or when the frequency falls gradually and sustained a steady output until the frequency recovered.

This demonstration shows the potential for a hybrid of flywheels and batteries to respond rapidly to a sudden fall in frequency. By responding rapidly the fall in frequency could be arrested faster and the frequency nadir reduced.

Despite being a novel approach in Europe, we have proven that we can deploy the plant very quickly, wherever it is needed. We have learnt very valuable lessons while commissioning the hybrid demonstration plant and the control algorithms. We are confident of our capabilities of building a new plant even quicker.