Network Innovation Competition: Enhanced Frequency Control Capability (NIC EFCC)

Demand Side Management Approaches to Enhanced Frequency Control in a Low Inertia System

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FLEXITRICITY

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Executive Summary

Flexitricity is the sole provider of Demand-Side Response (DSR) to the Enhanced Frequency Control Capability (EFCC) project. Flexitricity's role in EFCC was to explore and demonstrate ways in which Demand Side Response could provide support to a low inertia electricity system. To this end, Flexitricity developed three new services for this project:

- **Static RoCoF** involves an electrical load being switched off in response to the Rate of Change of Frequency (RoCoF) breaching a specified limit.
- **Spinning Inertia** involves operating synchronous embedded generators (CHP engines) at part and full load and monitoring their response to variations in mains frequency.
- **Dynamic RoCoF** involves adjusting flexible loads in response to a locally measured RoCoF value.

These new services were operated using generation and electrical load assets located on sites belonging to Flexitricity's commercial partners. Specifically, these sites were:

- Static RoCoF:
  - A chemical manufacturer with a 6MW compressor unit;
- Spinning Inertia:
  - A large greenhouse with two CHP engines;
  - A district heating plant with two CHP engines;
- Dynamic RoCoF:
  - A cold store facility with compressors;
  - A wastewater treatment work with blowers and pumps;
  - A wastewater pumping station.

Working with these partners, Flexitricity installed frequency and RoCoF monitoring equipment on each site and integrated these into the site equipment's control systems. We also installed outstations and communication channels to allow us to monitor the sites and to arm and disarm the RoCoF response when required. At some sites, the frequency and RoCoF monitoring equipment was provided by project partners GE, while on others, it was provided by Flexitricity.

A central element of the project was to determine the operational parameters that the monitoring equipment would work to and to create the technical functionality to support these parameters. In most cases technical parameters were adjusted following a period of observation after equipment was installed on site. This document explains underlying functionality and the initial and final operational parameters for all services.

Demonstrating the effectiveness of these services required observing the site's assets respond to real-life mains frequency detected locally. Of particular interest was each site's performance during instances of rapidly changing frequency and high RoCoF, these occasions being indicative of the more volatile frequency behaviour associated with a low inertia system. Field trials took place on all sites over several months during 2017 and 2018. The sites were monitored remotely from Flexitricity's control centre and data were logged during all periods of operation. Examples of site behaviour drawn from the trial period are included in this report and show locally recorded frequency and RoCoF data along with the corresponding power changes of the site's equipment.

The results show that both Dynamic RoCoF and Static RoCoF are technically feasible and economic. We concluded that Spinning Inertia from synchronous embedded generators does not naturally deliver the type of response required, and instead active control of synchronous embedded plant should be explored, in a similar manner to Dynamic RoCoF. The variability of RoCoF measurements between locations requires some site-specific tuning, but it is not necessary to install high-cost equipment on every participating site. Overall, the results demonstrate that DSR has strong potential to provide reliable and economic support to a future low-carbon, low-inertia electricity system.

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Nomenclature

CHP - Combined Heat and Power

DR - Dynamic RoCoF

EFCC - Enhanced Frequency Control Capability

FCDM - Frequency Control by Demand Management

FTFT - Flow To Full Treatment

GSP - Grid Supply Point

I/O Module – Input/Output Module

PhC - Phasor Controller

PMU - Phasor Measurement Unit

RAS - Return Activated Sludge

RoCoF - Rate of Change of Frequency

SI - Spinning Inertia

SR - Static RoCoF

U_{int} - Unsigned Integer

VSD - Variable Speed Drive

WwTW –Wastewater Treatment Works

1 Introduction

Flexitricity operates a 24-hour smart grid platform, delivering demand response by starting and stopping electrical loads and generation assets on third party commercial and industrial sites in response to network needs. We help to balance the national electricity system by aggregating these loads into dispatchable units of balancing capacity, allowing our commercial partners to unlock revenue using existing assets.

Flexitricity's objective within the EFCC project is to develop new services to help to steady the mains frequency in a low inertia, high renewables electricity system, and to demonstrate these services during live trials on third party sites. This requires us to demonstrate that industrial and commercial load and distributed generators can respond to the Rate of Change of Frequency (RoCoF) in fast-moving events.

2 Asset / Resource / Service Background Information

Flexitricity developed and tested three separate services for the EFCC project: Static RoCoF (SR), Dynamic RoCoF (DR) and Spinning Inertia (SI).

The purpose of **Static RoCoF** is to respond quickly to a significant RoCoF excursion measured in the local electricity supply, which would indicate the rapid loss of a major infeed such as a power station or interconnector. SR units should only respond when a specified RoCoF threshold has been breached, and should deliver full power very quickly. We aimed for delivery inside one second, but the ideal target in the EFCC project was 0.5 seconds. We looked for load types which would respond to negative RoCoF events only, that is, when frequency is falling. While a Static RoCoF service aimed at positive RoCoF events could be envisaged, for example by rapid tripping of embedded generation, this was not the objective of the project.

In the **Spinning Inertia** trial, we measured the natural (that is, uncontrolled) response of small CHP engines to rapid variations in mains frequency, to see whether they provided inertia in a similar manner to large power stations. We monitored individual engines at full output, and pairs of engines in a load-sharing mode, where one engine was part loaded.

The **Dynamic RoCoF** service is suitable for flexible electrical loads whose consumption can be modulated continuously. In DR, the load is varied in response to the locally measured RoCoF reading. These power excursions can be both positive and negative, and the scale of the power deviation corresponds to the magnitude of the RoCoF.

Each service has very definite operational parameters, and only specific sites and equipment are a suitable fit to these requirements. The sites and their loads that Flexitricity operated these services on are as follows:

- A chemicals manufacturer with a 6MW gas compressor unit which can be switched off very quickly on an electronic signal. When the compressor unit is operational, it can be made available for Static RoCoF.
- A large greenhouse with two 1.5MW Combined Heat and Power (CHP) generators. Both CHPs participates in Spinning Inertia. During periods agreed with the site outside of their usual running regime, we operated the engines at part load.

- A cold store facility with four compressors on site, two of which are used for Dynamic RoCoF. The two compressors have a variable capacity but typically operate at 50kW and 30kW respectively. When either or both of these compressors are operational they can be made available for Dynamic RoCoF.
- A District Heating plant with two 3MW CHP generators. Both CHPs participate in Spinning Inertia, and during certain periods agreed with the site outside of their usual running regime, we operated the generators at part load.
- A wastewater treatment works with two separate Dynamic RoCoF loads: the Aeration Blowers and the Return Activated Sludge (RAS) pumps. Both load types are operated on variable speed drives (VSDs) and hence are capable of continuous modulation.
    - Three aeration blowers control oxygen levels in the treatment works' secondary tanks. The blowers have a maximum power of 70kW and typically operate between 85% and 100% of full load, though can be turned down as low as 50%. All operational blowers have their power adjusted for Dynamic RoCoF operation; generally one or two blowers will be operational at any time.
    - Four RAS pumps return sewage sludge from the tertiary stage of the process to the secondary stage. The pumps have a combined maximum power of around 200kW though they are typically run at around 125kW. Site staff required that all four pumps be operational for the RAS system to be available for Dynamic RoCoF.
- A waste water pumping station which pumps sewage to a waste water treatment works. There are three Flow To Full Treatment (FTFT) pumps on site. The pumps can vary their power consumption but normally consume around 140kW each. The levels of the site tank determine which pumps are operational and the load on each. The pumps are operated on a duty/assist/standby regime, so that between zero and two pumps will be operational at any time. Dynamic RoCoF is operated on all running pumps.

3 Site setup

3.1 Static RoCoF

Static RoCoF operation requires a digital trip signal to be produced when a RoCoF threshold value is reached. The RoCoF trip signal is produced by GE equipment provided for this project, specifically, a Phasor Measurement Unit (PMU) and a Phasor Controller (PhC). The latter is also known as a Local Controller (LC).

The PMU is described in detail in the reports of other EFCC partners. In brief, the PMU consists of:

- RA332 Acquisition Unit;
- RPV311 Recorder;
- RT430 Clock.

The mains voltage is connected to the acquisition unit, which converts the input voltage to an analogue signal and communicates it to the recorder. The recorder is the processing unit which uses the input from the acquisition unit and the time from the clock to calculate frequency.

The PhC monitors the frequency output from the PMU, calculates the RoCoF and produces a digital output when the RoCoF threshold has been met.

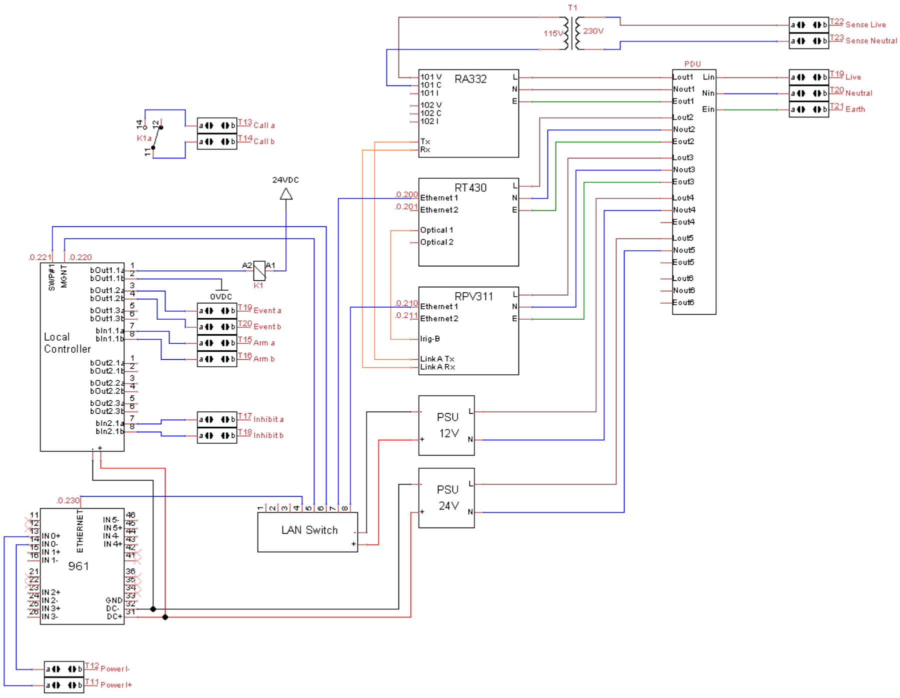


Figure 1 – Interfacing between PMU and PhC

The PhC produces a single digital output when the RoCoF condition has been met. The compressor has historically been operated by Flexitricity under the Frequency Control by Demand Management (FCDM) service. FCDM is a static low frequency response service; the compressor shuts down immediately when a low frequency event is detected. Static RoCoF requires a different condition to be detected but the same shutdown behaviour is required from the site equipment. The trip output from the PhC is wired in parallel to the pre-existing FCDM trip signal. The trip signal is wired via a timer so that the trip lasts for 30 minutes on each occasion. This trip period was chosen purely because existing frequency response participants are accustomed to it; a shorter or longer period could be considered depending on the load type. The timer is powered only when the site is ready to respond to for Static RoCoF.

3.1.1 RoCoF trip setting

In discussion with the site operator, we determined a limited number of trip events that would be acceptable during the trial in order to minimise the impact on the site's operations. It was decided that a RoCoF threshold that would be reached approximately ten times per year would be an appropriate target.

The initial RoCoF trip setting used by the PhC from the start of the trial was agreed through discussion with GE and National Grid. The most important of the PhC settings are given in Table 1.

For an event to be detected, both frequency and RoCoF conditions must be met at the same time. The frequency condition (sFrqLThr[SE1]) that must be met is to be less than 60Hz. Under normal circumstances this will always be true which means that the event detection is contingent upon the RoCoF condition only.

Name	Description	Value
Resource allocation settings		
sFrqLThr[SE1]	Low Frequency Threshold	60Hz
sUsrDefBnd	User Defined bands	1
sUsrRCFLims	RoCoF limits	False
sLocCtrl	Local Control	True
Event Detection settings		
sDtcrWinSz	Maximum size of detection	0.7 seconds
sDtcrDlyTm	Hysteresis value for detection	0.04 seconds
sUnFreqThr	Under frequency threshold	2%
sUnFrqRCFThr	Under frequency RoCoF	0.1Hz/sec
sLocCtrl	Local Control	True

Table 1- Initial PhC settings for Static RoCoF

The RoCoF uses a detection window containing frequency values which are received every 20ms from the PMU. The algorithms focus on fast detection to meet the requirements for the project, therefore employs multiple stages of detection for verification, and best-fit calculations to increase the accuracy of the detection method without unnecessary delay. There are a series of settings which allow the users to define the behaviour of the detection algorithms, such as changing thresholds and adjusting sensitivity. The algorithm has also been designed to ride through gaps in data which can occur in wide-area networks, and remain in operation despite the presence of gaps, up to a limit. Further information on the detection method can be found in the technical report by our partners in the project, GE.

3.1.2 Data collection

Data is constantly recorded from the PMU and PhC units using Phasorpoint. The Phasorpoint server is located in Flexitricity's office. Data is transferred from the site to the Phasorpoint server via the existing communications channels between Flexitricity's control room and the site. Of particular interest is the frequency calculated by PMU, RoCoF calculated by PhC, and the state of event and resource allocation digital signals.

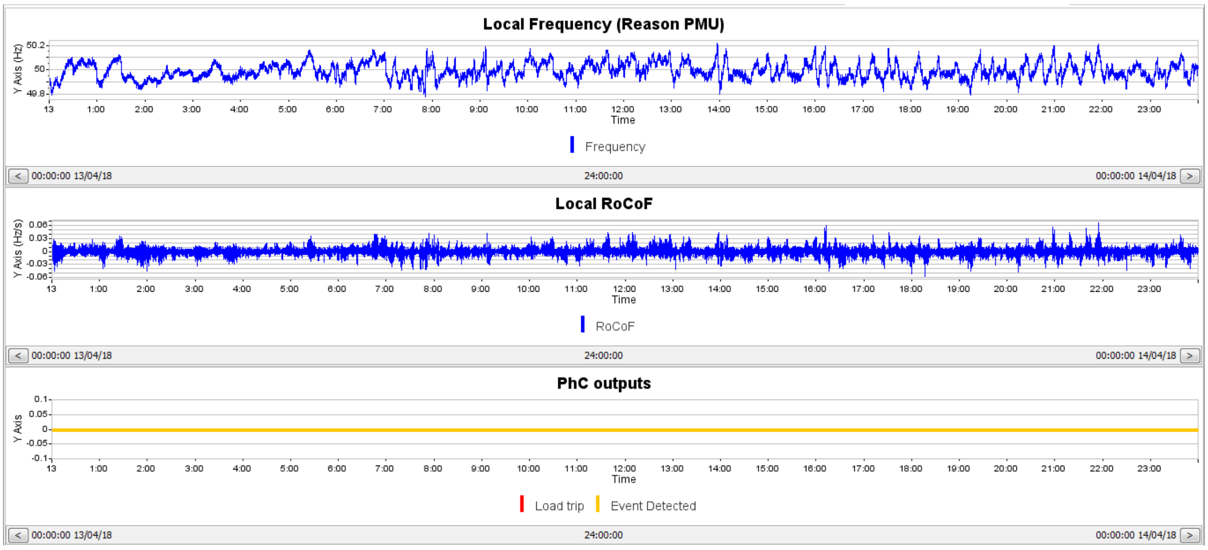


Figure 2 - Example of data displayed on Phasorpoint from Static RoCoF site

3.2 Spinning Inertia

Both Spinning Inertia sites have two CHP generators each, and both have historically operated their CHPs in demand response modes with Flexitricity. In both cases, Flexitricity already had equipment installed on site to allow remote start/stop of the CHPs and monitor status signals. There are also already dedicated communications channels between the sites and Flexitricity's control centre in Edinburgh.

To convert these sites for the Spinning Inertia trial, the CHPs were given an additional mode of operation where they operated at a reduced power level, rather than the normal full power mode. This involved reprogramming the site controls and adding new signals to the interface between Flexitricity and the control systems, to indicate when the new mode of operation is to be started/stopped.

3.2.1 Data collection

The pre-existing monitoring of equipment records power output from the CHPs but not to the granularity that would be required for RoCoF analysis. Additional equipment was installed at both sites to record data of the required quality.

At the horticultural site, a GE-provided PMU was installed on site, consisting of an RA332 Acquisition Unit, an RPV311 Recorder and an RT430 Clock. The PMU is used for monitoring only at this site and there is no PhC installed. The PMU is provided with voltage and current sensing inputs. Both of these are drawn from a location between the combined CHP outputs and the grid connection. The data collected by the PMU is transferred to the Phasorpoint server in the Flexitricity office via the existing communication channels.

At the district heating site a different data collection arrangement was put in place. A National Instruments cRIO-9038 data logger was installed on site in a dedicated cabinet. The data logger monitored voltage and current sensing supplies. Due to the electrical layout of the site, there was no single location where the gross electrical output of both CHPs could be measured before subtraction of the site's electrical load. Therefore it was decided to monitor the output of CHP1 only. Data collected by the data logger is organised into files containing approximately 40 minutes' worth of data. These log files are transferred to Flexitricity's on-site PC and then transferred back to Flexitricity's control room via the site's communication channels, where the data is then post-processed.

3.3 Dynamic RoCoF

Dynamic RoCoF site operation requires mains frequency to be monitored locally, RoCoF calculated on site, and an analogue output signal produced to indicate the magnitude of the power deviation required based on the measured RoCoF. Because sites suitable for dynamic RoCoF are typically smaller than the CHP and industrial load sites in the other two trials, we did not use the Phasor Measurement Unit and Local Controller to detect RoCoF. This is because for dynamic RoCoF to be viable as a service, it is essential for it to be economic to exploit on these smaller sites. Therefore one of our objectives was to demonstrate that we could do this at relatively low cost. As a result, a slightly different detection algorithm is used.

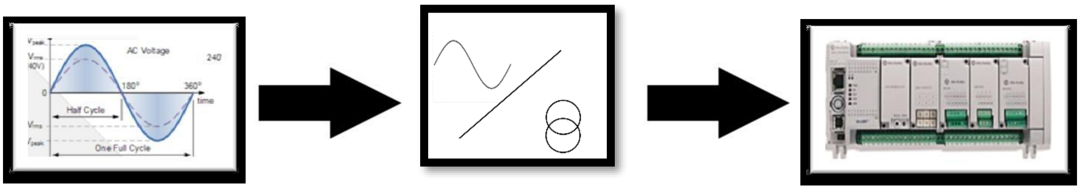
The equipment we used for this task was an Allen Bradley Micro 850 controller (except for the cold store plant, where we used an Allen Bradley Micro 820) and an off-the-shelf frequency transducer. The frequency transducer converts the mains supply voltage into a 4-20mA analogue signal which is fed to the Allen Bradley. We found a wide variety of performance in commercially-available frequency transducers; while many models may be suitable, the right combination of speed and accuracy is not present in all.

The Allen Bradley controller fulfils three roles:

1. Calculates RoCoF from the mains supply and produces an analogue output signal which indicates the power deviation requested to the site (see section 3.3.1).
2. Acts as a bridge between the site controls and the Flexitricity outstation, converting signals into the appropriate format for each side.
3. Produces logs of detected frequency and calculated RoCoF.

3.3.1 RoCoF detection and processing

The frequency transducer produces an analogue measurement of the frequency. The signal is a linear 4-20mA signal where 4mA is 45Hz and 20mA is 55Hz. This 4-20mA signal is an input to the Allen Bradley Micro controller which converts this analogue into a U_{int} (Unsigned Integer) value of range 13107 to 65535.



230V AC Mains	Frequency Transducer	Allen Bradley 800 Series controller
	Frequency to Current conversion 45-55Hz to 4-20mA	Analogue to Digital Conversion 4-20mA to 1307-65535 (U_{int} value)

Figure 3 - Measurement of frequency

The Allen Bradley controller processes U_{int} version of the frequency to produce to analogue output that is proportional to RoCoF. The steps involved in this process are shown in Figure 4.

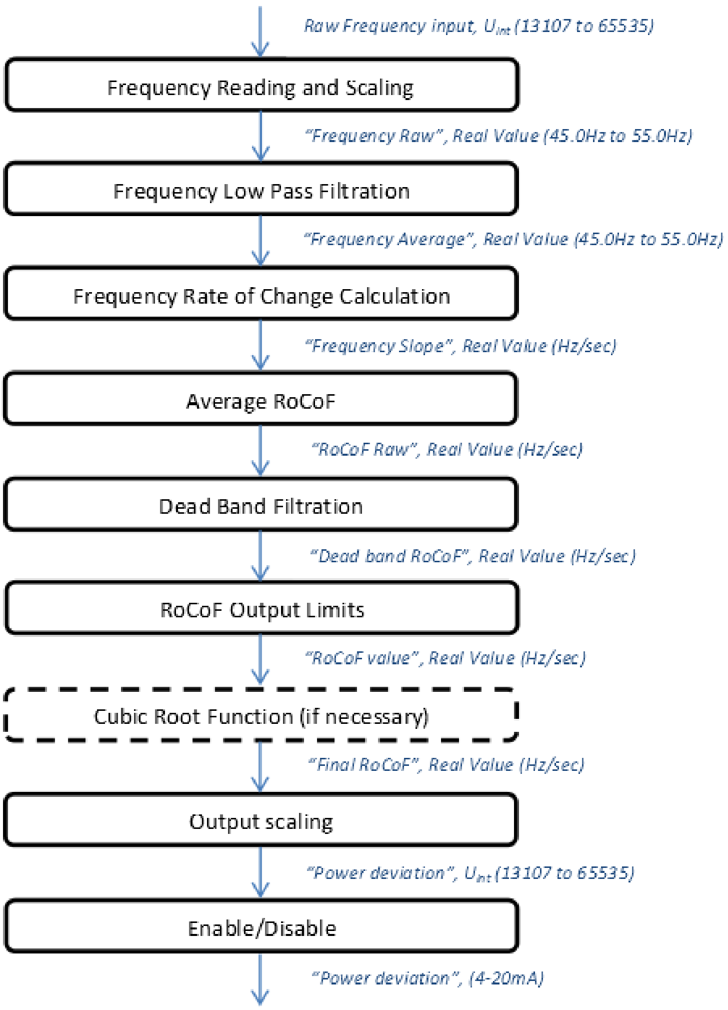


Figure 4 - The signal processing carried out by Allen Bradley Controller

Details of the internal processing contained within each block are described in the sections ahead.

3.3.1.1 Frequency Reading and Scaling

The unsigned integer is converted to Real data type (13107.0 to 65535.0). The Real data type limits values to the range of 13107.0 to 65535.0. Any value out of this range is replaced with the breached limit. The Real values (13107.0 to 65535.0) are converted to Hz (called "Frequency Raw"), using the formula:

Output = ((Input - Min_Input)/Resolution_input))*Resolution_output + Min_output;

Where:

Input: Real value from 13107.0 to 65535.0

Min_Input: 13107.0 (minimum value of the input range)

Resolution_output: 0.0125 (corresponds to the frequency transducer resolution in Engineering Units (Hertz))

Output: Real values from 45.0Hz to 55.0Hz ("Frequency Raw")

3.3.1.2 Frequency Filtering

The "Frequency Raw" is passed through a 2nd Order Butterworth Low Pass Filter to reduce noise.

Output: Real values from 45.0Hz to 55.0Hz ("Frequency Average")

3.3.1.3 Frequency Rate of Change Calculation

The "Frequency Average" is used to calculate the RoCoF (the "Frequency Slope") using the following formula:

Y_OUT = (X[1] - X[2]) / Diff_time

Where:

X[1]: is the current "Frequency Average" sample value on the instant of the calculation.

X[2]: is the previous "Frequency Average" sample value to the instant of the calculation.

Diff_time: is the time difference between samples in Seconds (0.005s)

Y_OUT: Calculated rate of frequency change in Hz/s ("Frequency Slope")

3.3.1.4 Average RoCoF

The RoCoF calculation produces a noisy signal due to quantization, rounding and white noise. The "Frequency Slope" is averaged over a moving block to smooth the RoCoF signal. The moving block is 250ms for pumping station and cold store and 350ms for the WwTW. The formula used is:

XOUT = (XIN[1] + XIN[2] + XIN[3] + …. + XIN[N]) / N

Where:

XIN[1]: is the current "Frequency Slope" sample value on the instant of the calculation in Hz/Seconds

XIN[2] to XIN[N]: are respectively the previous and the N times previous "Frequency Slope" sample to the instant of the calculation [Hz/s]

N: Number of Samples = 70 (initial commissioning value for WwTW) or 50 (initial value at pumping station and cold store) samples with 5ms interval period.

XOUT = Averaged RoCoF value in Hz/s ("RoCoF Raw")

3.3.1.5 Dead Band Filtration

To prevent the output signal being constantly active, smaller RoCoF values must be treated as if they are 0.0Hz/sec. To achieve this, an unresponsive zone is created called a dead band. When the input value (RoCoF Raw) is within the boundaries of the high and low dead band limits, the block will produce an output of 0 Hz/sec. When the input value is out of the dead band limits, it will be passed to the output of the block unaltered.

Output: is the resultant RoCoF output from the dead band in Hz/s ("Dead band RoCoF")

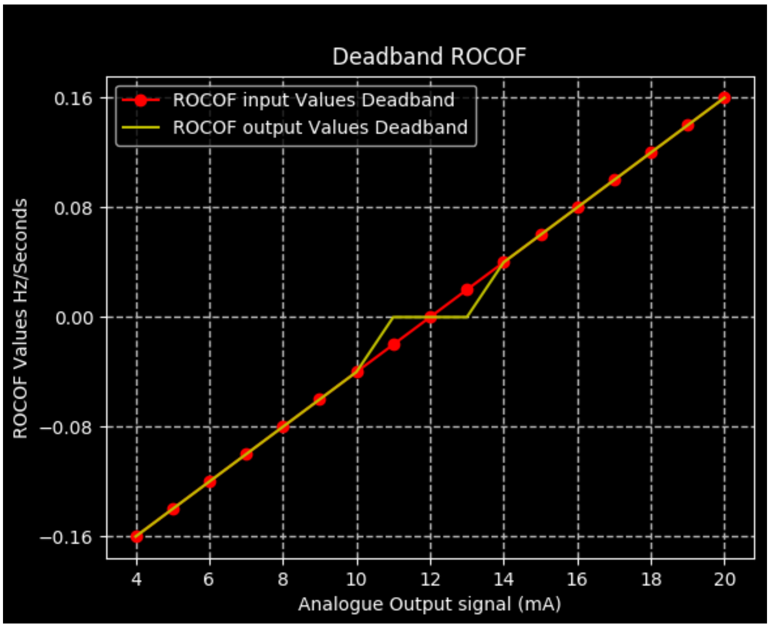


Figure 5 - Example of dead band block input and output values

3.3.1.6 RoCoF output limits

This stage limits "Dead band RoCoF" values to a minimum and maximum range so that the RoCoF value in Hz/seconds will be able to be scaled to power deviation signal output. RoCoF values beyond the maximum and minimum are limited to the maximum and minimum values. The output of this block is the "RoCoF Value".

Note that the maximum and minimum values of +/-160mHz/s have been assumed in this section but in any specific implementation, different values may be used.

3.3.1.7 Cubic Root Function (optional)

In some cases, e.g. pumping units, the equipment response to the power deviation signal is a proportional speed change rather than a proportional power change. Pumping power is proportional to speed cubed, therefore to produce a power change proportional to RoCoF, the RoCoF signal must be processed via a cube-root function.

Output: the adjusted RoCoF value ("Final RoCoF")

The "Final RoCoF" value has the same format and same maximum and minimum values as the input to this section ("RoCoF Value") but containing an adjusted value. In cases where the unit power change is proportional to the power deviation signal, this function block is removed and the "RoCoF Value" is fed directly to the Output Scaling block.

3.3.1.8 Output Scaling

This block converts the "RoCoF Value" or "Final RoCoF" (e.g -160mHz/s to +160mHz/s) to a range of U_{int} values "1307 to 65535". The U_{int} value is the "Power Deviation signal".

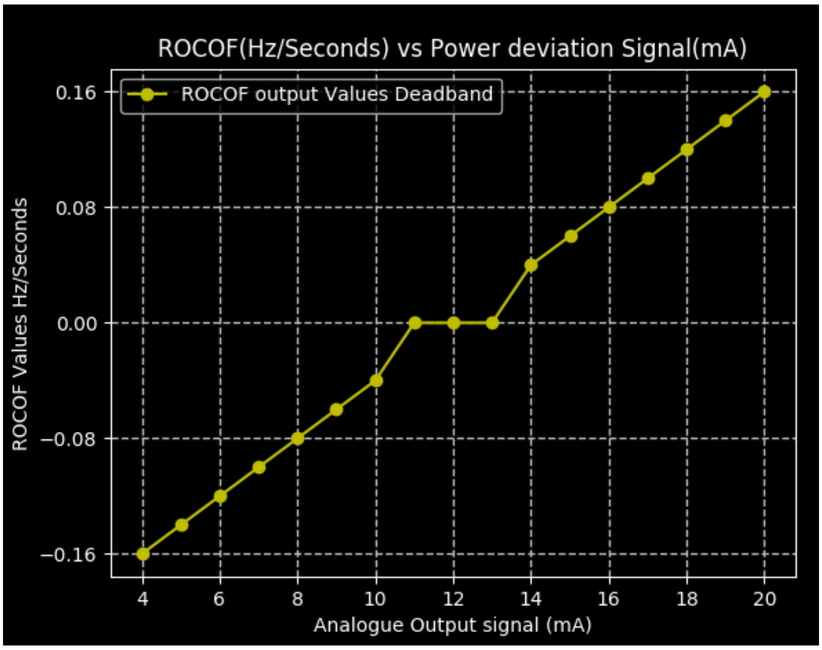


Figure 6 - RoCoF Hz/s vs Power deviation signal (mA)

3.3.1.9 Enable/Disable

The final stage before converting the power deviation signal to a 4-20mA signal is to decide whether it is appropriate for a power adjustment to be made to the site equipment.

When a power adjustment is considered acceptable, the U_{int} power deviation signal is converted to a 4-20mA signal and output to the site equipment. When power adjustment is not acceptable the output signal is held at 12mA (i.e. no power adjustment).

A power adjustment will be considered inappropriate if:

1. The arm/disarm signal indicates the unit is disarmed i.e. unit is not currently opted in for service. The arm signal will automatically be false if status signals from site indicate that power adjustment is currently unavailable.
2. The Allen Bradley's timers indicate there has been a power deviation signal within the last 15 minutes.

The Allen Bradley is programmed with two timers: T1, the maximum duration of a RoCoF activation, and T2, the minimum time between two activations. The purpose of T1 is to ensure that sites only respond in the initial, rapidly-moving period of a frequency disturbance. T2 is intended to remove nuisance activations.

For the purposes of the trial, T1 was set to 60s in accordance with our discussions with the participating sites. T1 starts counting if the RoCoF Value moves outside the dead band. Once 60 seconds have elapsed, it will stop counting; deactivate the output by setting the power deviation output to 12mA and start counter T2.

While T1 is active, if the RoCoF value returns to the dead band range and stays there for 15s, T1 stops counting, deactivates the output by setting the power deviation output to 12mA, and starts counter T2.

For the purposes of the trial, T2 was set to count until it reached 900 seconds. At this point it enables the RoCoF output signal which means that T1 can be activated again.

Timers T1 and T2 ensure that power deviations events are kept to a manageable level so that the participating equipment is able to satisfy its primary purpose. The timer settings chosen were deliberately conservative, to give assurance to the customers at this very early stage that Dynamic RoCoF events will be strictly contained in their impact. This does not imply that a future Dynamic RoCoF service must have these values. Both of these timers would be adjusted to specific service requirements in a commercial implementation.

4 Test Description and Objectives

4.1 Static RoCoF - Test Description and Objectives

The objective for the Static RoCoF trial is to demonstrate that a site can deliver a reduction in power demand in response to fast-moving frequency events. Our ideal target was response within 0.5–1.0s of detection, with the response lasting for 30 minutes, in the event of a negative RoCoF event. Specifically, the goal was to see the RoCoF event detected locally by the GE equipment in line with the agreed RoCoF trip requirements produce a trip output and for the required load drop to be delivered in response to this by tripping the compressor.

The field trials consisted of installing the equipment on site, carrying out commissioning testing and making the unit available for Static RoCoF service, always constrained by the limitations of the site's production schedule. This site and the Static RoCoF equipment were constantly monitored by Flexitricity's team at our Edinburgh control room.

An additional objective was to better define the RoCoF trip requirements. As this is a new service, the ideal trip requirements were unknown prior to commencing the field trials. A RoCoF threshold which would be expected to be breached ten times per annum was agreed with the participating site as the model operational requirement. This represents a level of interruption to routine activities that would realistically be acceptable to partner sites in normal commercial operation. The initial trip requirements represented a best estimate of what these parameters should be. They were chosen on the basis that too few trips would be preferable to too many, and they would be adjusted if required following a period of observation and recording of trip activity.

4.2 Spinning Inertia - Test Description and Objectives

The aim of Spinning Inertia field trials was to test whether additional inertia would be provided by small generation sites to the national electricity system as a natural part of their operating behaviour, that is, without specific frequency- or RoCoF-driven governor control. Of particular interest is the behaviour during fast-moving events when the frequency is markedly unstable.

The potential commercial context for the Spinning Inertia trials is a multi-engine high load factor site such as a district heating or horticultural site, where two CHP engines could be run at reduced power where otherwise one would be running. This will naturally provide greater inertia for the given electrical output. Therefore the trial consisted of (i) simultaneous measurement of power output and site-measured frequency, and (ii) where possible, operating below full power output.

While reduced power output creates “headroom” for greater generation in the event of low RoCoF, this was not the main reason for reducing power output; in fact, our hypothesis was that if CHP engines demonstrate inertia response they would do so at any power output. It was expected that CHP engines, which are governor controlled, would attempt to hold a steady power output regardless of frequency. The question is whether a natural RoCoF response to fast-moving events would be defeated by governor action.

The periods of greatest volatility in frequency and RoCoF cannot be anticipated, so the trial involves running the engines in Spinning Inertia mode for long periods while waiting for events to occur. During these periods of Spinning Inertia operation and other periods of engine usage, data for analysis is collected on site: specifically, frequency, RoCoF and real power output from the engines.

This service does not involve any analogue control signal to be produced from RoCoF measurements using Flexitricity’s equipment, so there were no calibration or adjustments to be made. Instead, the field trial consisted only of data collection and analysis.

4.3 Dynamic RoCoF - Test Description and Objectives

The ultimate goal of the Dynamic RoCoF field trials was to show that both negative and positive RoCoF events could be measured locally using low-cost equipment and that site power consumption could be adjusted to provide a power delta in response to both types of event without compromising normal site operations. We did not attempt to integrate the Dynamic RoCoF sites with Local Controllers or any other aspects of the proposed wide-area network.

To be able to see power deviation in response to a RoCoF event would be considered a success. The speed and flexibility of the response in the context of differing severities of event are additional factors of interest.

In the field trials, we installed our Dynamic RoCoF equipment on the three trial sites, connecting it to four distinct loads on those sites, and carried out commissioning tests. The sites were then made available for service so that the units’ power consumption adjusts in response to RoCoF deviations. Data was collected from sites in the form of daily logs. These contain measurements of the frequency, RoCoF, power deviation signal and the power consumption of the participating units.

The ideal Dynamic RoCoF algorithm for each location was unknown at the start of the trials. The initial settings were a reasonable first pass at choosing the algorithm values. Refining the algorithm was an essential transitional step to achieving the main objective of demonstrating the Dynamic RoCoF functionality. Specifically, this meant choosing suitable dead band, maximum/minimum and averaging parameters for RoCoF algorithm with a view to having a manageable number of RoCoF events and notable power deviations measured for the events.

We noted that the ideal parameters were different for each site, as some sites exhibited more noise on their incoming mains supply, presumably due to differences in their local distribution networks.

5 Test Process

5.1 Static RoCoF – Test Process

The equipment was installed on site and fully tested (including Site Acceptance Testing, SAT) on the 25th and 26th of October 2017. The compressor can only be made available for Static RoCoF when it is running. It has a variable operational schedule shaped by the site's production requirements; this usually involves running periods of several days in length followed by outages of similar timescale. The PMU and PhC remained switched on at all times detecting frequency, RoCoF and RoCoF events at all times even when the compressor was not available to respond to them.

Testing of the Static RoCoF response simply involved making the site load available for service when appropriate and waiting for a RoCoF trip event. Site staff made Flexitricity aware of the running schedule ahead of time through operational timetables sent on a weekly basis, with follow-up schedule adjustment communicated via email. The Flexitricity operations team managed the process of arming and disarming the unit when appropriate. In agreement with National Grid, the compressor was simultaneously available for Static RoCoF and FCDM services. Processes were in place to interrogate outstation logs to determine which equipment had caused the shutdown should both be triggered by the same event.

The process for the trip requirements was to monitor PhC trips and PMU data using Phasorpoint, observe and record any trips which occurred, and adjusting the trip setting if required. As with the original settings, any adjustment of the set points was discussed with GE, National Grid and site staff. As the ideal number of trips is less than one per month, we expected that it would take a lengthy period of time for the regularity of RoCoF events to be observed with any confidence for any given group set of trip settings.

5.2 Spinning Inertia – Test Process

5.2.1 Industrial Greenhouse

A GE PMU was installed on site at the industrial greenhouse site alongside a standard Flexitricity outstation. The site controls were modified to provide for a new mode of operation – Spinning Inertia mode – where the engines operate at approximately 70% of maximum power output. The control changes and installation work were carried out between December 2017 and May 2018. The site went live for service on 24th May 2017 and completed the trial on 1st June 2018.

Voltage and current measurements from the site's incomer are inputs to the PMU. This means that frequency, RoCoF and real power can be calculated, communicated via Flexitricity's communications channels and recorded by Phasorpoint. Unlike the Static RoCoF site, this PMU is used purely recording data; there is no trip output. The power reading is the net import/export for the entire site, that is, the site load minus the combined power generated by the CHPs. The site load is always relatively small in comparison to the CHP output – approximately 100kW in comparison to approximately 1MW per CHP engine. Phasorpoint also records RoCoF but as there is no PhC on site this is not a processed signal but instead the direct output from the PMU. It is therefore a much noisier signal than the RoCoF recorded by the Static RoCoF site, which is post-processed by the PhC.

A running schedule was designed for the site to keep engine start and stops to a minimum; this was to operate in Spinning Inertia mode between 1400 and 1600, Monday to Friday. These runs directly precede the usual red rate operation where the engines run at full power between 1600 and 1900, Monday to Friday (this is the period when export power is most valuable, as distribution charge benefits accrue at so-called "red rates"). Due to gaps in operation, the schedule was later adjusted to increase the number of operational hours. The new hours were 1200 to 1600 for weekdays and 1200 to 1900 for weekends. As the red rate running remained as before, effectively the engines ran from 1200-1900, seven days a week, with full power only during 1600 to 1900 Monday to Friday. This new schedule began on 12th April 2018 and continued until the trial ended on 1st June 2018.

5.2.2 District Heating

A National Instruments cRIO 9038 data logger was installed at the district heating site alongside a Flexitricity outstation. The site controls were modified to include a new mode of operation – Spinning Inertia mode – where the engines operate at approximately 70% of maximum power output. The control changes and installation work were completed on the 20th October 2017.

The data logger collects current and voltage measurements at 20ms intervals. From this data, power, frequency and RoCoF can be derived. The data is sent back to Flexitricity's office via the site's outstation and communication channels. The data is sent in packages of approximately 60MB which represent around 40 minutes' worth of data. The data was processed using tools developed by the data logger firmware providers Metis, providing frequency, RoCoF and power.

The site was initially made available from 1400 to 1600, Monday to Friday. The SI run was immediately followed by a scheduled red rate run at full power from 1600 to 1900 on these days. This schedule was agreed to fit in with existing operating patterns and to remove the need for additional engine starts. There were several gaps in availability due to maintenance and operational issues. For this reason, the schedule was later revised to allow for more hours of operation. From 12th March 2018, the Spinning Inertia running hours were increased to 0600 to 1600 and 1900 to 2300 Monday to Friday, with the full power period remaining from 1600 to 1900.

The power, RoCoF and frequency data are only accurate during periods in which CHP1 is running; none of these parameters can be accurately recorded at other times. This is an important difference from the greenhouse site and is due to the location on site where the voltage is detected.

5.2.3 RoCoF events

Occasions with particularly high RoCoF reading are of particular interest in determining the response of CHP engines during Spinning Inertia operation. Given the extremely large data volume, it was necessary to target specific periods of high RoCoF incidence for further investigation. Areas of specific interest include: static frequency response trips (<=49.7Hz); frequency warnings (<=49.8Hz); Static RoCoF trips recorded at our Static RoCoF site; known interconnector failures; known power station failures and particularly high RoCoF events detected during the Dynamic RoCoF sites analysis.

Once the time of an event has been identified the process of plotting this event is different for each site. For the industrial greenhouse, Phasorpoint can produce csv files with power, frequency and RoCoF. For the district heating site the data logger files require an additional processing as the recorded data contains voltage and current rather than power, with a reading every millisecond. A tool provided by our data logger software providers processes this raw data to produce files with frequency, RoCoF and power signals every 20ms.

A Python tool developed internally is used to produce graphs using the Phasorpoint logs for the industrial greenhouse and the processed datalogger logs for the district heating site.

5.3 Dynamic RoCoF – Test Process

The Dynamic RoCoF equipment was built into a cabinet and bench tested in the Flexitricity office. A frequency injector was used to test the RoCoF algorithm. Installation and commissioning were carried out in November 2017 at the pumping station and the WwTW, and in January 2018 at the cold store. Each site was made live for service once commissioning was complete, and remained so subject to site availability.

The installed equipment was set up to record daily logs which were transferred to Flexitricity. These logs were used to produce graphs displaying frequency, RoCoF, power deviation and power consumption, as shown in Figure 7. Figure 7 - Graph of frequency, RoCoF, power deviation and total power consumption for 24 hours at the wastewater pumping station, prior to optimisation of settings for the site.

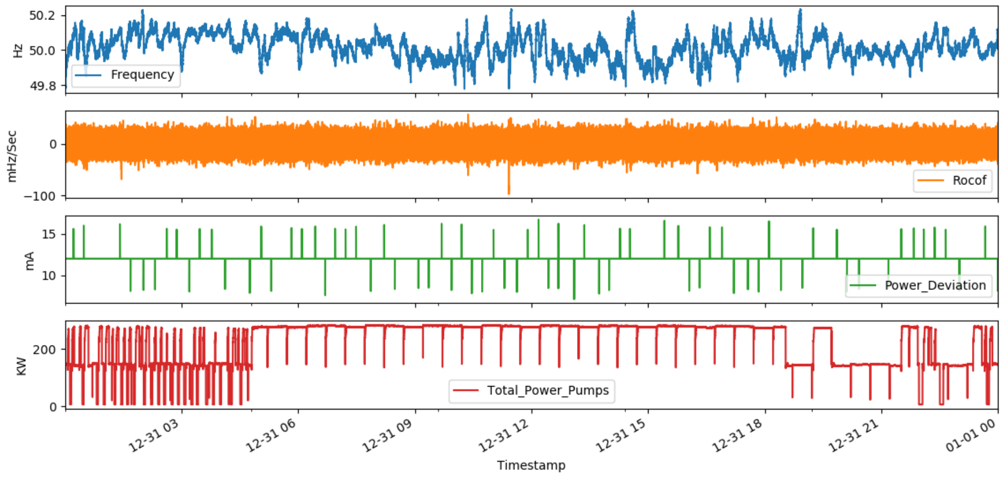


Figure 7 - Graph of frequency, RoCoF, power deviation and total power consumption for 24 hours at the wastewater pumping station, prior to optimisation of settings for the site.

The first part of the process was to adjust the algorithm to produce a workable number of power deviations events (occasions when a power adjustment is requested from the site). As each power deviation is followed by a 15-minute outage, an overactive algorithm (i.e. as illustrated by the green line in Figure 7) would react so often as to be unavailable most of the time, and would therefore be likely to be unavailable when the most significant RoCoF events occurred. An underactive algorithm would respond rarely or not at all. Initially, the algorithm was overactive, so the setpoints were adjusted accordingly. Once the number of RoCoF events was at an acceptable level, adjustments were made to the amplitude of the output. Adjusting the algorithm was an iterative process with several amendments made over time. The volume of RoCoF events can vary considerably from one day to the next, therefore changes were made gradually as each new set of parameters required to be judged over a prolonged period of time.

The final settings for each site are given in Table 2.

	df/dt sampling	Avg_Samples	Dead_Band_ (Hz/sec)	Min RoCoF (Hz/sec)	Max RoCoF (Hz/sec)
Pumping station	10	25	0.05	-0.08	+0.08
WwTW	10	25	0.14	-0.17	+0.17
Cold store	5	50	0.055	-0.08	+0.08

Table 2 - Final RoCoF algorithm parameters for DR sites

6 Results & Testing Outcomes

6.1 Static RoCoF – Results and Testing Outcomes

The initial part of the trial involved having the equipment installed but not armed so that the initial RoCoF trip requirements could be observed in action. During the initial disarmed period there were issues that prevented a clear assessment of the suitability of the original trip requirements.

Firstly, the high data volume led to gaps in the frequency data recorded by Phasorpoint. This issue did not impact the data that was transferred from the PhC, specifically the calculated RoCoF value and RoCoF event and trip digital signals, and was resolved by installing a higher bandwidth fibre connection. Prior to this upgrade, data was lost over the Christmas 2018 period including two significant frequency events on Christmas day and New Year's Eve.

Secondly, amongst the frequency data that was recorded were several examples of extremely high frequency readings, outside the range of reasonable frequency deviations. It was concluded that these high frequency readings were due to errors in frequency readings of the PMU. In December 2017 adjustments were made to the PhC event detection algorithm to reduce the likelihood of an erroneous frequency spike leading to a RoCoF trip, and in February 2018 a firmware upgrade was applied to the RT430 GPS Clock to reduce the number of frequency spikes.

During the first quarter of 2018, the trial continued with the original RoCoF settings. During this period there were no further RoCoF trips, and it was concluded that following correction of the PMU performance, the original trip settings were insufficiently sensitive. The parameters were adjusted as shown in Table 3.

	Original values	New values
RoCoF threshold for under frequency event(sUnFrqRCFThr) (Hz/sec)	0.1	0.08
Hysteresis value for detection, sDtcrDlyTm (sec)	0.04	0.06

Table 3 - Changes to RoCoF event detection made on 13th of March 2018

The adjustments to the settings mean that a smaller RoCoF reading can cause a RoCoF trip output, but the event must last slightly longer.

Following the change of settings, four RoCoF events were detected during the following five months. During these events the site was not armed for action and was unable to respond. This is because during early 2018, an unexpectedly high number of static frequency response trips occurred at the site, and site staff determined that both frequency response and Static RoCoF operation should be suspended for a period in order to ensure that production schedules were maintained.

However, frequency, RoCoF and trip data was recorded on Phasorpoint during the period, allowing the performance of the Static RoCoF detection method to be appraised.

6.1.1 First RoCoF trip - 03:10, 3rd April 2018

The first of these events occurred at 03:10 on 3rd April 2018. Phasorpoint data of this event is shown in Figure 8. It shows frequency on the top chart, RoCoF in the middle chart and PhC digital outputs on the bottom chart. On the digital signals charts, the event output is represented by the yellow line and a trip output is represented by red. An event will last for 30 seconds while the trip signal will last for 10 seconds. The event is a necessary precursor to a trip but does not necessarily lead to a trip output. The trip output will cause a shutdown if the equipment is armed; the event signal merely indicted that unusual RoCoF behaviour is being detected. The yellow line overlays the red line, so where they coincide (most of the time) the red line is not visible.

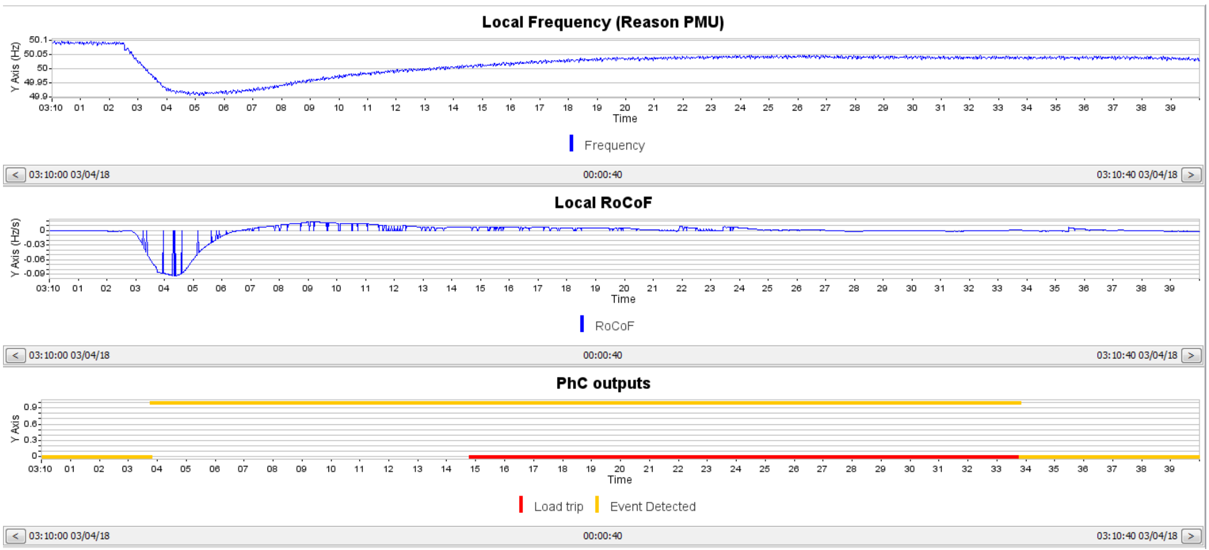


Figure 8 - RoCoF trip event at 03:10, 3rd of April 2018

The graph shows the frequency declining from 50.1Hz to 49.9Hz while at the same time RoCoF reaches approximately -0.09Hz/s. A closer look at the log shows that the -80mHz/sec threshold was broken at 03:10:04.78 and the event and trip outputs both became true at 03:10:04.82, that is, 40ms later. Of note in this event is that although the RoCoF reaches a relatively large magnitude, the frequency remains within normal limits, never going below 49.9Hz. So this event would not result in any conventional frequency response utilisation, or be flagged by National Grid as an event of particular note. Consequently the cause of the sudden frequency dip is unknown. Nevertheless the RoCoF has breached the PhC's RoCoF trip threshold and has correctly produced a trip output.

6.1.2 Second RoCoF trip - 02:42, 2nd May 2018

The second RoCoF event occurred at 02:42 on 2nd May 2018 and is shown on Figure 9. The frequency is seen to drop suddenly from 49.95Hz to 49.75Hz, caused by a 700MW drop in supply.

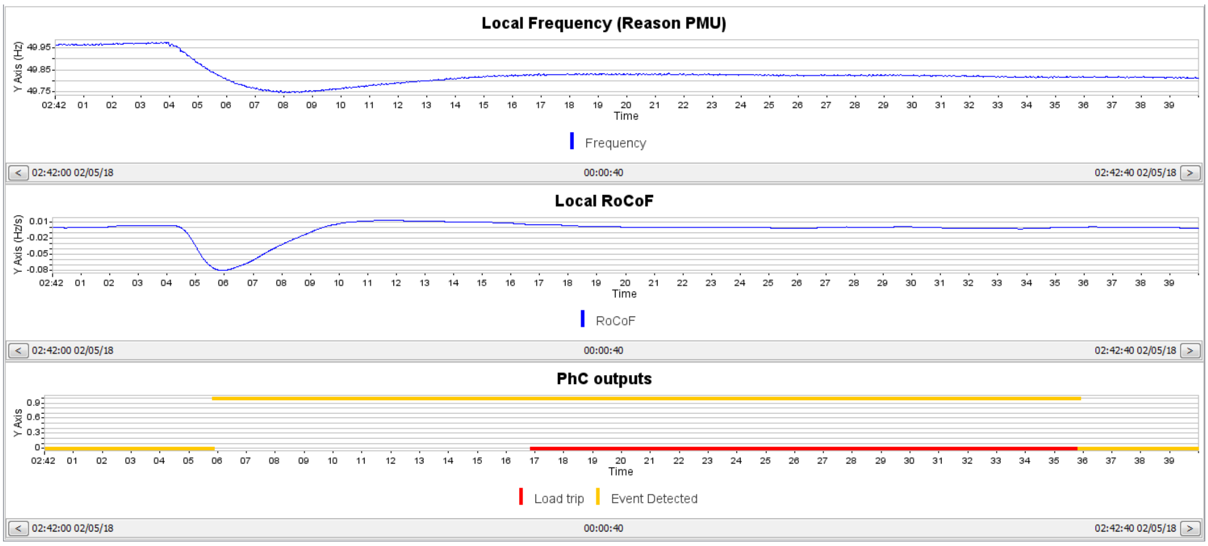


Figure 9 - RoCoF trip event at 02:42, 2nd May 2018

Figure 9 shows that the RoCoF value in the middle chart reaches the threshold value at 02:42:06, and the trip output becomes true shortly afterwards. Close examination of the logs show that the -80mHz/s RoCoF threshold was broken at 02:42:05.80 and the trip output was true at 02:42:05.84, that is, 40ms later. The RoCoF reading on this occasion was noticeably smoother than on other occasions.

6.1.3 Third RoCoF trip - 20:42, 19th May 2018

The third RoCoF trip occurred at 20:42 on 19th May and is show in Figure 10. The frequency drops from 50.05Hz to around 49.8Hz.

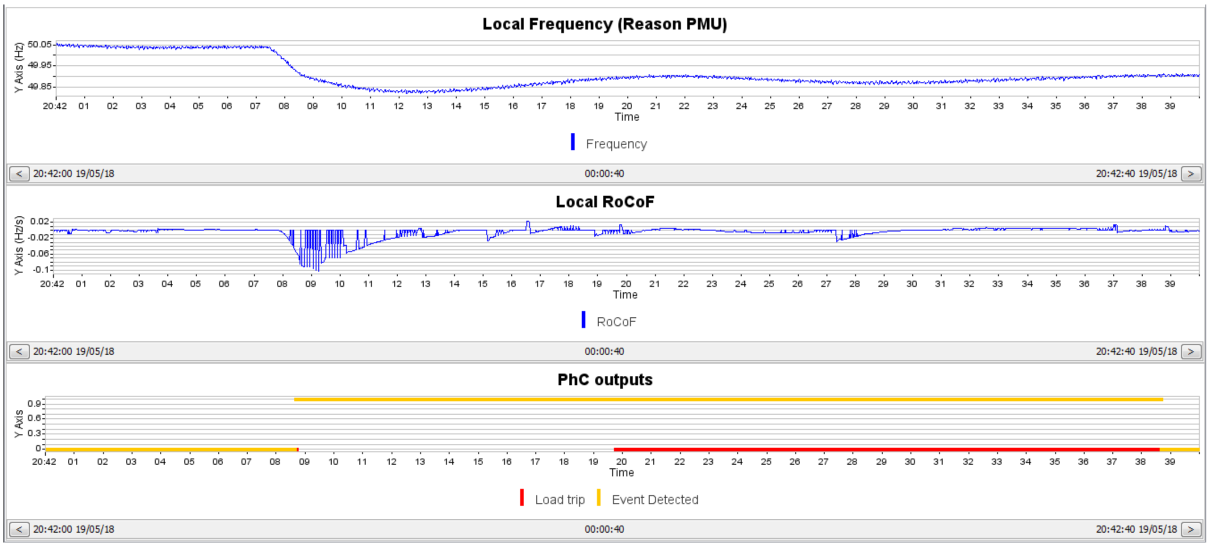


Figure 10 - RoCoF trip event at 20:42, 19th May 2018

The RoCoF breaks the -80mHz/sec threshold at 20:42:08.64, the event becomes true at 20:42:08.70 and the trip becomes true at 20:42:08.76. On this occasion the RoCoF value regularly returns to zero giving the RoCoF graph its disjointed form. One of the zero RoCoF readings occurs during the event detection, which presumably explains why it takes longer (120ms) from breaking the 80mHz/s threshold to the trip output becoming true.

6.1.4 Fourth RoCoF trip – 09:02, 27th May 2018

The fourth RoCoF trip occurred on 27th May at 09:02 and is shown in Figure 11. The frequency drops from around 49.95Hz to around 49.73Hz so would not have resulted in static frequency response. This was due to a drop in generation of 400MW in the national system.

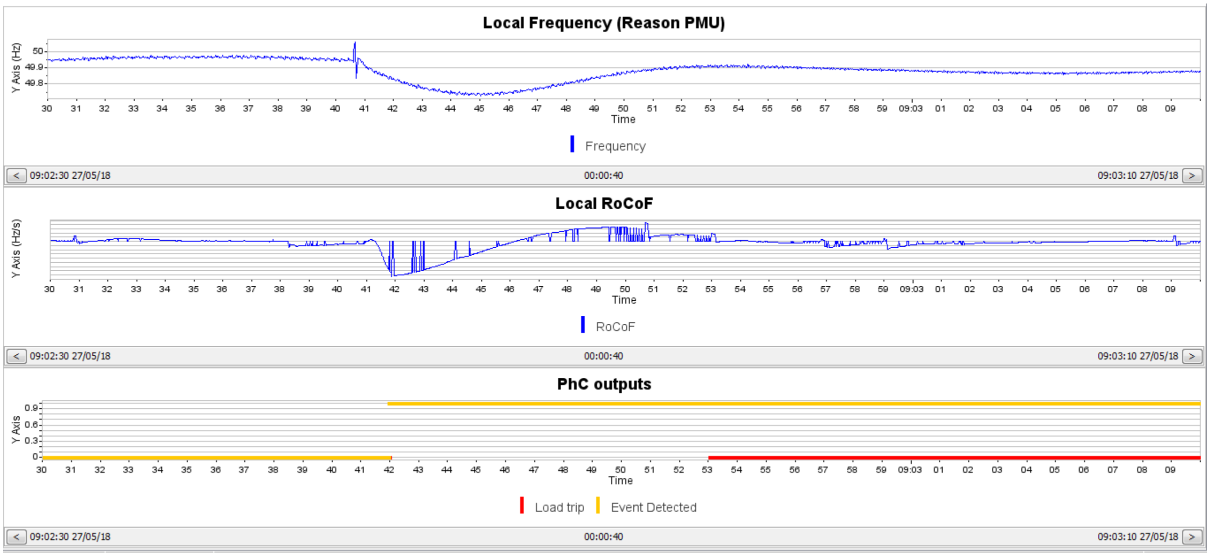


Figure 11 - RoCoF trip event at 09:02, 27th May 2018

The RoCoF breaks -80mHz/s at 09:02:41.92; it then returns to zero before breaking this threshold again at 09:02:42.00. The event becomes true at 09:02:42.02 and the trip becomes true at 09:02:42.06. So in this case it takes 140ms from initially breaking the RoCoF threshold until causing the trip output.

6.1.5 Simulated RoCoF event with equipment shutdown - 11:00, 20th August 2018

As the trial progressed, it became increasingly likely that demonstrating an equipment shutdown due to a RoCoF trip event would require manual intervention. This was because of the combination of reduced availability due to the excessive number of low-frequency trips, and the initial difficulty in determining the correct sensitivity of the RoCoF settings on the PMU. A manually instigated trip was arranged with the site to occur on 20th August 2018.

The trip was created using the PMU simulator package provided by GE. The PMU simulator operates on a PC in Flexitricity's control room. The site-based PhC is adjusted to interrogate the control room PC for PMU data rather than the real PMU. This is done via Flexitricity's existing communication channels to the site. The PMU simulator has two sets of PMU frequency data: one with a steady frequency output, and one with a frequency dip that is known to cause a trip output from the PhC. The PMU simulator runs the steady state dataset in a constant loop until indicated to shift to the frequency dip dataset.

The simulator was setup in the morning of 20th of August and was switched over to the frequency dip output dataset at around 11:00am. A graph of the phasorpoint data of this event is shown in Figure 12.

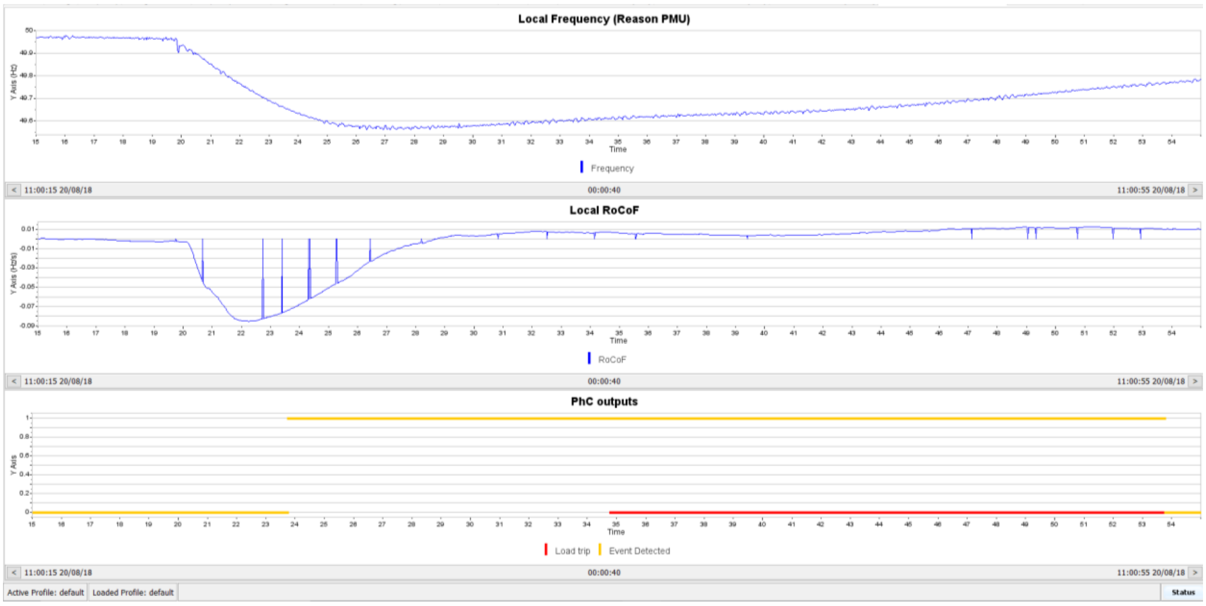


Figure 12 - Simulated RoCoF event at 11:00, 20th August 2018

The frequency data is from the PMU simulator, not from live data detected at this time, so the frequency is not related to a real-life incident. The RoCoF and digital output are real data from the PhC in response to the simulator input data. What is of importance is that the load trip and event detected digital outputs are both seen to become true at 11:00:23. Both of these digital signals are fed to the Flexitricity outstation from the PhC by hard-wired digital signals connected to discrete input/output (I/O) modules. The power consumption of the compressor is also fed to the outstation via a submeter unit which converts the power signal to a 4-20mA analogue signal, which is passed to the outstation via a discrete I/O module and a Modbus interface. Flexitricity's control room constantly monitors the site via communications channels to the outstation. The change in status of the event and load trip digital signals, and the compressor's power drop from 6.6MW to 0MW, were observed from the control room.

To understand the speed of the shutdown the log data shown in Table 4 was drawn from Flexitricity's outstation. The outstation log operates on GMT at all times while Phasorpoint is in BST, therefore an event occurring at 11:00:00 on Phasorpoint is represented as 10:00:00 in the outstation log.

Timestamp	Event Detected status	Trip Output status	Compressor Power
10:00:23.489	False	False	6629062.50W
10:00:23.846	True	False	6646406.25W
10:00:24.206	True	True	6646406.25W
10:00:24.562	True	True	6628125.00W
10:00:24.950	True	True	6628125.00W
10:00:25.310	True	True	1003593.75W
10:00:25.694	True	True	1003593.75W
10:00:26.063	True	True	4218.75W
10:00:26.414	True	True	4218.75W

Table 4 - Flexitricity outstation log data of simulated trip

The logs reveal that the data is recorded approximately once every 360ms; this is due to the rate at which the I/O modules update. The Event Detected signal became true at 10:00:23.846 and the RoCoF trip output status is true at 10:00:24.206. The RoCoF trip signal - the signal which cause the equipment shutdown when the unit is armed - will have become true at some point between these two timestamps.

It is known that the power drop on site is achieved by opening a breaker and that the power will drop to zero in a single step. The power reduction over two steps recorded in the log is due to the output signal from the submetering unit which provides an averaged output, therefore we can consider the 1003594W power reading at 10:00:25.310 to be indicative of the power being zero at this point. The power values of 4219W can be considered as noise at the 0W (representing a noise level of <0.1%).

The drop in the power signal input to the I/O module will have occurred at some point between the 10:00:24.950 and 10:00:25.310 timestamps. This means that the time between RoCoF trip and power signal drop being received is between 1.46s and 0.74s, with the most likely value being around 1.1 seconds. Examination of the log shows that the metering signal generally stays the same for two reading before changing: a sample of 33 datapoints shows the power signal always stays the same for two datapoints in succession except for one instance of the same power reading being recorded three times. It is therefore reasonable to assume that the sub meter unit providing the power signal to the I/O module updates its value approximately once for every two datapoints in the log or approximately once every 720ms. This means that any power change will take an average of 360ms to be detected by the I/O module. The time between RoCoF trip and power drop is therefore estimated to be 1.1s less 360ms, that is, approximately 0.75s.

The trial site participates in conventional static frequency response services with Flexitricity. Within that portfolio, it is among the slowest, though it reliably achieves the 2s trip requirement of those services. Other sites in the portfolio have different arrangements of circuit breakers and trip more quickly. Signalling limits at this site make it impossible to achieve a more precise measurement of trip time. However, considering the site in the context of its peers, we believe that the results indicate Static RoCoF to be a viable service for sites which have proven capability in static frequency response, and we expect that trip times of 0.5s will be achievable by the majority.

6.2 Spinning Inertia – Results and Testing Outcomes

Industrial Greenhouse – Results and Testing outcomes

As there is no trip or algorithm involved in Spinning Inertia there were no adjustments or refinements to be made to the equipment once fully installed and demonstrated to be working. Once the site equipment was installed, the CHPs were run to the agreed schedule, and afterwards specific time frames were investigated with Phasorpoint where notable events with high RoCoF values had occurred.

First Notable RoCoF event – 16:20, 13th July 2017

On 13th July 2017 there was a decrease in supply of approximately 1GW. A screenshot of the event as seen on Phasorpoint is show Figure 13. There are some gaps in the Phasorpoint data but there is clearly a sharp dip in frequency at 16:20:15 displayed on the top chart. The middle chart shows RoCoF – it must be noted that this is raw RoCoF from the PMU, not smoothed by post-processing in a PhC. In spite of the noise on this signal, there is clearly a double spike in the RoCoF coinciding with the start of the frequency dip. The third chart on the graph displays the power reading on site. The power signal is the total power reading for the whole site where import is shown as a positive number. That is, the power shown is the site's local load less the generation of the two CHPs. Only a single phase of current is recorded and the voltage signal used is phase-to-neutral, so the power shown must be multiplied by three to give the true power. The period of time in the graph shows one CHP operating in SI mode (1MW output) before ramping up to full power at 16:14. The ramp in power between 16:17 and 16:21 is the second CHP ramping up from zero to 1.5MW.

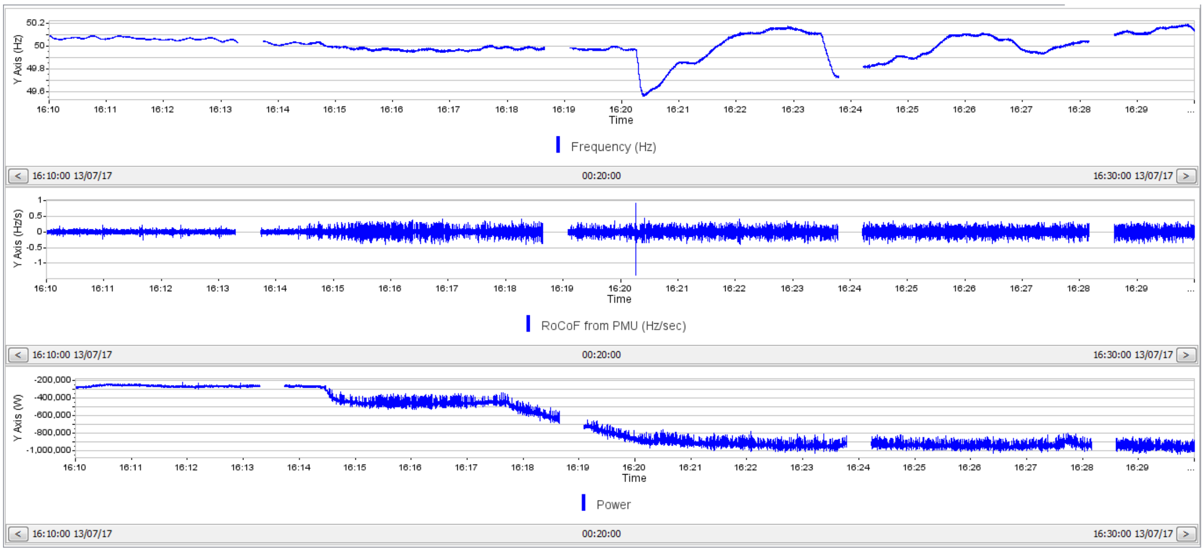


Figure 13 - 13th July 2017, 16:20, displayed on Phasorpoint

Figure 14 shows the power and RoCoF for a four-second period around 16:15:20. The blue line is the RoCoF and red line is the power. The graph is based upon logs taken from Phasorpoint containing one reading every 20ms. The power signal has been converted as described above, and inverted so that power export from the site is positive. At this point, the second engine is not yet at full power hence the generation is below 3MW. The power can be seen to vary by around 400kW during this period. The site load is typically in the region of 50-200kW so this variation in power must be due to changes in CHP output. It would appear that these variations in power are typical behaviour for the site and machine cause cannot be ruled out. We therefore cannot directly link these variations to RoCoF.

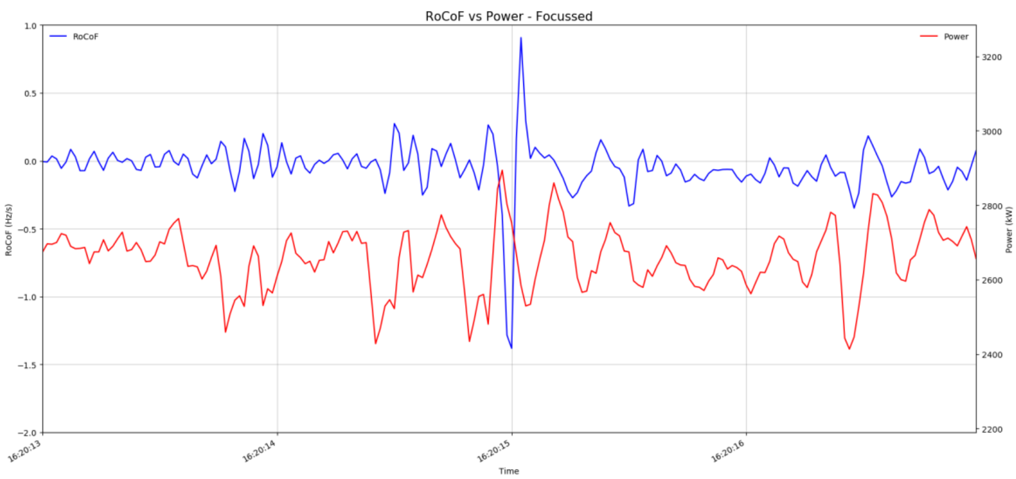


Figure 14 - 13th July 2017, 16:20, RoCoF and power exported

Second Notable RoCoF event – 17:00, 30th October 2017

A second notable RoCof event occurred on 30th October 2017. This was noted as generated a frequency response event under conventional static frequency response services. The Phasorpoint data (in Figure 15) show the frequency decline to 49.7Hz. The highest RoCoF values occur shortly after the lowest frequency event, where the highest and lowest RoCoF spikes occur around the same time at around 17:00:37.

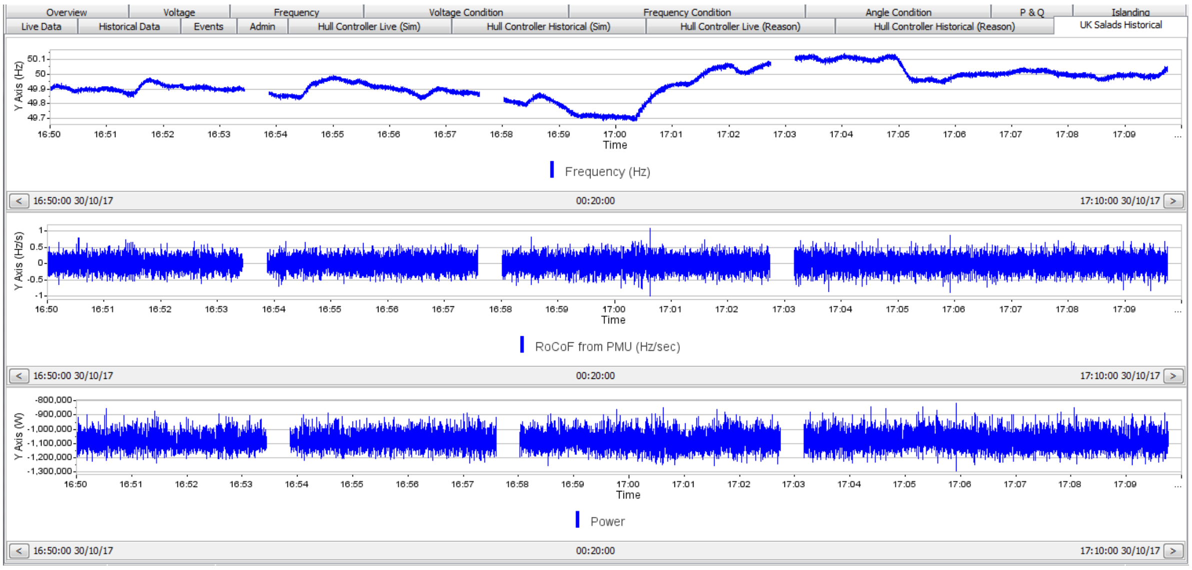


Figure 15 – 30th October 2017, 17:00 displayed on Phasorpoint

Figure 16 show the power and RoCoF for a four second period around 17:00:37. The total power averages around 3200kW, as both engines were running at full power. The power varies between 3000kW and 3600kW approximately with one negative spike where power drops as low as 2500kW. The lowest power value coincides with the negative RoCoF spike.

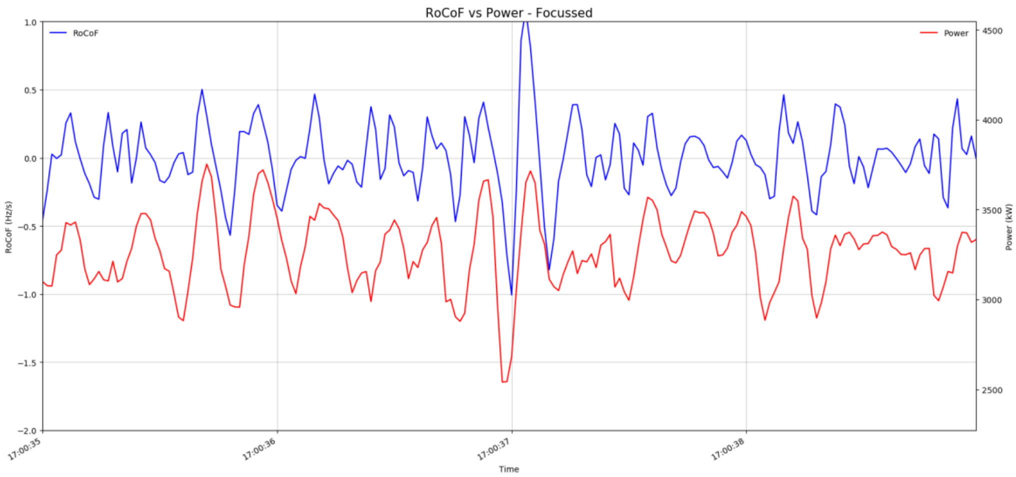


Figure 16 – 30th October 2017, 17:00, RoCoF and power exported

District Heating – Results & Testing outcomes

As there is no trip or algorithm involved in Spinning Inertia there were no adjustments or refinements to be made to the CHPs or controls once they were commissioned. The data logger produced considerable volumes of data, which initially restricted the amount of hours the data logger could be used for and requiring careful data management. Later, bandwidth was increased and a data server procured, removing this restriction.

First Notable RoCoF Event – 12:45, 8th January 2018

On the 8th of January 2018, there was a drop in supply of approximately 400MW. Though outside of the usual Spinning Inertia running hours, the district heating site's CHP was running at this time at around full power. The data recorded from the data logger was processed to produce Figure 17. This shows the power and RoCoF for around two seconds before and after the largest RoCoF spike. The power varies from around 2900kW to 3050kW – this is full power – with one large negative spike where the power reaches around 2750kW. The largest RoCoF values is -0.5Hz/s.

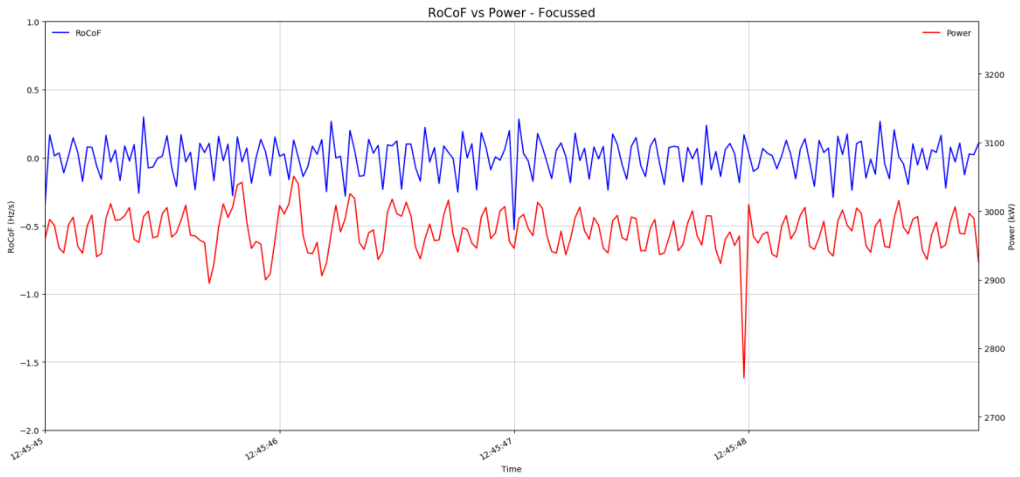


Figure 17 – 8th January 2018, 12:45, RoCoF and power generation

Second Notable RoCoF event, 07:25, 29th January 2018

On 29th January 2018 there was a frequency event to a drop in supply of approximately 635MW. At this time the CHP was running at around 2600kW, a little short of full power. Figure 18 shows power and RoCoF for two seconds before and after the largest RoCoF value. The power is seen to vary between 2550kW and 2770kW with six notable negative spikes where the power reduces to 2400-2450kW approximately. Because these negative spikes are not correlated with the RoCoF signal, we conclude that they are machine-related.

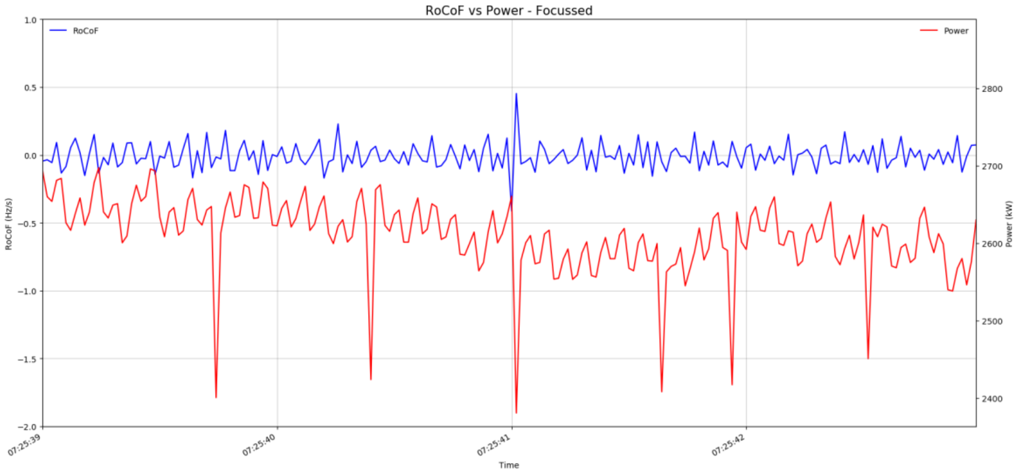


Figure 18 – 29th January 2018, 07:25, RoCoF and power generation

Third Notable RoCoF event, 20:57, 20th April 2018

On 20th April 2018 a decrease in supply of 500MW caused the frequency to drop to 49.75Hz. This frequency drop causes a negative RoCoF spike. Figure 19 shows the two seconds before and after this RoCoF spike. During this period the engine power was between 2250kW and 2300kW with three notable negative spikes where the power drops as low as 2100kW occurring in the two seconds after the RoCoF event.

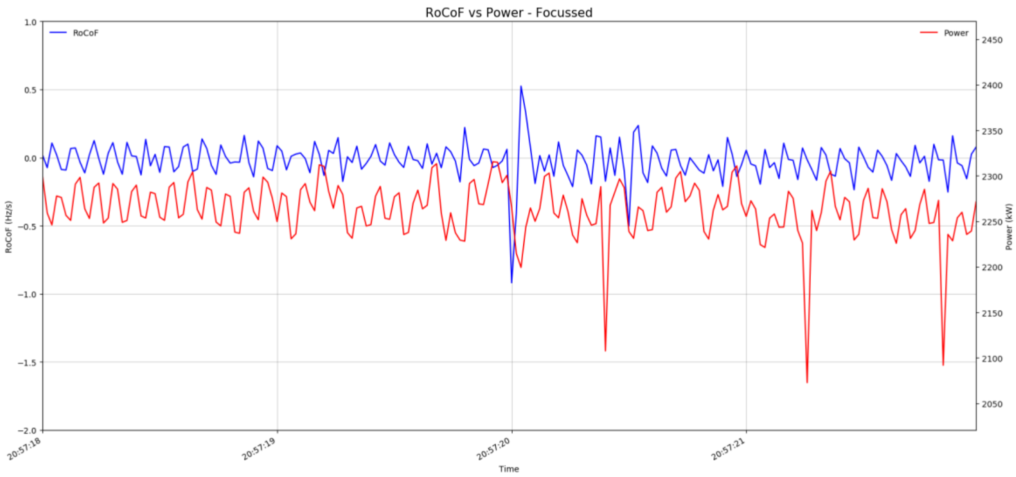


Figure 19 – 20th April 2018, 20:57, RoCoF and power generation

6.3 Dynamic RoCoF – Results & Testing Outcomes

Over the period of the trial, a number of power deviation events and associated power excursions were recorded at all participating Dynamic RoCoF sites. As an example of the typical number of events and power excursions experienced at each site, the average number of events over the seven day period starting on 28th April is given in Table 5.

	Average number of positive RoCoF events per day	Average number of negative RoCoF events per day	Average number of power deviations recorded per day
Pumping station	0.71	0.57	0.14
WwTW	9.29	9.43	5.43
Cold Store	0.29	0.43	0.29

Table 5 – The average number of RoCoF events and power deviations per day for 28/04/18 to 04/05/18

The WwTW is connected to Arbroath Grid Supply Point (GSP) in Tayside. It experiences the greatest number of RoCoF events by far, despite having a dead band significantly wider that the other two. This site's supply voltage is notably more volatile that the other two sites. The pumping station is connected to Milton of Craigie GSP in Dundee. It experiences fewer power deviations in comparison to the cold store (connected to Chatham GSP in the Kent), despite having a slightly narrower dead band. Both the pumping station and the cold store are in urban locations, while the WwTW is in a rural location.

Not all events lead to a power deviation, partly because of variations in the availability of units, but also because many RoCoF events were too brief to be translated into an adjustment of power demand of the site equipment.

6.3.1 Pumping station

The pumping station went live for operation on 13th November 2017. The initial equipment settings were a best estimate of the most suitable parameters for this site. Over time and through observation, refinements were made to the set points. The final settings for the pumping station were applied on 9th February 2018 and are described in Table 2. The settings remained unchanged from this point until the end of the trial in May 2018.

6.3.1.1 Many RoCoF events in one day

The number of RoCoF events experienced at this site could vary considerably from day to day, being zero on several occasions and higher than thirty at other times. Figure 20 shows the RoCoF signal in orange break both the upper and lower dead band several times during a single 24-hour period. The unit was not armed on this day hence the power deviation signal in green remained at 12mA (that is, no power adjustment in the period). The power consumption of the site in red show a mainly steady consumption of around 280kW with regular negative spikes. During this day, two pumps were running throughout, with one pump being routinely cycled, hence the negative spikes.

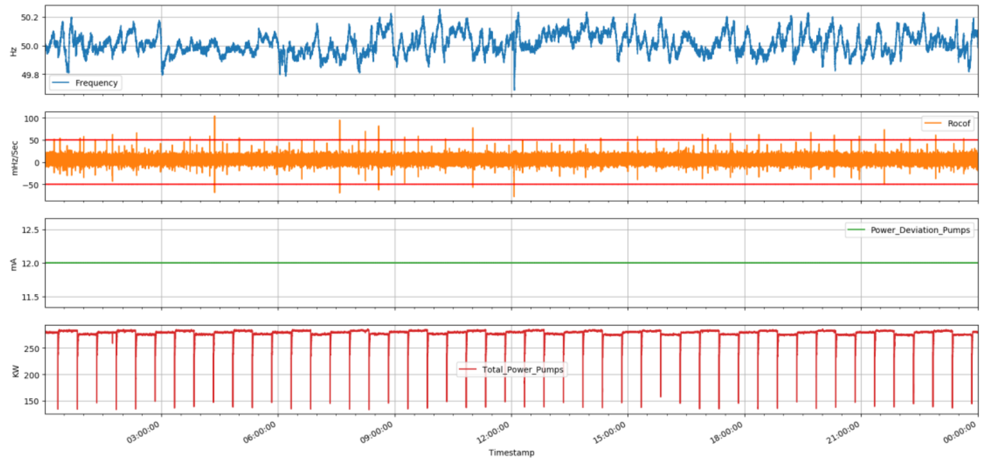


Figure 20 - Pumping station, 7th March 2018 – example of many RoCoF events in single day

6.3.1.2 Negative RoCoF event

Figure 21 shows an example of a power response to a negative RoCoF event. The orange RoCoF line breaks the deadband and remains outside the deadband for around one second. The green power deviation signal reaches and remains at its limit for around a second. The power consumed by the pumps shown in red reduces from around 290kW (two pumps running) to 175kW, before returning to its original value. Note that the nadir of the power deviation signal coincides with the RoCoF deviation, and that the power reduction occurs after a short delay. This shows the relative speed of converting RoCoF to a power deviation signal and of the site responding to the signal. In this example it would appear to take less than one second to fully respond.

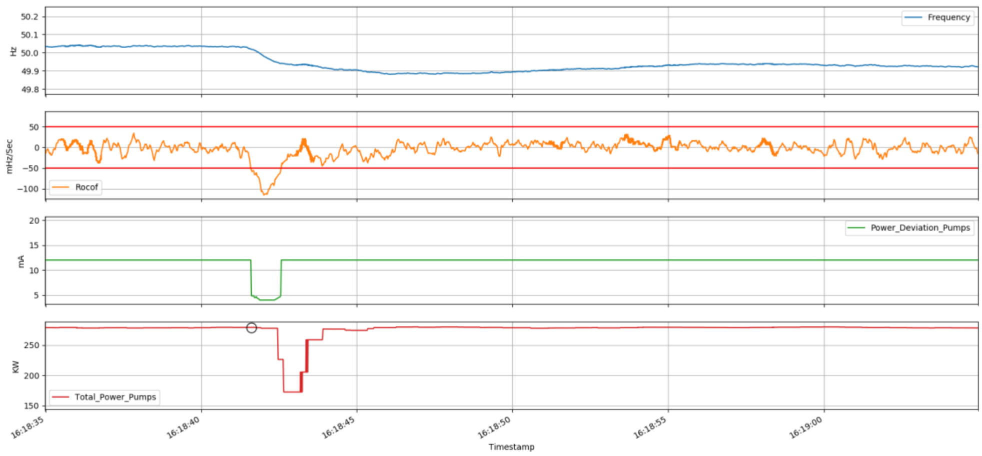


Figure 21 - Pumping Station, 1st March 2018, 16:18, example of negative RoCoF event

6.3.1.3 RoCoF event with multiple negative spikes.

Figure 22 shows a case of a RoCoF event with multiple negative spikes. The RoCoF signal crosses the deadband several times over a period of approximately 2.5 seconds. As the power deviation signal reaches its maximum at -80mHz/s and has the cubic root adjustment, the power deviation signal routinely get close to or reaches its limit. The slight delay in reaction from the equipment turns several close downward spikes in the power adjustment signal into one longer dip in power consumption of the pumps. During this example, only one pump was operational hence the lower baseline power of around 140kW. The resulting power change is similarly reduced.

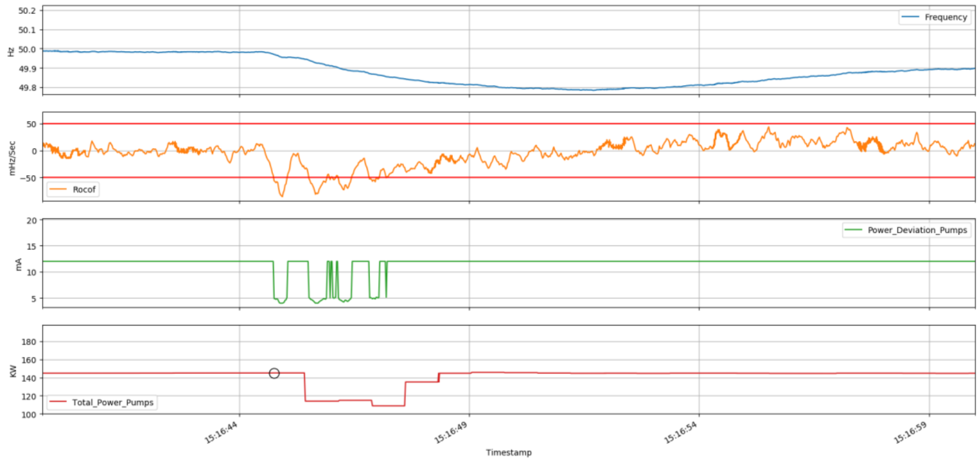


Figure 22 – Pumping Station, 24th February 2018, 15:16, example of RoCoF event with multiple negative spikes

6.3.1.4 Positive RoCoF event

The pumping station also experienced positive RoCoF events, where an increase in power consumption would be the required response. When two pumps are running they operate at the maximum permitted flow rate for the site therefore cannot increase power further during these periods. When one pump is running it operates at its maximum power therefore the only way power consumption can increase is to start a second pump.

An example of such an event is shown in Figure 23. The power increases from around 150kW to around 250kW but takes around three seconds to happen, by which time the RoCoF condition has passed. The system has in-built minimum run times for the pumps, so the power consumption remains at a higher level for several minutes. It must be concluded that this particular site is not suited to respond to positive RoCoF events due to restrictive characteristics of its operating parameters. This is a limitation of this particular site but not of pumping stations as a whole. It is conceivable that another pumping station would not have these limitations and would be able to respond as easily to positive RoCoF events as to negative ones. In fact, running sites with variable speed drives at 100% consumption is not the norm, as VSDs are normally specified where an energy saving can be made by running at part load.

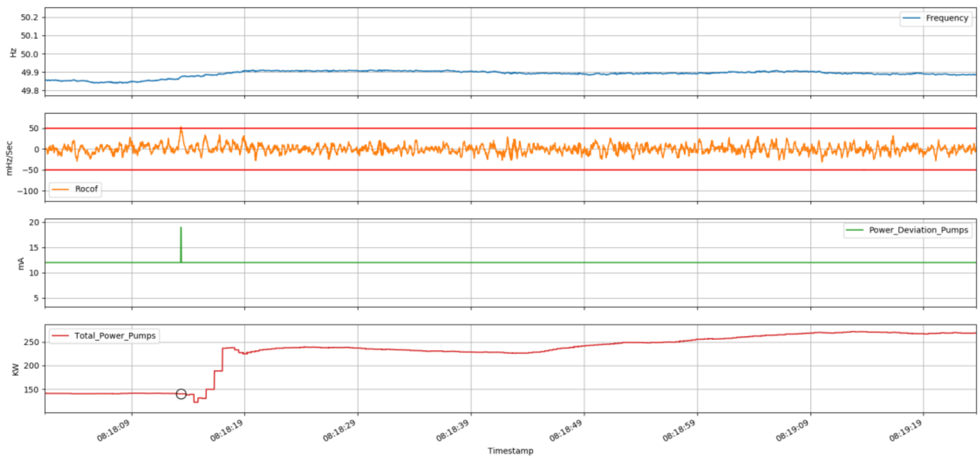


Figure 23 - Pumping Station, 1st March 2018, 08:18, example of positive RoCoF event starting second pump

6.3.2 Wastewater Treatment Works

The Wastewater Treatment Works first went live for operation on 5th December 2017. The months following were spent refining and adjusting the setting for the RoCoF calculation and power deviation output. The final changes were made on 13th March 2018 (see Table 2) after which the settings remained unchanged until the end of the trial. Of particular note at this site was that the RoCoF signal was particularly active; in fact it was by far the most active of the DR sites in the trial. This led to this site's deadband being expanded to 140mHz/sec. In spite of having the largest deadband, this site still experienced more RoCoF event and activations than the other DR sites (see Table 5), however, it also meant that the frequency events experienced at this site tended to be shorter in duration. It may be relevant that this site is in a rural location.

The sites has two units: the Aeration Blowers and the RAS Pumps. The blowers are on average available for 14.1 hours per day while the pumps averaged 19.3 hours of availability per day during the trial.

To better understand the site's equipment response, testing was carried out where the power deviation signal was manually controlled to produce the maximum or minimum output (4mA/20mA) but with pulses of varying lengths. The pulse testing of the blowers and pumps is shown in Figure 24, Figure 25, Figure 26 and Figure 27. The pulses were of 30, 50, 80, 100, 130, 150, 200, 350, 500, 1000, 2000, 5000 milliseconds in length and were injected in order of ascending length.

The positive RoCoF injection (20mA inputs for the power deviation signal) for the blowers (Figure 24) shows that a power increase of up to 25kW from a starting point of approximately 95kW is possible but only with the more long term spikes, in this case the last and widest spike which was five seconds long. Power increase of 5kW only occurs when pulse is greater than one second. The negative pulses (Figure 25) were carried out when only one blower was operational hence the lower baseline demand of around 65kW. Again it is noticeable that spikes in power are relatively small except for wider input pulses which correspond to the pulses wider than one second.

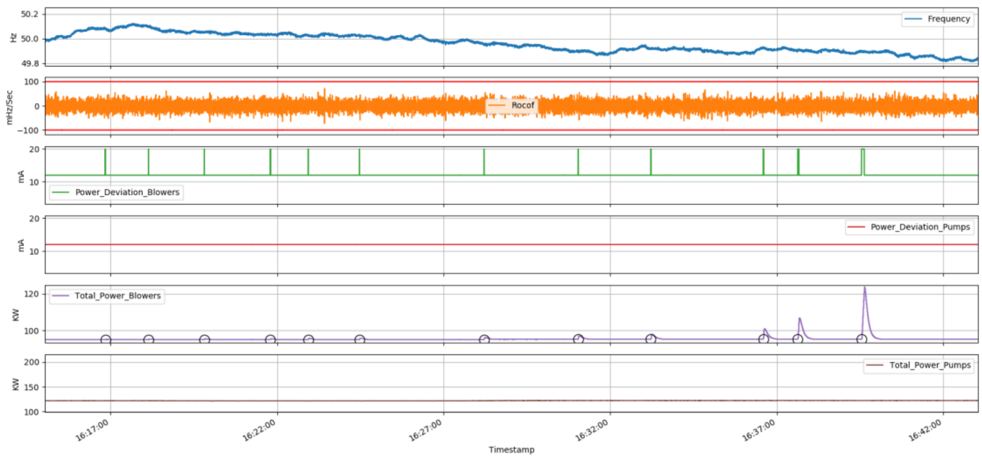


Figure 24 - WwTW, 27th February 2018, positive RoCoF injections for blowers with two blowers operational

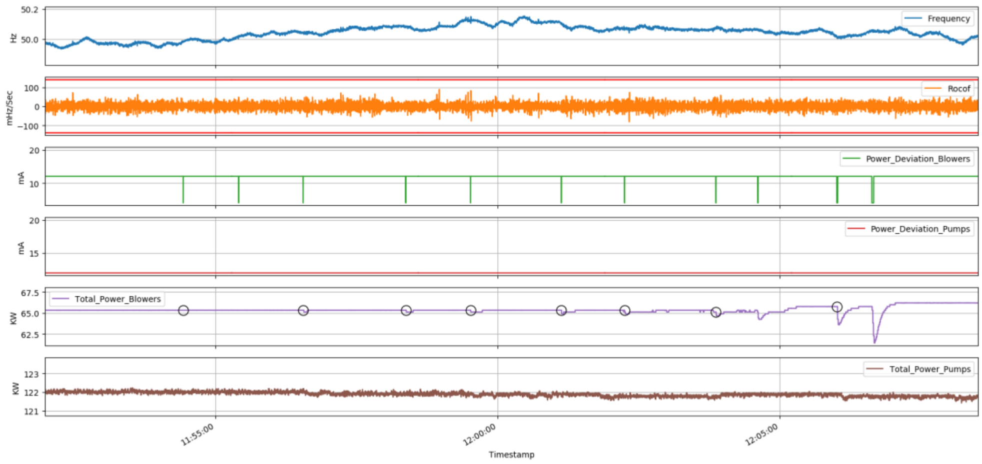


Figure 25 -WwTW, 23rd February 2018, Negative RoCoF injections for blowers with one blower operational

The RAS pumps showed similar behaviour to the blowers in that the larger power changes only occur for the wider pulses. A significant difference is that the pumps are providing greater power delta that the blowers particularly for power increase (Figure 26) where the power can increase by up to 75kW. Therefore it is expected that larger power deltas will be observed from the pumps than from the blowers.

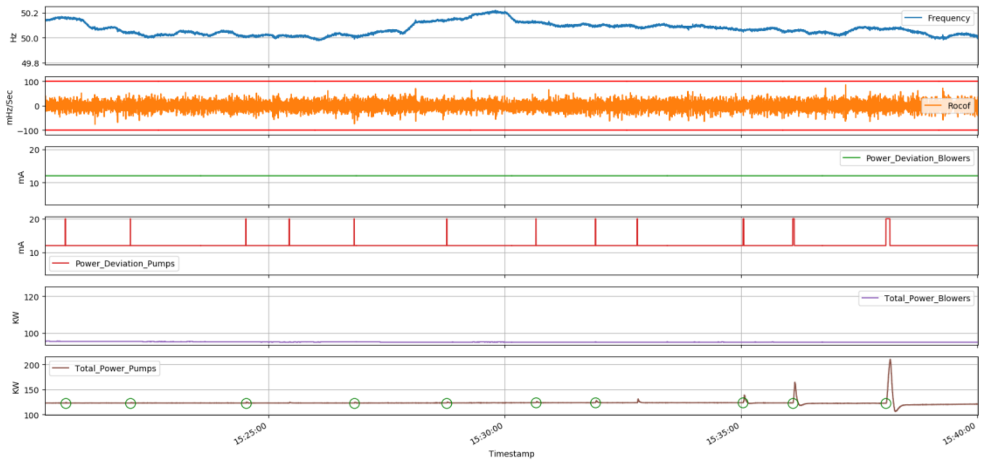


Figure 26 - WwTW, 27th February 2018, positive RoCoF injections for RAS Pumps

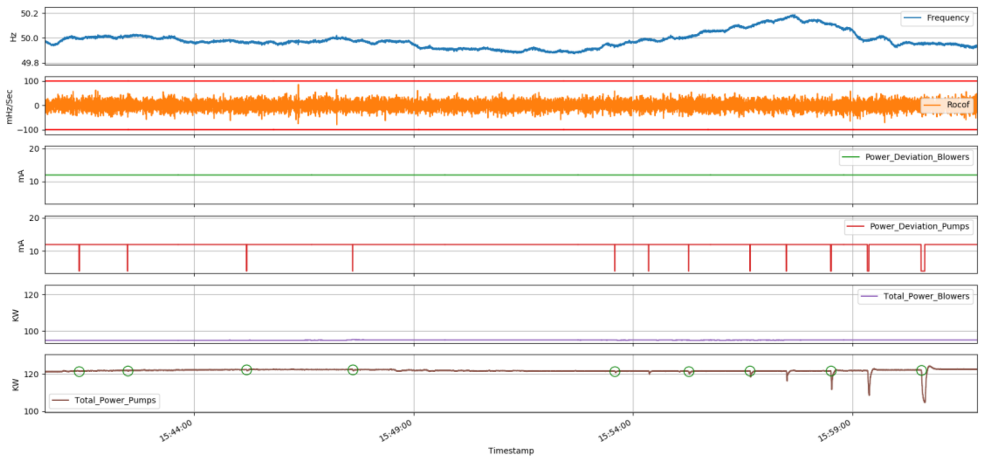


Figure 27 - WwTW, 27th February 2018, negative RoCoF injections for RAS Pumps

6.3.2.1 Positive RoCoF event for Blowers

An example of a positive RoCoF event impacting the blowers is shown in Figure 28. Interrogation of the logs show that the RoCoF increases beyond the dead band at 12:19:13.68 and returns inside the dead band 80ms later. During this event one blower was operational and it showed an increase of power from 50.64kW to 50.85kW at 12:19:14.18, which is 0.5 seconds after the event started. The blowers' power remained at 50.85kW level for over nine seconds before returning to the normal level at 12:19:23.54.

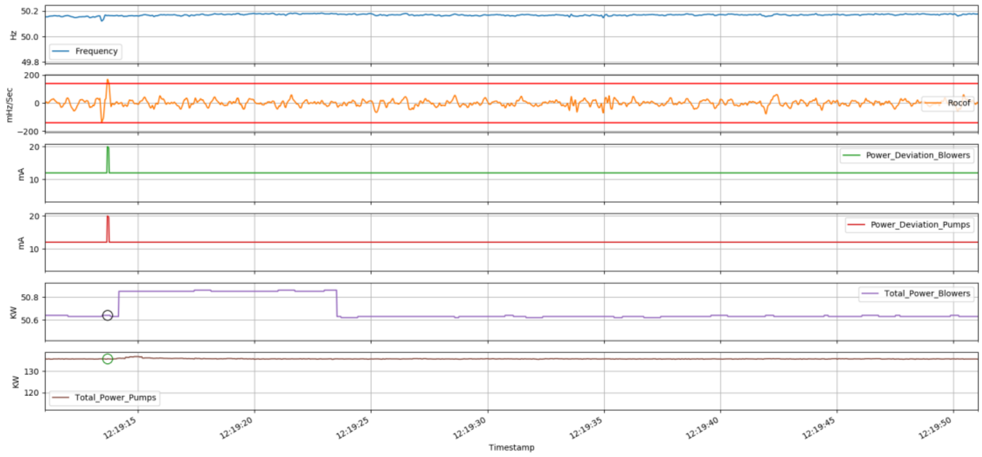


Figure 28 - WwTW, 3rd April 2018, 12:19, positive RoCoF event for Blowers

6.3.2.2 Negative RoCoF event for RAS Pumps

An example of negative RoCoF event response from the RAS Pumps is shown in Figure 29. The frequency breaks the lower deadband at 16:25:04.82 and returns within the deadband 60ms later. The power deviation signal responds 20ms after the frequency crosses the deadband. The RAS pumps power decreases from 125.6kW to 125.0kW. The decrease in power from the pumps begins at 16:25:05.06, with the minimum reached at 16:25:05.94, before returning to 125.5kW at 16:25:06.08. The pumps take around 0.25s to start, requiring about one second to reach its maximum response and about 1.2s to return to normal after the event. Only 20ms of this delay is due to the PLC producing the power deviation signal.

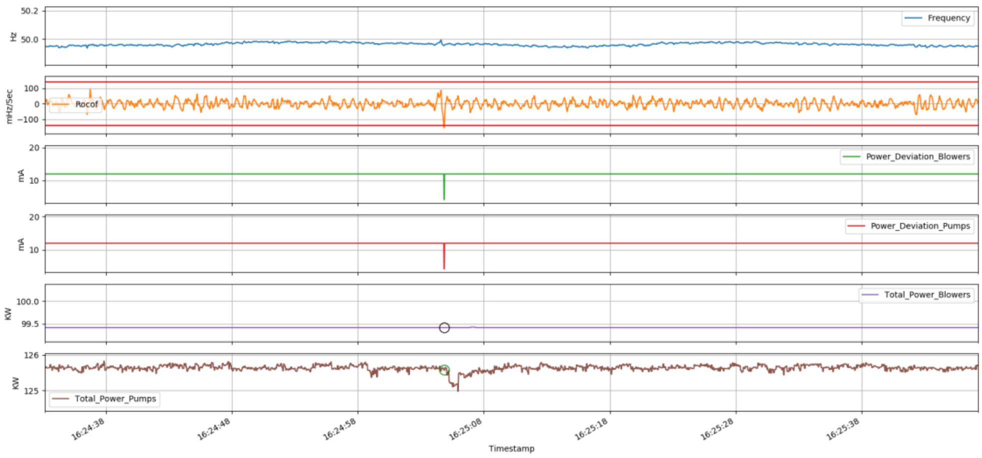


Figure 29 - WwTW, 28th May 2018, 16:25, negative RoCoF event for RAS Pumps

6.3.2.3 Positive RoCoF event for RAS Pumps

A positive RoCoF event response was recorded by the RAS pumps on 20th April 2018, at 19:32 (see Figure 30). The RoCoF breaks the upper deadband limit at 19:32:32.74 and returns within the deadband at 19:32:32.82. The power increases from 122.9kW to 124.9kW reaching its peak at 19:32:33.74 and returning to below 123kW at 19:32:35.34. Therefore the pumps took one second from the start of the event to reach maximum power, and 2.5 seconds to return to normal following the end of the event.

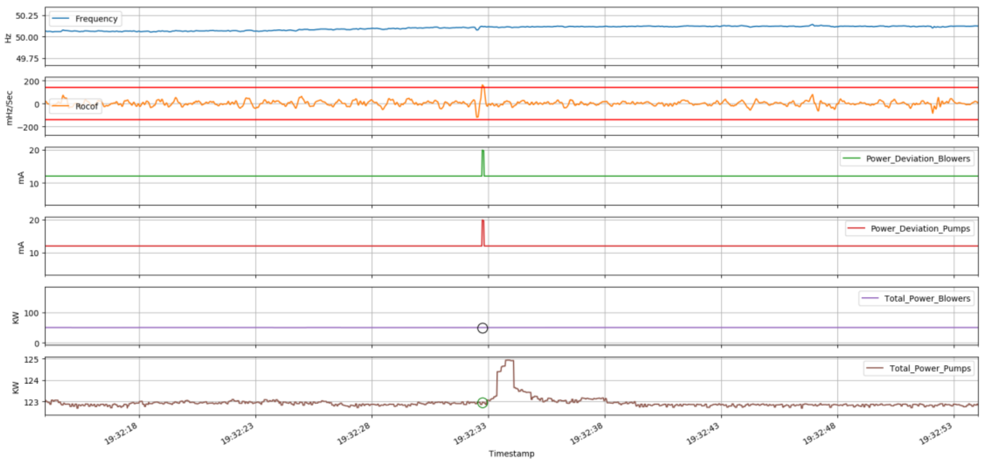


Figure 30 - WwTW, 20th April 2018, 19:32, example of positive RoCoF event for RAS Pumps

6.3.3 Cold Store Facility

The cold store facility went live for operation on 16th January 2018, with the final settings established by 26th January. The final settings include a dead band of +/-55mHz/s, which is slightly higher than the pumping station but much lower than the WwTW. Over the trial period the cold store was available for on average 10 hours per day. This cold store has participated in Short Term Operating Reserve and therefore has proven capability to sustain a load interruption for at least two hours without disruption to core business.

Where both compressors are operational they have an electrical load of around 85kW in total, and the maximum power deviation is around +/-10kW. When one compressor is operational the site remains available but the power consumption and available power delta is reduced. Pulse testing was carried out where the maximum power deviation input (4/20mA) was input for different durations. The results of these tests are shown in Figure 31 and Figure 32. It can be seen that even the shorter pulses (seen on left hand side) produce a noticeable change in power consumption and that the maximum power output delta can be achieved with a pulse as narrow as 150ms.

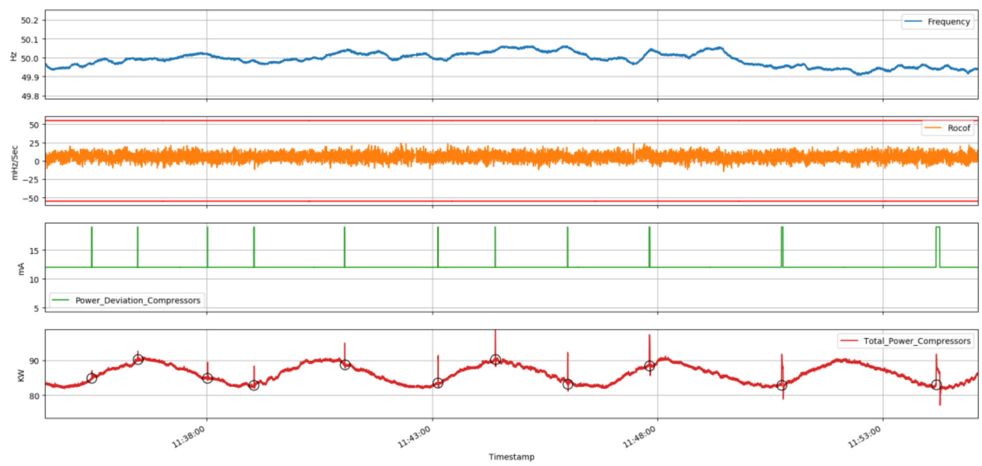


Figure 31 - Cold Store, 8th of March 2018 – positive RoCoF injections

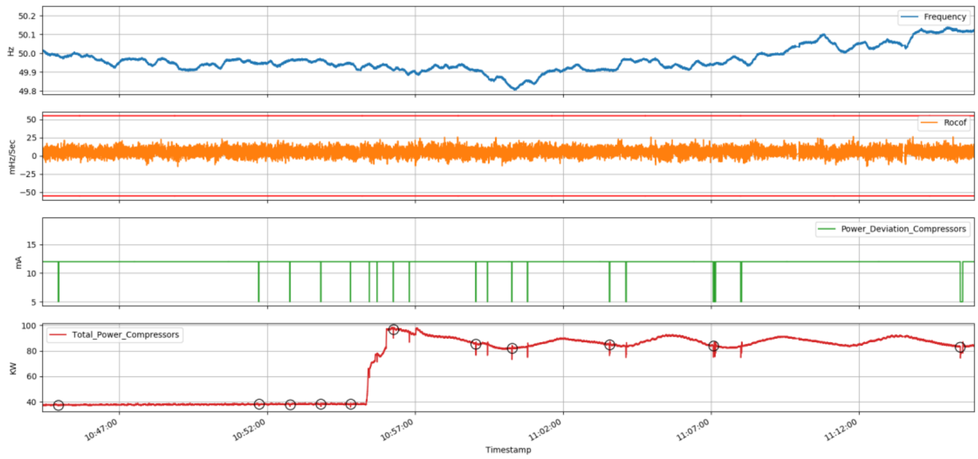


Figure 32 - Cold Store, 8th March 2018, negative RoCoF values injected with a series of time intervals

6.3.3.1 Negative RoCoF event

The cold store experienced many negative RoCoF events; one such event occurred on 29th January 2018 at 21:15. This was nationally noticeable frequency event, and mains frequency decreased to around 49.74Hz. The RoCoF broke the lower deadband on two occasions in quick succession. The initial power deviation lasted for 240ms while the second deviation lasted for only 50ms. The first event resulted in a power reduction from 84.3kW to 75.9kW, a reduction of over 8kW, while the second one gave a deviation of around 2kW. In both cases the power deviation began 10ms after the RoCoF crosses the deadband. In the first RoCoF event it took 0.3s from the start of the power deviation signal for the power to reach its minimum value.

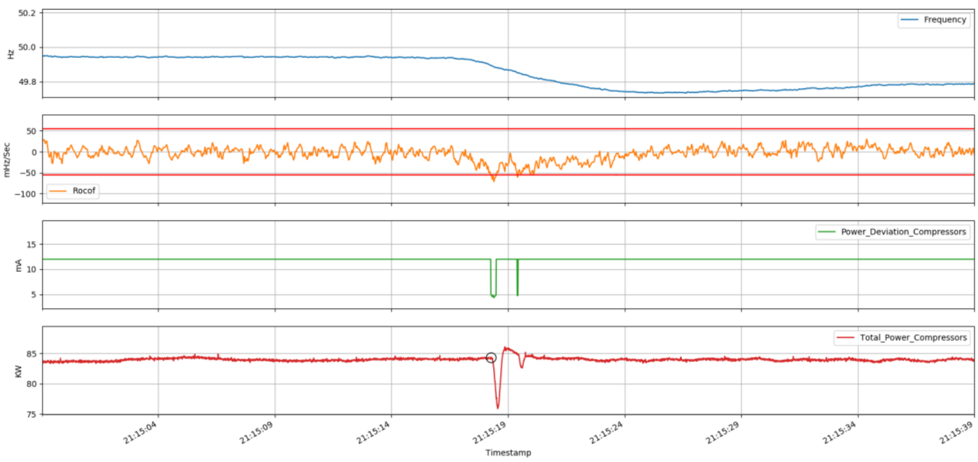


Figure 33 - Cold Store, 29th January 2018, 21:15, example of negative RoCoF event

6.3.3.2 Positive RoCoF event

The cold store also experienced numerous positive RoCoF events. One such example took place on 4th February 2018 and is illustrated in Figure 34. The frequency momentarily rises, leading to the RoCoF increasing beyond the upper deadband limit. Logging of the event shows that the RoCoF breaks the deadband at 15:41:41.46, and the power deviation signal begins to change at 15:41:41.47. The RoCoF remains above the deadband until 15:41:41.57. The power varied from a starting point of 80.1kW to a peak of 85.4kW at 15:41:41.68. So the RoCoF event lasted for 110ms, the power deviation signal took 10ms to respond, and the site equipment took around 210ms to provide 5kW of power adjustment.

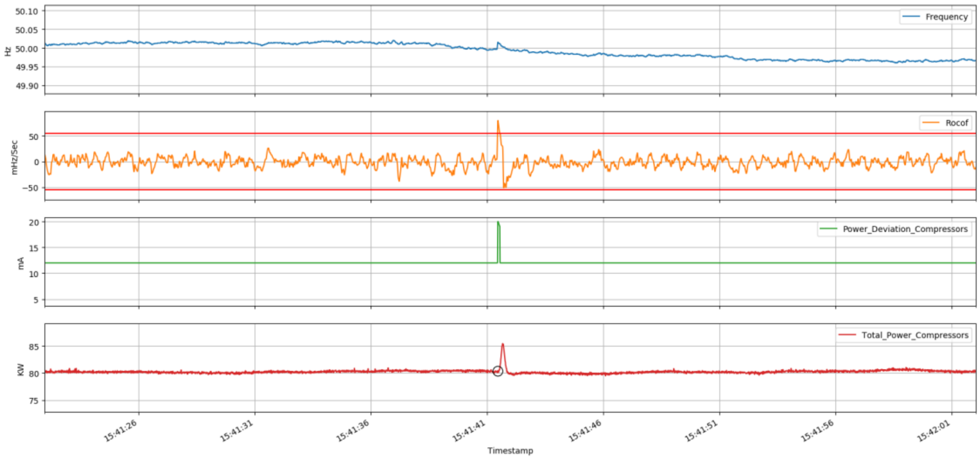


Figure 34 - Cold Store 4th February 2018, 15:41, example of positive RoCoF event

6.3.3.3 Positive and Negative RoCoF events in quick succession

Occasionally positive and negative RoCoF events can occur in quick succession. This happens when the frequency returns to its previous value following a short deviation. Such events may be driven by transmission circuit outages rather than failed infeeds. The cold store had such an event on 30th April 2018 as shown in Figure 35. The event involves a negative spike starting at 13:24:32.38 and ending at 13:24:32.48; the following positive spike started at 13:24:33.08 and ended at 13:24:33.18. The power deviated from a starting value of 86kW to a minimum value of 82.8kW at 13:24:32.64 (around 250ms after the negative event started) and reached its maximum of 89.5kW at 13:24:33.28 (200ms after the positive RoCoF event occurred).

Figure 35 - 30th April 2018, 13:24, example of positive and negative RoCoF events in quick succession

6.3.3.4 Multiple RoCoF events in with multiple spikes

Occasionally when the RoCoF is in the region of the deadband, it will cross the boundary several times, creating a series of spikes in the power deviation signal. This provides a good opportunity to demonstrate the speed and agility of response from the power deviation. A good example of this behaviour is shown in Figure 36 from 7th March 2018. It can be seen from this example that the compressor power signal largely follows the power deviation signal, though the response of the compressors is not quite as quick as the PLC's, hence the more rounded spikes and the absence of some of the narrower spikes in the compressor power signal. Nevertheless, the response is quick enough to provide eight distinct negative spikes in power in a period of less than 5 seconds. When compared to a similar event at pumping station (in section 6.3.1.3), the cold store clearly shows a more nimble response. This may in part be due to the more direct communications arrangement at the cold store, where the power deviation signal connects directly to the compressor controls, but is likely also to be assisted by more agile settings within the compressor controls.

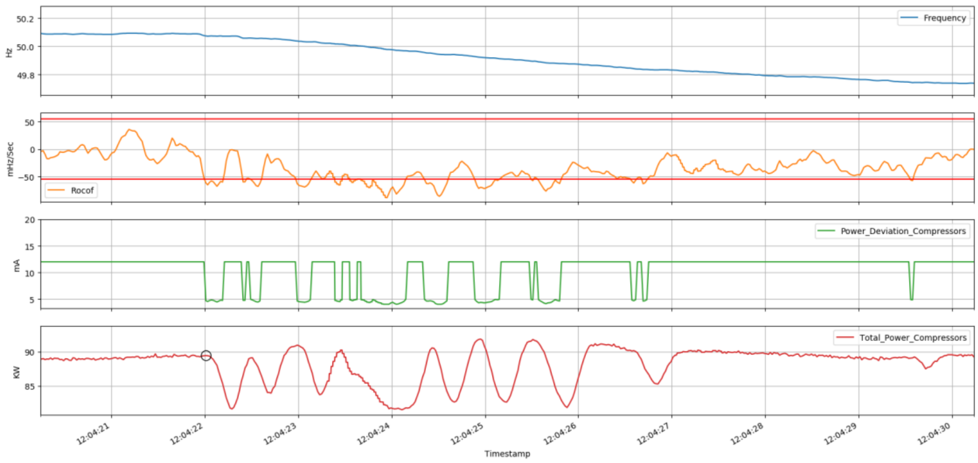


Figure 36 - Cold Store 7th March 2018, 12:04, example of multiple negative RoCoF event in quick succession

The cold store clearly has the capacity to respond to both positive and negative RoCoF events. The capacity provided is relatively small but the speed of response at this site is particularly fast. This demonstrates how differences in the technical configuration of sites can give rise to large differences in speed of response.

6.3.4 Comparison of RoCoF and Frequency measurement across Dynamic RoCoF sites

It has been noted through commissioning and trials at the Dynamic RoCoF sites that the RoCoF signal can differ from one site to another. This section considers this difference in the RoCoF and frequency at different sites rather than considering the site's response. The examples in this section consider frequency and RoCoF events that were notable national events.

The following graphs show frequency and RoCoF recorded for the same event and for the same time frame across all three Dynamic RoCoF site. The top two rows show the frequency and RoCoF at the pumping station, the middle two rows show the same data for the WwTW and the bottom two for the cold store. In all cases frequency is in blue and RoCoF in orange. Note that the y-axis scale for the RoCoF is not the same for each site. The dead band varies from site to site as described in Table 2 and is shown by straight orange lines on the graphs.

6.3.4.1 Event on 03:10, 3rd of April 2018

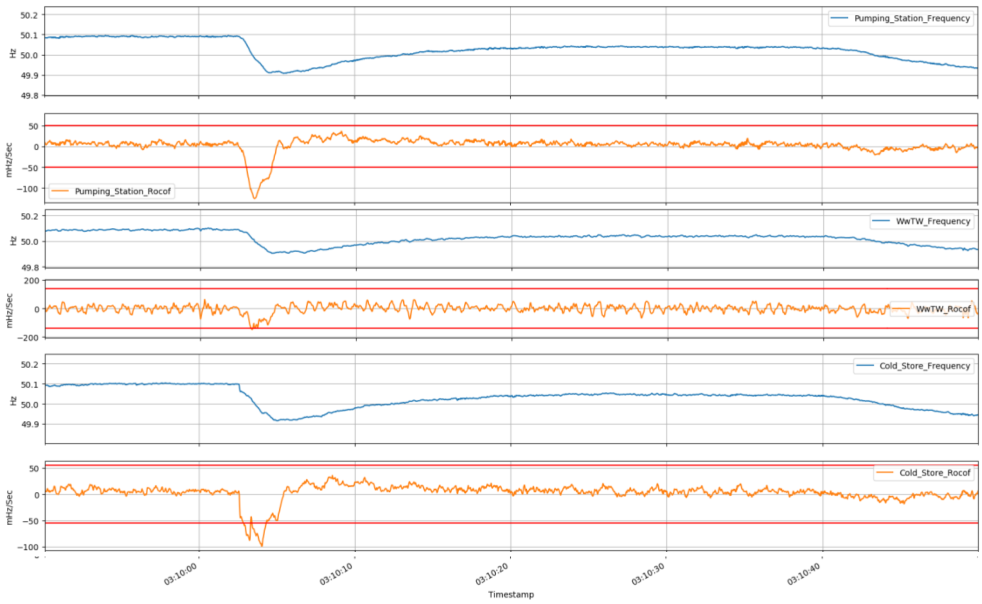


Figure 37 - Frequency and RoCoF for all Dynamic RoCoF sites 03:10, 3rd April 2018

Figure 37 shows the RoCoF event on 3rd of April. A visual inspection of the frequency profiles does not show an obvious difference between the three sites. The main RoCoF spikes at all sites coincide at approximately 03:10:04 and also return to normal values within a similar timescale. However, the RoCoF profiles show notable differences. Firstly, the downwards spike at the WwTW is larger in magnitude reaching -140mHz/s, while on the other sites the maximum value is around -100mHz/s. Note that the response at the WwTW would be less noticable that at the other sites due to the wider dead band with the RoCoF line barely cross the deadband limit. The RoCoF at this site is also significantly more active that at the other sites, with the RoCoF exceeding 50mHz/s several times within the sample period while at the other sites this happens only at the main event. The pumping station and cold store show a similar magnitude of RoCoF but the main spike is noticeably different with the pumping station having one wider spike versus the cold store’s two smaller spikes.

6.3.4.2 Event at 02:42, 2nd May 2018

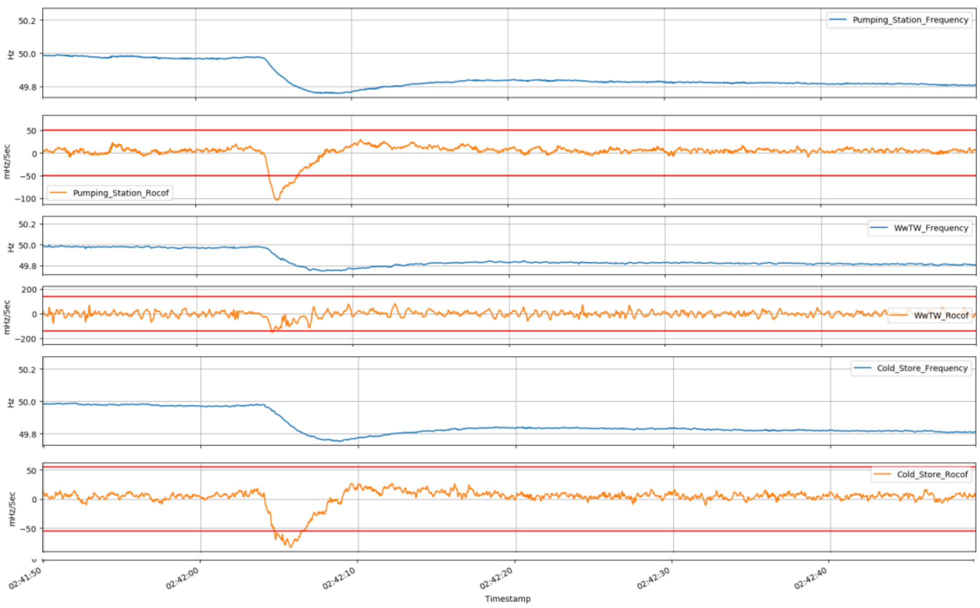


Figure 38 - Frequency and RoCoF for all Dynamic RoCoF sites 02:42, 2nd May 2018

The frequency profile at all three sites in Figure 38 show the frequency decline from 50Hz to 49.8Hz at approximately 02:42:05. The RoCoF profiles show each site's RoCoF reach its nadir at around the same time and recover to more normal levels within about five seconds. Notable differences between the sites are that the WwTW's largest spike is much larger than at the other sites (reaching the WwTW dead band of -140mHz/s). The WwTW's RoCoF profile is in general more noisy that the other two with the period following the RoCoF spike being particularly turbulent. In contrast the pumping station and cold store show a smoother return towards more normal RoCoF values. There are also noticeable differences between the pumping station and the cold store in this event. The maximum RoCoF value is larger at the pumping station reaching -100mHz/sec while the cold store reaches around -80mHz/s.

6.3.4.3 Event at 09:02, 27th May 2018

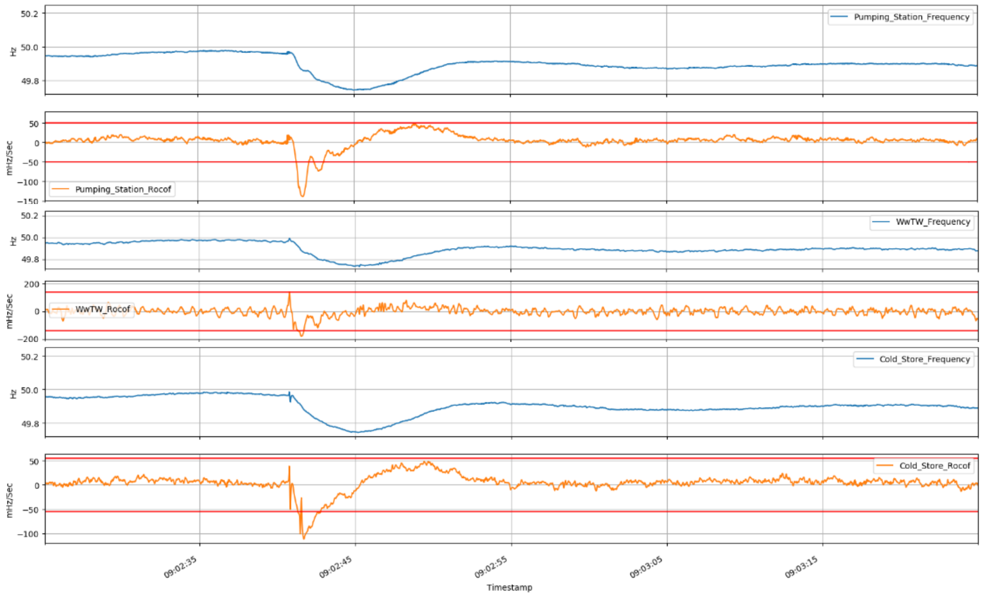


Figure 39 - Frequency and RoCoF for all Dynamic RoCoF sites 09:02, 27th of May 2018

Figure 39 shows the frequency event on the 27th of May. The frequency profile is similar on all three sites though, on this occasion, before the large drop in frequency there is a small positive spike. On visual inspection, this positive spike is less prominent at the pumping station than at the other two sites. The cold store also displays a noticeable sharp downwards spike - immediately after the positive spike but before the main frequency drop – which is not noticeable at the pumping station or WwTW. The RoCoF profiles again show the main RoCoF event occurring at the same time - around 09:02:41- then returning towards 0mHz/sec within a few seconds, but the shape of the response show differences between the sites. The WwTW displays greater upwards and downwards spikes at the start of the event – reaching both the upper and lower 140mHz/sec deadband – and shows a more active RoCoF throughout the sample period. The WwTW and cold store both show a positive RoCoF spike at the start of the event which is much less noticeable at the pumping station. The large negative RoCoF event is much smoother at the pumping station that the cold store where the downwards slope of RoCoF contains some noticeable spikes.

Scrutiny of these cases indicates that the recorded frequency across different locations will have a similar profile but that the RoCoF profile is noticeably different from one location to the other. Notable national events elicit a response at all sites, the RoCoF spikes occur at the same time and last for a similar period of time, but the shape of response differs from site to site. Also of note is that the site with a generally more active RoCoF – in this case the WwTW - appear to experience a noisy signal at all times and higher spikes during frequency events. This would suggest that setting of deadband levels and RoCoF algorithm would be a precondition of operating this service on further sites.

7 Testing Limitations

7.1 Static RoCoF – Testing Limitations

A Static RoCoF event leading to an equipment shutdown would have a significant bearing on our partner site, impacting production in the short term and leading to subsequent rescheduling in the longer term. For this reason, constraints on the Static RoCoF trial were a prerequisite condition for the participation of the site. The site limited the number of RoCoF trips in the trial to ten (later reduced to five) and the number of live hours to 2000 (later reduced to 1000). The compressor can only shut down when it is running, so the live trial had to be fitted in with the site's operating schedule. This meant that when a RoCoF event occurs, there is no guarantee that the unit is armed and ready to respond.

With a limited number of shutdowns permitted in the trial, it was imperative that any unnecessary shutdowns were avoided. This compelled us to commence the trial with cautious trip settings and with a lengthy disarmed period. The high frequency spikes also led to a further disarm period as a solution was pursued and, once applied, confidence was built that it was effective.

The target occurrence of RoCoF trips was ten per year. It would take a lengthy period – realistically longer than the trial – to know for certain that the correct settings are in place to achieve this regularity of events. Issues with data gaps led to uncertainty over the legitimacy of RoCoF trips that were detected in the early part of the trial. This restricted the opportunity to draw any firm conclusions about the suitability of any given set of trip requirements.

7.2 Spinning Inertia – Testing Limitations

The Spinning Inertia trial was limited by the number of hours during which engines were running. Data were collected during specific Spinning Inertia mode running and also during red rate running periods. For the majority of the trial – on both sites – this amounted to 25 hours per week or around 15% of the time. This assumes perfect availability which was not always the case. Because of the limited running hours, some RoCoF events occurred during periods in which the CHPs were not active.

In the case of the District Heating site, it was impossible to find a location electrically where the combined power output of both CHPs could be measured in isolation from significant site loads. Instead, the data logger was connected to read the output of CHP1 only. This was a problem during periods in which only CHP2 was running, where no useful data is recorded.

There were also limitations in relation to data collection as described above. Because RoCoF events are rapid, high resolution monitoring is required, which led to data management issues in this demonstration project. These were overcome by upgrading connections and adding a dedicated data server. In a commercial deployment, it may not be necessary to record the same volume of data, hence these issues may not be relevant.

7.3 Dynamic RoCoF – Testing Limitations

The trial involved working with the real mains power supply and real on-site equipment, both of which provide some restrictions.

The mains power supply is unpredictable and does not necessarily provide the most extreme RoCoF events at a suitable moment to demonstrate the equipment power response. The aim with a trial operating over several months was that it would show the equipment dealing with a realistic RoCoF profile which would include a share of the larger RoCoF events.

Each site's participating equipment had its own performance and availability limitations related to their equipment functional limitations and operational characteristics. All participating units consisted of a number of components (i.e. pumps, blowers or compressors) that are switched on and off in response to their site's operational needs. The available capacity is proportional to the number of components running at any given moment. This means that the available capacity change regularly including periods when it is zero.

It is important to note that these limitations were imposed largely because the EFCC project was a trial, and there was no track record for site staff to consider when considering the risk of disruption. In a fully commercial service, these limitations would be reviewed, and the availability could be monitored and re-declared continuously.

The pumping station mostly has one pump running, occasionally two pumps and more rarely no pumps are running. When one pump is running it typically runs at full power so there is capacity to turn down but power can only be increased by starting the second pump which is slower than turning up a running pump. When two pumps are running they are limited by the maximum flow rate and cannot increase power. So the pumping station is more suited to reducing power than to increasing it. The available capacity is larger when two pumps are operational

The WwTW's pumps are only available for Dynamic RoCoF when all four pumps are operational. The pumps normally operate at around 55% of full speed but can be adjusted within the range of 50-100%. So the pumps have greater capacity for increasing power.

The WwTW's blowers usually operate with one blower running, though occasionally a second blower will operate for 15-20 minutes at a time. The blowers typically operate at between 85-100% of full speed but can turn down to 50%, so can provide greater adjustment when decreasing power.

The cold store typically has one or two compressors running and occasionally has no compressors running. The compressors are equally capable of increasing as decreasing power consumption. The capacity increases when both compressors are operational.

On all participating sites, the available power varied substantially within day but in a non-uniform fashion. The trial was too short to identify any seasonal patterns in any of the sites capacities, though because of the natures of these loads it is highly likely that such patterns do exist.

8 Conclusions & Learning Outcomes

8.1 Static RoCoF – Conclusions and Learning Outcomes

Static RoCoF is a viable service, in that the site has shown that a load can be set up to respond to a RoCoF condition in a period of time shown to be less than 1.5seconds and estimated to be 0.75seconds. It is notable that none of the RoCoF events involve the frequency being less than or equal to 49.7Hz, so Static RoCoF units would generally be responding earlier than static frequency response units, or on occasions when there is no static frequency response.

The trial site had intermittent but generally predictable availability. It seems reasonable that its participation in a live Static RoCoF service could be managed. It also seems realistic that several of Flexitricity's current partner sites would have suitable operational characteristics for participation in any future service though it would need to be economically advantageous for them to do so.

For any live service it would need to be considered whether the equipment used for the trial would be the most suitable for this role. To decide this it would need to be considered exactly what the performance requirements are for the live service and what qualification testing is required.

It is clear that the original trip setting was unlikely to lead to the desired number of RoCoF events. The adjusted settings (post 13th March 2018) gave a result which was closer to the desired level of 10 trips per year. The trial was too short to be able to say if they require further refinement. It is also unknown whether the same RoCoF setting would provide the same or different amounts of RoCoF events at different locations.

8.2 Spinning Inertia – Conclusions and Learning Outcomes

CHP engines have the capability to adjust their generation output significantly in a sub-second timeframe. However, their natural behaviour in response to system disturbances may not be perfectly aligned with the needs of the national electricity system, and it may be preferable to introduce active RoCoF-related control.

It is known that all synchronous machines exhibit oscillation when a major disturbance occurs. The smaller CHP engines have been shown to do this, just as large power stations do. However, at times we noted that the inertia effect appeared to be in phase with the requirement, but at other times it appeared to be out of phase with it.

This may be a result of successful and rapid governor control at the CHP engines. It is normal in commissioning closed-loop control systems such as those which control power output at CHPs to be set with a slightly underdamped response, because this typically achieves the best compromise between speed and stability. The downside for EFCC is that such governors may be responding too quickly to the frequency deviation, and oscillating slightly about the target set point. This is technically plausible, given the capabilities of modern engine management units.

However, this conclusion suggests that more complex control is likely to be feasible. CHP engines could be given a control signal derived from locally-measured RoCoF which directly causes RoCoF delivery. This would be an application of Dynamic RoCoF to high-load-factor generation.

This was out of scope for the EFCC project, but it is a promising line of enquiry for future development.

8.3 Dynamic RoCoF – Conclusions and Learning Outcomes

It clearly possible for Flexitricity to provide Dynamic RoCoF through aggregation of assets on third party sites and to provide positive and negative capacity in response to changes in locally measured RoCoF. There are a number of notable lessons taken from these trials that would inform a future Dynamic RoCoF service.

On the basis of the units participating in this trial, availability of units and available capacity of individual units can vary considerably within each day. Development of algorithms to predict the available power for any given moment was out of scope for the EFCC project, but other work within Flexitricity shows that it is tractable. Additionally, a wider population of sites and site types would create diversity leading to greater security.

An important issue to consider is that the power delta that the units provide is the significant value, not the power deviation signal communicated to the site from Flexitricity's on-site equipment. Calibration of the power output is particularly important. Where the site load is inherently non-linear a correction to the power deviation signal is required.

A vital issue for a site participating in Dynamic RoCoF is the speed of response of the equipment. This contains two components: the speed of calculation, and the speed of action from the equipment. During this trial, the typical speed of calculation – from a RoCoF event to a power deviation signal – is around 0.02 seconds. The speed of response of the equipment is then a site-specific parameter. It takes approximately one further second to provide a power response at the pumping station and the WwTW, and around 200ms to respond at the cold store.

We note that no optimisation of the control parameters within those sites' internal control systems was carried out; we approached the equipment "as is".

At the cold store, the power deviation signal is wired directly into to the compressor controls rather than via a PLC controller. This control method may be partially responsible for the consistently faster response from the cold store. The cold store's faster response also allowed it to respond to shorter duration events but also to return to normal after the RoCoF has returned to zero faster as well. Additionally, internal control parameters within the other sites' control systems may be deliberately slowing down the response, purely because prior to the EFCC project, there was no need for anything to move any faster.

In terms of the stability of the incoming mains supply, different locations can have significantly different RoCoF behaviour, even if – as in the case of the pumping station and the WwTW – they are relatively close geographically. Therefore different sites would either require different sets of trip requirements or would experience different amounts of power adjustments. It would probably be difficult to know how many responses would be triggered by a given set of RoCoF parameters or indeed what parameters would be required for a given level of activity without local data collection. We therefore consider that site "tuning" is likely to be needed to determine the best control parameters for any given site.

9 Suggested Future Work

9.1 Static RoCoF - Suggested Future Work

Further work is required to remove the periodic frequency spikes from the PMU frequency data.

Significantly different frequency and RoCoF behaviour has been observed on the mains supply in different locations. For both Static RoCoF and Dynamic RoCoF, this would mean using different activation settings or having sites with different utilisation profiles. Further investigation into the variation in frequency and RoCoF by location, type of connection or supply voltage level could be valuable. Specifically, it would be useful to know to what extent RoCoF and frequency vary between locations, what local factors have an influence and whether a reasonable prediction of RoCoF behaviour can be made for a specific location before installing equipment on site.

It would be worth investigating if the required RoCoF trip functionality could be provided with less complex equipment.

9.2 Spinning Inertia – Suggested Future Work

The engines have the capability to adjust their input significantly in a sub-second timeframe. Managing the power output in response to an analogue input would be worth further investigation, specifically investigating how quickly the engine power can be adjusted and by what magnitude. We believe that this would be an essential stage in harnessing embedded synchronous generators to an inertia/RoCoF service. In theory, this could be done by adjusting the behaviour of engine governors in a manner similar to the strategy adopted by project partners at CCGT stations. However, we believe that a better approach to embedded generators is to apply an external demand signal to the generator controls, in a manner similar to the Dynamic RoCoF trials.

9.3 Dynamic RoCoF – Suggested Future Work

Further work could be carried out to understand speed and availability patterns of response that could be provided by different equipment types for Dynamic RoCoF. Further investigation into factors influencing frequency and RoCoF variations, as described in section 9.1, would also be relevant to Dynamic RoCoF.

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